INTEGRATED STRUCTURAL OPTIMIZATION IN THE PRELIMINARY AIRCRAFT DESIGN

G.Bindolino[†], M.Lanz[‡], P.Mantegazza[‡], S.Ricci[*1]
Dipartimento di Ingegneria Aerospaziale
Politecnico di Milano

Abstract

The paper presents a numerical procedure for the integrated design of structural and control parameters of aerospace structures in a preliminary to intermediate design phase. The approach is based on a multi-model formulation of the aeroservoelastic problem, allowing to take into account completely different and independent models and/or flight conditions coupled only by a set of structural and control design variables.

Several servo-structural responses, such as displacements, stresses, buckling loads and aeroelastic characteristics, can be evaluated and used in order to build up appropriate objective and constraint functions during the optimization process.

Some examples are discussed to demonstrate the soundness of the approach and its flexibility of use.

Nomenclature

- [M] mass matrix
- [C] damping matrix
- [K] stiffness matrix
- [A] aerodynamic transfer function matrix
- [B] feedback input matrix
- [F] external force input matrix
- [R] response matrix
- [S] measurement matrix
- [G] gain matrix
- [H] transfer function matrix
- [Φ] PSD matrix
- [Q] Covariance matrix
- {q} extended generalized coordinates
- {u} feedback input vector
- {f} external forces vector
- {y} response vector
- {m} measurement vector
- {x} design parameters
- G_j generic constraint function
- ρ air density
- V asymptotic air speed
- $\mathcal{M}$ asymptotic Mach number
- c reference aerodynamic chord
- ω circular frequency
- k reduced frequency ($\omega c/V$)
- s Laplace operator

Subscripts

- m motion
- g gust
- F fixed part
- S structural design variable
- C control design variable
- a acceleration
- v velocity
- d displacement
- y response
- f external force

Introduction

The adoption of new technologies related to composite materials and active control gives the designer of modern aerospace vehicles new tools and opportunities to achieve improved response, performances and reduced structural weight. As active structural control is now becoming feasible for practical engineering applications, it can be foreseen that its integration into structural design will lead to aerospace vehicles that more and more evolve into complex very flexible dynamic aeroservoelastic systems. Adverse interactions can then easily arise that hinder the obtainment of an optimum design if this is not faced in an integrated way from the very beginning. So the need to move from the mere structural optimization to an integrated servo-structural optimization is now evident[1-3] and, in view of the vast and multi-disciplinary design parameters space, the adoption of an integrated multi-model, multi-objective, multi-constrained optimal design procedure becomes a must. While several well established, but disjoint, techniques exist both for structural optimization and control design, efficient methodologies for an integrated, and possibly simultaneous, servo-structural design are not so well developed yet. In fact it is very difficult to decide how to accomplish this integration in the design process and different approaches to this specific problem found in the literature are briefly reviewed in the following.

In the first, the so called sequential approach, structural and control designs are performed in a separate way, i.e. control variables are held constant during the structural design and vice versa the structure is not modified during the design of the control system. The process is then iteratively repeated till convergence.[3-5] The main advantage of this methodology is in making it very easy to use the well established design algorithms generally adopted in each discipline making up the integrated design

† Researcher
‡ Associate professor
* Fellow of Ing. P.Foresio Foundation

process.

In the second approach the integrated servo-structural design is carried out by operating simultaneously on both structural and control design variables[6-11] and a possible way to profitably achieve a simultaneous servo-structural optimization is to define a weighted multi-objective formulation that allows an appropriate choice of the constraints and objective functions depending on the kind of design problem at hand. This generally implies the adoption of minimization algorithms capable of effectively working both on structural and control design parameters and constitutes a difficulty because of the little experience available in facing large order optimizations problems with an heterogeneous parameters space such as that of servo-structural design. Even the choice of the objective function is not easy because of the hard task of synthesizing various, and sometimes conflicting, design specifications into a single simple weighted objective function and/or constraints. In fact this can lead to different optimal solutions depending on the different weights adopted and, being it difficult to determine their relation to actual design specifications, different objective optimizations must be tried and verified a posteriori for their suitability to design specifications.

There is a third approach to integrated servo-structural optimization that can be placed between those previously presented. It consists in an extension of the multilevel optimization concept developed in recent years [12-14] and tries to couple the advantages of a sequential optimization with the concept of integrated simultaneous design. In this approach the control and structural design are considered just as separate second level problems that operate independently on structural and control design variables. The first level problem introduces an external loop related to an objective function integrating optimal servo-structural performances and constraints. The main difficulty of this method is still in the choice of an appropriate first level objective function and in the difficulty of calculating the sensitivities of this function with respect to the optimal values of the design variables separately obtained in the solution of second level problems.

This paper presents an approach to integrated simultaneous servo-structural optimization primarily aimed at the preliminary to intermediate design of aerospace structures that is based on the following features :

- A multi-configuration problem formulation that allows to simultaneously consider in the optimal design completely different and independent servo-structural models and/or flight conditions coupled only by a set of common design parameters. It should be noted that the terms: model, configuration, flight and design condition would be used interchangeably in the paper.
- A weighted multi-criteria minimization in which the objective and the constraint functions can be chosen in each optimization step among the different response and performance indices, allowing the interchange of constraints and objective function in the sense that a constraint can become an objective function and vice versa.
- Several analysis and sensitivity modules for the computation of different servo-structural responses and performance criteria such as displacement, stresses, buckling loads, flutter, different static and dynamic aeroservolastic responses.
- An integrated servo-structural design formulation in which the optimization phase is performed using simultaneously the structural and the control variables.

The present work illustrates the main structure of the program, called *AIDIA*, developed on the base of the above points and shows some results obtained using this code.

Description of *AIDIA*

AIDIA allows to solve several and different optimization problems aiming in particular at preliminary and intermediate design phases in which not excessively detailed models are needed.[15] In order to avoid the development of new basic analysis programs, while maintaining extensive and state of the art modeling capabilities, *AIDIA* can be interfaced to different structural and aerodynamic modules. Presently MSC/NASTRAN is being used because of its availability, easy user interaction with internal data and general capabilities including aerodynamics.

AIDIA makes an extensive use of two approximation concepts :

At first approximate modal bases for both the static and dynamic models are used to reduce the dimensions of the analysis problems. In this way a multi-model problem can be passed to *AIDIA* as a neutral model and the optimization has not to mind about its details but must just be capable to handle the different relations, mainly eigenproblems and linear algebraic and differential equations, implied in each model both for response and constraints analyses and sensitivities. In view of the use of reduced order models the numeric tools adopted tend, except for some peculiar aeroelastic problems, to be homogeneous and standard and thus effective numerical techniques of general use are readily adoptable. Often a condensed model cannot manage detailed design problems but this is not the kind of problems to be solved within *AIDIA*, as it is believed that optimized design integration should not be sensitive to small detail but mainly to overall performances. The detailed design can be left to specialized single discipline programs without major losses in the obtainment of good solutions. An approximate optimization is then generated by a convex linearization of the response functions [16-17] and the minimization is carried out on the approximate problem by a feasible directions method, i.e. CONMIN.[18-19] This clearly indicates that *AIDIA* aims at the development of simultaneous integrated servo-structural design by stemming from optimum structural design ground. After the minimization of the reduced order multi-model problem, a complete "exact" analysis is performed by looping back to large order models and external analysis programs and, if the results do not match those of the low orders models, the previous two steps are repeated till a satisfactory match is obtained.

From a software point of view, *AIDIA* is a general management program that integrates in an open architecture the different analyses and the minimization programs. In this manner it is always possible to introduce new response performances or goals just by adding the corresponding analysis and sensitivity modules.

Any problem is formulated in three distinct phases, see Fig.1. The first is the *Definition* phase, in which the type of analysis and the optimization required for any model are defined.

