

1N-35  
08-07

**Final Technical Report Submitted to  
to the National Aeronautics and Space Administration**

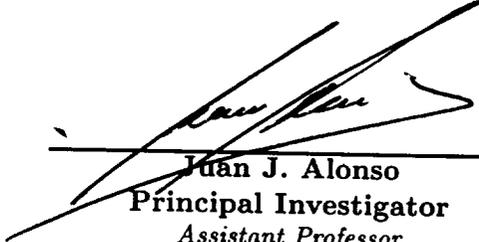
**Ref. Number: NCC2-5226**

*Department of Aeronautics & Astronautics  
Stanford University  
Stanford, CA 94305*

*February 3, 1999*

**Aero-Structural Optimization of HSCT Configurations in  
Transonic and Supersonic Flow**

*Funding Period: October 1, 1997 - September 30, 1998*

  
\_\_\_\_\_  
**Juan J. Alonso**  
**Principal Investigator**  
*Assistant Professor  
Stanford University*

*ucf*  
JUL 21 1998

CC: 202A-34

CASI

## Contents

<b>1 Summary</b>	<b>2</b>
<b>2 Introduction</b>	<b>2</b>
<b>3 Goals Attained</b>	<b>3</b>
3.1 Aero-Structural Calculation Pre-Processor - CSM_PRE . . . . .	3
3.2 CSM Application Programming Interface . . . . .	3
3.3 CSM Solver for Wind Tunnel Models . . . . .	4
3.4 CSM Solver for Realistic Aircraft Structures . . . . .	4
3.5 Implementation in SYN107-MB . . . . .	5
3.6 Sensitivity Analysis . . . . .	5
3.7 Demonstration Using Realistic Configurations . . . . .	5
<b>4 Continuing Work</b>	<b>5</b>
<b>5 Supported Personnel</b>	<b>5</b>

## 1 Summary

This document outlines the progress made under NASA Cooperative Research Agreement NCC2-5226 for the period 10/01/97-09/30/98. The work statement originally proposed was meant to extend over the period of two complete years of which only one was funded. Consequently, only a portion of the goals were achieved. Similar work will continue in our group under different sponsorship and will be available in the form of conference and journal publications. The following sections summarize the technical accomplishments obtained during the last year. Details of these accomplishments can be found in the accompanying paper that was presented at the AIAA 37th Aerospace Sciences and Exhibit Meeting which was held in Reno, NV in January of this year.

The original proposal outlined a research program meant to lay down the foundation for the development of high-fidelity, fully-coupled aerodynamic/structural optimization methods applicable to a variety of aerospace applications including the design optimization of High Speed Civil Transport (HSCT) configurations. The necessary research and development work was divided into two main efforts which addressed the necessities of the long term goal. Initially, our experience in the simulation of unsteady aeroelastic flows [1, 2, 3] was directly applied to existing aerodynamic optimization techniques in order to provide insight into the effects of aeroelastic deformations on the performance of aircraft which have been designed based on purely aerodynamic cost functions. The intention was to follow up this work with a detailed investigation into the basic research work that has to be completed for the development of an optimization framework which efficiently allows the truly coupled design of aero-structural systems. This follow-up effort was not funded.

The outcome of our efforts during the past year was the development of a coupled aero-structural analysis and design environment that was applied to the design of a complete aircraft configuration [11].

## 2 Introduction

Aerodynamic optimization methods have recently achieved a relative level of success due to the ability to compute flows over complex configurations with rapid turnaround and the development of novel ideas for the formulation of the design process which have considerably decreased the computational cost of the process. In particular, explicit multigrid methods combined with the exploitation of parallel, distributed memory architectures have allowed for the solution of the Reynolds Averaged Navier-Stokes equations in a matter of a few hours [6, 10, 9]. Moreover, the control theory approach to the formulation of the design problem has contributed to a very large reduction in the number of function evaluations (RANS flow solutions) required to improve an existing configuration, thus making the design problem entirely feasible [7, 13, 8, 12].

Although these methods are still in a relative level of infancy, they have matured enough to provide the basis for the inclusion of additional components into the optimization process. In particular, a second discipline which is of vital importance during the aircraft preliminary design phase is that of structural analysis/optimization. The designer constantly must decide on issues of aerodynamic performance vs. structural weight and integrity for which he or she has very little guidance. For example, a thicker wing will typically increase the drag of a wing in transonic flow,

but the degradation of aerodynamic performance is accompanied by a beneficial decrease in the structural weight of the wing. An increase in the aspect ratio of a wing can dramatically reduce its induced drag in the cruise condition, but it will also increase the weight of the structure needed to support it. The most favorable tradeoff between these competing trends can be very costly to identify in an iterative fashion. Moreover, the determination of the location of the true optimum within the design space solely guided by the designer's intuition is highly unlikely.

