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Free Vibrations of Cylindrical Tanks

Vibrações Livres de Recipientes Cilíndricos

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Abstract

A simple but effective method is presented for evaluating the free vibration characteristics of a fluid-filled cylindrical shell with classical boundary conditions of any type. Effects of static liquid pressure, in-plane inertias and liquid free surface motions are taken into account. A clamped-free cylindrical tank is analysed and the accuracy of the results is demonstrated by comparing them with experimental results found in literature.

Keywords: Thin Walled Shells, Free Vibrations, Fluid-Shell Interaction, Shell Boundary Conditions

Introduction

Knowledge of the free vibration characteristics of fluid-filled cylindrical shells is of considerable practical interest, considering that most cylindrical shells are utilised as containment vessels or tanks for the storage of fluids. The combined effects of inertial loading and hydrostatic pressure on the shell wall, the effects of the free surface motions in shells partially filled with liquid and the coupling between fluid and shell wall motions may affect significantly the dynamic behaviour of fluid filled shells. The study of such topics has led to an extensive literature on the subject. But the majority of these works is concerned with particular sets of boundary conditions for the shell and the fluid medium (Jain,1974, Yamaki et al.,1984, Chiba et al.,1985, Gonçalves e Batista,1987).

The purpose of the present work is to develop a general formulation for the problem, based on the underlying ideas of the hierarchical finite element method, which allows one to obtain the free vibration frequencies and vibration modes of cylindrical shells partially or completely filled with liquid and subjected to any consistent set of boundary conditions.

The vibrations of the shell are examined by using Sanders shell theory (Sanders,1963). The fluid is treated as non-viscous and incompressible and its motion is assumed to be irrotational. In order to solve the problem, the partial differential equations of motion in terms of the shell displacements are transformed into a system of first order ordinary differential equations in terms of the shell displacements and stress resultants and a solution based on the use of linear and trigonometric shape functions is derived. These system variables are those variables which describe the natural and geometric boundary conditions of the shell. The fluid velocity potential is expanded in terms of harmonic functions which satisfy the Laplace equation term by term and the relevant boundary conditions.

Solutions are presented to show the effect of a variable height of liquid on the fluid and shell natural frequencies. They show that the effect of the liquid on thin vertical cylindrical tanks is quite significant and must always be taken into account in design. Comparisons of the present numerical results with those obtained by other theories and from experiments are found to be good and demonstrate the validity of the present methodology (Ramos,1993).

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Basic Theory

Shell Equations

Consider a thin-walled circular cylindrical shell of length L, radius R and thickness h. The shell is assumed to be made of an elastic material with Young's modulus E, Poisson's ratio ν and mass density ρ_c. The bottom of the shell is assumed to be flat and rigid. The radial, circumferential and axial co-ordinates are denoted by, respectively, $\bar{r}$, θ and z and the corresponding displacements on the shell middle surface are in turn denoted by W, V and U, as shown in Fig. 1. The tank is filled to a height H with a non-viscous, incompressible and irrotational liquid of mass density ρ_F. The time is denoted by t.

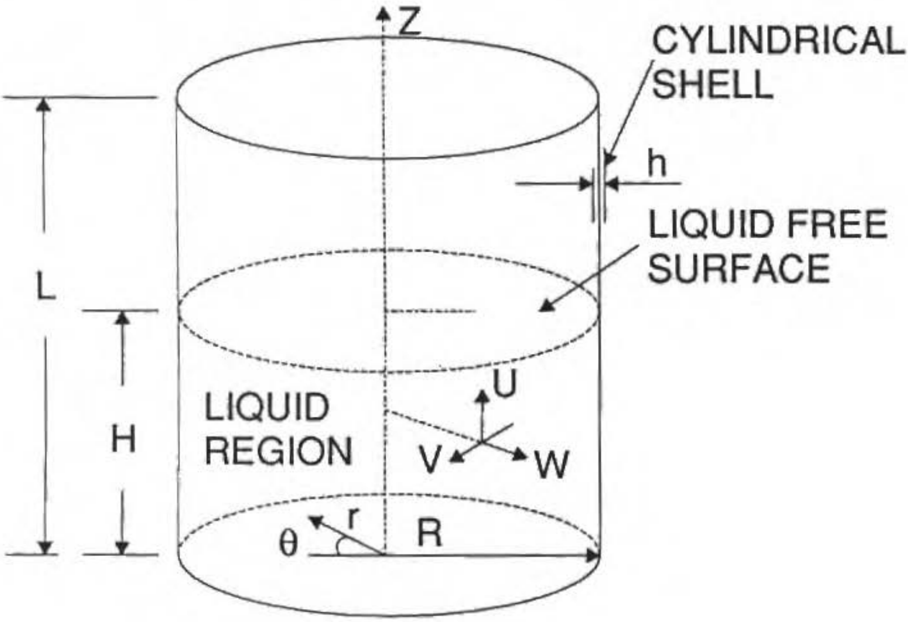

Fig.1 Tank geometry and co-ordinate system

The dynamic behaviour of elastic circular cylinders can be described by the following equations, according to the non-linear shell theory of Sanders (1963)

$$l\left[l\bar{u}_{,\xi} + l^2\delta\bar{w}^2_{,\xi} + \nu(\bar{v}_{,\theta} + \bar{w} + \delta(\bar{w}_{,\theta} - \bar{v})^2)\right]_{,\xi} + a\left[l\bar{v}_{,\xi} + \bar{u}_{,\theta} + 2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta} - \bar{v})\right]_{,\theta} +$$

$$ab\left[l\bar{w}_{,\xi\theta} + \bar{u}_{,\theta}/4 - 3l\bar{v}_{,\xi}/4\right]_{,\theta} - \gamma^2\bar{\ddot{u}} = 0 \qquad \text{(1a)}$$

$$\left[\bar{v}_{,\theta} + \bar{w} + \delta(\bar{w}_{,\theta} - \bar{v})^2 + \nu(l\bar{u}_{,\xi} + l\delta\bar{w}^2_{,\xi})\right]_{,\theta} + al\left[\bar{u}_{,\theta} + l\bar{v}_{,\xi} + 2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta} - \bar{v})\right]_{,\xi} +$$

$$2al\delta\bar{w}_{,\xi}[l\bar{v}_{,\xi}+\bar{u}_{,\theta}+2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta}-\bar{v})]-3abl[l\bar{w}_{,\xi\theta}+\bar{u}_{,\theta}/4-(3l\bar{v}_{,\xi})/4]_{,\xi}+$$
$$2\delta(\bar{w}_{,\theta}-\bar{v})\left[\bar{v}_{,\theta}+\bar{w}+\delta(\bar{w}_{,\theta}-\bar{v})^2+\nu(l\bar{u}_{,\xi}+\delta l^2\bar{w}^2_{,\xi})\right]-$$
$$b\left[\bar{w}_{,\theta\theta}-\bar{v}_{,\theta}+\nu l^2\bar{w}_{,\xi\xi}\right]_{,\theta}-\gamma^2\ddot{\bar{v}} = 0 \tag{1b}$$

$$\gamma^2\ddot{\bar{w}}-\bar{p}+\{\bar{v}_{,\theta}+\bar{w}+\nu l\bar{u}_{,\xi}+\delta\left[(\bar{w}_{,\theta}-\bar{v})^2+\nu l^2\bar{w}^2_{,\xi}\right]\}-$$
$$\{2\delta l^2\bar{w}_{,\xi}\left[l\bar{u}_{,\xi}+\delta l^2\bar{w}^2_{,\xi}+\nu(\bar{v}_{,\theta}+\bar{w})+\delta\nu(\bar{w}_{,\theta}-\bar{v})^2\right]\}_{,\xi}-$$
$$\{2\delta(\bar{w}_{,\theta}-\bar{v})\left[\bar{v}_{,\theta}+\bar{w}+\delta(\bar{w}_{,\theta}-\bar{v})^2+\nu(l\bar{u}_{,\xi}+\delta l^2\bar{w}^2_{,\xi})\right]\}_{,\theta}-$$
$$\{2\delta al(\bar{w}_{,\theta}-\bar{v})[l\bar{v}_{,\xi}+\bar{u}_{,\theta}+2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta}-\bar{v})]\}_{,\xi}-$$
$$\{2\delta al\bar{w}_{,\xi}[l\bar{v}_{,\xi}+\bar{u}_{,\theta}+2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta}-\bar{v})]\}_{,\theta}+bl^2\left[l^2\bar{w}_{,\xi\xi}+\nu(\bar{w}_{,\theta\theta}-\bar{v}_{,\theta})\right]_{,\xi\xi}+$$
$$b\left[\bar{w}_{,\theta\theta}-\bar{v}_{,\theta}+\nu l^2\bar{w}_{,\xi\xi}\right]_{,\theta\theta}+4abl[l\bar{w}_{,\xi\theta}+\bar{u}_{,\theta}/4-3/4l\bar{v}_{,\xi}]_{,\xi\theta} = 0 \tag{1c}$$

Solutions of the foregoing system must satisfy the following natural or geometric boundary conditions at $\xi = 0$ and $\xi = 1$ (Sanders,1963)

$$l\bar{u}_{,\xi}+\delta l^2\bar{w}^2_{,\xi}+\nu\left[\bar{v}_{,\theta}+\bar{w}+\delta(\bar{w}_{,\theta}-\bar{v})^2\right] = n^* \qquad \text{or} \quad \bar{u} = \vec{u}^*$$

$$a[l\bar{v}_{,\xi}+\bar{u}_{,\theta}+2l\delta\bar{w}_{,\xi}(\bar{w}_{,\theta}-\bar{v})]-$$
$$3ab\left[lw_{,\xi\theta}+\bar{u}_{,\theta}/4-3l\bar{v}_{,\xi}/4\right] = t^* \qquad \text{or} \quad \bar{v} = \vec{v}^*$$

$$2l\delta w_{,\xi}\left[l\bar{u}_{,\xi}+l^2\bar{w}^2_{,\xi}+\nu(\bar{v}_{,\theta}+\bar{w}+\delta(\bar{w}_{,\theta}-\bar{v})^2)\right]+$$
$$2\delta a(\bar{w}_{,\theta}-\bar{v})[l\bar{v}_{,\xi}+\bar{u}_{,\theta}+2\delta l\bar{w}_{,\xi}(\bar{w}_{,\theta}-\bar{v})]-$$
$$4ab[l\bar{w}_{,\xi\theta}+\bar{u}_{,\theta}/4-3l\bar{v}_{,\xi}/4]_{,\theta}-$$
$$bl\left[l^2\bar{w}_{,\xi\xi}+\nu(\bar{w}_{,\theta\theta}-\bar{v}_{,\theta})\right]_{,\xi} = q^* \qquad \text{or} \quad \bar{w} = \vec{w}^*$$

$$b\left[\bar{w}_{,\xi\xi}l^2+\nu(\bar{w}_{,\theta\theta}-\bar{v}_{,\theta})\right] = m^* \qquad \text{or} \quad -\bar{w}_{,\xi} = s^* \tag{2}$$

In the foregoing the following non-dimensional quantities have been introduced

$$\xi = \frac{z}{L};\quad r = \frac{\bar{r}}{R};\quad l = \frac{R}{L};\quad \delta = \frac{h}{2R};\quad a = \frac{(1-\nu)}{2};\quad b = \frac{h^2}{12r^2};$$

$$\bar{u} = \frac{U}{h};\quad \bar{v} = \frac{V}{h};\quad \bar{w} = \frac{W}{h};\quad \gamma^2 = \frac{\rho_c R^2(1-\nu^2)}{E};\quad \bar{p} = \frac{(1-\nu^2)p}{4E\delta^2};$$

$$n = \frac{N_x R}{Ch};\quad q = \frac{Q_x R}{Ch};\quad t = \frac{N_{x\theta} R}{Ch};\quad m = \frac{M_x R^2 b}{Dh} \tag{3}$$

where $C = Eh/(1-\nu^2)$, $D = Eh^3/12(1-\nu^2)$ and N_x, Q_x, $N_{x\theta}$ and M_x are the shell stress resultants and p is the fluid pressure.

Now the equations for the static deformation as well as the free-vibration analysis of a fluid-filled tank will be derived.

One of the purposes of the present paper is to present a general method for evaluating the free vibration characteristics of a circular cylindrical shell with classical boundary conditions of any type. For this, Sanders equations will be converted into a set of first order ordinary differential equations. By observing from the natural and geometric boundary conditions, one can conclude that there are, in effect, eight fundamental variables when the theory is applied to the analysis of shells under any possible combination of boundary conditions. These are the displacements $\bar{u}$, $\bar{v}$ and $\bar{w}$, the rotation s and the generalized stress resultants n, t, q and m (see Eqs. (2)). It is thus reasonable to seek a set of eight first order differential equations involving only these eight variables.

The eight variables associated with the vibrations of the prestressed shell consists of an axi-symmetric static pre-stress field

$$V_0(\xi) = \{u_0, n_0, v_0, t_0, w_0, q_0, s_0, m_0\} \tag{4}$$

which occurs prior to excitation, plus an additional field

$$\hat{V}_1(\xi,\theta,t) = \{\hat{u}_1, \hat{n}_1, \hat{v}_1, \hat{t}_1, \hat{w}_1, \hat{q}_1, \hat{s}_1, \hat{m}_1\} \tag{5}$$

resulting from the excitation.

For the free harmonic vibrations of a complete cylindrical shell it is appropriate to represent these additional variables as

$$\begin{aligned}\hat{V}_1(\xi,\theta,t) = \{&u_1(\xi)\cos(\kappa\theta), n_1(\xi)\cos(\kappa\theta), v_1(\xi)\sin(\kappa\theta),\\ &t_1(\xi)\sin(\kappa\theta), w_1(\xi)\cos(\kappa\theta), q_1(\xi)\cos(\kappa\theta),\\ &s_1(\xi)\cos(\kappa\theta), m_1(\xi)\cos(\kappa\theta)\}\cos(\omega t)\end{aligned}$$

where κ is the circumferential mode number and ω is the natural frequency.

Using Eqs. (1) and (2), eliminating the dependence of all the shell variables upon the co-ordinate # by means of expansions (6), and retaining only linear terms in the incremental quantities one obtains, after various algebraic manipulations, the following set of eight first order differential equations in terms of the eight incremental variables

$$u_{1,\xi} - (n_1 - \nu\kappa v_1 - \nu w_1)/l + 2\delta l s_0 s_1 = 0 \tag{7a}$$

$$n_{1,\xi} - \frac{ab\kappa}{9b+4}\left[\frac{16\kappa}{l}u_1 + \frac{(3b-4)}{l(4+9b)}t_1 - 16\kappa s_1 - 24\delta s_o(v_1+\kappa w_1)\right] + \Omega^2 u_1 = 0 \tag{7b}$$

$$v_{1,\xi} - \frac{4}{al(4+9b)}t_1 + \frac{\kappa(3b-4)}{lab}u_1 - \frac{12b\kappa}{4+9b}s_1 + \frac{8\delta}{9b+4}s_o(v_1+\kappa w_1) = 0 \tag{7c}$$

$$t_{1,\xi} - \frac{\nu\kappa}{l}n_1 + \frac{(\nu^2-1)}{l}\left[m^2(b+1)v_1 + \kappa(b\kappa^2+1)w_1\right] + \frac{\nu\kappa}{l}m_1 - \frac{2\delta\nu}{l}n_o v_1 -$$
$$\frac{2\delta\nu\kappa}{l}n_o w_1 - \frac{8a\delta}{9b+4}s_o t_1 - \frac{24a^2b\delta l\kappa}{9b+4}s_o s_1 - \frac{36a^2b\delta^2 l}{9b+4}s_o^2 v_1 - \frac{36a^2b\delta^2 l\kappa}{9b+4}s_o^2 w_1 +$$
$$\frac{24a^2b\delta\kappa}{9b+4}s_o u_1 + \frac{(\nu^2-1)}{l}\left[2\delta w_o v_1 - 2\delta\kappa w_o w_1\right] + \Omega^2 v_1 = 0 \tag{7d}$$

$$w_{1,\xi} + s_1 = 0 \tag{7e}$$

$$q_{1,\xi} - \frac{\nu}{l}n_1 + \frac{(\nu^2-1)}{l}\left[\kappa(b\kappa^2+1)v_1 + (b\kappa^4+1)w_1\right] + \frac{\nu\kappa^2}{l}m_1 - \frac{2\delta\nu\kappa}{l}n_o v_1 -$$
$$\frac{2\delta\nu\kappa^2}{l}n_o w_1 - \frac{8\delta\kappa}{9b+4}s_o t_1 - \frac{24ab\delta l\kappa^2}{9b+4}s_o s_1 - \frac{36ab\delta^2 l\kappa}{9b+4}s_o^2 v_1 - \frac{36ab\delta^2 l\kappa^2}{9b+4}s_o^2 w_1 +$$
$$\frac{24ab\delta\kappa^2}{9b+4}s_o u_1 + \frac{(\nu^2-1)}{l}2\delta\kappa w_0(v_1+\kappa w_1) + \frac{\bar{p}_F}{l} + \Omega^2 w_1 = 0 \tag{7f}$$

$$s_{1,\xi} + \frac{\nu\kappa}{l^2}v_1 + \frac{\nu\kappa^2}{l^2}w_1 + \frac{m_1}{bl^2} = 0 \tag{7g}$$

$$m_{1,\xi} - \frac{16ab\kappa^2}{l(9b+4)}u_1 - \frac{12b\kappa}{l(9b+4)}t_1 + \frac{q_1}{l} + \frac{16ab\kappa^2}{9b+4}s_1 + 2\delta s_o n_1 +$$

$$2\delta n_o s_1 + \frac{24ab\delta\kappa}{9b+4}s_o v_1 + \frac{24ab\delta\kappa^2}{9b+4}s_o w_1 = 0 \tag{7h}$$

where $\Omega^2 = \gamma^2\omega^2/l$.

The associated boundary conditions are

$$\begin{aligned} n_1 &= n_1^* \quad \text{or} \quad u_1 = u_1^* ; \\ t_1 &= t_1^* \quad \text{or} \quad v_1 = v_1^* ; \\ q_1 &= q_1^* \quad \text{or} \quad w_1 = w_1^* ; \\ m_1 &= m_1^* \quad \text{or} \quad s_1 = s_1^* \end{aligned} \tag{8}$$

In order to solve these equations one must obtain the axisymmetric solution of the shell subjected to the static liquid pressure. The equations for the static case are obtained from the foregoing as follows

$$u_{o,\xi} - (n_o + \nu w_o)/l = 0 \tag{9a}$$

$$n_{o,\xi} = 0 \tag{9b}$$

$$w_{o,\xi} + s_o = 0 \tag{9c}$$

$$s_{o,\xi} - m_o/(bl^2) = 0 \tag{9d}$$

$$m_{o,\xi} - q_o/l = 0 \tag{9e}$$

$$q_{o,\xi} - \left[\nu n_o + (1-\nu^2)w_o + \bar{p}_h\right]/l = 0 \tag{9f}$$

where $\bar{p}_h = \left[(1-\nu^2)\rho_F g R^2 L/Eh^2\right](1-\xi)$, while the boundary conditions are given by

$$n_0 = n_o^* \quad \text{or} \quad u_o = u_o^*$$

$$q_0 = q_o^* \quad \text{or} \quad w_o = w_o^*$$
$$m_0 = m_o^* \quad \text{or} \quad s_o = s_0^* \tag{10}$$

With the aim of applying the Galerkin procedure, the eight fundamental variables are represented in non-dimensional form by

$$u_1(\xi) = U_1 f_1 + U_2 f_2 + \sum_{i=3}^{NM} U_i f_i$$

$$n_1(\xi) = N_1 f_1 + N_2 f_2 + \sum_{i=3}^{NM} N_i f_i$$

$$v_1(\xi) = V_1 f_1 + V_2 f_2 + \sum_{i=3}^{NM} V_i f_i$$

$$t_1(\xi) = T_1 f_1 + T_2 f_2 + \sum_{i=3}^{NM} T_i f_i$$

$$w_1(\xi) = W_1 f_1 + W_2 f_2 + \sum_{i=3}^{NM} W_i f_i$$

$$q_1(\xi) = Q_1 f_1 + Q_2 f_2 + \sum_{i=3}^{NM} Q_i f_i$$

$$s_1(\xi) = S_1 f_1 + S_2 f_2 + \sum_{i=3}^{NM} S_i f_i$$

$$m_1(\xi) = M_1 f_1 + M_2 f_2 + \sum_{i=3}^{NM} M_i f_i \tag{11}$$

where the trial functions f_i, are given by

$$f_1 = (1-\xi) \qquad f_2 = \xi$$
$$f_i = \sin[(i-2)\pi\xi]; \qquad i = 3, NM \tag{12}$$

The first two linear functions are used to enforce the boundary conditions at $\xi = 0$ and $\xi = 1$. All the higher order trial functions are zero at each end of the shell and represent simply additive refinements of the displacement and stress fields. A similar modal solution is used to describe the axisymmetric static variables (4). The first four shape functions are illustrated in Fig. 2.

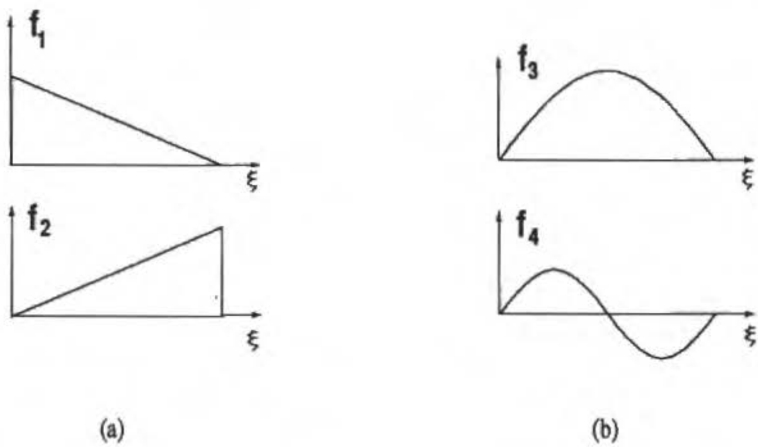

Fig. 2 Hierarchical shape functions of (a) linear and (b) trigonometric form

The use of Eqs. (7) together with the proposed modal solution allows one to satisfy all natural and geometric boundary conditions exactly and obtain all displacements and internal forces with the same degree of accuracy. Furthermore, no additional manipulation must be carried out after the solution is completed since the eight variables of the preceding formulation are the variables which are generally of interest in the analysis of shells.

Making use of the expansions (11) and applying a Galerkin error-minimization procedure, one obtains a set of 8NM algebraic equations. These equations are unfortunately too long to be presented here; the interested reader will find them in Ramos (1993).

Fluid Equations

The irrotational motion of an incompressible and non-viscous fluid can be described by a velocity potential $\phi(x, r, \theta, t)$ (Lamb, 1945). This potential function must satisfy the Laplace equation which can be written in non-dimensional form as

$$l^2\frac{\partial^2\Phi}{\partial\xi^2} + \frac{\partial^2\Phi}{\partial r^2} + \frac{\partial\Phi}{\partial r} + \frac{1}{r}\frac{\partial^2\Phi}{\partial\theta^2} = 0 \qquad (13)$$

where $\Phi = (\gamma^2\phi)/R$.

The dynamic fluid pressure acting on the shell surface is obtained from the equation

$$\bar{p}_F = -(\rho_F/\rho_c)\,(1/4\delta^2)\,(\partial\Phi/\partial t) \qquad (14)$$

At the liquid boundary the following conditions have to be satisfied:

$$\text{At} \quad \xi = 0: \qquad (\partial\Phi/\partial\xi) = 0 \tag{15}$$

$$\text{At} \quad \xi = H/L: \qquad (\partial^2\Phi/\partial t^2) + (g/L)(\partial\Phi/\partial\xi) = 0 \tag{16}$$

$$\text{At} \quad r = 1: \qquad (\partial\Phi/\partial r) = 2\gamma^2\delta(\partial w/\partial t) \tag{17}$$

Further, for a fluid-filled shell, the following restriction must be imposed

$$\lim_{r\to 0}(\partial\Phi/\partial r) = 0 \tag{18}$$

The boundary conditions suggest seeking the solution for the velocity potential in the form

$$\Phi = \sum_{m=1}^{NMF} A_m \cos(\zeta_m\xi)\, I_\kappa(\zeta_m r)\cos(\kappa\theta)\sin(\omega t) + \sum_{n=1}^{NM} B_n\omega\cosh(\alpha_n\xi)\, J_\kappa(\alpha_n r)\cos(\kappa\theta)\sin(\omega t) \tag{19}$$

where $\zeta_m = [((2m-1)/2)(\pi L/H)]$, J_κ and I_κ are, respectively, the κth order Bessel function and modified Bessel function of the first kind and α_n are the roots of the equation

$$dJ_\kappa(\alpha_n r)/dr\big|_{r=1} = 0 \tag{20}$$

This modal solution is obtained by the superposition of two complementary problems, as shown in Fig. 3.

The modal solution (19) already satisfies the Laplace equation and boundary condition (15). Substituting Eqs. (6), (11) and (19) into boundary condition (17), using $\cos(\zeta_p\xi)$ as a weighting function and applying the Galerkin method, one obtains the fluid modal amplitudes A_m as a function of the shell modal amplitudes W_j. Then the resulting potential function is substituted into the sloshing condition (16) and the Galerkin method is used once more to obtain a system of homogeneous linear equations in terms of the modal amplitudes B_n and W_j. The function $J_\kappa(\alpha_p r)$ is used as the weighting function in this Galerkin procedure.

With equation (19) the hydrodynamic pressure $\bar{p}_f$ takes the form

$$\bar{p}_F = \frac{\rho_F}{\rho_c}\frac{\omega^2\gamma^2}{2\delta}\cos(\kappa\theta)\cos(\omega t)\sum_{m=1}^{NMF}\cos(\zeta_m\xi)\frac{I_\kappa(\zeta_m)}{\dot{I}_\kappa(\zeta_m)\, Ic_{mm}}\sum_{j=1}^{NM} I5_{mj}w_j -$$

$$\frac{\rho_F}{\rho_c}\frac{\omega^2\gamma^2}{4}\cos(\kappa\theta)\cos(\omega t)\sum_{n=1}^{NM}\cosh(\alpha_n\xi)\,J_\kappa(\alpha_n)\,(B_n/\gamma^2\delta^2) \qquad (21)$$

Substituting this expression in (7), one obtains the additional terms necessary for the free-vibration analysis of fluid-filled tanks.

The resulting eigenvalue problem can be written in the form

$$\det\left[\begin{bmatrix}[K] & [0]\\ [K_1] & [K_{slo}]\end{bmatrix} - \Omega^2\begin{bmatrix}[M]+[M_2] & [M_1]\\ [0] & [M_{slo}]\end{bmatrix}\right] = 0 \qquad (22)$$

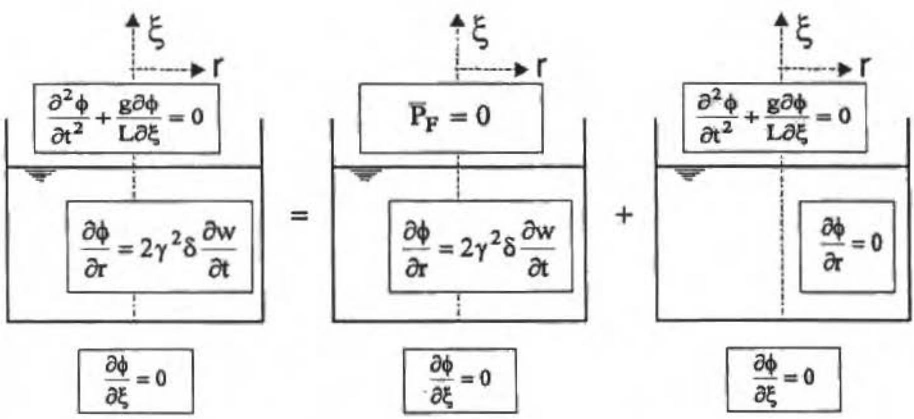

Fig. 3 Solution of the fluid problem by the superposition principle

The coefficient matrices [K] and [M] consist of the coefficients obtained from the shell equations (7), the submatrices $[K_{slo}]$, $[K_1]$ and $[M_{slo}]$ are given by Eq. (16) and $[M_1]$ and $[M_2]$ are derived from Eq. (21).

Due to the sparseness of the mass matrix, before attempting to establish the eigenvalues corresponding to the shell and fluid natural frequencies, a condensation procedure is used, leading to an eigenvalue problem of much lower dimension.

Results

Some calculations to test the theory in the case of partially filled shells is presented herein. The numerical parameters used for these studies and the adopted boundary conditions are shown in Fig. 3. This shell was previously studied numerically and experimentally by Chiba, Yamaki and Tani (1985).

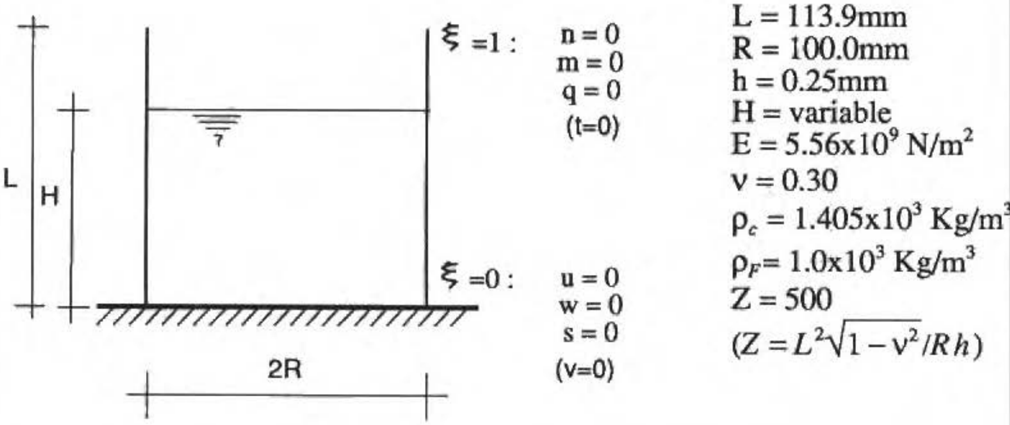

Fig. 4 Clamped-free circular cylindrical shell partially filled with liquid

To compare the results with experiment, the liquid depth was varied such that the fractional filling, H/L, took the following values $H/L = 0$, 1/4, 1/2, 3/4 and 1 and the corresponding frequencies and vibration modes were computed. These data were obtained by taking $NM = 30$ and $NMF = 3$. In all cases analysed here these numbers of terms were sufficient to attain convergence to within 1%. The three lowest shell frequencies and the lowest liquid sloshing frequency are shown in Fig.5 as a function of the circumferential wave number κ . Also shown in Fig. 5 are the experimental results obtained by Chiba et al. (1985). These experimental results were taken from the figures in Chiba et al. (1985) and the values' accuracy is as good as direct reading of these figures permitted. For each liquid height, the numerical results agree well with the experimental results. It can be observed that the shell frequencies decrease rapidly with increasing H/L. This lowering effect is mainly due to an increase in kinetic energy without a corresponding increase in the strain energy of the shell-liquid system. For all cases analysed here, there is the well known dip in the frequency curve as the shell makes transition through the lower values of κ.

To see the variation of the mode of vibration with the liquid depth, axial distributions of the vibration amplitude were determined for $\kappa = 8$. The results are illustrated in Fig. 6. The maximum vibration amplitude is taken as unity. As one can see, the effect of the contained liquid on the mode shape is most significant when $H/L = 1/4$, 1/2 and 3/4.

On the other hand, the effects of the filling ratio H/L on the sloshing frequencies are negligible as shown in Fig. 5f, especially for high values of κ. The fundamental sloshing frequencies for low values of κ are also listed in Table 1 and compared with the sloshing frequencies for a rigid tank (values between brackets). These frequencies may be conveniently expressed in the form (Ramos, 1993):

$$f_r = \frac{1}{2\pi}\sqrt{\frac{g\alpha_1}{L}\tanh\left(\alpha_1\frac{H}{L}\right)} \tag{23}$$

in which f_r is in Hz; and α_1 is the lowest root of Eq. (20). As expected, there is little influence of the flexibility of the tank on the lower sloshing frequencies

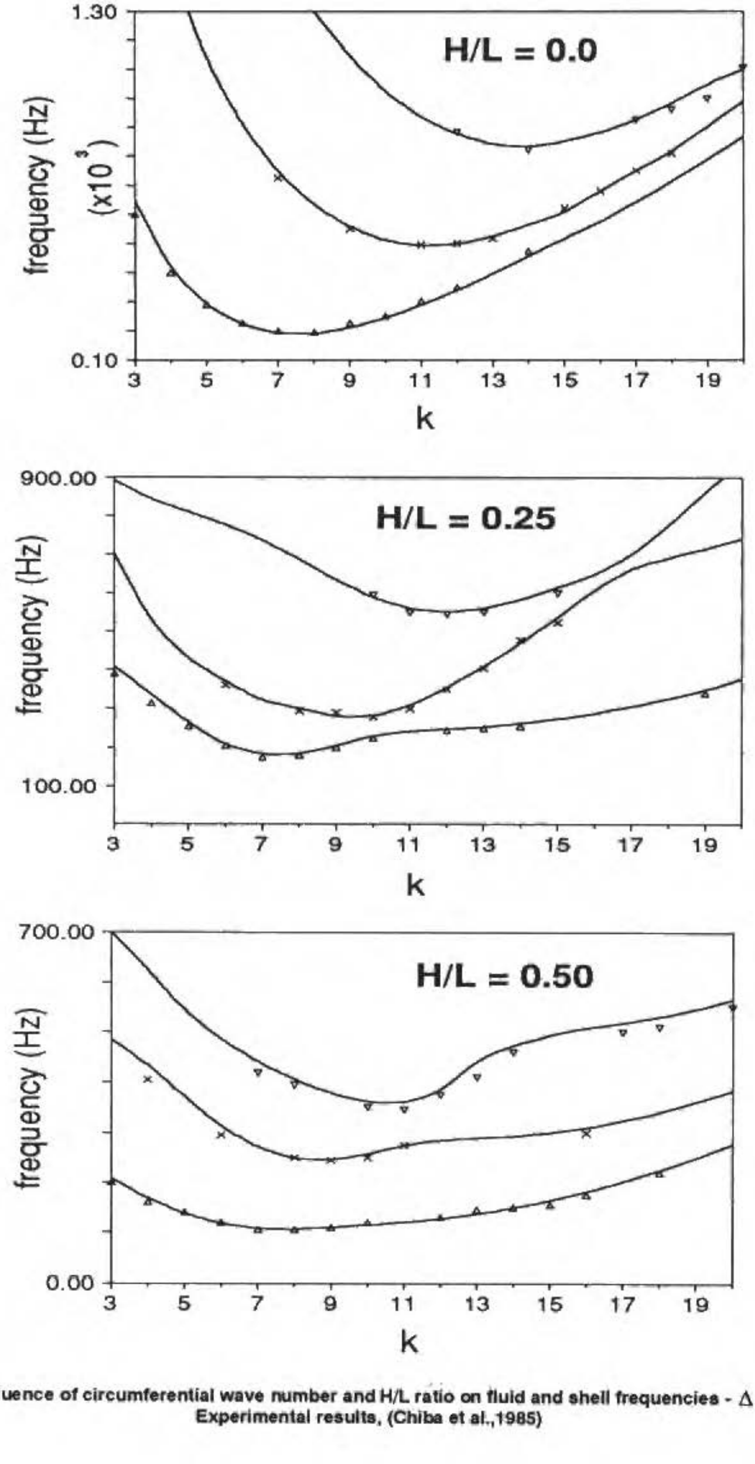

Fig. 5 Influence of circumferential wave number and H/L ratio on fluid and shell frequencies - Δ, $\times$, ∇ - Experimental results, (Chiba et al.,1985)

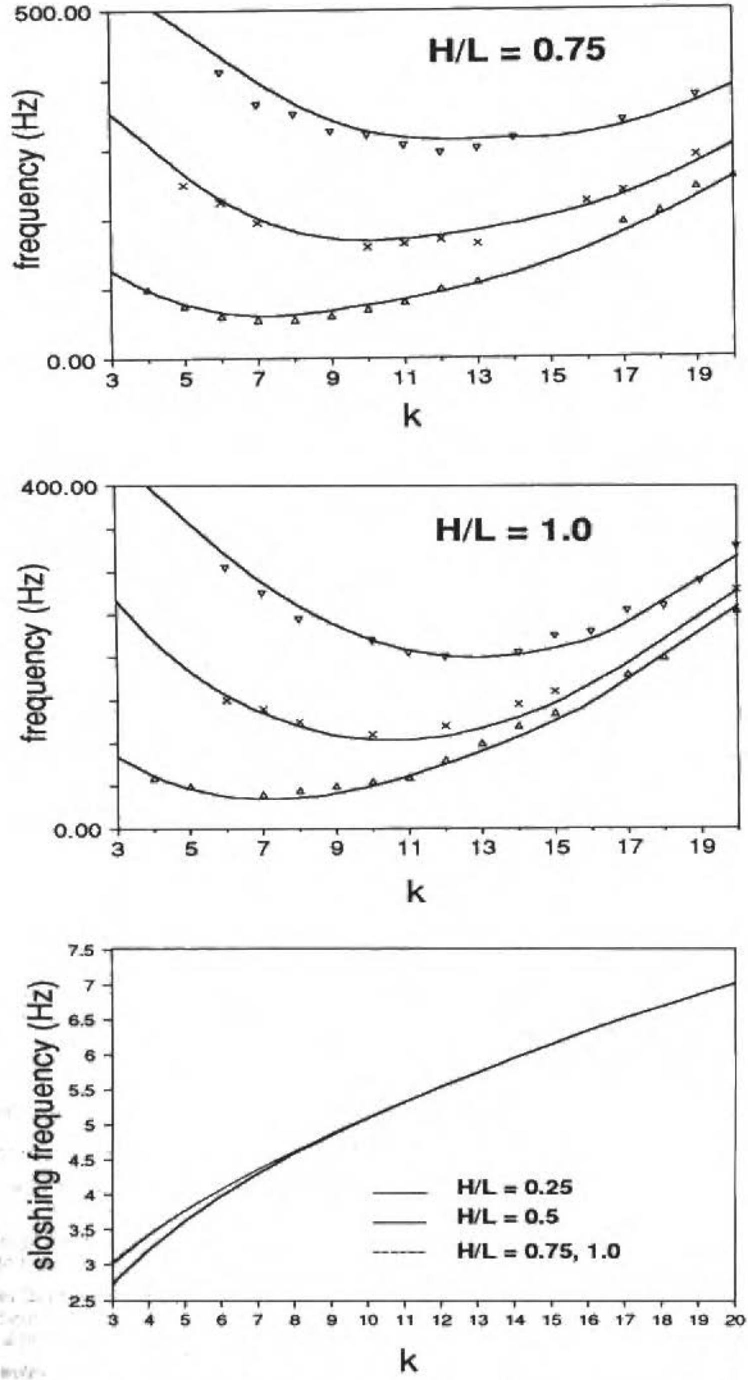

Fig. 5 Influence of circumferential wave number and H/L ratio on fluid and shell frequencies - Δ, $\times$, ∇ - Experimental results, (Chiba et al.,1985 - continued)

Table 1 Sloshing frequencies (Hz)

	H/L			
κ	0.25	0.50	0.75	1.00
3	2.6766 (2.6731)	2.9819 (2.9780)	3.0210 (3.0174)	3.0263 (3.0222)
5	3.5933 (3.5874)	3.7345 (3.7295)	3.7403 (3.7353)	3.7406 (3.7356)
7	4.2663 (4.2606)	4.3244 (4.3186)	4.3252 (4.3194)	4.3252 (4.3194)

Conclusions

A simple - yet effective - methodology has been proposed for evaluating the free vibration characteristics of a fluid-filled cylindrical shell with classical boundary conditions of any type. To examine the vibrations of the shell a set of first order differential equations in terms of the shell displacements and stress resultants, based on Sanders shell theory, was deduced and a simple modal solution based on the use of linear and trigonometric shape functions was derived.

By using a consistent shell theory, by choosing appropriate system variables and devising a modal solution that satisfies any set of boundary and continuity conditions for the shell and fluid medium and, finally, by taking into account the effects due to static deformations, in-plane inertias and liquid free

Nomenclature

C = Shell membrane stiffness
D = Shell flexural stiffness
E = Young's modulus
f_i = Trial functions
H = Liquid height
H/L = Filling ratio of the liquid
h = Shell thickness
I_k = Kth order modified Bessel function of the first kind
J_k = Kth order Bessel function of the first kind
K = Stiffness matrix
L = Axial length of shell
M = Mass matrix
$M_x, N_x, N_{x\theta}, Q_x$ = Shell stress resultants
m, n, q, t = Non-dimensional stress resultants
p = Fluid pressure
$\bar{p}$ = Non-dimensional load parameter
R = Radius of shell
$\bar{r}, \theta' z$ = Radial, circumferential and radial coordinates
s = Angle of rotation of shell edge
t = Time
U, V, W = Components of displacement of shell middle surface
$\bar{u}, \bar{v}, \bar{w}$ = Displacements divided by h
Z = Batdorf's geometric parameter
α_n = Roots of the first derivative of J_k
δ = Slenderness ratio $(h/2R)$
κ = Circumferential wave number
ν = Poissons's ratio
Φ = Velocity potential parameter $(\gamma^2\phi/R)$
ϕ = Velocity potential
ρ_F = Fluid mass density
ρ_c = Shell mass density
ξ = Non-dimensional axial co-ordinate $(0 \le \xi \le 1)$
ζ_m = Axial wave parameter
Ω = Frequency parameter
ω = Natural frequency
$(\ )_0$ = Related to static pre-stress state
$(\ )_1$ = Incremental time-dependent quantities
$(\ )_{,\xi}$ = Derivative with respect to the non-dimensional axial co-ordinate
$(\ )^*$ = Prescribed value
$(\ )_{slo}$ = Obtained from the sloshing condition

surface motions, the present analysis overcomes many of the shortcomings encountered in previous studies for shells in vacuum or partially filled with liquid. Hence the present formulation is capable of furnishing a consistent solution for a wide range of tank geometries and wave numbers.

Comparisons of the numerical results with those obtained by other theories and from experiments are found to be good and show the validity of the present methodology.

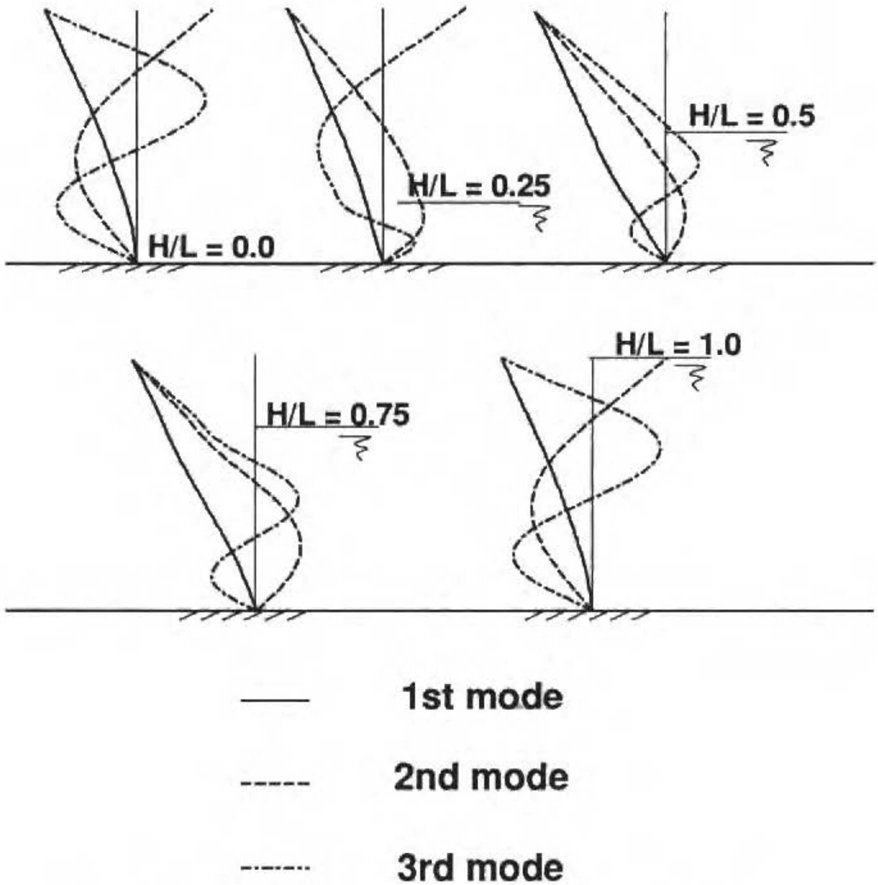

Fig. 6 Effects of the filling ratio H/L on the axial vibration mode shapes, $\kappa = 8$

References

Chiba, M., Yamaki, N., and Tani, J.,1985, "Free Vibration of Clamped-Free Circular Cylindrical Shell Partially Filled with Liquid - Part III: Experimental Results", Thin-Walled Structures, Vol. 3, pp. 1-14.

Gonçalves, P. B., and Batista R. C., 1987, "Frequency Response of Cylindrical Shells Partially Submerged or Filled with Liquid", Journal of Sound and Vibration, Vol. 113, pp. 59-70.

Jain, R. K., 1974, "Vibration of Fluid-filled, Orthotropic Cylindrical Shells", Journal of Sound and Vibration, Vol. 37, pp. 379-388.

Lamb, H., 1945, "Hydrodynamics", Dover, New York, USA.

Ramos, N. R. S. S., 1993, "Free Vibration Analysis of Cylindrical Tanks (in Portuguese)", M. Sc. Dissertation, Civil Engineering Department, Pontifical Catholic University, PUC-Rio.

