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HIGHLY EFFICIENT SENSITIVITY ANALYSIS FOR AERO-SERVO-ELASTIC OPTIMIZATION OF HELICOPTER ROTORS

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HIGHLY EFFICIENT SENSITIVITY ANALYSIS FOR AERO-SERVO-ELASTIC OPTIMIZATION OF HELICOPTER ROTORS

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An optimization algorithm for helicopter rotors with HHC (Higher Harmonic Control), using aeroelastic constraints and objectives is presented in its block layout. The most time expensive part of the optimization procedure was identified to be the sensitivity analysis for aeroelastic criteria and constraints. This paper briefly describes a new package of computer programs, named HELDYN, designed for the aeroelastic analysis of non-uniform rotor blades undergoing moderate deformation. The programs are presented in their essential aspects that make them highly efficient in the sensitivity analysis. The performances of HELDYN were tested in a comprehensive parametric study that also highlighted important aspects useful for the sensitivity analysis.

1. Introduction

Optimization is already common practice in helicopter rotors design. The complexity of the problem and the limited performances of the available computers have made the aeroelastic aspects to be included only recently in the optimization loops. The aeroelastic modeling of helicopter blades has made a spectacular progress in the late years [1,2]. Some positive results of using aeroelastic criteria and constraints in the optimization procedures were published and some other activities with similar objectives are under way [3]. The emerging trend for the proximate future is the development of effective Integrated Multidisciplinary Optimization (IMO) procedures to be used in helicopter design [5].

Extensive research in control-structure interaction (CSI) is a topic in the program of many laboratories [5]. At the Aviation Institute in Bucharest, Romania, a systematic work in helicopters theory and testing has been done in the last decade. Following important contributions on calculating the frequencies and mode shapes of rotor blades [6] and on rotor blades aeroelasticity in hover [7], extensive work has been dedicated to theoretical analysis, testing and in-flight measurements for helicopter blades, controls and other structural parts [8, 9, 10, 11, 12].

The activities now underway include developing an efficient method for optimization of rotor blades, ready to be used in practical industrial design. The aeroelastic analysis emerged as the key part of the algorithm (Fig. 3) and therefore important efforts were dedicated to improving this segment, especially in what the run time of the computer program is concerned.

2. The General Problem of Optimization

The problem of optimization for the helicopter rotor (or, further, for the rotors-fuselage assembly) can be set in one of the most general form, that of a nonlinear objective function with nonlinear constraints.

A mathematical formulation of the problem is: we search a global minimum of the objective function $J(D)$:

$$J(D) \rightarrow \min \tag{1}$$

with the constraints:

$$g_i(D) \in \{S_i\} \qquad i=1,\ldots,N_c \tag{2}$$

being simultaneously satisfied. In (1) and (2):

$$D=[D_j] \qquad j=1,\ldots,N_{dv} \tag{3}$$

are the design variables. For these we must provide a starting set at the beginning of the procedure. The general sets $\{S_i\}$ in (2) can be real domains, integer or rational values and so on.

In Figure 1, a block layout describes a procedure for the optimization of a helicopter rotor. The dotted lines show the feed-backs or parts of the optimization loops. Each block was developed in the perspective of the whole procedure but aiming to get a complete and independent solution for a part of the problem. If we take care of the data transfer compatibility, this modular design provides some important advantages:

-allows the precise assessment of the performances of each module and thus the identification of the weak parts of the algorithm;

-allows the independent improving or replacing of the modules. This enables the direct use of empirical-analytical models based on in-flight or test measurements.

In the numerical modeling of the helicopter rotors, the active control and the passive control, the latter using structural design variables, suggest the comprehensive approach that includes both in a unique control algorithm. But advanced techniques in optimization,when applied to complex problems, like that of a helicopter rotor, have so many procedure control parameters that they require genuine strategies for efficiently choosing the multi-objective function, the cost penalties, weighting functions and so on.

In applications on fix wing aircraft it was stated [13] that the integrated passive-active control aeroelastic optimization is feasible "at one level, without the need for multilevel decomposition".But in order to tackle the complex problem of rotor optimization,some modules had to be left outside the main passive control loop. These are modules very expensive in run time terms and that evaluate physical quantities less sensitive to small structural modifications of the blade. These quantities are updated only after significant changes occurred in the blade structure or in its dynamic response. In important, final stage practical applications, some of these modules can be also included in the main optimization loop.

2.1 Modal Shapes for the Rotating Blade

The calculation of the modal shapes for strongly nonuniform blades, requiring many discrete elements in the model, needs lot of computer time. An original method was adopted, based on the transfer matrix method [6]. It leads to outstanding performances, due to avoiding inverse and eigenvalue problems for large matrices. The rotating modal shapes are evaluated at the general pitch control set by the flight trim conditions. The Timoshenko corrections for the effect of the shear flexibility and rotatory inertia on the beam bending are also included.

These modules can be also called for quick calculation of the free rotating frequencies.

2.2 Induced Velocity Field

Many alternatives are available for this module, from measurements results to free wake vortex models [11,12]. The most advanced models include the simulation of the interaction with the fuselage and with other rotors.

No matter which is the chosen module, the computed or measured induced velocity field is stored using a representation by Zernike polynomials. This is, in fact, the procedure used for depicting all the quantities with irregular distribution on the rotor disk and it is responsible for much of the computing speed of HELDYN.

The Zernike polynomials have the general form:

$$P_{n,m}(\rho,\varphi)=R_{n,m}\cdot\cos(m\varphi) \qquad (4)$$

with the radial parts:

$$R_{n,m}(\rho)=\rho^{m}\cdot Q_{k,m}(t)\ ,\quad k=\frac{n-m}{2} \qquad (5)$$

where $Q_{k,m}$ are polynomials of grade k in $t=\rho^2$, orthogonal on (0,1), with the weight t^m:

$$\int_0^1 t^{m}Q_{k,m}(t)dt=\delta_{k,l}\frac{1}{2k+m+1}\ . \qquad (6)$$

That leads to the general expression of the orthogonality of Zernike polynomials:

$$\int_0^1\int_0^{2\pi} R_{n,m}(\rho)R_{k,l}(\rho)\cos(m\varphi)\cdot \cos(l\varphi)d\rho\, d\varphi=\delta_{k,l}\frac{1}{2k+m+1} \qquad (7)$$

with the norm:

$$\omega_{n,m}=\frac{\pi}{n+1}\begin{cases}1/2 & m\neq 0\\ 1 & m=0\end{cases}$$

The expansion of any quantity in a polar field using Zernike polynomials takes the form:

$$W(\rho,\varphi)=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}c_{n,m}R_{n,m}(\rho)\cos(m\varphi), \qquad (8)$$
$$n\geq m,\ n+m=2k$$

