UDK: 378.4;623.463.3:517.962.8
COSATI: 20-12, 19-07

# Development of a Coupling Procedure for Static Aeroelastic Analyses

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**In this paper, a fluid-structure coupling procedure consisting of a commercial flow solver, FLUENT, a finite element structural solver, MSC/NASTRAN, and the coupling interface between the two disciplines is developed in order to solve static aeroelastic problems. Inviscid Euler equations with finite volume discretization are used for the flow solver. Multiple processors are parallelized in order to perform faster computations. In order to transfer the pressure and displacement data between the structural grid and the aerodynamic one, the Linear interpolation using the Alternating Digital Tree data structure is performed. The Computational Fluid Dynamic mesh is moved based on spring-based smoothing and the local re-meshing method provided by the FLUENT moving mesh algorithm in order to adapt the new shape of the aerodynamic surface at each aeroelastic iteration. The AGARD Wing 445.6 and a generic slender missile are modeled and solved with the developed procedure while the obtained results are compared with numerical and experimental data available in literature.**

*Key words*: **aeroelastic, static aeroelastic, wing, missile, finite element method, algorithm.**

## Notation and symbols

| | |
|---|---|
| ADT | – Alternating Digital Tree |
| CFD | – Computational Fluid Dynamics |
| CSD | Computational Structural Dynamics |
| E | Modulus of elasticity |
| F | Flux vector |
| $\rho$ | Density |
| $\nu$ | Poisons' ratio |
| $\mu$ | Spanwise location |

## Introduction

AEROELASTICITY is the study which considers the interaction of inertial, structural and aerodynamic forces for elastic structures. An air-vehicle is usually susceptible to serious aeroelastic problems when light weight and low stiffness structures are used. Aeroelastic problems should be considered in the early phase of the air-vehicle structural design since any unstable response to aerodynamic loading may rapidly lead to disastrous structural failure, which may only be treated by major and usually expensive modifications. Wind-tunnels or flight tests are two expensive ways performed in the late phase of the design. Therefore, computational aeroelasticity methods are used in order to determine aeroelastic characteristics of the air-vehicle during its development stages. Static aeroelasticity considers the non-oscillatory effects of aerodynamic forces acting on the elastic structure [6]. Because of the flexible nature of the structure, aerodynamic forces acting on the structure give rise to structural deformation. This deflection of the structure tends to redistribute the aerodynamic forces acting on the structure and this interaction continues by leading to each other. Calculated load distribution may be significantly different from that which is computed for a rigid structure. The present method is applied to solve the static aeroelastic characteristics of the AGARD Wing 445.6, which is a well known test case for aeroelastic problems and a generic slender missile.

## Method

To conduct the static aeroelastic analysis, a fluid solver, FLUENT, is coupled with a finite element structural solver, MSC/NASTRAN. To achieve this, a code is developed in FORTRAN language to automate the entire procedure. The flow chart of the iterative procedure which shows the overall computational aeroelastic procedure developed for the static aeroelastic analysis is given in Fig.1. Static aeroelastic analyses are initiated by computing an initial steady-state solution for the rigid geometry. This converged flow solution is used as a starting point for static aeroelastic iterations. Aeroelastic iterations continue until the difference of the root mean square (RMS) values of structural displacements between two consecutive iterations is less than the prescribed tolerance. Since the FLUENT calculates pressures at the cell centers, for every time step, surface loads should be mapped from the face centroids of the aerodynamic grid onto the structural grid. The MSC/NASTRAN, finite element commercial software, is used for a static structural analysis in order to solve the displacements associated with the aerodynamic pressure loads calculated by the FLUENT. These displacements also need to be interpolated onto the CFD grid in order to obtain a new CFD surface grid. To achieve this, a linear interpolation method using the Alternating Digital Tree (ADT) is performed to transfer displacements and pressure loads between the structural and aerodynamic grid points.

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The aerodynamic mesh must be modified in order to adapt the new shape of the aerodynamic surface, representing the structural deformation at each aeroelastic time step. In this study, the FLUENT moving mesh algorithm is used for deforming process without generating a new grid at each time step. To achieve this, a user-defined function is created and implemented in a code which deforms the mesh according to the structural finite element analysis.

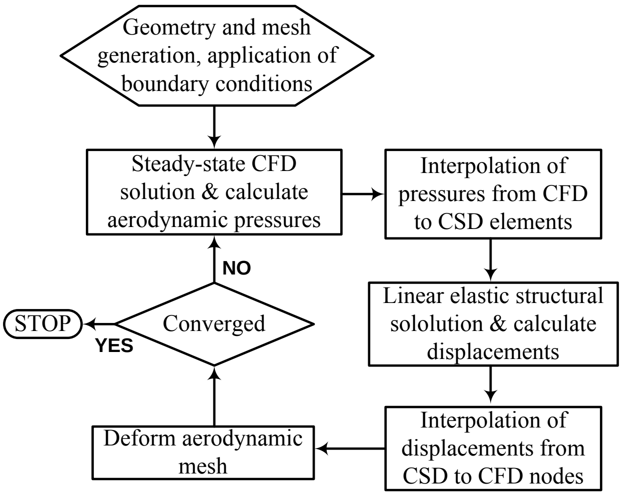


**Figure 1.** Flow Chart of the Static Aeroelastic Procedure

## Interference between the Grids

Computational aeroelasticity requires a fluid-structure interface to transfer the aerodynamic loads and structural displacements at this common boundary, which is usually the wetted surface on the structure. The aerodynamic and structural grids generally do not coincide and do not lie on the same surface since the requirements are different for the corresponding systems (Fig.2). Therefore, the interpolation of aerodynamic pressure loads and displacements must be implemented between the two systems by a carefully implemented method.

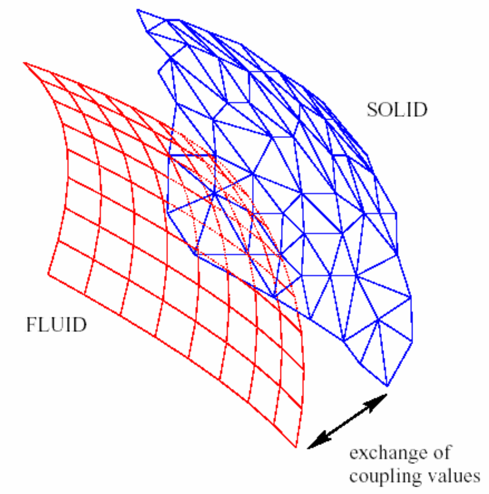


**Figure 2**: Data exchange between two non-matching grids (distance exaggerated)

Data structures such as binary tree, quad tree, oc tree, etc., convert the unstructured form of data into a structured form in order to speed up the search process. These algorithms impressively decrease the searching and sorting time when used for mapping applications in computational aeroelasticity.