Yamaki, N., Tani, J., and Yamaji, T., 1984, "Free Vibration of a Clamped-Clamped Circular Cylindrical Shell Partially Filled with Liquid", Journal of Sound and Vibration, Vol. 94, pp. 531-550.

Sanders, J. L.,1963, "Nonlinear theories for thin shells", Quarterly of Applied Mathematics, Vol. XXI pp. 21-36.

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Development of a Pyranometer with Electrical Compensation

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Abstract

A dynamically compensated electrical pyranometer with manufactured platinum film sensors was constructed, theoretical, and experimentally evaluated. The electronic circuit is constituted of a Wheatstone bridge, high gain voltage and current amplifiers, and a signal linearizer. Theoretical relations are derived to describe the effect of the sensors properties on the instrument steady and dynamic responses. The sensitivity of the instrument due to the angular dependence on the direction of the radiation, response time, effect of temperature, tilting and linearity have been also investigated.
Keywords: Pyranometer, Radiometer, Solarimeter

Introduction

According to the World Radiation Center - WRC (1984), the solar radiation received from a solid angle of 2π steradians on a horizontal surface is referred to as global radiation. This includes radiation received directly from the solid angle of the sun's disk and also diffuse sky radiation that has been scattered in traversing the atmosphere.

The instrument needed for measuring solar radiation from a solid angle of 2π steradians into a plane surface and a spectral range from 0.3 to 3.0 μm is the pyranometer. Still according to the WRC, the pyranometer is sometimes used to measure solar radiation on surfaces inclined to the horizontal and in the inverted position to measure reflected global radiation. When measuring the diffuse component of solar radiation alone, the direct solar component may be screened from the pyranometer by a masking device.

Pyranometers normally use thermoelectric, thermoresistive, photoelectric, pyroelectric or bimetallic elements as sensors. Since pyranometers are exposed continually in all weather conditions they must be robust in design while resisting the corrosive effects of humid air (especially near the sea). The receiver should be hermetically sealed inside its casing or the casing must be easily removable so that any condensed moisture can be removed. Where the receiver is not permanently sealed a desiccator is usually fitted in the base of the instrument. The properties of pyranometer which are of concern when evaluating the accuracy and quality of radiation measurement are: sensitivity, stability, response time, cosine response, azimuth response, linearity, temperature response and spectral response.

The WRC points that three classes of pyranometer can be defined on the basis of their accuracy and overall system performance, as outlined in Table 1.

In the pyranometer invented by Callendar at the start of this century (Coulson, 1975), the sensor contained two pairs of platinum wire grids wound on mica, constituting adjacent arms of a Wheatstone bridge. One pair of grids was coated with black enamel to absorb sunlight while the other pair was highly reflecting. The 5.8 cm square grids were mounted inside an evacuated glass bulb about 9 cm in

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diameter. When exposed to sunlight each pair of grids suffered a different resistance change, due to the temperature difference between them which was nearly proportional to the intensity of incident solar radiation. Variable resistors in the other two arms formed a self adjusting Wheatstone bridge whose output could be converted to incident solar radiation through a calibration factor furnished with each instrument. Two decades after Callendar, A.K. Angström developed an electrical compensation pyranometer in which the temperature of two white strips was maintained equal (by electrical heating to compensate for lower solar radiation absorption) to that of two black sensor strips of identical geometry. The temperatures of the strips were measured by thermocouples. In principle the instrument could belong to the standard class as does the Angström electrical compensation pyrheliometer (Coulson, 1980). However it was never widely used.

Table 1 Classification of pyranometers - WRC (1984)

Characteristic	Secondary Standard	First Calss	Second Class
Resolution (smallest detectable change in Wm^{-2})	1	5	10
Stability (percentage of full scale, change/year)	1	2	5
Cosine response (percentage deviation from the mean at 10° solar elevation on a clear day)	< 3	< 7	< 15
Azimuth response (percentage deviation from the mean at 10° solar elevation on a clear day)	< 3	< 5	< 10
Temperature response (percentage maximum due to change of ambient temperature within the operation range)	1	2	5
Non-linearity (percentage of full scale)	0.5	2	5
Spectral sensitivity (percentage deviation from mean absorptance 0.3 to 3μm)	2	5	10
Response time (99% response)	< 25s	< 1min	< 4min

Presently the best and most widely accepted pyranometers possess thermopile type sensors, because of their long term stability and because their response is only weakly wavelength dependent. However, since output depends on the temperature difference between sensor and heat sink which is a function of the thermal characteristics and geometry of each element, the sensitivity varies from one unit to another and each instrument must be individually calibrated.

Radiometers and or absolute solarimeters of electrical compensation and of substitution such the Angström pyrheliometer, the Wilson Active Cavity Radiometer and the electrical compensated pyranometer first developed by Lobo (Lobo and Belo, 1983) are instruments which have two absolutely equal sensors in their design.

By the above reason the instrument proposed in this study combines the self-adjusting feature of Callendar pyranometer with the electrical compensation of Angström instrument. The absorbing and non-absorbing thermoresistive sensors are maintained at approximately equal temperatures by an electronic feedback circuit which, through suitable choice of bridge ratio, preferentially heats the non absorbing sensor. This instrument is intrinsically much less sensitive to the thermal surroundings than thermopile units and is self calibrating due to the electrical compensation feature, dispensing individual calibration of instruments provided the solar (absorbing) and electrical (compensating) elements are geometrically and thermally identical in each unit. The installation of the absorbing sensor in a black body cavity could reduce the uncertainty in absorptivity by an order of magnitude (Wilson, 1983) and yield a standard class pyranometer at a relatively low cost.

Description of the Proposed Instrument

In the instrument proposed the sensor elements are connected according to the circuit in Fig. 1. The blackened solar sensor R_s and shielded compensation electrically heated sensor R_c, with high temperature coefficients of resistance occupy parallel arms of a Wheatstone bridge. The resistances of the other arms on the bridge are practically temperature independent. The relative resistance values of the solar and compensating sensors are such that electrical heating of solar sensor is negligible compared to the absorbed solar energy while solar heating of the compensating sensor is negligible in relation to electrical heat dissipation, if the compensating sensor is shielded. In the bridge circuit of Fig. 1, that condition is obtained when $R_c << R_s$. The sensors are constructed with the same geometry and orientation for equal thermal losses at equal temperatures (see Fig. 2).

Under operation the bridge is initially balanced with sensors shielded from sunlight. On exposure, absorption of solar energy raises the temperature of the solar sensor and unbalances the bridge. The unbalance electromotive force is amplified by the feedback circuit which increases bridge current, heats the compensating sensor R_c thus raising its temperature and resistance, and tends to rebalance the bridge. Bridge current is measured by the potential drop across the precision resistance R_f. If amplifier gain is sufficiently large, residual bridge unbalance is small and both sensors attain approximately the same temperature. Hence the instrument, especially if installed in a black body cavity, can yield a quasi absolute pyranometer since the electrical power supplied to the compensating sensor R_c equals the incident radiation in the solar sensor R_s.

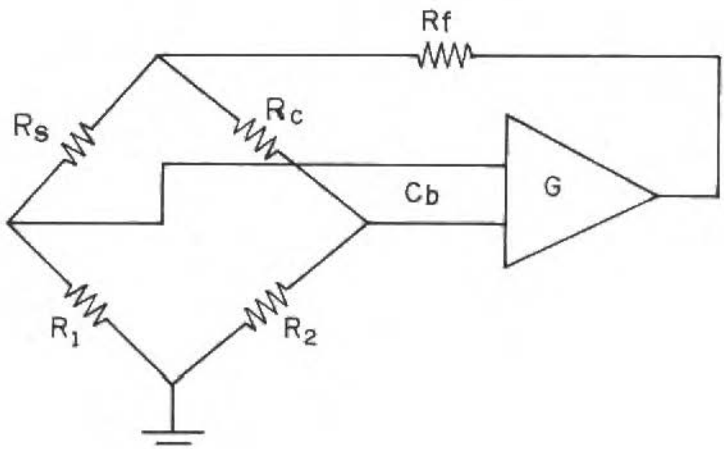

Fig. 1 Compensation bridge circuit diagram

In Fig. 2, the two sensors used for the present pyranometer are shown, and Fig. 3 shows detail of its sensing part. Although there are film sensors available commercially in almost any desired configuration, the special purpose of the present pyranometer in which both sensors should have the same geometry, spatial orientation, and surface and at the same time different electrical resistance, that is $R_s >> R_c$, it was decided to manufacture both sensors using the ceramic technique of paint and fire.

In theory any material could be used as the film sensing element. However, metallic conductors are most employed in film resistance-temperature transducers. Techniques such as sputtering and or evaporation can produce almost any metal film desired. In general the thin films do not reach the higher values of temperature coefficient of resistance of metallic wire. According to Sandborn (1972), the lack of facilities for sputtering or evaporating films has made metals such as platinum, gold and silver popular for film sensors. These metals were and still are used in simple thin film techniques by the glassware industry.

The liquid paint materials usually are a chloride, such as platinic chloride, and flux dissolved in an oil vehicle. The solution is painted on a glass or ceramic backing according to the design and then fired to a specific temperature. The heat reduces the chloride to a pure metal and fuses it to the backing material. Films made in that manner are also found to be stable and reproducible. The resistance of the film is controlled by the number of coats of film paint that are fired on the probe.

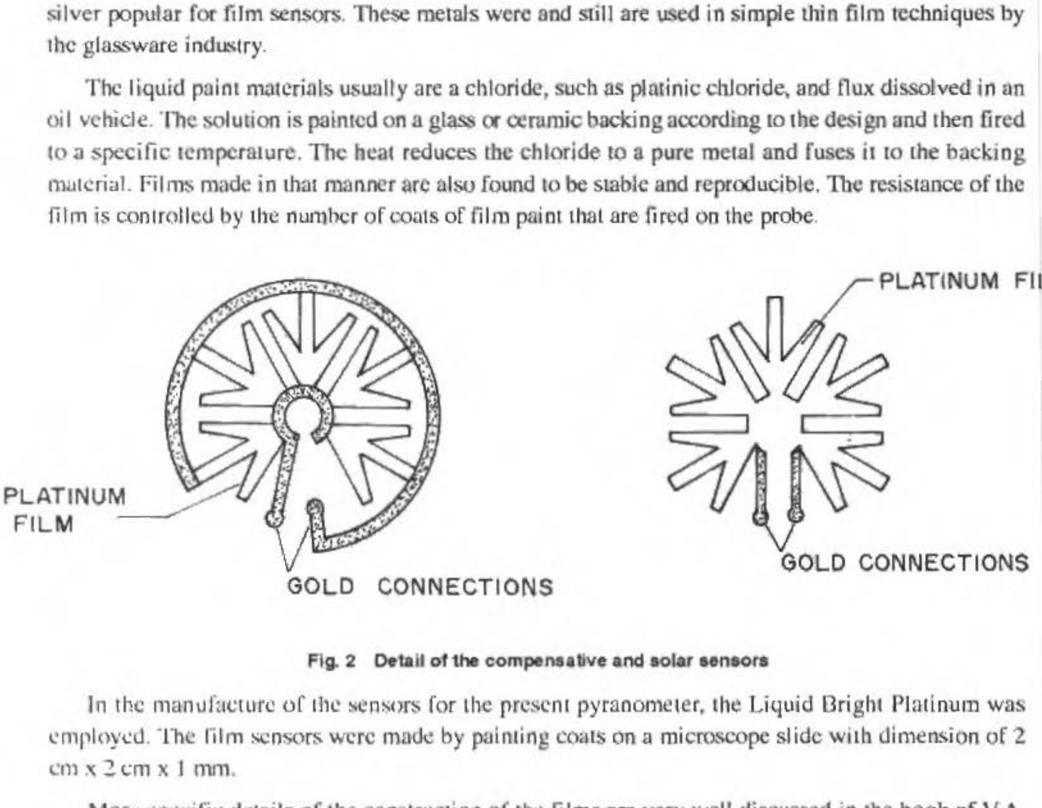

Fig. 2 Detail of the compensative and solar sensors

In the manufacture of the sensors for the present pyranometer, the Liquid Bright Platinum was employed. The film sensors were made by painting coats on a microscope slide with dimension of 2 cm x 2 cm x 1 mm.

More specific details of the construction of the films are very well discussed in the book of V.A. Sandborn (1972) and in the paper by De Lima (1987). With the same geometry and sensor effective area, excluding area of the electrical connections, under the ambient temperature of 29°C the compensative sensor had the resistance of 4.96 ohms and the solar sensor had a resistance of 498.26 ohms. As said before, both sensors have approximately the same effective area however very different value of electrical resistances. The way this was realized is simple: the compensative sensor has 10 strips of platinum films connected in parallel, and the solar sensor shows the same strips of platinum film aligned in series. Thick layers of gold films are the electrical connections.

The principle of operation for this pyranometer, whose electronic circuit is shown in Fig. 4, is basically the same as the one of a constant temperature hot wire anemometer or an absolute radiometer of electrical equivalence (Wilson, 1983). The electronics of the present instrument consists of a

Wheatstone bridge with the solar and compensative sensors in parallel, a differential voltage amplifier (IC1-IC2), a power amplifier on a Darlington configuration, an analog multiplier (IC3-IC8), and an analog-digital converter. The first stage, being a high gain voltage differential amplifier, was assembled observing care with regard to noise interference, offset control and thermal drift. Integrate circuits used for this amplifier are instrumentation operational amplifiers in a configuration showing CMRR of 110 dB, input offset voltage of 3 mV and thermal drift of 0.6 μV/°C, according to the manufacturer specification. Besides these requirements, it was necessary to distribute passive components around the integrated circuit to reduce noise and parasitic capacitances on the printed circuit board. The power amplifier is based on two coupled NPN transistors on a Darlington configuration.

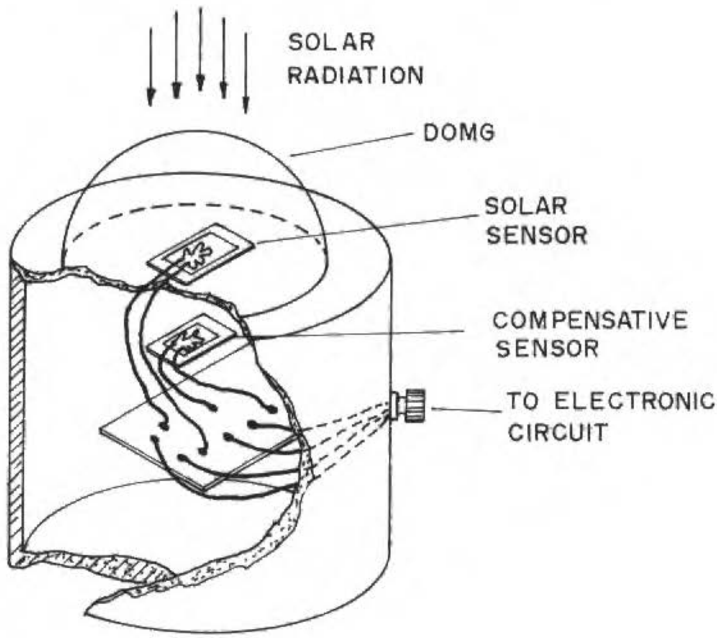

Fig. 3 Detail of the sensing body of the pyranometer

The circuit used to effectively determine the thermal dissipation on the compensative sensor is the analog multiplier. The multiplication is realized by means of the logarithm and antilogarithm operational amplifier circuit in which the set of integrated circuit IC3-IC8 is labeled in the Fig. 4.

Theory of Operation

The first law of thermodynamics for the two sensors is written in the following form:

$$(\tau\alpha)_s A_s H + V^2_s/R_s - U_s A_s (t_s - t_a) - C_s \, dt_s/d\theta = 0 \quad (1)$$

$$(\tau\alpha)_c A_c H + V^2_c/R_c - U_c A_c (t_c - t_a) - C_c \, dt_c/d\theta = 0 \quad (2)$$

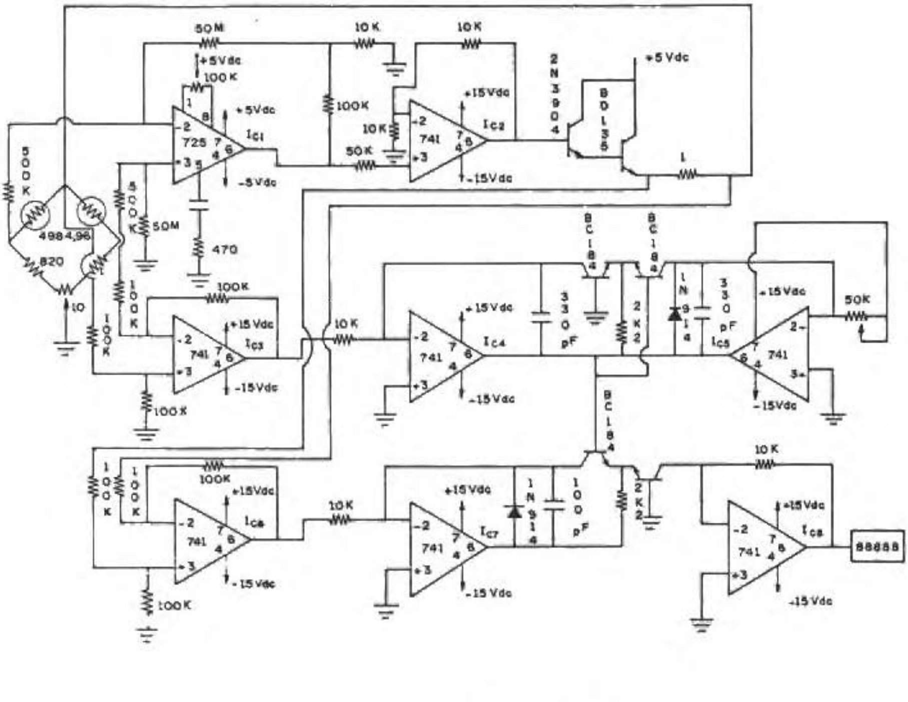

Fig. 4 Electronic circuit for the compensative pyranometer

where A is the sensor surface area, C is the composite thermal capacity of each sensor and its subtracte, U is the global heat transfer coefficient between the sensor and surrounding, H is the intensity of solar radiation falling on the sensor surface area A, t and t_a are sensor temperature and ambient temperature, respectively, τ is the dome optical transmissivity, α is the radiation coefficient of absorption, θ is the time, V^2/R is the electric power dissipated on the sensor, and R is the electrical resistance. Subtracting Eq. (1) from Eq. (2) the following expression is obtained:

$$V_c^2/R_c = H\left[(\tau\alpha)_s A_s - (\tau\alpha)_c A_c\right] + V_s^2/R_s - d\left(C_s t_s - C_c t_c\right)/d\theta - \\ - U_s A_s\left(t_s - t_a\right) + U_c A_c\left(t_c - t_a\right) \tag{3}$$

Replacing the resistance of each sensor by the expression:

$$R = R_a\left[1 + \beta\left(t - t_a\right)\right] \tag{4}$$

where β is the temperature coefficient of resistance and R_a is the electrical resistance at ambient temperature, the expression (3) will turn in

$$V_c^2/R_c = H\left[(\tau\alpha)_s A_s - (\tau\alpha)_c A_c\right] + V_s^2/R_s - \frac{C_s}{\beta_s R_{sa}}\frac{dr_s}{d\theta} + \frac{C_c}{\beta_c R_{ca}}\frac{dr_c}{d\theta} - \frac{U_s A_s}{\beta_s R_{sa}} r_s + \frac{U_c A_c}{\beta_c R_{ca}} r_c \tag{5}$$

being $r_c = R_c - R_{ca}$ and $r_s = R_s - R_{sa}$

The term V_c^2/R_c represents the electrical energy dissipated by Joule effect in the compensative sensor. The first term in the right hand side of the expression (5) represents the net radiant energy absorption between the solar and compensative sensors. The second term to the right side of that equation is the electrical energy dissipated by Joule effect in the solar sensor. The third and fourth terms is the net energy stored between both sensors and the fifth and sixth terms represent the net energy lost by convection between both sensors.

Expression (5) is the general equation for the present pyranometer. Considering the compensative sensor shielded from the solar radiation and by this reason the term $(\tau\alpha)_c A_c$ in the Eq. (5) is annulled, the general expression for the steady-state sensitivity of the pyranometer will be

$$\frac{dV_c}{dH} = \frac{R_c(\tau\alpha)A_s}{2V_c} + \frac{R_c}{2V_c}\frac{d}{dH}\left(V_s^2/R_s\right) + \frac{R_c U_c A_c}{2V_c\beta_c R_{ca}}\frac{dr_c}{dH} - \frac{R_c U_s A_s}{2V_c\beta_s R_{sa}}\frac{dr_s}{dH} \tag{6}$$

Both sensors were manufactured with the same material and geometry in such way that $A_s = A_c$, $C_s = C_c$, $U_s = U_c$ and $\beta_s = \beta_c$. The term $\frac{d(V_s^2/R_s)}{dH}$ in equation (6) will not be considered when compared with the $\frac{d(V_c^2/R_c)}{dH}$ since $i_c >> i_s$ and $R_s >> R_c$.

Equation (6) is then reduced to

$$\frac{dV_c}{dH} = \frac{R_c(\tau\alpha)A_s}{2V_c} \tag{6a}$$

Observing Fig. 1 we see that the output voltage in the differential amplifier is

$$G \cdot e_b = \frac{(R_c + R_2)V_c}{R_c} \quad \text{or} \quad V_c = \frac{G \cdot e_b \cdot R_c}{R_c + R_2} \tag{7}$$

where G is the differential amplifier voltage gain and e_b is the Wheatstone bridge unbalancing electromotive force.

Inserting Eq. (7) into Eq. (6a), the steady-state sensitivity of the present pyranometer will be written as

$$\frac{dV_c}{dH} = \frac{(R_c + R_2)(\tau\alpha)A_s}{2G \cdot e_b} \tag{8}$$

The sensitivity can also be put in terms of absolute sensitivity in the form

$$\frac{d(V_c^2 / R_c)}{dH} = (\tau\alpha)_s A_s \tag{8a}$$

Equations (6a) to (8a) show that basically the steady state sensitivity of the present pyranometer is most dependent to the resistance value of the compensative sensor R_c, the effective area of the solar sensor, and to the product $\tau\alpha$, the dome optical transmissivity and the radiation coefficient of absorption in the solar sensor, respectively. Although the amplifier gain G and the bridge unbalancing electromotive force e_b are parameters that improve the frequency response of this type of instrument, Eq. (8) shows that these parameters can cause low output sensitivity if their respectively values are not set appropriately.

In this study it was assumed that the thermal inertia of the platinum film is negligible in comparison to the thermal inertia of the substrate and the variation of temperature felt by the sensor is also felt by the substrate surface under the sensor.

The time constant of each sensor with two faces promoting convection is defined as

$$T = \frac{m_{su} \cdot C_{psu}}{2UA} \tag{9}$$

where m_{su} is the mass of substrate under the sensor, C_{psu} is the specific heat of the substrate, U is the global heat transfer coefficient of the sensor to the ambient, and A is the sensor effective area.

Experimental Procedures, Results and Discussion

With exception of the calibration in field where the present pyranometer was calibrated against an Eppley PSP pyranometer, all characteristics were observed in laboratory, using an artificial radiation source and the apparatus for the measurement of angular effects shown in the Fig. 5. The system is constituted of a base-support and an aluminum rod that holds the light source. Variation in the height of the light source permits different levels in the intensity of radiation. A residential Comptalux K light bulb of 100 watts was used as artificial radiation source. In the same system (Fig. 5) it is seen an angle indicator opposite to the viewer where by the movement of the light source make it possible to set incidence angles for the light source (cosine and azimuth effect measurement) as well inclination angles of the light source and simultaneously of the pyranometer for the determination of the tilting effect. Another angle indicator at the bottom of the system make it possible to show the angular rotation of the pyranometer in its base for the determination of the azimuth response.

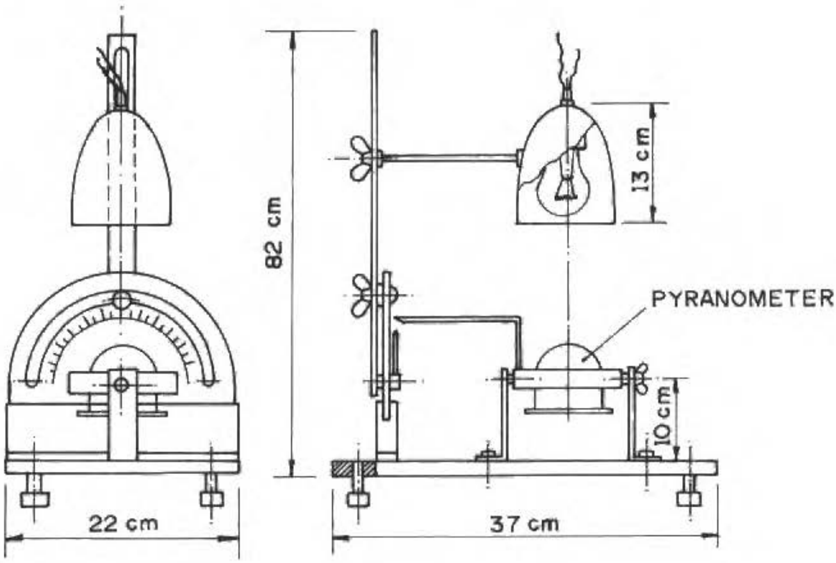

Fig. 5 System for the measurement of angular effects

In order to determine the response time and the time constant of the instrument the procedure was to submit the pyranometer to a radiation of approximately 1100 W/m^2. After that, the light source was turned off until the instrument reached a signal of approximately 1 W/m^2. As can be seen in Fig. 6, at the condition of heating, the time constant was of 16 s against a theoretical value of 17 s. The theoretical value was calculated by Eq. (9). In order to evaluate the expressions of sensitivities and time constant it was measured and assumed parameters as shown in Table 2. Under condition of cooling the measured time constant was of 27 s. There is a significant discrepancy between the measured time constants of heating and cooling. The reason for that discrepancy is that the pyrex substrates where both sensors are manufactured have different process of heating and cooling during transient operation of the instrument. Better explaining, when radiation falls on the solar sensor, it heats by the absorption of the solar radiation and simultaneously the substrate under and around the sensor will be heated in a smaller temperature. The electronic system of the pyranometer will compensate this behavior keeping the compensative sensor with the same temperature as the solar sensor one. The compensative sensor will always have the same temperature as the solar one, however during the process of cooling although both sensors have the same temperature the substrate of the compensative sensor has different thermal storage than the solar sensor and the stability of the signal will be reached when the natural convection on the solar sensor is completed. It is figured in this time that if both sensors are kept inside the dome of the pyranometer the time constants for heating and cooling certainly will be the same. As can be seen in Fig. 6 the response times, defined as the time to reach 95% of the final value, were of 50 s and 75 s respectively.

One of the most common errors in pyranometry is the cosine response which is the dependence of the directional response of the sensor upon solar elevation. Ideally, the response of the receiver should be proportional to the cosine of the zenith angle of the radiation beam. To determine the variation of response with angle of incidence, only lamp sources should be used, because the spectral distribution of the sun changes too much with elevation angle. Thus an apparent variation with solar elevation angle could be observed which, in fact, is a variation due to non-homogeneous spectral response.

Table 2 Value of Physical Parameters Measured or Assumed

$A_{ef} = 10^{-4} m^2$	$C_b = 7.6 \times 10^{-4} V$
$\tau = 0.94$	$G = 1000$
$\alpha = 0.90$ (assumed)	$m_{su} = 8.36 \times 10^{-4} Kg$
$R_c = 4.96\ \Omega$ at 29^0C	$C_{psu} = 840\ J/Kg^oK$
$R_s = 498.26\ \Omega$ at 29^0C	$UA = 0.0221\ W/^oK$

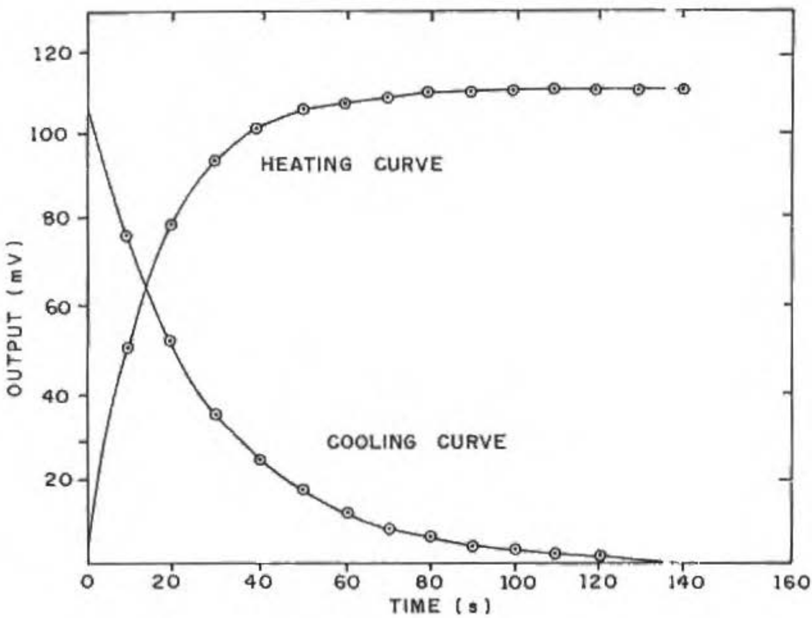

Fig. 6 Response time

Factors that contribute to the cosine errors are: the dependence of the incidence angle of the radiation beam with the absorption coefficient of the black paint used in the solar sensor; defects on the crystalline structure of the dome and incorrect sensor leveling. There are factors with less importance such as curvature in the surface of the sensor and internal reflection of the beam inside the dome. Using the system presented in Fig. 5 for the determination of the angular effects for several angles of incidence (0°, 10°, 20°, 30°, 40°, 50°, 60°, 70° and 80°) measurements were taken of the radiation in opposite positions and mean values were determined for every specific angle of incidence. The light source emitted a irradiation of about 200 W/m^2.

The following expression was used for the determination of the percentage deviation in the cosine response:

$$d\% = \frac{H - H_o \cos Z}{H_o \cos Z} \times 100 \tag{10}$$

where H_o is the radiation signal when the light beam is at a normal angle of incidence, cos Z is the cosine of the angle of incidence Z and H is the radiation measurement when the light beam is at the angle of incidence of interest.

As can be seen in the Fig. 7, the measured cosine response of the compensated pyranometer presented deviation from - 2% in the incidence angle of 10° to -23% in the incidence angle of 80°. According to Table 1, the deviation of 23%, in the cosine response does not classify the present pyranometer and one of the main reason for this substantial difference is due to the dome used. Dome adapted from residential lamp bulb is not the most appropriate for this kind of application.

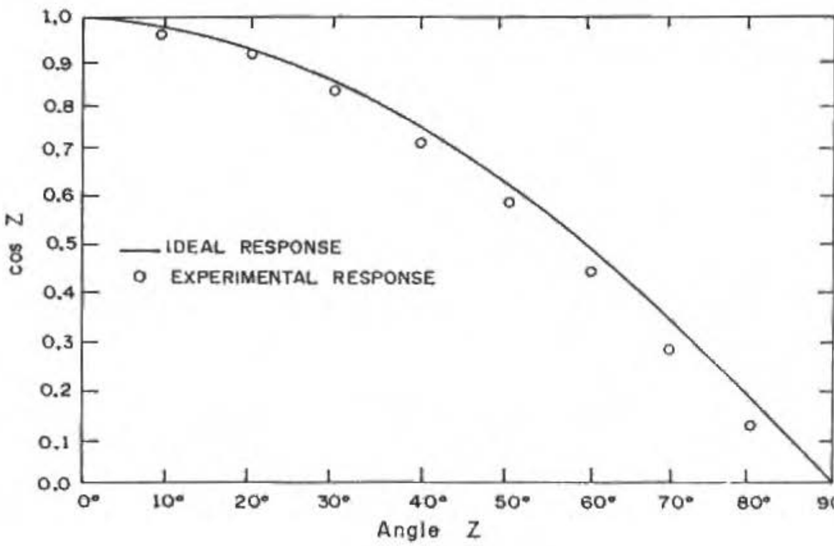

Fig. 7 Cosine response

Figure 8 shows the azimuth response of the proposed pyranometer. In this effect, the dependence of the response of the instrument to the azimuth angle formed by the solar radiation and the sensor level at horizontal position turns to be accentuated mainly at high angles of incidence. The superficial discontinuity in the dome and at the sensor surface contributes significantly for these deviations. For the angle of incidence 80° (or 10° of elevation of the light beam to the sensor plane), rotating the instrument in step of 10°, the deviations were between -3 to -23% from the measured mean value.

It has been observed by many researchers that even commercial pyranometers with high accuracy show variations in the sensitivity when operated with sensors in tilted positions.

It is usual to detect variations from 2 to 5% in the sensitivity of such pyranometers (Coulson, 1975). This kind of problem is associated with convective processes inside the domes of some pyranometers (De Lima and Parreira, 1990).

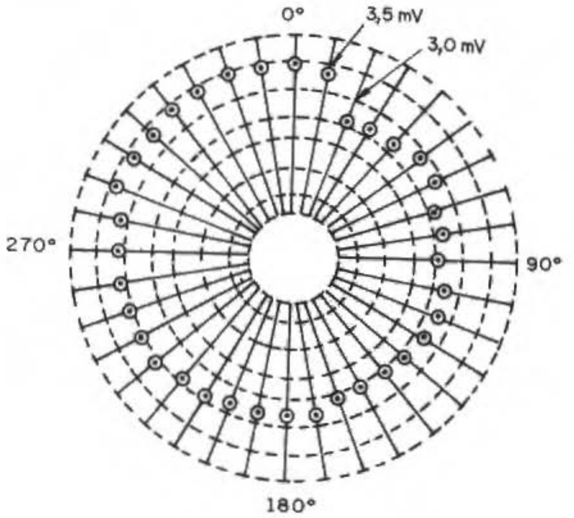

Fig. 8 Azimuth response

The tilting effect of the present pyranometer was observed by the use of the experimental apparatus shown in Fig. 5. Figure 9 shows the tilting effect of the present pyranometer. As can be seen in that figure this compensated pyranometer practically didn't show sensitivity when operated in tilted position. This behavior was expected because the compensative sensor was also designed to avoid the tilting and temperature effects.

Concerning the change of sensitivity due to ambient temperature variation, the WRC (1984) affirms that thermopile instruments exhibit changes in sensitivity with variations in instrument temperature. Some instruments are equipped with built-in temperature compensation circuits in an effort to maintain a constant response over a large range of temperatures. The temperature coefficient of sensitivity may be measured in a temperature-controlled chamber. The temperature in the chamber is varied over a suitable range (-40^{o} to $+40^{o}C$) in 10^{o} steps, and held steady at each step until the response of the pyranometers has stabilized. In the present case, the pyranometer and the system in Fig. 5 were installed inside a chamber where the temperature could be monitored from -10^{o} to $+40^{o}C$. Under a signal of 200 W/m^2, measurements were taken in steps of $10^{o}C$ and the results didn't show any significative difference from the expected value (less than 1%).

The calibration of a pyranometer consists of the determination of its calibration factor and the dependence of this on environmental conditions such as temperature, irradiance level, spectral distribution of irradiance, temporal variation, angular distribution of irradiance and inclination of the instrument

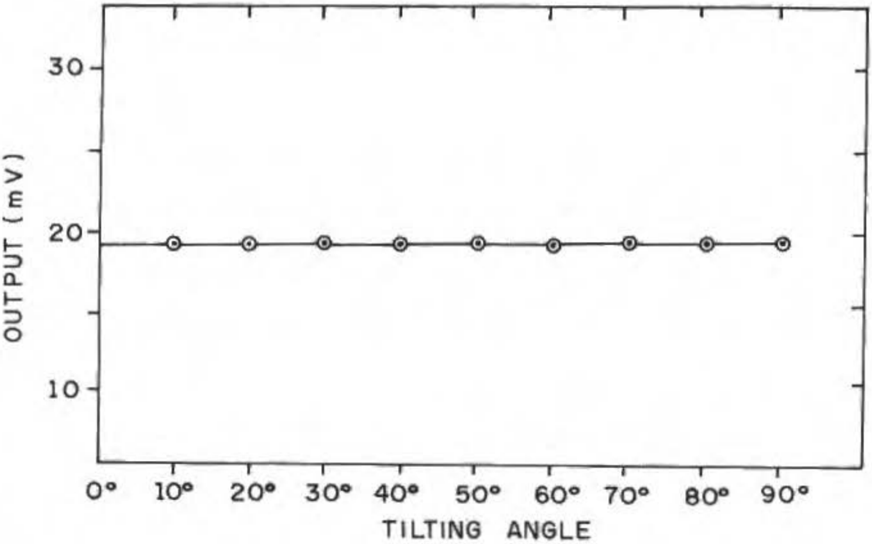

Fig. 9 Tilting effect

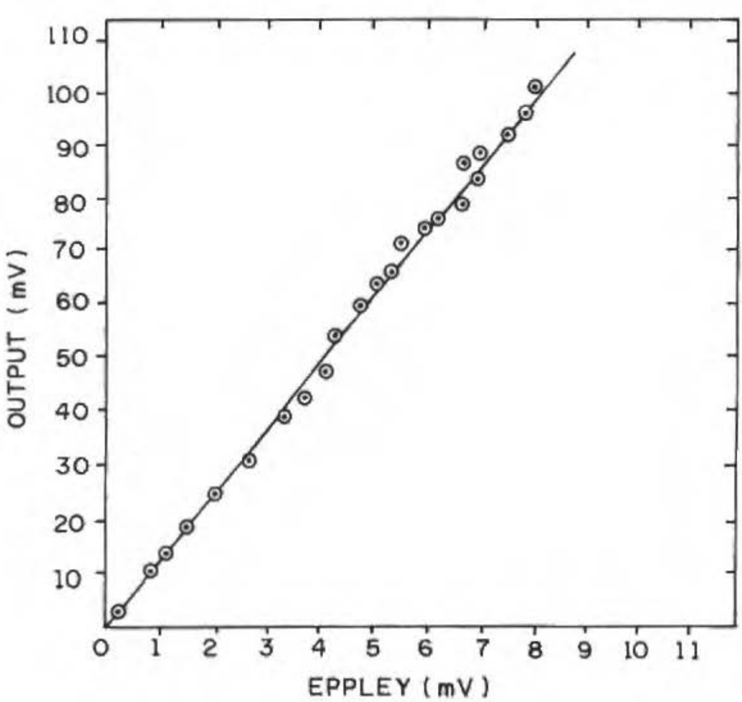

Fig. 10 Pyranometer measurement against Eppley PSP

The comparison of the present instrument with a reference pyranometer entailed the simultaneous operation of both pyranometer mounted horizontally, side by side, outdoors for a period of time of two days. The reference pyranometer used was the Eppley PSP pyranometer. The measurements interval was taken as 15 minutes.

The other method used for the calibration of the present pyranometer was realized in the laboratory. In this method the self compensated pyranometer was exposed to a stabilized tungsten-filament lamp installed in the system shown in Fig. 5. In that case the test pyranometer and the standard pyranometer were exposed to the same conditions.

The statistical analysis of the measured signals of the Eppley and of the compensated pyranometer presented values of coefficient of determination (correlation factor) close to unity (0.99). This demonstrates high correlation between the signals of the Eppley and of the present pyranometer.

Considering the indicator of the deviation of linearity as the result of three standard deviations from the mean of all readings, the deviation in the linearity was smaller than 1%.

The combined results of the calibration in field and in laboratory are shown in Fig. 10. The obtained calibration factor was of 10^{-4} V.m^2/W against the theoretical sensitivity defined by Eq. (8a) of $0.85.10^{-4}$ V.m^2/W. The uncertainty in the calibration factor was of 1%.

The resolution of a radiometer as defined by the WRC (1984) is the smallest detectable change in W/m^2. The resolution can also be defined as the relation between the resolution of the electrical measuring instrument (in this case a voltmeter) and the sensitivity of the pyranometer under study. Using such definition the present pyranometer presented a resolution of 1 W/m^2.

Nomenclature

A = sensor effective surface area, m^2
A_1, A_2, A_3 and A_4 = analog multiplier amplifiers
C = thermal capacity (mc_p) J/K
C_p = specfic heat at constant pressure, J/Kg K
e_b = Wheatstone bridge unbalancing electromotive force, V
d% = percentage deviation in the cosine response
G = differential amplifier gain
H = intensity of solar radiation, W/m^2
H_o = intensity of solar radiation at normal incidence, W/m^2
K = thermal condoctivy, W/mK
IC = integrated circuit
m = mass Kg
R = electrical resistance, Ω
r = variation of electrical resistance, Ω
t = temperature, °C
T = time constant, s
U = global heat transfer coefficient, W/m$_2$K
V = electrical voltage, V
Z = angle of radiation incidence
α = radiation coefficient of absorption
β = temperature coefficient of resistance, 1/K
τ = dome optical transmissivity
θ = time, s

Subscripts

a = ambiente
c = compensative
ef = effective
f = feedback
s = solar
su = substrate

Conclusions

Through the theoretical formulation of the present pyranometer with electrical compensation, its manufacture, and evaluation, it was possible to reach the following conclusions:

- Response time of less than 1 minute encompass this as a first class pyranometer according to the classification of the World Radiation Center (Table 1);

- The dome used for this pyranometer was not the most appropriate and consequently the angular effects didn't present good results;

- The present pyranometer accused an excellent resolution of 1 W/m^2;

- The instrument practically didn't show sensitivity to the variation of ambient temperature and to the operation in tilted position, and

- Developments in the design of sensors and electronics will conduct the present instrument to a standard class pyranometer.

Acknowledgments

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References

Coulson, K. L., 1975, *Solar and Terrestrial Radiation - Methods and Measurements*, Academic Press, New York, USA.

Coulson, K. L. and Howell, Y., 1980, "Solar Radiation Instruments", Sun World, Vol. 4, No. 3, pp. 87-94.

De Lima, L. C. and Parreira, E. P., 1990, "Experiment of Natural Convection in a Hemispherical Cavity with Discrete Thermal Source", ENCIT-90, Florianópolis SC, Brazil, pp. 125-127.

De Lima, L. and Lobo, P. C., 1988, "An Electrical Compensated Pyranometer with Plane Sensors", First World Conference on Experimental Heat Transfer, Fluid Mechanics and Thermodynamics, Dubrovnic, Yugoslavia, pp. 392-346.

De Lima, L. C., 1987, "Construction and Evaluation of Thermoresistive Sensors of Platinum Films", IX Brazilian Congress of Mechanical Engineering, Florianópolis SC, Brazil, pp. 255-257.

De Lima, L. C. and Duarte, M. A. V., 1990, "Noise and Sensitivity Analysis in Electrically Compensated Pyranometers", ENCIT-90, Florianópolis SC, Brazil, pp. 465-468.

Lobo, P. C. and Belo, F. A., 1983, "Experimental Validation of a Loss Compensated Radiometer", Proc. ASME Solar Energy Division 5th. Anual Technical Conference, New York, USA.

Sandborn, V. A., 1972, *Resistance Temperature Transducers*, Colorado State University, Metrology Press, Fort Collins, Colorado, USA.

Wilson, R. C., 1983, "Advances in Pyrheliometric Instrumentation", Report of the NSF/RANN, Solar Energy Data Workshop, nov 29-30, Silver Spring, Md. USA, pp. 50-54.

WRC, 1984, "Measurement of Radiation", World Radiation Center, Chapter IX, Davos, Switzerland.

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Tolerance Synthesis of Cylindrical Fits: A Simple Method Based on the Rectangular Distribution Model

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Abstract

Form and dimensions of mechanical elements vary from one part to another due to the peculiarities of manufacturing processes. Those variations are not dependent on the size of the manufacturing batch and affect the functional and assembly performances of the products in which the parts work. Dimensional synthesis during design stage must include the proper transformation of the functional and assembly requirements, and its allowable variation, in cost-effective dimensions and tolerances.

In this paper a statistical tolerance synthesis procedure is described. It is based on the assumption that the dimensions of the individual parts can be considered uniformly distributed within the interval of allowable dimensional variation. The formulation is directed to solve the case of fits which functional requirements depend on the linear combination of two length dimensions, (i.e. cylindrical fits). The small number of combined dimensions leads to a distribution of the functional requirement which departs strongly from normal, depending on the dimensional tolerance values still not assigned. In the described procedure, the form and properties of the distribution of the functional requirement can be infered a priori, due to the earlier incorporation of economic tolerance distribution criteria.

Keywords: Tolerances, Fits, Statistical synthesis

Introduction

Some variability must always be expected in the size and shape of mechanical components produced by manufacturing processes. These variations affect the functional and assembly relations among components within a product, in such a way that the performance of the product departs from design optimum values. Therefore, functional requirements and its allowable variation must be considered during design stage if adequate dimensions and tolerances are to be assigned.

During dimensioning task, the designer might take in mind the whole life cycle of the product, which could be thought composed of design itself, manufacture, assembly and operation. Tight tolerances are required to ensure proper operation and interchangeability, that are critical matters for the two latter stages. On the other hand, since tolerance values are inversely proportional to manufacturing costs (Lee and Woo, 1989), loose tolerances are required to allow economical manufacturing. This dichotomy must be managed by tolerance synthesis procedures which, in addition, might be simple enough to meet the requirements of a rapid and effective design.

Tolerance synthesis process evolves in four steps (Roy, Liu and Woo, 1991):

(a) Identification, description and quantification of the requirements related with product performance. These requirements could be imposed by assembly and/or operation conditions.

(b) Identification of the dimensional characteristics affecting functional and assembly requirements.

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(c) Development of functional equations, relating functional and assembly requirements (as dependent variables) with dimensions and tolerances affecting those requirements (as independent variables).

(d) Determination of a cost-effective solution to the problem of tolerance distribution.