The second is the *Analysis* phase, in which the structural and control responses and sensitivities are computed for each configuration. Finally it comes the

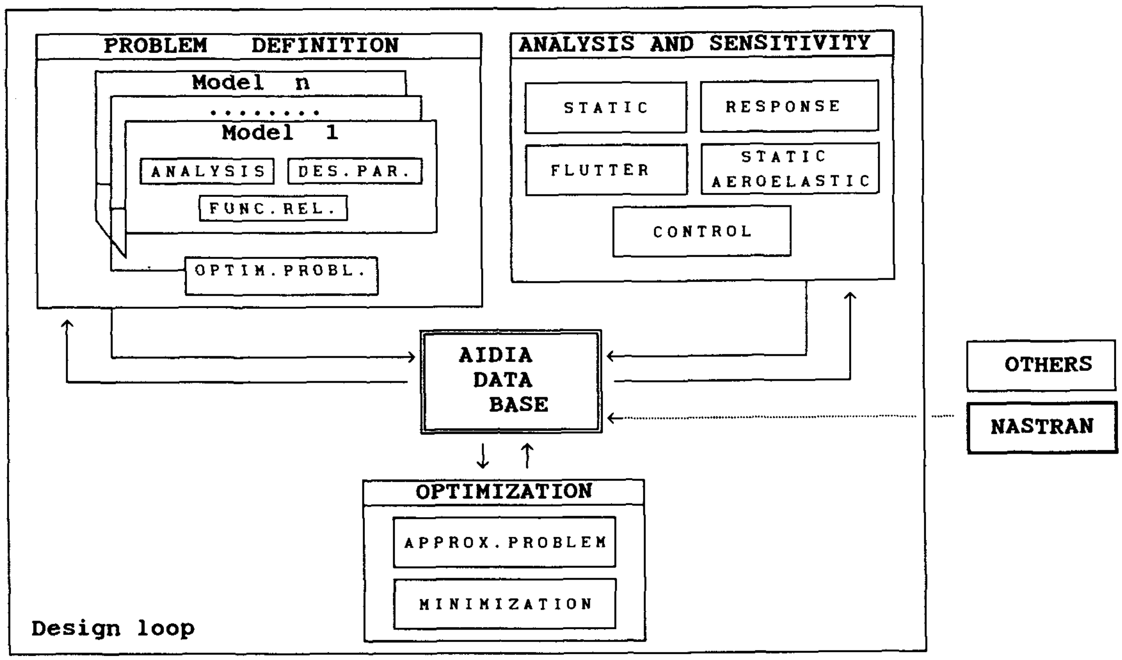


Fig.1 *AIDIA* functional description

Optimization phase in which the results of the analysis and sensitivity phases are gathered to generate an analytical approximate problem on which the minimization of the chosen objective functions is carried out and the design variables updated.

The versatility of the procedure is enhanced by the possibility of maintaining the designer in the loop to monitor and interact with the different phases, up to the definition phase, allowing him to choose among the different computational strategies and the different kinds of servo-structural problems to be solved. The different phases are described below.

Problem Definition

In *AIDIA* configurations or models assume a fundamental role. Any configuration is composed by all the modal data describing the aeroservoelastic system, the specific analysis requested by the problem associated to it and all the informations that allow this analysis to be performed. In particular any configuration includes the definition of the set of design parameters selected from the overall design space that are specific to it, the structural and/or control responses and the functional relations that are briefly detailed in the following after an explanation of the type and use of modal bases.

Modal Bases

The basic assumption in the modal approach is that the true displacement of the structure can be represented as a linear combination of a limited set of mode shapes of unknown amplitude. In *AIDIA* the modal formulation is adopted both for dynamic and static problems. The modal base can be a combination of vibration modes, static deformations, inertia relief self balanced static deformations, Guyan modes or a combination of any of the aforementioned modes. The static modes are always mass orthogonalized to rigid body modes to maintain a consistent definition of mean axes and to establish consistent elastic correction for aerodynamic derivatives.[20-21] The choice of the type of modes to be used depend on the type of analyses that must be carried out on each particular model. The use of modal bases is a standard approach in dynamic analyses and is generally accepted because of the need to maintain a balanced compromise between precision and economy for the most demanding aeroservoelastic analyses. The adoption of modal bases in static aeroelasticity is more recent and gives advantages as it allows to use a common aerodynamic formulation for all aeroelastic problems while affording models as valid as those arising from the more common flexibility formulation of static aeroelastic problems.[20-23] The adoption of static modal bases related to a limited set of elementary loads in static analyses often causes a poor approximation of the stresses of the modified structure imposing the need of many iterations with external analyses when stress constraints are critical. This type of modal basis is in fact a *zero-order approximation of the structural* displacement with respect to design parameters. The level of approximation can be improved by adopting a perturbation base in which the structural displacements corresponding to the real load condition and its derivatives with respect to design parameters are chosen as mode shapes.[24] In this way it is often possible to solve very complex optimization problems by one or two modal bases generation i.e. cycles on the external analyses. The adoption of perturbation modes could be profitably used also for other type of analyses available in *AIDIA* but this is not worth the cost because of the response performances associated to them, e.g. stability or control effectiveness conditions, are less sensitive to the type of modes being mainly associated to eigenvalue problems for which sensitivity to eigenvector shapes is second order. This would not be the case for dynamic stress calculations but the cost of computing eigenvector derivatives for many design parameters discourages their use.

Design Parameters

The design parameters that can be used in an optimization problem are : section properties of truss and beam elements, thickness of isotropic plates including bending behavior, thickness and fiber orientation of layers of plane stress composite plates, positions of balancing or tuning masses and the gains of active control systems including parameters of compensators dynamics. It is possible to link the structural design parameters to reduce the dimension of the design space.

Structural and Control Responses

The indices that can be computed by the different analysis modules are :

- stresses in any structural element
- physical displacements at discrete points
- natural frequencies and modes shapes
- aeroelastic eigensolutions- responses to external excitations
- divergence speed
- control effectiveness including inversion
- corrections of stability derivatives due to structural deformation.

Functional Relations

A functional relation establishes an arbitrary relation among different design parameters and/or responses. Several relations can be used in a general optimization process e.g.:

- stress or strain components of any element to compute safety margins, e.g. Von Mises criteria for isotropic elements or Tsai criteria for composite elements.
- physical nodal displacements to impose a particular deformation to the overall structure.
- admissible flutter solutions to define acceptable damping and frequency domains within the flight envelope allowing to: define a limit flutter condition, avoid unacceptable damping humps and define desired frequency separations both between modes and with respect to zero. The latter can be helpful in preventing zero frequency flutter conditions with the ensuing possible troublesome coupling with static aeroelastic problems.[25]
- design variables to compute global performances, e.g. structural weight or gains norms, to be adopted as objective function in the control problems.
- design variables to impose some technological constraints.

Optimization Problem Definition

Following the definition of the structural geometry, the modal bases and the kind of analysis necessary to compute the needed responses we must now define the *Optimization Problem*. This is composed by the design variables and the objective and constraint functions.

Design Variables

In the previous section the design parameters have been defined depending on the servo-structural models taken into account. At this time those design parameters that must be considered either constant or variable in the minimization phase are determined. The sensitivities of the responses of interest and the defined functional relations will be calculated, during the analyses and sensitivity phase, only with respect to those variables.

Objective and Constraint Functions

Based on the multi-objective formulation adopted for the minimization phase, *AIDIA* allows to choose any of the responses and/or functional relations established in the definition phase either as objective or constraint function. It is worth noting that problems that often cannot be considered in the most common structural optimizations, such as min-max problems can be routinely faced by *AIDIA*. This can be very useful in forcing a feasible design or to alleviate particularly critical constraints , e.g. the minimization of the maximum stress in certain part of the structure.

Analysis Modules

The outcome of the analysis definition phase are mainly the elements of the following equations in which {q} is the vector of the extended generalized coordinates, i.e. including sensor, compensator and actuators dynamics :

Open-loop dynamic response and stability

$$(s^2[M] + s[C] + [K] - \frac{1}{2}\rho V^2[A_m(k,\mathcal{M})])\{q\} =$$

$$\frac{1}{2}\rho V^2[A_g(k,\mathcal{M})])\{v_g\} + [B]\{u(s)\} + [F]\{f(s)\} \tag{1}$$

Definition of responses of interest

$$\{y\}=[R(s)]\{q\}+[R_g(s)]\{v_g\}+[R_u(s)]\{u\}+[R_f(s)]\{f\} \tag{2}$$

Measurements equations

$$\{m\}=(s^2[S_a]+s[S_v]+[S_d])\{q\} \tag{3}$$

Feedback law

$$\{u\} = [G]\{m\} \tag{4}$$

Equivalent structural matrices defined by feedback

$$\begin{aligned} [M_c] &= [B][G][S_a] \\ [C_c] &= [B][G][S_v] \\ [K_c] &= [B][G][S_d] \end{aligned} \tag{5}$$

Closed-loop dynamic response and stability

$$[Z(s)]\{q\}= \frac{1}{2}\rho V^2[A_g(k,\mathcal{M})])\{v_g\}+[F]\{f(s)\} \tag{6}$$

$$([Z(s)]=([M_F+M_S+M_C]s^2+[C_F+C_S+C_C]s+[K_F+K_S+K_C]+ - \frac{1}{2}\rho V^2[A_m(k,\mathcal{M})])\{q\} \tag{7}$$