An important property of the Zernike polynomials is that the RMS of the expanded quantity over the disk is easily found as:

$$\overline{W}_{RMS}=\left(\frac{1}{\pi}\sum_{n=1}^{\infty}\sum_{m=0}^{n}c^2_{n,m}\omega_{n,m}\right)^{1/2}=$$
$$=\left(\sum_{n=2}^{\infty}\frac{c^2_{n,0}}{n+1}+\frac{1}{2}\sum_{n=1}^{\infty}\sum_{m=1}^{n}\frac{c^2_{n,m}}{n+1}\right)^{1/2} \quad (9)$$

The concrete form of the Zernike polynomials is computed using the recurrent procedure of Forsyte. For polynomials P(x) orthogonal on the domain Ω, with the weight q(x), one can write:

$$P_{k+1}(x)=\gamma_{k+1}[(x-\alpha_{k+1})P_k(x)-\beta_{k+1}P_{k-1}(x)] \quad (10)$$

with α, β, γ functions of Ω, q(x) and normalization. For $\Omega=(0,1)$ and the canonical norm (P(1)=1), the coefficients for the Zernike polynomials are:

$$\alpha_{k+1,m}=\frac{\int_0^1 t^{m+1}Q^2_{k,m}(t)dt}{2k+m+1}$$
$$\beta_{k+1,m}=\frac{2k+m-1}{\gamma_{k,m}(2k+m+1)} \quad (11)$$
$$\gamma_{k+1}=\frac{1}{1-\alpha_{k+1}-\beta_{k+1}}$$

The Zernike polynomials are an excellent tool, compared with the Fourier series, for depicting and storing values of physical quantities in a polar field. Depending on the concrete form of the approximated distribution, the Zernike coefficients need 0.2-0.5 of the storage space for the similar Fourier coefficients. The Zernike polynomials are widely used in optics design, but they also find remarkable application in rotors analysis.

2.3 Pitch Control

The trim control is calculated using the moment equilibrium equations for the in-flight helicopter with flexible rotor blades. Iterative convergent loops are used, calling the modules for the dynamic response of the rotor and for the fuselage model.

The active controls may include controllers for improving flight performances and stability and/or a Higher Harmonic Controller.

The concrete form of the HHC objective function is an important and delicate problem [14].

The objective function can be written:

$$J_{HHC}=\mathbf{Z}^T\mathbf{W}_Z\mathbf{Z}+\boldsymbol{\theta}^T\mathbf{W}_\theta\boldsymbol{\theta}+\boldsymbol{\Delta\theta}^T\mathbf{W}_{\Delta\theta}\boldsymbol{\Delta\theta} \quad (12)$$

with:

$$\boldsymbol{\theta}=\left[\theta_{0s},\theta_{0c},\theta_{cs},\theta_{cc},\theta_{ss},\theta_{sc}\right] \quad (13)$$

being the coefficients of the HHC law applied through a conventional swash-plate:

$$\theta_{HH}=\left[\theta_{0s}\sin(\varpi_{HH}\psi)+\theta_{0c}\cos(\varpi_{HH}\psi)\right]+ \quad (14)$$
$$+\left[\theta_{cs}\sin(\varpi_{HH}\psi)+\theta_{cc}\cos(\varpi_{HH}\psi)\right]\cos(\psi)+$$
$$+\left[\theta_{ss}\sin(\varpi_{HH}\psi)+\theta_{sc}\cos(\varpi_{HH}\psi)\right]\sin(\psi)$$

The variables that minimize the objective function are the coefficients $\boldsymbol{\theta}$, with cost penalties imposed on their variations $\boldsymbol{\Delta\theta}$. Minimizing (12) is achieved by repeated calls of HELDYN, thus spending a lot of computer time. The delicate problem is the efficient choice of the weighting coefficients W and of the functions (physical quantities) Z that are to be reduced. A complementary distribution of the objectives between the two cost functionals should lead to best results and the whole procedure is designed in regard of that.

2.4 The Structural Optimization Procedure

For this module subroutines based on the modules of IMSL and MINPACK libraries are used, implementing standard efficient procedures, dedicated to minimizing a nonlinear multi-variable function with nonlinear constraints. The concrete form of the objective function and of the constraints depend on the application, on the available assets and time, generally on the objective of the study or project. [4] provides a list of (some of) the possible design variables and constraints. As design variables, subject to optimization, can be used: tuning masses at various locations, locations of the tuning masses, structural dimensions of the blade (e.g. wing boxes dimensions, ply thicknesses, depth of blade at root, ratio of blade depth at tip and root, ratio of blade chord at tip and root, percent blade span where taper begins, blade root chord, swept configuration), airfoil distribution, hinge offset, blade angular velocity, number of blades on rotor, rotor radius. Constraints can be imposed on: all the design variables, main rotor horsepower, airfoil section stall, blade frequencies, blade vertical and inplane loads and inside structural stresses, loads transmitted to the hub, blade response, autorotational inertia, aeroelastic stability, blade tip

Mach number, blade thickness, blade lift distribution, ground resonance, rotor/airframe frequency coupling, vibration levels on the fuselage. All the constraints must also be satisfied, generally with looser bounds, in the case of disabled active controls. A strategic decision is the proper complementary sharing, by weighting functions, of the objectives between the structural optimizer and the HHController.

The sensitivity analysis is the key element of the optimization procedure, especially after including the aeroelastic constraints and criteria. The analytical direct method for evaluating the sensitivity derivatives [18] seems difficult to be applied in practical complex configurations. Such configurations imply numerical simulation for the calculation of structural properties and strong nonlinear effects. The Finite Differences Method is therefore the practical method for many applications. Although this was also our basic approach, most of the significant original elements that led to the high performances of HELDYN also apply in the case of the analytical direct calculation of the derivatives.

3. The Aeroelastic Analysis

The HELDYN program was designed for the aeroelastic analysis of nonuniform rotor blades, undergoing moderate deformation and working in a mixed axial-transversal flow regime. The typical, comprehensive application is the helicopter rotor in forward flight.

The package of computer programs has also a modular structure, with the previously mentioned advantages. The main modules are the structural model of the blade, the aerodynamic model and differential system solver. For this application, only the periodic stationary regimes are of interest, but quasi-periodic approximations for transitory regimes were taken into account since the early stages of HELDYN design. In Figure 2 sample results of this advanced capability are shown (see §4 for some of the assumptions used). One of the various forms of the computer program that are available, the one used in the demonstrative parametric study, is briefly presented here.