Functional equations can be either dimension condition equations or tolerance equations. The first ones relate the functional and assembly requirements to the actual values of dimensions. The second ones relate the variation of the functional and assembly requirements to the dimensions and tolerances involved in the problem. The formulation of the tolerance equations requires the previous assumption of a basis of dimensioning. Basis of dimensioning concerns to the expected values of dimensions and the way they will combine to create extreme conditions of assembly and operation (Fortini, 1985). The most common basis of dimensioning are the worst-limit and the statistical. In the worst-limit basis, the limit values of the dimensions, determined by tolerances, are expected to combine in a deterministic way. Tolerances assigned under the assumption of this basis lead to high manufacturing costs but ensure absolute interchangeability and operation performance between the desired limits for all the products assembled with parts which dimensions are "in tolerance". This design criteria is also known as "full-acceptability dimensioning" (Michael and Siddall, 1981). The statistical basis of dimensioning consider that the dimensions of the elements in a fit will combine according to the laws of chance. As the worst combination of parts with limit dimensions is not likely, tolerance values could be increased if a little number of products having functional or assembly performances out of the desired limits can be justified. Economic advantages could be reached if cost increments, related to part rejection and additional operations that might be performed during assembly, are balanced or exceeded by the machining cost reduction due to greater tolerance values allocation. This design/manufacturing principle has been described by Bjorke (1989) as limited interchangeability.

Statistical tolerancing requires an adequate knowledge of the distribution of the dimension condition. This distribution depends on de distributions of the individual dimensions involved in the fit and on the mathematical relations among them. Attending to the distribution of the individual dimensions, two main cases can be identified. The first one is when the dimensions can be considered normally or gaussian distributed, which is the case for parts produced within a statistical process control environment. If the functional performance of a fit can be considered dependent on the linear combination of normally distributed dimensions, the distribution of the dimension condition results also normal and the solution of the problem is simple. The second case is when the distributions of the individual dimensions are expected to depart from normal, as a consequence of manufacturing process peculiarities. In such case, the exact calculation of the distribution of the dimension condition is difficult and time consuming. As a consequence of this fact, approximate methods have been proposed to estimate these distribution. The most common one is based on the application of the central limit theorem (Meyer, 1970). The application of this theorem implies that the distribution of the dimension condition tends to become normal, independent of the distributions of the individual dimensions, as long as the number of dimensions in the assembly is large enough. This approximate criteria can not be applied to the tolerance synthesis of a great number of mechanical products because of the limitation imposed on the number of dimensions involved in the dimension condition formulation. In such cases, a distribution model must be adopted for the individual dimensions to calculate the distribution of the dimension condition.

Distributions of individual dimensions depend on the peculiarities of the manufacturing processes and are not always known. It has been suggested that such distributions generally meet the following set of assumptions (He, 1991): (a) the range of shapes could vary from a rectangular or equal-likelihood to an approximately normal distribution; (b) they may not be symmetrical about the mean value; (c) their upper and lower limits are finite. These assumptions could also be considered valid for previously inspected elements, ready to be assembled. It must be pointed here that the standard deviation value of the rectangular distribution is the greatest among the standard deviations of other alternative distribution models postulated to be used in the statistical analysis of manufactured dimensions (Mansoor, 1963-1964). Then, the rectangular distribution could be applied to allow a conservative statistical tolerance synthesis when the process characteristics are not well known (Bjorke, 1989). A tolerance synthesis procedure assuming a statistical basis with rectangular distribution is described in this paper. It is directed to be applied during the design stage of cylindrical fits and other mechanical systems, when the equation of dimension condition can be expressed as the linear combination of two dimensions and two unrestricted tolerances must be allocated. The dimensions will be assumed uniformly distributed within the interval determined by the upper and lower allowable dimensional limits. As the shape of the distribution of the dimension condition departs from normal and depends on the tolerances of the individual dimensions involved in the fit, a modification in the order of the procedure is proposed. The economical tolerance distribution criteria are applied early during the synthesis process to infere the shape and properties of the distribution of the dimension condition. The distribution criterion adopted in this paper is an approximate one, known as the "difficulty factors method" (Fortini, 1985; Bjorke, 1989).

The Distribution of the Dimension Condition

In this paper, functional requirements whose values depend on the linear combination of two independent variable dimensions will be considered. The most common and simple example of this situation in mechanical construction is given by isolated cylindrical fits. The assembly and functional performances of such fits depend strongly on the difference between the diameters of shaft and hole, both variable due to the uncertainties associated with manufacturing processes. Functional requirements on cylindrical fits could be either represented by length dimensions, like the clearance in a shaft/plain bearing assembly, or other dimensions, like the force or torque transmitted by an interference fit. In the later situation, a nearly constant factor depending on the elastic properties of the elements involved in the fit relates the value of the interference to the corresponding value of the functional requirement. Attending to the scope of this paper, functional requirements that can be expressed by the following general equation could be managed:

$$y_w = \sum_{i=1}^{2} A_i X_i \qquad (1)$$

Equation (1) is also known as equation of the dimension condition. In this paper the concept of dimension condition will be used as an equivalent to the concept of functional requirement. It must be noted that the scale factors A_i in equation (1) relate each variable length dimension X_i to its effect on functional requirement y_w. These factors can be positive or negative, so including in the scope of the proposed methodology the fits whose functional requirements depend on the sum of individual dimensions. The absolute values of these factors can be either one equal to each other, as in the case of interference fits, or one different to each other. An example of the later situation is given by the synthesis of fits that must meet a functional requirement at non reference temperature when the elements involved are made of materials with different thermal expansion factors.

It has been stated that the distribution of individual dimensions depends on he peculiarities of the manufacturing processes. The dimensions of similar parts are variable from one part to another and may be considered as random variate, independently on the size of the manufacturing batch. In addition, parts are manufactured in different machine tools or in different moments, so that dimensions could be also considered independent. In this paper, individual dimensions are expected to be stochastic and independent variables and a rectangular distribution will be assumed for them. Each dimension will be considered composed of a constant part, whose value is the distance to the middle of the tolerance interval μ_i, and a variable part determined by the corresponding tolerance value t_i, (Fig. 1). Then, the assumed distributions of the dimensions can be expressed as follows:

$$X_i \sim R\left[\mu_i - \frac{t_i}{2}; \mu_i + \frac{t_i}{2}\right] \tag{2}$$

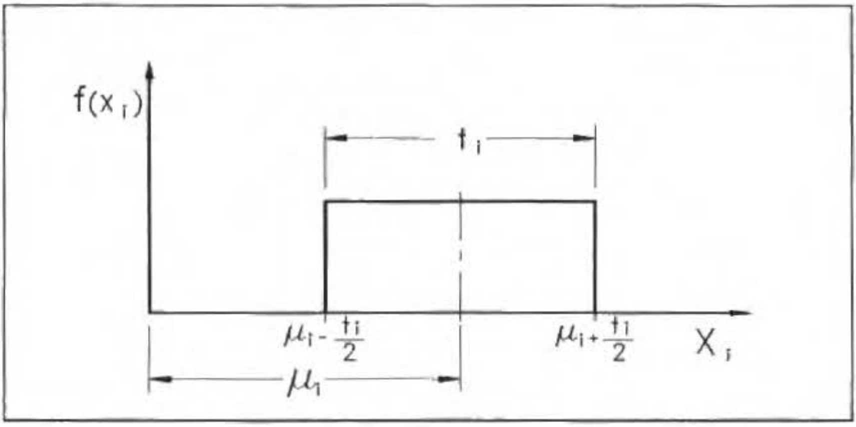

Fig. 1

The statistical properties of the individual dimensions can be obtained from rectangular distribution formulas. The expectation value is equal to the above defined medium value μ_i and the variance $\sigma^2_{X_i}$ could be calculated in terms of the corresponding tolerance value:

$$\sigma^2_{X_i} = \frac{t_i^2}{12} \tag{3}$$

The characteristic values of the distribution of the dimension condition can be obtained through the application of the properties of both expectation and variance to Eq. (1). The linear combination of uniformly distributed dimensions leads to a distribution of dimension condition which is always symmetrical respect of its medium value. Then, the expectation μ_{yw} and variance σ^2_{yw} of the distribution of the dimension condition are, respectively:

$$\mu_{yw} = \sum_{i=1}^{2} A_i \mu_i \tag{4}$$

$$\sigma_{yw}^2 = \frac{1}{12}\sum_{i=1}^{2}(A_i t_i)^2 \qquad (5)$$

The shape of the distribution of the dimension condition depends on the relationship between the values of the two dimensional tolerances, which are already not known. If the values of both tolerances are assigned to be equal, the distribution of dimension condition results in a triangular shape. The shape of the distribution becomes a trapezoid when different values are assigned to the dimensional tolerances. In this paper, a tolerance synthesis procedure will be derived to manage the later situation, as it includes logically the possibility of equal-value tolerances.

When partial interchangeability criteria is applied, the statistical tolerance synthesis of fits requires of an explicit formulation of the relationship between the extreme allowable values of the functional requirement and the number of products in the production batch whose functional requirements are expected to be out of such desired limits. The required formulation can not be obtained yet, because of its dependency on the values of the dimensional tolerances. The first step in order to achieve this objective is to standardize the distribution of the dimension condition. This could be achieved by applying the following equation:

$$Z_{yw} = \frac{y_w - \mu_{yw}}{\sigma_{yw}} \qquad (6)$$

The distribution of the standardized variable of dimension condition Z_{yw} (Fig. 2) can be mathematically defined for different intervals of the variable.

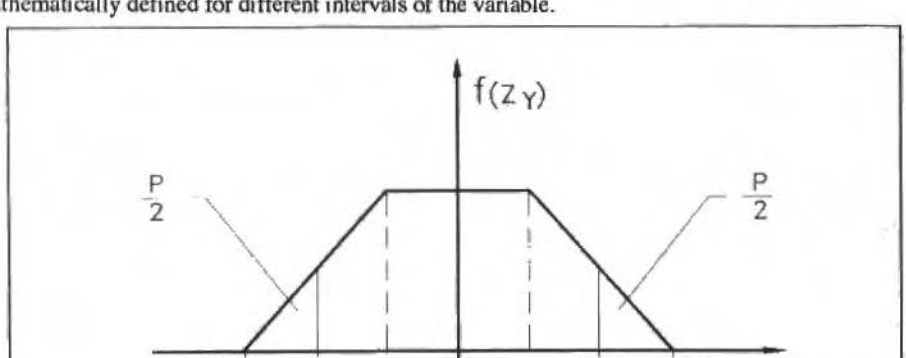

Fig. 2

Considering that different values could be expected for the two dimensional tolerances, the corresponding distribution is a trapezoid, symmetric respect of zero value. In order to achieve a simple statement of the problem, only equations of the distribution for positive values of the standardized variable will be given in this paper.

Within the first interval (7), the formulation of the probability density function is independent on the value of the standardized variable (8):

$$0 < Z_{yw} \leq \frac{\mathrm{abs}\,(\mathrm{abs}A_1 t_1 - \mathrm{abs}A_2 t_2)}{2\sigma_{yw}} \tag{7}$$

$$f_1(Z_{yw}) = \frac{2\sigma_{yw}}{\sum_{i=1}^{2} \mathrm{abs}A_i t_i + \mathrm{abs}\,(\mathrm{abs}A_1 t_1 - \mathrm{abs}A_2 t_2)} \tag{8}$$

The second interval (9) is characterized by a linear dependency of the probability density function on the value of the standardized variable of the dimension condition (10).

$$\frac{\mathrm{abs}\,(\mathrm{abs}A_1 t_1 - \mathrm{abs}A_2 t_2)}{2\sigma_{yw}} < Z_{yw} \leq \frac{\sum_{i=1}^{2} \mathrm{abs}A_i t_i}{2\sigma_{yw}} \tag{9}$$

$$f_2(Z_{yw}) = \frac{\sigma_{yw}}{2\prod_{i=1}^{2} \mathrm{abs}A_i t_i}\left[\sum_{i=1}^{2} \mathrm{abs}A_i t_i - 2\sigma_{yw} Z_{yw}\right] \tag{10}$$

The range of allowable variation of the functional requirement, which is related to quality performance considerations, is a known value during dimensional synthesis. Then, the tolerance of dimension condition V_w can be defined as the difference between upper and lower acceptable limits of the functional requirement. If such limits are replaced in Eq. (6), the corresponding functional limit values of the standardized variable can be obtained. Formulation for positive limit is:

$$Z_{lim} = \frac{V_w}{2\sigma_{yw}} \tag{11}$$

As a consequence of the adoption of the limited interchangeability concept, a proportion of the manufacturing batch would be expected to have functional requirements out of allowable design limits. So, the worst possible combination of the limit dimensions, dependent on tolerance values still not assigned, will define an actual range of variation of functional requirement greater than one defined by specified functional limits. This fact could be expressed in terms of the standardized variable of dimension condition. For positive values of such variable it could be written as follows:

$$Z_{lim} \leq \frac{\sum_{i=1}^{2} absA_i t_i}{2\sigma_{yw}} = Z_w \tag{12}$$

An additional consideration must be done in order to relate the limit values of the dimension condition to the number of products which are expected to have functional requirements out of such limits. Within the common practice of mechanical design, tolerances of similar order are assigned to the different parts involved in a fit. As a consequence, the accumulation of events in the two symmetric triangular areas of the distribution of the standardized dimension condition will result greater than the generally accepted rejection ratios. Then, the equation of the probability density function corresponding to the second interval of the standardized dimension condition $f_2(Z_{yw})$ (10) can be integrated to relate the limit values of the standardized variable to the amount of products having its functional requirements out of such limits P (see shaded areas in Fig. 2):

$$P = \int_{Z_{lim}}^{Z_w} \frac{\sigma_{yw}}{\prod_{i=1}^{2} absA_i t_i} \left[\sum_{i=1}^{2} absA_i t_i - 2\sigma_{yw} Z_{yw} \right] dZ_{yw} \tag{13}$$

Replacing the known values in equation (13) and solving it, the desired equation can be obtained:

$$P = \frac{1}{\prod_{i=1}^{2} absA_i t_i} \left[\frac{\sum_{i=1}^{2} absA_i t_i}{2} - \sigma_{yw} Z_{lim} \right]^2 \tag{14}$$

The last equation depends on the unknown values of the individual tolerances. Then, it can not be still used in order to relate the limit value of the standardized dimension condition to the corresponding proportion of functional-faulty products.

Tolerance Synthesis Formulation

The second functional equation or tolerance equation must relate the variation of the functional requirement V_w to the dimensions and tolerances. In the particular case of requirements depending on the linear combination of two individual dimensions, the tolerance equation can be derived from Eqs. (5) and (11):

$$V_w^2 = \frac{Z_{lim}^2}{3} \sum_{i=1}^{2} (A_i t_i)^2 \tag{15}$$

In this equation, the allowable variation of the functional requirement depends on tolerance values and on the limit value of the standardized dimension condition. Any pair of tolerance values satisfying simultaneously Eqs. (14) and (15) will result in an acceptable solution to the functional problem: the expected proportion of fits assembled with randomly selected parts will function within the specified limits. But, not any of such pairs of tolerances will give a cost-effective solution to the dimensioning problem. In consequence, a tolerance synthesis formulation must include the consideration of manufacturing costs and its relationship to dimensional tolerance values to facilitate an optimum tolerance assignment.

During design stage of mechanical products, there is a lack of information on cost components and its dependence on tolerance values. On the other hand, cost calculations require processing facilities not always available and are time consuming. To overcome such contrary state of affairs, a simplified method have been proposed providing an approach to optimum tolerance allocation. The procedure, called the difficulty (or complexity) factors method (Fortini, 1985; Bjorke, 1989), involves the evaluation of the relative complexity of manufacturing the different parts in a fit. It is based on the fact that there is a close correlation between the relative difficulties of machining the mating parts and the relative manufacturing costs.

The difficulty of manufacturing a dimension to a specified precision level depends on the material from which the part is made, the manufacturing process to be used, the size and shape of the element and other less important factors. The evaluation of such difficulty can be expressed by a number K_i associated to each dimension involved in a fit. An approximation to the lowest overall manufacturing cost of a fit could be achieved assigning greater tolerance values to the dimensions having greater difficulty factors. Applying this criteria to dimension conditions depending on the linear combination of two uniformly distributed dimensions, the tolerance values result:

$$t_i = \frac{\sqrt{3} V_w}{Z_{lim} \, \mathrm{abs} A_i} \left[\frac{K_i}{\sum_{i=1}^{2} K_i} \right]^{1/2} \tag{16}$$

Attending to the later equation, tolerance values depend on the limit value of the standardized dimension condition, yet not known, and on difficulty factors, tolerance of the functional requirement and scale factors, all of them already known during tolerance synthesis. The proposal of the authors is to replace the unknown tolerance values in Eq. (14) by the equivalents in terms of difficulty factors. This leads to an explicit relationship between the allowable proportion of functional-faulty products and the corresponding limit value of the standardized dimension condition. In order to achieve a greater simplicity in the derived equations, the relative difficulty concept is introduced in this paper. The relative difficulty of manufacturing the mating parts D_r is defined as the square root of the ratio between the difficulty factors corresponding to each element involved in the fit:

$$D_r = \left[\frac{K_1}{K_2}\right]^{1/2} \tag{17}$$

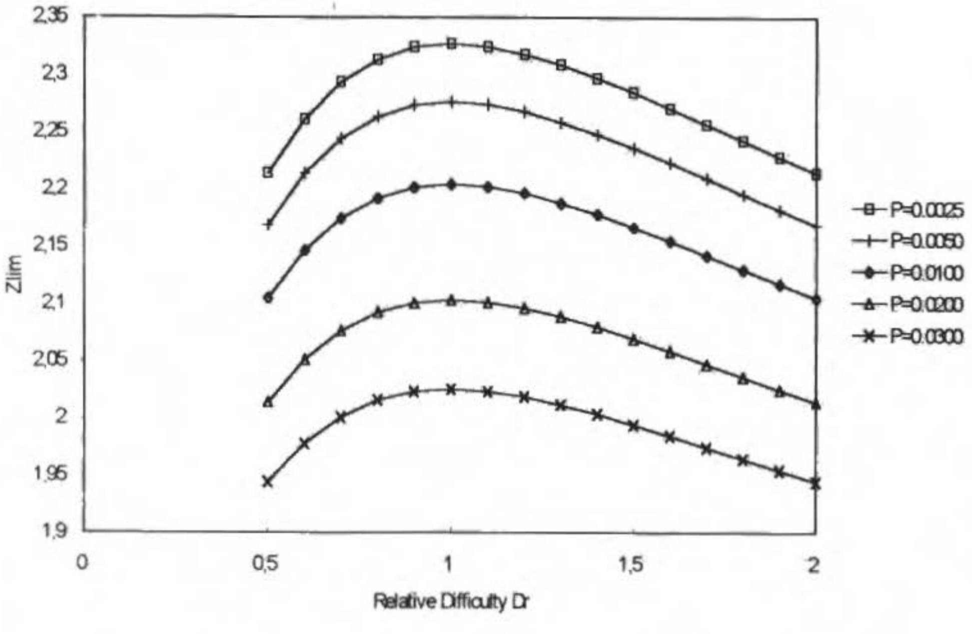

Fig. 3

Tolerance distribution Eqs. (16) can be modified by expressing them in terms of this concept:

$$t_1 = \frac{\sqrt{3}V_w}{Z_{lim}\,\mathrm{abs}\Lambda_i}\frac{D_r}{(1+D_r^2)^{1/2}} \tag{18}$$

$$t_2 = \frac{\text{abs}A_1}{\text{abs}A_2}\frac{t_1}{D_r} \tag{19}$$

An explicit relationship between the acceptable proportion of functional-faulty products and the corresponding limit value of the standardized dimension condition can be derived when Eqs. (18) and (19) are replaced in Eq. (14):

$$Z_{lim} = \frac{\sqrt{3}}{(1 + D_r^2)^{1/2}}\left[1 + D_r - 2\sqrt{PD_r}\right] \tag{20}$$

This way, the characteristic values and statistical properties of the distribution of the dimension condition could be known without knowing the value of the dimensional tolerances. The value of the relative difficulty concept, depending on complexity factors, can be assigned a priori to the solution of the functional-related problem. A plot has been obtained relating the limit value of the standardized dimension condition to the relative difficulty factor for different values of the allowable proportion of functional-faulty products (Fig. 3). As in common industrial practice the difficulties of manufacturing the parts involved in a fit are rather similar, values of relative difficulty factor D_r have been varied between 0.5 and 2. This allows as indifferent assignment of the sub-index to each matting part.

Then, the proposed statistical synthesis procedure could be resumed as follows:

(1) Determine the complexity factors K_i based on manufacturing considerations. Calculate the relative difficulty D_r using Eq. (17).

(2) Assume a permissible proportion P of functional-faulty products, based on manufacturing and quality control policies.

(3) Determine the limit value of the standardized dimension condition Z_{lim} using the Eq. (20) or the plot in Fig. 3.

(4) Finally, calculate the desired tolerance values t_i replacing the values already calculated in Eqs. (18) and (19).

Tolerance values synthesized this way will give a cost-effective solution to the functional problem in hands. The desired proportion of assembled products will function within the desired limits if the actual distributions of the dimensions could be represented conservatively by equal-likelihood distributions.

Discussion

As it has been stated previously, the shape of the distribution of the dimensions produced by a manufacturing process depends on the particularities of the process itself and is not related to the amount of parts that are going to be manufactured. Statistical tolerance synthesis is based on an adequate knowledge of the distribution of individual dimensions and on the possibility of determining the shape of the distribution of dimension condition. No problems arise if individual dimensions could be considered normally distributed or if the amount of dimensions involved in the fit is large enough to result in an approximately normal distribution of the dimension condition (consequence of the application of the central limit theorem).

When manufacturing small batches, or even unique parts, it is nearly impossible to obtain the shape of the actual distributions (which generally depart from normal). In addition, the functional performance of a large number of mechanical systems depends on a small number of individual dimensions. In such cases it has been a common practice to synthesize dimensional tolerances under the assumption of the worst limit basis of dimensioning, so resulting in restrictive tolerance values. As the tolerance synthesis procedure proposed here represents an alternative to the application of the worst combination criterion, it is reasonable to evaluate the benefits that could be achieved rating the tolerance values calculated using both methods.

The second functional equation or tolerance equation derived from the assumption of the worst limit basis can be expressed as follows:

$$V_w = \sum_{i=1}^{2} \mathrm{abs}A_i t_i^w \tag{21}$$

The tolerance of the dimension condition V_w and the scale factors A_i in Eq. (21) are equal in value that those considered in the statistical formulation: they depend on the product function. Tolerance values corresponding to the assumption of the worst possible combination has been identified with the supra-index (w). The corresponding tolerance distribution equations can be derived from Eq. (21) based on the distribution criteria already applied for the statistical formulation. In terms of the relative difficulty concept, the equations are as follows:

$$t_i^w = \frac{V_w}{\mathrm{abs}A_i} \frac{D_r^2}{1 + D_r^2} \tag{22}$$

$$t_2^w = \frac{\mathrm{abs}A_1}{\mathrm{abs}A_2} \frac{t_1^w}{D_r^2} \tag{23}$$

The gain of applying the proposed statistical tolerancing methodology can be expressed as the ratio between the sum of the dimensional tolerances calculated by both methods to be compared:

$$\mathrm{Gain} = \frac{\sum_{i=1}^{2} t_i}{\sum_{i=1}^{2} t_i^w} \tag{24}$$

Replacing the tolerance distribution equations in (24), the gain can be expressed in terms of the scale factors A_i, the relative difficulty D_r and the acceptable proportion of functional faulty products P as follows:

$$\text{Gain} = \frac{\text{abs}\left(\dfrac{A_1}{A_2}\right) + D_r}{\text{abs}\left(\dfrac{A_1}{A_2}\right) + D_r^2} \frac{1 + D_r^2}{1 + D_r - 2(PD_r)^{1/2}} \qquad (25)$$

A family of plots have been obtained in order to test the behavior of the gain for different values of the involved variables. Each plot corresponds to a different value of the ratio between scale factors affecting both dimensions A_1/A_2. In common engineering practice, the scale factors are not expected to be quite different one to each other. Then, the extreme values considered in this paper are $A_1/A_2 = 0.5$ (Fig. 4) and $A_1/A_2 = 2$ (Fig. 5). To illustrate the behavior of the gain when the influences of both dimensions on the performance of the fit are equal, a plot corresponding to $A_1/A_2 = 1$ is also shown (Fig. 6). In the provided plots the relative difficulty has been considered to be the independent variable. The parameter characterizing each curve is the proportion of functional-faulty products, being the selected values 0.0025, 0.005, 0.010, 0.020 and 0.030.

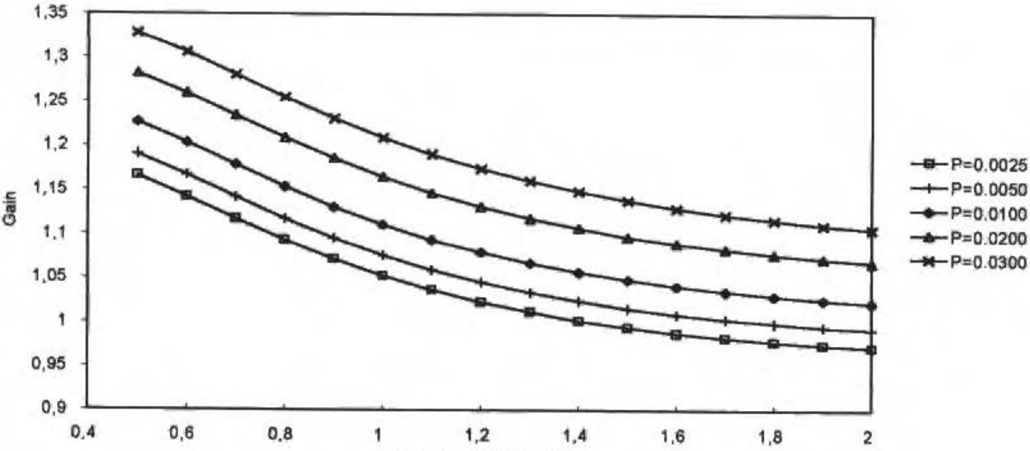

Fig. 4

For each constant value of the ratio between scale factors, the gain increases with an increase in the permissible proportion of functional-faulty products. In the cases characterized by an equal influence of the dimensions in the functional performance of the product ($A_1/A_2 = 1$), the gain exhibits little variation with the variation of the relative difficulty, though maximum values must be expected when the complexity of manufacturing both parts in the fit are equal (see Fig. 6). In the aforementioned cases, the values of the gain are small for the minor values of the acceptable proportion of functional-faulty products. Increasing such proportion, more interesting benefits could be reached (gains up to 1.20 for P = 0.03).

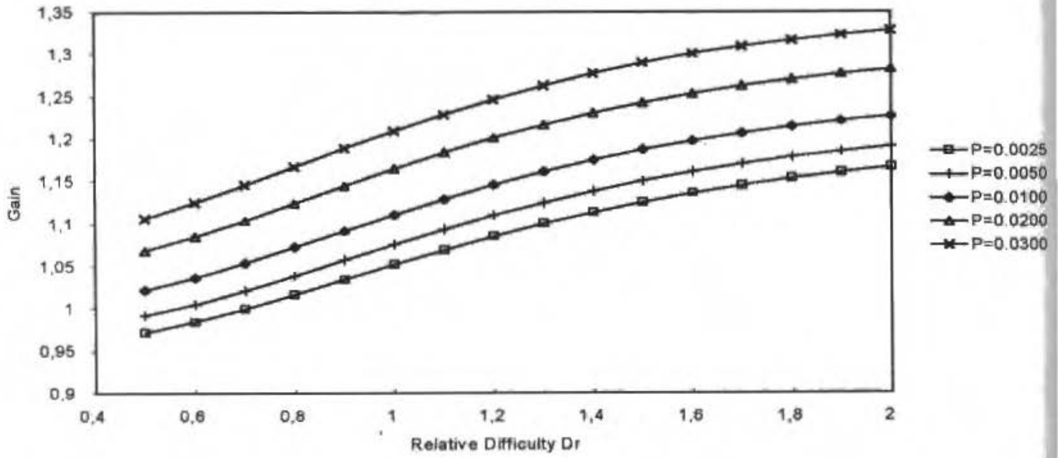

Fig. 5

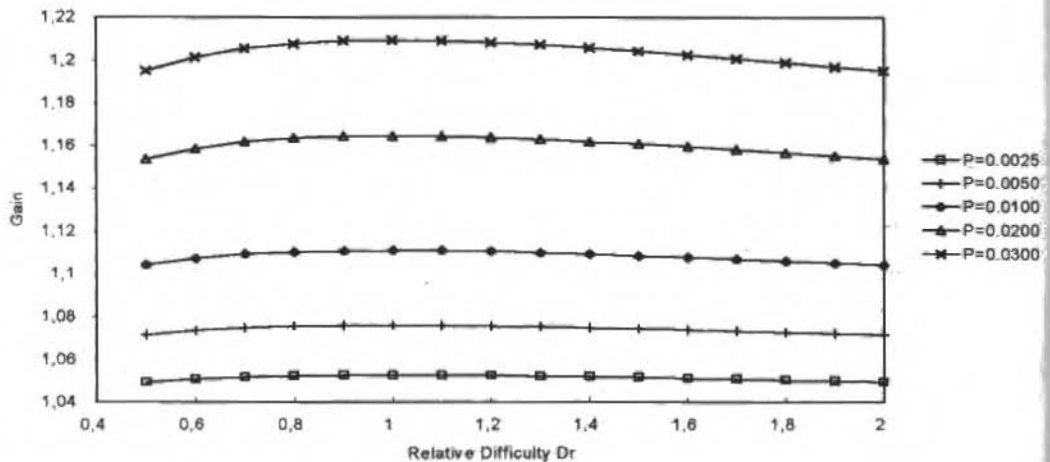

Fig. 6

When the scale factors associated to each dimension are not equal, nor are the manufacturing complexities, higher and lower values of the gain for each constant value of the proportion P can result. Such values are associated with particular combinations of the relative difficulty D_r and the scale factor ratio A_1/A_2. When the ratio between scale factors is less than the unit (see Fig. 4 for example), the gain increases while relative difficulty decreases. If a small proportion of functional-faulty products is allowed, this behavior could lead to cases in which no gain can be obtained performing the proposed statistical tolerancing method. A similar situation is reached when the ratio between scale factors is greater than the unit (see Fig. 5) simultaneously with a value of relative difficulty minor than the unit. Conversely, the aforementioned behavior of the system could be managed by the designer to increase the benefits that can be achieved. If the fit is designed in such a way that the scale factors ratio and the relative difficulty are simultaneously greater or smaller than the unit, the resultant values of the gain will be higher.

Though the gains associated with the application of the proposed methodology are rather small, it provides a feasible alternative to the tolerancing procedure based on the worst possible combination of limit dimensions because of its simplicity. No complex calculus or special information are required to synthesize dimensions and tolerances of the elements involved in the fit. Future efforts will be directed to extend the application of the proposed procedure to fits characterized by functional requirements witch depend on more than two dimensions. As the number of dimensions involved in a dimension condition increases, the tendency of the distribution of dimension condition is to cluster more events around the medium value. Then, if the desired formulation is obtained for such problems, it could be expected that the gain will increase as the number of dimensions associated in the fit increases.

Conclusions

A statistical tolerance synthesis method based on the assumption that the unknown distributions of dimensions could be conservatively represented by means of the rectangular or equal-likelihood distribution have been proposed in this paper. Equations have been developed to be applied in mechanical systems whose functional performance depends on the linear combination of two independent dimensions. The methodology is simple enough to be applied during conceptual and embodiment design stages and provides an approach to optimum tolerance allocation, as long as it is supported on simultaneous analysis of functional performance and manufacturing costs.

The application of the proposed method could produce economical benefits during manufacture, via the enlargement of dimensional tolerance values (respect of those that can be obtained by the assumption of the worst possible combination of limit dimensions). As it has been discussed above, greater benefits are expectable if the method can be extended to fits depending on a greater number of individual dimensions.

References

Bjorke, O., 1989, *Computer-Aided Tolerancing*, ASME Press, 2nd ed.

Fortini, E. T., 1985, "Dimensions and Tolerances" in Rothbart, H., *Mech. Design and Systems Handbook*, Mc Graw-Hill, pp. 19.1-19.22.

He, J. R., 1991, "Estimating the Distributions of Manufactured Dimensions with the Beta Probability Density Function", Int. J. Mach. Tools Manufact., Vol. 31, No. 3, pp. 383-396.

Lee, W. J., and Woo, T. C., 1989, "Optimum Selection of Discrete Tolerances", Trans. of the ASME, J. of Mechanisms, Transmissions and Automation in Design, Vol. 111, pp. 243-251.

Nomenclature

- y_w = Dimension condition (or fit condition)(variable)
- X_i = Individual dimensions of the parts involved in a fit (variable)
- A_i = Scale factors for the individual dimensions
- μ_i = Mean dimensions of the parts, defined at the center of the corresponding tolerance intervals
- t_i = Tolerance intervals for the individual dimensions involved in the fit
- $\sigma^2_{X_i}$ = Variances of the frequency distributions of the individual dimensions
- μ_{yw} = Mean value of the dimension condition
- σ^2_{yw} = Variance of the frequency distribution of the dimension condition
- Z_{yw} = Standardized variable of the dimension condition
- V_w = Tolerance interval of the dimension condition
- Z_{lim} = Limit values of the standardized variable of the dimension condition
- P = Proportion of functional-faulty products
- K_i = Difficulty factors for the individual dimensions
- D_r = Relative difficulty
- t_i^w = Tolerance values of the individual dimensions assigned assuming the worst-limit basis of dimensioning
- Gain = Gain

Meyer, P. L., 1970, *Introductory Probability and Statistical Applications*, Addison-Wesley Pub. Co.

Michael, W., and Siddall, J. N., 1981, "The Optimization Problem With Optimal Tolerance Assignment and Full Acceptance", Trans. of the ASME, J. of Mechanical Design, Vol. 103, pp. 842-848.

Roy, U., Liu, C. R., and Woo, T. C., 1991,"Review of Dimensioning and Tolerancing: Representation and Processing", Computer-Aided Design, Vol. 23, No. 7, pp. 466-483.

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A Stochastic Approach to the Problem of Spacecraft Optimal Maneuvers

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Abstract

In this paper the problem of spacecraft orbit transfer with minimum fuel consumption is considered. A new version of the suboptimal and hybrid control approach of numerically treating the problem, where one can take into account the accuracy in the satisfaction of constraints is developed. To solve the nonlinear programming problem in each iteration, a stochastic version of the projection of the gradient method is used together with the well-known hybrid approach to find the optimal control in this kind of dynamic problem. For the maneuvers considered, the spacecraft is supposed to be in Keplerian motion perturbed by the thrusts whenever they are active. The thrusts are assumed to be of fixed magnitude (either low or high) and operating in an on-off mode. The solution is given in terms of the location of the "burning arcs", "time"-histories of thrust attitude (pitch and yaw), final orbit acquired and fuel consumed. Numerical results are presented.

Keywords: Optimal Transfer, Stochastic Approximation, Optimal Control, Spacecraft Orbit Maneuver

Introduction

This paper comes in sequence of a previous one, where the autors (Prado and Rios-Neto, 1989) numerically solved the problem of spacecraft maneuvers with minimum fuel expenditure using suboptimal and optimal control associated with a nonlinear programming projection of the gradient method. Here, the same problem is considered with the difference that the constraints do not need to be exactly satisfied and a stochastic version of the projection of the gradient is used (Rios-Neto and Pinto, 1987). This is done to realistically treat the numerical inaccuracies and/or flexibility in terms of tolerance in mission requirements, leading to situations where the final state is constrained to lie inside a given region, instead of being an exact value. The results of numerical simulations are compared to assess the fuel savings given by the stochastical approach. A more general study of the problem of orbit transfer maneuvers is available in Prado and Rios-Neto (1993).

Definition of the Problem

The basic problem discussed in this paper is the problem of orbit transfer meneuvers. The objective of this problem is to modify the orbit of a given spacecraft. In the case considered in this paper, an initial and a final orbit around the Earth is completely specified. The problem is to find how to transfer the spacecraft between those two orbits in such a way that the fuel consumed is minimum. There is no time restriction involved here and the spacecraft can leave and arrive at any point in the given initial and final orbits. The maneuver is performed with the use of an engine that is able to deliver a thrust with constant magnitude and variable direction. The mechanism, time and fuel consumption to change the direction of the thrust is not considered in this paper.

Model Used

The spacecraft is supposed to be in Keplerian motion controlled only by the thrusts, whenever they are active. This means that there are two types of motion.

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i) A Keplerian orbit, that is an orbit obtained by assuming that the Earth's gravity (assumed to be a point of mass) is the only force action on the spacecraft. This motion occurs when the thrusts are not firing, and

ii) The motion governed by two forces: the Earth's gravity field (also assumed to be a point of mass) and the force delivered by the thrusts. This motion occurs during the time that the thrusts are firing.

Figure 1 shows this situation. F_E is the gravitational force of the Earth (assumed to be a point of mass) and F_t is the force given by the thrusts.

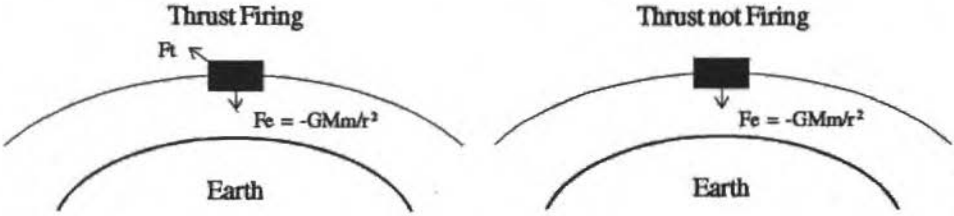

Fig. 1 Forces acting in the satellite

The thrusts are assumed to have the following characteristics:

i) Fixed magnitude: the force generated by them is always of constant magnitude during the maneuver. The value of this constant is a free parameter (an input for the algorithm developed here) that can be high or low;

ii) Constant ejection velocity: meaning that the velocity of the gases ejected from the thrusts is constant. The importance of this fact can be better understood by examining Prado (1989);

iii) Either free or constrained angular motion: this means that the direction of the force given by the thrusts can be modified during the transfer. This direction can be specified by the angles u_1 and u_2 called pitch (the angle between the direction of the thrust and the perpendicular to the line Earth-spacecraft) and yaw (the angle with respect to the orbital plane). The motion of those angles can be free of constrained (constant, linear variations, forbidden regions for firing the thrust, etc.), and

iv) Operation in on-off mode: it means that intermediate states are not allowed. The thrusts are either at zero or maximum level all the time.

The solution is fiven in terms of the time-histories of the thrusts (pitch and yaw angles) and fuel consumed. Several numbers of "thrusting arcs" (arcs with the thrusts active) are tested for each maneuver.

Instead of time, the "range angle" (the angle between the radius vector of the spacecraft and an arbitrary reference line in the orbital plane) is used as the independent variable.

Optimal Control Problem Formulation

The minimum fuel spacecraft maneuver can be treated as a typical optimal control problem, formulated as follows.

Objective Function: Let M_f, the final mass of the vehicle, to be maximized with respect to the control $\underset{\sim}{u}(.)$;

Subject to:

$$\dot{\underline{x}} = \underline{f}(\underline{x}, \underline{u}, s) \quad (1)$$

$$\underline{Ce}(\underline{x}, \underline{u}, s) = \underline{Ee} \quad (2)$$

$$\underline{Cd}(\underline{x}, \underline{u}, s) \le \underline{Ed} \quad (3)$$

$$\underline{h}(\underline{x}(t_f), t_f) = \underline{Eh}, \; t_0 \text{ and } \underline{x}(t_0) \text{ given} \quad (4)$$

where $\underline{x}$ is a state vector, $\underline{f}(.)$ is the right hand side of equations of motion, as in Biggs (1979) and Prado (1989); s is the independent variable $(s_0 \le s \le s_f)$, $\underline{Ce}(.)$ and $\underline{Cd}(.)$ are the algebraic dynamic constraints on state and control of dimensions m_e and m_d; $\underline{h}(.)$ are the boundary constraints of dimension m_h; and $\underline{Ee}$, $\underline{Ed}$, $\underline{Eh}$ error vectors satisfying:

$$|Ee_i| \le Ee_i^T, \; i = 1, 2, 3, ..., m_e \quad (5)$$

$$|Ed_i| \le Ed_i^T, \; i = 1, 2, 3, ..., m_d \quad (6)$$

$$|Eh_i| \le Eh_i^T, \; i = 1, 2, 3, ..., m_h \quad (7)$$

where the fixed given values Ee_i^T, Ed_i^T, Eh_i^T characterizes the region around zero within which errors are considered tolerable.

Suboptimal Method

In this approach (Biggs, 1978; Rios-Neto and Ceballos, 1979; Rios-Neto and Bambace, 1981; Ceballos and Rios-Neto, 1981, Prado and Rios-Neto, 1989), parametrization is used for an approximation of the control (angles of pitch u_1 and yaw u_2), and for the problem at hand:

$$u_1 = p_1 + p_2(s - s_s) \quad (8)$$

$$u_2 = p_3 + p_4(s - s_s) \quad (9)$$

where p_1, p_2, p_3, p_4 are the parameters to be found; s is the instantaneous range angle and s_s is the range angle of the instant when the motor is turned on.

With this, for each "burning arc" in the maneuver, there is a set of six variables to be optimized (start and end of thrusting and the four parameters for the angles of pitch and yaw). Note that the number of "burning arcs" is chosen "a priori".

With control parametrization, the problem is reduced to one of nonlinear programming, which will be solved by the stochastic version of the projection of the gradient method.

Optimal Method

This approach is based on Optimal Control Theory (Bryson, 1975). First order necessary conditions for a local minimum are used to obtain the adjoint equations and the Pontryagin's Maximum Principle to obtain the control angles at each range angle, leading to a "Two Point Boundary Value Problem" (TPBVP), where the difficulty is to find the initial values of the Lagrange multipliers. The treatment given here (Biggs, 1979) is the hybrid approach of guessing a set of values, integrating numerically all the differential equations and then searching for a new set of values, based on a nonlinear programming algorithm. With this approach, the problem is again reduced to parametric optimization, as in the suboptimal method, with the difference that the angle's parameters are replaced by the initial values of the Lagrange multipliers, as variables to be optimized.

The method by Biggs (1979) was used, where the "adjoint-control" transformation is performed and instead of the initial values of Lagrange multipliers one guesses control angles and their rates at the beginning of thrusting. With this, it is easier to find a good initial guess, and the convergence is faster. This hybrid approach has the advantage that, since the Lagrange multipliers remain constant during the "ballistic arcs", it is necessary to guess values of the control angles and its rates only for the first "burning arc". This transformation reduces very much the number of variables to be optimized and, in consequence, the time of convergence.

Numerical Method

To solve the nonlinear programming problem, the stochastic version of the projection of the gradient method (Rios-Neto and Pinto, 1987) was used.

Its general scheme is resumed in what follows:

Given a value $\bar{\underline{p}}$ of the searched vector of parameters $\underline{p}$, from an initial guess or from an immediately previous iteration, a first order, direct search approach is adopted in a typical iteration to determine an approximate solution for the increment $\Delta\underline{p}$ in the problem:

Minimize:

$$J(\bar{\underline{p}} + \Delta\underline{p}) \tag{10}$$

Subject to:

$$\underline{Ce}(\bar{\underline{p}} + \Delta\underline{p}) = \alpha\underline{Ce}(\bar{\underline{p}}) + \underline{Ee} \tag{11}$$

$$\underline{Cd}(\bar{\underline{p}} + \Delta\underline{p}) = \beta\underline{Cd}(\bar{\underline{p}}) + \underline{Ed} \tag{12}$$

where $J(p)$ is the objective function, $\underline{Ce}(p)$ the equality constraints, $\underline{Cd}(p)$ the active inequality constraints at p, and $0 \le \alpha < 1$, $0 \le \beta < 1$ are chosen close enough to one to lead to increments $\Delta\underline{p}$ of a first order of magnitude.

Linearized approximations are taken for the left hand sides of Eqs. (11) and (12) together with a stochastic interpretation for the errors $\underline{Ee}$ and $\underline{Ed}$, resulting in:

$$(\alpha - 1)\,\underline{Ce}(\bar{p}) = (d[\underline{Ce}(\bar{p})]/dp)\,\Delta p + \underline{Ee} \quad (13)$$

$$(\beta - 1)\,\underline{Cd}(\bar{p}) = (d[\underline{Cd}(\bar{p})]/dp)\,\Delta p + \underline{Ed} \quad (14)$$

where $\underline{Ed}$ and $\underline{Ee}$ are now assumed to be zero mean uniformly distributed errors, modeled as:

$$E\left[(\underline{EeEe})^T\right] = \text{diag}[e_i, i = 1, 2, ..., m_e]$$

$$E\left[(\underline{EdEd})^T\right] = \text{diag}[d_i, i = 1, 2, ..., m_d]$$

where E[.] indicate the expected value of its argument.

The condition of Eq. (10) is approximated by the following "a priori information":

$$-g\underline{\nabla}J^T(\bar{p}) = \Delta\underline{p} + \underline{n} \quad (15)$$

where $g \ge 0$ is to be adjusted to guarantee a first order of magnitude for the increment, that is, such that $\Delta\underline{p}$ is small enough to permit the use of a linearized representation of $J(\bar{p} + \Delta\underline{p})$ and $\underline{n}$ is taken as a zero mean uniformly distributed random vector, modelling the a priori searching error in the direction of the gradient $\underline{\nabla}J(\bar{p})$ with:

$$E[\underline{nn}^T] = \bar{\underline{P}}$$

as its diagonal covariance matrix. The values of the variances in $\bar{\underline{P}}$ are chosen such as to characterize an "adequate order of magnitude" for the dispersion of $\underline{n}$. The diagonal form adopted is to model the assumption that it is not imposed any a priori correlation between the errors in the gradient components.

