INTEGRATED STRUCTURAL OPTIMIZATION IN THE PRELIMINARY AIRCRAFT DESIGN

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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 aeroviscoelastic 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
- [Q] PSD matrix
- [P] covariance matrix
- [q] extended generalized coordinates
- [u] feedback input vector
- [f] external forces vector
- [y] response vector
- [m] measurement vector
- [x] design parameters
- [G] generic constraint function
- [ρ] air density
- [V] asymptotic air speed
- [M] asymptotic Mach number
- [c] reference aerodynamic chord
- [ω] circular frequency
- [k] reduced frequency (ωc/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 aeroviscoelastic systems. Adverse interactions can then easily arise that hinder the attainment 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 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. 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...
process.
In the second approach the integrated servo-structural design is carried out by operating simultaneously on both structural and control design variables 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 devised 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 and tries to combine the advantages of 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 aerodynamics 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 non-excessively detailed models are needed. 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 condense 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 and the minimization is carried out on the approximate problem by a feasible directions method, i.e. CONMIN. 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
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. 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 aeroservoelasticity 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. 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.
- 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 defined. 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 particular 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

\[
(s^2[M] + s[C] + [K] - \frac{1}{2} \rho V^2 \{A_{m}(k,M)\})(q) = 0 \]

(1)

Definition of responses of interest

\[
(y) = [R(s)](q) + [R_g(s)](v_g) + [R_u(s)](u) + [R_f(s)](f) \]

(2)

Measurements equations

\[
\langle m \rangle = s^2[I_s] + s[I_v] + s[I_d] \]

(3)

Feedback law

\[
(u) = [G](m) \]

(4)

Equivalent structural matrices defined by feedback

\[
[B] = [B][G][S_g] \]

(5)

Closed-loop dynamic response and stability

\[
([Z(s)]q) = \frac{1}{2} \rho V^2 \{A_{m}(k,M)\}(v) + [F](f(s)) \]

(6)

Frequency response

\[
(y(\omega)) = [H_g(\omega)](f(\omega)) + [H_{g^g}(\omega)](v_g) \]

(7)

PSD response

\[
[H_{g^g}(\omega)] = [H_g(\omega)](f(\omega)) + [H_{g^g}(\omega)](v_g) \]

(8)
Covariance calculations

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

Quasi steady aerodynamic approximation

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

Using the index \( r \) for rigid body modes and \( e \) for deformation modes the following are defined for static aerelastic problems:

Static aerelastic stiffness matrix:

\[ [K_{ae}] = [K_{ee}]^{-1} - 1/2pV^2[K_{ae}] \] (12)

Aerelastic divergence condition for the aircraft

\[ [K_{ee}]/[q_e] = 1/2pV^2[K_{ee}] [q_e] \] (13)

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

\[ [M_e] = [M_{ee}^{re}] [K_{ee}]^{-1} [M_{ee}^{re}] \] (14a)

\[ [C_e] = [C_{ee}^{re}] - [K_{ee}]^{-1} [C_{ee}^{re}] \] (14b)

\[ [K_e] = [K_{ee}^{re}] - [K_{ee}]^{-1} [K_{ee}^{re}] \] (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.

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. 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 \textit{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 aerelastic stability and response formulations. \textsuperscript{30-32} Thus the integration of control design within \textit{AIDIA} simply means to include the elements of the gain matrix [C] into the design variables. Generally control variables influence mainly flutter and dynamic response analysis, 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 \textit{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". 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:

\[ G(x) = \sum_{i=1}^{N} \left( \frac{\partial G}{\partial x_i} \right) x_i \]  

\[ N_I = \text{number of variables with gradient } < 0 \]  

\[ N_D = \text{number of variables with gradient } > 0 \]  

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

**Multi-objective Minimization**

In AIDIA the minimization is performed with the feasible directions method implemented in CONMIN. 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:

\[ \min_{x} \text{OBJ}(x) \]

subject to \[ G_j(x) = 0 \]

\[ i=1, \ldots, N \]

\[ j=1, \ldots, M \]

(Problem 1)

OBJ is the objective function and \( G_j \) are the constraint functions. We can write the same problem in a more general way, by using an approach close to that presented in [16], i.e.

\[ \min (\max) \beta_j \text{ or } \gamma \]

subject to:

\[ \beta_j - G_j(x) \leq 0 ; \gamma - \text{OBJ} \leq 0 \]

\[ i=1, \ldots, N \]

\[ j=1, \ldots, M \]

(Problem 2)

Problem 2 includes Problem 1, as the latter is readily obtainable by minimizing \( \gamma \) while setting \( \beta_j=0 \). However, by minimizing \( \beta_j \) and setting \( \gamma=\gamma \), 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 \( \beta_j \) 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 \( \beta_j \), 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 adaptable 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 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.](image)
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.](image)

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 attainment of minimum weight in twelve iterations. It must be noted that 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 plot obtained from NASTRAN; it should be compared to the initial design shown in Fig. 3.
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 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.

1 layers at 0
2 layers at ±45
3 layers at 90

Fig. 9 Composite swept wing final thickness distribution for assigned layers 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 byroid 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. 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. The adopted weight coefficients were equal to unity for velocity gains and directly or inversely proportional to the expected flutter 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

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 those obtained by using an eigenvalue assignment method that was verified experimentally.

In a final design the coefficients determining the integrator dynamics have been considered as design variables allowing the integral compensators 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.
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.

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<th>g2=vel2</th>
<th>g3=dis1</th>
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Case I and III - Results of reference N.4

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<th>g1=vel1</th>
<th>g2=vel2</th>
<th>g3=dis1</th>
<th>g4=dis2</th>
<th>AREA1</th>
<th>AREA2</th>
<th>Nor</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,12,14</td>
<td>6.417</td>
<td>16.73</td>
<td>34.89</td>
<td>1.39</td>
<td>.78</td>
<td>203.98</td>
<td>82.98</td>
<td>1500</td>
</tr>
</tbody>
</table>

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. 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 be 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 such 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 nonstandard 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 aeroviscoelastic 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 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. 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.

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


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