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Integrated Servostructural Optimization in the Design of Aerospace Systems

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Multidisciplinary optimization is playing a fundamental role in the design of aerospace vehicles because of the need to simultaneously take into account the strong interactions among different disciplines to ensure an efficient design. This paper presents a multimodel, multiobjective formulation of the servostructural optimization problem specifically tailored toward airplane preliminary design. Structural and control design variables are simultaneously treated along with constraints and objective functions related to different aeroservoelastic and structural performances. Reduced-order models, based on finite element method/boundary element method, are adopted to reduce the computational burden of the optimization process.

Introduction

MULTIDISCIPLINARY design optimization (MDO) is playing an increasingly important role in the design of aerospace vehicles because the strong interactions among several disciplines, such as structures, aerodynamics, control, flight mechanics, and costs, as well as the increasing complexity of aerospace systems, require the use of multidisciplinary methodologies in all design phases. In fact, the opportunities offered to the designer by the new technologies developed in all of these disciplines are likely to be fully exploited only if multidisciplinary interactions are taken into account starting right from the conceptual and preliminary design phases.[1]

A partial but important application of MDO is the simultaneous optimization of aerospace structures and active control systems, e.g., active flutter suppression, load alleviation, and vibration suppression. Improvements in the analysis and synthesis of aeroservoelastic systems are now making multidisciplinary servoelastic optimization increasingly viable for real aerospace structures.[2]

To test the possibilities offered by an integrated servostructural optimization, a computer code, called AIDIA, was developed at the Aerospace Department of the Politecnico di Milano in the late 1980s.[3] Its main feature is the possibility of simultaneously changing structural and control-design variables by taking into account performances of models characterized, for example, by different control laws, mass distributions, and loading conditions. Reduced-order models are also extensively adopted because AIDIA was developed as an optimization procedure aimed at preliminary design, in particular, when several different viable solutions must be analyzed and synthesized in a short time. In the following sections, the AIDIA approach is reviewed and some results and comments are reported.

AIDIA Approach

In the development of the AIDIA synthesis system, the following requirements have been taken into account.[3,4]

1) A multimodel formulation allowing the simultaneous consideration of completely different and independent servostructural models and/or operating conditions, e.g., dynamic pressure, Mach number, and control laws, in an effective and reliable way.

2) Integration of several analysis and sensitivity modules for the computation of different structural and aeroservoelastic responses such as displacements, stresses, buckling loads, natural frequencies, flutter damping, and control-surfaces effectiveness.

3) A weighted multicriteria minimization with objective and constraint functions chosen during each optimization cycle among different responses and performance indices, allowing the interchange of objective and constraint functions as the design process evolves.

4) An integrated servostructural design in which the optimization procedure is carried out using structural and control design variables simultaneously.

5) An open architecture that offers the possibility of adding new analysis and sensitivity modules with data exchange through a central database.

An important consequence of these requirements is that only multidisciplinary analysis modules, i.e., those taking into account the interaction among different disciplines, have been included in AIDIA. All of the raw modeling and basic data needed for these analyses, i.e., those concerning structural, aerodynamic and control-system models, are retrieved from external codes to which AIDIA is properly interfaced. In this way it is possible to maintain extensive and state-of-the-art modeling capabilities while adopting different structural and aerodynamic formulations.

The tradeoff between computational accuracy and cost can easily be established because of the possibility of using models with different levels of complexity for the structures and aerodynamics. In particular, because AIDIA has been conceived as an optimization procedure to be used mainly in preliminary design, when many and different conceptual solutions must be evaluated in a short time, condensation techniques or reduced bases have been adopted. In fact, because it has been considered appropriate to adopt finite element method/boundary element method (FEM/BEM) approximate solutions for the structures and aerodynamics, without turning to other alternative simplified formulations,[5] approximate low-order modal models are employed to reduce the computational burden related to analysis and sensitivity calculations.

A general overview of AIDIA is shown in Fig. 1. Starting from first-guess structural, aerodynamic, and control designs, the reduced models are obtained according to the procedures reported in the following sections and, subsequently, inherited by AIDIA. The multidisciplinary optimization is then carried out until an optimum design is found; at this point the results of AIDIA analyses are compared with those obtained from

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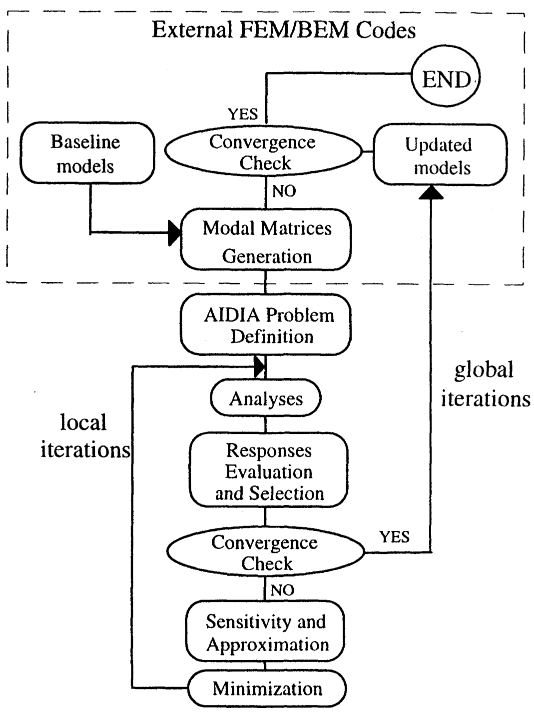


Fig. 1 AIDIA system synthesis.

detailed models using the final set of design variables, and if the detailed results do not match those of the reduced-order models, the modal bases are updated and the optimization loop is repeated. Each optimization cycle on the approximate low-order models is herein called *local iteration*, whereas the verification loop is called *global iteration*. In this way it is often possible to solve very complex optimization problems by one or two modal basis generations, dramatically reducing the size of the problem.