The simultaneous consideration of Eqs. (13-15) characterize a problem of parameter estimation, which in a compact notation can be put as follows:

$$\underline{\bar{U}} = \underline{U} + \underline{n} \tag{16}$$

$$\underline{Y} = \underline{M}\underline{U} + \underline{V} \tag{17}$$

where $\underline{\bar{U}} \Delta - g\nabla J^T(\underline{\bar{p}})$ is the "a priori information"; $\underline{U} \Delta \Delta \underline{p}$;

$\underline{Y} \Delta \left[(\alpha - 1)\, \underline{Ce}^T(\underline{\bar{p}}) :\; ((\beta - 1)\, \underline{Cd}^T(\underline{\bar{p}})) \right]$ is the observation vector;

$\underline{M}^T \Delta \left[(d(\underline{Ce}(\underline{\bar{p}}))/d\underline{p})^T :\; (d(\underline{Cd}(\underline{\bar{p}}))/d\underline{p})^T \right]$; $\underline{V}^T = \left[\underline{Ee}^T : \underline{Ed}^T \right]$.

Adopting a criterion of linear, minimum variance estimation, the optimal search increment can be determined using the classical Gauss-Markov estimation, which in Kalman form (e. g. Jazwinski, 1970) gives:

$$\underline{\hat{U}} = \underline{\bar{U}} + \underline{K}(\underline{Y} - \underline{M}\underline{\bar{U}}) \tag{18}$$

$$\underline{P} = \underline{\bar{P}} - \underline{K}\underline{M}\underline{\bar{P}} \tag{19}$$

$$\underline{K} = \underline{\bar{P}}\underline{M}^T (\underline{M}\underline{\bar{P}}\underline{M}^T + \underline{R})^{-1} \tag{20}$$

where $\underline{\bar{P}}$ is defined as before; $\underline{R} \Delta E\left[\underline{V}\underline{V}^T\right] = \mathrm{diag}[R_k, k = 1, 2, ..., m_e + m_d]$; and $\underline{P}$ has the meaning of being the covariance matrix of the errors in the components estimates of $\underline{U}$, i. e.:

$$\underline{P} = E\left[(\underline{U} - \underline{\hat{U}})\, (\underline{U} - \underline{\hat{U}})^T \right] \tag{21}$$

To build a numerical algorithm using the proposed procedure, the following types of iterations are considered:

i) Initial phase of acquisition of constraints, when starting from a feasible point that satisfies the inequality constraints, the search is done to capture the equality constraints, including those inequality constraints that eventually became active along this phase;

ii) Search of the minumum, when from a point that satisfies the constraints in the limits of the tolerable errors $\underline{V}$ in Eq. (17), the search is done to take the objective function (Eq. (10) to get nearer to the minimum, this search is conducted relaxing the order of magnitude of the error bounds around de constraints;

iii) Restoration of the constraints, when from a point that resulted from a type (ii) iteration, the search is done to restore constraints satisfaction, within the limits imposed by the error $\underline{V}$ in Eq. (17).

Rios-Neto and Pinto (1987) suggest how to choose good values for the numerical parameters, that must be different for each type of iteration.

Simulations and Numerical Tests

The algorithm was coded in single precision FORTRAN IV, and the calcularions where performed at the Instituto Nacional de Pesquisas Espaciais (INPE) in a Burroughs 6800 computer.

To verify the algorithm proposed, the maneuver for the initial phase (orbit transfer) of the First Brazilian Remote Sensing Satellite was simulated. These results were compared with the ones obtained by the deterministic version (Prado and Rios-Neto, 1989), without flexibility in constraint's satisfaction.

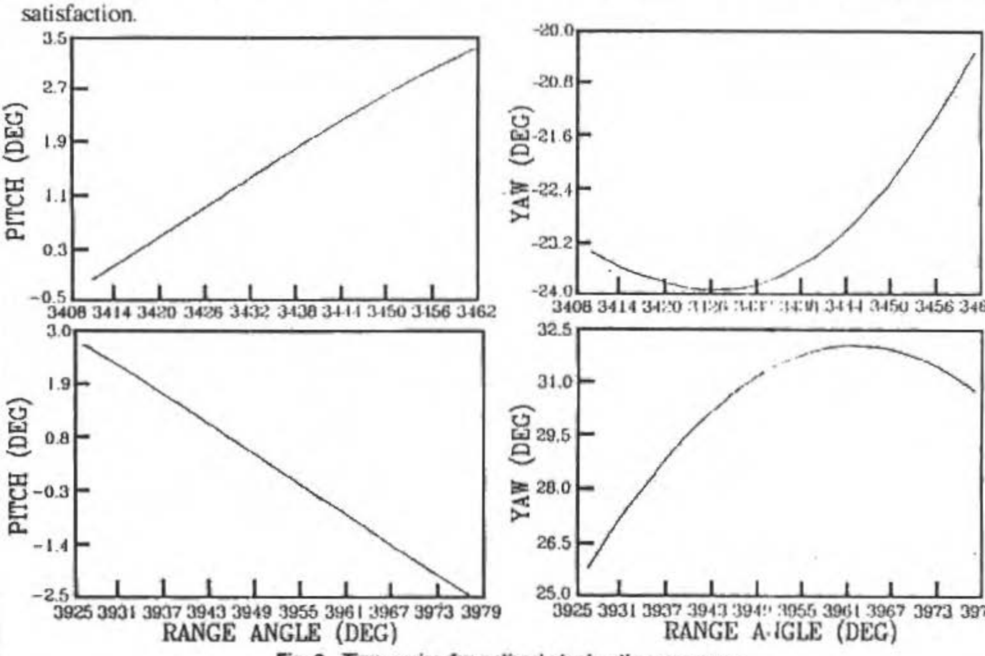

Fig. 2 Time-series for optimal stochastic maneuvers

This transfer phase will occur with the data given in Table 1 (Carrara and Souza, 1988), Table 2 (Prado, 1989) and Table 3 (Prado, 1989).

Table 1 Data for transfer phase of the First Brazilian Remote Sensing Satellite mission

Orbits	Initital	Final
Semi-major axis (km)	6768.14	7017.89
Eccentricity	0.0591	0.000
Inclination (degrees)	97.44	97.94
Ascending node (degrees)	67.27	Free
Argument of perigree (degrees)	97.66	Free
Mean anomaly (degrees)	270.0	Free

Table 2 Errors allowed for final Keplerian elements

Semi-major axis	5.0 Km
Eccentricity	0.001
Inclination	0.01 deg

Table 3 Algorithm parameters

	Constraints restoration	Minimum Search
α	0.5	1.0
β	0.5	1.0
$\underline{P}$	diag [10000 : ... : 10000]	diag [0.01 : ... : 0.01]
g	0.2	0.2

The choice of the number of "burning arcs" was done after testing different values and concluding for 8 as being a good number (Prado, 1989).

The solutions found (time-series of the thrusting angles) are showed in Table 4 (suboptimal method) and Fig. 2 (optimal method). The comparison with deterministic methods are shown in Table 5.

Conclusions

The problem of spacecraft maneuvers with minimum fuel consumption and consideration of accuracy tolerance in constraint's satisfaction was treated and solved using the new nonlinear programming algorithm proposed by Rios-Neto and Pinto (1987).

The results showed that some fuel can be saved by exploring tolerable errors allowed for constraint's satisfaction. The amount saved in both examples is not negligible, since it represents half of the amount necessary for one orbit correction (Carrara, 1988), and since it certainly could be higher with more flexibility in constraint's satisfaction.

Table 4 Transfer phase with suboptimal scheme

Arc	s_s(deg)	s_e(deg)	p_1(deg)	p_3(deg)	p_2	p_4	Fuel (kg)
1	525.9	578.6	0.4	-19.2	0.010	-0.126	-
2	1053.5	1097.2	5.1	32.9	-0.147	-0.085	-
3	1619.0	1667.4	1.3	-36.8	-0.002	0.533	-
4	2132.7	2185.6	5.6	33.1	-0.138	-0.071	-
5	2326.4	2372.1	0.2	-20.5	0.010	-0.129	-
6	2852.7	2905.5	5.9	33.9	-0.150	-0.096	-
7	3418.7	3467.1	1.2	-36.9	-0.002	0.532	-
8	3932.6	3985.3	5.6	33.2	-0.138	-0.080	11.66

Table 5 Fuel expenditure comparisons

	Fuel consumed (optimal (kg))	Fuel consumed (suboptimal (kg))
Stochastic approach	11.62	11.66
Deterministic approach	11.87	11.93

Acknowledgments

The authors are greatful to the Instituto Nacional de Pesquisas Espaciais (INPE) for the support given during the development of this work, to Dr. Kondapalli Rama Rao for the help in use of the numerical integration subroutines implemented by him (Rama Rao, 1984 and 1986) and to M. Sc. Waldemir Carrara for the help in the use of the graphic subroutines implemented by him (Carrara, 1984).

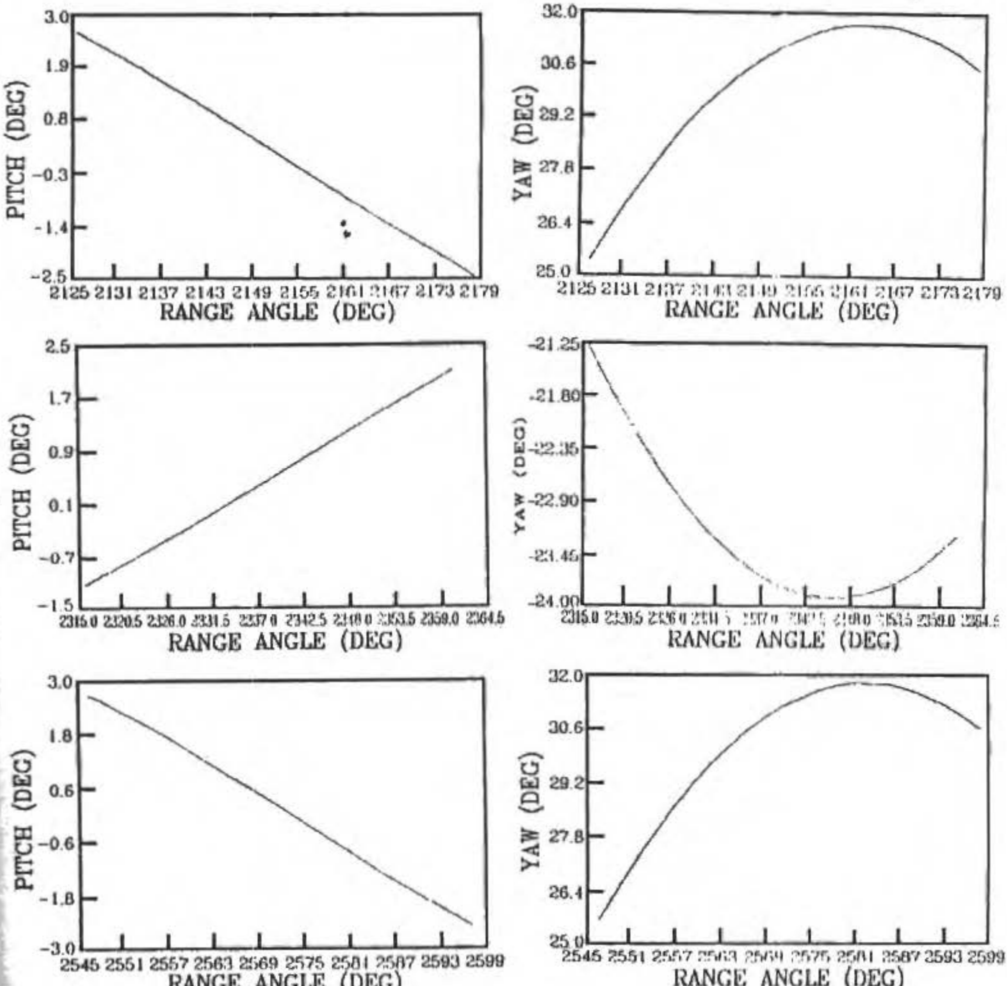

Fig. 2 Time-series for optimal stochastic maneuvers (cont.)

References

Biggs, M. C. B, 1978, "The Optimization of Spacecraft Orbital Maneuvers - Part I: Linearly Varying Thrust Angles", The Hatfield Polytechnic, Numerical Optimisation Centre.

Biggs, M. C. B, 1978, "The Optimization of Spacecraft Orbital Maneuvers - Part II: Using Pontryagin's Maximum Principle", The Hatfield Polytechnic, Numerical Optimisation Centre.

Bryson, A. E. and Ho, Y. C., 1975, *Applied Optimal Control*, Wiley, New York.

Carrara, V., 1984, "As Rotinas Gráficas CURVA e GRAFI: Descrição e Utilização", INPE, São José dos Campos.

Carrara, V., 1984, "Orbit Maintenance Strategy", INPE, São José dos Campos.

Carrara, V. and Souza, L. C. G., 1988, "Orbital Maneuver Strategies for Acquisition Phase", INPE, São José dos Campos.

Ceballos, D. C. and Rios-Neto, A., 1981, "Linear Programming and Suboptimal Solutions of Dynamical Systems Control Problems", Proc. of the Intern. Symp. on Spacecraft Flight Dynamics (ESA SP160), Darmstat, Federal Republic of Germany.

Jazwinski, A. H., 1972, *Stochastic Processes and Filtering Theory*, Academic Press, New York.

Rama Rao, K., 1984, "A Review on Numerical Methods for Initial Value Problems", INPE, São José dos Campos.

Rama Rao, K., 1986, "Manual de Uso de um Conjunto de Integradores Numéricos para Problemas de Condições Iniciais", INPE, São José dos Campos.

Rios-Neto, A. and Ceballos, D. C., 1979, "Approximation by Polynomial Arcs to Generate Suboptimal Numerical Solutions in Control Problems", Proc. Fifth Mech. Brazilian Congress, C 034-043, Campinas.

Rios-Neto, A. and Bambace, L. A. W. B., 1981, "Optimal Linear Estimation and Suboptimal Numerical Solutions of Dynamical Systems Control Problems", Proc. of the Intern. Symp. on Spacecraft Flight Dynamics (ESA SP160), 223-238, Darmstadt, Federal Republic of Germany.

Rios-Neto, A. and Pinto, R. L. U. F., 1987, "A Stochastic Approach to Generate a Projection of the Gradient Type Method", Anais do VIII Congresso Latino-Americano e Ibérico sobre Métodos Computacionais para Engenharia (Proc. VIII Latin.-Amer. and Iberic Congress in Comp. Meth. for Eng.), A, 331-345, PUC, Rio de Janeiro.

Prado, A. F. B. A., 1989, "Análise, Seleção e Implementação de Procedimentos que Visem Manobras Ótimas em Órbitas de Satélites Artificiais", MSc Thesis, INPE, São José dos Campos (INPE-5003-TDL/397).

Prado, A. F. B. A. and Rios-Neto, A., 1989, "Suboptimal and Hybrid Numerical Schemes for Orbit Transfer Maneuvers", Proc. of Colloque Space Dynamics, pp. 749-760, CNES, Tolouse, France.

Prado, A. F. B. A. and Rios-Neto, A., 1993, "Um Estudo Bibliográfico sobre o Problema de Transferências de Órbitas", Revista Brasileira de Ciências Mecânicas, Vol. XV, no. 1, pp. 65-78.

Nomenclature

$\underline{Cd}$ = Inequality constraints on state/control

$\underline{Ce}$ = Equality constraints on state/control

$E[.]$ = Expected value of $[.]$

$\underline{Ee}, \underline{Ed}, \underline{Eh}$ = Errors in the constraints

$\underline{f}$ = Right-hand side of the equations of motion

Fe = Gravitational force Earth-Satellite

Ft = Force provided by the thrust

g = Parameter used in equation (15)

G = Gravitational constant

$\underline{h}$ = Boundary constraints

J = Objective function

$\underline{K}$ = Kalman matrix

m = Mass of the Earth

m_e, m_d, m_h = Integer numbers

M = Mass of the satellite

$\underline{M}^T = [\,(d(\underline{Ce}(\bar{\underline{p}}))/d\underline{p})^T : (d(\underline{Cd}(\bar{\underline{p}}))/d\underline{p})^T\,]$

$\underline{n}$ = Zero mean uniformly distributed random vector

$\underline{p}$ = Vector of parameters to be found

$\underline{P}$ = Covariance matrix

r = Distance Earth-Satellite

$\underline{R} = E\left[\underline{V}\underline{V}^T\right]$

s = Range angle

t = Time

$\underline{u}$ = Control

$\underline{U}$ = "A priori information"

$\underline{V}^T = \left[\underline{Ee} : \underline{Ed}^T\right]$

$\underline{x}$ = State

$\underline{Y} = [\,(\alpha-1)\underline{Ce}^T(\bar{\underline{p}}) : (\alpha-1)\underline{Cd}^T(\bar{\underline{p}})\,]$ is the observation vector

α, β = Parameters used in equation (11-12)

Subscripts and Symbols

f = Final

o = Initial

s = Start

Δ = Variation

_ = Vector

^ = Estimated value

$\frac{d(.)}{dp}$ = Derivative of $(.)$ wrt p

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Effects of Mass Transfer on Transient Free Convection Flow Past an Infinite Vertical Isothermal Plate

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Abstract

An exact solution to the transient free convection flow past an infinite vertical isothermal plate is presented on taking into account the presence of species concentration. It is observed that an increase in the Schmidt number leads to a decrease in the velocity when the buoyancy ratio parameter $N > 0$. However, when $N > 0$, an increase in N leads to an increase in the velocity whereas for $N < 0$, a decrease in N leads to a fall in the velocity. For $N > 0$, an increase in Sc leads to a fall in the skin-friction and opposite is the case for $N < 0$. The skin-friction is more for $N > 0$ as compared to that for $N < 0$.

Keywords: Free Convection with Mass Transfer, Unsteady State, Infinite Vertical Isothermal Plate

Introduction

Transient free convection flows past an infinite vertical isothermal flows were studied by many in past. Some of these are by Siegel (1958), Schetz and Eichhorn (1962), Menold and Yang (1962), Sparrow and Gregg (1960), Chung and Anderson (1961), Goldstein and Briggs (1964) etc. All these studies are confined to the flow of pure fluids like air, water, etc. These are studies in which the buoancy driving force is arising solely due to temperature differences. However, in many instances, along with temperature difference, flows also arise due to differences in concentration or material constitution. A commonly occuring example is the atmospheric flows which occur due to difference in temperature and H_20 concentration. Again, in water, the density is affected by temperature, concentration of dissolved materials and suspended particulate matter. Such flows due to combined effect of concentration and temperature differences have received little attention. Steady free convection flow in the presence of mass transfer past a semi-infinite vertical plate was studied by Gebhart and Pera (1971) by similarity analysis. References to earlier studies on free convection with mass transfer are cited in the paper by Gebhart and Pera (1971).

However, mass transfer effects on transient free convection flow past an infinite vertical isothermal plate have not been studied in the literature. Hence the motivation to undertake this study here. Exact solutions are derived to coupled linear equations governing the flow and the velocity profiles for air and water in the presence of different foreign masses are shown graphically.

Mathematical Analysis

Consider the unsteady free convective flow of an incompressible viscous fluid past an infinite vertical isothermal plate. Initially, the fluid and the plate are assumed to be at the same temperature T'_∞ and the concentration level in the fluid is also assumed to be low so that the Soret-Dufour effects can

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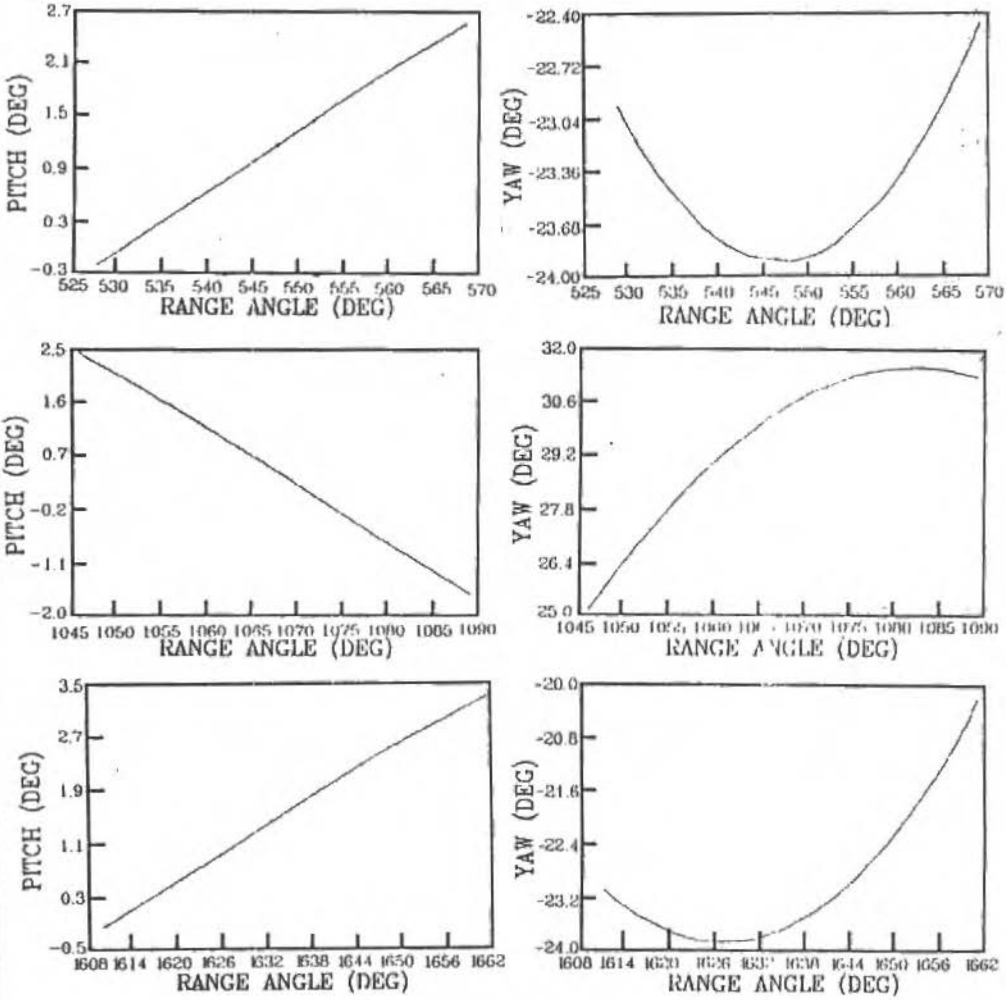

Fig. 2 Time-series for optimal stochastic maneuvers (cont.)

Resumo

Este trabalho considera o problema de transferência de órbita de um veículo espacial com mínimo consumo de combustível. É desenvolvida uma nova versão dos métodos híbridos e sub-ótimos de tratar o problema numericamente, onde a precisão na satisfação dos vínculos podem ser consideradas. Para resolver o problema de programação não-linear, em cada iteração, uma versão estocástica do método da projeção do gradiente é combinada com o conhecido método híbrido de controle ótimo nesse tipo de problema dinâmico. Para as manobras consideradas, o veículo espacial é suposto estar em movimento Kepleriano perturbado apenas pelo controle. O controle consiste de um empuxo de magnitude constante (alto ou baixo) e que opera no modo liga-desliga. A solução é dada em termos da localização dos arcos com propulsão, direção do empuxo em cada instante, órbita final atingida e combustível consumido. Resultados numéricos são apresentados.

be negligible. In many industrial applications, this assumption is true. So is in the atmospheric flows where the presence of water-vapour is many times at very low level. We take the x'-axis along the plate in the vertically upward direction and the y'-axis is taken normal to the plate. Also, initially the concentration level throughout the fluid is assumed to be C'_∞. At time $t' > 0$, the plate temperature is raised to T'_w and the concentration level near the plate is also raised to C'_w such that $T'_w - T'_\infty$ and $C'_w - C'_\infty$ are both greater than zero. Then under the usual Boussinesq's approximation, the fully-developed unsteady flow, being independent of the axial distance, can be shown to be governed by the following system of equations:

$$\frac{\partial u'}{\partial t'} = \nu \frac{\partial^2 u'}{\partial y'^2} + g\beta (T' - T'_\infty) + g\beta^* (C' - C'_\infty) \tag{1}$$

$$\vartheta C_p \frac{\partial T'}{\partial t'} = K \frac{\partial^2 T'}{\partial y'^2} \tag{2}$$

$$\frac{\partial C'}{\partial t'} = D \frac{\partial^2 C'}{\partial y'^2} \tag{3}$$

with following initial and boundary conditions:

$$t' \le 0, \quad u' = 0, \quad T' = T'_\infty, \quad C' = C'_\infty \quad \text{for all} \quad y'$$

$$t' > 0, \quad u' = 0, \quad T' = T'_W, \quad C' = C'_W \quad \text{at} \quad y' = 0$$

$$u' = 0, \quad T' \to T'_\infty, \quad C' \to C'_W \quad \text{as} \quad y' \to \infty \tag{4}$$

Here u' is the velocity of the fluid, t' the time, ν the kinematic viscosity, g the acceleration due to gravity, β the volumetric coefficient of thermal expansion, β^* volumetric coefficient of expansion with concentration, C' the species concentration, ϑ the density, C_p the specific heat at constant pressure, T' the temperature of the fluid, K the thermal conductivity, D the chemical molecular diffusity, T'_W the plate temperature and C'_W is the species concentration near the plate.

Equations (1) to (4) reduce to following non-dimensional form

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial y^2} + \theta + NC \tag{5}$$

$$Pr\frac{\partial\theta}{\partial t} = \frac{\partial^2\theta}{\partial y^2} \tag{6}$$

$$Sc\frac{\partial C}{\partial t} = \frac{\partial^2 C}{\partial y^2} \tag{7}$$

with following initial and boundary conditions:

$$t \le 0, \quad u = 0, \quad \theta = 0, \quad C = 0 \quad \text{for all} \quad y$$

$$t > 0, \quad u = 0, \quad \theta = 1, \quad C = 1 \quad \text{at} \quad y = 0$$

$$u = 0, \quad \theta = 0, \quad C = 0 \quad \text{as} \quad y \to \infty \tag{8}$$

The non-dimensional quantities are defined as follows:

$$U = (\nu g\beta\Delta T)^{1/3}, \quad L = (g\beta\Delta T/\nu^2)^{-1/3}$$

$$t^* = (g\beta\Delta T)^{-2/3}\nu^{1/3}$$

$$u = u'/U, \quad y = y'/L, \quad t = t'/t^*, \quad \theta = \frac{T' - T'_\infty}{T'_w - T'_\infty}$$

$$C = \frac{C' - C'_\infty}{C'_w - C'_\infty}, \quad Pr = \frac{\mu C_p}{K}, \quad Sc = \frac{\nu}{D}$$

$$N = \frac{\beta^* \Delta C}{\beta\Delta T}, \quad \Delta C = C'_w - C'_\infty, \quad \Delta T = T'_w - T'_\infty \tag{9}$$

Here U, L, t* are some characteristic velocity, length and time repectively. Also Pr is the Prandtl number, Sc the Schmidt number and N is the ratio of the chemical and thermal diffusion. So N measures the relative importance of these diffusivities which cause the density difference thereby causing the flow. In the absence of species diffusion, $N = 0$. N is infinite when thermal diffusion is absent, $N > 0$ corresponds to the flow due to combined effects of these diffusivities and then $N < 0$ corresponds to these diffusivities opposing each other.

To solve these coupled linear Eqs. (5)-(7), we employ the usual Laplace transform technique. It is defined as

$$\bar{u} = \int_0^\infty e^{-st} u\, dt = L(u)$$

$$\bar{\theta} = \int_0^\infty e^{-st} \theta\, dt = L(\theta) \tag{10}$$

Applying these to Eqs. (5)-(7) and taking account of the initial conditions in (8), we get

$$s\bar{u} = \frac{d^2\bar{u}}{dy^2} + \bar{\theta} + N\bar{C} \tag{11}$$

$$sPr\bar{\theta} = \frac{d^2\bar{\theta}}{dy^2} \tag{12}$$

$$sSc\bar{C} = \frac{d^2\bar{C}}{dy^2} \tag{13}$$

with following boundary conditions in the transformed state

$$\bar{u} = 0, \quad \bar{\theta} = 0, \quad \bar{C} = 0 \quad \text{for all} \quad y, \quad t \le 0$$

$$\bar{u} = 0, \quad \bar{\theta} = 1/S, \quad \bar{C} = 1/S \quad \text{at} \quad y = 0, \quad t > 0$$

$$\bar{u} = 0, \quad \bar{\theta} = 0, \quad \bar{C} = 0 \quad \text{as} \quad y \to \infty, \quad t > 0 \tag{14}$$

On solving Eqs. (11) - (13), subject to the boundary conditions (14), we get on taking the inverse Laplace-transform,

$$
\begin{aligned}
u = & \frac{t}{1-Pr}[(1+\eta^2)\,\mathrm{erfc}(\eta) - (1+Pr\eta^2)\,\mathrm{erfc}(\eta\sqrt{Pr})] \\
& + \frac{2}{\sqrt{\pi}}\{\eta\sqrt{Pr}e^{-Pr\eta^2} - \eta e^{-\eta^2}\}] \\
& + \frac{Nt}{1-Sc}[(1+\eta^2)\,\mathrm{erfc}(\eta) - (1+Sc\eta^2)\,\mathrm{erfc}(\eta\sqrt{Sc}) \\
& + \frac{2}{\sqrt{\pi}}\{\eta\sqrt{Sc}e^{-\eta^2 Sc} - \eta e^{-\eta^2}\}]
\end{aligned}
\tag{15}
$$

$$
\theta = \mathrm{erfc}(\eta\sqrt{Pr}), \quad C = \mathrm{erfc}(\eta\sqrt{Sc}) \tag{16}
$$

where $\eta = y/2\sqrt{t}$ and $Sc \neq 1$.

For $Sc = 1$, the solution is given as follows:

$$
\begin{aligned}
u = & \frac{t}{1-Pr}[(1+\eta^2)\,\mathrm{erfc}(\eta) - (1+Pr\eta^2)\,\mathrm{erfc}(\eta\sqrt{Pr}) + \\
& \frac{2}{\sqrt{\pi}}\{\eta\sqrt{Pr}e^{-Pr\eta^2} - \eta e^{-\eta^2}\}] + 2Nt\left[\frac{2}{\sqrt{\pi}}\eta e^{-\eta^2} - \eta^2\mathrm{erfc}(\eta)\right]
\end{aligned}
\tag{17}
$$

Knowing the velocity-field, we can now derive the expression for the skin-friction. It is given by

$$
\tau = \frac{1}{2t^*\sqrt{t}}\frac{du}{d\eta}\bigg|_{\eta=0} \tag{18}
$$

From (17) and (18), we have

$$
2\tau t^*\sqrt{t} = \frac{1}{1+\sqrt{Pr}} + \frac{N}{1+\sqrt{Sc}} \tag{19}
$$

Results and Discussion

In order to gain physical insight into the problem, we have carried out the numerical calculations for u, θ and C for different values of Pr = 0.71 (air), 7.0 (water), N and Sc. The values of the Schmidt number are assumed such that they represent a physical reality. Thus Table 1 gives the values of the Schmidt number. The values of the Schmidt number in water are very high. Hence they are chosen as 500, 600.

Table 1 Values of the Schmidt number at 20°C

Pr	Species	Sc
0.71	Hydrogen	0.24
	Helium	0.30
	Water	0.60
	Ammonia	0.78
	Carbon dioxide	1.00
	Ethyl benzone	2.00
7		500
		600

Table 2 Values of t^*_τ

t	Pr	Sc/N	-0.6	-0.4	-0.2	0.2	0.4	0.6
0.2	0.71	0.16	0.1276	0.2873	0.4470	0.7664	0.9262	1.0859
		0.24	0.1565	0.3033	0.4567	0.7568	0.9069	1.0570
		0.30	0.1733	0.3178	0.4623	0.7512	0.8957	1.0402
		0.60	0.2288	0.3548	0.4808	0.7328	0.8588	0.9848
		0.78	0.2505	0.3693	0.4880	0.7255	0.8442	0.9630
		1.00	0.2714	0.3832	0.4950	0.7186	0.8304	0.9422
		2.00	0.3289	0.4215	0.5141	0.6994	0.7920	0.8846
0.2	7.00	500.00	0.2780	0.2875	0.2971	0.3162	0.3258	0.3354
		600.00	0.2804	0.2891	0.2979	0.3154	0.3242	0.3330
0.4	0.71	0.16	0.0902	0.2032	0.3161	0.5419	0.6549	0.7678
		0.24	0.1107	0.2168	0.3229	0.5352	0.6413	0.7474
		0.30	0.1226	0.2247	0.3269	0.5312	0.6334	0.7355
		0.60	0.1618	0.2509	0.3399	0.5181	0.6072	0.6963
		0.78	0.1772	0.2611	0.3451	0.5130	0.5970	0.6809
		1.00	0.1919	0.2709	0.3500	0.5081	0.5872	0.6662
		2.00	0.2326	0.2981	0.3630	0.4445	0.5600	0.6255
0.4	7.0	500.00	0.1965	0.2033	0.2101	0.2236	0.2304	0.2372
		600.00	0.1982	0.2044	0.2106	0.2230	0.2293	0.2355

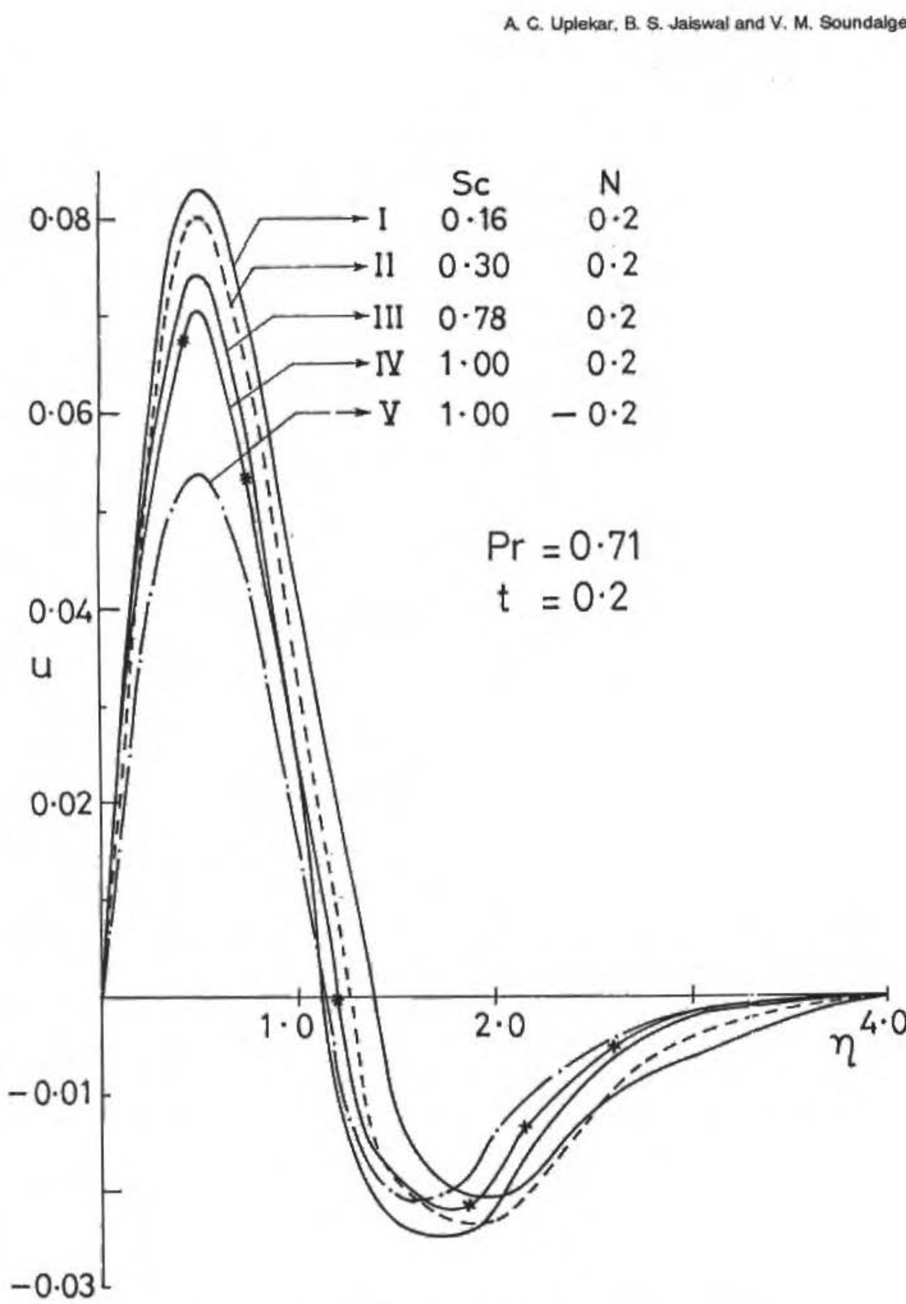

Fig. 1 Velocity profiles

The velocity profiles are shown on Figs. 1-2 for Pr = 0.71 and on Fig. 3 for Pr = 7.0 (water). We observe from Fig. 1 that for N > 0, the velocity of air decreases as Sc increases. The effect of the buoyancy ratio N on the velocity field is shown on Fig. 2, for air and Sc = 0.60 (water vapour). When N > 0, the buoyancy forces act in the same direction and hence an increase in N leads to an increase in the velocity of air but for N < 0, the buoyancy forces oppose each other and hence an decrease in N

(< 0) leads to a fall in the velocity of air. The effect of the presence of species concentration in water is not significant and hence we have shown the velocity profiles for only Sc = 600. As compared to air, the maximum velocity of water is less as compared to that case of air due to buoyancy effects.

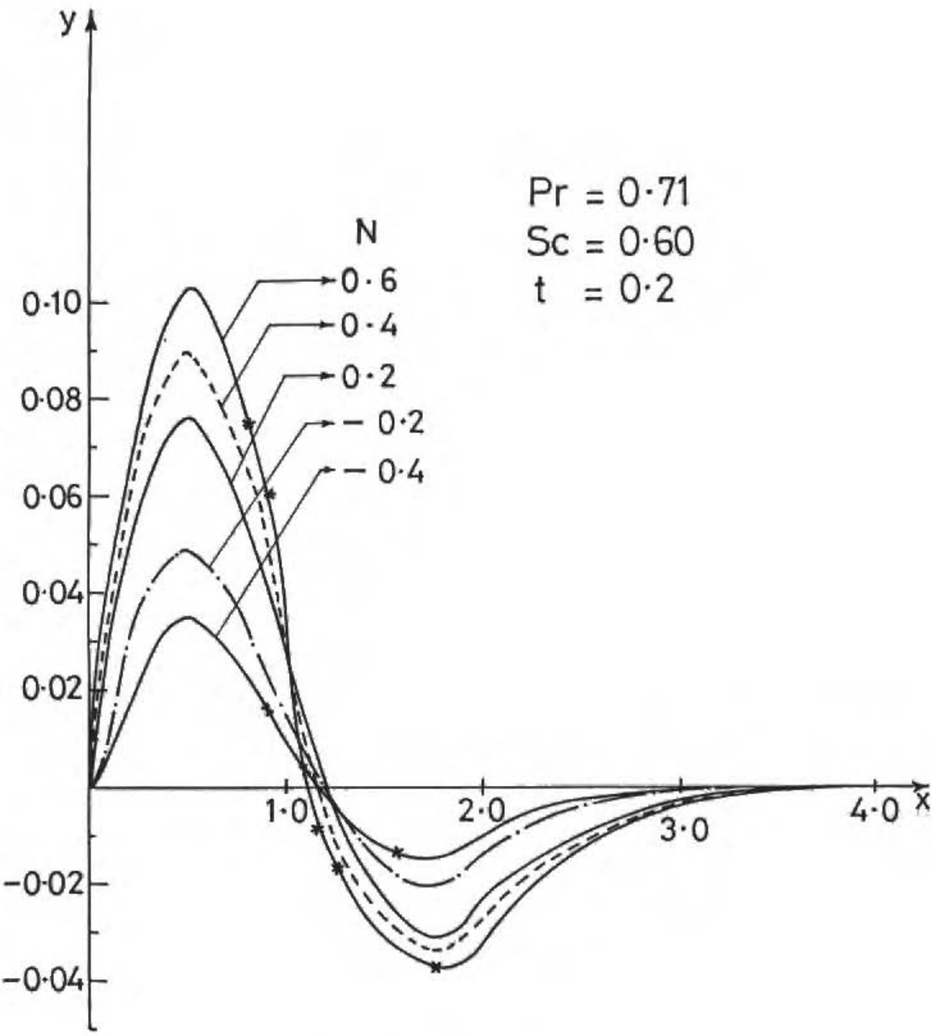

Fig. 2 Velocity profiles

The numerical values of τ are listed in Table 2. We observe from this table that when N is constant and positive, an increase in Sc leads to decrease in the skin-friction whereas exactly opposite is the case for N constant and negative. In this case, the opposing buoyancy forces are present and then an increase in Sc leads to an increase in the skin-friction.

Again, the skin-friction is more when N > 0 than that when N < 0, both in case of air and water. The skin-friction in case of air, decreases as t, the time, increases.

An increase in the Prandtl number leads to a decrease in the skin-friction.

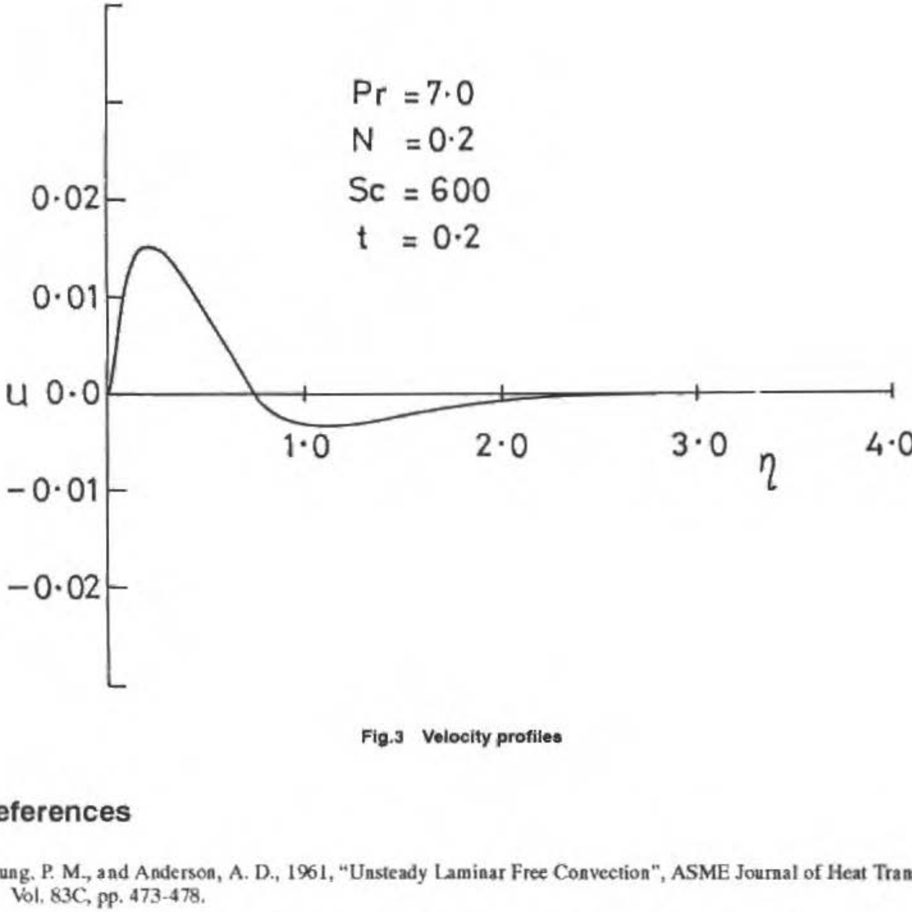

Fig.3 Velocity profiles

References

Chung, P. M., and Anderson, A. D., 1961, "Unsteady Laminar Free Convection", ASME Journal of Heat Transfer, Vol. 83C, pp. 473-478.

Gebhart, B., and Pera, L., 1971, "The Nature of Vertical Natural Convection Flows Resulting from the Combined Buoyancy Effects of Thermal and Mass Diffusion", Int. J. Heat Mass Transfer, Vol. 14, pp. 2025-2050.

Goldstein, R. J., and Briggs, D. C., 1964, "Transient Free Convection About Vertical Plates and Circular Cylinders", ASME Journal of Heat Transfer, Vol. 86 C, pp. 490-500.

Menold, E. R., and Yang, K. T., 1962, "Assimptotic Solutions for Unsteady Laminar Free Convection on a Vertical Plate", ASME Journal of Applied Mechanics, Vol. 29 E, pp. 124-126..

Schetz, A., and Eichhorn, R., 1962, "Unsteady Natural Convection in Vincinity of a Doubly Infinite Vertical Plate", ASME Journal of Heat Transfer, Vol. 84 C, pp.334-338.

Siegal, R., 1958, "Transient Free Convection from a Vertical Flat Plate", Trans. Amer. Soc. Mech. Eng., Vol. 80, pp. 347-359.

Sparrow, E. M., and Gregg, J. L., 1960, "Nearly Quasi-Steady Free Convection Heat Transfer", ASME Journal of Heat Transfer, Vol. 82 C, pp. 258-260.

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Motores a Combustão Interna com Taxa de Compressão Variável - uma Análise Teórico-Experimental

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DEM, PUC - RJ

Abstract

The present work is concerned with a theoretical and experimental study of variable compression ratio ignition internal combustion engines. A theoretical analysis of the engine, operating with a mechanism which allows for variable compression ratio, is carried out. For that a simulation program is used. In the present work the simulation model was updated with the inclusion of friction, knocking and hidrocarbon emission models, among other things. An experimental work was also carried out, with a CRF engine. The objective was two-fold: to validate the results of the thoretical model and to assess the benefits of running an engine with variable compression ratio. A comparison is also made between the results of the present work and those from other authors.