The ADT is a spatial binary tree data structure used for searching and sorting data operations. In order to construct an ADT, firstly a root domain is defined. An element is assigned to one of two branches based upon the geometric conditions which are satisfied by the bounding box of that element. This procedure is repeated for all the elements in the domain and finally an ADT is built up.

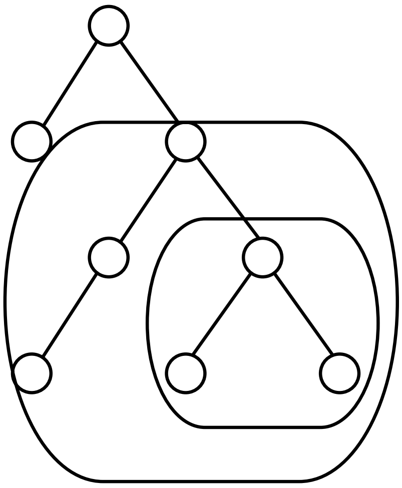


**Figure 3**. Alternating Digital Tree Construction

In the present static aeroelastic analyses, the ADT geometric search algorithm (ADTSearchIn) and the linear interpolation method developed in [2] are used to transfer displacement and pressure data between the two grid systems. This study [2] creates an ADT for a given region described by its points (source), searches for surface elements which enclose the specified points (target), and evaluates the values of a variable by linear interpolation.

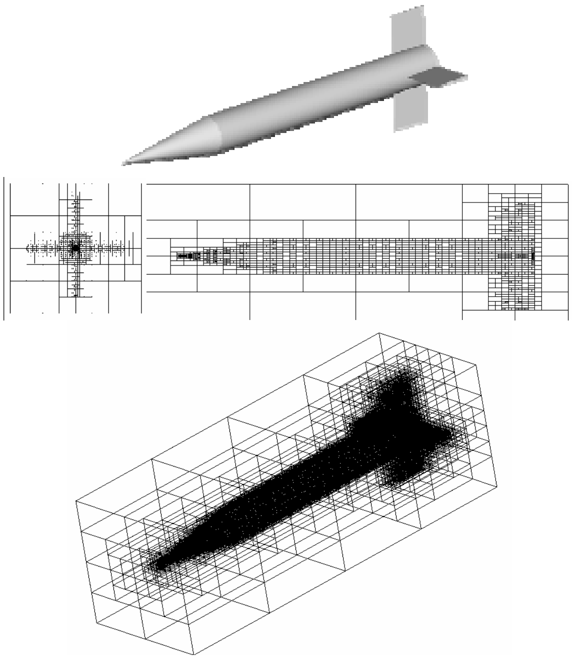


**Figure 4**. Example of an ADT Built with the Points of the Grid Boundaries for a Basic Finner Rocket [2]

In Fig.4, an example of building up an ADT for a Basic Finner Rocket is shown. As it can be seen, the generated digital trees are concentrated near to the grid boundaries of the structure.

Once the ADT is built up, linear interpolation is conducted using the Inverse Distance Weighting method. The aerodynamic grid points are projected onto the structure surface. Then, a structural element which an aerodynamic grid point lies within is defined for each aerodynamic node. The degree of influence of each structural grid of the corresponding element is calculated based upon the weighted distance of the aerodynamic grid node from the grid points of the structural element. In other words, the points that are closer to the node will have higher degree of influence on the calculated value than those that are farther away.

The result of an application of linear interpolation using the ADT data structure is shown in Fig. 5. It is concluded that linear interpolation gives acceptable results for static aeroelastic analyses and that the ADT search algorithm dramatically reduces the interpolation time.

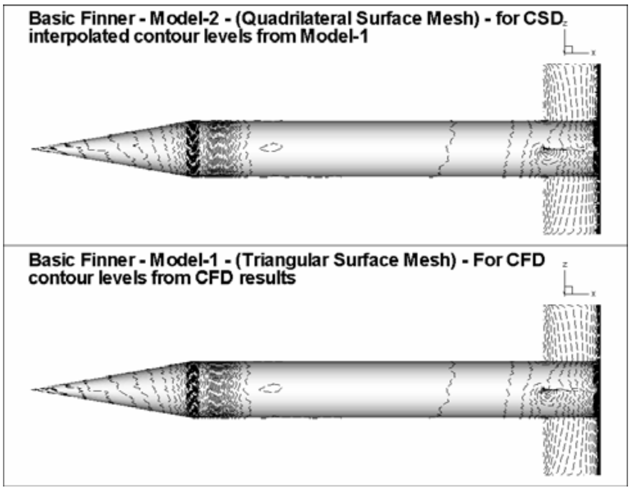


**Figure 5**. Application of `AdtSearchIn` to Non-matching Discrete Interfaces between Fluid and Structure Mesh of a Basic Finner Rocket [2]

## Mesh Deformation

Mesh deformation in computational aeroelasticity applications is one of the important aspects and therefore it must be handled carefully. In order to represent the deformation of the structure during the aeroelastic simulation, the aerodynamic grid must be deformed consistently and the mesh quality must be maintained to avoid any numerical problem. Simply deforming the CFD grid is considerably cheaper and more convenient than re-meshing the entire CFD domain; therefore, it is commonly used in computational aeroelasticity. In this study, the FLUENT moving mesh algorithm is used since the quality of the mesh can be easily controlled and preserved according to the pre-defined parameters. The FLUENT consists of three mesh deformation methods which can be used to update the volume mesh in the deforming regions at the boundaries subject to the motion [5]. These methods are known as spring-based smoothing, dynamic layering and local re-meshing.