Frequency response

$$\{y(\omega)\}=[H_f(\omega)]\{f(\omega)\} + [H_g(\omega)]\{v_g(\omega)\} \tag{8}$$

PSD response

$$[\Phi_{yy}(\omega)]=[H_f][\Phi_{ff}(\omega)][H_f]^H+[H_g][\Phi_{gg}(\omega)][H_g]^H \tag{9}$$

Covariance calculations

$$[Q_{yy}] = \int_{-\infty}^{\infty} [\Phi_{yy}(\omega)] d\omega \tag{10}$$

Quasi steady aerodynamic approximation

$$[A(s)] = \left(\frac{s\ c}{V}\right)^2 [M_A] + \left(\frac{s\ c}{V}\right) [C_A] + [K_A]) \tag{11}$$

Using the index r for rigid body modes and e for deformation modes the following are defined for static aeroelastic problems:
Static aeroelastic stiffness matrix:

$$[K_{AE}] = [K_{ee}] - 1/2 \rho V^2 [K_{A\,ee}] \tag{12}$$

Aeroelastic divergence condition for the aircraft

$$[K_{ee}]\{q_e\} = 1/2 \rho V^2 [K_{A\,ee}]\{q_e\} \tag{13}$$

Aerodynamic derivatives of the elastic vehicle (see Ref.26 for their correspondence to flight mechanics derivatives)

$$[M_{A\,e}] = [M_{A\,rr}] - [K_{A\,re}][K_{AE}]^{-1}[M_{A\,er}] \tag{14a}$$

$$[C_{A\,e}] = [C_{A\,rr}] - [K_{A\,re}][K_{AE}]^{-1}[C_{A\,er}] \tag{14b}$$

$$[K_{A\,e}] = [K_{A\,rr}] - [K_{A\,re}][K_{AE}]^{-1}[K_{A\,er}] \tag{14c}$$

The above equations are used according to the required analyses as briefly described below. More details can be found in the cited references and need not to be repeated here.

Static Analysis

Static analysis implies the solution of Eq.(1) for s = 0 and the recovery of desired responses by Eq.(2). Calculation of the sensitivities is done by standard methods, either directly by taking the derivatives of Eqs.(1,2) or by the so called unit load method. The solution of linear symmetric systems of equations is all is needed.

Flutter Analysis

Flutter analysis solves [Z(s)]=0 for all the desired root at varying flight condition and guaranteeing the alignment to the points determining the boundary of admissible frequency and/or damping domains, the latter being defined either as relative or absolute. It is remarked that it is possible to define different acceptable eigensolution domains for different modes. Due to the s-k, usually known as p-k, approximation implied in Eqs.(1,6) the solution of the flutter problem represent a non standard eigenproblem that is solved by combining a continuation solution that unifies the analysis and sensitivity calculations in a very effective way.[27-29]

Static Aeroelastic Analysis

Static aeroelastic analyses adopt the quasi steady approximation of the aerodynamic transfer functions described by Eq.(11) whose matrices are obtained by interpolation of [Am] and [Ag] at low reduced frequencies. It takes into account the divergence condition relative to Eq.(13) and different responses for consistent trim or steady state response conditions that can be defined on Eq.(1) using quasi-steady aerodynamic. For each trim condition a dynamic divergence, an effectiveness and inversion condition can be defined and taken as constraint or objective function. Only solutions of system of equation and eigenvalues calculation are required. The variation of aerodynamic derivatives, i.e. Eqs.(14), can be also included as design condition. An extensive and detailed presentation of these problems can be found in [20-22].

Dynamic Response Analysis

The response analysis can be easily carried out in the frequency domain since the unsteady aerodynamic formulation provides the generalized harmonic aerodynamic forces defining the transfer functions to structural and control motions and gust inputs.[27] The only condition that must be satisfied to apply the frequency approach is clearly the stability of the system to allow the use of the Fourier Transform to synthesize deterministic responses into the time domain. Random ergodic responses can be obtained directly in the frequency domain in the form of PSDs by using Eq.(9). Design criteria are generally defined in term of allowables that can be related to covariances calculated by using Eq.(10). The evaluation of response sensitivities follows closely the techniques used in static analyses as the equations to be solved and the relations involved in the frequency response are formally the same except that complex number are used. Sensitivities for deterministic time responses can be obtained by inverse transforming the corresponding frequency domain quantities.

Control Analysis

The approach to control modeling introduced in *AIDIA* appears clearly from the equations presented above which make no conceptual distinction between passive and active control. Control laws are simply considered just as another way to modify the mass, damping and stiffness properties and easily fit the classical aeroelastic stability and response formulations.[30-32] Thus the integration of control design within *AIDIA* simply means to include the elements of the gain matrix [G] into the design variables. Generally control variables influence mainly flutter and dynamic response analyses, i.e. active flutter suppression and structural load alleviation, and nothing needs to be added to the analyses and sensitivity calculation already presented for those topics. Actually the matrices [S] and [B] are constant but it could be possible to associate the elements of those matrices to design variables to include optimal sensors and actuators positioning in the integrated design process.

Optimization

The last phase is devoted to the minimization of the chosen objective function. This is the only point in the global optimization process in which all design variables, structural and control responses and the functional relations are simultaneously considered. In fact in *AIDIA*, until the optimization phase, all the configurations describe independent design problems that can be characterized by a completely different structural and/or control model, design parameters and flight conditions. Generally the structural design variables common to different configurations have the same values since they are associated to the same structural elements. On the contrary the control variables can assume different values for different and independent configurations. In fact since the latter ones are not associated to an invariant geometrical property of the structure they can be reconfigured depending on the flight condition. Thus the adoption of several configurations to design an active control system can reflect a possible gain scheduling policy. On the other hand maintaining the same gains for different models can reflect either the search of robust controllers and/or insensitivity to sensors and/or actuators failures or both.

The Approximate Problem

One of the most useful techniques actually adopted in the optimization algorithms to generate the approximate problem is the so called "convex linearization".[16-17] The convex linearization is applied to the servo-structural responses and functional relations except for those that are known in analytical form, i.e. structural weight or gains norm. This approximation leads to a linear Taylor expansion expressed in direct or reciprocal variables depending on the positive or negative sign of the derivatives with respect to any design variable :

$$G(x)=G(x_0)+\sum_1^{NI}\left(-x_0^2\frac{\partial G}{\partial x_i}\right)_{x_0}\left(\frac{1}{x_i}-\frac{1}{x_0}\right)+\sum_1^{ND}\left(\frac{\partial G}{\partial x_i}\right)_{x_0}\left(x_i-x_0\right) \quad (15)$$

NI = number of variables with gradient < 0

ND = number of variables with gradient > 0

This approximation is generally conservative [33] and allows the use of relatively large move limits on design variables.[34] All the responses and gradients are computed analytically and this represent the most expensive operation in the optimization process.[35]

Multi-objective Minimization

In *AIDIA* the minimization is performed with the feasible directions method [18] implemented in CONMIN.[19] This has been experienced as one of the most efficient methods both for the minimization of the objective function and for the search of a feasible design point starting from a very infeasible design condition. To improve the versatility of the global optimization process, the optimization problem is formulated in a more general way. The classical minimization problem is written as

$$\min \text{ OBJ } (x_i)$$
$$\text{subject to } \; G_j(x_i)\le 0$$
$$i=1,\ldots N \; ; \; j=1,\ldots M$$
$$\text{(Problem 1)}$$

OBJ is the objective function and G_j are the constrain functions. We can write the same problem in a more general way by using an approach close to that presented in [36] i.e.

$$\min (\max) \; \beta_j \text{ or } \gamma$$
$$\text{subject to :}$$
$$\beta_j - G_j(x_i) \le 0 \; ; \; \gamma - \text{OBJ} \le 0$$
$$i=1,\ldots N \; ; \; j=1,\ldots M$$
$$\text{(Problem 2)}$$

Problem 2 includes Problem 1, as the latter is readily obtainable by minimizing γ while setting $\beta_j=0$. However, by minimizing β_j and setting $\bar{\gamma}=\gamma$, it is now possible to minimize any response function included in the constraints and considering the original objective function just as another generic constraint.

This formulation requires only the introduction of the coefficients β_j as the derivatives of response function with respect to these new variables are trivial. In *AIDIA* the structural weight, the gains norm and a sum of these quantities are the standard objective functions but it is easily possible, using β_j , to transform these functions in constraint functions and any response or *functional relation in a* new local objective function.

The capability of taking any constraint as an objective function is very important in producing feasible starting solutions for the optimization process and one of the reason leading to the adoption of CONMIN is its capability to produce a feasible design for a general constrained optimization problem by optimizing violated constraints. In fact determining a feasible solution is the main difficulty in starting the optimization when control design variables are taken into account as in this case the trivial upward scaling adoptable for structural variables does not suffice. The extensions of this approach to the whole design iteration, under the control of the designer, has proved very valuable.