The structural model is based on the Rosen & Friedmann equations for rotating beams undergoing moderate deformation [15]. The Hodges & Dowell equations [16] were also implemented as an alternate form but no significant changes of the results were revealed. The equations can simulate general coupled flap-lag-torsional dynamics of hingeless rotor blades with arbitrary mass and stiffness distributions and offsets between blade elastic axis, cross sectional center of mass and cross sectional aerodynamic center. An original iterative procedure aimed at correcting the referential projections enabled the extension to articulated blades. An advanced FEM model is in final testing stages. For the evaluation of the aerodynamic loads, a quasi-stationary model was used, derived from that of Lowey. As stated above, the induced velocity field program module allows a proper modeling of time and radial dependent inflow, along with reversed flow. Compressibility effects were considered in this variant only by the use of the Prandtl correction on the local incompressible lift coefficient: $C_L = C_{L(M=0)}/\sqrt{1-M^2}$. Dynamic separation and stall, simulated by analytical or empirical models, can be easily included by placing the closing point of the periodic loop of integration in a zone of the azimuth with linear aerodynamic and minimum hysteresis.

The solving procedure is based on the method described by Friedmann *et al.* in several papers [17]. The elastic degrees of freedom v, w, φ (inplane bending, flap bending, torsion) are expanded over a modal base $\bar{v}$, $\bar{w}$, $\bar{\varphi}$ represented by the uncoupled free vibration modes of a rotating blade, at the general pitch control for flight trim, ignoring the cyclic pitch:

$$\begin{aligned} v &= \sum_{i=1}^{N_v} a_i(\psi)\bar{v}_i(\xi) \\ w &= \sum_{j=1}^{N_w} b_j(\psi)\bar{w}_j(\xi) \\ \varphi &= \sum_{k=1}^{N_\varphi} c_k(\psi)\bar{\varphi}_k(\xi) \end{aligned} \tag{15}$$

With these forms, using the Galerkin's method to eliminate the space variable, the system of general, coupled, partial differential equations of motion is transformed into a system of ordinary nonlinear differential equations with periodic coefficients. If 3 free modes are used for each degree of freedom ($N_v=N_w=N_\varphi=3$) then 9 second order equations are obtained and hence 2N=18 first order equations in a_i, b_j, c_k. The new, space independent system of nonlinear equations with periodic coefficients can be written:

$$\dot{q} = Z(\psi) + L(\psi)q + N(q,\psi) = F_{NL}(\psi,q,\dot{q}) \tag{16}$$

in which Z(ψ) represents a known excitation, L(ψ) is a matrix containing the time dependent coefficients of the linear system, the vector N(q,ψ) represents all the nonlinear terms in the equations and q contains the state vector of the system.

The problem of finding the solution of this system (dynamic response) and evaluating the stability of the solution is solved using the Floquet theory [19] that is now common procedure and needs not to be detailed here.

If $\boldsymbol{\Phi}(\psi)$ is the transition matrix of the homogenous linear system:

$$\dot{\boldsymbol{q}}_H(\psi)=\boldsymbol{L}(\psi)\boldsymbol{q}_H(\psi) \tag{17}$$

then the general solution of the linear system:

$$\dot{\boldsymbol{q}}_L(\psi)=\boldsymbol{Z}(\psi)+\boldsymbol{L}(\psi)\boldsymbol{q}_L(\psi) \tag{18}$$

can be written:

$$\boldsymbol{q}_L(\psi)=\boldsymbol{\Phi}(\psi)\boldsymbol{q}_L(0)+\boldsymbol{\Phi}(\psi)\int_0^{\psi}\boldsymbol{\Phi}^{-1}(s)\boldsymbol{Z}(s)ds \tag{19}$$

with the initial condition given by:

$$\boldsymbol{q}_L(0)=[\boldsymbol{I}-\boldsymbol{\Phi}(2\pi)]^{-1}\boldsymbol{\Phi}(2\pi)\int_0^{2\pi}\boldsymbol{\Phi}^{-1}(s)\boldsymbol{Z}(s)ds \tag{20}$$

The condition for the stability of the homogenous system (17) is that all the real parts of the eigen values of the transition matrix $\boldsymbol{\Phi}(2\pi)$ are $\zeta_i<0$, $i=1,\ldots, N$. This includes the condition for the existence of a unique periodic solution for (18).

The solution of the complete nonlinear system (16) is obtained using a Newton-Raphson type method. This approach takes advantage, by quasi-linearization, of the same Floquet theory based procedure presented above for the linear system.

Thus, a finite order Taylor series expansion is performed in a k iterative loop:

$$\dot{\boldsymbol{q}}^{k+1}=\boldsymbol{F}^k_{NL}+\left(\frac{d\boldsymbol{F}_{NL}}{d\boldsymbol{q}}\right)^k(\boldsymbol{q}^{k+1}-\boldsymbol{q}^k) \tag{21}$$

leading to a linear equation:

$$\boldsymbol{q}^{k+1}=\boldsymbol{A}^k\boldsymbol{q}^{k+1}+\boldsymbol{f}^k \tag{22}$$

in which:

$$\begin{aligned}\boldsymbol{A}^k&=\boldsymbol{L}^k+\left(\frac{d\boldsymbol{N}}{d\boldsymbol{q}}\right)^k\\ \boldsymbol{f}^k&=\boldsymbol{Z}(\psi)+\boldsymbol{N}^k(\boldsymbol{q},\psi)-\left(\frac{d\boldsymbol{N}}{d\boldsymbol{q}}\right)^k\boldsymbol{q}^k\end{aligned} \tag{23}$$

The transition matrix of the homogenous system selected from (16) is obtained by direct integration. After testing several proposed methods, among which the Hsu method, based on the expansion in power series of the matrix exponential or predictor-corrector variable step methods, a Runge-Kutta method was chosen, with Gill coefficients and constant step. The constant step allows the improving of the procedure speed by pre-calculating and storing many of the involved quantities.

But further important remarks can be made on the concrete form of the equations in (16), leading to spectacular speeding of the analysis. The consistent ordering scheme used in obtaining the equations of motion [15,16] provide nonlinear terms that generally can be put in a quadratic form.

