AEROELASTIC SIMULATION TOOL FOR INFLATABLE BALLUTE AEROCAPTURE*

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ABSTRACT

A multidisciplinary analysis tool is under development for predicting the impact of aeroelastic effects on the functionality of inflatable ballute aeroassist vehicles in both the continuum and rarefied flow regimes. High-fidelity modules for continuum and rarefied aerodynamics, structural dynamics, heat transfer, and computational grid deformation are coupled in an integrated multi-physics, multi-disciplinary computing environment. This flexible and extensible approach allows the integration of state-of-the-art, stand-alone NASA and industry leading continuum and rarefied flow solvers and structural analysis codes into a computing environment in which the modules can run concurrently with synchronized data transfer. Coupled fluid-structure continuum flow demonstrations were conducted on a clamped ballute configuration. The feasibility of implementing a DSMC flow solver in the simulation framework was demonstrated, and loosely coupled rarefied flow aeroelastic demonstrations were performed. A NASA and industry technology survey identified CFD, DSMC and structural analysis codes capable of modeling non-linear shape and material response of thin-film inflated aeroshells. The simulation technology will find direct and immediate applications with NASA and industry in ongoing aerocapture technology development programs.

INTRODUCTION

Aerocapture by means of large size inflatable ballute structures attached to spacecraft promises to be an enabling technology for future planetary exploration of the solar system. Ballutes employ large drag area structures with diameters of tens of meters to perform deceleration at relatively high altitudes in a planetary atmosphere. A ballute is a flexible, inflated device, a combination of balloon and parachute, made from thin film material with thickness on the order of 1 to 10 mils, which is deployed to increase the drag of the vehicle to which it is attached. The large size of the decelerator allows the aerocapture maneuver to take place at much higher altitudes, which reduces the aeroheating effects and allows the use of materials with lower temperature limits. Ballutes may be directly attached to a vehicle, either clamped to the base or as an extension to the forebody aeroshell or towed behind the vehicle as a semi-independent device. Figure 1 shows representative trailing and attached ballute concepts developed by Ball Aerospace Corporation.

Ballute aerocapture is in an early stage of technological development. The key challenge is to design a lightweight ballute configuration that can withstand the aerodynamic and aerothermal environment during hypersonic flight through the atmosphere. In particular, structural integrity risk issues arise from the use of inflated thin film material for the large ballutes. The impact of dynamic motion and aeroelastic hull deformation on ballute performance remains an unresolved issue. The overall drag, tether and ballute forces, and localized ballute surface heating will all be affected, perhaps in catastrophic ways. Critical and unresolved risks for ballutes include:

- Flow instability and unsteadiness induced by wake and shock wave interactions between ballute and spacecraft,
- Aeroelastic shape changes under aerodynamic loads inducing local stress and heating,
- Dynamic aeroelastic phenomena such as wrinkling and flutter arising from nonlinear shape and nonlinear material response of the thin membrane structure, and

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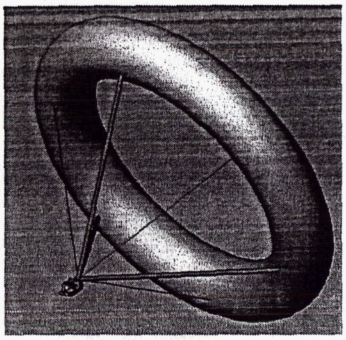
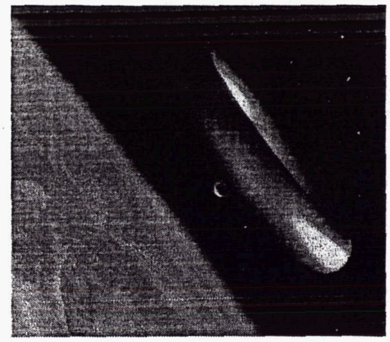
- Coupling and potential amplification of aeroelastic deformation and dynamic stability.



Trailing Ballute Concept



Attached Ballute Concept

Figure 1. Ballute Aerocapture Concepts (Courtesy Ball Aerospace Corp.)

Computational analyses of ballute configurations have been performed at NASA/LaRC for both, the continuum and the rarefied flow regime (Gulick, 2003). The LAURA code was applied to conduct continuum regime CFD analysis (Cheatwood, 1996; Gnoffo, 2003). The DAC (**D**SMC **A**nalysis **C**ode) code provided flow analysis in the rarefied flow regime (LeBeau, 2001). Aeroelastic shape predictions have only been accomplished in uncoupled sequential applications of fluid flow and structural analyses.