Examples

Some examples related to integrated servo-structural optimization will now be presented. In view of the extensive use of modal bases, one of the many applications [15-37] carried out to verify their suitability to design problems with simultaneously critical stress and flutter constraints is reported here as the first example.

Example N.1

In this example two design of a swept wing are performed. In the first *AIDIA* is used to obtain the minimum weight of an all metal structure subjected both to static and flutter constraints. In the second the use of composite materials and fibers orientation to satisfy the flutter constraints with the lowest weight penalty is investigated.

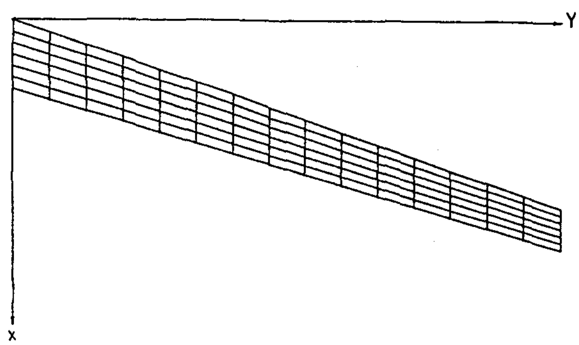


Fig.2 Swept wing structural discretization.

Case 1

The structure of Fig.2 is a swept all aluminum alloy wing subjected to two distinct load conditions, i.e. maximum wing root bending and torsion. Static constraints are imposed on the von Mises stresses in all the structural elements, on the maximum tip displacement for the first load condition and on the maximum tip rotation for the second load condition. The flutter constraints are shown in Fig.3 with the initial *V*-g plot.

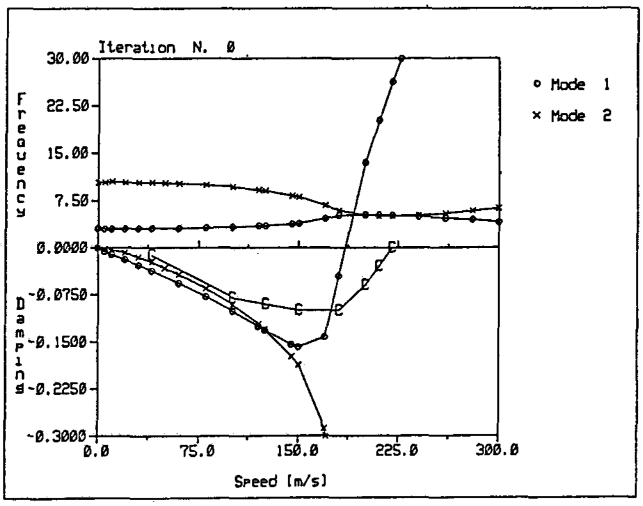


Fig.3 Swept wing initial *V*-g plot with damping constraint.

Two static and one dynamic model have been adopted. The static configurations are associated to the different load conditions and require a static analysis to compute the structural responses, i.e the stresses and the displacements. Both static models are based on perturbation modal bases. The dynamic model is the aeroelastic model required for flutter analysis and is based on the first ten vibration modes. The design variables are the thicknesses of the skin and web panels and the cross section areas of all stringers. The number of design variables has been limited through a linking operation in which all the structural elements have been grouped into five structural blocks across the wing span.

Fig.4 displays the structural weight versus iteration cycle showing the obtainment of minimum weight in twelve iterations. It must be noted that

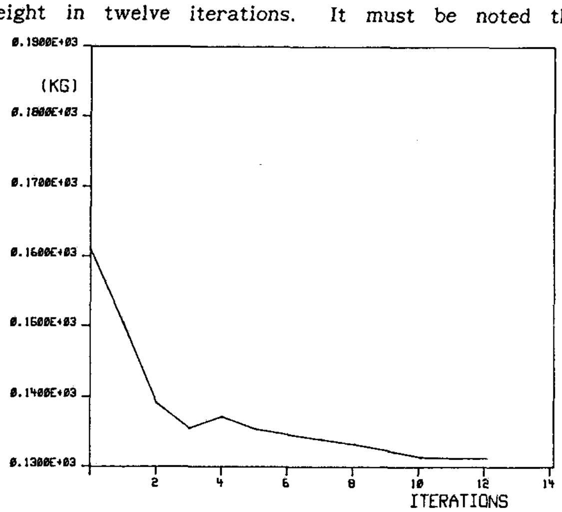


Fig.4 Swept wing weight history.

two modal bases generation have been used. The second was carried out after the sixth design iteration within *AIDIA* and the switch to a new modal base is evidenced by the corresponding slight jump shown in Fig. 5-6 in which the most critical stress and displacement constraints are reported. Both the intermediate and final NASTRAN verifications of the results obtained with *AIDIA* showed no discrepancies and the second base generation was carried out because of the cautious attitude of the designer while the weight was still decreasing. Fig.7 shows the final *V*-g

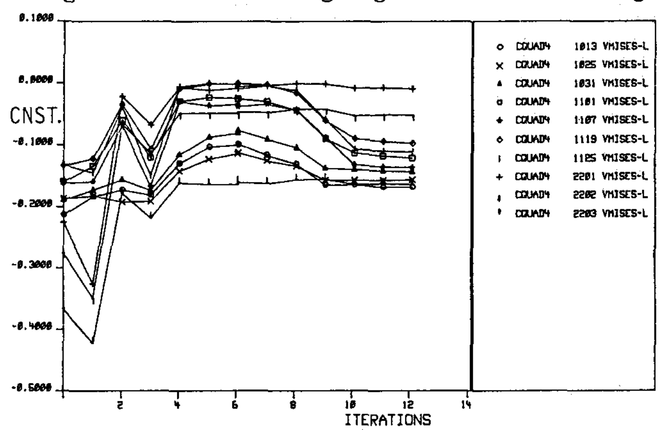


Fig.5 Swept wing critical stress constraints.

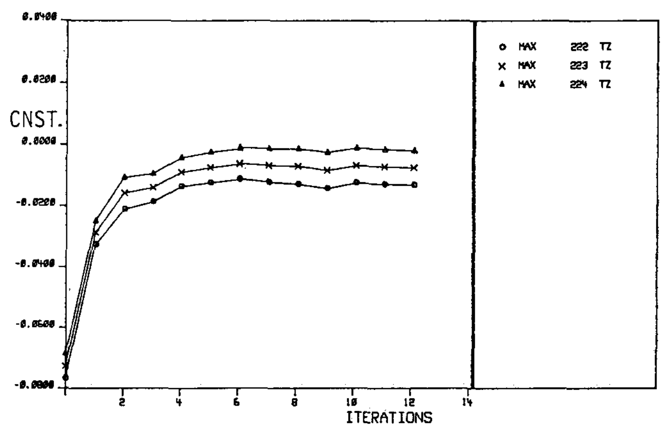


Fig.6 Swept wing critical displacement constraints.

plot obtained from NASTRAN; it should be compared to the initial design shown in Fig. 3.

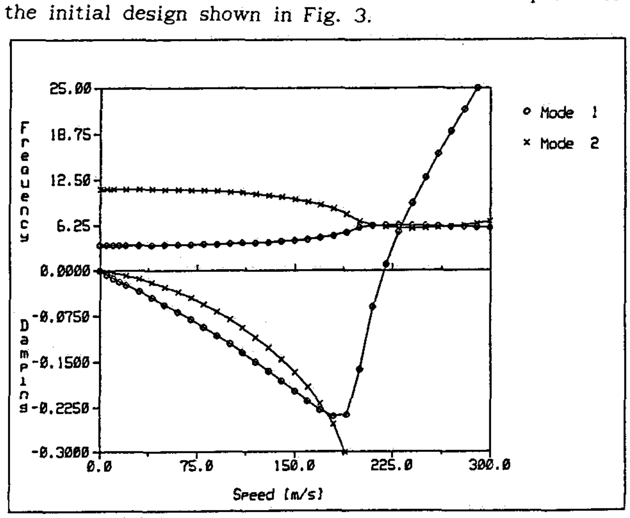


Fig.7 Swept wing final NASTRAN *V*-g plot.

