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Study on the Use of High-Fidelity Methods in Aeroelastic Optimization

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Multidiciplinary optimization is a key element of the design process. To date multidisciplinary optimization methods that use low-fidelity methods are well developed. Gradient-based optimization methods that use data from three-dimensional linear aerodynamic solvers and two-dimensional structural solvers have been applied to complex aerospace configurations. However, use of high-fidelity methods such as Euler/Navier–Stokes methods for fluids and three-dimensional finite element method for structures is not as well developed. As an activity of the Multidisciplinary Design Optimization Technical Committee (MDO TC) of AIAA, an effort was initiated to assess the status and use of high-fidelity methods in multidisciplinary optimization. Contributions were solicited through the members of the MDO TC. This paper provides a summary of that effort.

Introduction

MULTIDISCIPLINARY optimization is becoming important for aerospace structures, primarily to address aeroelastic issues and weight reduction. Aeroelasticity that involves the strong coupling of fluids, structures, and controls is an important element in designing an aerospace vehicle.

Computational aeroelasticity based on low-fidelity methods, such as a linear aerodynamics model coupled with the modal model for structures, is well advanced.

Although these low-fidelity approaches are computationally less intensive, they are not adequate for the analysis of configurations that can experience complex flow/structure interactions. For example, supersonic transports can experience vortex-induced aeroelastic oscillations, and subsonic transports can experience transonic buffet associated structural oscillations.[1] Both types of aircraft may experience a dip in flutter speed in the transonic regime. The vertical tail of the F18A experienced structural oscillations due to unsteady vortical flow.[2] An abrupt wing-stall phenomenon associated with structural motions was observed from the F18E/F (Ref. 3). The X-34 launch vehicle experienced aeroelastic instability at low supersonic speeds.[4] For all of these cases, current analysis and design methods based on low-fidelity methods were not adequate. To avoid undesirable aeroelastic behavior, multidisciplinary optimization is needed in the aeroelastic design process. Current high-fidelity methods used for fluids typically involve the finite difference or finite volume approachs for solving the Euler/Navier–Stokes equations and for structures the finite element (FE) approach for solving the Lagrange equations. Using these high-fidelity methods, optimization can be performed to avoid undesirable aeroelastic behavior and to minimize weight.

Multidisciplinary optimization involves large number of aeroelastic computations. Aeroelastic computations are typically an order of magnitude more expensive than calculations on rigid configurations because multidisciplinary coupling adds additional complexity in the physics. Figure 1 shows typical computational requirements for a single aeroelastic response as a function of geometric complexity. All computational times are presented in terms of a single processor on a Cray C-90 computer. The growth in CPU time required is exponential. Thousands of such computations are required for a single design. Advances in parallel computers are making such computations more feasible.[5]

The fluid and structural domains in an aeroelastic computation can be modeled at various levels of complexity both in terms of physics and geometry. For design, aerodynamic data may be used at several levels of fidelity starting from low-fidelity look-up tables and ending with high-fidelity Navier–Stokes solutions. Similarly for structures, the data can be obtained starting from low-fidelity assumed shape functions and ending with detailed three-dimensional FEs. As the fidelity of modeling increases, it becomes more difficult to handle complex geometry. Figure 2 illustrates the typical levels of modeling complexity involved for both fluids and structures.

To date there is significant advancement in the use of computational fluid dynamics (CFD) for aeroelastic computations. With use of the state-of-the-art parallel computer program HiMAP,[6] aeroelastic computations are made for a full aircraft (34 blocks, 10 million grid points) by solving the Navier–Stokes equations coupled with modal structures.[7] In addition, recent aeroelastic computations of highly flexible wings were made by Garcia.[8] by coupling the Navier–Stokes equations with nonlinear beam FEs.

In this study, the levels of fidelity shown in Fig. 2 are taken as a road map to assess the status of high-fidelity methods in multidisciplinary optimization (MDO).

Status of Optimization Methods

In the field of high-fidelity MDO for aerospace applications, one of the key issues is being able to perform flow and structural simulations, particularly when each discipline is nonlinear and strongly coupled. Use of high-fidelity equations for single discipline optimization is well advanced in aerospace and other engineering fields. In Ref. 6, use of FE analysis for structural optimization is illustrated. The aerodynamic influence coefficient method (AIC) that can compute coupled flow/structure data is well developed for linear methods.[9–11] The AIC method along with gradient approach method is in routine use for MDO optimization.[12] The response surface method[13] is becoming successful for uncoupled systems because it decouples the optimization into construction of response surfaces generated for CFD and structures separately. Response surface methods are used for optimization based on gradient methods.