The state vector of the system can be written:

$$\begin{aligned}\boldsymbol{q}=[&a_1,\ldots,\ a_{N_v},\ b_1,\ldots,\ b_{N_w},\\ &c_1,\ldots,\ c_{N_\varphi},\ \dot{a}_1,\ldots,\ \dot{a}_{N_v}\\ &\dot{b}_1,\ldots,\ \dot{b}_{N_w},\ \dot{c}_1,\ldots,\ \dot{c}_{N_\varphi}]\end{aligned} \tag{24}$$

and the nonlinear term takes the form:

$$\boldsymbol{N}(\boldsymbol{q},\psi)=[0,\ldots,\ 0,\ N_1,\ N_2,\ldots,\ N_N] \tag{25}$$

with:

$$\begin{aligned}N_i&=\boldsymbol{q}^T\boldsymbol{E}_i\boldsymbol{q}\quad,\quad i=1,\ldots,N_v\\ N_j&=\boldsymbol{q}^T\boldsymbol{H}_j\boldsymbol{q}\quad,\quad j=1,\ldots,N_w\\ N_k&=\boldsymbol{q}^T\boldsymbol{G}_k\boldsymbol{q}\quad,\quad k=1,\ldots,N_\varphi\end{aligned} \tag{26}$$

The consequences on the organization of the procedure are obvious, corroborating the (26) forms with (23) and stressing on the possibility of storing $\boldsymbol{E}_i$, $\boldsymbol{H}_j$, $\boldsymbol{G}_k$. For example, we can directly write:

$$\frac{dN_j}{d\boldsymbol{q}}=2\boldsymbol{q}^T\boldsymbol{H}_j \tag{27}$$

When nonlinear terms that do not fit the form (26) are considered, then only for them permanent updating is apllied. The storage procedure for $\boldsymbol{L}$, $\boldsymbol{E}_i$, $\boldsymbol{H}_j$, $\boldsymbol{G}_k$ and Φ at various azimuthal positions was also adapted to the specific application involving various optimization loops. The Zernike polynomials have provided such a spectacular reduction of the required storage space that a further improvement was encouraged. Each element of the matrices to be memorized was stored in several separate partitions, each of them containing the terms involved in different optimization loops

(HHC or structural optimizer). A computer program for symbolic calculus is of maximum utility for writing the computer codes that implement this procedure. The option is definite and clear: reducing computing time on the expense of data storage. Updating quantities unaffected by the current loop is avoided as much as possible. But such a procedure is allowed only by proper distribution of objectives between the HH controller and the structural optimizer.

4. The Parametric Study

In order to illustrate the capabilities and performances of HELDYN programs, some significant results of a parametric study are presented here.

The analysis was performed on a test blade used in many recent research applications on the issue [15], roughly similar to the MBB BO-105 hingeless blade. Compared to the standard configuration and set of assumptions used in [15], some important differences occurred:
-although uniform mass and stiffness distribution was used, the model had 21 discrete elements, with potential different proprieties each. Compared to [15], the torsional rigidity was increased up to $\Lambda_p = GJ/m\Omega^2R^4 = 0.006$;
-a complex nonuniform distribution was used for the induced velocity field, based on the Mangler & Squire model;
-a viscous lead-lag damper was included in the model. The results of the analysis with the auxiliary damper, although atypical for hingeless blades, were considered worthy to be presented because they might reveal some modifications of the known correlations between the advance ratio and the mode damping. The nonlinear inflow model could also have a contribution to such differences;
-each degree of freedom was represented by 3 free rotating modes.

Figs. 4,5 show the influence of the flap bending on the lag and flap first mode stability. The corresponding derivative for the lag mode has a swift variation in the 0.2-0.4 advance ratio domain and changes its sign. A different situation is revealed for the flap stability derivative: it is positive and almost constant in the flight domain.

Similar observations emerge from Figs. 6-9, although no other dramatic evolution, similar to that of Fig. 4, can be seen. The influence on first modes stability of the inplane and torsional stiffness also show that the derivatives of the lag damping have the swiftest and irregular variation and therefore need a smaller step of perturbation in the FDM evaluation.

Figs. 10-11 illustrate the influence of the built-in preconing on the lag and flap stability. In Figs. 12-13 is represented the impact of the blade pretwist on the lag and flap stability. The lag damping derivative by linear pretwist changes its sign in the 0.2-0.3 domain of the advance ratio, but the absolute value of the derivative seems to remain moderate in the flight domain.

In Figs. 14-15 it was shown the influence on the blade stability of the Lock number, expressing the ratio between the aerodynamic forces acting on the blade and the blade inertia: $\gamma = (3\rho_\infty acR)/m$. In this application the Lock number was varied both by changing the linear aerodynamic lift derivative a and by changing the linear mass density of the blade m, but no significant differences were revealed, that proves the relevance of this criterium. Again, the derivative of the lag mode damping changed its sign in the 0.2-0.3 domain of the advance ratio.

In figs. 16-17 a synthesis of the lag stability derivatives is shown. They can be directly compared because of the nondimensional terms that are related by the plotted values:

$$\Delta\bar{\alpha} = \frac{\partial\bar{\alpha}}{\partial\bar{d}_i}\Delta\bar{d}_i \tag{28}$$

with:

$$\Delta\bar{\alpha} = \frac{\Delta\alpha}{\alpha_0}\ ,\ \Delta\bar{d}_i = \frac{\Delta d_i}{d_{i_0}} \qquad \alpha_0 = \alpha(d_{i_0}) \tag{29}$$

α being a term of the objective function and d_i a structural variable.

One suggestion that emerged is that both hovering and high advanced ratio flight regimes have to be considered if the lag stability is a chosen criterium.

This parametric study also aimed to evaluating the speed performances of HELDYN programs. This is considered to be a major factor for an efficient use in the sensitivity analysis. In Fig. 18 a comparison is made between the performances proved for HELDYN (if used in a single structural optimization loop) and for similar procedures in the dedicated literature [18]. The results in [18] were obtained on a UNISYS 1100/90 computer. The HELDYN applications were performed on a CDC CYBER 720 computer. Considering the already mentioned intrinsic limitations of the direct analytical approach, the efficiency of the HELDYN procedure, called by a Finite Difference Method can be appreciated as very good. This assessment takes into account that the HELDYN analysis considered 21 discrete elements in the blade structural model, 3 free rotating modes for each degree of freedom in the modal expansion and complex nonlinear distribution for the induced velocity. Further advantages of HELDYN will become effective in multi-loop procedures.

5. Conclusions

The Integrated Multidisciplinary Optimization has become an outstanding trend in helicopter rotor design. In the perspective of a procedure for general optimization of helicopter rotors with active controls, the complementary distribution of the objectives between the cost functionals of the active (HH) controller and the structural optimizer is a strategic choice.