Keywords: Internal Combustion Engines, Variable Compression Ratio, Modelling and Experimental Study

Introdução

O presente trabalho pretende fazer uma análise mais detalhada da proposta de Rychter e Teodorczyk (1985), em que um motor é concebido para operar com taxa de compressão variável. Por essa proposta em questão, a taxa de compressão passa a ser um parâmetro de regulagem assim como o avanço de ignição e relação ar-combustível. Com esta característica, o motor pode operar na máxima taxa de compressão possível para qualquer regime de rotação e carga, o que não acontece nos motores convencionais onde ela é determinada pela condição crítica de rotação e carga, ou seja, alta carga e baixa rotação. À primeira vista é de se esperar que os melhores resultados sejam aqueles obtidos em regimes de baixa e média cargas, onde taxas de compressão mais elevadas poderiam ser utilizadas.

No trabalho de Rychter e Teodorczyk (1985) relacionado com a variação da taxa de compressão durante a operação de um motor o mecanismo proposto é apresentado e comparado a outros existentes na literatura. Neste, o agente responsável pela variação da taxa de compressão, ou seja, o excêntrico, e também o dispositivo de acionamento do mesmo, isto é, um trem de engrenagens acionado pela árvore de manivelas.

A aplicação desta proposta a motores de ignição por centelha revelou certos valores de velocidade de acionamento do excêntrico para os quais os efeitos foram mais pronunciados.

Recentemente, os primeiros resultados com um protótipo, construído pela Universidade de Roma, foram apresentados por Abenavoli et alli (1991). Os resultados obtidos por esses pesquisadores comprovaram que a proposta de um motor de taxa de compressão variável é factível e que o motor funciona suavemente para uma vasta gama de parâmetros operacionais.

O objetivo deste trabalho é quantificar, por intermédio de simulação em computador e por procedimentos experimentais, o percentual de ganho apresentado por um motor de combustão interna operando com taxa de compressão variável. Devido a dificuldades técnicas e financeiras não foi possível a construção do protótipo de um motor que apresentasse a referida característica, tal qual foi

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idealizada por seus criadores; assim sendo, optou-se pela execução dos testes em motor de pesquisa de combustíveis (motor CFR - Cooperative Fuel Research) o qual possibilita a variação da taxa de compressão, ainda que de forma diversa da proposta original, mas que não inviabiliza os resultados obtidos uma vez que termodinamicamente não há, praticamente, diferença entre os dois procedimentos.

O presente trabalho envolve fundamentalmente duas áreas de estudo. Uma focalizou o estudo teórico enquanto a outra, a parte experimental. A parte teórica envolveu a simulação numérica em computador de um motor com taxa de compressão variável, a partir de um modelo já existente para motores convencionais. A parte experimental envolveu testes com um motor CFR, para quantificação dos benefícios quando se opera um motor com a referida característica. Os testes foram realizados tendo como combustível o gás natural comprimido.

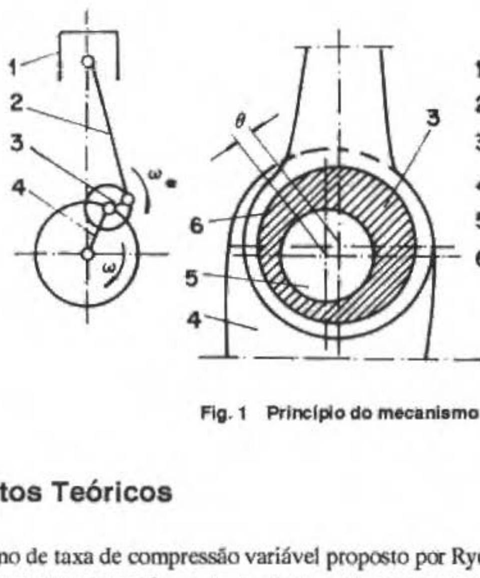

Fig. 1 Princípio do mecanismo

Fundamentos Teóricos

O mecanismo de taxa de compressão variável proposto por Rychter e Teodorczyk (1985) tem como principal característica o contínuo ajuste da taxa de compressão para cada condição específica de operação do motor. O objetivo principal do mecanismo em questão é manter os picos de pressão e temperatura adequados às condições de rotação e carga do motor, de modo a otimizar seu desempenho.

A mudança da taxa de compressão é conseguida mediante a instalação de um excêntrico na ligação biela-manivela, que de acordo com sua posição angular, varia a relação raio da manivela-comprimento da biela; assim é determinada a posição do pistão e finalmente, a taxa de compressão.

O mecanismo em questão é composto por um pistão, uma biela, um eixo de manivelas e um excêntrico, o qual é instalado na ligação biela-manivela. São utilizados rolamentos entre o excêntrico e a biela e também entre o excêntrico e o pino da manivela. Este mecanismo é, portanto, similar ao biela-manivela convencional, apenas equipado com um excêntrico.

O efeito da variação da taxa de compressão, junto com a mudança de outros parâmetros geométricos do motor, tais como comprimento dos cursos e posição dos pontos mortos é obtido pela rotação do excêntrico em torno do pino da manivela.

Além do excêntrico poder ser ajustado para um determinado regime de operação do motor, ele também pode ser acionado com velocidade angular constante (ω_α), relacionada com a da árvore de manivelas (ω). O deslocamento do pistão pode ser, neste caso, calculado por meio da seguinte expressão:

$$x = r\left[\frac{1}{\lambda} - \left\{\frac{1}{\lambda^2} - [\sin\varphi - \delta\sin(\alpha_t + \varphi)]^2\right\}^{1/2} + \delta[1 - \cos(\alpha_t + \varphi)] - \cos\varphi + 1\right] \quad (1)$$

onde:

φ = deslocamento angular da árvore de manivelas

$$\gamma = r/l \quad (2)$$

onde r é o raio da manivela e l o comprimento da biela, e o tamanho relativo do excêntrico (δ)

$$\delta = e/r \quad (3)$$

onde e é a excentricidade.

α_t = deslocamento angular total do excêntrico

O deslocamento angular total do excêntrico é uma soma de dois ângulos, a saber:

$$\alpha_t = \alpha_0 + \alpha \quad (4)$$

onde (α_0) é o ângulo de rotação do excêntrico ajustado durante o funcionamento do motor, independentemente do ângulo (α), que resulta da rotação do excêntrico, com velocidade angular constante determinada pelo projeto do mecanismo de acionamento.

O ângulo (α_0) é sempre medido na posição em que o raio da manivela (r) está paralelo ao eixo do cilindro e com o pistão na sua posição mais alta, durante o curso de compressão. O ângulo de fase (α_0), pode ser ajustado dentro dos limites de 0^o a 360^o e é um parâmetro de regulagem contínua da geometria do mecanismo de raio cinemático variável.

Rychter e Teodorczyk (1985) propuseram 3 valores de velocidades de acionamento do excêntrico: $\omega_\alpha = 0$, $\omega_\alpha = \pm 0{,}5\,\omega$ e $\omega_\alpha = \pm\omega$. No primeiro caso obtem-se apenas uma variação da taxa de compressão enquanto que nos demais também variam os comprimentos dos cursos e consequentemente o deslocamento do motor.

Modelo Básico para a Simulação

Este trabalho utilizou como programa base o trabalho de Souto (1987), onde é feita a simulação de um motor de combustão interna, quatro tempos, operando segundo ciclo Otto e utilizando combustível da $C_nH_mO_p$.

Para que esse modelo pudesse simular o funcionamento do motor de taxa de compressão variável, foram necessárias várias modificações. A principal delas consistiu na nova equação que rege o deslocamento do pistão e todas as demais que se fizeram necessárias para que se reproduzisse o funcionamento do referido motor (Teixeira, 1992).

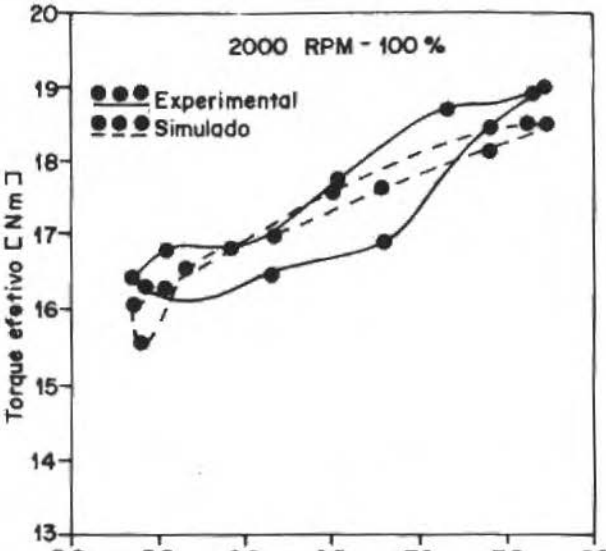

Fig. 2 Torque efetivo versus taxa de compressão

Técnicas Experimentais

Os testes experimentais tiveram por fim a verificação das vantagens apresentadas pelo motor de taxa de compressão variável teoricamente. Tentou-se comprovar o benefício em termos de melhoria da eficiência térmica, ou seja, um menor consumo específico de combustível e/ou um melhor desempenho. Observou-se, também, como se comportaram as emissões de CO do motor. As experiências foram realizadas no Laboratório de Motores do INMETRO.

Alimentação de Gás

O gás natural, ao sair dos cilindros, seguia até a válvula redutora de pressão, de fabricação Rodagás, onde sua pressão era reduzida a um valor variável de acordo com uma regulagem feita no último estágio. A seguir, o gás tinha a sua temperatura e pressão medidas antes de passar por um rotâmetro, após o qual chegava ao motor.

O gás natural foi cedido e analisado por cromatografia gasosa pela PETROBRÁS, que revelou um teor de CH_4 de 90,002%, de C_2H_6 de 7,404% e de N_2 de 1,227% entre outros.

Equipamentos e Instrumentação

O motor utilizado, ASTM-CFR, possui taxa de compressão continuamente variável entre os limites 4:1 e 16:1, sendo portanto adequado aos objetivos deste trabalho.

Para medida de temperatura do gás e do ar foram utilizados termopares, com incerteza global de ± 0,6°C. O consumo de gás foi medido por meio de rotâmetro com incerteza de ± 1,3%. Como dispositivo medidor de consumo de ar foi utilizado o método do tanque e orifício, sendo o tanque um tambor de 200 litros e o orifício um bocal de 19,0 mm de diâmetro, indicado como adequado para a faixa de vazão de ar do motor. A incerteza dessa medida foi calculada em ± 5%. Como instrumento indicador da velocidade de rotação do motor, foi utlizado um medidor digital portátil, com resolução de 1,0 rpm e incerteza de ± 0,2%.

Para se quantificar o torque desenvolvido pelo motor, foi instalada uma célula de carga, atuada diretamente pelo braço do dinamômetro. A referida célula teve seu projeto e construção realizados para este trabalho, com capacidade máxima de 5,0 kgf e incerteza avaliada em ± 1,7 %

O dispositivo encarregado de frear o motor e dissipar a energia absorvida foi um dinamômetro hidráulico, operando com água em cicuito aberto.

Foi monitorado o nível de emissões de CO, Bosch, modelo ETT 008.14, pertencente à PETROBRÁS, apresentando menor divisão de 0,001% com capacidade para até 9,90%.

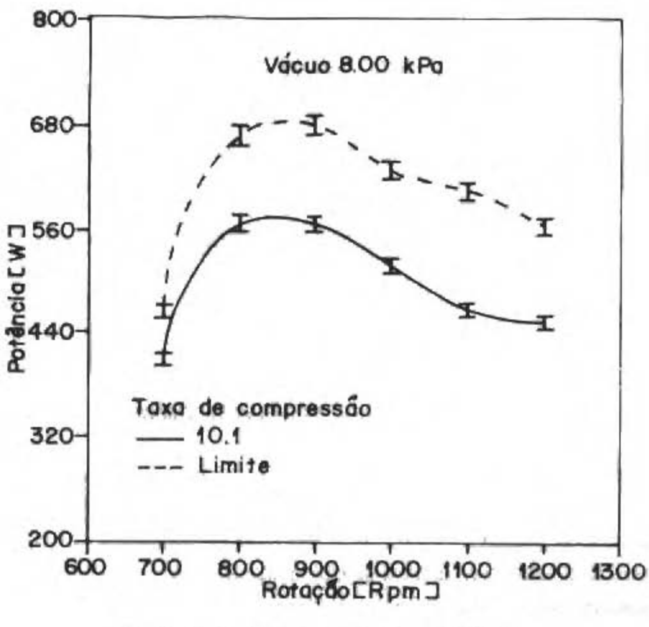

Fig. 3 Potência versus rpm - vácuo 8,00 kPa

Procedimentos Experimentais

Primeiramente foi determinado que seriam mantidos fixos o ponto de ignição e, sempre que possível, a relação ar-combustível. A rotação foi variada entre 700 e 1200 rpm enquanto que a taxa de compressão seria variada entre um mínimo, o qual seria a de um motor convencional, a um máximo, o qual vem a ser limitado pela ocorrência da detonação. O vácuo do coletor de admissão foi variado desde um mínimo próximo de zero (borboleta do acelerador plenamente aberta) até um máximo para uma mesma rotação.

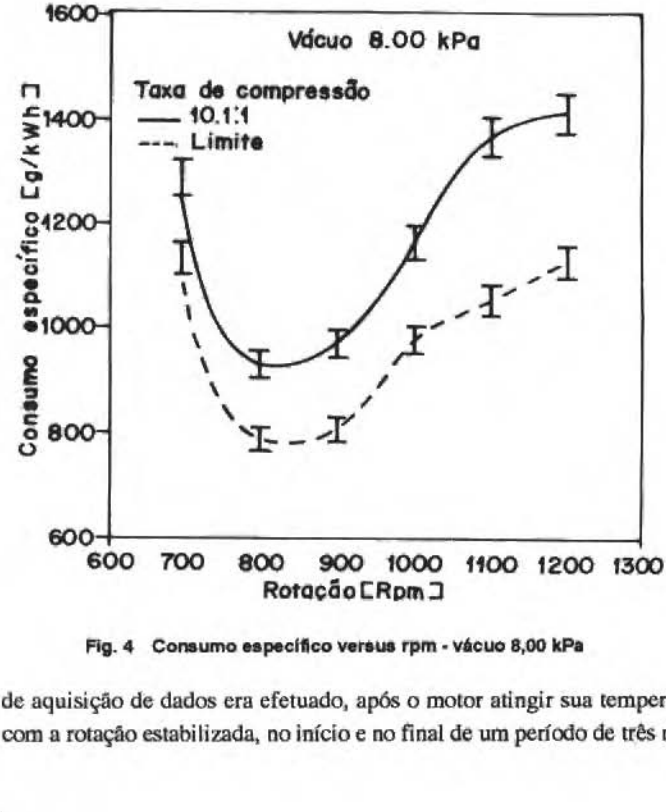

Fig. 4 Consumo específico versus rpm - vácuo 8,00 kPa

O processo de aquisição de dados era efetuado, após o motor atingir sua temperatura normal de funcionamento, com a rotação estabilizada, no início e no final de um período de três minutos.

Resultados

Protótipo Italiano de Motor com Taxa de Compressão Variável

O modelo de simulação utilizado neste trabalho foi comparado com os resultados experimentais de Abenavoli et alli (1991), obtidos a partir de um motor de taxa de compressão variável, conforme proposto por Rychter e Teodorczyk (1985). Esses testes foram realizados na bancada dinamométrica do Departamento de Mecânica e Aeronáutica da Universidade de Roma "La Sapienza". Os dados desse referido motor foram introduzidos no programa de simulação e assim comparam-se os resultados, para duas velocidades de rotação, 2000 e 3000 rpm.

Observa-se na Fig. 2 como variam as curvas de torque efetivo, variando com a taxa de compressão, experimental e simulado, para 2000 rpm. São comparados os resultados obtidos por Abenavoli et alli (1991) e os obtidos pela simulação. Nota-se que os resultados do modelo utilzado no presente trabalho foram adequados, já que os níveis de torque obtidos com o modelo foram semelhantes aos experimentais, com diferenças máximas entre os resultados comparados da ordem de 5%.

As diferenças apresentadas podem ser justificadas pelo fato do modelo utilizado não considerar os efeitos de inércia do fluxo de gases, de propagação de ondas de pressão na admissão e descarga, entre outros.

Foi também feita uma comparação do comportamento das curvas de potência efetiva variando com a taxa de compressão para 3000 rpm. Foi observado que os efeitos ora mencionados se tornam significativos nesta rotação, o que faz com que o modelo utilizado não consiga reproduzir o nível de torque e potência apresentado experimentalmente, já que apresenta diferenças variando entre um mínimo de 18% e um máximo de 35%.

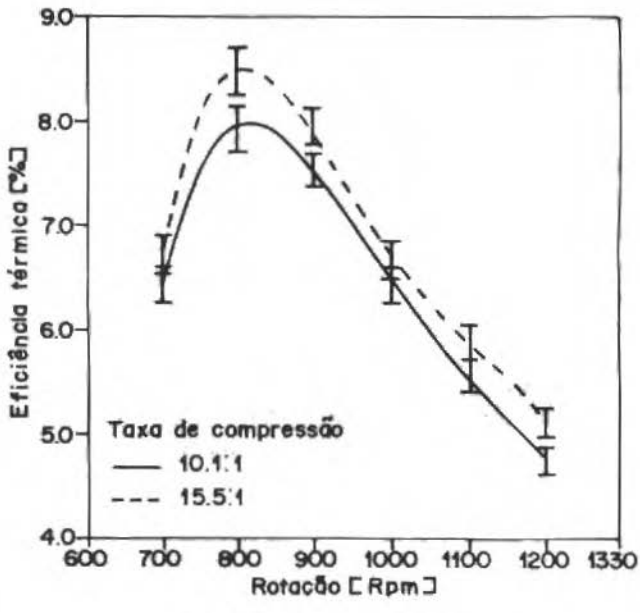

Fig. 5 Eficiência térmica versus rpm

Como forma de se comparar o desempenho de um motor de taxa de compressão variável com o de um motor convencional, foram simulados alguns casos mantendo-se a potência efetiva constante para cada rotação. Desta forma, estipulou-se que o motor convencional teria a taxa de compressão 5,2:1, que é a mínima do motor de Abenavoli et alli (1991), enquanto que no motor de taxa de compressão variável esta seria a máxima, dentro do limite do motor (5,2:1 a 7,93:1), desde que não houvesse detonação. Assim sendo, para o motor convencional foi determinado um valor de vácuo de 20 kPa, constante para todas as rotações, enquanto que no outro motor, este parâmetro seria variado de modo a manter a potência efetiva constante. Como a simulação foi realizada a cargas parciais, não foi detectada a detonação. Assim, a taxa de compressão foi a máxima possível, com o excêntrico acionado, que é de 7,71:1.

Assim sendo, foi observado o comportamento da eficiência térmica para os dois casos. Notou-se que o motor de taxa de compressão variável consegue obter um ganho na ordem de 14% sobre o motor convencional.

A seguir estudou-se o comportamento da emissão de HC. A emissão de HC aumenta com a elevação da taxa de compressão. No caso em questão, esse aumento varia entre 41% e 78%.

Conforme os resultados da simulação demonstram, é vantajoso operar um motor com taxa de compressão variável. Os maiores valores de emissão de HC, recomendam que se utilize algum dispositivo de controle dessa emissão, como por exemplo o catalisador de gases de exaustão. Tal fato, contudo, não inviabiliza o desenvolvimento de motores com tal característica.

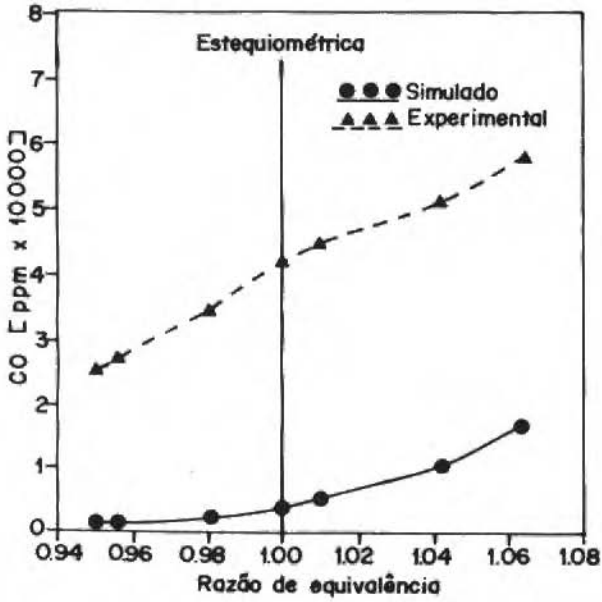

Fig. 6 Emissão de CO versus razão de equivalência

Motor CFR

Como forma de demonstrar os benefícios em se operar um motor com taxa de compressão variável, foram realizados alguns testes experimentais com o motor CFR, nas seguintes condições:

1) Rotação (rpm): 700, 800, 900,1000, 1100 e 1200
2) Vácuo (kPa): 8,00 e 9,33
3) Temperatura da mistura (K): 383
4) Ponto de ignição (°APMS): 10
5) Relação ar-combustível: 16,9:1
6) Pressão atmosférica (kPa): 100,36
7) Pressão de descarga (kPa):0,20

Na Fig. 3 pode-se observar como a potência varia de acordo com a rotação, com um valor de vácuo de 8,00 kPa, constante para todas as rotações. A linha cheia representa a curva de potência para a taxa de compressão de 10,1:1, que foi a máxima possível de se operar o motor sem detonação, em qualquer condição. A linha tracejada representa essa mesma curva para a taxa de compressão 15,5:1, que foi a máxima para essa condição, sem detonação. Como pode ser observado, operando a uma taxa mais elevada obtém-se uma potência efetiva em torno de 22% superior, mantendo-se o mesmo consumo horário de combustível. Na Fig. 4 pode-se observar o comportamento do consumo específico, o qual é menor para valores de taxa de compressões mais elevados. O mesmo percentual de ganho entre as duas condições, apresentado para a potência efetiva se repete aqui. Para um vácuo de 9,33 kPa, obteve-se percentual de ganho médio de 38%, que vem a ser superior ao obtido com vácuo de 8,00 kPa. Conclui-se então, que o benefício é maior à medida que se aumenta o vácuo de admissão.

Pode ser observado, na Fig. 5, o comportamento da eficiência térmica com a rotação, para dois valores de taxa de compressão, sendo que agora a potência foi mantida constante em cada rotação, sendo então variado o vácuo do coletor de admissão.

As condições destes testes visam comparar o comportamento de um motor de automóvel que, tendo um mesmo trajeto a cumprir a uma determinada velocidade, exigindo, portanto, uma determinada potência do motor. As duas condições de taxa de compressão seriam a apresentada por um motor convencional (mais baixa, limitada pela detonação em cargas mais elevadas do que a em questão) e a de um motor de taxa de compressão variável (mais elevada). Como pode ser visto nas figuras, com uma taxa mais elevada, desde que não se verifique a ocorrência de detonação, consegue-se obter os mesmos níveis de potência, com maior eficiência térmica, como era de se esperar.

Análise de Emissões

É apresentada neste item uma análise de emissões para o motor CFR. Além das medições feitas no referido motor, são apresentadas comparalóes entre o modelo de emissão de CO com valores experimentais.

Na Fig. 6 é realizada uma comparação dos resultados experimentais e numéricos para as seguintes condições:

1) Rotação (rpm):900
2) Ponto de ignição (°APMS):10
3) Temperatura da mistura (K):373
4) Vácuo de admissão (kPa):0,80
5) Taxa de compressão:10:1

Como o modelo utilizado neste trabalho não considera alguns efeitos, como inércia dos gases e propagação de ondas de pressão nos dutos de admissão e exaustão, e também por não se saber a duração da combustão, deve-se fazer uma comparação apenas qualitativa, uma vez que os citados efeitos podem ser importantes na determinação dos resultados.

Conclusões

De acordo com os resultados apresentados, chega-se à conclusão que a proposta de um motor de taxa de compressão variável possui um potencial que merece ser estudado mais a fundo, principalmente no campo experimental.

Ao serem comparados os resultados simulados obtidos neste trabalho com os obtidos experimentalmente de um motor equipado com o dispositivo variador da taxa de compressão, apesar de falta das características do motor em questão e de alguns dados de operação, pode-se afirmar que os resultados obtidos conseguiram reproduzir os resultados experimentais. Isso foi verificado principalmente em 2000 rpm, onde os efeitos não considerados no modelo utilizado não são preponderantes.

Finalmente, pode-se observar resultados experimentais que comprovam o benefício em se operar um motor com taxa de compressão variável. Operando um motor em cargas parciais, em taxas de compressão mais elevadas, pode-se obter potências mais altas, mantido o vácuo do coletor constante, resultando em consumo específico mais baixo assim como uma eficiência térmica superior. Esse comportamento foi observado nos dois valores de vácuo de admissão testados. Mantendo-se a potência constante em taxas mais elevadas, consegue-se obter uma redução no consumo específico e, em consequência, uma maior eficiência térmica.

Referências

Abenavoli, R. I, Sciaboni, A. e Wardzinski, W., 1991,"Performance Analysis of a Variable Stroke Reciprocating Engine", Proceedings of the 26th Intersociety Energy Conversion Engineering Conference - IECEC, Boston, USA, Vol. 5.

Rychter, T. J. e Teodorczyk, A., 1985, "VR/LE Engine with a Variable R/L During a Single Cycle", SAE Paper nº 850206, SAE Annual Congress, Detroit, USA.

Souto, H. P. A., 1987, "Simulação Numérica de um Motor a Combustão Interna com Ignição por Centelha", Dissertação de Mestrado, Departamento de Engenharia Mecânica, PUC/Rio, Rio de Janeiro, Brasil.

Teixeira, R. N., 1992, "Motores a Combustão Interna com Taxa de Compressão Variável - Uma Análise Teórica e Experimental", Dissertação de Mestrado, Departamento de Engenharia Mecânica, PUC/Rio, Rio de Janeiro, Brasil.

Resumo

É realizado um estudo teórico e experimental sobre motores a combustão interna, com ignição por centelha, operando com taxa de compressão variável. É feita uma análise teórica sobre mecanismo que permite variar a taxa de compressão. No presente trabalho um modelo de simulação existente foi aprimorado, com a inclusão de previsão de detonação, de emissão de hidrocarbonetos, do cálculo da potência de atrito, assim como a inclusão do dispositivo do mecanismo de taxa de compressão variável. Neste trabalho, um motor CFR foi utilizado, com o objetivo de validar os resultados do modelo teórico, incluinto o teor de CO.

Palavras-chave: Motores de Combustão Interna, Taxa de Compressão Variável, Modelagem e Verificação Experimental

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Design of a Distributed Database for a Concurrent Engineering Environment

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Abstract

Concurrent Engineering concepts are strongly considered by today's industry as a means of improving all aspects of the product life-cycle. This approach primarily suggests the use of teamwork, where the team is formed by engineers and experts from all activities related to the product life-cycle. One main function of the concurrent engineering team is to negotiate the best solution for the product development. The team is created in the earliest life-cycle phases and is responsible for all decisions made regarding the product until the product is out of the market. Teamwork involves intense collaboration and exchange of information. Different tools are proposed to ease the teamwork, namely Design for Manufacturing, Design for Assembly, Quality Control and CAE/CAD/CAM, etc. This paper describes the Concurrent Engineering Environment (CEE), as a powerful computer-aided tool to support the use of concurrent engineering ideas in a distributed platform. A natural framework to support the management and sharing of information among different manufacturing phases or activities is a network (federation) of heterogeneous and autonomous agents that are either loosely of some tightly-coupled. In this federation, an agent is involved in one activity (e.g. design) related to the product life-cycle, while several agents may take part in the same activity. On one hand production related activities are independent, (heterogeneous and autonomous) to serve different purposes. On the other hand, trivially these activities are interrelated (coupled) and need to cooperate and exchange information among themselves. In this paper, we describe the distributed/federated database design that supports the information manipulation in the CEE for an aerospace industry in Brazil. The design of CEE is based on the federated information management system PEER. We will distinguish the different kinds of PEER agents that constitute the CEE federation network. We describe the role of the "product" in the CEE environment and present a schema description for products. This research describes the second phase of the cooperation between the University of Amsterdam (The Netherlands) and Universidade Federal de Santa Catarina (Brazil) in the scope of the CIM-ECLA program.
Keywords: Concurrent Engineering Environment, Distributed Database, Database Design, CIM.

Introduction

Due to the complexity of the production process, many problems arise daily in the manufacturing industries. Concurrent Engineering aims to solve these day to day problems. Contrary to the traditional production system where the product life-cycle follows a sequence of isolated activities, in a Concurrent Engineering Environment these activities are made simultaneous and compatible, and consider the parameters that affect the entire cycle of product development. A team of engineers and experts is created in the earliest life-cycle phase and is responsible for all decisions made, concerning a specific product domain. The activities involved will be performed in a close cooperation among all team members.

Information representation heterogeneity and the information distribution among different activity areas is necessary to be supported within the CEE. A federated database framework is needed to efficiently support the management and the sharing and exchange of information among the team

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members in such an application. Each team member has a large degree of autonomy in structuring and organizing his own information (drawings, documents, analysis results, etc). Simultaneously, he must also consider the needs of the other team members permitting distinct views to the same set of information. To supply information and handle it over to the entire production process, each phase (activity) must make some of its own information sharable, to be accessed, queried and analysed by other partners.

The requirements described above call for a distributed information management architecture. A natural framework however, is a network (federation) of heterogeneous and autonomous agents. An agent represents an application environment activity. Every agent stores some data locally, performs some local computations, and needs to access some remote data from other agents. An agent in this network is heterogeneous in the sense that it is developed independently and has its own private representation of the data. An agent is autonomous in the sense that it can decide to conditionally share a part of its information with other agents and keep another part private and explicitly for its own local use. Agents involved in one specific activity area (e.g. design) are tightly interrelated, while two agents involved in different activity areas (e.g. design and sales) are loosely interrelated. Tightly-related agents represent a cluster in the network.

PEER (Afsarmanesh et al., 1993b, Tuijnman and Afsarmanesh, 1993a, Afsarmanesh et al., 1994, Afsarmanesh et al., 1993a) is a federated, object-oriented database management system designed and implemented at the University of Amsterdam primarily to support industrial automation apllication environments. The research in (Afsarmanesh et al., 1993a), describes the CEE requirements and the PEER capabilities that satisfy them. Based on those results, in this paper, we have developed an information model to represent the Concurrent Engineering Environment. This effort is partially supported by the ESPRIT program through the ECLA-CIMIS.net project.

The rest of the paper is organized as follows: section 2 briefly describes the CEE Concurrent Engineering Environment. An overview of the PEER facilities and modeling concepts necessary for the CEE information model definition are presented in section 3. In section 4 the production process information modeling and the approach to the product representation is described. Finally, in section 5, some conclusions and the next steps are presented.

Concurrent Engineering Environment: An Overview

Productivity and quality improvement, and cost reduction are the most important criteria of the production process. To satisfy these criteria, design, manufacturing, maintenance, etc. information must be available to all phases that need it.

Many approaches are applied to the Concurrent Engineering implementation and most of them are based on multifunctional teams. Engineers and experts from different product life-cycle activities work together in a team all through the product life-cycle. A main requirement of the concurrent enfineering approach is the availability of all the information related to any life-cycle activity, to all team members who need to access it. The information is distributed among different autonomous agents and information representation is heterogeneous. Two different facilities must be available to users from any life-cycle activity: information query and analysis tools. These facilities are modeled by the Computer Integrated Manufacturing tools. In this sense, each CAx (CAD, CAM, CAE, CAPP, CAQ) must be a server, providing necessary information and supporting analysis needs of a client.

Each manufacturing activity needs to access the information about the product specification. To support the needs of many different agents a powerful, comprehensive product model (description) must be represented. Feature technology (Cunninghan and Dixon, 1988, Shah, 1991, Moreira, 1993) is used to model different manufacturing information, like processes, tools, therm-chemical processes, tolerance, etc. As such, the product model must integrate different kinds of information in a homogeneous chema, so that this representation can work a a unifying "access key" to the manufacturing information. The Feature Technology supports this requirement by providing access to manufacturing information from any production process phase. Through this key any team member can obtain the necessary manufacturing process information for production.

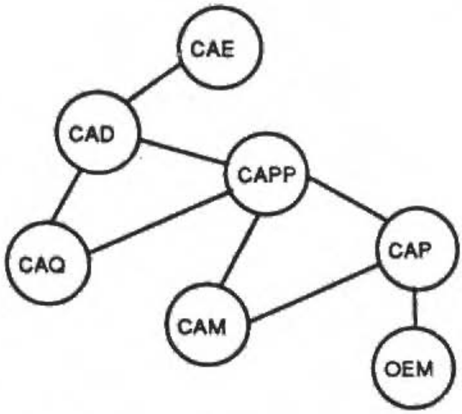

Fig. 1 Concurrent Engineering Environment

Each server must be modeled as an autonomous agent that cooperates and share information with others to solve problems. For instance, if a CAD user must know if a part can be produced inhouse with minimal cost, he can submit the design to a manufacturability analysis agent. Then, the CAPP, CAQ and CAP agents will work together to analyze the part design and to deduce the best option, in terms of the production process costs and parts/machines availability. Besides, OEM information should be analyzed to decide if it is more efficient to procure the part from other manufacturers. Several agents need to access the process planning and scheduling information.

Figure 1 describes this interrelation and information sharing approach. In this example, a CAD user can get information from a process planning (CAPP) server and an analysis engineering (CAE) server. Also, the CAPP user can receive information about functionality and design quality standards, processed by the CAD information server, etc.

The analysis tools are expert systems developed as an agent with federated database management system support. The tool intelligence degree depends of the analysis difficulty. In most cases, the user's help is necessary for good analysis. In this case, a friendly user interface and proper communication among the tools must be additionally developed.

Peer: An Overview

PEER is a federated object-oriented database management system designed and developed at the University of Amsterdam. In this section, we give an overview of several concepts developed in PEER (Afsarmanesh et al., 1993b, Tuijnman and Afsarmanesh, 1993, 1993b, 1993c) to support the rich and complex CIM application area. PEER supports the autonomy of agents involved in the cooperation team allowing them to share and exchange information as they wish. This is achieved by a sophisticated schema derivation/integration mechanism, which supports importing remote information and restructuring and integrating it with the local information (Afsarmanesh et al., 1993b). The interrelation among the information handled by different team members is negotiated in PEER to preserve their referential integrities (Tuijnman and Afsarmanesh, 1993b). PEER also offers support for object clusters shared in the network where the definition and the data related to the object cluster can be distributed among many agents. The subject of object-cluster, -representation, -identification, and -boundary, and a linearization mechanismo developed for object clusters' transformation into messages is fully described in (Tuijnman and Afsarmanesh, 1993c). Support for object identity and naming is treated in (Tuijnman and Afsarmanesh, 1993a).

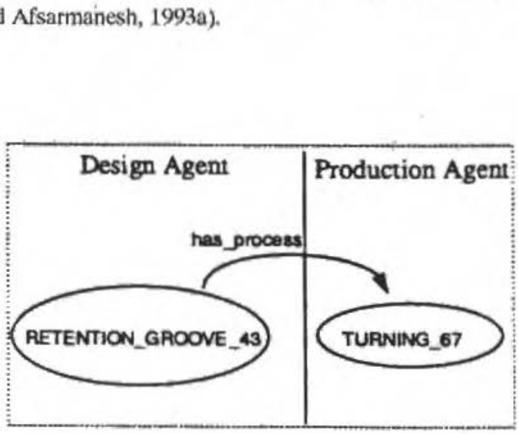

Fig. 2 Relationship between objects in different PEER Objectbases

A prototype implementation of the PEER federated system is developed in C that runs on UNIX, on a network of SUN workstations. This implementation of PEER was partially supported by the ESPRIT-Archon project, which developed a system to integrate cooperating expert systems (Witting, 1992). This prototype was tested at the control rooms of power distribution networks in two different industries, in Spain and England. PEER is designed around a global database model, the object-oriented PEER data model, to represent the information of each agent, and a global database language, the object-oriented query/update PEER language. Through using the global data model, agents' heterogeneous schemas are made homogeneous. However, the homogeneity of schema representation does not address the semantic interrelationships (loose or tight integration) that may exist among the data and knowledge of different agents. These interrelationships are established systematically and incrementally through a set of derivation/integration operations defined for distributed schema management of PEER.

Several schemas coexist in every PEER, namely: the local, export, import, and integrated schemas. The integrated schema can be interpreted as one user's global classification of objects that are classified differently by the schemas in other databases. Information management in a network of agents is supported by PEER through distributed schema management including integration and derivation of local information and information that is available from other PEER agents. Reliability is supported by enforcing the integrity of relationships established among local and remote information. For the interaction with end-user and applications, PEER offers support for object naming, object clusters and interface support through linearization of object clusters.

Schema Integration/Derivation

The local schema in each PEER agent specifies the type structure of the information stored locally at that agent. Part of the local information can be made available to certain other PEERs, by specifying one or more export schemas, each defining a view on the local information. An export schema in a PEER can restrict the exported information to a subset of local information to make it available to certain other PEER agents. PEER agents can locally import the export schemas of others in order to access the remote information available from other PEERs.

PEER offers two approaches to integrate the local information and remote information (of other PEERs) imported into import schemas. The first approach is to define an integrated schema, derived from the local and the import schemas. An integrated schema defines a single uniform type structure on the information available both locally and remote. The SDDL language (Schema Definition/ Derivation Language) of PEER supports the definition of integrated/derived schemas (Afsarmanesh et al., 1993b). Since the integrated schema is defined local to a site, different PEERs may establish different correspondences between their own schemas and other sites' schemas, thus there is no single global schema for the entire network. Another integration approach is also necessary to support the direct interrelation among the local information and the remote information (please see Fig. 2). The local schema of a PEER will be transformed into an extended local schema. To support one such direct relationship, within the extended local schema, the local type definition will be extended with a mapping to reference the remote objects defined in an import schema (Tuijnman and Afsarmanesh, 1993a).

Queries in PEER are always evaluated in the context of one schema. The default context for a query is the local schema, but any other schema context can be specified in a query. Distributed query evaluation in PEER is discussed in (Afsarmanesh et al., 1993b).

Remote Referencing

Integrity of objects that contain references to remote objects can be violated when the remote objects are deleted by a remote PEER. Figure 2 shows a relationship (RETENTION_GROOVE_43, has_process, TURNING_67), where RETENTION_GROOVE_43 is in the Design Agent in site A and TURNING_67 is in the Production Agent in site B. The deletion of TURNING_67 in site B violates the referential integrity. PEER preserves the necessary referential integrity constraints, by requiring a reference access right for every remote reference on a certain imported type to be negotiated and bilaterally agreed by both PEER sites involved. For example, de Design Agent must first request a reference access right on the type TURNING (of which TURNING_67 is an instance) that is represented in an import schema obtained from Production Agent. With this acces right request, the Design Agent can also ask for an action level (delete condition) to be followed by the Production Agent. The delete condition, is the condition requested by the Design Agent to be followed by the Production Agent in the case that the Production Agent decides to delete an instance of TURNING to which the Design Agent has a remote reference (Tuijnman and Afsarmanesh, 1993b and 1993c). There are three possible action levels that the Design Agent can request: warning that an object will be deleted after remote PEER's permission. These delete conditions are of different severities and must be negotiated by the two PEER's.

Production Process Information

The main problem in implementing a concurrent engineering environment is the information representation heterogeneity and complexity. Each product life-cycle activity uses different kinds of information; e.g. product definition, technological data, geometric data, algorithms and process knowledge. Besides, each phase treats some specific kinds of information. This information is distributed over different phases and must be carefully handled to avoid inconsistent redundancies. This section presents our approach to the production process information modeling, where the concurrent engineering is fully applied.

Each enterprise has its own information flow. In general, they are different in details, but the main structure is similar for the same kind of industry. As an example we have studied the information flow of a Brazilian aerospace industry, approximately described in Fig. 3 using the IDEF approach. Each box represents one activity in the production process, and the arrows show the information flow among the activities.

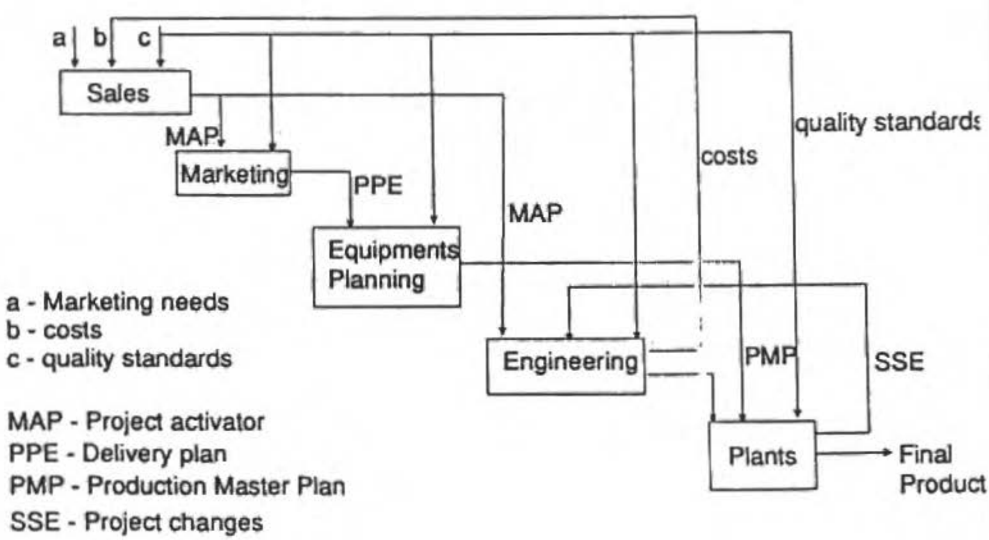

Fig. 3 Production process information flow

The "product life-cycle" can be briefly described as follows. The Sales Department develops the market prospects and prepares the first draft study in order to analyze the product cost and its convenience. A database containing the manufacturing process cost's information is used in this activity. If every market requirement is satisfied, then a project activator document (MAP) is prepared manually. The MAP initalizes the activities in the Marketing Department to manage the new product. Simultaneously in the Design Department, the MAP simultaneously initializes the design of the details of the product. In the Marketing Department the final product plan is generated, describing deadlines and the amount of each product to be produced, and a delivery plan (PPE) is prepared. This document is used in the scheduling of the production process by the Equipments Planning Department. Using the PPE and the process planning information, a Production Master Plan (PMP) is generated, defining the production scheduling. The first draft made by the engineers from the Sales Department gets expanded in the Design Department. Using CAD systems the engineers construct the final version of the product design. The product subparts are described considering both the internal and the external standards that represent the enterprise manufacturing culture. The product/parts designs are plotted and used by the Production Department to develop the process planning for the part production process. The process planning information is stored in the mainframe, and is printed on papers to be used in the shopfloor. Every activity in the enterprise must follow the quality standards. The quality standard procedures are all described in several booklets and are constantly used by the people involved in manufacturing on the shopfloor.

During the product life-cycle, described above, many different kinds of information are handled by each activity, where each activity uses its own representation approach and storage strategies. This information melting-pot makes it difficult to share and exchange the information and potentially increases the information inconsistency problems. As mentioned before, the product definition is the main concept to which other manufacturing information is related. Marketing, design and manufacturing phases develop activities where the product information is defined and used to generate the final product. During this process, several other pieces of information are defined and aggregated to the product definition, so that it can be used as an integration element in a concurrent engineering environment.

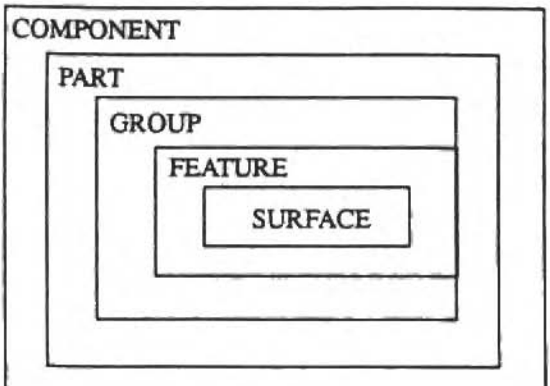

Fig. 4 Hierarchical product representation

The product is defined hierarchically as presented in Fig. 4. The component level is user defined and can be reused in other product definitions. In this hierarchic definition, the component complexity is decreased in its sub-component definition, while the functionality and characteristics of subcomponents are more detailed. A simple component is described by one or more parts. A part is defined as a non-assembled element produced by one piece of raw material. Parts constitute the last level that can be defined by the user. One part can be composed of as many different preexistent groups and features as necessary to represent its functionality. Groups are composed of features and generally describe a standard constructive element. Both groups and features are available in libraries. Each library supports the manufacturing needs of one specific product domain.

Each feature represents a design function used by the designer in the product conception phase. With this constructive element the part is built in a funcion assembly process. One feature can be generic, like the groove in Fig. 5. It is a shape, with some dimensions that can be used for many different purposes. In this basic feature a function can be aggregated, so that it can define more information. Surface finishing and tolerances, machining process and therm-chemical process are example of such functions. An example feature is represented on the left side of the part illustrated in Fig. 6.

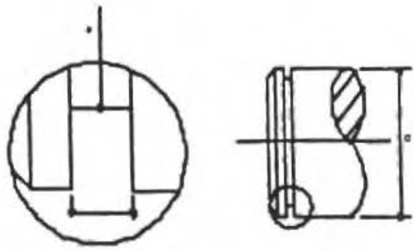

Fig. 5 A generic feature

Figure 6 presents a part modeled by its features. This part is composed of 3 groups defined by their funcionality. On the left side Support-roller-ball-group supports the pulley in its location. This group is composed of several features that develop specific functions. The Joint-group describes the union between the other two contructive groups.