In the spring-based smoothing method, the edges between any two mesh nodes are idealized as interconnected springs which form a network. A displacement at a given boundary node will generate a force proportional to the displacement along all the springs connected to the node [5]. The spring-based method preserves mesh connectivity but needs a large amount of CPU time and memory. It is also limited to relatively small deformations when it is used as a standalone mesh deformation scheme. The second method, dynamic-layering, can be used in prismatic (hexahedral or wedge) mesh zones in order to add or remove layers of cells adjacent to a moving boundary, based on the height of the layer adjacent to the moving surface [5]. The third method is re-meshing. The cell quality may deteriorate and cells may degenerate if the boundary displacement is large compared to the local cell sizes. This leads to negative cell volumes which results in convergence problems in a flow solution. Re-meshing can eliminate the collapsed cells, but adds extra computational costs. The FLUENT locally replaces the degenerated cells until new cells or faces satisfy the size and skewness criteria [5].

## CFD Modeling and Simulation

The FLUENT commercial flow solver was used to compute the rolling moments and the flow field around wrap-around and flat finned missiles. The density-based, implicit, compressible, unstructured-mesh solver was used.

The computational grids for CFD simulations were generated using the GAMBIT commercial programs. The analyses were done with an unstructured commercial CFD solver FLUENT which solves the governing integral equations for the conservation of mass, momentum, energy and other scalars such as turbulence.

$$\frac{\partial}{\partial t}\int_V W dV + \oint [F]\cdot dA = \int_V H dV \tag{1}$$

where

$$W = \begin{Bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho E \end{Bmatrix}, F = \begin{Bmatrix} \rho v \\ \rho v u + p i \\ \rho v v + p j \\ \rho v w + p k \\ \rho v E + p v \end{Bmatrix} \tag{2}$$

The density-based, implicit, compressible, unstructured-mesh solver was used in this study. The inviscid flux vector F is evaluated by a standard upwind flux-difference splitting. In the implicit solver, each equation in the coupled set of governing equations is linearized implicitly with respect to all dependent variables in the set, resulting in a block system of equations. A block Gauss-Seidel, point implicit linear equation solver is used. The second-order discretization was used for all flow variables.

The details of the CFD modeling and simulations will be explained in the following sections.

## AGARD Wing 445.6

In this study, the present method is applied to solve the static aeroelastic characteristics of the AGARD Wing 445.6, which is a well known test case for aeroelastic problems. Wind tunnel experiments have been conducted on the AGARD Wing 445.6 in order to predict the dynamic response characteristics and the flutter boundary in the Langley Transonic Dynamics Tunnel [1]. The AGARD 445.6 Wing has a taper ratio of 0.66, an aspect ratio of 1.65 and a wing swept of 45° at the quarter chord. It has root and tip chords of 0.558m and 0.368m, and a semi span of 0.762m. The airfoil section in the stream-wise direction is a NACA 65A004 airfoil, which is a symmetric airfoil with a maximum thickness of 4% of the local chord. The wing platform is shown in Fig.6.

The dimensions of the computational domain and the defined boundary conditions for the AGARD Wing 445.6 are shown in Fig.7. The aerodynamic surface is defined as wall boundary conditions. Flow conditions such as Mach number, operating pressure, temperature and angle of attack are defined in the far-field boundary condition.

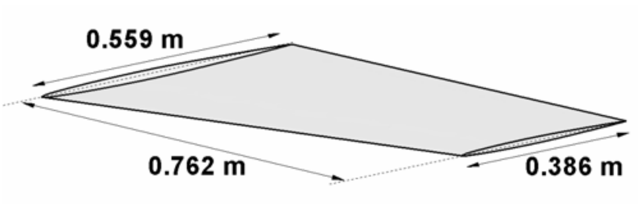


**Figure 6.** AGARD Wing 445.6 Platform

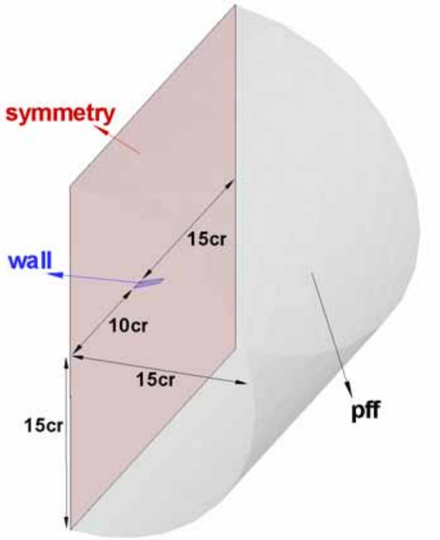


**Figure 7.** Dimensions of the CFD Domain

The optimum numbers of surface triangular elements and volume tetrahedral elements which are determined from grid sensitivity analyses are shown in Table 1. The computational fluid domain is shown in Fig.8. The flow solution calculated with this grid is compared with the numerical results obtained by Cai [4], Lee and Batina [3].

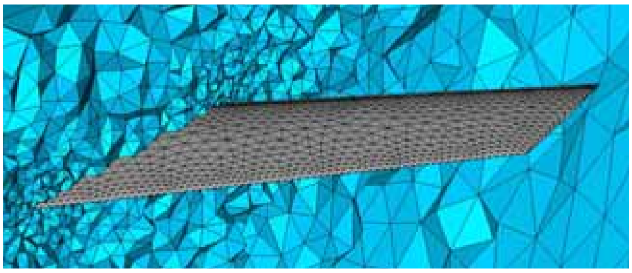


**Figure 8.** Computational Fluid Domain of the AGARD Wing 445.6

The pressure coefficient distribution over the AGARD Wing 445.6 is compared with the study of Cai [4]. Cai conducted a static aeroelastic analysis of the AGARD Wing 445.6 at a flow condition of M=0.85 α=5°. Pressure coefficient distributions over the wing at % 34 span-wise locations for this flow condition are shown in Fig.10.

The pressure coefficient distribution over the AGARD Wing 445.6 is compared with the study of Lee and Batina [3]. Lee and Batina conducted a dynamic aeroelastic analysis of the AGARD Wing 445.6 at flow conditions M=1.141 and α=0°. Pressure coefficient distribution over the wing at 26% span-wise location is shown in Fig.11.