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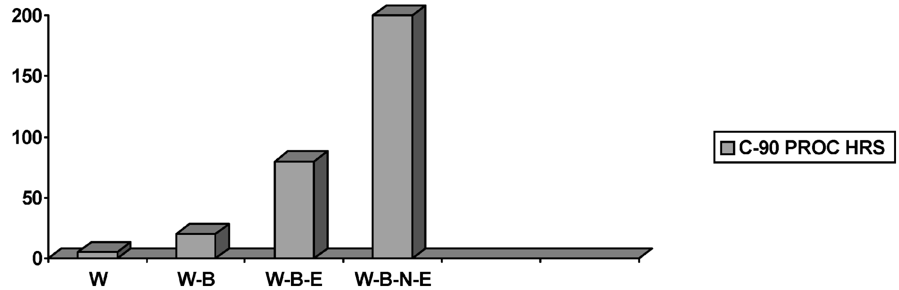

Fig. 1 Computer time in C-90 processor hours needed for a typical aeroelastic computation using coupled NS and modal equations: W, wing; B, body; E, empennage; and N, nacelle.

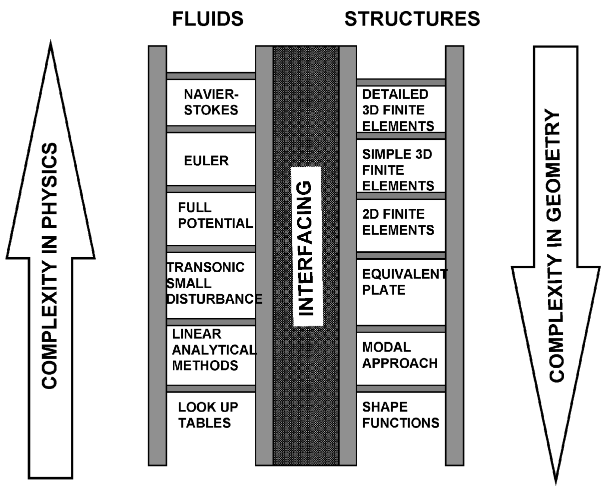

Fig. 2 Varying levels of fidelity in modeling for fluids and structure.

Recently the sensitivity approach, an extension of the AIC method, has been demonstrated for cases when flow/structure interaction is weakly non-linear.[14]

MDO may involve either a single objective function or multi-objective functions. In optimization involving a single objective function, the system is optimized for performance of one of the disciplines. The discipline that is not considered for optimization provides constraint information. An example is to optimize a wing for maximum lift/drag for constraints on structural deflections. In multi-objective optimization, two or more disciplines are simultaneously optimized. An example is to optimize simultaneously for maximum lift/drag ratio and minimum weight of a wing.

Evolutionary algorithms (EAs), sometimes called genetic algorithms (GAs), are alternate optimization algorithms mimicking the mechanism of the natural evolution, where a biological population evolves over generations to adapt to an environment by selection, recombination, and mutation. When EAs are applied to optimization problems, the terms fitness, individual, and gene usually correspond to an objective function value, a design candidate, and a decision or design variable, respectively. One of the key features of EAs is that they are a global search method. Because gradients are never formed, they work well in multimodal or noisy design environments. These features lead to the advantages of robustness and suitability to parallel computing.[15,16]

Approach Used for this Study

For the purpose of assessing the state of the art in the field of MDO, a questionnaire was compiled and distributed to a number of leading experts. A sample of the questionnaire is included in the Appendix. In an attempt to reach the largest cross section of individuals, the distribution list included members of the AIAA MDO Technical Committee (TC), as well as other individuals who are currently active in the field of MDO applications and research. A distribution among the various individuals sought out for this exercise by organization is presented in Fig. 3. Only responses that replied with objective evidence of use, for example, an archived publication or a web site, were accepted. Based on the information provided by the authors, responses were placed in different categories.