Accordingly, a new package of computer programs was developed for the aeroelastic analysis of rotor blades undergoing moderate deformation and working in a mixed axial-transversal flow regime. Several procedures were implemented for speeding the program by efficient temporary data storage:

-implementation in quadratic form of the nonlinear terms;

-separate storage for terms involved in various loops (e.g. structural optimization, HHC, vortex aerodynamic model) allowing minimum updating;

-Zernike polynomial approximation for all the quantities with non-uniform distribution on the rotor disk.

A comprehensive parametric study proved the capability of the program to reveal the influence of structural changes on aeroelastic behavior. It has also provided information useful in the sensitivity analysis, as guidelines for the choice of the step in the FDM calculation of the aeroelastic sensitivity derivatives. An accuracy validation has not been within reach yet, because of unavailable experimental data. However, even at this stage of the program development, the results were considered relevant for the efficiency of the new software.

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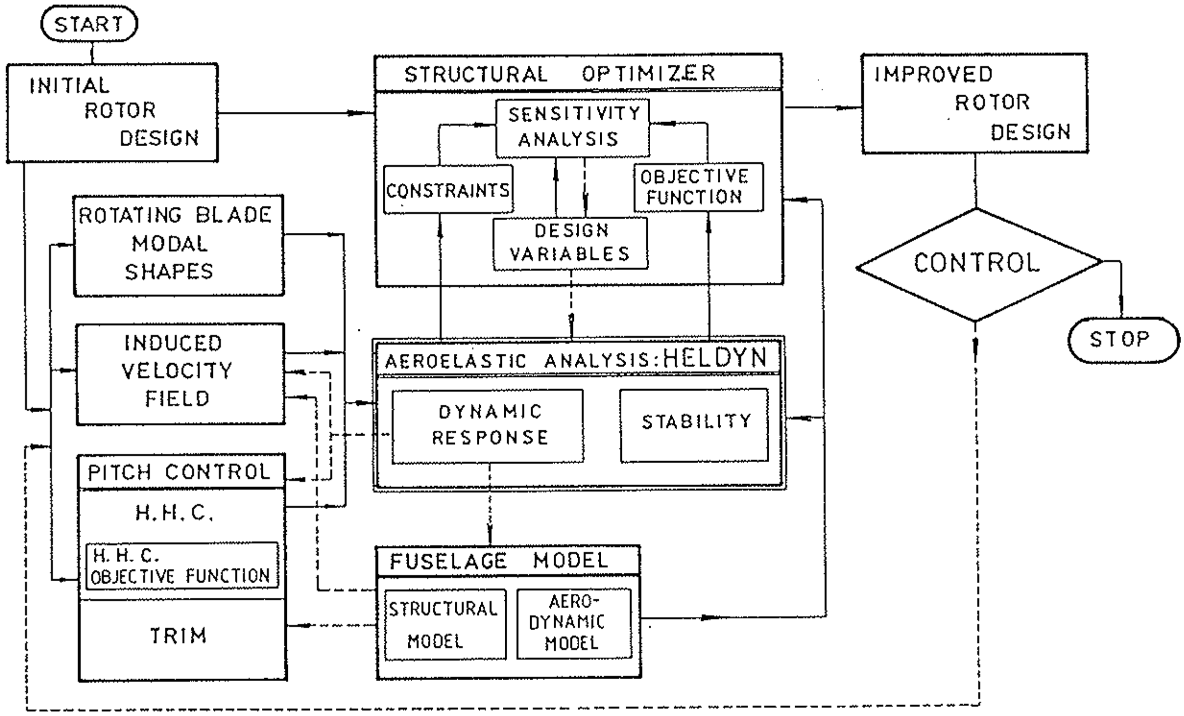

Fig. 1 **Organization of the rotor optimization procedure**

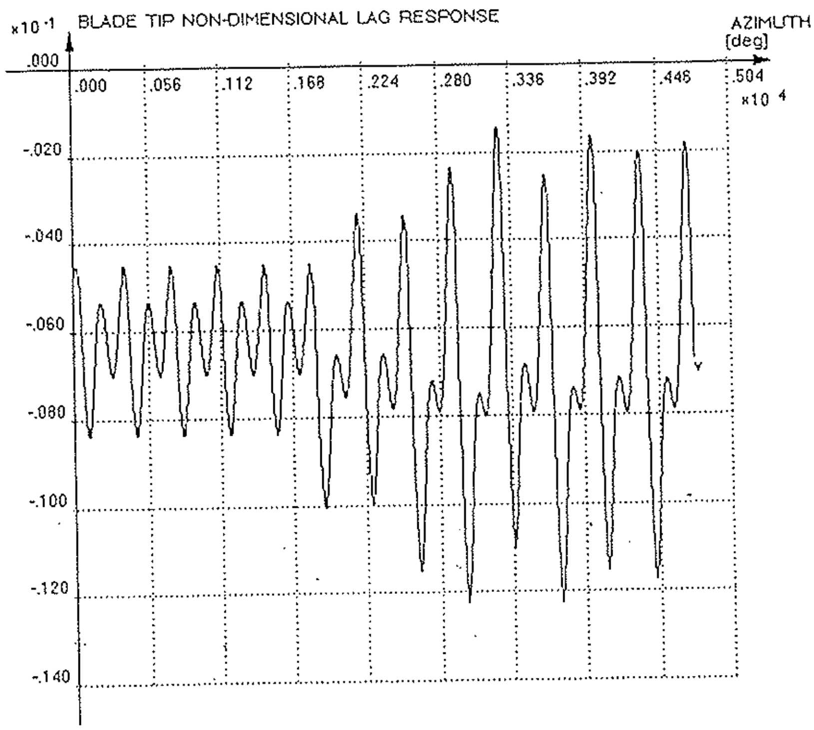

Fig. 2 **Transitory dynamic response obtained by quasi-periodic approximations (sudden ciclic-pitch change, μ=0.2)**