The feature representation is structured in classes using a similar criterion. A feature can be defined under the object-oriented paradigm. This approach simplifies its representation and handling. As such, a feature is defined as an object with attributes, methods and inheritance. Figure 7 describes how groups are composed of functional features. For example, Support-roller-ball-group has many functional features. The feature Retention- Groove is a sub-class of Groove, and inherits the shape information from it. On the other hand, some important characteristics can be deduced by its own function, like surface finishing and tolerances.

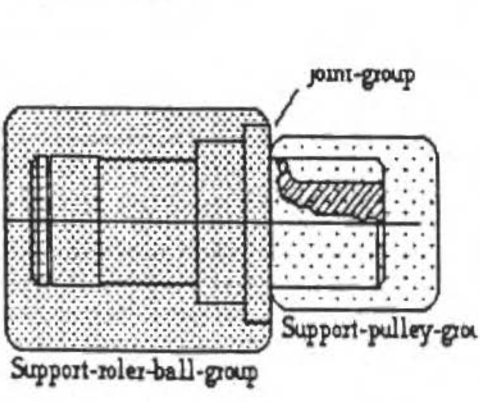

Fig. 6 A part composed of several groups

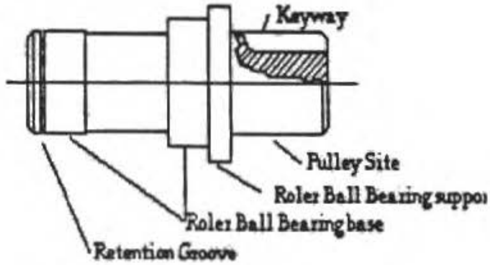

Fig 7. Design by features

As described earlier, the production process information is distributed among many different enterprise areas. Each of them maintains its own information structure. Basic relationships among objects are defined with the three fundamental abstraction mechanisms of generalization, classification and aggregation (Tuijnman and Afsarmanesh, 1993a). The subtype/supertype (generalization) hierarchy for Concurrent Engineering information is shown in Fig. 8. In this figure, boxes represent type objects, the arrows represent subtype/supertype relationships, and the undirected lines that come out of the boxes lead to mappings (properties or attributes) that describe members (instances) of the type. CONCURRENT-ENGINEERING-ACTIVITY is a type described by the information represented in sales, marketing, design and production activities, as it is described in section 1.2. For example, the DESIGN-ACTIVITY is described by its PROCESSes, COMPONENTs and STANDARDs. Some of this information is distributed over other agents that can be accessed and interrelated with local information using the remote reference mechanism.

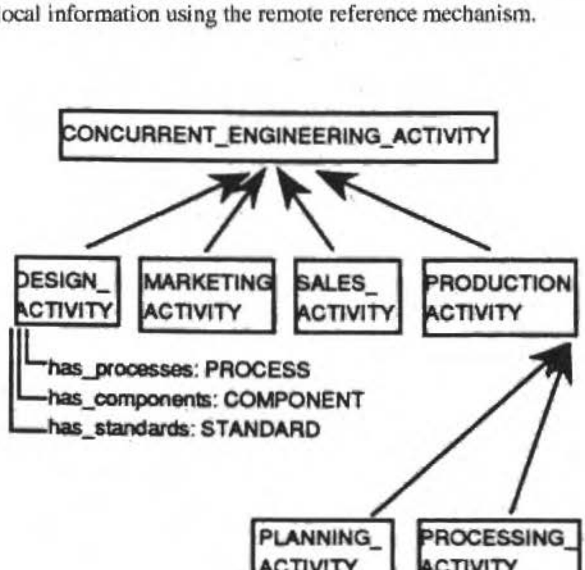

Fig. 8 Concurrent engineering information modeling

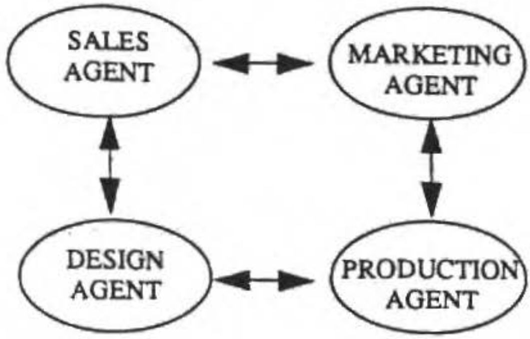

Fig. 9 Concurrent engineering environment agents

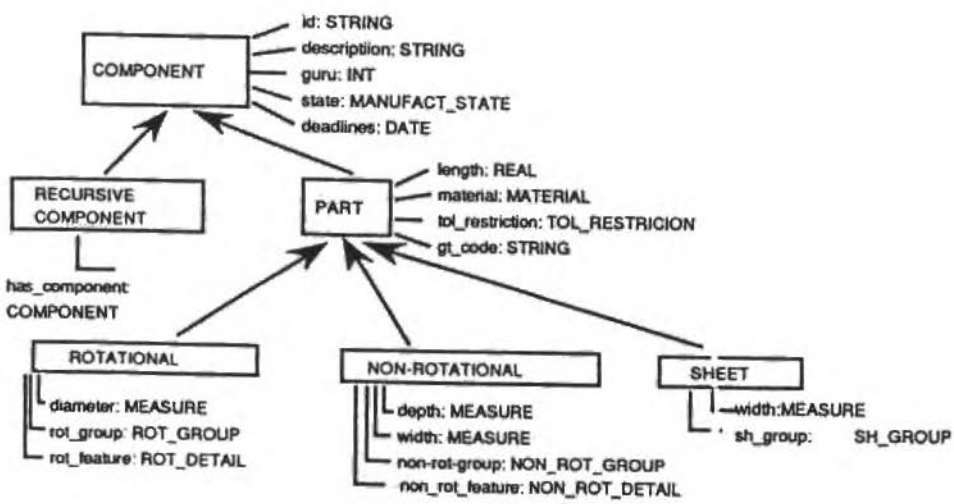

Fig. 10 Product representation

The information described above is distributed over four distinct and autonomous "kinds" of PEER agents as presented in Fig. 9. These agents are interrelated and constitute the cooperation network, where the information can be shared and exchanged among them. Obviously, for simplicity reasons, only one agent from each activity is represented in this figure, while in a realistic situation, there are many interrelated agents e.g. design agents performing the design activity. Within this CEE network the first draft made by the engineers in the sales activity can be used by the designers during the design phase, as well as, by the marketing activity. Due to the difference in goals and purposes of each activity, generally, the information generated or stored in one activity is not entirely interesting to another one. In these cases, the correspondence between different agent's schemas, must be established through the schema derivation/integration or through the remote referencing.

The product model is the important unifying piece of information among different activities within the Concurrent Engineering environment. As described in section 1.2, it is represented hierarchically. In Fig. 10, the type COMPONENT represents the recursive definition of the "Component" in Fig. 4. The two sub-types of the COMPONENT are disjoints. A component is defined through its recursive subcomponents; while each subcomponent is a component itself. The recursive definition ends when at the lowest level a component can be fully defined in terms of parts. So, one product is decomposed into many (sub)COMPONENTs, each one composed of some PARTs and come other (sub)COMPONENTs. A part, as described earlier, is then defined by any number of GROUPs and FEATUREs. The subtype ROTATIONAL represents rotational groups and features.

The type rotational group (ROT_GROUP) has two sub-types (see Fig. 11) that represent the information described in section 1.2. A rotational group is composed of features, as represented in Fig. 11 by the aggregation relationships "has_primitive" and "has_detail". Both ROT_JOINT and ROT_CONSTRUCTIVE are characterized by their features detail (ROT_DETAIL), and the constructives groups have "one" primitive feature for the ROT_CONSTRUCTIVE entities must be modeled as an "integrity constraint" defined on the type ROT_CONSTRUCTIVE, and will be discussed in a future paper.

Features are structured in subtypes that represents a specific part domain, for instance, rotational parts, prismatic parts, sheets, etc. Every feature (FEATURE) is described by its surfaces. Figure 12 represents the description of rotational features (ROT_FEATURE). The type RETENTION_GROOVE is a functional feature derived from a generic feature GROOVE and is described by additional attributes.

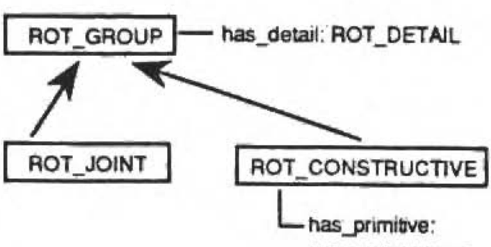

Fig. 11 Group representation

When a feature describes the information about its machining process, it represents a link between two different agents. For example, if a CAD user chooses a feature RETENTION-GROOVE, a member of this type is accessed (or created). This feature has associated production information, that is modeled in another agent. So the design can access many kinds of manufacturing information like machining process, machines, tools and fixtures available for this specific feature using remote referencing facility described in section 3. The main advantage here is that, the information is stored in the network only once and there is no redundancy to cause the information inconsistency problem.

Conclusions

This paper presents the basic premises of designing a framework for CEE information management and information sharing. Several information modeling requirements necessary to support concurrent engineering applications are distinguished. Then, the PEER federated object management system is described addressing those information management requirements. Four specific kinds of PEER agents are distiguished to constitute CIM activities. Product is described as the common unifying source of information among agents, and and object-oriented schema description is provided to present the hierarchic definition.

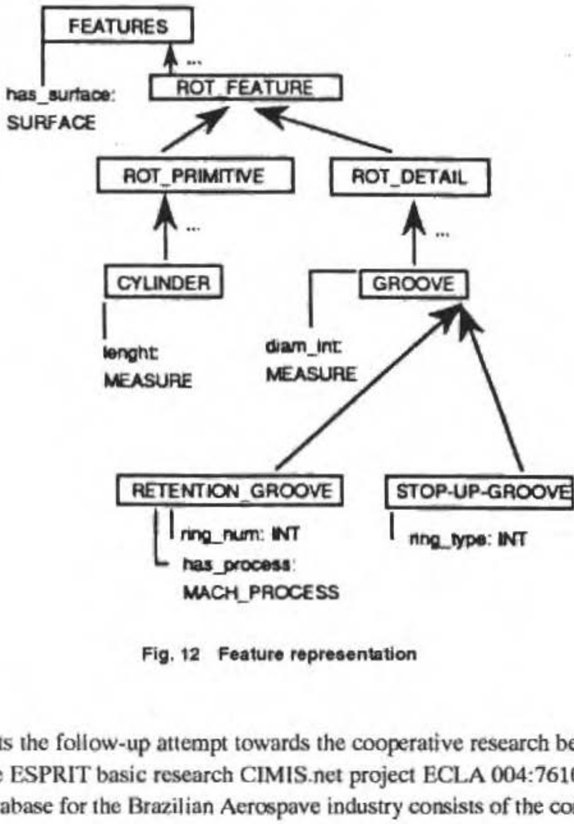

Fig. 12 Feature representation

The paper presents the follow-up attempt towards the cooperative research between two research teams involved in the ESPRIT basic research CIMIS.net project ECLA 004:76102. The next step in developing a CIM database for the Brazilian Aerospave industry consists of the complete design of the four kinds of PEER agents, representing their complex application information and then implementing these distinct CIM activities.

References

Afsarmanesh, H., Wiedijk, M., Ferreira, A. C., and Moreira, N. P., 1993a, "An Approach to the Design of a Distributed CIM Database for a Brazilian Aerospace Industry", Proceedings of the European-Community-Latin America Workshop on Computer Integrated Manufacturing 93, Monte de Caparica, Portugal.

Afsarmanesh, H., Tuijnman, F., Wiedijk, M., and Hertzberger, L. O., 1993b, "Distributed Schema Management in a Cooperation Network of Autonomous Agents", Proceedings of the 4th IEEE International Conference on Database and Expert Systems Applications (DEXA), Lecture Notes in Computer Science (LNCS) 720, pp. 565-576, Springer Verlag.

Afsarmanesh, H., Wiedijk, and Hertzenberger, L. O., 1994, "Flexible and Dynamic Integration of Multiple Information Bases", Accepted by the 5th IEEE International Conference on Database and Expert Systems Applications (DEXA), to be published in Lecture Notes in Computer Science (LNCS), Springer Verlag.

Tuijnman, F. and Afsarmanesh, H., 1993a, "Management of Shared Data in Federated Cooperative PEER Environment", International Journal of Intelligent and Cooperative Information Systems (IJICIS), 2(4) pp. 451-473.

Tuijnman, F. and Afsarmanesh, H., 1993b, "Sharing Complex Objects in a Distributed PEER Environment", in 13th Int. Conf. on Distributed Computing Systems, pp. 186-193, IEEE.

Tuijnman, F. and Afsarmanesh, H., 1993c, "Distributed Objects in a Federation of Autonomous Cooperating Agents", in Int. Conf. on Intelligent and Cooperative Information Systems, pp. 256-265, IEEE/AAAI.

Wittig, T., editor, 1992, "ARCHON: An Architechture for Multi-agent Systems", Ellis Horwood.

Cunningham, J. J., Dixon, J. R., 1988, "Design with Features: The Origin of the Features", ASME Computers in Engineering Conference, San Francisco.

Shah, J., 1991, "Assessment of Feature Technology", Computer Aided Design, Vol. 23, no. 5.

Moreira, N. P., 1993, "An Information Modeling Proposal to the Manufacturing Integration and Concurrent Engineering, Master Thesis, Universidade Federal de Santa Catarina.

Resumo

Conceitos de engenharia concorrente são considerados como uma maneira de incrementar todos os aspectos do ciclo-de-vida de um produto. Essa abordagem primeiramente sugere o uso de grupos multi-funcionais formado por engenheiros e especialistas de atividades do ciclo-de-vida do produto. Uma das funções principais da engenharia concorrente é negociar a melhor solução para o desenvolvimento do produto. Trabalho em grupo exige intensa colaboração e troca de informações. Este trabalho descreve o Concurrent Engineering Environment (CEE - Ambiente de Engenharia Concorrente) como uma ferramenta potente de auxílio na implementação dos conceitos de engenharia concorrente. A abordagem natural para o gerenciamento e compartilhamento das informações entre as diferentes fases do processo de manufatura é uma rede de agentes autônomos e heterogêneos fortemente acoplados. Nesta rede, um agente é envolvido em uma atividade (por exemplo: projeto) desenvolvida durante o ciclo-de-vida do produto e auxiliado por outros agentes que também tomam parte na mesma atividade. Se por um lado as atividades são independentes, por outro são interrelacionadas e necessitam cooperar e compartilhar informações entre elas. Neste trabalho é descrito o projeto de um banco de dados distribuído que suporta a manipulação da informação no CEE para uma indústria aeronáutica brasileira. O projeto do CEE é baseado em um Sistema de Gerenciamento de Informações Distribuído - PEER. Este trabalho descreve a segunda etapa da cooperação entre a Universidade de Ambsterdam (Holanda) e a Universidade Federal de Santa Catarina (Brasil).

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A STEP Based Information Management System as a Support to a Concurrent Engineering Environment

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Abstract

This work presents a proposal to a Concurrent Engineering Aided Environment. It is supported by a generic STEP-based integrating platform providing a powerful assistance to information modeling and distribution. This effort is a cooperation between the UNINOVA-Universidade Nova de Lisboa-Portugal and Universidade Federal de Santa Catarina-Brazil.

Keywords: Integration, Concurrent Engineering, Information System, Information Modelling, STEP

Introduction

Countries around the world expand its economy in a global perspective. Its effects, in the industry, imply in a deep reorganization in its procedures to improve competitiveness. This new approach must provide a close control over the role life-cycle product development, including suppliers, marketing, design and production. Concurrent Engineering (CE) is a methodology to achieve this.

This paper presents a proposal to a Concurrent Engineering Environment (CEE) supported by a STEP based Information Management System (IMS). It is a first effort to define the role of an IMS in CEE. The paper is organized as follows: section 2 defines Concurrent Engineering in a CIM perspective; section 3 presents the CEE and its requirements; section 4 describes UNINOVA's STEP based Integrating Platform; section 5 brings some improvements to this platform to fulfil CEE requirements; finally, section 6 presents conclusions and future works.

Concurrent Engineering

Concurrent Engineering (CE) is a methodology that provides a product development based on cooperation among the people working in its elaboration. It includes a teamwork approach. In many works (Reimann and Huq, 1992, Terpenney and Diesesnroth, 1992) Concurrent Engineering is defined as a methodology that brings to the design phase considerations about factors that can induce errors in the future steps. In other point-of-view (Moreira, 1993), a CE team must be responsible for all decisions over the product life-cycle. By this way all factors that could affect the product development should be analyzed and solved by experts in each aspect of the product.

Some CE tools as Design for Manufacturing, Design for Assembly and Computer Integrated Manufacturing technologies (CAE/CAD/CAM) could be used to help in the team activities. A good example of this type of programs is the Boothroyd-Dewhurst design for assembly system. Their

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computer program asks the user for a series of questions about the fastening method, symmetry of the parts, general size of the parts, angle of insertion and so on, and gives an evaluation in terms of the assembly time, its breakdowns, and the assembly efficiency. Similar evaluation programs exist for other manufacturing issues, and when integrated in a wide CEE could be effective on helping any life-cycle activity. Other important point, on which the teamwork is structured, is the information query distributed in the CEE.

Huthwaite describes a Concurrent Engineering team as a group responsible for the project since its earliest phase. To be effective, the team's partners must talk the same language and exchange information by the same channel. As well as the analysis tools, used by the partners, must understand the output of the other tools. From the information system perpective the integration of a set of heterogeneous applications implies on the solution of several problems, including (Camarinha-Matos and Osório, 1992):

- definition of common models for shared information;
- definition/adoption of an Information Management System (IMS), and
- in conjunction with the IMS realization of an integrating infrastructure that provides a functional support for integration, i.e., a kind of "software bus" offering high level interprocess communication services to the connected tools.

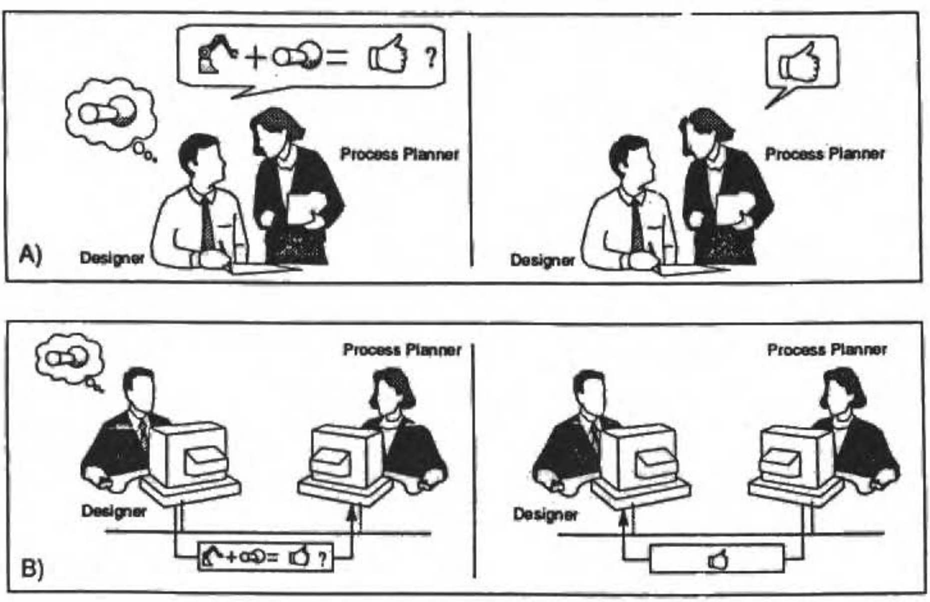

Fig. 1 Concurrent Engineering (CE) teamwork approach (A) and CE environment (B)

Concurrent Engineering Environment: Overview and Requirements

In a traditional product life-cycle, the information is strongly centralized in each activity. Meanwhile, during the development of some activities information about other process should be necessary, and its lack could imply in errors. A computational environment should decentralize the information by a distributed information support. Follow Terpenny and Diesenroth (1992), three points are basic in a concurrent engineering environment implementation: improvement in the design strategy; decision make aid; and information support. By this way, improvements are centralized just in the design phase, anyway this proposal is interesting because treat the problem non-specifically in terms of information handling and decision make support. The Concurrent Engineering Environment (CEE) is based in CIM concepts, where each CAx (CAD, CAE, CAM, CAPP, etc.) is a tool which function is to aid whole product life-cycle. More details about it can be found in Moreira (1993).

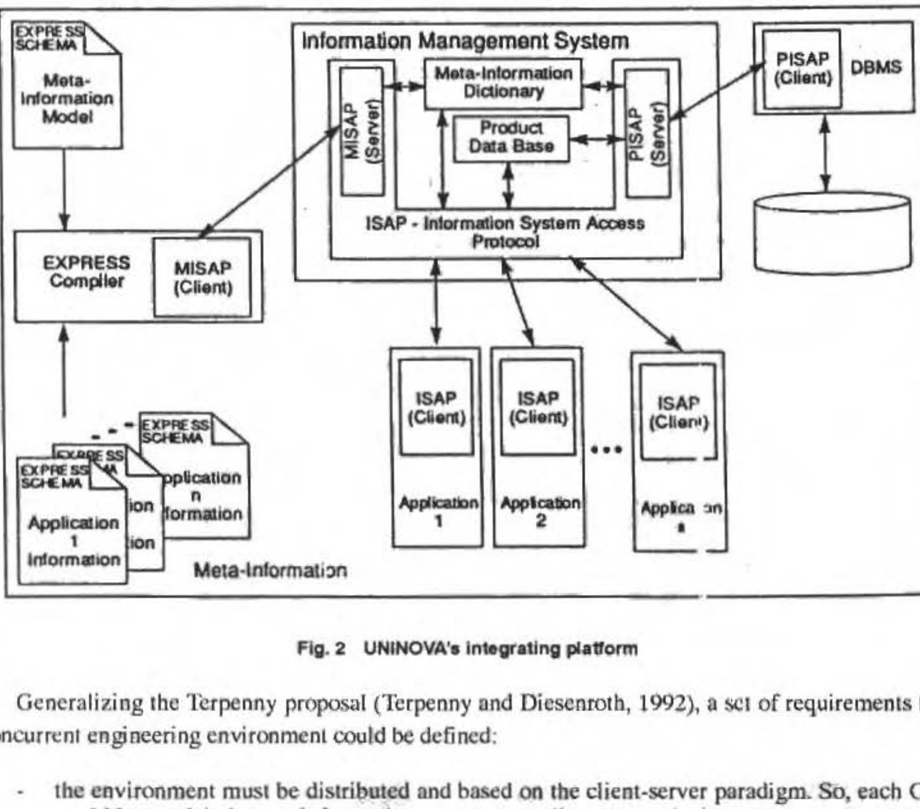

Fig. 2 UNINOVA's integrating platform

Generalizing the Terpenny proposal (Terpenny and Diesenroth, 1992), a set of requirements to a concurrent engineering environment could be defined:

- the environment must be distributed and based on the client-server paradigm. So, each CAx could be modeled as an information server, as well as, an analysis tool. Agents may work concurrently, exchanging information, in order to solve a problem;
- data independency must be supplied for agents;
- product information must be widely handled by every activity/agent, so it has to be modeled in a standard way. Geometric and technological information must be available for every activity;
- each activity manages an amount of information. Part of them could be used by other activities, but mostly information is internal and must be protected, then vision facility must be provided;
- agents have to exchange information, then a communication protocol has to be defined. This protocol must provide queries, analysis and answers facilities for any agent that needs it, and
- the environment must be evolutive, it means that new agents can be added to the system step by step, according to the enterprises strategies.

Integrating Platform

This section presents a STEP based integrating platform developed at UNINOVA (Tavares et al., 1993), and its use in a Concurrent Engineering Environment.

STEP (ISO 10303) is an International Standard for the computer-interpretable representation and exchange of product data. The objective is to provide a neutral mechanism capable of describing product data throughout the life cycle of the product, independently from any particular system.

STEP includes a formal language (Express) developed to the information modelling. Express allows for the definition of universes of discourse, that is, specific aspects of the product life cycle. This is done through the schema constructor, that aggregates objects of interest (entities) of specific domains of application (e.g. design, process-planning), constituting application information models.

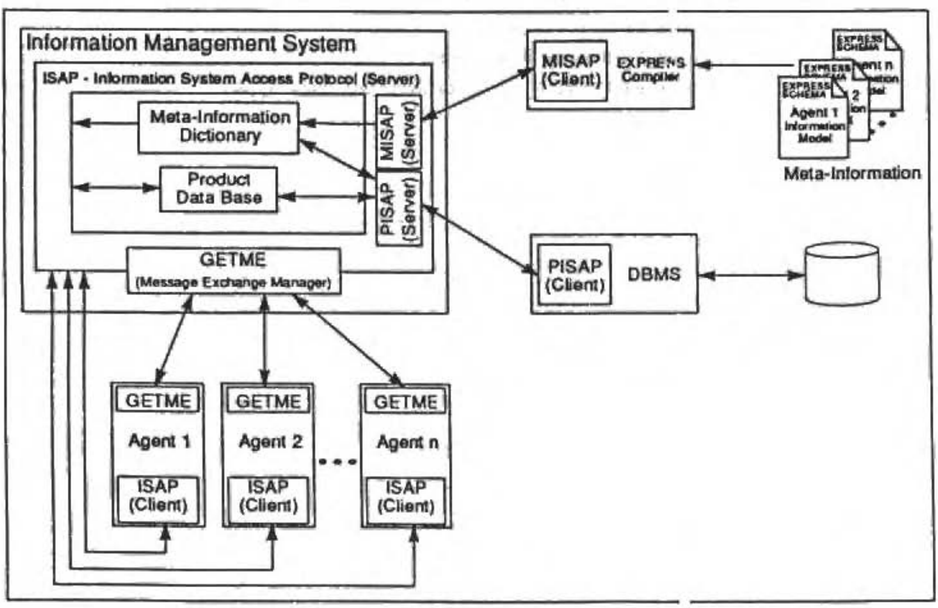

Fig. 3 Integrating platform with improved peer-to-peer capability

The Integrating Platform, depicted in Fig. 2, has two major components: an EXPRESS Compiler and an Information Management System (or simply Information System - IS).

By means of the EXPRESS Compiler, an application information model, as called application meta-information, is translated to the IS meta-information dictionary internal representation. Therefore, information communication and validation depends strongly on this component.

The Information System is the heart of the integrating platform and acts as an information server. It is composed of three components:

- ISAP - Information System Access Protocol: Set of funcions providing capability of local/ remote data communication among the IS and external systems such as CIM applications, the EXPRESS Compiler and persistent data storage systems. It provides also the validation of the transmitted data, by using the application meta-information. Two subsets of ISAP - MISAP and PISAP - are provided to communication of meta-information and persistent data, respectively;

- MID - Meta-information Dictionary: IS internal meta-information storage structure.
- PDB - Product Data Base: IS internal application data storage structure.

The integration of application is carried out through a tight connection mechanism, by which neutral format files are exchanged by ISAP client-server interfaces. In present implementation, RPC was used to accomplish client-server mechanism requirements.

```
ENTITY Task_Specification
  ...
  task_name: task_name_type;
  task_number: task_number_type;
  task_kind: task_kind_type;
  task_associated_data: associated_data_type;
  ...
END_ENTITY;
```

Fig. 4 Simplified EXPRESS entity modelling task specification

However, to achieve the CEE requirements identified in section 2, the platform must be improved with a new capability: the message handling mechanism. This improvement is described in the next section.

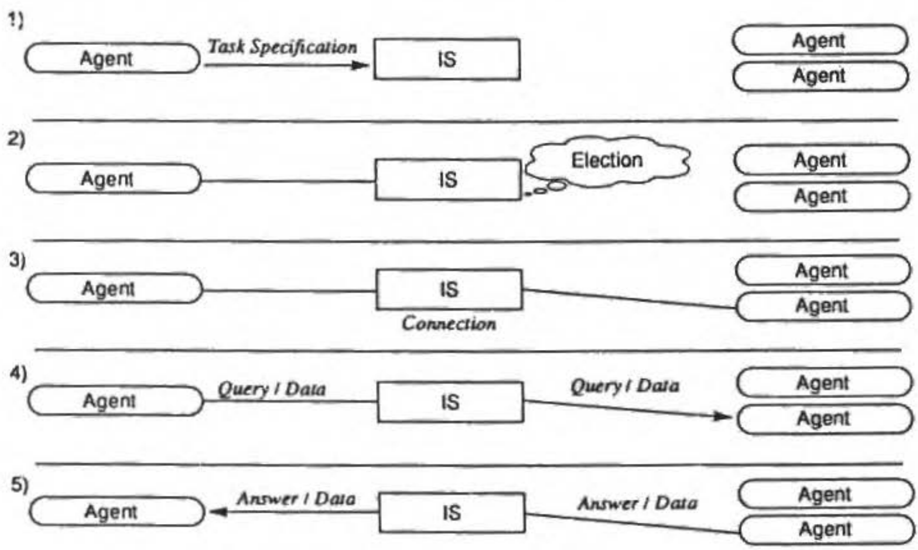

Fig. 5 Message handling capability - peer to peer transaction

A Message Handling Mechanism for the Integrating Platform

From now on, the term agent will substitute the term application used in the last section. This is because the higher level of iteration between the several activities of the product life-cycle, typical on concurrent engineering. Further, it is not enough to a CEE a simple product data exchange mechanism.

In the last section a STEP based integrating platform was described as an apprach to the implementation of a CEE. Indeed, it is a powerful solution to the distribution of information to every agent involved in the product life cycle.

However, a new capability must be considered, in order to accomplish the identified requirements of a CEE.

The first point to consider in a CEE is that agents must be autonomous, or must have a high level of autonomy, in order to interact with other agents. To conduct these interactions, they need to obtain information about other agents - their capabilities, their actual status, their availability, etc.

As an example, suppost that the agent Design, during the product design, need to realize an analysis of manufacturability. First of all, it must be known which Process_planner agents are available to deal with the design to be analyzed. Then it must establish a connection to the selected partner, sending the design and receiving the analysis.

By this example it is clear that the IS must have an additional capability: peer-to-peer transaction.

Actually, the communication between two agents is performed in two steps: the first agent connects the IS, transmits data to be shared, and disconnects. Afterwards, the second agent connects the IS, gets the data and disconnects.

Peer-to-peer transaction means that agents can, through IS, ask other agents for information (e.g. geometrical information of a part) or services (e.g. the assembling analysis of manufacturability in the example above), even before those agents make information available in the IS.

It implies that the IS needs to provide a message exchange mechanism. GETME (from "GErenciador de Troca de MEnsagens", or message exchange manager in portuguese), is this mechanism, and should allow agents to be information/service servers (and IS to be client, consequently), beyond the actual agent information client capability.

GETME should be able to help agents to choose prospective partners by analyzing some conditions, as availability, offered services, and so on. It is clear that the IS should be able to receive these information from the agents. Further, it must manage the entire transaction between the agents.

To fully achieve peer-to-peer communication, a complete message exchange model must be specified. This model should use EXPRESS on its formalization, so that messages could be exchanged via an ISAP based interface. A simplified example of EXPRESS entity modeling task specification is shown in Fig. 3 (Integrating Platform after the inclusion of peer-to-peer capability) and Fig. 5 (the peer-to-peer transaction itself).

Conclusions

This paper presented a Concurrent Engineering Environment being developed by UNINOVA-Portugal with cooperation of UFSC-Brazil. This is one important effort to popularize STEP in the manufacturing world. In the last year several Application Protocols were created by ISO, showing that STEP is becoming a well accepted standard, and that its adoption by manufacturers is evident.

The actual work status is a first industrial version of the integrating platform being finished, running in AIX, SunOS and Linux. This first version is being put available for demonstrations simultaneously in Lisboa-Portugal and Florianópolis-Brazil.

Future work will be done with the implementation of message handling capability, among other improvements as a toolkit to aid information modeling (browsers, graphical representation, etc).

References

Camarinha-Matos, L. M., Osório, L., 1992, "CIM Information Management System: an EXPRESS-based Integration Platform", IFAC - Workshop on CIM in Process and Manufacturing Industry, Espoo, Finland.

ISO TC184/SC4/WG7 N262, "ISO 10303 - Part 1 - Overview and Fundamental Principles", 1992.

ISO TC184/SC4/WG5 , "ISO 10303 - Part 11 - EXPRESS Language Reference Manual", 1991.

ISO TC184/SC4/WG7 N262, "ISO 10303 - Part 21 - Clear Text Encoding of the Exchange Structure", 1992.

ISO TC184/SC4/WG7 N262, "ISO 10303 - Part 22 - Standard Data Interface Specification", 1992.

ISO TC184/SC4/WG4 , "ISO 10303 - Part 23 - Configuration Controlled Design", 1992.

Moreira, N. P., 1993, "Integração da Manufatura: uma Proposta de Base", Doctor Thesis - Universidade Federal de Santa Catarina.

Reimann, M. D., Huq, F., 1992, "A Comparative Analysis Approach for Evaluating the Effect that Concurrent Engineering has on Product Life-Cycle Cost", Flexible Automation and Information Management, FAIM.

Tavares, M., Jardim-Gonçalves, R., Barata, M. M., Steiger-Garção, A. S., 1993, "Integration of Furniture Design/ Evaluation Tools. A STEP/EXPRESS Approach", ECLA-CIM'93, Lisbon.

Terpenny, J. P., Deisenroth, M. P., 1992, "A Concurrent Engineering Framework. Three Basic Components." Flexible Automation and Information Management, FAIM.

Weston, R. H., with collaboration of Aprotec International, Loughborough University of Technology and Weir Systems, "A Requirement Definition for Software Interoperability in Multi-Vendor Manufacturing Systems".

Resumo

Este trabalho apresenta uma proposta para um Ambiente de Engenharia Concorrente (CEE). Este é suportado por um sistema de informações, de uso genérico, baseado em STEP que provê assistência para a modelagem e distribuição da informação. Esta pesquisa vem sendo desenvolvida em cooperação entre a UNINOVA-Universidade Nova de Lisboa (Portugal) e a Universidade Federal de Santa Catarina (Brasil).

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Integration of an Optimization Expert System within a CIM Distributed Database System

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Abstract

This work presents an approach to the integration of an optimization system with the other CIM activities using a distributed/federated database architecture. The CIM application environment addressed here is the shoe and handbag manufacturing industry and the optimization system is for cutting the layouts of irregular shapes out of the base leather material. Here, the optimization system is specified by the complete separation of the user-interface from the optimizing aspects of the problem and defines them as two distinct cooperative agents. The integration of separate activities within a CIM distributed database system is attained by, using a federated object-oriented database management system. The federated architecture used here supports the cooperation and information exchange among autonomous and heterogeneous agents.
Keywords: Distributed/Federated Database, Optimization Expert System, CIM.

Introduction

An intelligent optimization system for CIM can be thought of as an agent performing the activity of optimization in a network (federation) of cooperating agents, where the agents represent different CIM activities. To support the concurrent engineering approach, different CIM activities must cooperate and exchange information. The optimizer agent shares the data provided by other CIM agents, that for example encapsulate the design, production planning, and manufacturing activities. This paper presents an approach to integrate and support an optimization expert system (**DSS- VIM-cutting**) within such a federated information management framework (**PEER**) designed to support a CIM application.

We will first realize two specific kinds of agents, one to represent the optimization system (OS) and the other to represent the user-interface (UI) for the optimization system. Second, an information sharing layer will be developed to support the cooperation and information exchange between these two agents. Third, we describe the framework in which one OS agent and several UI agents can be interconnected within a **PEER** network of cooperative CIM agents in order to fully integrate the optimization expert system within the CIM database. The resulting system will support the access to the optimization system from any UI agent defined in the network, and will automatically support the distributed query processing on optimization data.

The optimization expert system described in this paper is the DSS-VIM-Cutting, a Decision Support System based on the Visual Interactive Modelling. This expert system aims to optimize the layout of a set of moulds to be cut on a piece of raw material. To gain the best layout, the system must be integrated with other CIM's subsystems such as CAD, CAQC, PPC, and with a numeric control

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machine that executes the actual cutting. We first focus on defining a PEER agent, called DVG, to represent the DSS-VIM-Cutting system. The DVC agent will be primarily defined in terms of its data structures. We define the data that the DVC agent needs to access from other agents and we indicate from which other agent(s) that data must be retrieved. We also specify the data that the DVG agent can make available to the other agents in the federation. Then, we will design the information sharing layer of the DVC agent, in order to integrate the DSS-VIM-Cutting system within the PEER federated architecture, to complete its integration with the other CIM application activities.

The federated architecture described in this paper is based on the PEER information management framework (16^{th}, 4^{th}, 7^{th} references). PEER is an object-oriented federated/distributed database system designed and implemented at the University of Amsterdam. It primarily supports the complex information management requirements set by the industrial automation application environments. The research described in (Afsarmanesh et al., 1993b) describes some concurrent engineering requirements and the specific PEER capabilities to satisfy them. The federated architecture of PEER introduces an integration facility to support the cooperation and information sharing of autonomous GIM agents with heterogeneous data representation organizations (Afsarmanesh et al., 1994b). To better support users of the integration facility and for high level access to data and meta-data, two powerful and user-friendly interface tools are developed. The Schema Manipulation Tool and the Database Browsing Tool are both window-oriented and implemented using X-Windows on SUN workstations. These interface tools support users with their access, retrieval and modification of both data and meta-data in PEER agents. A prototype implementation of the PEER federated system is developed in the C language that runs on UNIX, on a network of SUN workstations. One of the application areas to which the PEER system is applied so far is within the ESPRIT project ARCHON. The ARCHON project develops a system to integrate cooperating, heterogenous and autonomous expert systems. In this project, PEER was tested in the control rooms of power distribution networks in two different industries in Spain and England.

The remaining of this paper is organized as follows. Section 2 presents a description of the optimization expert system. A description of the PEER's federated architecture is given in Section 3. The realization of the optimization system agent and the user interface agent is described in Section 4. Finally, Section 5 contains the conclusion of the paper.

Specification of the Optimization Expert System

The Optimization expert system can be defined by two distinct subsystems of: **Optimization subsystems** (OS) and **User interface subsystems** (UI). The Optimization Subsystem is formed by two processes: **problem processing** and **knowledge processing**. The problem processing performs the central control of the solution search process, while receiving the basic algorithms from the knowledge processing and coupling it with the interactive requirements of the user. OS contains both the knowledge to perform the heuristic search, and the production rules to represent the problem.

The User Interface Subsystem performs the interaction with the user, based on the Visual Interactive Modelling (VIM) paradigm. This subsystem is based on the idea of Modelling by Example (MbE) as a means of enhancing cooperation between user and the system. The UI supports decision making while taking into consideration four important dimensions of: End-user (decision-maker) modelling, Modelling as a concrete, visual and incremental process, Reactive system behavior, and Supplying active support (act as a consultant).

Data Structures used in OS and UI

In this section we will describe the data structures used in OS and UI as well as the relationships existing between those structures. On doing this we will be formalizing our data structures through an algebraic notation. We suppose the existence of the polymorphic type Set of χ, denoting the concept of sets containing elements of type χ.

The objective of the system is to define a layout describing the allocation of pieces on plates of leather. On a topdown view the UI agent receives information about the leather pieces and the moulds to be cut and requests the OS to find a minimal cost layout while sending to it a description of the initial state of the plate and of the moulds to be allocated on it. Plate and moulds as well as the final layout are each represented by polygons.

OS Subsystem

This subsystem is responsible for the layout production: it allocates pieces, represented by polygons, on the plates, that represent the leather to be cut.

The pieces received by the OS are represented through a closed polygonal line, which is represented through a set of vertices - vertices are pairs (2-tuples) of coordinates:

```
PolyLine = Set of Vertice
Vertice = (Real,Real)
```

For each piece that OS receives from the UI, it generates a set of polygons defining the possible rotations for the allocation on the piece. The polygons are 3-tuples describing the polygonal line of the original piece, a **PieceId**, associating each polygon to the piece it was generated from, and a rotation angle.

```
Polygon = (PolyLine,PieceId,Angle)
```

For every polygon allocated on the plate the OS defines an entity stating the polygon and the position of allocation.

```
DrawnPolygon = (Polygon,Position)
Position = (Real,Real)
```

The first step taken by the OS is the generation of a set of polygons from the set of pieces received from the UI agent.

The task of layout design is accomplished by an algorithm adapted from the A* algorithm described by Nillson (1984). Each step of this algorithm takes a state, describing the set of polygons drawn on the plate, and creates a set of successors for it, each one with a new polygon inserted. This procedure generates a tree where the leafs represent the most recently drawn polygons. Every branch in this tree represents a possible layout for the task. In each step a minimal cost function selects a branch of the tree where a new polygon must be added.

As mentioned before a state is represented by a set of (drawn) polygons:

```
State = Set of DrawnPolygon
```

An important concept for the algorithm is the set of polygons to be drawn. At each step there will be a different set of polygons to be inserted and every time a polygon is drawn, The polygon itself together with all of the other polygons with the same **PieceId** must be excluded from the original set. We will use a **Universe** to designate the set of polygons to be drawn:

```
Universe = Set of Polygon
```

The A* uses the following procedures:

- **class** that defines the set of all polygons with the same **PieceId**.

```
class::(p:Polygon,u:Universe) -> Set of Polygon =
{ x ∈ u : PieceId(x) = p }
```

- **put** that inserts a new polygon in a given state

```
put:: (s::State,p::Polygon) -> State
```

- **create** that creates the successors of a given state

```
create:: (u:Universe,s:State) -> Set of State =
{ put(s,x) : x ∈ Un(u,s) }
```

- **Un** that states the set of polygons to be inserted

```
Un:: (u:Universe,s:State) -> Universe =
```

$u - \bigcup\{\text{class}(\text{Polygon}(x)):x \in s\}$

- **minState** that returns a state with minimal cost associated

```
minState:: (O:Set of State) -> State =
oneOf({x ∈ O : f(x) = f Min(O)})
```

Where **oneOf** selects an element from a set and **fMin** obtains the minimal of the costs of all states in a set.

- **layout** that produces a layout given a plate (defined by a **Polyline**, an initial state, and the universe of polygons to be allocated.

```
layout:: (p:Polyline,initial:State,u:Universe) -> State
createLayout(create(initial),0) -> state
```

where **createLayout** generates the searching tree:

```
createLayout::(open::Set of State, u::Universe) -> State
if create(minState(open)) = 0 then open
else createLayout(newopen, u-class(minstate(open)))
where newopen = (open-minstate(open)) ∪ create(minState(open))
```

In the definitions above, $x \cup y$ and $x - y$ denote respectively the union and difference of the sets x and y, and $\cup^X$ denotes the union of the sets that are elements of X.

UI Subsystem

This subsystem realizes the transformation of user-oriented structures to the OS-oriented structures. The UI agent will receive from other agents the following structured information (Negreiros, 1993):

Leather Plate: an abstract representation of a two-dimensional bounded region, possibly generated by a CAD system. From a Leather Plate two subclasses of objects can be generated. These subclasses are:

Graded Leather Plate: contains additional attributes such as texture, thickness and boundary.

Defective Leather Plate: represents a leather plate that encloses a defect.

Mould: an abstract two-dimensional region with the following attributes: identification of the piece, required material quality, directional properties, allowable cutting plate regions.

Following interrelationships can be established and defined among the leather plate and mould objects:

Overlap: to detect overlap among moulds;

Direction: feasible set of cutting directions;

Identification: technical specification of a mould.

This object framework (model) described above is the essential core for modelling the cutting problem. The "model" is captured by the OS and the resulted cutting plan is returned to the UI. Since there are several different kinds of users involved in such a system, most of the objects described above need to have a dynamic behavior (Pinheiro-Pita e Camarinha-Matos, 1993).

Data Required from other Agents

Since all information necessary to the DOV must be first visualized by the user, we consider that the interaction between OS and other CIM agents, involved in any activity, is done through the UI agent. As pointed out by Alvarenga et al. (1993), the DOV interacts with the following manufacturing systems:

CAD: that provides information about shoe design (moulds, shape, dimensions, tolerances, etc.);

CAQC: that provides automatic vision inspection of leather plates (shapes, dimensions, texture and defects);

PPC: that provides information concerning type and volume of leather pieces, schedule, storage, state of the shop floor, etc., and

NC: to which the DOV provides the numerical control program to execute the actual cutting.

PEER Federated Information Management System

PEER is a federated object-oriented database management system (4^{th}, 7^{th}, 16^{th}, 17^{th}, 15^{th} references) that primarily supports the cooperation and information exchange among autonomous and heterogeneous agents. The PEER federated architecture consists of a network of tightly/loosely interrelated agents. Several concepts developed in PEER support the complex information management requirements of CIM application area. Concurrent engineering, where there is a team of cooperating experts each involved in a different CIM activity can be represented by a PEER network. Every such activity (such as design, planning, manufacturing and the optimization activities) constitutes one or more PEER agents. By definition, such agents are autonomous in their activities and decisions, heterogeneous in their information representation, but cooperate with each other and share and exchange information to reach the ultimate goal of the industry.

In the federated architecture of PEER, both the **information** and the **control** is distributed within the network. Namely, PEER can be characterized by: (1) there is no single global schema defined on the information shared among the agents, unlike many other distributed object-oriented database systems (such as in Kim et al. (1991)) that defines one global schema to support the entire network of database systems; (2) the interdependencies between two agents' information is established through interrelating their schemas (defined on the shared data); thus there is no need to store the data redundantly in different agents; (3) there is no central (global) control within the network. The functionality of the PEER federated system is supported by the specific architecture of each PEER agent and its PEER-**kernel**, and by the existence of the **community dictionary** within the network.