Case 2

In this case it is assumed that a good static design is already available for the wing of Fig. 2 having a composite skin, but that the flutter requirements are badly violated (Fig. 11a). It is then desired to change the design with a minimum weight penalty. At first an optimized distribution of the layer thicknesses for an assigned orientation is tried an even better solution is searched by designing also the fibers orientation. In the initial design a balanced symmetric laminate, with layers oriented at 0/90/±45 with respect to the mean wing axis has been

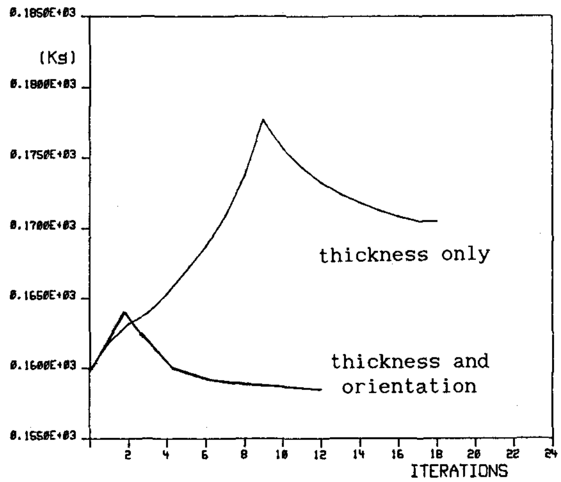
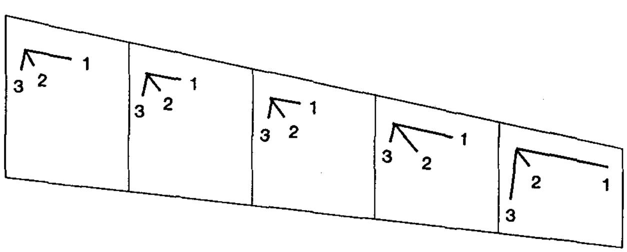


Fig.8 Composite swept wing weight histories.

adopted. Looking at Fig.8, in which the weight histories for the different designs are reported, it can be seen that only by considering the layers orientation as design variables a weight saving with respect to the initial infeasible design is made possible. Figs.9-10 summarize the final values of the thicknesses and orientations of the layers in the skin panels for the two cases. It should be noted that the length of the displayed segments is proportional to the element thickness. Fig.11b shows the final V-g plot obtained by the design check with NASTRAN. It is worth remarking that the final solution shows a backward optimal fiber orientation similar to other examples reported in the literature and presenting only flutter constraints.[38]

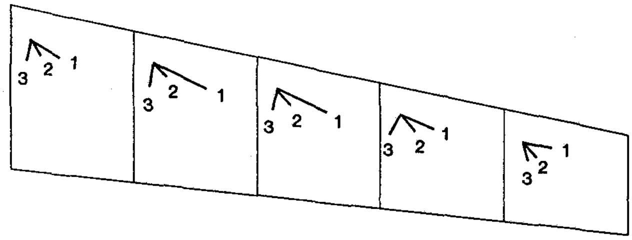


1 = layers at 0

2 = layers at +- 45

3 = layers at 90

Fig.9 Composite swept wing final thickness distribution for assigned layers orientation.



1 = layers at 0 final orientation

2 = layers at +- 45 final orientation

3 = layers at 90 final orientation

Fig.10 Composite swept wing final distribution and layers orientation.

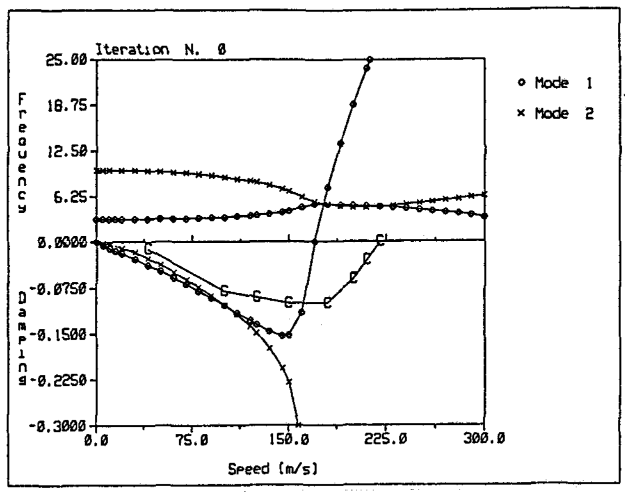


Fig.11a Composite swept wing initial V-g plot with damping constraint.

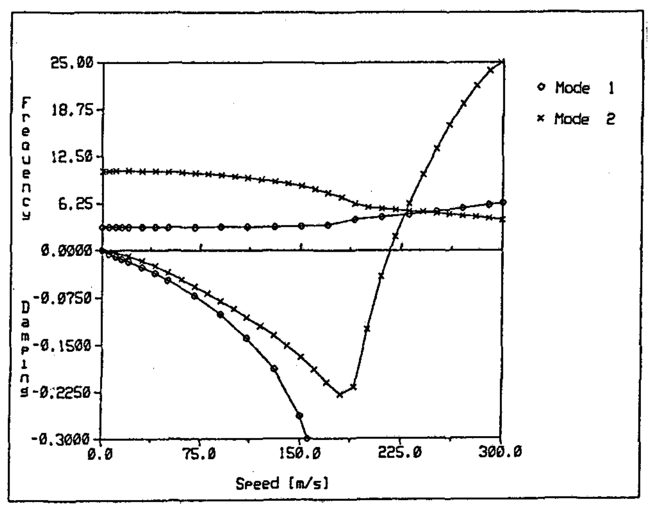


Fig.11b Composite swept wing final NASTRAN V-g plot.

Example N.2

This example verifies that the convex approximation concepts adopted by *AIDIA* can be extended to the design of active flutter suppression systems including

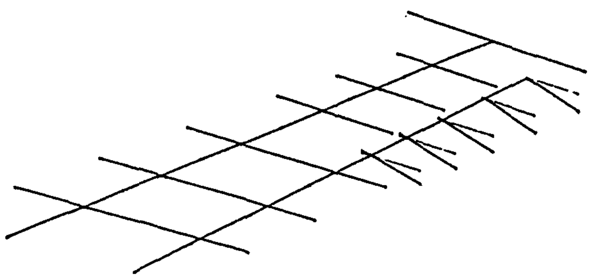


Fig.12 Beam discretization of the aeroelastic wing model.

compensators. To this aim the application of *AIDIA* to the design of a flutter suppression system for the aeroelastic model of a wing shown in Fig.12 is shown. Only one aeroelastic configuration is necessary to solve this problem because only a flutter constraint has been imposed. The mathematical model has seven degrees of freedom: five structural vibration and two control modes representing the dynamic behavior of two integrators used to obtain the velocity and the displacement from accelerations measured at the wing tip.[39] Fig.13 presents the

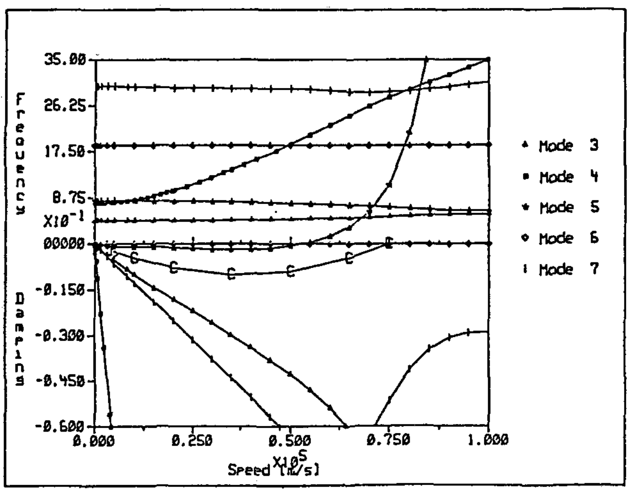


Fig.13 Aeroelastic wing model initial *V*-g plot.

initial *V*-g plot for the uncontrolled system. The design goals are an increase of the flutter speed and a general improvement of the aeroelastic damping below the flutter onset. To obtain this result the flutter constraint shown in Fig.13 is imposed. The objective function is a gain norm imposed in view of reducing actuator power by reducing feedback gains. The system is single-input, i.e. aileron, and multi-output, i.e. two accelerometers placed at the wing tip.