**Table 1.** Number of Surface Triangular and Volume Tetrahedral Elements

| | |
|---|---|
| Number of Surface Triangular Elements | 3.798 |
| Number of Tetrahedral Elements | 158.161 |

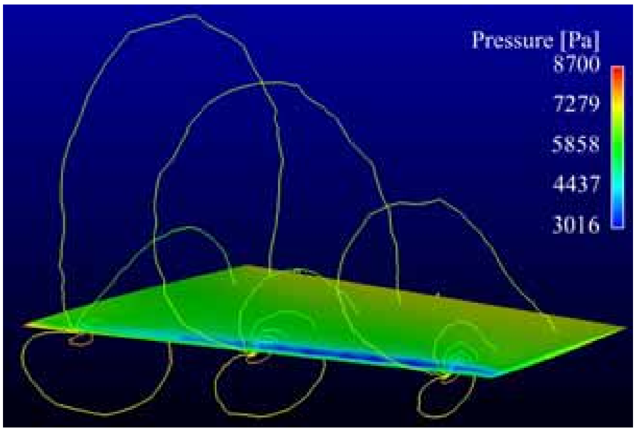


**Figure 9.** Pressure Contours over the AGARD Wing 445.6 (M=0.85 α=5°)

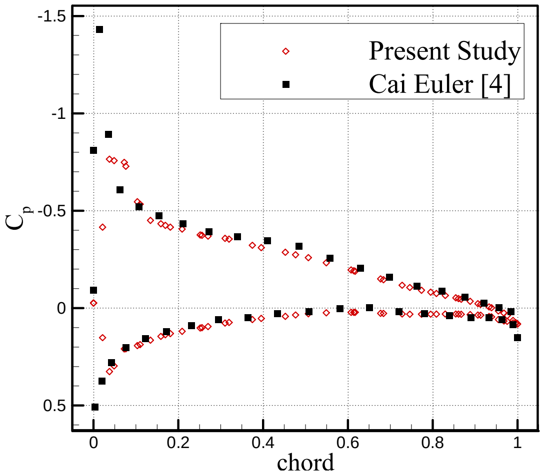


**Figure 10**. Comparison of Cp Distribution at %34 Semispan (M=0.85 α=5°)

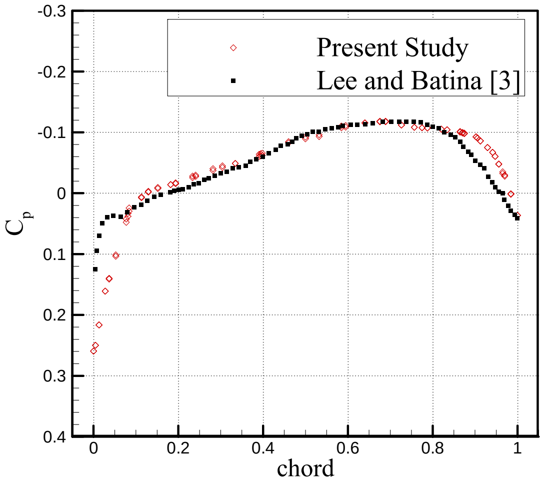


**Figure 11**. Comparison of Cp Distribution at %26 Semispan (M=1.141 α=0°)

The results appear to agree well except for the leading edge. This difference may be attributed to the meshing technique. Cai [4] uses the O-Type structured grid, Lee and Batina [3] use the C-H type of grid which captures the leading edge radius accurately and gives better resolution of the leading edge radius as compared to the present study. In the present work, the unstructured grid and a limited number of triangular mesh are used.

## Slender Missile

A missile body is a slender, elastic structure. Slender missiles are usually susceptible to body bending during high speed flights. Thus, aerodynamic and dynamic forces acting on the missile at high speeds lead to deformation of the body. The elastic deformation on the missile body also results in a variation of aerodynamic loads. This affects the missile aerodynamic performance in terms of stability and control effectiveness. The objective of the present work is to determine static aeroelastic properties for a canard controlled supersonic slender missile shown in Fig.12. The missile has a blunted ogive nose with fineness ratio 1. The total length of the missile is 28 calibers. The control surfaces are deflected as 10° in both pitch and yaw plane to determine aeroelastic characteristics of the missile at drastic flight conditions during a maneuver of the missile at Mach number 1.85.

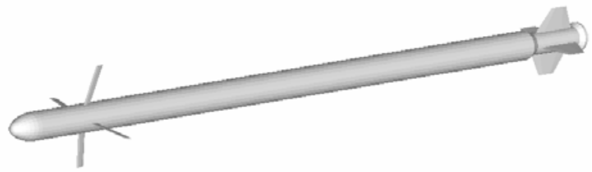


**Figure 12**. Generic Canard Controlled Slender Missile

The CFD analysis in this study is carried out using the density-based, with second order upwinding discretization flow solver, FLUENT. Flow streamlines and calculated pressure contours over the slender missile are shown in Fig.14. In the CFD model, the missile is meshed using unstructured tetrahedral meshes. The model grid size is about 2,291,346 cells (Fig.13).

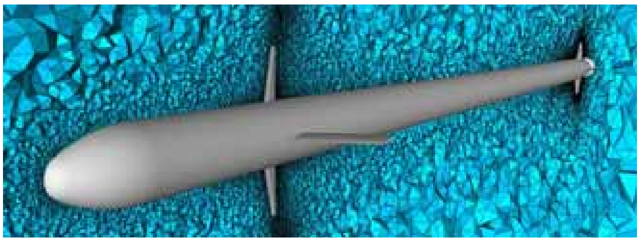


**Figure 13**. Unstructured CFD Grid for the Canard Controlled Generic Slender Missile

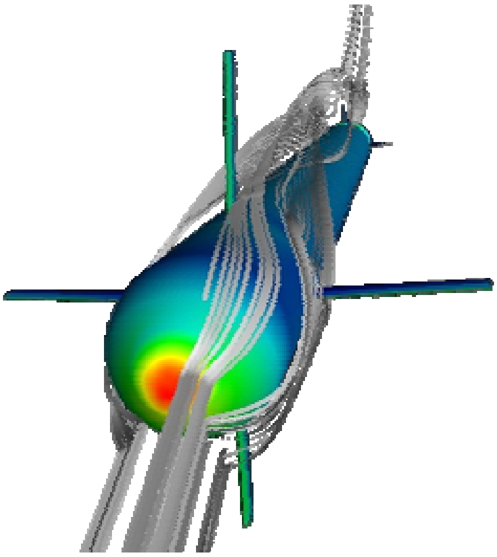


**Figure 14**. Pressure Contours and Streamlines over Slender Missile

## CSD Modeling and Simulation

The finite element mesh for CSD analyses was generated using the PATRAN commercial program. The analyses were done with the finite element structural solver, MSC/NASTRAN. The details of CSD modeling and simulations will be explained in the following sections.