A recent survey of the importance of aeroelasticity reiterated the risks posed by the flexibility of lightweight aeroshell structures to the overall stability of the vehicle and to the structural stability of individual components (Bartels, 2005). There is currently no multidisciplinary analysis tool available in the NASA CFD arsenal that can perform coupled aeroelastic, aerothermal, and moving body dynamic analyses of inflated ballute aerocapture vehicles. Yet, the hypersonic aeroelasticity problem has been declared a potential showstopper for inflatable decelerator technology. Aeroelastic computational tools must be developed to model the effects of large and nonlinear deformations of such highly flexible structures across the flight regime, a task that cannot be accomplished in wind tunnel tests.

The computational aeroelastic problem is a complex multidisciplinary problem that involves strong interaction between several physical and numerical disciplines. An integrated multi-physics computing environment is required in which high-fidelity modules for aerodynamics, stress, heat transfer, and computational grid deformation are applied simultaneously. Giant monolithic codes combining all of these modules are difficult to develop, and because of their complexity, cannot easily maintain up-to-date technology. A more flexible approach is to integrate state-of-the-art, stand-alone analysis codes into a multidisciplinary computing environment in which the modules can run concurrently with synchronized data transfer between modules. The ***M***ulti-***Di***sciplinary ***C***omputing ***E***nvironment (***MDICE***) developed by CFDRC provides such a framework where execution of fluid, structures, and thermal analysis codes can be synchronized to function as a tightly coupled system with conservative-consistent force and energy interfacing.

The capabilities of the MDICE software functionality for coupling standalone software tools into a multi-disciplinary simulation tool for thin-walled ballute vehicles were demonstrated during this study (NASA SBIR Phase I project). Continuum flow regime demonstrations were performed using the CFD-FASTRAN flow solver and the CFD-FEMSTRESS structural dynamics finite element solver, both already fully integrated in the MDICE environment. Rarefied flow regime fluid-structure coupling was demonstrated using the DAC code and the CFD-FEMSTRESS structural dynamics code. A suite of proven fluid flow and structural analysis codes was identified in cooperation with NASA and industry ballute experts as candidates for implementation in the ballute aeroelastic simulation system during the Phase II program which is now in progress.

This paper presents an overview of the MDICE architecture, sample analyses performed for a clamped ballute configuration, and the road map for establishing a ballute aeroelastic simulation suite.

MDICE COMPUTING ENVIRONMENT

The MDICE environment was originally developed by CFDRC for NASA/GRC engine applications and later considerably expanded for AFRL/VA aircraft applications (Kingsley, 1998). MDICE enables engineering analysis codes to perform synchronized multi-disciplinary analysis in a distributed computing environment. MDICE consists of a GUI, software libraries, application program interfaces (API's), and generic controller processes to enable dissimilar legacy analysis codes to dynamically exchange data with each other, and facilitate arbitrary, conservative/consistent fluid-thermal-structure interfaces.

The integration of programs into MDICE is accomplished by implanting and invoking MDICE API calls from within the program for direct code-to-code communication. A unique aspect of MDICE is that the data exchange between modules is on-the-fly, i.e. while applications are running. This allows data to be exchanged on the iteration level for a very fine level of control. For this purpose all data is modeled as an MDICE object and those objects are exchanged between applications. Objects may represent a mesh, a solution, or an aeroelastic or thermal interface. MDICE provides standard methods with each object for data and unit conversions, interpolation, etc. The synchronization of the various applications and their data exchange is critical for a multi-disciplinary analysis and is controlled by means of a user-defined script.

MDICE has been demonstrated with a variety of CFD codes at a variety of fidelity levels, from linear panel methods to full Navier-Stokes solvers. Examples are Quadpan, CAP-TSD, ENS3DAE, CFD-FASTRAN, Splitflow, Falcon and AVUS. The most prominent and successful applications of this high-fidelity multidisciplinary analysis tool has been for the prediction and control of tail buffet characteristics of fighter aircraft such as the F/A-18 and the implementation of active flow control, simulations of the AFRL Active Aeroelastic Wing (AAW) research vehicle, and for aeroelastic high-altitude UAV concepts with high aspect ratio wings and blended wing-body bodies (Sheta et al., 2000; Sheta et al., 2001; Sheta et al., 2003; Beran et al., 2005).