Multimodel Approach

In AIDIA, the concept of models or configurations assumes a fundamental role. A model consists of all the modal data describing the aeroservoelastic system and of all the information required to specify the analyses to be performed. In particular, each model includes the definition of the design variables and the structural and/or control responses of interest and the functional relations, to be briefly detailed in the following sections. This approach allows the definition of independent yet simultaneous design problems that can be characterized by completely different structural and/or control models, design variables, and loading conditions. In this way it is possible to schedule different control laws throughout the flight envelope and ensure the robustness of the aeroservoelastic system against major modeled uncertainties.

Modal Approach

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 amplitudes. In AIDIA, the modal formulation is adopted for dynamic and static problems, thus obtaining a common formulation for all of the aeroservoelastic analyses.[6] The modal basis can be an appropriate combination of vibration modes, static deformations, inertia-relieved self-balanced static deformations, and Guyan modes. From a general point of view, a modal approach based on the low-frequency eigensolutions is often appropriate; in fact, because of the need to maintain a balanced compromise between accuracy and cost for the most demanding aeroservoelastic analyses, it is the de facto standard approach in dynamic analyses. Instead, when it is used within an optimization process including stress constraints, the approximation level must be improved by using, for example, a modal perturbation scheme.[7] The perturbation scheme presently adopted in AIDIA approximates the displacements resulting from each loading condition by a linear combination of the reference displacement vector and its derivatives with respect to the design variables. This approach was proven to provide accurate results in the presence of static and buckling constraints,[8] but it may become inefficient in MDO problems with multiple loading conditions and/or when a significant number of design variables is used. However, recalling that AIDIA is mainly aimed at preliminary and intermediate design phases, this is not believed to be a significant drawback because, usually, only a relatively limited set of design variables is used. It is also important to emphasize that the open architecture of AIDIA allows the modification and addition of new modal approximations according to the experience of the users, always aiming at the best compromise between computing resources and cost.

Multiobjective Optimization

In AIDIA, the objective function is a suitably balanced mix of different performance indices. In the integrated structure-control optimization, a weighted sum of structural mass and control-related performances is generally used, with relative weighting factors chosen by subjective judgment. A noteworthy difference between mere structural and servostructural optimizations lies in finding a feasible starting region. In fact, while in the first case it is always possible and easy to find a feasible initial design, e.g., by stiffening the structure, in the second case the determination of a feasible starting point is not trivial because of the presence of gains, compensator coefficients, and/or other control-system parameters among the design variables. Sometimes the mere production of a feasible design can already be a possible solution for the active control system.

To increase the efficiency of the minimization module in achieving a feasible design and to supply the global minimization problem with greater versatility, it is possible to formulate the optimization problem as min β or γ, subject to[9]

$$(g/g_a) - \beta \leq 0, \qquad \mathrm{OBJ} - \gamma \leq 0$$

where OBJ is the objective function and, for the sake of clarity, only one inequality constraint function g is considered. The classical optimization problem is obtained by setting $\beta = 1$, whereas by imposing $\gamma = \gamma^*$, it is possible to minimize (maximize) a constraint function by considering the original objective function just as a generic constraint function. In such a formulation, a clear difference between the objective and constraint functions no longer exists. It should be noted that minimum weight design is not always considered to be the only goal of the optimization process because other requirements must often be satisfied, e.g., the minimization of the maximum stress in a structural element or the minimization of the control-surface activity required by an active flutter suppression system.

The algorithm used by AIDIA for the minimization of the approximate problem is the feasible directions method, as implemented in CONMIN.[10] Its choice is mainly a result of its efficiency in producing feasible designs starting from infeasible initial guesses and to the large experience gathered in using it for several optimization problems. Of course, other algorithms can easily be included.

Key Equations

Structural Modal Bases

The modal approach approximates the structural displacements with

$$\{u\} = [X]\{q\} \tag{1}$$

where $\{u\}$ are the nodal displacements, $[X]$ is the generic modal basis, and $\{q\}$ are the generalized coordinates. In a finite element formulation, the global stiffness matrix can be written as

$$[K_G] = \sum_{e=1}^{NE} [K_e] \tag{2}$$

where NE is the total number of finite elements or the number of finite element groups, called *structural blocks*, when a design variable linking reduction is carried out. The modal global stiffness matrix becomes

$$[k] = [X]^T[K_G][X] = \sum_{e=1}^{NE} [k_e] \tag{3}$$

where the modal stiffness matrix of each structural block is

$$[k_e] = [X]^T[K_e][X] \tag{4}$$

For example, in the case of a block of isotropic rod elements, the stiffness matrix can be a constant matrix $[\bar{k}_e]$ multiplied by the cross-sectional area x_e,

$$[k_e] = [X]^T[\bar{K}_e][X]x_e = [\bar{k}_e]x_e \tag{5}$$

In general, for every element type, it is always possible to write its $[k_e]$ matrix as

$$[k_e] = \sum_{j=1}^{NPE} F_j(\{x_e\})[X]^T[\bar{K}_e]_j[X] = \sum_{j=1}^{NPE} F_j(\{x_e\})[\bar{k}_e]_j \tag{6}$$

where $\{x_e\}$ is the design variable vector of the eth structural block, F_j are the relations defining the properties of the analysis model as a function of the design variables, and $[\bar{k}_e]_j$ is the elementary modal matrix calculated for a unitary value of F_j. For example, the stiffness matrix of isotropic structural plate elements coupling in-plane and bending stresses is given by a linear combination of two constant matrices, multiplied by the plate thickness and its third power, respectively. In the case of composite material elements, the function F_j assumes more complex expressions because the thickness and fiber orientation of the single layer are both available as design variables in AIDIA (for the sake of simplicity the complete formulation is not reported[11]). The mass matrix is assembled in the same way, even though, in many situations, a mass matrix depending linearly on the design variables represents a good approximation. Finally, the same matrix notation can be adopted for the strain and stress matrices

$$\begin{aligned}\{\varepsilon_e\} = [B]\{u\}, \quad \{\varepsilon_e\} = [B][X]\{q\}, \quad \{\varepsilon_e\} = [\bar{\varepsilon}_e]\{q\} \\ \{\sigma_e\} = [E]\{\varepsilon_e\}, \quad \{\sigma_e\} = [E][\bar{\varepsilon}_e]\{q\}, \quad \{\sigma_e\} = [\bar{\sigma}_e]\{q\}\end{aligned} \tag{7}$$

$[E]$ and $[B]$ being, respectively, the elastic and the strain-displacement matrices. In this way the resulting strain and stress vectors are obtained by multiplying constant matrices by $\{q\}$. In AIDIA, any structural modal basis is a collection of all modal stiffness, mass, and stress/strain matrices. All of these matrices do not change during local iterations, but are updated from one global iteration to the next.