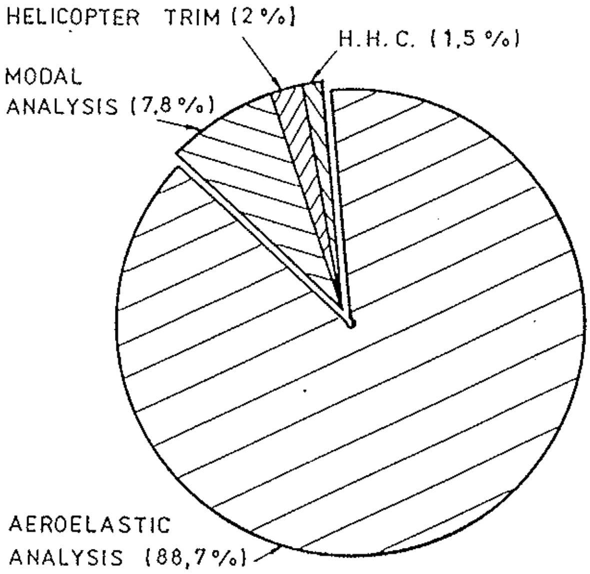

Fig. 3 Typical structure of computing time for a rotor optimization application

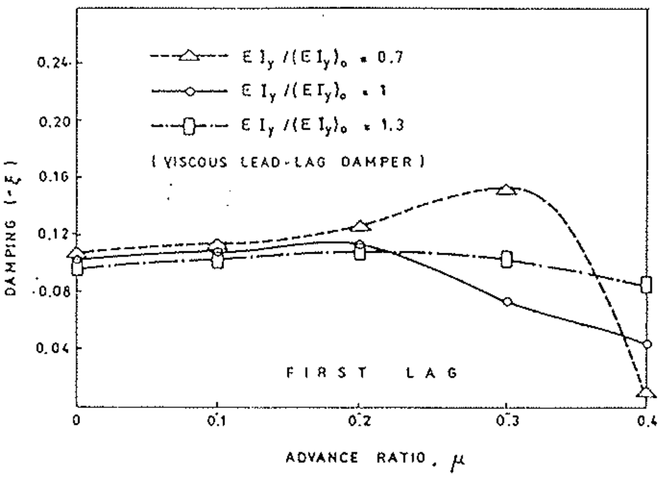

Fig. 4 Influence of flap bending stiffness on lag stability

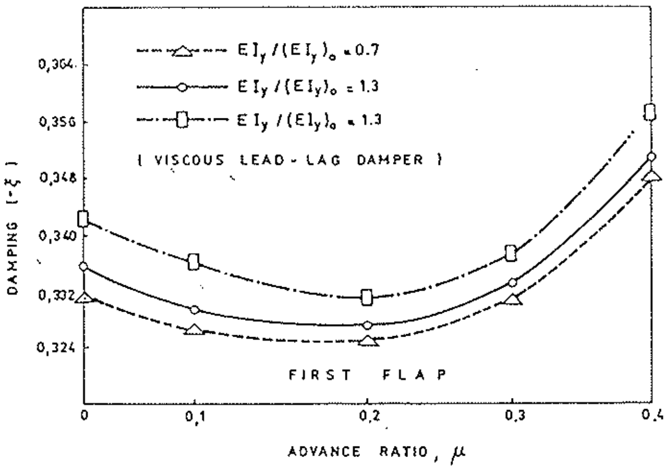

Fig. 5 Influence of flap bending stiffness on flap stability

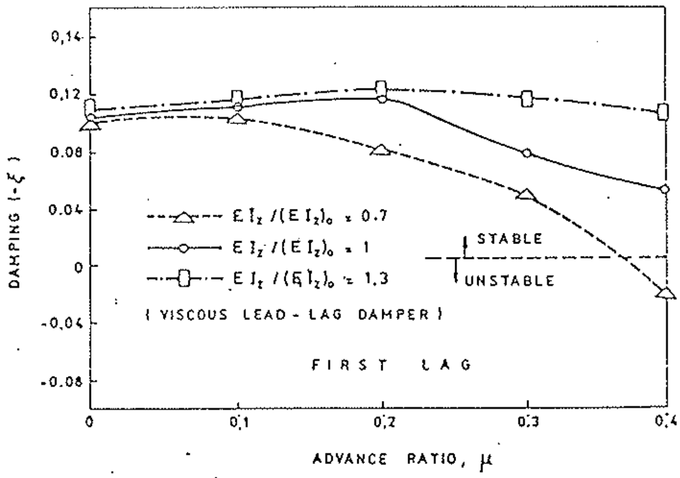

Fig. 6 Influence of inplane bending stiffness on lag stability

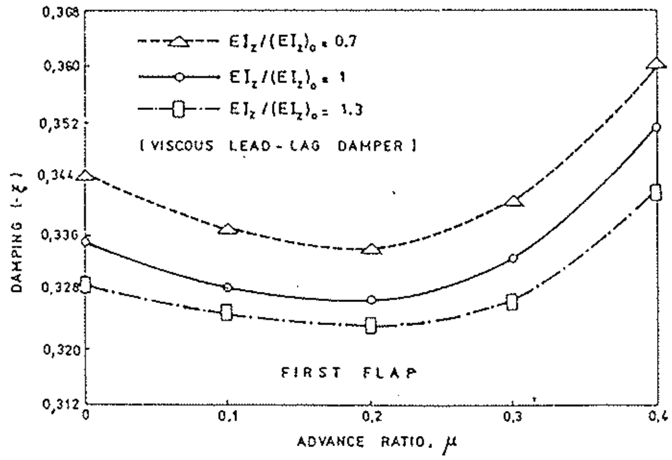

Fig. 7 Influence of inplane bending stiffness on flap stability

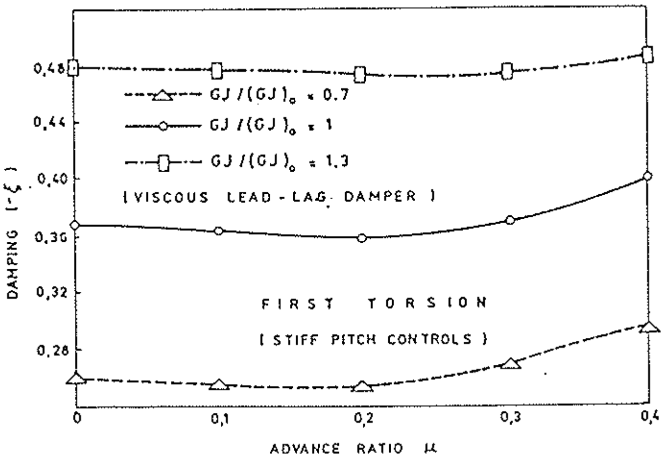

Fig. 8 Influence of torsional stiffness on torsional stability