The controller structure is a direct feedback of the accelerations measured at the wing tip and of the velocities obtained by a band pass integrating filter suppressing low frequency signals related to possible rigid motions.[39] The adopted weight coefficients were equal to unity for velocity gains and directly or inversely proportional to the expected flutter circular frequency for acceleration gains. Figs.14-15 report two solutions corresponding respectively to an acceleration-velocity control with direct and inverse proportional weights. In both cases the optimal design has been carried out in few iterations, with the differences in the final solutions being mainly determined by the weight matrix adopted. Fig. 14 shows that for direct proportional weighting the only critical mode is the first torsion meeting its

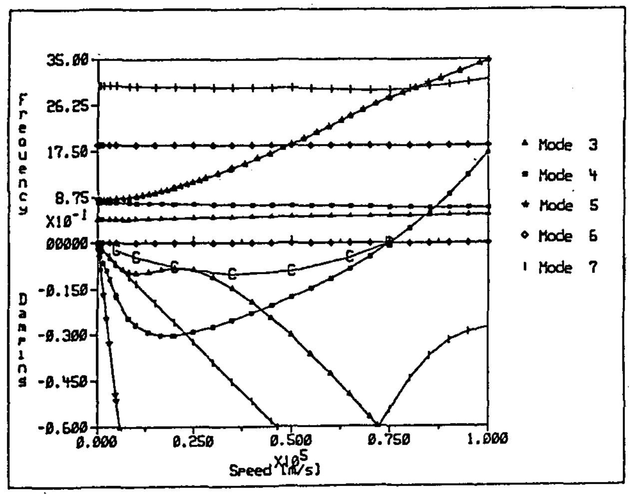


Fig.14 Aeroelastic wing model final *V*-g plot for inverse weights.

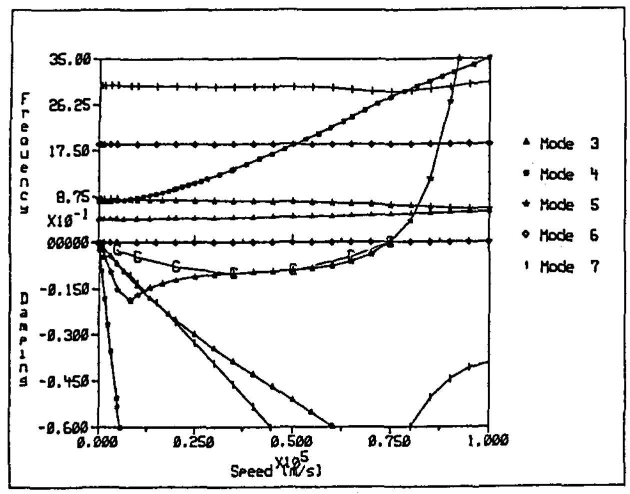


Fig.15 Aeroelastic wing model final *V*-g plot for direct weights.

critical condition at the flutter speed of 75 m/s. On the contrary Fig. 15 shows that for inverse proportional weighting the first torsional mode maintains the same flutter condition, but is much more damped at lower speeds and it is the first bending mode that becomes critical with a highly damped hump at 25 m/s. Analyzing the final gains it appears that the differences are mainly determined by the acceleration gains that change by a factor three because of the different weights. It is important to note that the results obtained using *AIDIA* are very similar to these obtained by using an eigenvalue assignment method [39] that was verified experimentally.

In a final design the coefficients determining the integrator dynamics have been considered as design variables allowing the integral compensations to freely evolve into an arbitrary second order dynamic system to demonstrate the capability to design compensators dynamics. Fig.16 reports the final solution obtained by designing with an inversely proportional weight matrix. In this case both the flutter speed and the aeroelastic damping largely exceed the imposed constraints. A feasible solution was obtained in two iterations and the final dynamics of the compensators results in a higher frequency band while maintaining a good separation between the compensation and the structural modes.

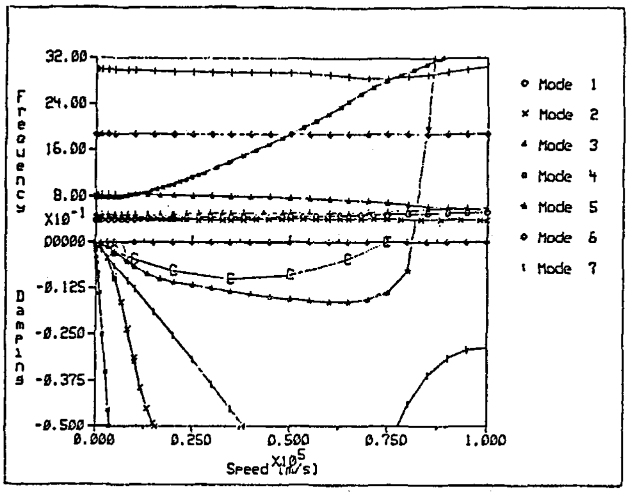


Fig.16 Aeroelastic wing model final *V*-g plot with compensator design.

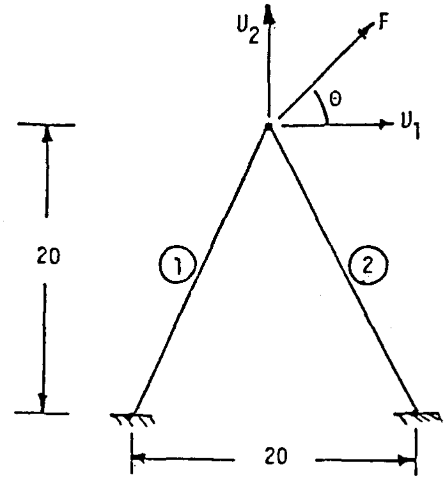


Fig.17 *Two bars structure.*

Example N.3

In this example the very simple structure presented in Fig.17 is analyzed. Several computation regarding this structure are reported in the literature. In fact it represents one of the few available examples of integrated servo-structural optimization. This is a single input problem in which a control force is applied at the free node of the structure to satisfy a set of design requirements assigning the first natural frequency in open-loop and a couple of eigenvalues for the closed-loop. The controller structure is a direct feedback of the velocity and displacement measured at the free node. The control performance is a constraint imposed on the maximum admissible value of a gain norm. The design objective is the minimum structural weight and the design variables are the cross section areas of the truss elements and the velocity and displacement gains.

In Ref.4 many cases are reported regarding different initial designs and different constraints. In Tab.1 three final results corresponding to three different initial designs are reported. A comparison with respect to the results of the literature shows a good correspondence between the final values of the design variables. The small differences are due to the difficulty of imposing exact equality constraints in CONMIN.

Example N.4

The last example aims at demonstrating the validity of the integrated servo-structural optimization by applying an active flutter suppression system to the all metal wing of the first example. As previously noted some difficulties can arise in setting up an integrated servo-structural optimization due to the large number of potential design variables and to preliminary decisions that must be taken before starting the optimization. For example we must establish the controller structure, i.e. compensator dynamics, number and location of sensors and actuators, and the optimization problem, i.e. constraints, objective function and how to embed control performances into the objective function. Due to the lack of similar integrated examples no comparison can be made and we can simply try to develop a reasonable application. The first hope in setting up the example was the obtainment of a major reduction of weight for the same design conditions. This turned out to be impossible since the flutter suppression system alleviates the flutter constraint but has nothing to do with a critical static stress constraint that determined the final design. Thus the only possible improvement obtainable with the active flutter suppression system was the extension of the safe flight domain without weight

Case I - *AIDIA* results

In.Des.	Weight	g1=vel1	g2=vel2	g3=dis1	g4=dis2	AREA1	AREA2	Nor
I1	6.38	16.77	34.88	1.396	.774	202.41	82.93	1500
I2	6.27	15.49	35.42	1.364	.824	195	85.33	1500

Case III - *AIDIA* results

In.Des.	Weight	g1=vel1	g2=vel2	g3=dis1	g4=dis2	AREA1	AREA2	Nor
I4	5.71	13.14	36.4	1.304	.863	163.06	92.66	1500

Case I and III - Results of reference N.4

In.Des.	Weight	g1=vel1	g2=vel2	g3=dis1	g4=dis2	AREA1	AREA2	Nor
I1 I2 I4	6.417	16.73	34.89	1.39	.78	203.98	82.98	1500

Tab.1 Comparison of different designs for two bars.

penalties. This fact makes less gorgeous the results obtainable from the use of the integrated design but it nonetheless demonstrates the need of integration at least to avoid that the active flutter suppression designed alone causes the violation of other important design requirements.

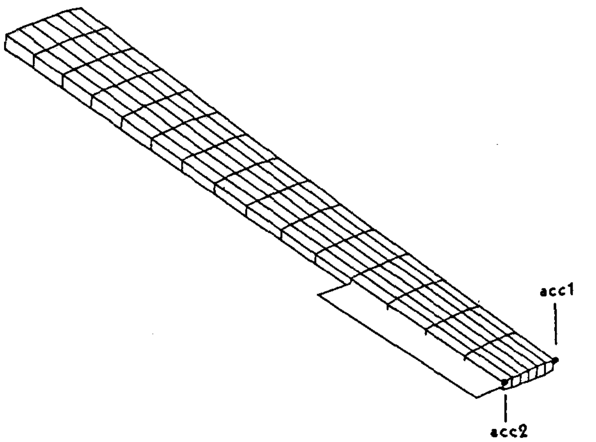


Fig.18 Swept wing structural discretization with aileron.