In the present version, AIDIA is interfaced to MSC/NASTRAN because it is a standard code in the aerospace community, allows an easy user interaction with internal data, and offers extensive analysis capabilities, including aerodynamics. Appropriate interfaces to MSC/NASTRAN are easily established by altering some standard solution sequences; a more effective approach could be a direct interface to the MSC/NASTRAN database.

Active Control Systems

One of the most useful features of AIDIA is represented by its capability of designing, in an integrated way, structures and active control systems. The chosen approach leads to a description of the control systems, in the frequency domain, as equivalent mass, damping, and stiffness matrices, thus avoiding a state-space representation of the unsteady aerodynamic forces.[12] In fact, some control algorithms, such as linear quadratic Gaussian control, have not been considered because they require a representation of the unsteady aerodynamic forces in the time domain that is not yet implemented in AIDIA aeroservoelastic modules. The linearized open-loop aeroelastic response equations, in the Laplace transform domain s, are

$$\begin{aligned}(s^2[m] + s[c] + [k] - q[H_{AM}(k, M)])\{q(s)\} \\ = q[H_{AG}(k, M)]\{vg(s)\} + [B]\{u(s)\} + \{d(s)\}\end{aligned} \tag{8}$$

where $\{q(s)\}$ is a generalized coordinates vector, extended to include the free coordinates related to structural motions as well as the states related to actuators, sensors dynamics, signal conditioning, and compensator dynamics. $[m]$, $[c]$, and $[k]$ are the related mass, damping, and stiffness matrices of the aeroservoelastic system, respectively; q is the dynamic pressure; $[H_{AM}]$ and $[H_{AG}]$ are the Mach-depending, zero-order p-k approximation of aerodynamic transfer matrices related to structural motions and to a gust and/or turbulence input $\{vg(s)\}$; $\{u\}$ is the vector of the generalized input; $[B]$ is the related modal input distribution matrix; and $\{d\}$ is the vector of modal external forces and/or disturbances. Without any limitation on the controller structure because arbitrarily structured compensator parameters can be included in the system matrices, we can consider the input as a direct feedback of available measures:

$$\{u\} = [G_a]\{m_a\} + [G_v]\{m_v\} + [G_d]\{m_d\} \tag{9}$$

where $[G_a]$, $[G_v]$, and $[G_d]$ are the gain matrices for acceleration, velocity, and displacement, respectively, whereas the measurement vectors are obtained from the available output:

$$\{m_a\} = [S_a]\{\ddot{q}\}, \quad \{m_v\} = [S_v]\{\dot{q}\}, \quad \{m_d\} = [S_d]\{q\} \tag{10}$$

where $[S_a]$, $[S_v]$, and $[S_d]$ are the modal displacement matrices at the sensors locations. Defining

$$[m_c] = [B][G_a][S_a], \quad [c_c] = [B][G_v][S_v], \quad [k_c] = [B][G_d][S_d] \tag{11}$$

and taking into account Eqs. (9–11), Eq. (8) becomes

$$\begin{aligned}[Z(s)]\{q(s)\} = (s(^2[m] - [m_c]) + s([c] - [c_c]) + ([k] - [k_c]) \\ - q[H_{AM}(k, M)])\{q(s)\} = q[H_{AG}(k, M)]\{vg(s)\} + \{d(s)\}\end{aligned} \tag{12}$$

The selected formulation of the control system leaves the analytical structure of the original aeroelastic problem substantially unchanged, so that the integrated optimization can be carried out as a mere aeroelastic case. Available design variables are the gains of the control system and the coefficients of the transfer functions of actuators and sensors. In this formulation the matrices $[S]$ and $[B]$ are constant matrices, but, to include sensor and actuator positions among the design parameters, it is possible to assign some particular design variables to them.

Static Analysis

Static analyses imply the solution of Eq. (8) for $s = 0$. The load distribution is assigned and kept constant throughout the optimization cycles. The structural modal basis consists of the baseline displacement vector and its derivatives with respect to the design variables. This approach, called *modal perturbation*, is only valid for a single load condition and may become time consuming in the modal data definition and during the optimization cycles when a significant number of design variables is used, as the problem size is proportional to this number. Nevertheless, it allows an accurate evaluation of stresses and buckling constraints.

Flutter Analysis

The flutter analysis solves $[Z(s)]\{\boldsymbol{q}(s)\} = \{\boldsymbol{0}\}$. Because of the *s-k* (usually known as *p-k*) approximation implied in Eq. (12), the solution of the flutter problem is formulated as a nonstandard eigenproblem that is solved by a continuation method unifying analysis and sensitivity calculations in a very effective way.[13,14]