The simulation modules to be integrated in the MDICE environment must only be equipped with library calls to deliver and receive data and information through the MDICE system. MDICE has a full interface for codes written in F77, F90, C, or C++. The code module must then be linked to the MDICE library and recompiled. Once all necessary modules are integrated (deemed 'MDICE-compliant'), analyses are coordinated in a multidisciplinary simulation through a scripting language. The disciplinary analyses are initiated from within MDICE. Each analysis module loads grid and restart information and then releases execution control to MDICE. Once each module is placed in a wait mode, the simulation is controlled through the scripting language, which is executed through the MDICE GUI. The first command issued to each module creates an interface object within MDICE. An interface object stores pointers to the grid and variable information that resides directly in the analysis modules' memory. MDICE then assembles the interface objects, or performs calculations necessary for the data transfer between the disciplinary grids. The MDICE script then coordinates the execution sequence of the modules.

MDICE SIMULATION FRAMEWORK FOR AEROELASTIC BALLUTE ANALYSIS

The configuration of MDICE for aeroelastic ballute analysis involves aerodynamics modules (flow solvers), structural dynamics modules, and multi-physics interfacing modules for the fluid-fluid, and fluid-structure and fluid-thermal interactions. The motion of the computational grid in response to the deflections of the flexible structure must also be considered. The environment therefore contains three main parts:

- Multi-Physics Simulation Controller
- Multi-Physics Analysis Modules

- Multi-Physics Interfacing Modules

The first part is the MDICE controller, which controls the temporal synchronization of the data transfer and the multi-level parallelism of the multi-physics analysis modules and coupling routines. The second part is a set of multi-physics fluid and structure analysis modules for the analysis of the multi-physics characteristics of a hypersonic vehicle. The third part is the multi-physics interfacing modules such as fluid-fluid, fluid-structure, thermal-solid interfacing modules.

MDICE Controller

The first component in MDICE is a central controlling process that serves as an object repository and provides application control via MDICE specific script language and remote procedure calls. The remote procedure calls are the mechanism by which MDICE controls the execution and synchronization of the participating applications:

- Launching of application modules on distributed hosts in the MDICE environment
- Workflow control of a simulation by means of scheduling tasks to the application modules
- Facilitate data transfer between application modules.

Multi-Physics Analysis Modules

The second part of the environment consists of a set of analysis modules that model the multi-physics characteristics of ballute vehicles. For the demonstrations presented in this paper, the CFD-FASTRAN and CFD-FEMSTRESS codes were applied since they were fully integrated in the MDICE framework. The individual analysis modules are equipped with the required interface calls to exchange data through MDICE and allow process control for a coupled simulation.

Multi-Physics Interfacing Modules

The third part of the environment consists of the multi-physics interfacing modules. The interfacing modules are used for data exchanges between the various grids of the multi-physics domains. The grids usually have different density, data may reside cell-centered or on nodes, and the grids may not coincide along the boundaries. Interpolation methods are physics based and are tailored to conserve virtual work on both sides of the interface.

The Fluid-Fluid Interfacing Module

In the simulation of very complex configurations, the overall grid is usually divided into sub-domains. The boundaries between the domains may not coincide with one-to-one grid connectivity. This is either due to complexity of the geometry, different grid architecture (structured versus unstructured), different grid density (fine versus coarse grids), or due to domain decomposition for parallel execution of the modules. An interfacing module between these fluid domains is therefore necessary to interpolate the fluxes through the boundaries. The division of the flux between a given local face and multiple opposing faces is determined using geometrical clipping of opposing faces (Sutherland-Hodgman Clipping algorithm). A high-order distribution of fluxes is obtained using Laplacian interpolation algorithm.

The Fluid-Structure Force Interfacing Module

The fluid-structure interface algorithm is used to project forces from the fluid cells into equivalent forces and moments to the structure cells and to project the deflections of the structure to the fluid. A conservative-consistent interfacing module is used for the fluid-structure coupling. The fluid-structure interfacing is formulated in the most general sense for maximum flexibility. There are no inherent assumptions that the fluid grid is matched with the structure grid, either through different mesh densities, mesh architecture, or through physical separation between the interfaces as seen with thick shell finite-element models.