Architecture

Every PEER agent in the cooperation network contains several interrelated schemas (i.e. LOC, IMPs, EXPs and INT schemas described in Section 3.3). The PEER-**kernel** is itself a predefined schema that acts as a unifying super-structure to support the investigation of data, meta-data, and meta-meta-data of the PEER (Afsarmanesh et al., 1994a). It primarily supports the representation of multiple schemas, the information on the agent's involvement in the cooperation network and provides an environment to model the schema integration/derivation relationships. The meta-meta-data is the information that describes the meta-data (schema elements) of the database. Therefore, any component of a typical schema, such as types and maps, as well as the schema definitions themselves (being derived such as INT,or defined such as LOC), and their interrelationships are all systematically represented in the PEER-kernel. In specific, the PEER-kernel supports the following: (1) the co-existence of several schemas in one agent and representing them individually; (2) the representation of meta-meta-data to represent the defined/derived-schemas, defined/derived-types and defined/derived-maps; (3) the representation of information regarding other agents in the network by their network-id, network-address, and their export schemas shared within the community, and (4) the representation of detailed derivation specifications for derived types and derived maps through storing the information on their source-types and source-maps. The information represented by the PEER-kernel is vastly used, through the PEER interface tools, by database designers/developers to organize their information and create/modify their schemas in the PEER and by the distributed query processor of the agent.

The **community dictionary** is the "source of information" within the network and can be consulted at any time by other agents. Its function is to provide up-to-date information on all agents in the network. It contains the network addresses of the active agents and their current state. For every agent, it also stores its export schemas and the specific access rights and schema modification rights that the agent supports. The dictionary can also be used as the general store for other static information that concerns the entire community such as objects' name-tables. Although, in the architectural design of PEER the community dictionary is represented as a separate agent to be accessed when needed, any other agent in the community can keep local copies of all or parts of its information.

Information Model and Language

The PEER information base model and the PEER language has roots in the 3DIS (Afsarmanhesh and McLeod, 1989, Afsarmanesh et al., 1990) database model and the 3DIS/ISL language (Afsarmanesh et al., 1989, Bergman, 1992). The PEER data model is a binary-based object-oriented database model. Any identifiable piece of information is uniformly represented as objects. It represents atomic, composite, and type objects. Atomic objects are strings of characters, numbers, booleans, text, etc. usually referred to as 'values' in other systems. Composite objects are non-atomic entities and concepts of the application environments and can be decomposed into further objects. Mapping objects, usually referred to as 'attribute' in other documents, are a special kind of composite object. Mappings can be single-valued or multi-valued and represent both the descriptive characteristics of an object as well as its association with other objects. A type object is a structural specification of a group of atomic or composite objects. It denotes a collection of database objects called its members (instances). The PEER supports multiple inheritance; the subtype/supertype relationships defined among types form a Directed Acyclic Graph (DAG).

The information retrieval/manipulation language designed for PEER supports both the local access and modification of agents' information, and the remote access and sharing of information among agents. The retrieval of information is based on queries on binary relations among objects. The 'retrieval' of information is simply formulated as an ordered triple with: domain-object, mapping-object, and range-object, being its three elements, and in a typical query one or more of these elements is replaced by a '?'. The query: 'retrieve (engine-790, ?, ?)' retrieves all the attribute values of the object engine-790, as well as retrieving all other objects in the database that are related to it. For instance the 'designer' of engine-790 (e.g. ENG-C3) that is another object in the database is also returned as results, as follows: (Engine-790, has-designer, ENG-C3). A path expression -several mappings connected by dots can replace the mapping in a query- denotes indirect relationships between objects. For example, by the query

'retrieve (?, has-designer.experience-record.project-involved,"GL340")'

all engine objects will be retrieved that have a 'designer' object for which an 'experience-record' object has the 'project-involved' value "GL340".

PEER Integration Facility

The main principle behind the design of the integration facility is to preserve the agent's autonomy. Cooperating agents wish to share with other agents as much as possible a part of their information that they want to **release**, while there is always a part of the information that is **underdevelopment**, and the agents wish to keep it private. Another principle, is to decouple as much as possible the design decisions made by individual agents concerning their object organizations and object representations private to the agent. Typically, agents are developed and evolved independently of each other, but preexisting agents may decide to merge together in a bigger cooperation network. An example situation is the merging of preexisting hospitals into one chain of hospitals.

The integration facility presented in PEER is supported by a sophisticated schema integration mechanism and two user-friendly and powerful interface tools. The schema integration mechanism supports the re-classification of objects by a different organization (than their origin) through a specific set of type derivation operations, and the re-interpretation of relationships defined between objects through some map derivation operations (Afsarmanesh, 1993a). The approach of PEER is principally different than the other methodologies presented for distributed database integration since it provides an environment for cooperation and information integration where the main emphasis is on agent's autonomy and agent's heterogeneity of the represented information.

Schema Integration

For each PEER agent there is one schema that specifies the type structure of all objects stored locally. This schema is called the **local** schema (LOC). Derived from the local schema are one, or more, **export** schemas (EXPs) that each define a particular view on the local objects. Usually, an export schema contains only a part of the concepts (types and mappings) defined in the local schema. An export schema can be imported by other PEERs; that will be called **import** schema (IMP). Each PEER agent has one **integrated** schema (INT), which is derived from the local schema and the various imported schemas. The integrated schema provides a single uniform type structure defining all the objects that are accessible by this PEER, both locally and remote. Since the integrated schema is defined local to an agent, different PEERs may establish different correspondences between their schema and other agents' schemas, and thus there is no single global schema for the network.

The Schema Definition/Derivation Language (SDDL) of PEER (Afsarmanesh, 1993a) offers both a set of 'schema definition environments' and a number of 'type-derivation' and 'map-derivation' primitives that support the integration/derivation of different schemas within a agent. The type and map derivation primitives are defined formally by their operational semantics (Afsarmanesh, 1993a). The operational semantics is given in terms of rewriting rules that specify how a query in the context of a derived schema should be rewritten into queries that can be evaluated in the context of the defined schemas.

User Interface Tools

The **integration facility** introduces two user-friendly interface tools for data and meta-data manipulation in the cooperative environment. An interface tool SMT (Schema Manipulation Tool) is introduced to support the manipulation of the schema-definitions, schema-derivations, and schema-integrations within the network of agents. This is a necessary tool to support complex interrelated schemas defined among different agents since it automatically performs many syntactic and semantic consistency checks when the definition of one schema is modified in the agent. Another user-friendly tool DBT (Database Browsing Tool) is introduced t `ÿ ~ø |rt the user of the agent with browsing through both data and meta-data (schemas) accessible through the agent. The browsing tool replaces the need for an interface language by which the user of an agent can access both local and remote information, while hiding the physical distribution of the information.

Realization of OS agent and UI agent

The UI agent receives input from users describing the leather to be cut and the design of the pieces to be allocated on it. It should transform the abstract structures representing those entities into suitable ones for OS agent processing.

From those abstract structures the UI, defined on section 2.1.2, agent generates the structures to be passed to the OS agent:

- Mould generates Piece.

  A piece is a pair stating a closed polygonal line (PolyLine), defining the mould shape, and a type establishing that mould properties as material quality, cut directions, etc.

  `Piece = (PolyLine,Type)`

  The set of pieces will be used by the OS to generate a set of polygons (rotated pieces) to be drawn.

- Graded Leather generates Plate.

  A Graded Leather specifies a set of regions of leather with specific properties associated. UIS uses objects of this class to generate the plates it will pass to the OS for the layout process. A plate is described by a polygonal line and an associated type specifying properties.

  `Plate = (PolyLine,Type)`

The UI will provide the OS with the plates and pieces to be allocated with coincident types.

Object instances of these classes have a visual representation in the UI system. In order to provide a core of visual interactive facilities we need to define classes like: window, icon, mouse, pulldown menu and browser, which are common in modern graphical user interfaces.

Conclusions

We have introduced an approach to the integration of an optimization expert system within a CIM distributed database system. This approach is achieved by representing and modelling the optimization system by two agents that can be integrated with other CIM activities within a federated architecture.

Formal description of the DSS-VIM cutting optimization system is presented. A description of certain features of PEER that support the requirements of integrating CIM activities is provided. Using PEER as a framework for the integration, a federated architecture is achieved which supports the sharing and exchange of informaiton among autonomous and heterogeneous CIM activities presented as individual agents. The federated architecture described here opens a wide range of possibilities for also the integration of other agents within a CIM distributed database system.

This paper describes the first phase of the research cooperation between the University of Amsterdam and Universidade Federal do Espirito Santo.

Resumo

Este trabalho apresenta uma abordagem para a integração de um sistema de otimização com outras atividades de CIM usando uma arquitetura de banco de dados distribuída. O ambiente de aplicação para CIM descrito aqui é para a indústria de sapatos e bolsas e o sistema de otimização é utilizado para corte de leiaute de formas irregulares em uma base de couro. Aqui o sistema de otimização é especificado pela completa separação entre a interface com o usuário dos aspectos de otimização, sendo defmidos como dois agentes distintos. A integração das atividades separadas através de um sistema de banco de dados distribuído para CIM é obtido pelo uso de um sistema Gerenciador de Banco de Dados Federado e Orientado por Objetos. A arquitetura federada utilizada suporta a cooperação e troca de informações entre agentes autônomos e heterogêneos.

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Graphical Interfaces Supported on Objects with Dynamic Behavior - An Application in Visual Interactive Modeling

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Abstract

The design of graphical interfaces supported on objects with dynamic behavior is introduced in the context of Visual Interactive Modeling for CIM decision support systems.
This paper starts with a presentation of the Dynamic Behavior concept. After that, it presents a brief description of the use of this concept in the design of intelligent graphical interfaces. The paper is concluded with the presentation of an application to the leather cutting problem where this concept is being tested.
Keywords: Graphical Interfaces, Visual Interactive Modeling, Dynamic Behavior, CIM

Introduction

The Visual Interactive Modeling - VIM - techniques can be seen as a combination of friendly interactive interfaces with computer generated models (mathematics and symbolic), as well as, with processes that help the user to make decisions (Bell, 1991).

From one side there is the visualization as an important characteristic of the modeling environment because it supports users of an expert system in:

- acquiring new understanding of the dimensioning of their problems and to enable the automatic generation of different views of such problems, and
- exploring the user visual ability for recognizing important alternatives and/or strategies during the process of achieving the problem's solution.

A major aspect in this scenario is the interactivity. In our days the idea of considering a human as an integrating component of a complex computer assisted system has been increasing. It is accepted that to assure the economic viability and safety of advanced manufacturing systems, it is necessary to understand and give "opportunity" to the roles the human can perform in such systems (Rouse and Cody, 1991). Some international projects have been studying this problem, namely, the European project ESPRIT 1217 - Anthropocentric CIM Systems - which states that "a CIM system is more efficient, cheaper, more robust and more flexible if there are people directly responsible instead of a similar system without people".

Comparing the ability of people and computers it is obvious that a human is less efficient in performing tasks that require systematic activities like continuous attention, repetitive actions, consistency checking, inspection of many variables, etc. But these tasks can be easily computerized. However, the human beings are more efficient than computers in other tasks because of their capacity to deal with unknown situations, to handle complex quality criteria (like texture, visual attributes, and so on), making decisions with incomplete information, use their creativity, etc. The systems that try to computerize these actions have a tendency to be expensive and insecure (Hamlin, 1990). It seems that there is a need for an anthropocentric CIM system where human beings and computers work together to achieve better levels of fulfillment than the levels achieved by the users or by the computers

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working alone. In other words, there is a need for creating a cooperation environment where the human performs the tasks where he is more effcient and the computer the tasks for which the user has more difficulties. One of the main conditions to concretize such environment is related to human factors, i.e., in what way the user can be integrated. The concept of human factor is, normally, related to the interface man-machine. In the current context there are two approaches for the development of an interface: an instrumental approach that looks to the user as a spectator and an organizational approach that looks to the human being as a fundamental part of the whole system (Kovács and Moniz, 1990). But, what kind of characteristics should an interface have that valorize the human factor? The user hopes are: consistency, simplicity (easy to leam, easy to use) and efficiency. An interface for an interactive system should enable the user to drive the interaction with simplicity and flexibility, should reduce the need of commands' memorization, and take care of all dialogue consistency. This interface should avoid, as much as it can, the possibilities of mistakes and, when they happen, should provide an easy way to recover from them.

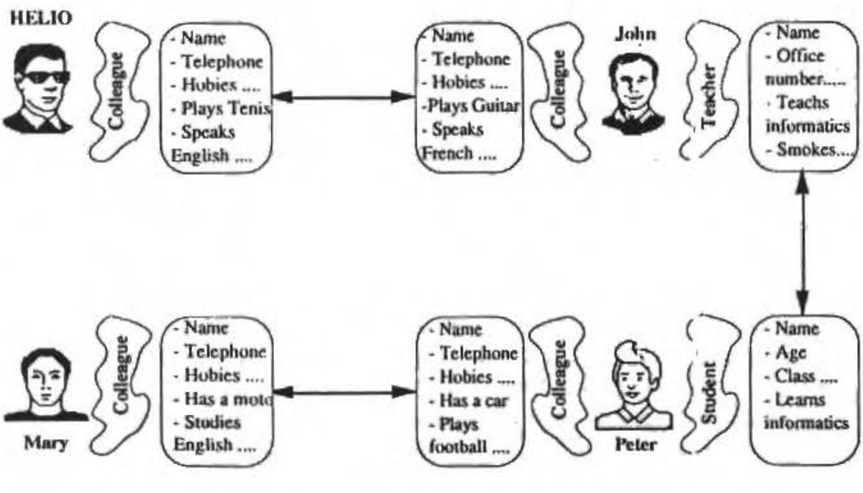

Fig. 1 Dialogue among people and played roles

A proper arrangement of the visualization and interactivity features may enable an effective cooperation between the user and the system. The user can, in an incremental way, build, change, complete and test his models. On the other hand, the expert system should have the capacity of complementing the user activity providing:

- A mechanism that operates over functional relations (formulas) dynamically introduced by the user among the different components of the model, making the appropriated calculations. This assures the consistency of the model at any stage, promoting the incremental development and enabling a kind of "what if" analysis;
- A mechanism that supports the introduction of semantic information into the model using constraints to dynamically specify the user preferences (visual optimization), and
- A mechanism that controls the structural consistency when the user applies modeling primitives to specify the relationships among the model components.

This paper shows how the concept of objects with dynamic behavior can be used to fulfill the requirements of an interface with such characteristics. Finally, we describe the environment where such graphical interface is being tested in the leather cutting application domain.

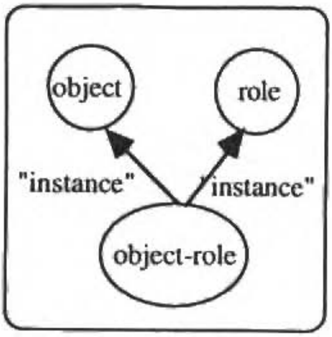

Fig. 2 An object role

Objects with Dynamic Behavior

Lets now introduce the UNL's approach to object's dynamic model, making an analogy with the world of people. We can admit that every person in a society play various roles. Persons are teachers, students, chiefs, workers, parents, sons, and so on. From other side, when a dialog is established between two persons, each one playing a specific role, the "access" one has to the information of his interlocutor (including the actions he can perform) is a function of the status he has regarding the role he is assuming. For instance, John assuming the role of teacher, can, obviously, evaluate Peter, assuming the role of student, but it is not so obvious that he can evaluate Helio assuming the role of his colleague. Using a simplistic view of the society, we can conclude that when a person communicates assuming a role, the information, as well as the functionalities that he makes available, are a function of the status of his interlocutor. We call this sub-set of information and functionalities a view of the role. Figure 1 shows an example of people's communication. Dynamic Behavior is, therefore, the facility that a person has to make different sub-sets of data/functions available as a function both of the role he is playing and of the status of his interlocutor.

Taking these ideas into account, lets consider the objects' world. Under the Object Oriented Paradigm an object has a behavior defined by the set of methods that compose its interface. Sometimes, when an application is developed using that methodology, the objects are, at the same time, instances of multiple concepts. This is particularly important when we are using a frame oriented approach, where multiple relationships among objects with different inheritance rules can be defined. Using this mechanism the programmer defines a structural behavior of an object. Making an analogy with the concepts introduced for the people's world, we can imagine a system where the objects also play roles. In addition, we can also imagine that during the execution of an application only a sub-set of the inherited data/methods of an object is relevant in that context, taking into account some status variables, while in other context a different subset will be relevant.

An algorithm that supplies a base to support objects with dynamic behavior was developed by UNL's team and is introduced in the next paragraph.

Lets suppose that in an application we have defined a set of objects that can dialogue with other objects - Interactive Objects - and a set of auxiliary objects that model the roles an Interactive Object can play - Interlocutors. When someone wants to dialogue with an interactive object assuming some role, a new entity is created as an instance of both this object and the interlocutor that models the desired role (Fig. 2). We call this new entity Object-Role (OR). However, only a subset of the inherited attributes will be available for the dialogue as a function of the status of the object that has started the communication. Therefore, a view of that new entity will be created. We call that view, - Object-View (OV).

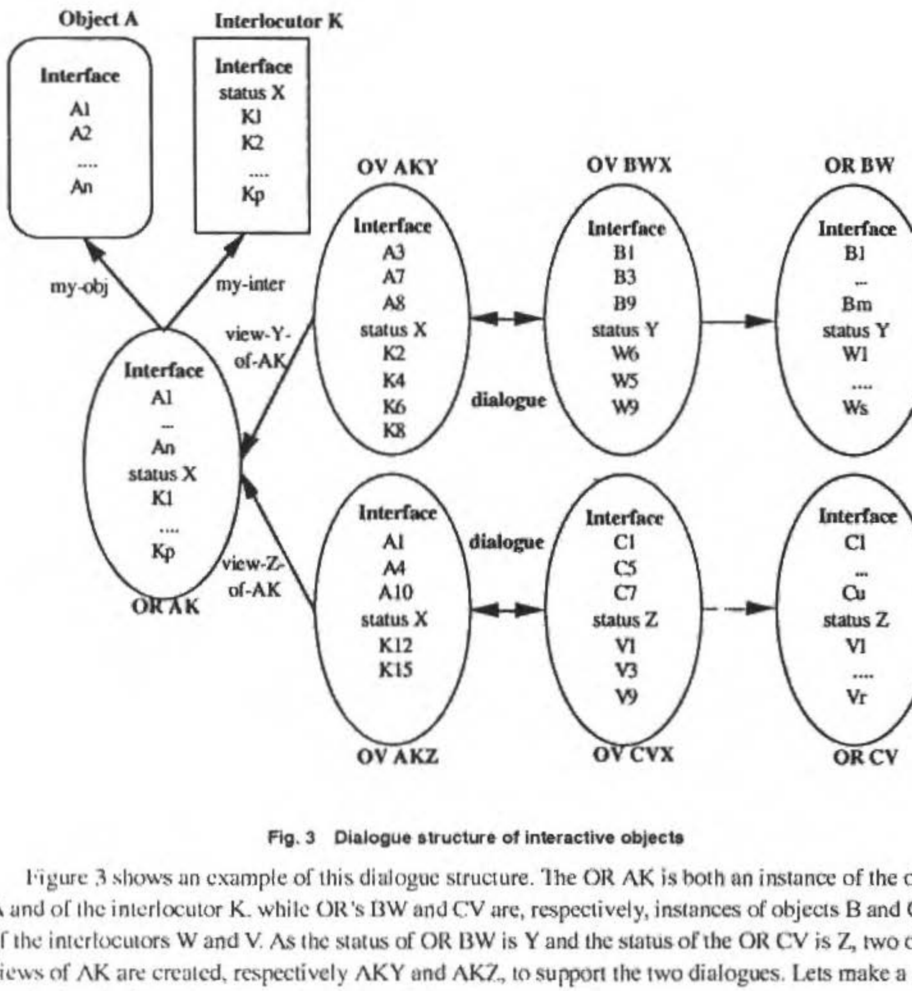

Fig. 3 Dialogue structure of interactive objects

Figure 3 shows an example of this dialogue structure. The OR AK is both an instance of the object A and of the interlocutor K. while OR's BW and CV are, respectively, instances of objects B and C and of the interlocutors W and V. As the status of OR BW is Y and the status of the OR CV is Z, two object views of AK are created, respectively AKY and AKZ, to support the two dialogues. Lets make a more detailed analysis on how the OV's AKY and BWX were created:

1) The OR BW sends a message to the Interactive Object A saying it wants to dialogue with A playing the role K and it also informs A about its status - (do :interlocutor K :my-status is Y);
2) The object A sends to interlocutor K a message asking it to create an OR for the status Y-(start-OR :status-is Y);
3) The Interlocutor K starts a set of actions:

3.1)if an OR AK does not exist, it is created;

3.2)if an OV AKY does not exist, the relation View-Y-of-AK is created; an inheritance rule from OR AK specifies only the attributes/methods that are available for status Y;

3.3)if the OV AKY does not exist it is created;

3.4)the interlocutor K returns to object A the name of the created view and its status;

4) The object A sends a message to OR BW containing the name of the created OV and its status - (Done:view-name OV-AKY:mystatus X), and

5) If an appropriate view does not exist then steps 3.1 to 3-3 will be performed at OR BW.

Application of Dynamic Behavior in the Design of Graphical Interfaces

An important application of this algorithm is in the management of flexible user interfaces. The problem can be simplified if we assume the dialogue is always started by the human expert. Therefore, the interactive objects are internal entities that can dialogue with an expert through different kind of interaction forms (different roles).

Another important aspect that appears as a result of the mentioned simplification is that is only makes sense to talk about status at the user side and, this status is always related to the different kinds of users supported by the system.

```
{{ INTER-OBJECT   ; Interactive Object
   do-interlocutor-map:
        ((desk DESKTOP) (edit EDITOR)
         ..................................................
         (browse TREE-BROWSER)
        )
   Do-Function-Map ((...))
   AskFor-drivers-Map:
        ((Object-Menu   Get-Object-Menu)
         (Window-title   Get-Window-title)
         ..................................................
         (Tree-Information  Get-Tree-Information)
        )
   Display-Information-Map:
        ((0 (......)) (1 (.......) (2 (.......))
   Object-Menu-Map:
        ((0 (......)) (1 (.......) (2 (.......))
   is-delegated-of:
   Do-Delegated-Map:
   Description:
;METHODS
   Do-Option:    Object-Do-Option-mt
   AskFor:       Object-AskFor-mt
}}
```

Fig. 4 Interactive object - general concept

Some experiments were made to test the efficiency of this concept in the development of graphical interfaces for CIM systems. Taking these experiments as the base, in the next points a brief description of the interactive object concept, interlocutor concept, implementation platform, as well as, a more detailed description of the algorithm will be introduced.

Interactive Object

Lets suppose that is a knowledge base all objects have dynamic behavior, i. e., they are able to dialogue with an authorized user, through different kinds of interaction forms and exporting to the dialogue a set of different menu options, based on the user status. The interactive objects can be simple objects (like an activity, an application domain, etc.) or they can be collections of simple objects (like taxonomies, lists, etc.). Figure 4 illustrates a possible model of an interactive object. Only the attributes that take part in the interaction are shown. The attribute Object-Menu-Map has, for each level of interaction (3 in the example) the menu options that can be fired over the object. These options can be used to start new forms of interaction. In this case, the slot Do-Interlocutor-Map is consulted to make the correspondence between the key associated to the option and the respective interlocutor - or to start actions over the object itself - in this case the content of the slot Do-Function-MAP indicates the function that is associated to the option key.

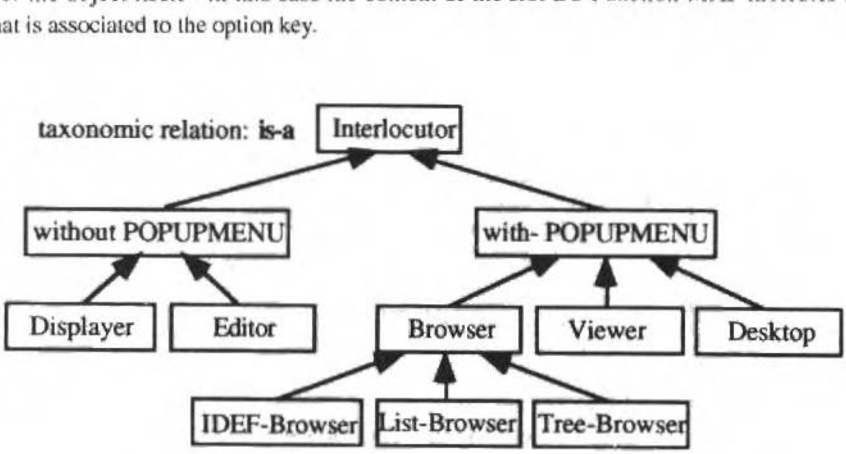

Fig. 5 Taxonomy of interlocutors

Sometimes it is useful that a simple object exports to the interface an option that is not directly related to its behavior, i.e., not directly executed by itself, but it is related to the behavior of the collection of objects to which it belongs. For instance, an object like an activity that belongs to a taxonomy can show on its menu the option TREE-BROWSE that is a typical option offered by a taxonomy. For these cases, delegation mechanism was implemented.

The attributes Do-Delegated-Map and Is-Delegated-Of give, for each object, the delegated options and their executor. In the example, the executor is the Taxonomy of Activities and as a result of this option a Tree-Browser interaction form is launched showing a taxonomy of activities whose root is the activity that receives the option.The method Do-Option is used to start the creation of an object-role as well as the respective view for the current user status. On other hand, the method AskFor and the slot Ask-For-Drivers-Map is used by an object-role to ask all information needed for the interaction form. For example, all interaction forms need a name. Therefore, the method AskFor will return this name if it is fired with the parameter Window-Title.

Interlocutors

Interlocutors are the roles an interactive object can play. There is one interlocutor for each type of interaction form available on the graphical interface. Figure 5 illustrates an example of a taxonomy of interlocutors. This taxonomy has two main parts: the interlocutors that have POP-UP-MENU, used by collections of objects, enabling the communication with the objects displayed inside the interaction form and, the interlocutors without POP-UP-MENU, used by simple objects.

Figure 6 illustrates the general aspect of an interaction form Tree-browser displaying a sub taxonomy of activities and an example of an activity's internal structure. Inside the interaction form there are some other objects - Internal Objects - that belong to such taxonomy.

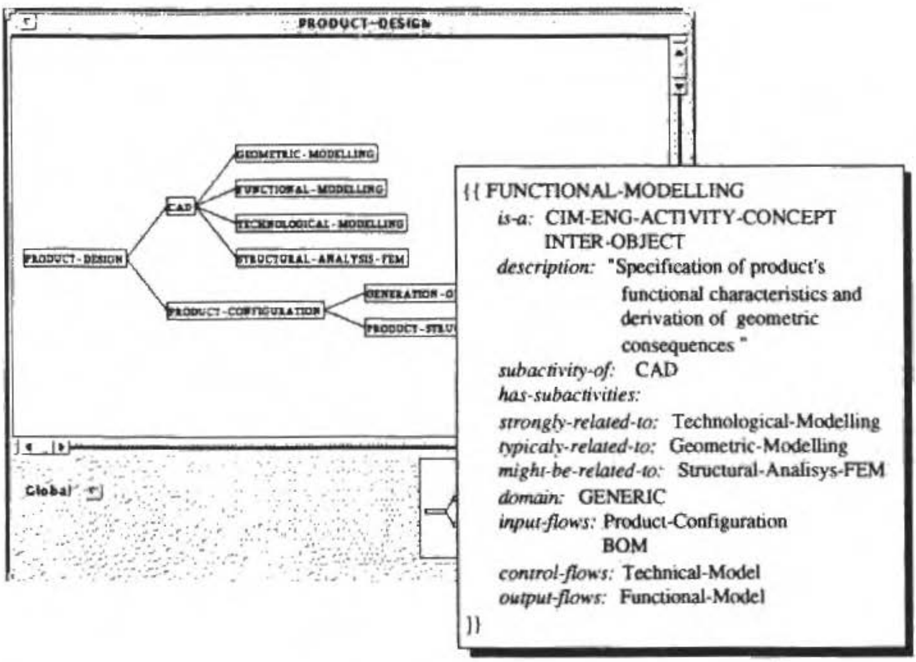

Fig. 6 General aspect of a tree-browser

Figure 7 shows a model for the general concept of interlocutor. When an object receives a message to start a new interaction form, i.e., to play a specific role, it sends the message Inter-New to the respective interlocutor. This method creates an object-role (including the view for the current status) and fires the method Inter-Start over the new object-role that will create the respective interaction form. After that, using the method AskFor, the object is inquired about the information needed to fulfill the different parts of the interaction form. The object replies through the created object-role's method Send-Spec-Information, that sends the information to the interaction form. The attribute Type-Of-Graphic-Object contains the keyword that specifies the kind of interaction form, while in the attribute GraphicsObject the identifier of that interaction form is saved. The attributes A-Option-Map and C-Option-Map specify the different options the interlocutor exports to the dialogue. The A-Option-Map contains options for the global menu, while the C-Option-Map, that only makes sense for interlocutors with POP-UP-MENU, contains options to be associated to the menu of the internal objects displayed inside the interaction form.

```
{{INTERLOCUTOR
   GraphicsObject:
   Type-of-Graphics-Object:
   A-Option-Map: ((0 (...))(1 (....)) (2(....)))
   B-Option-Map:
   C-Option-Map: ((0 (...))(1 (....)) (2(....)))
;Methods
   Send-Spec-Information: Send-Specific-Info-mt
   Inter-New:             Inter-new-mt
   Inter-Start:           Inter-Start-mt
   Inter-End:             Inter-End-mt
}}
```

Fig. 7 Interlocutor - general concept

When an object receives a message to finish an interaction form it will send the message Inter-End to the interlocutor that deletes the associated object-role and sends a message to the graphical interface for removing the associated interaction form.

User Levels

During an interaction session different levels of users can exist but not at the same time. Therefore, the current level is saved on the slot Current-User-Level of the Environment Object and it can be changed using a password. This implies that each time an action of refresh is required as well as when the object-role has to send a menu to the interaction form, the slot current-user-level should be checked and if it has changed the object-role and the interaction form information are updated.

Another important aspect is how the user levels are organized. The levels form a hierarchy, i.e., all the options available at level 0 are also available at levels 1 and 2 and the specific options of level 1 can be used by the level 2.

Implementation Platform

The implementation of this Graphical Interface framework has two main parts:

1) Objects Management - that handles all aspects related to interactve objects, interlocutor, object-roles - was developed using Common Representation Language of Knowledge Craft system;

2) Graphical Interface Management - that handles the graphical representations - was developed in C, using the Sun Open Windows library;

Figure 8 illustrates the flow of information between these parts. All communications between the Objects Management part and the Graphical Interface Management part is done using two functions: XCOMMAND and XEVENT. The first function is used to send information from the Object

Management part to the Graphical Interface Management part and XEVENT in the other direction. Each of these functions has a set of keywords that specify the type of action to be performed. For the XCOMMAND function, 5 keywords are available:

INITGRAPHICS: starts Graphical Interface Management;

NEWOBJECT: is used when a new interaction form is required;

NEWITEM: is used to send the internal information of an interaction form;

DISPLAYOBJECT: activates the display of a new interaction form;

DESTROYOBJECT: removes an interaction focm;

XEVENT function has four keywords:

SELECT: indicates that an internal object of an interaction form was selected. Associated with this option, the name of the object is indicated too. When this keyword is received by an object-role, the method AskFor of the object selected inside the interaction form is activated asking for Object-Menu. After that, a POP-UP-MENU, composed by the Interlocutor C options (for the current user level) and the result of the execution of AskFoc method, is displayed and the system waits until an option is selected by the user. Finally, if the opton belongs to the Object-Menu, the message Do-Option will be sent to the object; otherwise the object-role executes the adequate action.

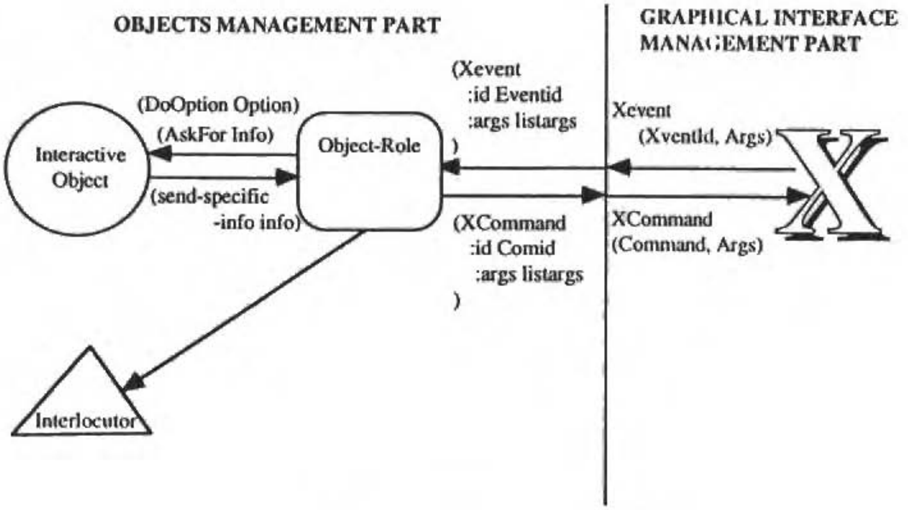

Fig. 8 Flow information on the interface

MENU: indicates that an option of the global menu was selected. When this option is received by the object-role, it verifies if the option belongs to the Object-Menu. In this case the message Do-Option is sent to the object, otherwise the object-role executes the adequate action.

BUTTON: indicates that the user has selected a button of the interaction form. The action associated to the button is performed by the object-role. Typical buttons are: close, iconify, etc.

DRAG: indicates that an internal object displayed inside an interaction form was dragged to another position. In this case the new position is sent to the object, and all information at the interaction form is updated.

Lets see an example. Lets suppose that an internal object was selected on a TREE-BROWSER interaction form. The next steps are performed:

1) the associated object role receives a XEVENT with the keyword SELECTED and the name of the internal selected object - object-x, for instance;
2) the object role sends a message AskFor with the keyword Object-Menu to the object-x; after receiving an answer and composing the POP-UP-MENU for the current user level, it sends a XCOMMAND to the Graphical Interface Management part with the keyword NEWITEM and the flag WITH-WAIT a T. The answer to the execution of this XCOMMAND is the selected POP-UP-MENU option. Lets suppose the user has chosen the EDIT option, that means he wants to dialogue with the internal object through an Editor interaction form;
3) the object role, as the option belongs to the Object-Menu, activates the object's method Do-Option;
4) using the Do-interlocutor-map slot's values, the object finds the associated form of interaction and sends the message Inter-New to the appropriated interlocutor (editor in this case);
5) the method Inter-New creates the respective object-role and activates the method Inter-Start;
6) the method Inter-start asks to object-x all information required to fulfill the different parts of the interaction form like Window-Name, internal information, Menu Options and, using XCOMMAND function, creates and activates the new interaction form.

The Leather Cutting Application

The UFES team is working on the development of an intelligent graphical interface for a leather cutting process.

The leather cutting is an open class problem where:

- the boundaries of the problem are not clearly stated;
- there are no strict rules to characterize the boundaries, and
- there are more than one objective which can be conflicting.

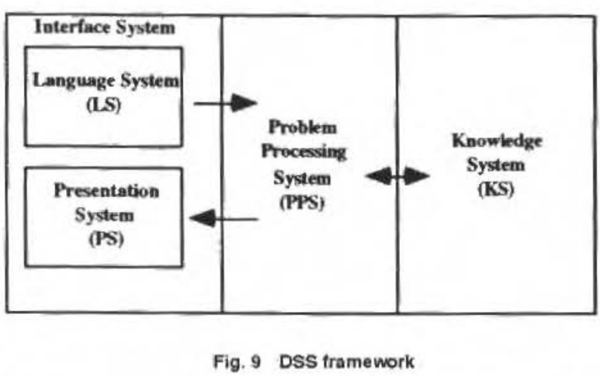

Fig. 9 DSS framework

In the solution of open problems, one often applies non-visual modeling techniques that require the modeler to try to specify a closed problem that approximates, as closely as possible, the open problem. Solving a closed problem (well-defined boundaries and objectives) is usually trivial; but such techniques do not help in the process of defining the closed problem from the open one. This can be thought as a representation gap. An approach to reduce this 'gap' is to use the framework for design Decision Support System (DSS), which suggests that a DSS should have three subsystems: an user Interface System (IS), a Knowledge System (KS) and a Problem Processing System (PPS). This framework is represented in Fig. 9.

The KS contains the knowledge about the problem domain, i.e., data models and algorithms, rule sets, forms, templates, etc. The PPS is a processor that is capable of accepting problems stated in the Interface System and manipulating knowledge in the KS to generate appropriate responses to the decision making process. The LS includes all the linguistic facilities made available to a decision making process by a DSS. The responses from the PPS to the user are the means by which the DSS communicates with the user and are referred to as the Presentation System (PS). Like the LS, the PS is a system of representation. Together, the LS and PS characterize the user interface. If a DSS is to be used by many different users for different tasks, its interface must be easily adaptable. In this way, the dynamic behavior concept is being tested for the implementation of the adaptive interfaces.

Characterization of the Objects to be Visualized

The classes of objects to be identified and visualized in such environment, in the context of the leather cutting problem are:

- Leather Piece: Based on an appropriate input device (camera, scanner, etc.), that captures the geometry of the piece, we define the 'leather piece class' by an abstract representation of a two-dimensional bounded region.

Associated to the 'leather piece class' we define the following derived classes:

- Graded Leather Piece: From the technical point of view, it is well known that in a piece of leather there exists a classification (1st, 2nd, 3rd and 4th) in sub-regions based on the quality of the material.

The derived class, 'Graded Leather Piece' should therefore contain additional attributes such as texture, thickness and boundary type. A partition operator may be defined on a leather piece object in order to generate, based on a quality criteria, new objects of this class.

- Defective Leather Piece: A sub-region of the leather piece that encloses a defect such as a stain, hole, scratch, etc.

A Defect operator may be defined mapping the leather piece class into objects of this derived class.

- Mould: An abstract two-dimensional region with additional attributes that identifies the pieces will be produced by the layout, the quality of the material required for its manufacture, the directional properties as well as other additional details.

Analyzing the classes 'leather piece' and 'mould', in the sense of establishing a dialog between objects of those classes the following operators are defined:

- Overlap: its purpose is to detect an overlap between the moulds over the layout generated by the system on the leather piece;
- Direction: to inform a 'mould' object of the feasible set of directions for realizing the layout on the leather piece, and
- Identification: based on its technical specification it is identified whether a mould object may be manufactured from a given 'graded leather piece' or not;

After the execution of the cutting process the production line needs to establish the seheduling of operations to be realized in the final product. In this sense, the representation and manipulation of the mould objects that belong to a given final product are better expressed using an abstract graph object. In this graph, nodes represent the mould objects, and the arcs establish the relationship between moulds with common boundaries.

The job scheduling, using this representation, is implicitly given by the order of the nodes in the graph.

Desired Interaction Model

The solution space must be represented by pictures. This provides for an open-problem methodology as long as the pictures could be easily redesigned. It would be wise to provide a 'core' of visual interactive facilities, which can be used to build any visual interactive model. Examples of these facilities include windows, icons, menus, tables, variables, etc. Extensions of these facilities can be provided for the particular application domain (leather cutting).

The user should deal with a modeling system which combines WIMP-style (Windows, Icon, Mouse, Pull-down menus) workstation capabilities with extension of conventional optimization algorithms. These combinations allow the end user to explore a model from several perspectives within an animated display.

For the initial implementation, the set of objectives include:

1) accessibility by end users, without technical intermediaries ;
2) flexible user interaction, allowing incremental development, exploration and editing of a cutting plan, and
3) fluent and strongly graphical presentation of the results.

The Interface

The system combines the functionality of spreadsheets and optimization algorithms with the graphical presentation of the results. The interaction method is through a WIMPB (windows, icon, mouse, pull-down menus and browser) interface. Control over the evolution of an interactive section can be almost entirely mouse-driven, and even the entry/amendment of numerical values can be largely achieved by using the mouse in conjunction with an analog display of variable value.

The end-users could operate with a number of defined models which may be used with different data at different times. After loading a model, the user can edit it in a number of ways. For example:

a) by clicking the mouse on an action and selecting the target figure (piece) and putting it over the sheet (leather) to perform the desired action.
b) use a non-visual modeling language to define variables, constraints and parameters, and
c) filling-up dialog boxes which are linked to defined models.

To create a new model, a definition facility translates the user input (in the form of a collection of visual language and algebraic expressions) into on internal representation of the system. Also the user is provided with the ability to incorporate heuristic rules appropriate for model-based reasoning procedures.

The desired model interface should have four regions:

1) Graphic Objects Menu: this is composed by visual objects (Icons) which can be selected by the user to execute a desired action;

2) Working Area: user area reserved to the problem selection, interaction and solution presentation;

3) Actions Menu: it displays the provided built-in operations (Methods) that can be applied to a previously selected object, and

4) Status Line: this area is reserved to display warning/error messages, the current process status, environment state and so on.

Classes of Users

The leather cutting system has four class of users:

- Design expert: this kind of user is responsible, for instance, for the shoe design model definition. He prepares the pieces to be cut, the piece region possible allocations, precedence constraints, the tolerance parameters for the piece/plate placement;
- Planner: this is the end user of the system. He is responsible for obtaining an 'optimal' cutting plan to the specific model. Leather piece image acquisition and cutting plan generation;
- Administrator: this user performs the system maintenance action such as: user definition, models catalog, knowledge base updates, product order, and
- Client: this user can see a model solution. He is provided with the appropriate sequence of cutting steps within an order and its visualization.

Conclusions

The concept of objects with Dynamic Behavior seems to be appropriated for the development of leather cutting tool's user interface. This appropriateness becomes quite evident if we compare the description of leather cutting environment made in section 4 with the description of the approach made in section 3. Therefore the bilateral activity between UNL and UFES pursuing the merging of the two approaches for the leather cutting problem. The first phase of the project required the achievement of a mutual understanding of the approaches and the definition of a common glossary. Current state addresses the implementation of a demonstration prototype. This approach was successfully applied in other CIM related prototypes (CIM-CASE (Camarinha-Matos and Pinheiro-Pita, 1993) and CIM-FACE (Camarinha-Matos, 1994)) developed at UNL but the development environment, based on Knowledge Craft, is quite heavy. One of the tasks in this joint activity is, therefore, the migration of the original prototype to a "lighter" development system.

Acknowledgments

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References

Bell, P., 1991, "Visual Interactive Modelling: the Past, the Present, and the Prospects", in European Journal of Operation Research 54, pp. 274-286.

Rouse, W., and Cody, W., 1991, "The Human Factors of Systems Design: Understanding and Enhancing the Role of Human Factors Engineering", in International Journal of Human Factors in Manufacturing 1, pp. 87-104.

Hamlin, M., 1990, in "Sistemas Integrados de Produção - Uma Abordagem Antropocêntrica", C. I. e Desenvolvimento, Eds. Lisboa, vol.1, pp.10-18.

Kovács, I., and Moniz, A. B, 1990, in "Sistemas Integrados de Produção - Uma Abordagem Antropocêntrica", C. I. e Desenvolvimento, Eds. Lisboa, vol.1, pp. 20-36.

Camarinha-Matos, L., Pinheiro-Pita, H., 1993, "Interactive Planning in CIM-CASE, R. W. & L.", O'Conners, Eds., IEEE International Conference on Robotics and Automation (IEEE Computer Society Press, Atlanta, Georgia, EUA), vol. 3, pp. 63-70.

Camarinha-Matos, L., 1994, "An Integrated Platform for Concurrent Engineeging", M. Tavaress, Eds., III Workshop of Cimis.net - Distributed Information Systems for CIM (GRUCON, Florianópolis, 1994), pp. 25-34.

Pinheiro-Pita, H., and Camarinha-Matos, L., 1993. "Comportamento de Objectos Activos na Interface Gráfica do Sistema CIM-CASE", 4ªs Jornadas Nacionais de Projecto, Planejamento e Produção Assistidos por Computador (Ordem dos Engenheiros, Lisboa, 1993), vol.1, pp.189-198.

Negreiros, F., 1992, "SAD's Inteligentes para Planejamento em Manufactura: uma Abordagem via Modelagem Visual Interativa", in Robótica e Automação 10, 91-93.

Alvarenga, A., and Negreiros, F., 1993, "The Irregular Cutting Stock Problem and its Application in Shoe Industry", Universidade Federal do Espirito Santo.

Negreiros, F., Alvarenga, A., Lorenzoni, L., Pinheiro-Pita, H. and Camarinha-Matos, L., "Objects Dynamic for Graphical Interfaces in VIM - An Application Case Study", in Studies in Informatics and Control Vol 3, n. 2-3 pp. 165-171.

Resumo

O projeto de interfaces gráficas suportado por objetos com comportamento dinâmico é introduzido no contexto de Modelagem Visual Interativa (Visual Interactive Modeling) para sistemas de suporte a decisão para CIM. Este trabalho inicia com a apresentação de conceitos de comportamento dinâmico. Após é apresentada uma breve descrição do uso destes conceitos no projeto de interfaces gráficas inteligentes. O trabalho é concluído com a apresentação de uma aplicação para o problema de corte de couro, onde esses conceitos estão sendo testados.

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An Integrated Platform for Concurrent Engineering

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Abstract

The requirements for a platform for Concurrent Engineering (CE) are discussed in parallel with an analysis of the evolution of integrated manufacturing systems and new organizational paradigms in industrial companies. CIM-FACE system is introduced as a prototype federated architecture for CE, addressing the aspects of modeling, information sharing and management, and engineering processes supervision. Cucrent status of developments and experimental results are discussed and open challenges pointed out.
Keywords: Concurrent Engineering, Integrated Manufacturing, Industrial Information, CIM

Introduction

Information based Integration

Information integration has been recognized, since long ago, as a basic requirement for the implantation of advanced manufacturing systems and for concurrent engineering in particular.

Integrated Manufacturing Systems are complex systems that can be analyzed from various perspectives, not limited to the technologic aspects - in their many facets - but including also organizational and social views. From a software engineering perspective, a CIM system can be seen as an integrated federation of multiple heterogeneous modules. The heterogeneity comes from a diversity of reasons, such as the use of different development and data management technologies, heterogeneous computational platforms and operating systems, and even from being based on different underlying "cultures" in terms of the target users. These software modules typically run in a distributed computational infrastructure and show a considerable degree of autonomy either because:

i) they were developed as stand alone or loosely integrated components, specially in the case of legacy systems; and
ii) the decision making process is, to a large extent, based on the humans that use such tools or on the characteristics/behavior of the machines being controlled, in spite of the increasing level of intelligence of computer aided tools.