Static Aeroelastic Analysis

The static aeroelastic analysis adopts the quasisteady approximation of the aerodynamic transfer function, which is written in the time domain as

$$\{\boldsymbol{F}^a\} = q[K^a]\{\boldsymbol{q}\} + q(l/V)[C^a]\{\dot{\boldsymbol{q}}\} + q(l/V)^2[M^a]\{\ddot{\boldsymbol{q}}\} \tag{13}$$

where the aerodynamic matrices $[K^a]$, $[C^a]$, and $[M^a]$ are obtained by interpolating $[H_{AM}]$ at low reduced frequencies; V is the aircraft velocity; and l is an aerodynamic reference length.[15] Using the indices r and e, respectively, for the rigid-body modes, including control-surfaces deflections, and for the elastic modes, for a generic input $\{\boldsymbol{F}\}$, we obtain the time-domain equation of motion in partitioned form:

$$\left(\begin{bmatrix} m^s_{rr} & 0 \\ 0 & m^s_{ee} \end{bmatrix} - q\left(\frac{l}{V}\right)^2 \begin{bmatrix} M^a_{rr} & M^a_{re} \\ M^a_{er} & M^a_{ee} \end{bmatrix}\right)\begin{Bmatrix} \ddot{\boldsymbol{q}}_r \\ \ddot{\boldsymbol{q}}_e \end{Bmatrix} + \left(\begin{bmatrix} 0 & 0 \\ 0 & c^s_{ee} \end{bmatrix} - q\left(\frac{l}{V}\right) \begin{bmatrix} C^a_{rr} & C^a_{re} \\ C^a_{er} & C^a_{ee} \end{bmatrix}\right)\begin{Bmatrix} \dot{\boldsymbol{q}}_r \\ \dot{\boldsymbol{q}}_e \end{Bmatrix} + \left(\begin{bmatrix} 0 & 0 \\ 0 & k^s_{ee} \end{bmatrix} - q \begin{bmatrix} K^a_{rr} & K^a_{re} \\ K^a_{er} & K^a_{ee} \end{bmatrix}\right)\begin{Bmatrix} \boldsymbol{q}_r \\ \boldsymbol{q}_c \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{F}_r \\ \boldsymbol{F}_e \end{Bmatrix} \tag{14}$$

where it has been assumed that the elastic modes belong to the orthogonal complement of the rigid modes with respect to the mass matrix (mean axis definition). Neglecting the forces associated with $\{\dot{\boldsymbol{q}}_e\}$ and $\{\ddot{\boldsymbol{q}}_e\}$ (the definition of static aeroelasticity), it is possible to obtain $\{\boldsymbol{q}_e\}$ as

$$\{\boldsymbol{q}_e\} = [K^{sa}_{ee}]^{-1}(\{\boldsymbol{F}_e\} - [M^{sa}_{er}]\{\ddot{\boldsymbol{q}}_r\} - [C^{sa}_{er}]\{\dot{\boldsymbol{q}}_r\} - [K^{sa}_{er}]\{\boldsymbol{q}_r\}) \tag{15}$$

where (l and m are the generic indices r and e)

$$\begin{aligned} [M^{sa}_{lm}] &= [m^s_{lm}] - q(l/V)^2[M^a_{lm}] \\ [C^{sa}_{lm}] &= [c^s_{lm}] - q(l/V)[C^a_{lm}] \\ [K^{sa}_{lm}] &= [k^s_{lm}] - q[K^a_{lm}] \end{aligned} \tag{16}$$

In deriving Eq. (15), we have assumed that the divergence pressure of the airplane, i.e., the lowest positive eigenvalue of the matrix $[K^{sa}_{ee}]$, is greater than the actual value of q. Introducing Eq. (15) into Eq. (14), the time-domain system becomes

$$[M_{ae}]\{\ddot{\boldsymbol{q}}_r\} + [C_{ae}]\{\dot{\boldsymbol{q}}_r\} + [K_{ae}]\{\boldsymbol{q}_r\} = \{\boldsymbol{F}_{ae}\} \tag{17}$$

with

$$\begin{aligned} [M_{ae}] &= [M^{sa}_{rr}] - [K^{sa}_{re}][K^{sa}_{ee}]^{-1}[M^{sa}_{er}] \\ [C_{ae}] &= [C^{sa}_{rr}] - [K^{sa}_{re}][K^{sa}_{ee}]^{-1}[C^{sa}_{er}] \\ [K_{ae}] &= [K^{sa}_{rr}] - [K^{sa}_{re}][K^{sa}_{ee}]^{-1}[K^{sa}_{er}] \\ \{\boldsymbol{F}_{ae}\} &= \{\boldsymbol{F}_r\} - [K^{sa}_{re}][K^{sa}_{ee}]^{-1}\{\boldsymbol{F}_e\} \end{aligned} \tag{18}$$

Possible static aeroelastic performance indices are divergence dynamic pressure, aerodynamic stability derivatives, which can be obtained by processing the matrices

$$\begin{aligned} [K^{ae}_{rr}] &= [K^a_{rr}] + q[K^a_{re}][k^s_{ee} - qK^a_{ee}]^{-1}[K^a_{er}] \\ [C^{ae}_{rr}] &= [C^a_{rr}] + q[K^a_{re}][k^s_{ee} - qK^a_{ee}]^{-1}[C^a_{er}] \\ [M^{ae}_{rr}] &= [M^a_{rr}] + q[K^a_{re}][k^s_{ee} - qK^a_{ee}]^{-1}[M^a_{er}] \end{aligned} \tag{19}$$

and any performance index associated to the solution of Eq. (17), after a trim condition has been specified.

A modal approach based on low-frequency normal modes and/or static modes gives the trim load distributions with good accuracy, but is totally inadequate when stresses must be taken into account. Different strategies based on the use of higher-order modal perturbations are proposed with good results in Ref. 16. In AIDIA, the adopted scheme is based on the use of a modal approach for solving the trim problem, whereas for the evaluation of the stresses, a *static* modal problem is used. The static problem is based on aerodynamic and inertia loads updated at each cycle, starting from the results of the trim solution, and can be seen as an ad hoc adaptation of the mode acceleration technique in a perturbation modes approach. In fact, at each iteration, the sum of the aerodynamic and inertia loads can be written as

$$\{\boldsymbol{F}^a_G\} + \{\boldsymbol{F}^i_G\} = q[K^a_G]\{\boldsymbol{q}\} + q(l/V)[C^a_G]\{\dot{\boldsymbol{q}}\} + q(l/V)^2[M^a_G]\{\ddot{\boldsymbol{q}}\} - [M^s_G][X]\{\ddot{\boldsymbol{q}}\} \tag{20}$$

where the subscript G refers to the fact that these loads are in the discrete coordinate set, i.e., that of the FEM model. Thus, after introducing a modal reduction $[X_{SA}]$ based on the displacement vector of the reference trim solution and its derivatives with respect to the design variables, we obtain

$$[X_{SA}]^T[K_G][X_{SA}]\{\boldsymbol{q}_{SA}\} = [k_{SA}]\{\boldsymbol{q}_{SA}\} = [X_{SA}]^T(\{\boldsymbol{F}^a_G\} + \{\boldsymbol{F}^i_G\}) \tag{21}$$

which is analogous to the static case except for the load that is re-evaluated at every iteration. A drawback of this approach is that a different static configuration must be defined for each value of the dynamic pressure.