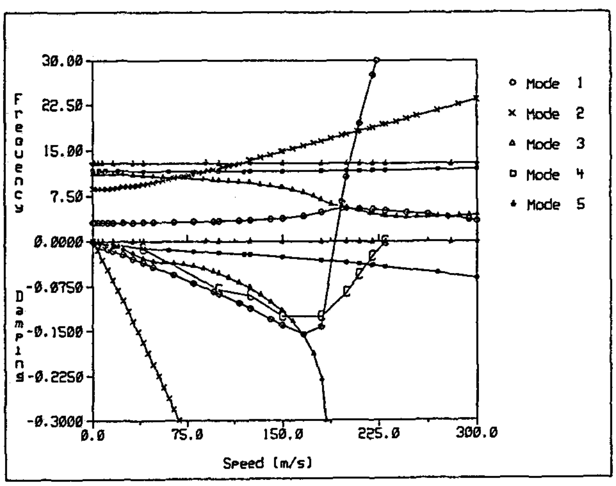


Fig.19 Actively controlled swept wing initial V-g plot with extended damping constraint.

Fig.18 shows the structural layout with the aileron control surface and two accelerometers located at the wing tip. A direct feedback of accelerations and integrated velocities is used and an objective function composed by the structural weight and a control gains norm, with homogeneous weight coefficients, have been chosen for the optimization. Fig. 20 shows the total structural weight versus iteration number and Fig. 21 presents the final V-g plot. We can see that the first outcome is a design with a final weight close to that obtained in the first example, but with increased flutter speed. Unfortanatley Fig. 21 shows also that while the passive design of the first example did not drive other modes unstable the active control does. To precisely understand how such a solution could arise a short explanation is necessary. In *AIDIA* any flutter constraint is assigned to one or more modes. In this way it is possible to exclude all the modes that are assumed as never becoming critical thus avoiding to uselessly take into account an excessive number of constraints. For this reason the flutter constraint has been applied only to the first mode, being the

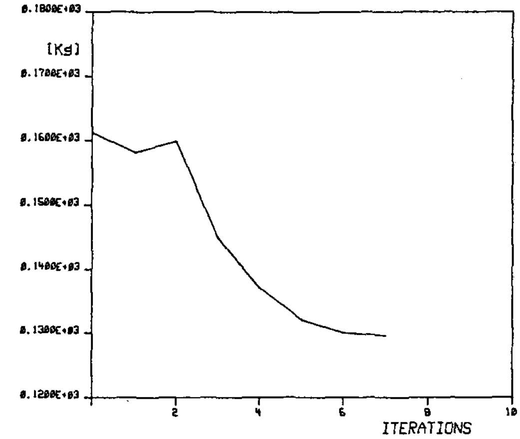


Fig.20 Actively controlled swept wing first weight history.

other modes very stable. On the contrary the extension of the flutter requirement and the structural/control interaction drive the second mode unstable and a further flutter constraint is needed. This is clearly shown in the final V-g plot obtained through NASTRAN

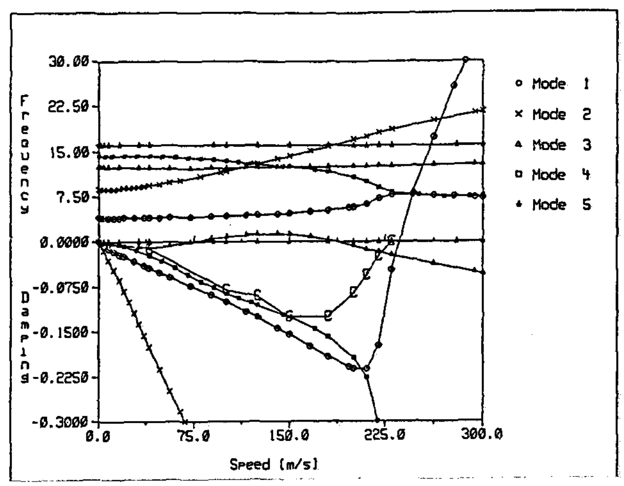


Fig.21 Actively controlled swept wing final V-g plot showing unstable mode.

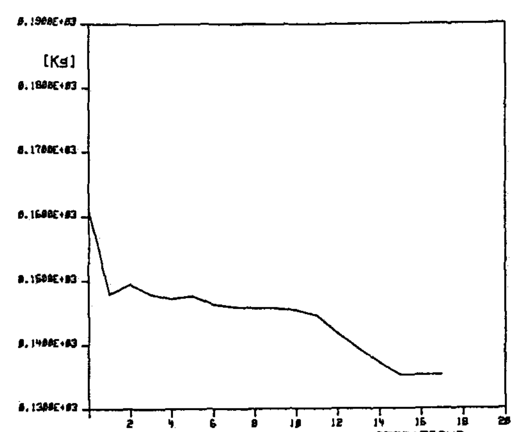


Fig.22 Actively controlled swept wing second weight history.

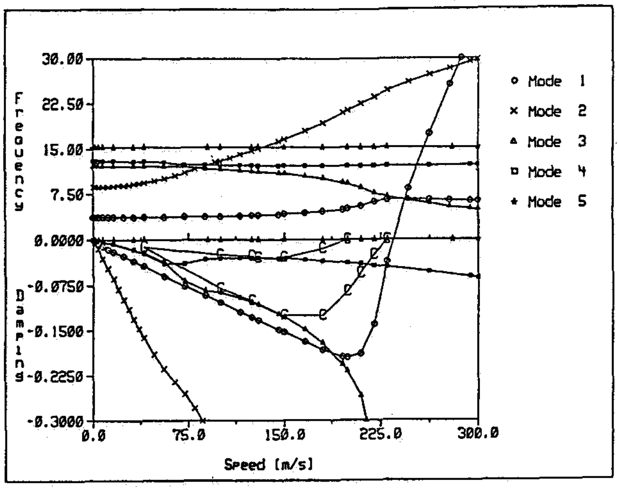


Fig.23 Actively controlled swept wing final *V*-g plot and flutter constraints.

(Fig. 23). It is remarked that in view of the steady increase of the damping shown in Fig. 23 a lower relative damping is accepted for the second mode.

It must me noted that the introduction of the aileron has somewhat changed the flutter behavior with respect to the first example in which the aileron was roughly modeled because of its reduced participation in the flutter mechanism. Thus, to verify the possible uniqueness of the final design and to simulate a more homogeneous design condition, a new computation has been completed through two steps, and the related weight history is shown in Fig. 22. In the first step only the structural design variables were modified till a minimum weight was obtained at the tenth iteration. This solution can be taken as representative of the optimum design achievable by passive means only. Then a second integrated step, considering both structural and control design variables, was undertaken till a possible new optimum. From Fig.22 it can be seen that a substantial improvement is caused by the integrated design and the possible benefits of integration seem now to be much more consistent. The final design variables were practically the same indicating a likely true optimum condition.

Concluding Remarks

The paper has presented an effective way of facing integrated simultaneous servo-structural optimal design by extending state of the art methods available for minimum weight structural design. This extension appears feasible at least for preliminary and intermediate design phases.

The results achieved are far from establishing a definite assessment of the pros and cons of the method implemented in *AIDIA*. It is believed that realistic and standardized test examples, assuming the role of the well known many bars or delta wing structures that have been used for comparing minimum weight design methods, are needed in evaluating integrated design capabilities. The experience gathered in carrying out on test examples allows to say that the adoption of reduced order models introduces no major problems and presents sure advantages allowing an easy addition of capabilities by a simple interface to already available and specialized programs. Nonetheless certain difficulties can be encountered in those analyses and sensitivity calculations requiring non standard numerical tools, e.g. flutter. In fact the p-k approximation adopted has demonstrated once more its effectiveness both as an analysis and sensitivity tool for aeroservoelastic flutter calculations. However the presence of complicated control systems can often cause singular points to be met when two real eigenvalues merge in a complex conjugate couple or the latter split into two real poles. This does not cause the procedure to go astray but dangerous solutions can be lost. Due to the designer in the loop such situation can be detected and often cured but improved algorithms would be very valuable. An improvement can come from the adoption of a state formulation of the aerodynamics that would allow the flutter problem to be mapped to standard linear eigenproblems.[40] In view of the state augmentation, because of the many "spurious" roots added by the above formulation and because of the need of sensitivity analyses, the state formulation should not be used extensively but only to generate new initial conditions for the p-k continued solution at singular points. So the adoption of modern aeroelastic analyses is being considered for inclusion as an alternative choice to the classical approach, effective analyses and sensitivity calculation methods being already available for all the problem to be solved in *AIDIA*.[30,41]

Future expansions and improvements will take into account the possibility of implementing a multilevel optimization in *AIDIA* as this can be easily carried out by simply changing the definition phase. Moreover the modal multi-model formulation of *AIDIA* can be very effectively exploited in a parallel or distributed computer architecture since the most demanding phase of response analysis and sensitivity can be easily parallelized.