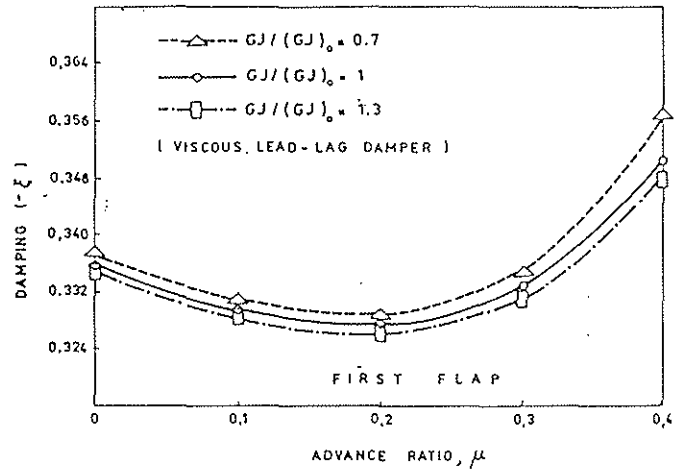

Fig. 9 Influence of torsional stiffness on flap stability

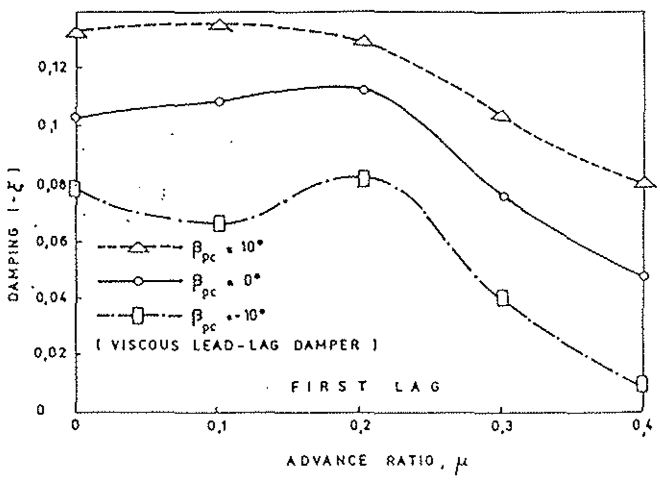

Fig.10 Influence of built-in preconing on lag stability

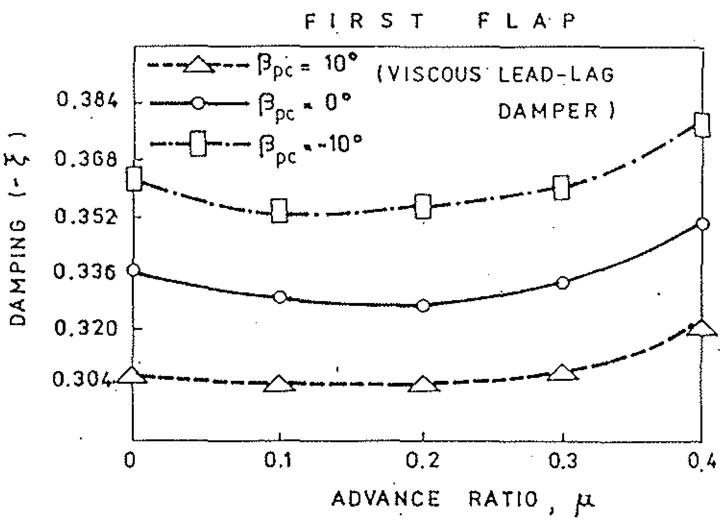

Fig.11 Influence of built-in preconing on flap stability

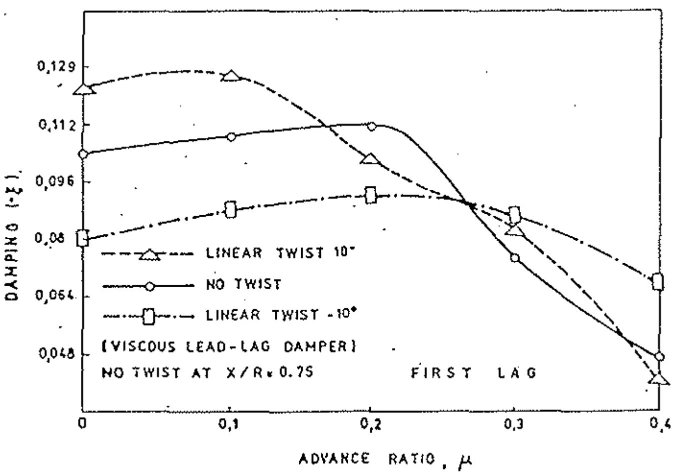

Fig.12 Influence of blade pretwist on lag stability

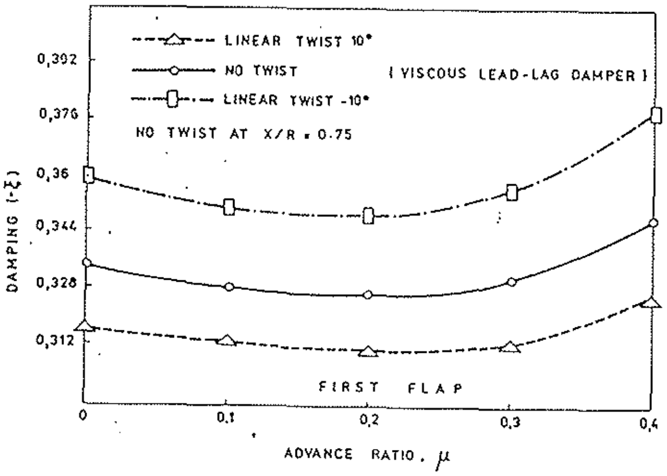

Fig.13 Influence of blade pretwist on flap stability

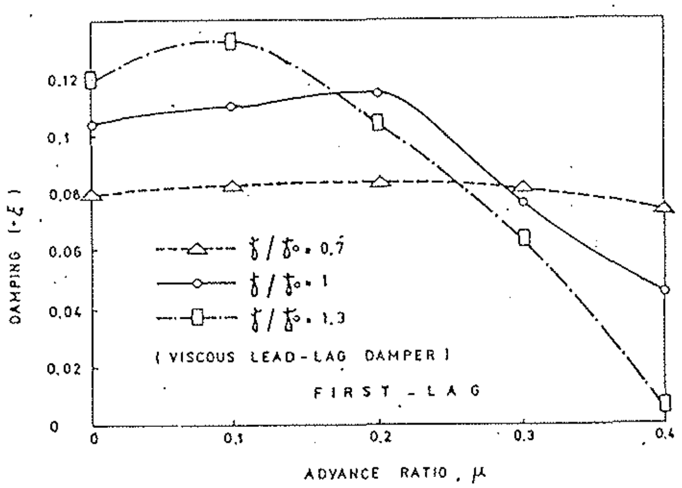

Fig.14 Influence of Lock number on lag stability

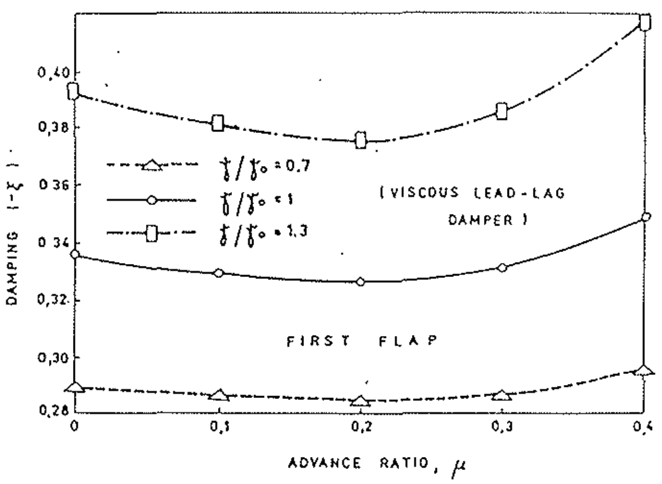