A common Information System (IS) provides, therefore, a basic "glue" to support the integration of heterogeneous and distributed functional modules in an engineering and manufacturing environment.

Concurrent Engineering

The increasing globalization of the economy and openness of markets is imposing tough challenges to manufacturing companies, leading to the concept of lean/agile manufacturing. One of its manifestations is the recognition of the product, and thus product data, in its entire life cycle, as the main "focus of attention" in CIM IS.

Product Data Management is being considered an essential tool for tracking products from conception/design to retirement/recycling. The concept of Concurrent Engineering has become more and more popular in recent years as a result of the recognition of the need to integrate diversified expertises and to improve the flow of information among all "areas" involved in the product life cycle.

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Evolving from earlier attempts, represented by the paradigms of "Design for Assembly/Design for Manufacturing", Concurrent Engineering is consequence of the recognition that a product must be the result of many factors, including:

- Marketing and sales factors;
- Design factors;
- Production factors;
- Usage factors (intended functionalities / requirements), and
- Destruction/recycling factors.

On the other side, team work based on concurrent or simultaneous activities, potentially leads to a substantial reduction in the design-production cycle time, if compared to the traditional sequential "throw it over the wall" approach.

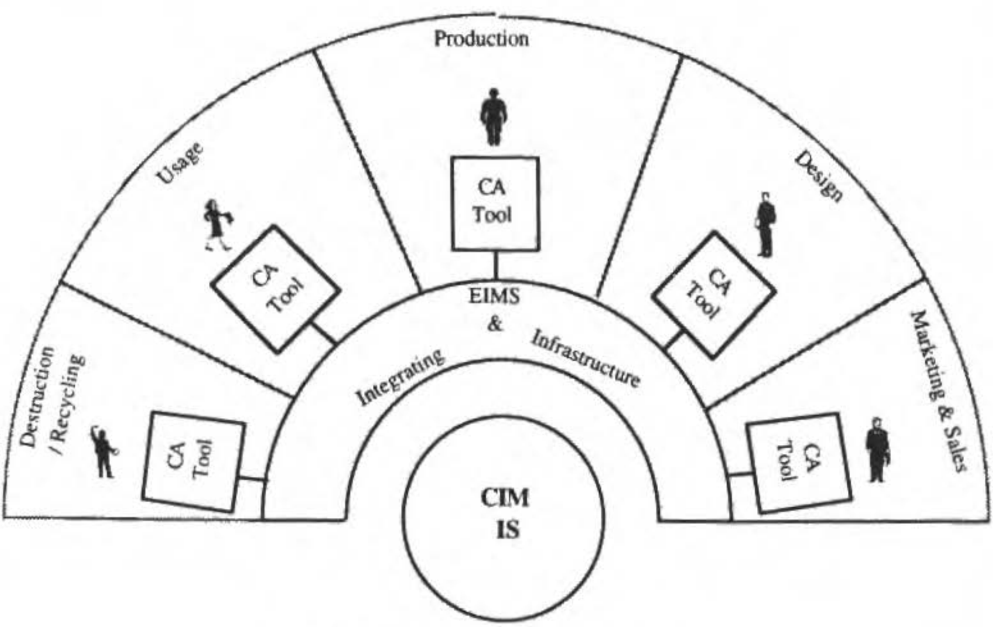

Fig. 1 A framework for concurrent engineering

New Organizational Structures

On the other side, observing companies' evolution in terms of organization, a strong paradigm shift towards team-based structures is becoming evident. Team work, as a practical approach to integrate contributions from different experts, is being extended to all activites and not only to the engineering areas.

Complementarily there is a tendency to establish partnership links between companies, namely between big companies and networks of components' suppliers. Similar agreements are being established between companies and universities.

This tendency creates new scenarios and technologic challenges, specially to Small and Medium Enterprises (SMEs). Under classical scenarios, these SMEs would have big difficulties - in terms of human and material resources - to access/use state of the art technology. Such partnerships facilitate the access to new technologies and new work methodologies and, at the same time, impose the use of standards and new quality requirements.

In terms of the IS, this new situation requires the definition of common models (sometimes the use of common tools). Standards, like STEP (1991), are expected to play an important role in such inter-enterprises cooperation.

The efforts being put on the implantation of high speed networks (digital highways), supporting multimedia information, open new opportunities for team work in multi-enterprise/multi-site networks. But this new scenario also brings new requirements in terms of control: access rights to the information, scheduling of access, control of interactions, etc.

Integration Perspectives

Taking into account the scenario described above, the definition of a platform for Concurrent Engineering involves, in our opinion, three related sub-problems:

i) Definition of Common Models

This is a basic requirement in order to enable communications between members of the engineering team. Achieving agreements on models or integrating views from different domains of expertise is a quite difficult task. Even to start with a simple definition of a common glossary it requires a non-negligible effort. This is an important task in every collaborative project.

The adoption of common modeling formalisms is a first requirement. Formalisms like IDEF0, NIAM, EXPRESS/EXPRESS-G, Petri nets are being widely used. The consolidation of STEP may help in terms of product modeling, but many other aspects not covered by STEP have to be considered, like process and manufacturing resources modeling. MANDATE seems still far from offering usable results. Business Processes modeling, as proposed by CIMOSA (Esprit Consortium AMICE, 1989), is also contributing to facilitate dialogue.

ii) Engineering Information Management

Definition of integrating infrastructures and information management systems able to cope with the distributed and heterogeneous nature of CIM, has been the subject of many research projects from which various approaches and prototypes have been proposed in last years. Management of versions, a difficult problem in engineering data management, is even more complex when different versions may be produced/explored in parallel/concurrent way.

Various centralized and decentralized solutions have been experimented, the concept of federated architectures developed and the issue of interoperability between different data management technologies and standards has been pursued.

The need for a more mature technology for Engineering Information Management, combining features from Object Oriented and Knowledge Based Systems, Concurrent/multi-agent systems, is becoming evident.

iii) Process Supervision

To build a platform for supporting concurrent engineering it is not enough to guarantee that the various computer-aided tools used by a team are able to communicate and share information. It is not enough to provide an integrating infrastructure and to normalize information models. Even though these aspects are essential, there is also the problem of coordination. It is necessary to establish a supervision architecture that controls or moderates the way and time schedule under which computer-aided tools (team members) access the infrastructure and modify shared information. In other words, it is necessary to model the engineering processes and to implement a federated loose-control process interpreter or supervisor. However, this aspect is in its "infancy", being absent from most international R&D projects. Even though some "inspiration" may be inherited from other research on work groups from in computer science, this topic represents an important challenge for the next future.

The platform for integration and concurrent engineering - CIM-FACE: Federated Architecture for Concucrent Engineering — being developed at New University of Lisbon addresses these three issues.

Modeling in Discrete Manufacturing Systems

As mentioned before, the definition of common models is a pre-requisite for information integration and sharing, and therefore an essential component of Concurrent Engineering. In our experiments, like in many other projects in the CIME area, some "popular" formalisms have been used, such as:

- IDEFO, for functional modeling;
- NIAM and EXPRESS-G as graphical formalisms for data modeling and EXPRESS as a textual representation (EXPRESS Language, 1991);
- Petri nets and the CIMOSA Business Processes/Enterprise Activities/Procedural Rule Sets to represent dynamic processes and discrete events.

In a prototype systems - CIM-CASE - developed at UNL (Camarinha-Matos and Pinheiro-Pita, 1993 and Camarinha-Matos, Pita and Osório, 1993), IDEF0 was successfully used and extended to represent the functionalities of a CIM system. CIM-CASE is a prototype of a hierarchical planning system providing functionalities to manage an electronic catalog of CIM software tools and support the interactive generation of particular configurations of tools dedicated to specific cases, i.e., particular architectures in the CIM-OSA sense. In close connection with the catalog of tools, another central component of this system is a metaknowledge base containing knowledge about CIM activities, application domains, reference information concepts and configuration knowledge - CIM reference models. The main components of the CIM-CASE knowledge base comprise:

- Taxonomy of CIM activities;
- Taxonomy of application domains;
- Taxonomies of basic concepts (glossary of CIM-related terms);
- Library of models of software tools;
- Configuration knowledge, and
- Historic of configurations.

These reference models are used to guide the process of deriving new architectures and also to derive the basic information concepts shared by selected software tools to be integrated in the target architecture. These concepts will feed the IS of the generated system.

During the planning process an IDEF0 - like hierarchical model is created. The following example illustrates an extended representation of an activity represented by an IDEF0 box:

```
{{
  GRASP-PLANNING
   IS-A : cim-eng-activity-concept
   SUBACTIVITY-OF : motion-oriented-
                         planning
   HAS-SUBACTIVITIES: gen-of-grasp-points
                     gen-of-grasp-configuration
                      grasp-simulation
   INPUT-FLOWS : task-program
   OUTPUT-FLOWS : hand-command
                      grasp-configuration
   STRONGLY-RELATED-TO : fine-motion-
                                planning
   TYPICALY-RELATED-TO : gross-motion-
                                planning
   MIGHT-BE-RELATED-TO : conveyor-routing
   IS-PERFORMED-BY : BRINCA
   DESCRIPTION  : "Generation of Specialized
                      plans for grasp-parts"
}}
```

A description of the taxonomy of activities developed for CIM-CASE and also used as background knowledge for CIM-FACE can be found in (Camarinha-Matos, Pita, Rabelo and Barata, 1994).

EXPRESS/EXPRESS-G/NIAM, showing an object oriented flavor but not full object oriented capabilities, proved to be quite satisfactory to represent static structural characteristics of objects: products, process plans, etc. The main importance of these formalisms results from being originated or being used in STEP.

However, we found out they are not so satisfactory when it comes to model dynamic systems, i.e., the dynamic behavior of objects. Frame based representations proved to be more effective in modelling dynamic behavior due to their object oriented and reactive programming facets.

The possibility of creating new relations, with user defined inheritance mechanisms, provides a powerful descriptive tool to capture the semantics involved in complex objects.

On the other side, reactive programming (demons) and methods provide for dynamic behavior modeling. Complementary, these paradigms allow for "linking" the objects model to external sources of information, like external data bases or even the controllers of manufacturing equipment (1).

In the CIM-FACE prototype CRL, the frame representation language of Knowledge Craft, is used as a modeling tool.

Another limitation of EXPRESS is that it was designed to represent classes of concepts and don't provide an explicit representation for instances. The representation of an instance of a complex object like a cell or an assembly is quite difficult, as the specific relationships between the various components cannot be clearly expressed unless we represent the instances of each part that belongs to this complex object (Barata, Camarinha-Matos and Rojas, 1994).

The language Express-I might eliminate this difficulty.

Another important aspect is that in a complex system like CIM, information models have a strongly dynamic nature, being almost unpractical to have fully standardized and stable models. The design of flexible information management functionalities, together with the definition of a rich set of administrative information, is a direction to be explored in order to cope with the uncertainty introduced by this dynamism of the information models. Instead of assuming that an "agreement" in terms of data models was somehow established a-priori between both the IS developers and accessing tools - as is the basic assumption of STEP - we have to move towards a level in which a-priori knowledge about concepts present in the IS is incomplete. We don't think that a Concurrent Engineering platform can be supported by a static data schema. In our opinion, in a dynamic engineering process it is not only the concept instances that change but the concepts themselves evolve quite frequently. This will have consequences at the level of Information Management Functionalities and also on tools development. The platform, as a federation of tools, has to provide mechanisms that help the federaton in overcoming this uncertainty. Frame based representations, allowing for dynamic change of data schema, seem more appropriate to deal with this facet.

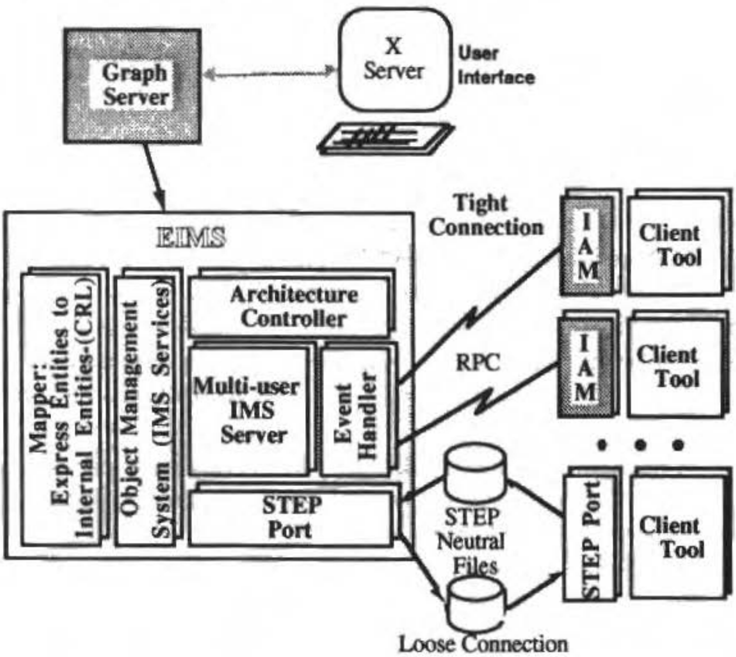

Fig. 2 Implementation architecture of the EIMS component

Engineering Information Management System

Goals

One important part of the CIM-FACE prototype is the EIMS subsystem (Camarinha-Matos and Sastron, 1991; Camarinha-Matos and Osório, 1993; Osório and Camarinha-Matos, 1994).

EIMS was developed in the context of our participation in CIM-PLATO, an Esprit project funded by the European Community, involving 14 partners (universities and companies) from 7 countries. The main goal of this project was the development of an industrial toolbox consisting of computer-aided procedures and tools which support the design, planning and installation of FMS and FAS in a CIM environment. One crucial aspect of this project was the definition of an integration strategy in order to facilitate the integration of subsets of tools selected from the toolbox. The EIMS module provides basic information management functionalities as well as an integrating infrastructure to support the connection of a federation of heterogeneous software tools.

Implementation and Results

The implemented EIMS prototype is based on a hybrid and distributed programming environment supporting the connection of tools implemented in Unix and MSDOS environments. Kernel functionalities are implemented on top of Lisp and the Frame representation language of Knowledge Craft (CRL component).

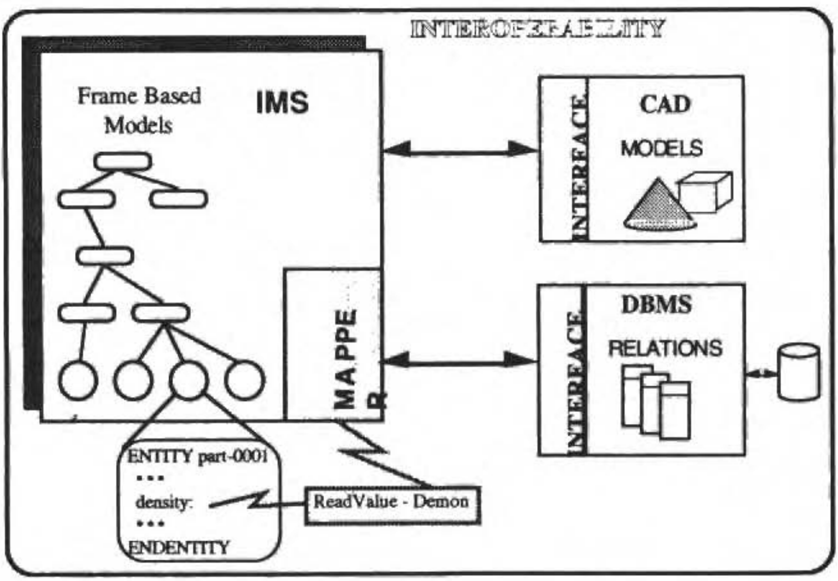

Fig. 3 Interoperability among different technologies

The integrating infrastructure supports two connection modes: tight and loose connection.

Under the tight connection mode, each tool that wants to access the IS must send a request command to the IMS Server. The list of Information Access Methods (IAM) was defined based on the object oriented characteristics of Express and following the initial guidelines in discussion inside the STEP community. As this development started well before the appearance of STEP SDAI (Standard Data Access Interface), we had to define our own data access interface.

The logical channel connecting all components (tools) is supported by inter-process communication mechanisms. The base platform is a set of workstations connected through a local or global network and supporting Remote Procedure Calls (RPC) capabilities. The specificities of the interprocess communication are hidden by a library of C functions (implementation of the IAM). Each tool, to use this connection mode, has to be linked with that library. In our prototype, different tools running on workstations (UNIX) and PC's (DOS+PC-NFS) are able to communicate - concurrently - with EIMS.

Loose coupling or file based communication is a kind of connection to be used when only rare interactions (and predominantly unidirectional) are needed. The implementation, in this case, is based on the concept of file transfer. STEP neutral file format is used in our implementation.

On the other side, even though the IMS has a centralized structure at a logical level, the actual information repositories can be distributed and even supported by different technologies based on the interoperability concept. Each tool is allowed to keep its own private information structures. In this approach the common IS is basically a support for communication between tools and, therefore, it contains only shared concepts and shared data.

Using this integration approach, demonstration systems were developed in CIM-PLATO. One example of these demonstrators (OtoM: from Order to Manufacturing) (Welz et al., 1993) integrates a set of tools, developed by different industrial and academic partners, that cooperate to carry out the main planning activities from product configuration to manufacturing at shop floor level. The particular application area for this demonstration was the configuration and assembly of a computer system, more specifically using the Bull computer family DPS7000 as test example.

The development environment, based on Knowledge Craft, being quite satisfactory for prototype developments, is too "heavy" for practical applications and constituted a strong obstacle to the implantation of the system in industrial companies. In current stage we are progressively migrating the system to a lighter frame based system developed on top of Prolog.

Interoperability

The use of reactive programming proved to be an effective mechanism to implement interoperability between different data management technologies. Fig. 3 shows an example where EIMS frame-based representation is used as a kind of "front-end" to data that is actually stored in other data bases (Camarinha-Matos and Osório, 1993) . Nowadays new data base management tools, combining part of the expressiveness of object oriented and rule based systems with the persistency and query efficiency of relational DBMS, are appearing on the market. IMS tools based on STEP developments may start to appear soon. Even though an improvement in such tools might be expected, we think the interoperability mechanisms will play a role in the migration of legacy systems to more advanced Engineering Information Management Systems.

Platform for Concurrent Engineering

This chapter discusses current (post-CIM-PLATO) activities towards the definition of a supervision architecture that coordinates activities or processes being carried out by the engineering/ manufacturing system.

If we follow the CIMOSA approach to model a company - and to model Concurrent Engineering activities in particular - as a hierarchy of Business Processes/Enterprise Activities, the intended supervision architecture can be thought of as a Business Processes Interpreter.

One difficulty is that there is no tradition in terms of modeling concurrent activities, which may be quite nondeterministic. On the other hand, these activities, performed by human experts, are supported by computer aided tools with multiple functionalities.

Each application tool can be modeled as an activity box whose inputs and outputs represent the tool's access to the IS (and Integrating Infrastructure). In other words, in heterogeneous federated systems each component has large autonomy and we can think that only "contact points" - data Inputs and Outputs - are important for the global coordination. Therefore, a first attempt to the supervision architecture could be based on these IO's, i.e., monitor tools' behavior by the information they manipulate. However:

- Application tools are progressively becoming multi-functionality packages, able to perform/ support multiple activities. During a work session, one tool might have several interactions with the IS (long-transactions), depending on the human's decision;
- The actual I/Os in each activation of a given tool are not known a priori. Transactions depend on the human that is using the tool;
- The "intervention" of a tool in the integrated "community" cannot be separated from the status of other concurrent activities, i.e., the synchronization aspects are strictly related to the transformations other tools made on the common IS, and
- CIM IS contains complex models coping with different views of the same concepts and showing considerable dynamics.

  Therefore, the "granularity" of the control has to be less detailed, i.e., a control of tool's access based on the manipulated information is, to a large extent, unpractical. An alternative is to rely on the members of the engineering team that effectively know what they are doing with each tool. Therefore, even though some automatic verifications can be done, in our approach, the control is mainly based on an access protocol between CIM-FACE and tools' users.

Architecture and Multi-level Control

In order to implement a control strategy it is necessary to be able to model the dynamic behavior of the system being controlled. In our current experiment, the CIM-OSA concepts of Business Process and Enterprise Activity [7] are being used. The dynamic behavior is thus modeled by hierarchies of Business Processes and Enterprise Activities. In each level of the hierarchy, a Procedural Rule Set (PRS) defines precedence constraints between BP or EA of that level as well as their starting (firing) conditions.

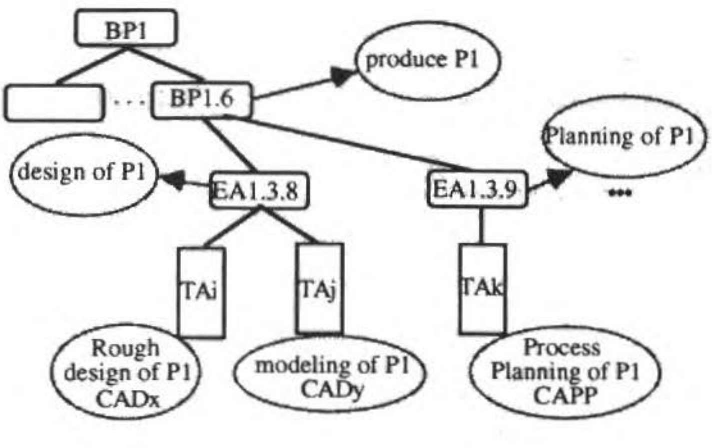

Fig. 4 Example of a hierarcgy of BP/EA and supporting tools

Another important formalism to model system's dynamic behavior being extensively used in manufacturing systems is Petri nets (in its various derivations). In order to take advantage of tools and methods available for Petri nets, namely for qualitative and quantitative analysis, attempts to derive PN models from BP/EA/PRS are justifiable. In our approach we are using a derivation of the basic PN model called Mark Flow Graph (MFG)(9). In other words, we start from a hierarchy of BP/EA, as a "global plan" whose execution has to be controlled, and automatically derive a MFG representation from it.

The supervision strategy is determined or "instantiated" by the "execution" of such MFG. Fig.5 shows how a "circle" (BP/EA) in the CIM-OSA model is transformed into a MFG graph. Control "actions" are implemented as side effects of transition firings. However, an important remark shall be made here: the generation of a control algorithm from a PN is a well known topic when controlled agents are more or less "obedient slaves", with deterministic behavior (apart exceptions)(15). In our case, as tools have a large degree of autonomy, it is not possible to anticipate which functionalities of the tool will be applied by the user and "when", as this is a totally external decision. As a consequence it is difficult to "recognize" when the system is ready for a state transition, i.e., to "decide" whether or not a mark appeared in the external box (Fig.5).

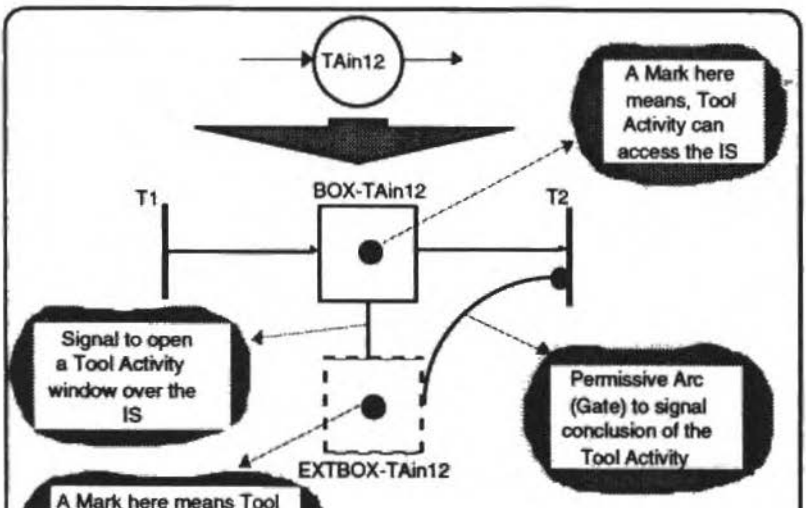

Fig. 5 Detail clarifying the relationship between tool operation and MFG entities

Therefore our system implements a kind of loose control that acts more in terms of preventing/ enabling situations, but the actual events (completion of actions) is decided externally. The user is assumed to "inform" the control system about the conclusion of activities. Nevertheless. some control rules can be used then to check whether "typical" consequences of that activity have been achieved or not. These rules will perform a "verification" ofthe "arrival" of a mark to the external box.

As a consequence of the approach followed, there might be a problem of confidence. As the control events are decided externally, by the human operator, how can the control system be sure the decision was appropriate? For instance, lets suppose that current user of tool T_i informed the system that he has finished a generation of a process plan for a given production task. Should the control system simply accept such information as a fact or should it be cautious and try to investigate the accuracy of the information? Therefore different "kinds" of control systems could be defined, ranging from a totally confident system to a totally cautious one.

For some cases, and in some application domains, it will be possible to define a set of verification rules to test the validity/accuracy of each access protocol action issued by tool assistants. In other cases that might be difficult. Therefore, our proposal is to have an architecture that can start from a level of total confidence and progress towards a more cautious system once verification rules are added to its control knowledge base. In reference to Fig.5, this means the appearing of a mark in an external box is due to an access protocol action that has "passed" the test of all rules associated to that action.

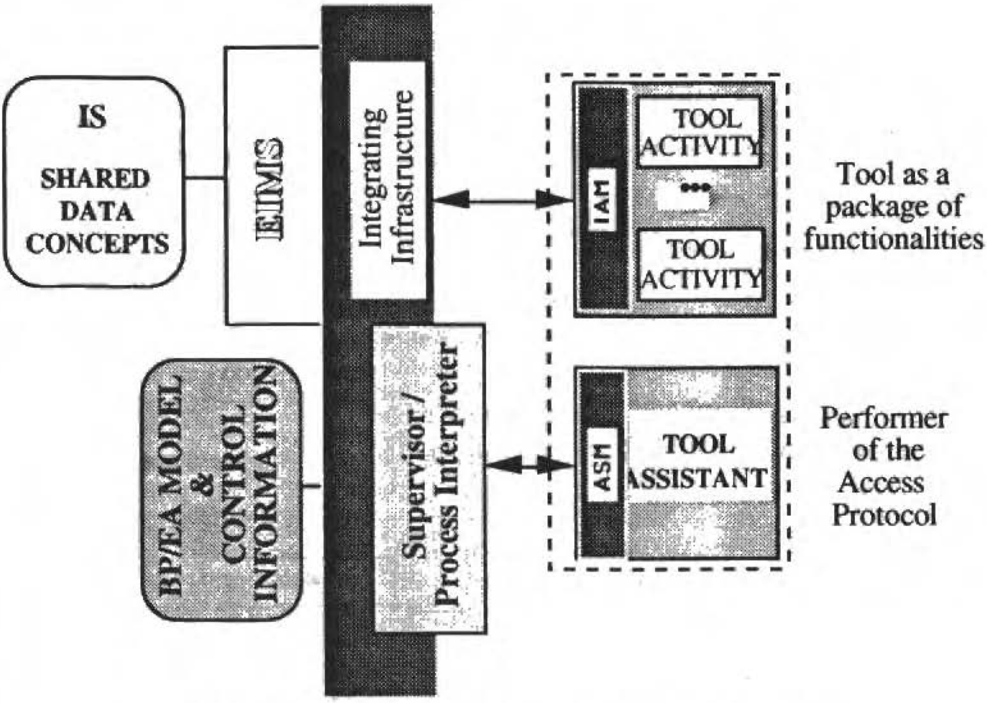

Fig. 6 The interaction of a tool and a tool assistant with CIM-FACE

Control Assistance

A protocol is necessary to specify the interactions between a tool and the integrated system. The "performer" of this protocol can be a layer separated from the applicative part of the tool. For new tools this "protocol performer" can be seen as a common script (library) that can be linked to the tool. For legacy systems it is quite hard or nearly impossible to modify their control architectures.

Therefore, the proposed architecture assumes the idea of separation between the tool itself and the protocol performer, here called tool assistant. From the implementation point of view, the tool assistant can be a module linked to the tool or even a parallel (detached) process. The second alternative is more suited to legacy systems.

It is assumed the human expert will use the tool assistant in order to perform the protocol necessary to get "access" to CIM-FACE. From the user point of view, the control part is therefore clearly "identifiable" by a separate window, for instance. This window may show a graphical representation of the system status, based on the hierarchy of BP/EAs.

Supervision Rules

Consider, for instance, the example in Fig 4. To start a process planning activity it is necessary that, a rough design of the intended product was produced before. A minimal level of control would enable the start of "process planning for P1" activity if a user, through a tool assistant, had declared the activity "Rough design of P1" finished. This is the level of total confidence on the human declarations. The supervisor system assumes that a rough product P1 model was produced and stored in the IS. A less "confident" approach could be based on a rule that states:

```
enable (Process Plan, P1) if
   requested(ProcessPlan, P1)
and
   exists(roughmodel(P1)).
```

The "exists" predicate would check the IS to confirm if the rough model was produced before. We could ever think about more detailed checking rules. However it is not possible to generate generic rules, except for particular cases.

These rules would depend on the particular approach for structuring information models. In other words, these rules have to be defined for each particular system.

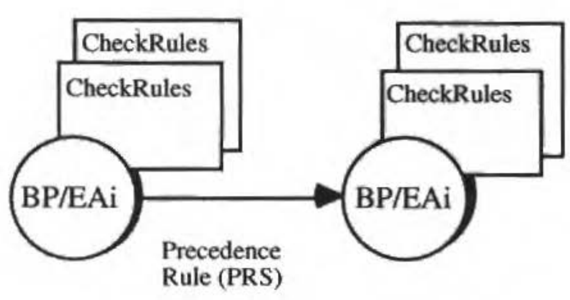

Fig. 7 Detail of the supervision subsystem

Our approach is to provide a platform that allows definition of such rules and takes them into account during process supervision.

Conclusions

CIM-FACE, a prototype Federated Architecture for Concurrent Engineering was developed as an integration vehicle for a set of heterogeneous application tools in a CIM environment and a platform to support the interaction of engineering teams. The approach aimed at giving a contribution to various aspects of systems integration and concurrent engineering:

1) Information integration: modeling, management and sharing;
2) Integrating infrastructure, and
3) Coordination or supervision architecture to manage the way and time schedule in which tools get access to shared data and models.

The first two aspects have been subject of major research efforts in various international projects and, as a consequence, some standard results are emerging, like STEP and CIM-OSA. The implemented prototype system tries to follow these standards. Regarding the topic of supervision architecture, it is currently a major challenge for which only preliminary results can be found. This control architecture represents, in our opinion, a basic requirement for concurrent engineering. In this paper some of the aspects involved in such an architecture were discussed and solutions being tested were introduced. However this topic, being quite complex, needs further research.

Acknowledgments

The work here described received partial support from the European Community - the Esprit CIM-PLATO, ECLA CIMIS.net and FlexSys projects - and from the Portuguese Agency for Scientific and Technologic Research (JNICT) - the CIM-CASE project. We also thank the contributions given by Helder Pita, Luis Lopes and Ricardo Rabelo.

References

Barata J. A., Camarinha-Matos, L. M., Rojas, F., 1994, "Dynamic Persistence and Active Images for Manufacturing Process, Accepted for publication in Journal Studies on Informatics and Control.

Camarinha-Matos, L., and Sastron F., 1991, "Information Integration for CIM Planning Tools", CAPE'91- 4th IFIP Conference on Computer Applications in Production and Engineering, Bordeaux.

Camarinha-Matos, L. M., and Osório, A. L., 1993, "CIM Information Management System: An EXPRESS-based Integration Platform", IFAC Workshop on CIM in Processes and Manufacturing Industries, Espoo, Finland, Pergamon Press.

Camarinha-Matos, L. M., and Pinheiro-Pita, H. J., 1993, "Interactive Planning in CIM-CASE", Proceedings of IEEE Int. Conference on Robotics and Automation, Atlanta, USA.

Camarinha-Matos, L. M., Pita, H., and Osório, L., 1993, "Hybrid Programming Paradigms in CIM-CASE", Proceedings of the IFIP/IFAC Working Conference on Knowledge Based Hybrid Systems in Engineering and Manufacturing (IFIP Transactions B-11, North-Holland), Budapest, Hungary.

Camarinha-Matos, L. M., Pita, H., Rabelo, R., and Barata, J., 1994, "Towards a Taxonomy of CIM Engineering Activities, Accepted for Publication in International Journal of Computer Integrated Manufacturing.

Esprit Consortium AMICE, 1989, "Open System Architecture for CIM", Springer-Verlag.

EXPRESS Language, 1991, *Reference Manual*, ISO/TC 184 /SC4, Aug 91.

Myiagi, P. E., 1988, "Control System Design, Programming and Implementation Systems for Discrete Event Production Systems by Using Mark Flow Graph", PhD Thesis, Tokyo, Japan, 1988.

Osório, A. L., and Camarinha-Matos, L. M., 1994, "Information Based Control Architecture", Proceedings of the IFIP Intern. Conference Towards World Class Manufacturing, Phoenix, USA, edited by Elsevier, North Holland.

Schenk, D. A., and Wilson, P. R., 1994, *Information Modelling: The EXPRESS Way*, Oxford University Press.

Steiger-Garção, A., and Camarinha-Matos, L. M., 1992, "Design of a Knowledge-based Information System", in Integration of Robots into CIM (Ed. Bernhardt, Dillman, Hörmann, Tiemey), Chapman & Hall, Cap. 21 & 22.

STEP, 1991, *Reference Manual*, ISO/TC 184 /SC4.

Welz, B. G. et al., 1993, "A Toolbox of Integrated Planning Tools - a Case Study", IFIP Workshop on Interfaces in Industrial Systems for Production and Engineering, Darmstadt, Germany.

Zhon, M., and DiCesare, F., 1993, *Petri net Synthesis for Discrete Event Control of Manufacturing Systems*, Kluwer Academic Publishers,1993.

Resumo

Os requisitos para uma plataforma de engenharia concorrente são discutidos em paralelo com uma análise da evolução dos sistemas de manufatura integrados e novos paradigmas organizacionais nas indústrias. O sistema CIM-FACE é introduzido como um protótipo de arquitetura federada para engenharia concorrente, focalizando os aspectos de modelagem, gerenciamento e compartilhamento das informações e supervisão dos processos de engenharia. O estado corrente do desenvolvimento e resultados experimentais são discutidos e novos desafios são apontados.

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Abstracts

Gonçalves, P. B., and Ramos, N. R. S. S., 1994, "Free Vibrations of Cylindrical Tanks", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 222-236.

A simple but effective method is presented for evaluating the free vibration characteristics of a fluid-filled cylindrical shell with classical boundary conditions of any type. Effects of static liquid pressure, in-plane inertias and liquid free surface motions are taken into account. A clamped-free cylindrical tank is analysed and the accuracy of the results is demonstrated by comparing them with experimental results found in literature.

Keywords: Thin Walled Shells, Free Vibrations, Fluid-Shell Interaction, Shell Boundary Conditions

Lima, L. C., and Lobo, P. C., 1994, "Development of a Pyranometer with Electrical Compensation", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 237-251.

A dynamically compensated electrical pyranometer with manufactured platinum film sensors was constructed, theoretical, and experimentally evaluated. The electronic circuit is constituted of a Wheatstone bridge, high gain voltage and current amplifiers, and a signal linearizer. Theoretical relations are derived to describe the effect of the sensors properties on the instrument steady and dynamic responses. The sensitivity of the instrument due to the angular dependence on the direction of the radiation, response time, effect of temperature, tilting and linearity have been also investigated.

Keywords: Pyranometer, Radiometer, Solarimeter

Donatelli, G. D., and Boche, S., 1994, "Tolerance Synthesis of Cylindrical Fits: A Simple Method Based on the Rectangular Distribution Model", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 252-266.

Form and dimensions of mechanical elements vary from one part to another due to the peculiarities of manufacturing processes. Those variations are not dependent on the size of the manufacturing batch and affect the functional and assembly performances of the products in which the parts work. Dimensional synthesis during design stage must include the proper transformation of the functional and assembly requirements, and its allowable variation, in cost-effective dimensions and tolerances.

In this paper a statistical tolerance synthesis procedure is described. It is based on the assumption that the dimensions of the individual parts can be considered uniformly distributed within the interval of allowable dimensional variation. The formulation is directed to solve the case of fits which functional requirements depend on the linear combination of two length dimensions, (i.e. cylindrical fits). The small number of combined dimensions leads to a distribution of the functional requirement which departs strongly from normal, depending on the dimensional tolerance values still not assigned. In the described procedure, the form and properties of the distribution of the functional requirement can be infered a priori, due to the earlier incorporation of economic tolerance distribution criteria.

Keywords: Tolerances, Fits, Statistical synthesis

Almeida Prado, F. B., and Rios Neto, Atair, 1994, "A Stochastic Approach to the Problem of Spacecraft Optimal Maneuvers", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 267-277.

In this paper the problem of spacecraft orbit transfer with minimum fuel consumption is considered. A new version of the suboptimal and hybrid control approach of numerically treating the problem, where one can take into account the accuracy in the satisfaction of constraints is developed. To solve the nonlinear programming problem in each iteration, a stochastic version of the projection of the gradient method is used together with the well-known hybrid approach to find the optimal control in this kind of dynamic problem. For the maneuvers considered, the spacecraft is supposed to be in Keplerian motion perturbed by the thrusts whenever they are active. The thrusts are assumed to be of fixed magnitude (either low or high) and operating in an on-off mode. The solution is given in terms of the location of the "burning arcs", "time"-histories of thrust attitude (pitch and yaw), final orbit acquired and fuel consumed. Numerical results are presented.

Keywords: Optimal Transfer, Stochastic Approximation, Optimal Control, Spacecraft Orbit Maneuver

Uplekar, A. G., Jaiswal, B. S., and Soundalgekar, V. M., 1994, "Effects of Mass Transfer on Transient Free Convection Flow Past an Infinite Vertical Isothermal Plate", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 278-286.

An exact solution to the transient free convection flow past an infinite vertical isothermal plate is presented on taking into account the presence of species concentration. It is observed that an increase in the Schmidt number leads to a decrease in the velocity when the buoyancy ratio parameter $N > 0$. However, when $N > 0$, an increase in N leads to an increase in the velocity whereas for $N < 0$, a decrease in N leads to a fall in the velocity. For $N > 0$, an increase in Sc leads to a fall in the skin-friction and opposite is the case for $N < 0$. The skin-friction is more for $N > 0$ as compared to that for $N < 0$.

Keywords: Free Convection with Mass Transfer, Unsteady State, Infinite Vertical Isothermal Plate

Teixeira, R. N., Orlando, A. F., and Parisi, J. A. R., 1994, "Motores a Combustáo Interna com Taxa de Compressão Variável - uma Análise Teórico-Experimental", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 287-296.

The present work is concerned with a theoretical and experimental study of variable compression ratio ignition internal combustion engines. A theoretical analysis of the engine, operating with a mechanism which allows for variable compression ratio, is carried out. For that a simulation program is used. In the present work the simulation model was updated with the inclusion of friction, knocking and hidrocarbon emission models, among other things. An experimental work was also carried out, with a CRF engine. The objective was two-fold: to validate the results of the thoretical model and to assess the benefits of running an engine with variable compression ratio. A comparison is also made between the results of the present work and those from other authors.

Keywords: Internal Combustion Engines, Variable Compression Ratio, Modelling and Experimental Study

Afsarmanesh, H. , Wiedijk, M., Moreira, N. P., Ferreira, A. C., 1994, "Design of a Distributed Database for a Concurrent Engineering Environment", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 297-309.

Concurrent Engineering concepts are strongly considered by today's industry as a means of improving all aspects of the product life-cycle. This approach primarily suggests the use of teamwork, where the team is formed by engineers and experts from all activities related to the product life-cycle. One main function of the concurrent engineering team is to negotiate the best solution for the product development. The team is created in the earliest life-cycle phases and is responsible for all decisions made regarding the product until the product is out of the market. Teamwork involves intense collaboration and exchange of information. Different tools are proposed to ease the teamwork, namely Design for Manufacturing, Design for Assembly, Quality Control and CAE/CAD/CAM, etc. This paper describes the Concurrent Engineering Environment (CEE), as a powerful computer-aided tool to support the use of concurrent engineering ideas in a distributed platform. A natural framework to support the management and sharing of information among different manufacturing phases or activities is a network (federation) of heterogeneous and autonomous agents that are either loosely of some tightly-coupled. In this federation, an agent is involved in one activity (e.g. design) related to the product life-cycle, while several agents may take part in the same activity. On one hand production related activities are independent, (heterogeneous and autonomous) to serve different purposes. On the other hand, trivially these activities are interrelated (coupled) and need to cooperate and exchange information among themselves. In this paper, we describe the distributed/ federated database design that supports the information manipulation in the CEE for an aerospace industry in Brazil. The design of CEE is based on the federated information management system PEER. We will distinguish the different kinds of PEER agents that constitute the CEE federation network. We describe the role of the "product" in the CEE environment and present a schema description for products. This research describes the second phase of the cooperation between the University of Amsterdam (The Netherlands) and Universidade Federal de Santa Catarina (Brazil) in the scope of the CIM-ECLA program.

Keywords: Concurrent Engineering Environment, Distributed Database, Database Design, CIM.

Tavares, M., Moreira, N. P., Jardim-Gonçalves, R., Barata, M. M., and Steiger-Garção, A. S., 1994, "A STEP Based Information Management System as a Support to a Concurrent Engineering Environment", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 310-316.

This work presents a proposal to a Concurrent Engineering Aided Environment. Ir is supported by a generic STEP-based integrating platform providing a powerful assistance to information modeling and distribution. This effort is a cooperation between the UNINOVA-Universidade Nova de Lisboa-Portugal and Universidade Federal de Santa Catarina-Brazil.

Keywords: Integration, Concurrent Engineering, Information System, Information Modelling, STEP

Afsarmanesh, H., Wiedijk, M., Negreiros, F., Lopes, R. H. C., and Martins, R. C., 1994, "Integration of an Optimization Expert System within a CIM Distributed Database System", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 317-326.

This work presents an approach to the integration of an optimization system with the other CIM activities using a distributed/federated database architecture. The CIM application environment addressed here is the shoe and handbag manufacturing industry and the optimization system is for cutting the layouts of irregular shapes out of the base leather material. Here, the optimization system is specified by the complete separation of the user-interface from the optimizing aspects of the problem and defines them as two distinct cooperative agents. The integration of separate activities within a CIM distributed database system is attained by using a federated object-oriented database management system. The federated architecture used here supports the cooperation and information exchange among autonomous and heterogeneous agents.

Keywords: Distributed/Federated Database, Optimization Expert System, CIM.

Pinheiro-Pita, H. J., Camarinha-Matos, L. M., Negreiros Gomes, F. J., and Lessa Lorenzi, L., 1994, "Graphical Interfaces Supported on Objects with Dynamic Behavior - An Application in Visual Interactive Modeling", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 327-340.

The design of graphical interfaces supported on objects with dynamic behavior is introduced in the context of Visual Interactive Modeling for CIM decision support systems.

This paper starts with a presentation of the Dynamic Behavior concept. After that, it presents a brief description of the use of this concept in the design of intelligent graphical interfaces. The paper is concluded with the presentation of an application to the leather cutting problem where this concept is being tested.

Keywords: Design of Graphical Interfaces, Visual Interactive Modeling, Dynamic Behavior, CIM.

Camarinha-Matos, L. M., and Osório, A. L., 1994, "An Integrated Platform for Concurrent Engineering", RBCM - J. of the Braz. Soc. Mechanical Sciences, Vol. 16, no. 3, pp. 341-353.

The requirements for a platform for Concurrent Engineering (CE) are discussed in parallel with an analysis of the evolution of integrated manufacturing systems and new organizational paradigms in industrial companies. CIM-FACE system is introduced as a prototype federated architecture for CE, addressing the aspects of modeling, information sharing and management, and engineering processes supervision. Cucrent status of developments and experimental results are discussed and open challenges pointed out.

Keywords: Concurrent Engineering, Integrated Manufacturing, Industrial Information Integration, CIM.

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Bordalo, S.N., Ferziger, J.H. and Kline, S.J., 1989, "The Development of Zonal Models for Turbulence", Proceedings, 10th ABCM - Mechanical Engineering Conference, Vol. I, Rio de Janeiro, Brazil, pp. 41-44.

Clark, J.A., 1986, Private Communication, University of Michigan, Ann Arbor, MI.

Coimbra, A.L., 1978, "Lessons of Continuum Mechanics", Editora Edgard Blucher Ltda, São Paulo, Brazil.

Kandlikar S.G. and Shah, R.K., 1989, "Asymptotic Effectiveness - NTU Formulas for Multiphase Plate Heat Exchangers", ASME Journal of Heat Transfer, Vol. 111, pp. 314-321.

McCormak, R.W., 1988, "On the Development of Efficient Algorithms for Three Dimensional Fluid Flow", Journal of The Brazilian Society of Mechanical Sciences, Vol. 10, pp. 323-346.

Silva, L.H.M., 1988. "New Integral Formulation for Problems in Mechanics", (in portuguese), Ph.D. Thesis, Federal University of Santa Catarina, Florianópolis, SC, Brazil.

Sparrow, E.M., 1980a, "Forced-Convection Heat Transfer in a Duct Having Spanwise-Periodic Rectangular Protuberances", Numerical Heat Transfer, Vol. 3, pp. 149-167.

Sparrow, E.M., 1980b, "Fluid-to-Fluid Conjugate Heat Transfer for a Vertical Pipe-Internal Forced Convection and External Natural Convection", ASME Journal of Heat Transfer, Vol. 102, pp. 402-407.

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