It is envisaged that very complex optimization tasks can be undertaken on a PC with transputer board, provided that NASTRAN is available in the distributed computing network.

A final point that deserves attention is the assumption of assigned external loads in integrated flexibility of the optimized structure and to active control systems the loading conditions tend to be strongly influenced during the design and should probably become part of the optimization procedure, at least by adding corrective perturbations to basic assigned loads. This does not imply simply the substitution of static analyses with static aeroelastic analyses since it is likely that when some experience will be available in integrated design with load alleviation, the whole problem of defining load conditions is likely to be restated.

References

[1] "Impact of active control technology on airplane design", AGARD CP 157.

[2] Weisshaar T.A., Newsom J.R., Zeiler T.A. and Gilbert M.G., "Integrated structure/control design - present methodology and future opportunities", ICAS 86, London, 1986, pag.1119.

[3] Junkins J.L. and Rew D.W., "Unified optimization of structures and controllers", Large Space Structures : Dynamic and Control, Atluri S.N. and Amos A.K. editors, Springer-Verlag, 1988.

[4] Khot N.S., Oz H., Granghi R.V., Eastep F.E. and Venkayya V.B., "Optimal structural design with control gain norm constraint", AIAA Journal, Vol.26, N.5, 1988, pag.604.

[5] Khot N.S., "Structure/control optimization to improve the dynamic response of space structures", Computational Mechanics, Vol.3, N.3, 1988, pag. 179.

[6] Onoda J.,Haftka and R.T., "An approach to structure/control simultaneous optimization for large flexible spacecraft", AIAA Journal, Vol.25, N.8, 1987.
[7] Zeiler T.A. and Weisshaar T.A., "Integrated aeroservoelastic tailoring of lifting surfaces", Journal of Aircraft, Vol.25 N.1, 1988, pag.76.
[8] Venkayya V.B. and Tischler V.A., "Frequency control and its effect on the dynamic response of flexible structures", AIAA Journal, Vol.23, N.11, 1985, pag.1768.
[9] Lust R.V. and Schmit L.A., "Control augmented structural synthesis", AIAA Journal, Vol.26, N.1, 1988, pag. 86.
[10] Miller D.F. and Shim J., "Gradient based combined structural and control optimization", Journal of Guidance, Control, and Dynamics, Vol.10, N.3 1987.
[11] Gupta K.K., Brenner M.J. and Voelker L.S., "Integrated aeroservoelastic analysis capability with X-29A comparisons", Journal of Aircraft, Vol.26, N.1, 1989, pag.84.
[12] Kam T.Y. and Lai M.D., "Multilevel optimal design of laminated composite plate structures", Computer and Structures, Vol.31, N.2, 1989, pag.197.
[13] Sobieski J.S., James B.B. and Dovi A.R., "Structural optimization by multilevel decomposition", AIAA Journal, Vol.23, N.11, 1985, pag.1775.
[14] Gilbert M.G. and Schmidt D.K., "Integrated structure/control law design by a multilevel optimization", AIAA Guidance, Navigation and Control Conference, Part I, 1989 Boston, pag.376.
[15] Bindolino G., Lanz M., Mantegazza P. and Ricci S., "AIDIA-Una procedura per l'ottimizzazione strutturale integrata nell'ambiti del progetto preliminare", X National Congress of AIDAA, 1989, Pisa.
[16] Starnse J.H. and Haftka R.T., "Preliminary design of composite wings for buckling, strenght, and displacement constraints", Journal of Aircraft, Vol.16, N.8, pag.564.
[17] Fleury C., "A unified approach to structural weight minimization", Computer Methods in Appl. Mech. and Eng., Vol.20, 1979, pag.17.
[18] Vanderplaats G.N. and Moses F., "Structural optimization by methods of feasible directions", Journal of Computer and Structures, Vol.3, N.4, 1973, pag.359.
[19] Vanderplaats G.N., "CONMIN a Fortran program for constrained minimization", NASA TM X-62282, 1973.
[20] Franchi C., "Un moderno inquadramento dei problemi di aeroelasticita' statica", Thesis, Dipartimento di Ingegneria Aerospaziale , Politecnico di Milano, 1988, Milano.
[21] Franchi C. and Mantegazza P., "A unified approach to response and sensitivity analysis of static aeroelastic problems", X National Congress of AIDAA, 1989, Pisa.
[22] Mantegazza P. and Ricci S., "A direct approach to the control reversal analysis and its sensitivities", accepted for publication on AIAA Journal.
[23] Nicot Ph. and Petiau C., "Aeroelastic analysis using finite element models", European Forum on Aeroelasticity and Structural Dynamics, 1989, Aachen.
[24] Noor A.K. and Lowder H.E., "Approximate techniques of structural reanalysis", Computer & Structures, Vol.4, 1974, pag.801.
[25] Lanz M., Mantegazza P.,Merlini T.,Basso W.and Faccetti D., "An integrated methodology for aircraft aeroelastic design", L'Aerotecnica Missili e Spazio, Vol.64, N.3, 1985, pag.170.
[26] Mejier J.J. and Zwaan R.J., "Calculation of frequency response function for flexible aircraft", National Aerospace Laboratory the Netherland, NLR-TR-75147U, 1975.
[27] Lanz M. and Mantegazza P., "Numerical methods for predicting the aeroelastic stability and response of flexible airplanes", L'Aerotecnica Missili e Spazio, Vol.63, N.2, 1984, pag.105.
[28] Cardani C. and Mantegazza P., "Calculation of eigenvalue and eigenvector derivatives for algebraic, flutter and divergence eigenproblems", AIAA Journal, Vol.17, N.4, 1979, pag.408.
[29] Bindolino G.P. and Mantegazza P., "Aeroelastic derivatives as a sensitivity analysis of nonlinear equations", AIAA Journal, Vol.25, N.8, 1987,pag. 1145.
[30] Lanz M. and Mantegazza P., "Design of compensated flutter suppression systems", ICAS Paper ICAS-82-3.2.1, 1982.
[31] Lanz M. and Mantegazza P., "Design of multi input-output flutter suppression system by eigenvalue assignment", l'Aerotecnica Missili e Spazio, Vol.59, N.4,1980, pag.303.
[32] Lanz M. and Mantegazza P., "An improved method for the design of flutter suppression systems by eigenvalue assignement", l'Aerotecnica Missili e Spazio, Vol.60, N.51, pag.92.
[33] Nguyen V.H. and Strodiot J.J., "A mathematical convergence analysis of the convex linearization method for engineering design optimization", Engineering Optimization, Vol.11, N.5, 1987, pag.869.
[34] Pope G.G. and Schmit L.A., "Structural design applications of mathematical programming techniques", AGARD CP 149, 1971.
[35] Adelman H.M. and Haftka R.T., "Sensitivity analisys of discrete structural systems", AIAA Journal, N.5, Vol.24, 1986, pag.823.
[36] Olhoff N., "Multicriterion structural optimization via bound formulation and mathematical programming", IUTAM Symposium on structural Optimization, 1988, Melbourne.
[37] Ricci S., "Ottimizzazione strutturale integrata nell'ambito del progetto preliminare", Ph.D. Thesis, Dipartimento di Ingegneria Aerospaziale,Politecnico di Milano, 1989, Milano.
[38] Weisshaar T.A. and Ryan R.J., "Control of aeroelastic instabilities trough stiffness cross-coupling", Journal of Aircraft, Vol.23, N.2, 1986, pag.148.
[39] Ghiringhelli G.L., Lanz M. and Mantegazza P., "Active flutter suppression for a wing model", ICAS Paper ICAS-88-1.2.2, 1988.
[40] Lanz M. and Mantegazza P., "Modern methods for the analysis of the dynamic response of aeroelastic systems", l'Aerotecnica Missili e Spazio, Vol.64, N.3, 1985, pag.170.
[41] Lanz M. and Mantegazza P., "Design of gust and maneuver load alleviation systems for transport aircrafts", X National Congress of AIDAA, 1989, Pisa.

Acknowledgments

This work has been partially sponsored by the Consiglio Nazionale delle Ricerche (CNR) under contract N.86.00865.59.