Fig.15 Influence of Lock number on flap stability

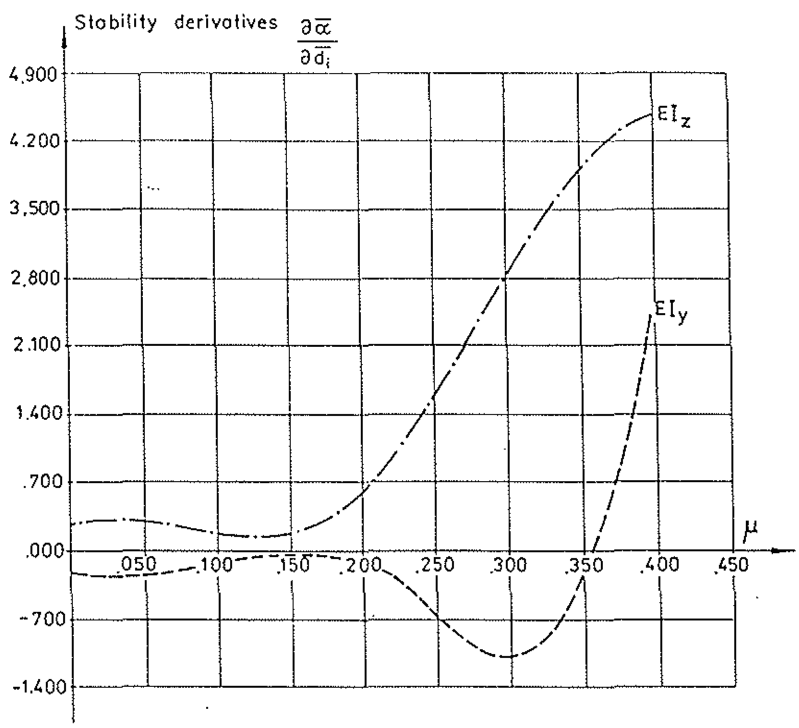

Fig.16 First lag mode stability derivatives associated with bending stiffness (EIy-flap; EIz-inplane)

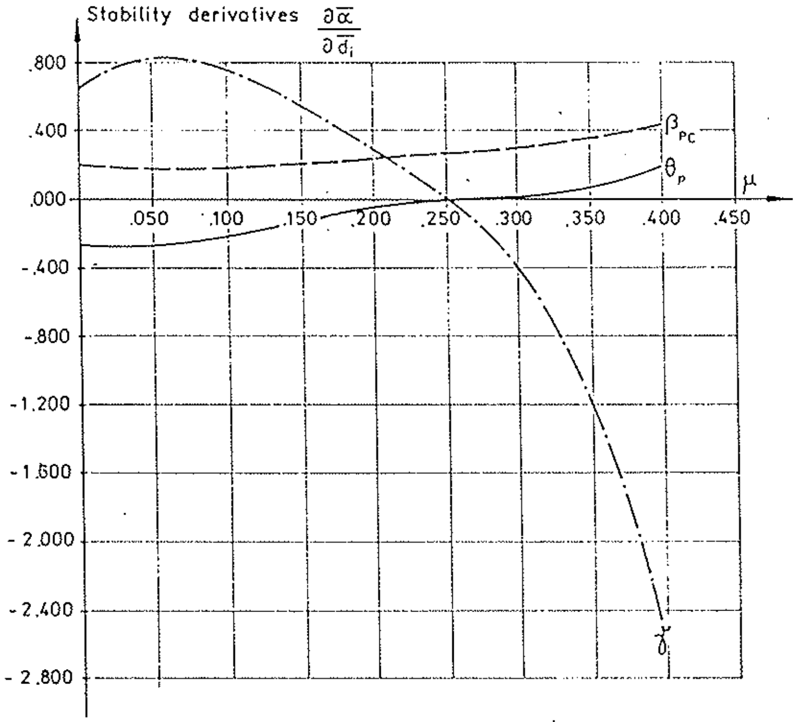

Fig.17 **First lag mode stability derivatives associated with built-in preconing, blade linear pretwist (both in degrees) and Lock number**

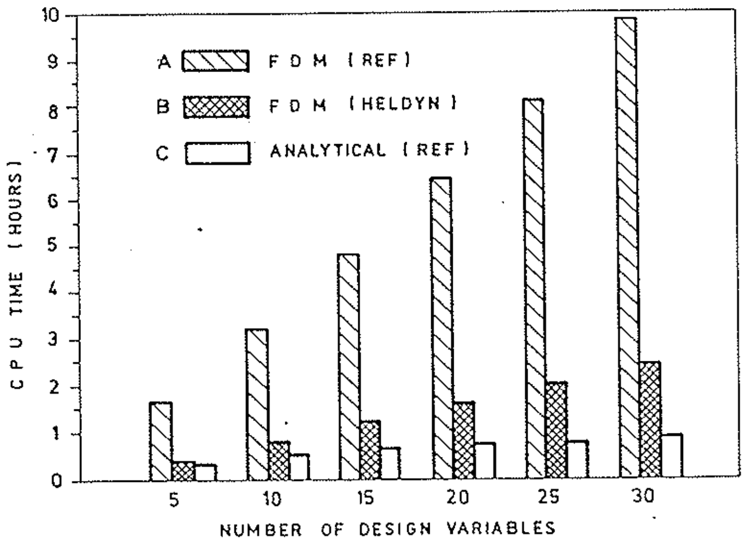

Fig.18 **CPU time for the sensitivity analysis (the reference case from [18])**

EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

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