Results

There have been 20 responses that use high-fidelity methods. Out of them, only nine responses that belonged to MDO have been considered for review. In all responses selected, coupling of aerodynamics and structural dynamics was addressed for optimization. In dealing with these disciplines, the research effort can be classified into three major categories.

1) Category 1 consists of multidisciplinary coupling in both analysis and sensitivity levels, which involves computing cross derivatives that depend on more than one discipline.

2) Category 2 consists of coupling only in the analysis level.

3) Category 3 consists of uncoupled analysis.

The multidisciplinary coupling here means aeroelastic effects. The aerodynamic load will deform the structure, and the deformed structure will create a different aerodynamic load. If this coupling is taken into account at the analysis level, the analysis has to be iterated between CFD and computational structural dynamics. For the sensitivity level, the aerodynamic quantities have to be differentiated with respect to the structural variables, which entails a large computational burden. On the other hand, in the uncoupled analysis, the aeroelastic deformations are often ignored. In this sense, the aerodynamic and structural analyses can be carried out independently and the resulting data can be fed to a utility function for the optimization.

Category 1 requires a coupled aeroelastic sensitivity analysis. This sensitivity analysis is performed within the framework of a global sensitivity equations (GSE) method.[17−20] The GSE method provides a mathematical expression for the total sensitivity derivatives of a coupled system. It requires the computation of interdisciplinary coupling terms (partial derivatives) between the aerodynamic and structural models. Optimization is then performed by gradient-based algorithms.

An example of category 2 can be found in Ref. 21. The aeroelastic deformation is considered in the analysis level, but the optimization is carried out only for the structures. Because weight is a major element in the MDO process, it can be treated as a separate discipline. In Ref. 22, an optimization procedure is described that uses a high-fidelity structural model to minimize weight, which is another example of category 2.

In category 3, computations are made independently for each discipline. For aeroelastic optimization response surfaces (RS) are generated from the uncoupled analysis. The optimization then utilizes RS. Coupling, which is typically analytical in nature, takes place during the optimization process. The main benefit of the uncoupled analysis is the numerical efficiency in generating the data because the analysis deals with a single discipline at computationally intensive analysis level. The use of the RS method in association with uncoupled analysis offers a number of benefits. First, the RS models smooth out numerical noise, which may mislead the gradient search. Second, the analysis is completely separated from the optimization. This eliminates difficulties in integrating the grid generation, flow calculation, and post-processing utilities. Finally, by using simple

Table 1 Assignment of FC index

POC	Fluids/structures other Grid/elements	PROP/CONR	Optimization method	FC index
Raveh and Karpel[21]	Euler/500,000	Two-dimensional/Wing-Box (Span-Rib-Skin) (W-B)/1,000	Gradient	16
Knill et al.[23]	Euler/500,000	Two-dimensional/plate	Gradient	15
Oyama et al.[16]	NS/500,000	One-dimensional/beam	Genetic algorithm (GA)	16
Giunta[17]	Euler/300,000	Two-dimensional/plate/1,000	Gradient	14
Blair and Canfield[22]	Panel	Two-dimensional/W-B/nonlinear	Gradient	10
Gumbert et al.[19]	Euler/50,000	Two-dimensional/W-B/5,000	Gradient	16
Kim et al.[20]	Euler/100,000	Two-dimensional/plate	GA/gradient	11
Maute et al.[18]	Euler/50,000	Two-dimensional/FE model/6,000[a]	Gradient	16

[a]Elements derived using two-dimensional structural equations.

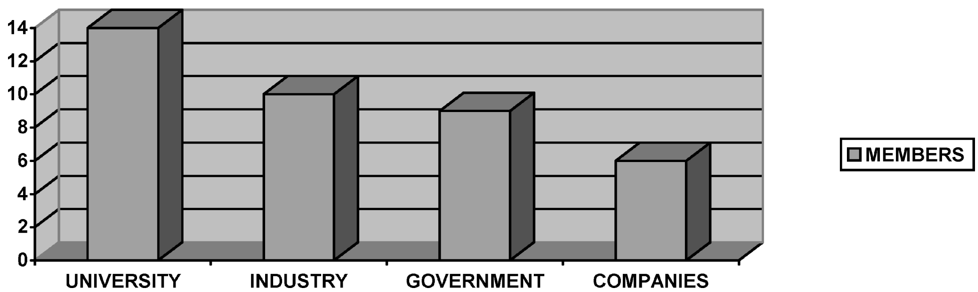

Fig. 3 Distribution of MDOTC members among different organizations.

polynomial surfaces, one can obtain global information about the design space, such as design tradeoffs, sensitivities on design variables, and constraint boundaries in the design space. In Ref. 23, a detailed optimization process based on uncoupled analysis using response surfaces is demonstrated.