Dynamic Response

The response analysis is easily carried out in the frequency domain and may include responses to discrete gusts, transient loads, and random ergodic inputs. The direct and inverse fast Fourier transform (FFT) is used for the deterministic input, whereas random ergodic responses are available in the form of power spectral densities (PSDs).

AIDIA Architecture

In AIDIA, any integrated optimization process can be split into four distinct phases. In the first, the *definition* phase, the type of analysis required for each model is specified; in the second, the *analysis* phase, all of the analyses are carried out and the aeroservostructural responses evaluated for each model; in the third, the *selection* phase, an approximate optimization problem is defined by selecting the objective function and by screening the constraint functions; in the fourth, the *minimization* phase, sensitivities, local approximations, and the minimization are set up. The versatility of the procedure is enhanced by the possibility of keeping the designer in the loop to monitor and interact with the different phases, allowing him to choose interactively among the different computational strategies and the different kinds of servostructural problems to be solved at each iteration. The different phases are briefly illustrated next.

Definition Phase

The purpose of this phase is the definition of the structural, aerodynamic, and control modal bases; the aeroservoelastic responses; the functional relations; and the set of design variables.

Design Variables

Possible design variables are the section area of truss elements, the section properties of beam elements, the thickness of isotropic plates, taking into account the in-plane and bending behavior, the thickness and fiber orientation of the layers of composite plates, the position of balancing or tuning masses, and the gains and compensator parameters of active control systems. A linking of design variables is also available.

Aeroservoelastic Responses

The main available responses are strains/stresses in any structural element, nodal displacements, natural frequencies, aeroelastic damping and frequencies for flutter problems, responses to an external excitation, divergence speed, control-surfaces effectiveness, and variations of the aerodynamic stability derivatives.

Functional Relations

A functional relation establishes a link between different design variables and/or structural responses. Possible relations are failure criteria for isotropic and composite materials, stiffness criteria through the imposition of constraints on linear combinations of nodal displacements, flutter damping to define a safe acceptable damping domain within the flight envelope, structural weight, gains norms, aeroelastic variations of the aerodynamic derivatives, any linear or nonlinear combination of different design variables to take into account technological and manufacturing constraints, etc.

Analysis Phase

The analyses presently included are linear static analysis, modal analysis, flutter analysis, static aeroelastic analysis, deterministic, and stochastic response analysis.

Selection Phase

To satisfy the multiobjective formulation adopted in the design process, it is possible to choose either any of the structural responses and/or functional relations or a weighted sum of these terms as objective and/or constraint functions. The optimization problem selection then establishes which of the calculated indices must be considered as objective and constraint functions.

Minimization Phase

The last phase in which a minimum (maximum) value for the chosen objective function is looked for is the minimization phase. This is the only step in the design loop where all of the design variables, the structural-control responses, and the functional relations are considered simultaneously. Generally, the structural design variables have the same values in all cases considered because they are associated with the same structural elements. On the other hand, the control design variables can assume different values for different and independent models. In fact, because these variables are not associated with an invariant geometrical property of the structure, they can be reconfigured depending on the flight condition, and so the adoption of several control models to design an active control system can reflect a possible gain-scheduling policy. Maintaining the same gains for different models can reflect the search for robust controllers and/or insensitivity to sensor and actuator failures, or both. The minimization is performed on an explicit approximate analytical problem. A convex linearization is implemented. It is also used for the servostructural responses and for functional relations, except those that are known in analytical form, i.e., structural weight or gain norms. This approximation is generally conservative, even if usually more restrictive move limits are necessary for control design variables in comparison with the structural ones. All responses and sensitivities are computed analytically.

Numerical Applications

Two numerical test cases concerning the optimization of a generic advanced fighter aluminum wing (AFA), subject to static and aeroelastic constraints, and the integrated servostructural optimization for the control of flexible structure Mast flight system (COFS-I), are presented. In the first example, a comparison between AIDIA results and those obtained by using MSC/NASTRAN SOL200 is also reported. Other examples concerning integrated servostructural optimization can be found in Refs. 4 and 12. Detailed comparisons between AIDIA and MSC/NASTRAN SOL200 results are reported in Ref. 8.

Example 1: Advanced Fighter Aluminum

The first example is based on the ASTROS model reported in Ref. 16. Its structure is modeled by 1276 grid points and 4449 elements, for a total of 3761 degrees of freedom with symmetric boundary conditions. Figures 2 and 3 show the aerodynamic and the wing-structural MSC/NASTRAN models. By means of a linking operation, the wing box has been divided into 13 zones, shown in Fig. 3. In each zone, the thickness values of the upper and the lower skin have been considered, for a total of 26 design variables. The optimization goal is the minimum structural weight of the wing box skin, with stress constraints related to a symmetric 9-g pull-up maneuver at Mach 0.95. The von Mises stresses of the skin elements are constrained to be less than 36,700 psi.