## AGARD Wing 445.6

In this part, the details of the finite element analyses and the results of the modal analyses are given for the AGARD Wing 445.6. The modal frequencies are compared with experimental data [7] in order to validate the structural finite element model, which is used in static calculations in the following sections. In addition to the calculated modal frequencies, the mode shapes of the structure are also compared with the experimental study [7].

A weakened AGARD Wing 445.6 is modeled with plate elements as a single layer orthotropic material the property of which is given in Table 2.

**Table 2.** Mechanical Properties for the Weakened AGARD Wing 445.6

| Material Property | Value |
|---|---|
| $E_1$ | 3.1511 Gpa |
| $E_2$ | 0.4162 Gpa |
| G | 0.4392 Gpa |
| $\rho$ | 381.98 kg/m$^3$ |
| $\nu$ | 0.31 |

The rotations and translations of the nodes at the root section of the finite element model are fixed. Other nodes are allowed to translate in the out-of-plane direction. The CQUAD4 type of element is used for the finite element discretization. The grid sensitivity analysis for the structural grids is performed and the numbers of nodes for the span-wise and chord-wise directions for each finite element model are shown in Table 3.

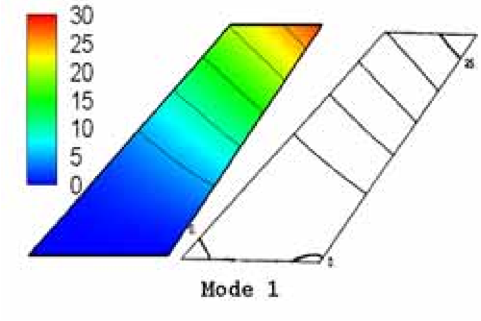
**Table 3.** Number of Elements Used in the Finite Element Model

| | |
|---|---|
| Number of Nodes for the Span-wise Direction | 12 |
| Number of Nodes for the Chord-wise Direction | 12 |
| Total number of Structured Elements | 121 |

The modal analysis of the weakened AGARD Wing 445.6 is performed using MSC/NASTRAN. The first four natural frequencies are given in Table 4 along with the experimental results [7] and those computed by Kolonay [8], Lee and Batina [3].

**Table 4.** Calculated Natural Frequencies for the Weakened AGARD Wing 445.6 [Hz]

| | Mode 1 | Mode 2 | Mode 3 | Mode 4 |
|---|---|---|---|---|
| Present Study | 9.41 | 39.46 | 48.96 | 94.35 |
| Exp. (Yates) [7] | 9.60 | 38.10 | 50.70 | 98.50 |
| Kolonay [8] | 9.63 | 37.12 | 50.50 | 89.94 |
| Lee and Batina [3] | 9.60 | 38.17 | 48.35 | 91.54 |



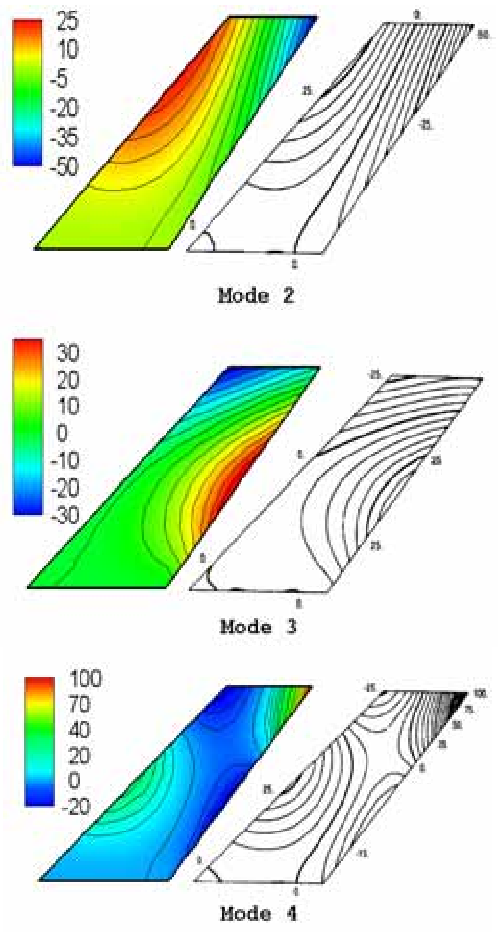


**Figure 15**. Comparison of the Calculated Mode Shapes of the AGARD Wing 445.6 (left) with Experiments (right)

The mode shapes obtained from the finite element analysis of the weakened wing are scaled up so that the maximum and minimum values are the same as those of the experiments. The out-of-plane deflection contours are compared in Fig.15. It can be concluded that the results obtained from the finite element model appear to agree well with the experimental results.

## Slender Missile

The MSC/NASTRAN finite element commercial software is used for a structural analysis. The model consists of a shell (CQUAD4) type of the element for the finite element discretization. The wings are attached to the missile body with the rigid RBE2 elements. The finite element model of the missile is shown in Fig. 16. In order to calculate the deformations of the missile in flight, the Inertia Relief module of MSC/NASTRAN is used. A support point is chosen as the center of gravity location and relative displacements are calculated with respect to this point.

**Figure 16**. Finite Element Model of the Missile for Structural Analysis

The material of the missile body is chosen as aluminum whereas canards and tails are modeled as steel. The mechanical properties are shown in Table 5.

**Table 5.** Mechanical Properties for the Generic Canard Controlled Slender Missile

| Material Property | Missile Body (aluminum) | Canards and Tails (steel) |
|---|---|---|
| E | 70 GPa | 200 GPa |
| ρ | 2700 kg/m$^3$ | 7750 kg/m$^3$ |
| ν | 0.35 | 0.3 |

## Results

The results of the static aeroelastic simulations for the AGARD Wing 445.6 and the generic slender missile are given here.