New optimization techniques based on GA have started making an impact on aeroelastic optimization. The uniqueness of this approach is that it does not require computation of gradients. Instead, it will search for an optimum solution using GA from several possible solutions. Possible solutions can be obtained using any one of the methods described for the described three categories. The GA approach is suitable for multi-objective optimization. It is accomplished by computing solutions that represent tradeoffs among competing objective functions selected. A designer can then chooses a solution based on the tradeoff information selected. Examples of GA for the multi-objective optimization based the category 2 analysis approach are given in Refs. 16 and 24.

An attempt is made in this paper to provide a quantitative measure for the level of fidelity used in MDO. A fidelity/complexity index (FC) is assigned to each approach. It is assumed that the complexity of the problem is represented by the grid size used for modeling flows and structures. Indices for various disciplines selected are given in the next section

Fidelity Index

For Fluids the approaches and their indices are Navier–Stokes (NS) (10); Euler (5); full potential (4); linear/panel (2); and empirical/tables (1).

For structures, the approaches and their indices are three-dimensional nonlinear FE method (10); two-dimensional nonlinear/three-dimensional FE method (7); two-dimensional FE method (5); one-dimensional FE method, modal(3); and shape functions (1).

For controls, the approaches and their indices are time domain (4) and frequency domain (2).

For propulsion, the approaches and their indices are three-dimensional NS (4), two-dimensional NS (3); one-dimensional NS, and empirical (1).

In the complexity index, for fluids, the number of grid points is in hundred thousands, for structures, the number of elements is in thousands, and for detailed FE model-based weight model, two points are added.

A summary of the responses is given in Table 1, which shows that the highest fidelity for fluids is the NS equations. Structures is still limited to low-fidelity models such as two-dimensional plate or wing-box (W-B) elements (spar, skin, rib). Traditional optimization approaches based on the gradient method are still in strong use. EA that may have an advantage for multiobjective multidisciplinary applications are becoming popular.

Conclusions

A study has been conducted to define the state-of-the-art use of high-fidelity equations in MDO. A key element of this study was a survey in which information about MDO tools was solicited from users and researchers within the MDO community. Based on the responses received, all MDO work in involving high-fidelity methods were in the area of aeroelasticty. Use of the NS equations for fluids and the FE-based Lagrange's equations for structures are becoming popular. The gradient approach is most common among optimization methods. The sensitivity approach is widely used to compute coefficients for multidisciplinary optimization. Evolutionary methods such as GA are still in the early stages of research but are growing rapidly. An effort to continue this study to find more extensive information about the use of high-fidelity equations in MDO is needed.

Appendix: Questionnaire

As an activity under the applications sub-committee of the AIAA MDO technical committee we plan to conduct a survey to find the status of MDO applications using high fidelity methods. Please send information (publication details) about work you have done in related area. An electronic version of full report/paper (MS Word, PDF, HTML) is appreciated. Please forward this message to others who may be working in this or related fields.

Requirements for the information to be included in literature survey.

1. Minimum 2 disciplines
2. Unclassified/non-proprietary/Public Domain

Please indicate the level of fidelity of discipline modeling and optimization method. Following is a guideline

Fluids: (Include the type of configuration and grid size where applicable)

1. Navier Stokes
2. Euler
3. Full potential
4. TSP

5. Linear
6. Empirical/Other (Specify)

Structures: (Include the type of configuration and number of elements where applicable)

1. 3D FEM
2. 2D FEM
3. Equivalent Plate
4. Modal
5. Shape Functions
6. Empirical/Other (Specify)

Controls:

1. Time Domain Feed Back
2. Frequency Domain
3. Empirical/Other (Specify)

Propulsion

1. 3D Navier Stokes
2. 2 D Navier Stokes
3. 1D Navier Stokes
4. Empirical

Optimization Methods.

1. Gradient Method
2. Evolutionary Algorithm
3. Other (e.g. Physical program)

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