To investigate the effectiveness of the modal approach adopted in AIDIA, particularly in relation to static aeroelastic problems, two different optimizations have been carried out using MSC/NASTRAN SOL200 and AIDIA. According to the modal reduction scheme proposed in AIDIA, two configurations must be defined: the first for solving the trim problem and the second for the evaluation of stresses. The modal basis of the aeroelastic problem contains the first 20 low-frequency normal modes of the baseline structure, whereas 27 modes (the

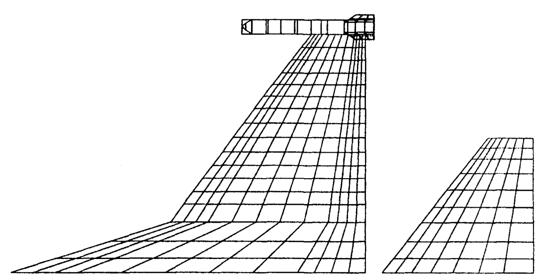


Fig. 2 AFA MSC/NASTRAN aerodynamic model.

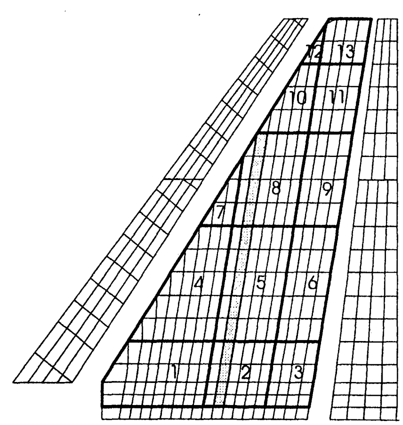


Fig. 3 AFA MSC/NASTRAN wing structural model.

Table 1 AFA MSC/NASTRAN vs AIDIA weight history[a]

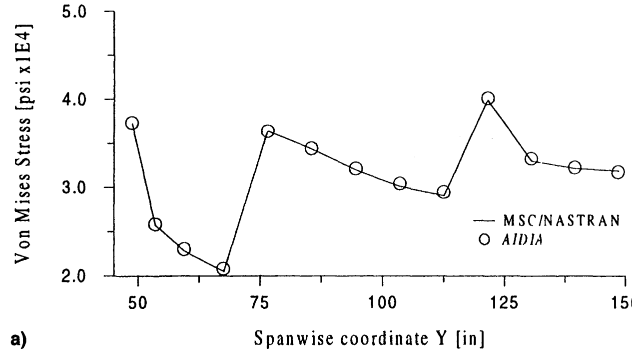
Iteration	MSC/NASTRAN	AIDIA
1	678.53	678.53
2	518.65	521.08
3	510.11	508.38
4	510.13	504.36

[a] In pounds.

Table 2 AFA MSC/NASTRAN vs. AIDIA final skin thicknesses[a]

Zone	Initial	Final MSC/NASTRAN	Final AIDIA
1U	0.95	0.685	0.687
1L	1.00	0.678	0.686
2U	0.80	0.717	0.742
2L	0.80	0.596	0.588
3U	0.70	0.561	0.518
3L	0.60	0.413	0.415
4U	0.45	0.407	0.400
4L	0.65	0.432	0.442
5U	0.45	0.344	0.347
5L	0.45	0.287	0.239
6U	0.10	0.055	0.034
6L	0.15	0.090	0.104
7U	0.45	0.434	0.433
7L	0.60	0.510	0.532
8U	0.25	0.230	0.237
8L	0.20	0.193	0.200
9U	0.08	0.042	0.028
9L	0.07	0.034	0.029
10U	0.20	0.200	0.201
10L	0.20	0.214	0.215
11U	0.06	0.029	0.026
11L	0.06	0.030	0.023
12U	0.25	0.226	0.125
12L	0.22	0.195	0.115
13U	0.15	0.113	0.116
13L	0.17	0.124	0.130
Weight lb	678.53	510.130	504.360

[a] In inches.



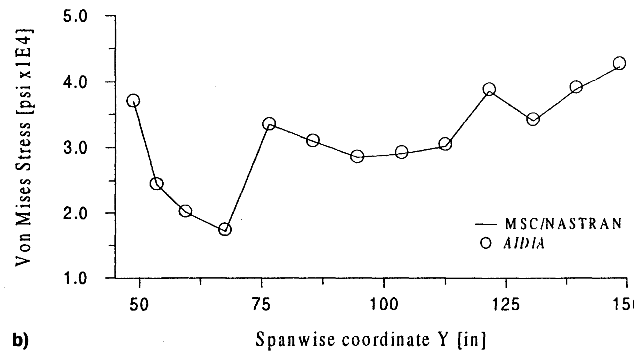


Fig. 4 AFA final design-stress distribution: a) upper skin and b) lower skin.

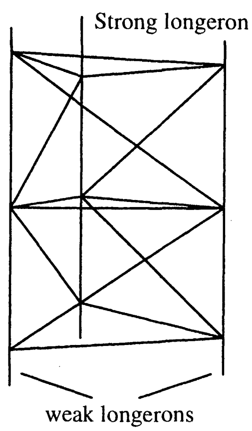


Fig. 5 Cross section of the COFS-I Mast structure.

baseline displacements vector and its 26 derivatives) form the modal basis for the static aeroelastic problem. Table 1 compares the weight history of both MSC/NASTRAN and AIDIA. It appears that the trend and final values are very similar. Analogous conclusions may be drawn for the final thickness distributions of the wing box that are compared in Table 2. It has not been necessary to carry out any further global iteration because the final results of AIDIA, using only the initial reference modal bases, compared well with MSC/NASTRAN results, as can be inferred from Fig. 4, where the final von Mises stresses along the lower and upper skin elements marked in Fig. 3 are shown. Differences with the results reported in Ref. 16 can be justified by the different module analyses, structural, but above all aerodynamic, adopted in ASTROS and MSC/NASTRAN.