## AGARD Wing 445.6

The static aeroelastic analyses are initiated by computing an initial steady-state solution for the rigid AGARD Wing 445.6. This converged flow solution is used as a starting point for static aeroelastic iterations. Aeroelastic iterations continue until the difference of the RMS values of structural displacements between two consecutive iterations is less than the prescribed tolerance (10-6). The change of the RMS of the out-of-plane deformation during the aeroelastic simulation is shown in Fig.17. The convergence history of lift coefficient for rigid and elastic wings during the aeroelastic simulation is shown in Fig.18. Each iteration step continues until the constant lift and drag coefficient values are obtained and the nodal grid point locations in the flow domain are updated based on the results of the static structural finite element analyses.

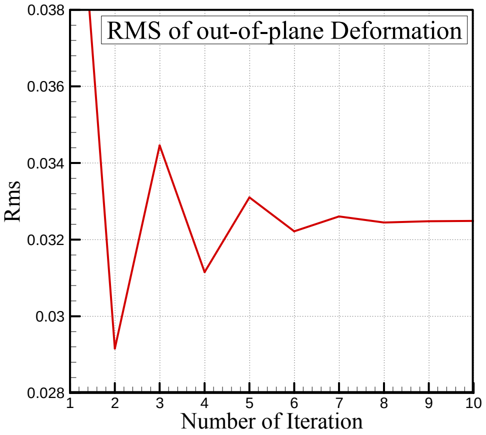


**Figure 17**. The RMS of the out-of- plane Deformation at Each Aeroelastic Time-step

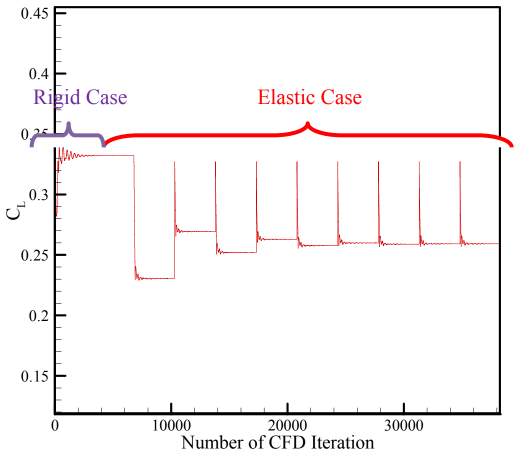


**Figure 18**. Lift Coefficient Convergency during Aeroelastic Simulation

The rigid and elastic wing pressure coefficient distributions calculated in the present study are given in Fig.19 and 20 at two different span-wise locations. The CP values on the surface decrease in the elastic wing due to the decreased pressure values. The lift coefficient of the elastic wing is reduced by 22% as compared to the rigid wing case.

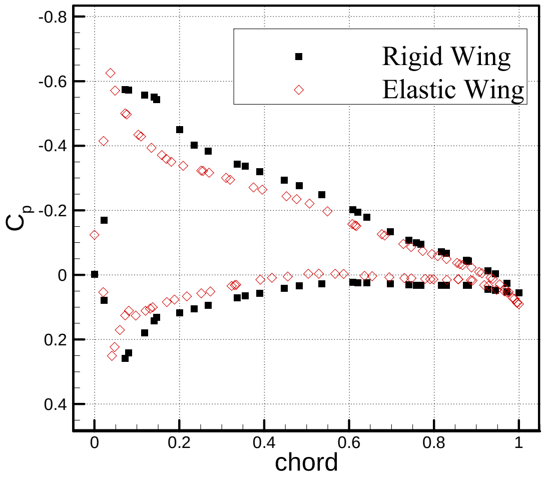


**Figure 19.** Elastic and Rigid Wing CP Distribution at 34 % Semispan (M=0.85 α=5°)

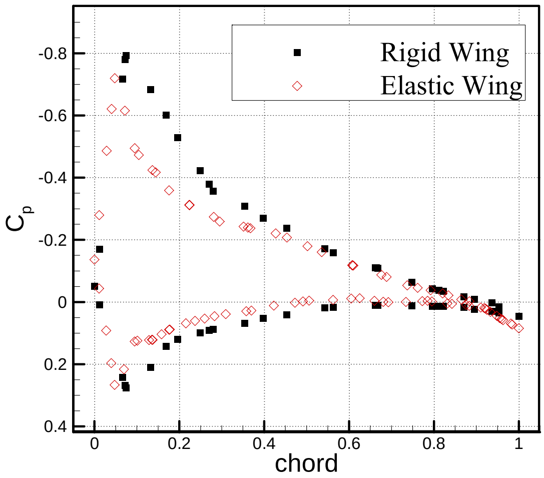


**Figure 20.** Elastic and Rigid Wing CP Distribution at 67 % Semispan (M=0.85 α=5°)

The out-of-plane deformations of the AGARD Wing 445.6 at leading and trailing edges are compared with the results of Cai [4] in Fig.21 and 22. It can be concluded that the results of the present study appear to agree well with the results of Cai [4]. The maximum difference occurs at the wing tip. At the leading edge of the wing tip, Cai calculates 2.181 inch deflection whereas it is calculated as 2.176 inch in the present study. At the trailing edge, Cai calculates 2.418 whereas it is calculated as 2.591 inch in the present study. This difference diminishes towards the root of the wing.

It should be considered that in the present study, the finite element model of the AGARD Wing 445.6 consists of plate elements. Structural analyses are performed with MSC/NASTRAN by allowing only the out-of-plane deformation of the structural grid nodes in order to simplify the calculations. In the present static aeroelastic calculations, the flow and structural solvers are separate, whereas Cai [4] uses a monolithic approach where fluid and structure equations are combined in one single system in order to calculate the deformation of the wing under the aerodynamic loading.