For these reasons we felt that it was appropriate to pursue a course of research aimed at the solution of the coupled optimization problem. The potential benefits derived from the completion of this effort will be the ability to design lighter, high-performance aerodynamic structures which meet their specified design constraints, a more thorough understanding of the multidisciplinary design problem, and the development of cross-discipline optimization tools that could be extended to more complete descriptions of the aerospace systems in question. It needs to be emphasized that existing algorithms and frameworks for multidisciplinary optimization (MDO) problems revolve around models of the relevant disciplines whose level of fidelity and sophistication is determined by: 1) the number of function evaluations which are necessary to complete the design, 2) the computational power available, and 3) the required turnaround of the process. Due to the large number of function evaluations which are necessary to carry out these designs, the level of fidelity that can be afforded in order to retain a fast turnaround has not reached the sophistication of RANS simulations. Although the computational power of the current generation of computers is increasing at a steady rate, keeping the number of function evaluations at bay must be the focus of any multidisciplinary optimization effort that proposes to use high-fidelity models for the governing equations of the various disciplines involved.

### **3 Goals Attained**

The following is a list of goals achieved during the course of the last year. Brief descriptions are attached to each item. In depth technical descriptions and more complete discussion on their significance can be found in the attached paper [11].

#### **3.1 Aero-Structural Calculation Pre-Processor - CSM\_PRE**

Development of an aeroelastic pre-processor (CSM\_PRE) for the multiblock design program SYN107-MB that automatically computes the necessary weight matrices for the conservative and consistent transfer of loads and displacements between aerodynamic and structural surface meshes. CSM\_PRE is based on Reference [4].

#### **3.2 CSM Application Programming Interface**

In order to allow for the possibility of utilizing an arbitrary finite element model for the description of the structure, a detailed Application Programming Interface (API) was developed. This API explicitly outlines both the content and format of the information that must be provided by a Computational Structural Mechanics (CSM) solver intended for aeroelastic design. The API definition has also been kept general enough to allow for a variety of element types within the same model.

The integration of existing and future structural solvers with the design code is therefore accomplished through the use of this API. A typical sequence of calls to the structural model is as follows: the first function call in the API consists of an initialization process that builds the structural model and all ancillary arrays, matrices, and matrix decompositions. Additional functions in the API provide the design algorithm with the complete geometry description of the external surface of the structural model and the interpolation functions for both the coordinates and displacements at any point of the structural model surface. Simple function calls exist in the API to obtain the structural displacement vector and a list of element principal stresses. Finally, since the design module continuously updates the OML geometry, an additional API call is used to update the structural model geometry and its stiffness matrix such that they conform to the OML.

### 3.3 CSM Solver for Wind Tunnel Models

A simple CSM solver was developed to compute deflections of wind tunnel model wings. Because wind tunnel models are typically machined from a single billet, 8-node isoparametric hexahedral solid elements were chosen to represent this type of solid structure. These “brick” elements have 24 degrees of freedom, representing the 3 components of the displacement at each node. The stiffness matrix for each element is found using an 8-point (2 points in each coordinate direction) Gauss quadrature of the strain energy distribution within the element. These elements are called “isoparametric” because the same interpolation functions are used to describe the displacement field and the metric Jacobians used for the global coordinate transformation.

The CSM solver was designed to exploit the convenience of an ordered arrangement of elements; element connectivity is implied by the point ordering of the input CSM mesh. This approach greatly simplifies input, and allows the flexibility of modeling the channels typically cut in the wing surface to install pressure orifices and route pressure tubing. For this purpose, finite element nodes can be located along the channel edges, so that distinct brick elements occupy the volume of the pressure channels. The modulus of elasticity is then set to zero for these elements, thus simulating the missing material.

### 3.4 CSM Solver for Realistic Aircraft Structures

A different CSM solver was developed to model the behavior of realistic aircraft structures. This solver models a wing with multiple spars, shear webs, and ribs located at various spanwise stations, and the skins of the upper and lower surfaces of the wing box. The structural solver is based on a finite element code, *FESMEH*, developed by Holden [5] at Stanford.

Two types of finite elements are used: truss and triangular plane-stress plate elements. Both element types have 3 translational degrees of freedom per node, so the truss has a total of 6 degrees of freedom and the plate has 9 degrees of freedom.

Neither of these elements can carry a bending moment, since their nodes do not have rotational degrees of freedom. The wing bending, however, is still well-captured since the contributions of the second moments of inertia for the plates and trusses due to their displacement from the wing neutral axis is dominant when compared to their individual moments of inertia about their own neutral axes. The only limitation when using these kinds of elements is that each of the nodes must

be simply supported, implying that we can have only one set of plate elements between any two spars.