Example 2: Integrated Design of COFS-I Mast Flight System

The second example concerns an integrated structure-control optimization. The detailed description of the optimization problem can be found in Ref. 17, whereas, in this paper, only the most significant results and comments are reported. The subject of this example is the COFS-I Mast, the first of three research projects developed at NASA Langley Research Center as test cases for the study of the dynamics and control of large space structures. The Mast is a 60-m-long structure of triangular cross section. Three longerons with unequal cross-sectional areas (two weak and one strong longeron) are used to couple bending and torsion natural modes (Fig. 5). One inertial wheel on the tip and eight collocated proof-mass actuators (PMA) and sensors distributed at various locations along the truss are employed to control the structural motion. This kind of actuator applies an electromagnetically generated force to the structure by reacting onto an inertial mass, free to slide along a linear guide.[18,19] Despite their good dynamic performances, particularly for low-amplitude vibrations, their response to low-frequency and large-amplitude vibrations may be quite unsatisfactory because of their intrinsic design limitations. In particular, the dynamic response is dominated by the high-pass behavior required to impose a limited motion of the mass and by the maximum control forces available.[20] Because of this dynamic coupling, the design of the control system cannot be carried out independently from that of the structure. This is therefore a meaningful test case for the application of integrated servostructural optimization procedures.

Design Requirements

Literature reports several optimization examples applied to COFS-I.[21-23] COFS-I design requirements are as follows. Minimum values for the relative damping: first bending mode *XZ* and *YZ* planes = −0.05, second bending mode *XZ* and *YZ* planes = −0.02, first torsional mode = −0.012, third bending mode *XZ* and *YZ* planes = −0.012, f^1_{min} = 0.18 Hz, f^1_{max} = 0.27

Hz, f^D_{min} = 18 Hz, Δ = 0.254 mm, σ_{lim} = 400 MPa, ξ = 0.25 m, η = 0.2 m, and φ = 2 deg. In the example reported here, the following design requirements have been considered.

1) The first natural frequency f^1 of the structure must be in the $f^1_{min} - f^1_{max}$ range to maintain a good separation from the shuttle control-system frequencies (the lower limit) and from the individual truss elements frequencies (the upper limit).

2) The fundamental bending frequencies about the principal axes must be sufficiently well separated. This can be obtained by imposing a minimum assigned difference, Δ, between the inner radius of the weak and the strong longerons.

3) The first natural frequency of each diagonal truss element must be greater than an assigned value f^D_{min}.

4) The relative damping (approximated by the ratio real/imaginary part of the eigenvalues) of the first seven structural modes must be lower than assigned values.

5) The structure must safely endure a statically assigned tip deflection, η, and rotation, φ, in the fully deployed configuration. Constraints on the Euler buckling loads are also taken into account.

6) The maximum dynamic displacement of every proof-mass actuator, ξ must be limited during the transient excitations taken into account. Note that this specific limit is assigned a priori only to maintain the proof-mass motion within the cross section of the Mast.

Dynamic Loads for Response Analysis

The Mast structure is subject to several and different dynamic loads. Nevertheless, to evaluate the capabilities of the servostructural integrated approach proposed here, only the dynamic loads caused by a docking maneuver, simulated by enforcing an assigned displacement at the base of the structure, and to a generic extravehicular activity (EVA), are considered.

Structural Model

The structural model consists of 489 truss elements. All finite elements of longerons and diagonals are linked into four structural *modules*. Each module contains six design variables, i.e., the inner radius and the thickness of the cross-sectional areas of the weak and strong longerons and of the diagonal elements: in this way there are 24 structural design variables. All of the remaining structural elements are kept constant.

Control Model

Figure 6 shows a schematic representation of the considered PMA. The main difference between ideal and real PMAs consists of the limited motion allowed to the mass, called *stroke length*, which is related to the physical limitations related to the size of this device. This constraint on the stroke has a heavy influence on the dynamic response of the actuator because the force generated may not always follow the long-run low-frequency commands of the structural control system when these require the mass to impact its end-of-stroke stops. Usually some kind of restoring forces, acting on the movable mass and depending on its displacement from the middle of the stroke, are introduced to partially solve these problems. For this study we consider only simple PMA actuators composed of a mass, coil, and linear elastic spring to generate the restoring forces, even if a dedicated electronic solution can be used[24] to produce more complex and often nonlinear control forces, able to cope more effectively with the previously cited limitations. The dynamic equation of the proof-mass actuator, neglecting its inherent damping, is

$$M_a(\ddot{r} + \dot{\nu}) + K_a r = -F \tag{22}$$

where M_a is the actuator mass, K_a is the actuator spring, r is the relative displacement of the actuator mass with respect to the Mast structure, ν is the Mast structure velocity, and F is the internal control force exchanged between the proof-mass and the structure. Assuming that the proof-mass is controlled by a speed drive, the control force generated by this kind of actuator can be related to the speed error[21]

$$F = -g(\nu - \dot{r}) \tag{23}$$

where a collocated velocity control scheme has been adopted. Following the procedure adopted in AIDIA, it is possible to write the second-order dynamic equation representing the Mast structure and the nine active control systems (eight PMAs and one reaction wheel). The order of this system is 35, and it is composed of the first 26 natural modes (six rigid and 20 elastic modes), plus the nine equations describing the dynamics of the actuators. Because one of the main difficulties in an integrated servostructural optimization is the choice of an appropriate initial set of the control design variables, a preliminary design of the control system has been carried out using a state-space suboptimal approach on a simplified structural model.

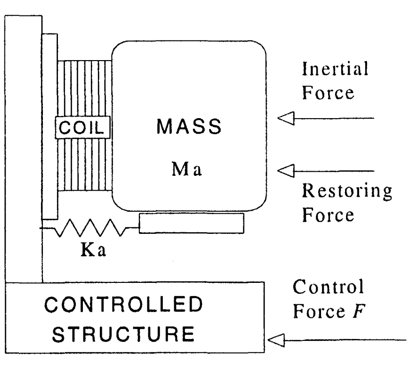


Fig. 6 Schematic representation of a PMA.

Objective and Constraint Functions

To consider all of the COFS design requirements previously presented, four AIDIA models have been used. Table 3 reports the description of these models with the corresponding modal bases and constraint functions (the number in the last column refers to the general design requirements list earlier). The global objective function is a weighted sum of the structural weight and control norm. The weight coefficient for the control norm has been chosen relating the energy cost of the control system to its weight. In this way the final global objective function is related to the total weight of the servostructural system.