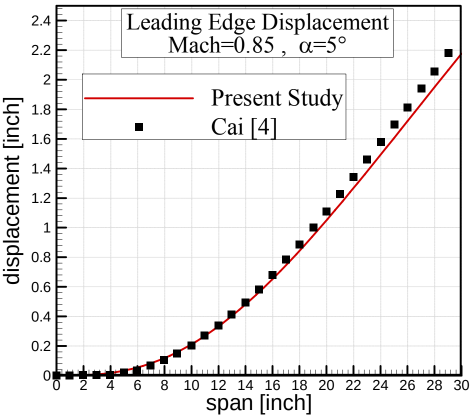


**Figure 21.** Leading Edge Out-of-Plane Deformation

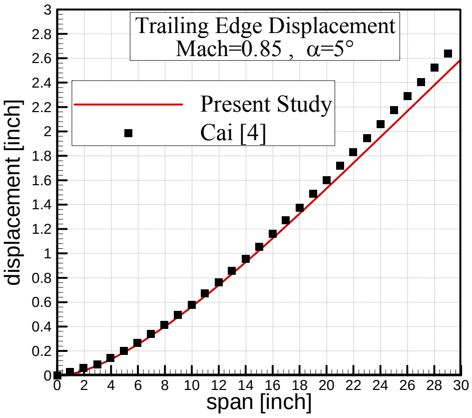


**Figure 22.** Trailing Edge Out-of-Plane Deformation

The elastic wing pressure coefficient distributions at 34% and 67% span-wise locations are compared with the results of Cai [4] in Fig.23 and 24.

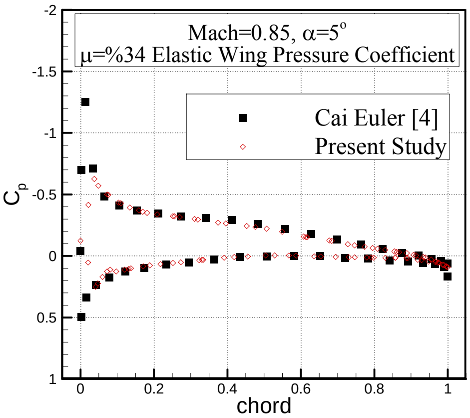


**Figure 23.** Comparison of Elastic Wing CP Distribution at 34% Semispan

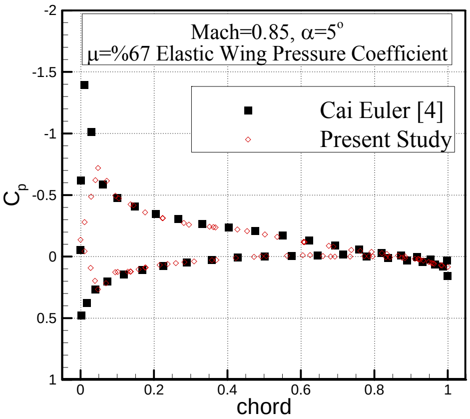


**Figure 24.** Comparison of Elastic Wing CP Distribution at 67% Semispan

The equilibrium position for the elastic wing is compared with the rigid wing and given in Fig.25.

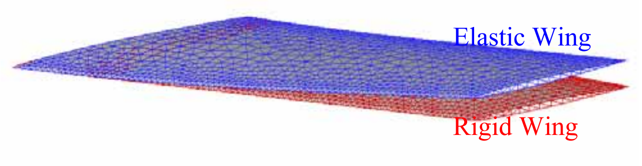


**Figure 25.** Rigid (red) and Elastic (blue) Position of the AGARD Wing 445.6

## Slender Missile

The objective of the static aeroelastic analysis of the slender missile is to determine the aeroelastic effects on the stability and the control effectiveness of the missile. Static aeroelastic analyses are initiated by computing an initial steady-state solution. This converged flow solution is used as a starting point for static aeroelastic iterations and aeroelastic iterations continue until the difference of the RMS values of structural displacements between two consecutive iterations is less than the prescribed tolerance (10-7).

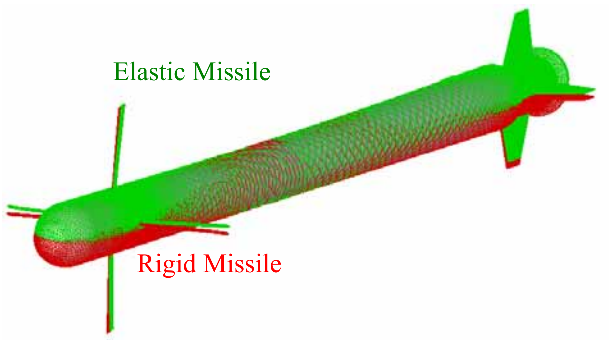


**Figure 26.** Rigid (red) and Elastic (green) Position of Slender Missile

Each iteration step continues until the constant lift and drag coefficient values are obtained and the CFD grid point locations are updated based on the structural finite element analyses. The equilibrium position for the elastic missile is compared with the rigid missile and given in Fig.26.

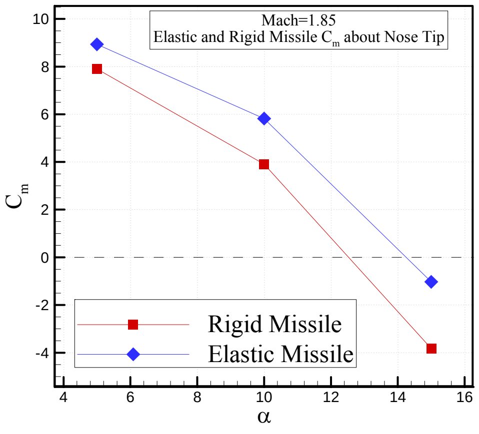


**Figure 27.** Elastic and Rigid Missile Pitching Moment Coefficient about cg

The deformations due to elasticity of the structure have an influence on the missile aerodynamic loads. At a 10° angle of attack, the normal force coefficient of the elastic missile is reduced by 2%. As body bends about the center of gravity, the equivalent angle of attack of the canards increases and that of the tails decreases. The center of pressure of the missile changes by amount of 0.45 caliber of the missile at a 10° angle of attack. Since the stability of the missile changes, the control effectiveness of the missile also changes by amount of 15% as can be seen in Fig.27. For the rigid case, the 10° elevator deflection angle gets the missile in the trim condition at a 12.1° angle of attack, whereas it gets the missile in the trim condition at a 14.2° angle of attack for the elastic case.

## Conclusion

In this paper, a coupling approach is developed in order to solve the static aeroelastic problems. Since this approach gives the variability in choosing different solvers depending on the complexity of the applications, it is an efficient way to couple CFD and CSD solvers.

To conduct a static aeroelastic analysis, a three-dimensional inviscid CFD solver, FLUENT, is coupled with a finite element structural solver, MSC/NASTRAN, that is used to solve the displacements associated with the aerodynamic pressure loading. The mode shapes and corresponding natural frequencies are obtained using MSC/NASTRAN and used for the validation of the structural model.