In the modeling of a typical wing structure, triangular plates are used to model the wing skins. Plates are also used for the shear webs of spars and ribs, while the upper and lower spar caps are modeled using trusses.

### **3.5 Implementation in SYN107-MB**

All of the preceding tasks were implemented in the framework of SYN107-MB. In addition to incorporating these modules into the existing multiblock automatic design program SYN107-MB, items such as the proper mesh deformation due to aeroelastic deflections, and the calculation of sensitivities to variations in structural parameters needed to be accounted for.

### **3.6 Sensitivity Analysis**

The derivation of coupled adjoint equations for the aero-structural problem was carried out and presented in the accompanying paper. In addition, the actual formulation used in the results section (a simplified version of the final goal) was also developed and implemented.

### **3.7 Demonstration Using Realistic Configurations**

Demonstrations of the aeroelastic analysis and design capability of the framework were carried out for both Euler and Navier-Stokes governed flows using both wind tunnel and flight regime full configurations.

## **4 Continuing Work**

Work continues to implement a truly coupled aero-structural framework for optimization of complete aircraft configurations. Several alternatives are being pursued:

- Coupled aero-structural adjoint equations.
- Use of the Global Sensitivity Equations (GSE) for large-scale, high-fidelity problems.
- Use of order reduction techniques such as the Proper Orthogonal Decomposition (POD) to make the design task more manageable.

## **5 Supported Personnel**

The funds provided by this Cooperative agreement were exclusively used to fund the time of Prof. Alonso (at the rate of 23% during the academic year), and the efforts of a doctoral candidate (Mr. Sangho Kim at 50% during the complete calendar year).

## References

- [1] J. J. Alonso. *Parallel Computation of Unsteady and Aeroelastic Flows Using an Implicit Multigrid-Driven Algorithm*. PhD thesis, Princeton University, Dept. of Mechanical and Aerospace Engineering, February 1997.
- [2] J. J. Alonso and A. Jameson. Fully-implicit time-marching aeroelastic solutions. *AIAA paper 94-0056*, AIAA 32nd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1994.
- [3] J. J. Alonso, L. Martinelli, and A. Jameson. Multigrid unsteady Navier-Stokes calculations with aeroelastic applications. *AIAA paper 95-0048*, AIAA 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1995.
- [4] S. A. Brown. Displacement extrapolation for CFD+CSM aeroelastic analysis. *AIAA paper 97-1090*, 35th Aerospace Sciences Meeting and Exhibit, Reno, NV, January 1997.
- [5] M. Holden. Optimization of dynamic systems using collocation methods. *Ph. D. Dissertation*, Stanford University, Stanford, CA, February 1999.
- [6] A. Jameson. Multigrid algorithms for compressible flow calculations. In *Second European Conference on Multigrid Methods*, Cologne, October 1985. Princeton University Report MAE 1743.
- [7] A. Jameson. Aerodynamic design via control theory. *J. Sci. Comp.*, 3:233–260, 1988.
- [8] A. Jameson. Optimum aerodynamic design using the Control Theory. *Computational Fluid Dynamics Review*, pages 495–528, 1995.
- [9] A. Jameson and J. J. Alonso. Automatic aerodynamic optimization on distributed memory architectures. *AIAA Paper 96-0409*, Reno, NV, 1996.
- [10] L. Martinelli and A. Jameson. Validation of a multigrid method for the Reynolds Averaged Navier-Stokes equations. *AIAA paper 88-0414*, AIAA 26th Aerospace Sciences Meeting and Exhibit, Reno, NV, 1988.
- [11] J. Reuther, J. J. Alonso, J. R. R. A. Martins, and S. C. Smith. A coupled aero-structural optimization method for complete aircraft configurations. *AIAA paper 99-0187*, AIAA 37th Aerospace Sciences Meeting, Reno, NV, January 1999.
- [12] J. Reuther, A. Jameson, J. J. Alonso, M. J. Rimlinger, and D. Saunders. Constrained multipoint aerodynamic shape optimization using an adjoint formulation and parallel computers. *AIAA paper 97-0103*, AIAA 35th Aerospace Sciences Meeting, Reno, NV, January 1997.
- [13] J. J. Reuther, J. J. Alonso, M. Rimlinger, and A. Jameson. Aerodynamic shape optimization of supersonic aircraft configurations via an adjoint formulation on distributed memory parallel computers. Bellevue, WA, September 1996. 6th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization. AIAA Paper 96-4045.