Results

To complete the integrated optimization process, three global iterations, i.e., complete MSC/NASTRAN modal bases, are necessary, corresponding to AIDIA's iteration numbers 0 (the initial design), 3, and 8, respectively. Figure 7 shows the history of the structural design variables of the most critical module. A change of behavior of the diagonal element variables after the sixth iteration is evident; in fact, at this cycle the

Table 3 COFS-I Summary of the AIDIA models used during the optimization

Model	Analysis	Modal basis	Requirements
1	Static	Perturbation basis	5
2	Dynamic	35 modes (mast + nine actuators)	1, 2, 3, 4
3	Response	35 modes + docking loads	6
4	Response	35 modes + extravehicular loads	6

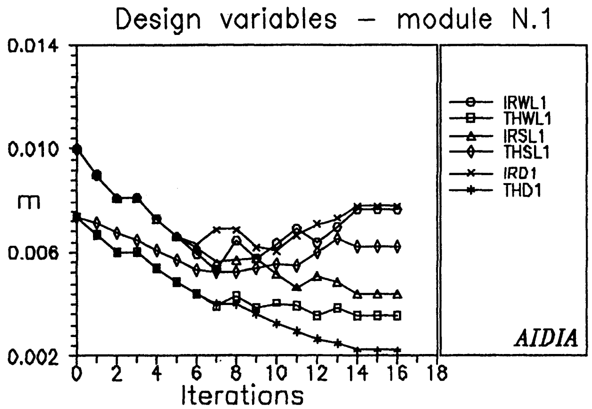


Fig. 7 COFS-I design variables history (IR = inner radius; TH = thickness; WL = weak longeron; SL = strong longeron; D = diagonal).

buckling constraints become active and lead to a greater value of the inner radius to increase its moment of inertia. The control design variables continuously decrease during all optimization cycles. An MSC/NASTRAN verification has demonstrated the accuracy of the final solution.

These results have been carried out considering the proof-mass restoring stiffness as constant and equal to 15 N/m, which determines an actuator frequency lower than the first structural frequency. It is well known that above this break frequency, the actuator can be considered an almost ideal force generator, as its output directly follows the input command. To guarantee an actuator response closely tracking the structural control-system commands, it is therefore mandatory to keep the high-pass actuator bandwidth well below the first natural frequency of the controlled structure. If this condition is not satisfied, the actuator dynamics becomes intrinsically coupled to that of the structure, and it has been demonstrated that this makes the coupled structure–actuators system stability critical.[22,23] In other trial designs, this stiffness and, thus, the actuator frequency, has been included in the set of design variables. In all of those cases, starting from an initial actuator frequency greater than the first structural frequency, the minimization algorithm always worked to push this frequency below the first structural frequency. On the other hand, it turned out that trying to constraint the actuator frequency to be greater than the first structural frequency, makes it impossible to determine a feasible design because of the difficulty of satisfying the requirements on the eigenvalues. This result, obtained without any a priori assumption, confirms what is reported in Ref. 20, and emphasizes the need to consider both the control and structure dynamics during the integrated design to obtain the most efficient interaction between structures and control systems, particularly if different configurations, with significantly differing dynamics, must be taken into account. Instances of these conditions arise during the structure construction or when a large concentrated mass, such as a docking shuttle, is suddenly connected to a flexible structure, considerably altering its structural mode shapes and frequencies.

Concluding Remarks

The numerical examples shown in this paper, along with those reported in other related works, demonstrate that AIDIA can be considered as a valid methodology for the integrated preliminary servostructural design of aerospace systems. Nevertheless, it is important to note that at this stage of development only realistic industrial applications would draw meaningful conclusions about the viability and effectiveness of any integrated servostructural optimization procedure and multidisciplinary optimization methodology in general. In fact, to fully assess the reliability of MDO, it is necessary to gather substantial experience in relation to many real design applications, because the multidisciplinary design methodologies should be verified in a true industrial environment organized in different departmental divisions that, while aiming at the same *optimal* design, often work separately. On the other hand, the benefits of multidisciplinary optimization procedures are now so evident that it is impossible to delay their use in the design of new vehicles, from the conceptual to the detailed level, even though the preliminary design phase is believed to be the most relevant to MDO applications.

In this view, the adoption of reduced-order models appears meaningful in building a numerical procedure that is capable of quickly leading to reliable answers to the *what if* questions of designers, and, within this framework, the modal schemes proposed in AIDIA have shown to guarantee satisfactory results. The possibility of adopting simplified models is a fundamental requirement for an efficient MDO methodology, but this does not represent the only key aspect. The most important aspect is most likely an efficient interaction between different disciplines, including the possibility of using several modelization philosophies within each discipline. From this point of view, the choice of a representation of the aeroservoelastic systems in the Laplace domain must be seen as a limitation of the actual implementation of AIDIA that must be overridden as soon as possible to allow the designer the possibility to access modern control design techniques in the state-space domain. The extension of the approximation concepts typical of the structural optimization, e.g., convex linearization, to the integrated structures-control optimization can be retained, even if more restrictive move limits must occasionally be adopted for the control design variables.

Concerning the choice of maintaining the designer in the loop, it is fundamental to underline that human interaction within the optimization cycles is still essential, not only for obtaining a final efficient solution, but also for a better understanding of the nature of possible couplings that can arise as the design progresses. It is, in fact, believed to be the only way to ascertain that a reformulation of the optimization problem and/or of the basic design concepts is what is required, instead of continuing the optimization of a conceptual solution that appears severely inadequate.

Looking at the future of MDO methodologies, it seems that the key aspect will be represented by a real open architecture, i.e., the capability to communicate easily across many different analyses codes for structures, aerodynamics, and control. From this point of view, the AIDIA approach, because of its capability of being easily interfaced to different analysis modules, is believed to be valid for testing new design concepts with real MDO challenges.

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