The mesh deformation methods based on the FLUENT mesh deformation algorithm are used in this study. Since FLUENT replaces the collapsed or deteriorated cells with new cells, the quality of the mesh can be easily controlled and preserved during the deformation of the aerodynamic grid.

For static aeroelastic problems, the linear interpolation method using the ADT is applied successfully to transfer displacements and pressure loads between the structural and aerodynamic grid points. The ADT reduces the interpolation time by amount of the logarithm of the number of points.

The static aeroelastic problem of the AGARD Wing 445.6 is solved with the developed procedure and the obtained results are compared with the numerical data available in literature. The out-of-plane deformations of the AGARD Wing 445.6 at leading and trailing edges are compared with the results of Cai [4]. The results of the present study appear to agree well with the results of Cai [4] except for small differences at the leading and trailing edges of the wing tip. These differences may be attributed to the different flow solvers, meshing technique, and coupling approach. The rigid and elastic wing pressure coefficient distributions calculated in the present study are compared to each other. The $C_P$ values on the surface decrease in the elastic wing due to the decreased pressure values. The lift coefficient of the elastic wing is reduced by 22% as compared to the rigid wing.

As another test case, the static aeroelastic problem of the canard controlled slender missile is solved using the developed procedure. For the structural analysis, the MSC/NASTRAN inertia relief option, which is used to simulate unconstrained structures in flight, is used with the linear elastic solver. The displacements of the structure under the aerodynamic loading are calculated with respect to the missile center of gravity. The normal force and the pitching moment coefficients of the rigid missile and the elastic one are calculated and compared to each other. The normal force coefficient does not change significantly. The pitching moment coefficient about the nose tip of the missile changes by amount of 6%, as the center of pressure changes due to missile bending. This affects the aerodynamic performance of the missile in terms of stability and control effectiveness. The control effectiveness changes about 15 % as compared to the rigid missile.

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Received: 01.12.2011.

# Razvoj spregnute procedure za analizu statičke aeroelastičnosti

**U ovom radu je prikazana spregnuta procedura fluid-struktura koja se sastoji od primene komercijalnog solvera FLUENT za modeliranje obstrujavanje i komercijalnog solvera MSC/NASTRAN za strukturalnu analizu na bazi konačnih elemenata a interfejs između ove dve discipline je razvijen da bi se rešio problem statičke aeroelastičnosti. Metod konačnih zapremina je korišćen za rešavanje Ojlerovih jednačina i opisivanje strujanja. Više procesora je korišćeno u paralelnoj sprezi da bi se obezbedili brzi proračuni. Da bi se uspostavila veza između polja pritiska I polja deformacija odnosno aerodinamičke i strukturne mreže kojima je opisan domen problema izvršena je preko ADT alagoritma. CFD premeštanje mreže je baziran na modelu opruga koristeći metod peglanja i reformulacije mreže pomoću softverskog paketa FLUENT koristeći algoritam pomeranja mreže da bi se formirao novi oblik aerodinamičke površine u svakoj aeroelastičnoj iteraciji. AGARD tip krila 445.6 i generički vitka raketa su modelirani i rešeni sa razvijenom procedurom a dobijeni rezultati su upoređeni sa numeričkim i eksperimentalnim rešenjima raspoloživih u literature.**

*Ključne reči*: **aeroelastičnost, statička aeroelastičnost, krilo, raketa, metoda konačnih razlika, algoritam.**

# Разработка соединённых процедур для анализа статической аэроупругости

**В этой статье показаны соединённые процедуры жидкость-структура, которые состоят в применении коммерческого программного пакета FLUENT для моделирования потока и коммерческих программных пакетов MSC/NASTRAN для структурного анализа, основанного на конечных элементах, а взаимодействие между двумя дисциплинами было разработано для решения проблемы статической аэроупругости. Метод конечных элементов использован для решения уравнений Эйлера, и для описывающих потоков. Более процессоров использовано в параллельном сочетании для обеспечивания быстрых расчётов. Чтобы установить связь между полем давления и полем деформации, т.е. между аэродинамической и структурной сетями, в которых описывается предметная проблема, был сделан ADT алгоритма. CFD перемещение сетки обосновано на модели с использованием пружин и гладильного метода внесения поправки в сети с помощью программного пакета FLUENT с использованием подвижных алгоритм сетки, чтобы сформировать новую форму аэродинамических поверхностей на каждой аэроупругой итерации. AGARD тип крыла 445.6 и общая тонкая ракета смоделированы и решены с разработанной методикой, а полученные результаты сравниваются с экспериментальными и численными решениями находящимися в литературе.**

*Ключевые слова:* **аэроупругость, статическая аэроупругость, крыло, ракета, метод конечных элементов, алгоритм**.

# Le développement de la procédure couplée pour l’analyse de l’élasticité statique aérienne

**Dans ce travail on a présenté la procédure couplée des structures fluides qui consiste en solveur commercial FLUENT pour la modélisation du courant et du solveur commercial MSC/NASTRAN pour l’analyse structurale basée sur les éléments finis. On a développé l’interface entre ces deux disciplines pour résoudre le problème de l’élasticité statique aérienne. La méthode des volumes finies est employée pour résoudre les équations de Euler et décrire les courants. On a utilisé plusieurs processeurs couplés parallèlement afin d’assurer les computations rapides. Pour établir la liaison entre le champs de pression et le champs de déformation, c’est-à-dire entre les réseaux aérodynamiques et structurales au moyen desquels le domaine a été décrit, on a utilisé l’algorithme ATD. Le transfert CFD du réseau est basé sur le modèle des ressorts en appliquant la méthode de repassage et la reformulation du réseau par le progiciel FLUENT et l’algorithme du déplacement du réseau pour obtenir une nouvelle forme de surface aérodynamique dans chaque itération élastique aérienne. Le type de l’aile AGARD 445.6 et le missile générique élancé sont modelés et résolus par la procédure développée. Les résultats obtenus ont été comparés avec les données numériques et expérimentales disponibles dans la littérature spécialisée.**

*Mots clé*: **élasticité aérienne, élasticité aérienne statique, aile, missile, méthode des éléments finis, algorithme.**