The conservation property aims to conserve the forces and moments in the interpolation process between two or more grids. In this case, the sum of all forces and moments on the fluid interface is equivalent to the sum of all forces and moments on the structure interface. Requiring that the virtual work performed by the solid interface is equivalent to the virtual work performed by the fluid interface provides the necessary consistency or virtual work conservation.

Fluid-Solid Thermal Interfacing Module

The ballute aerothermal environment involves multiple heat transfer mechanisms to and from vehicle surfaces. The surface temperature is determined from the balance of: 1) the heat transfer from the fluid to the surface through convection and through diffusive chemical heat flux resulting from surface catalytic recombination reactions (if present); 2) the energy transfer in the structure by solid conduction; 3) radiative heat loads from solar and shock wave radiation; and 4) re-radiation of energy from the surface back to the flow field. The surface temperature must be obtained by solving this energy balance in an iterative manner. MDICE initiates and controls the exchange of data at the interface between the relevant modules to solve this equation. This solid-fluid heat transfer capability is currently being added under a current contract with the AFRL.

The Grid Deformation Module

A versatile grid deformation module is needed to adjust the CFD and structural region grids to the structural deformation. The flow field conservation equations must account for moving/deforming volumes due to the grid cell motion that occurs in aeroelastic deformation cases. It is essential that fluid codes integrated into the aeroelastic simulation are equipped with this capability to accommodate large deformations without degradation in grid quality and to ensure conservation for time-accurate simulations. CFDRC has developed several remeshing technologies as MDICE modules including a Transfinite Interpolation (TFI) technique for structured grids and a Solid-Brick Analogy (SBA) for unstructured grids that treats the fluid CFD volume mesh as an elastic quasi-solid region where the grid deforms smoothly in response to surface deformations.

RESULTS

The capabilities of the MDICE software functionality for coupling standalone software tools into a tightly coupled multi-disciplinary simulation tool for thin-walled ballute vehicles were demonstrated. Continuum flow regime demonstrations were performed using the CFD-FASTRAN compressible flow solver and the CFD-FEMSTRESS structural dynamics finite element solver. Rarefied flow regime demonstrations were performed using the NASA DAC code and the CFD-FEMSTRESS structural dynamics code.

The sample configuration analyzed in this study is a clamped ballute configuration concept developed by Ball Aerospace Corp. A spacecraft with a diameter of 1.5m and a height of 0.5m is connected to an aft-attached ballute at its base. The ballute aeroshell is formed by a thin film conical surface with a half-angle of 70 degrees stretched between the spacecraft and an inflated torus. The torus has an inflated cross section diameter of 3.46m and the ballute overall outer diameter is 27.66m. Figure 2 shows the surface model of the clamped ballute configuration.

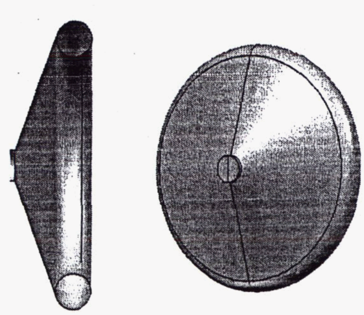
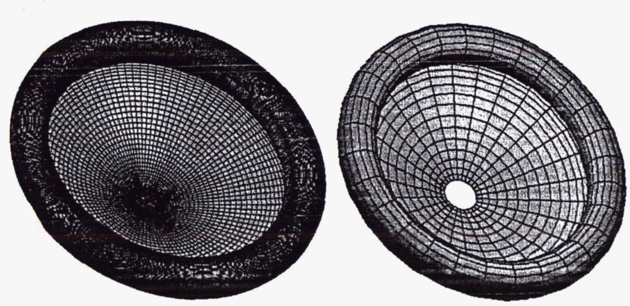


Figure 2. Surface Model of Clamped Ballute Concept



CFD Surface grid *CSD Surface grid*

Figure 3. Surface Grids at Interface of CFD and CSD Modules

The CFD and CSD surface grids of the flexible ballute and torus are shown in Figure 3. The CFD-GEOM geometry modeling and grid generation package was used for geometry modeling and grid generation. The CFD and CSD grids are not identical, typical for aeroelastic simulations, with the CSD grid being much coarser than the CFD grid. The forces and deflections are transmitted between the two grids using the conservative/consistent interfacing modules provided by the MDICE library.

The film material for the actual design varies due to local material reinforcements. For simplicity, a constant material thickness of 0.5 millimeter (approximately 20mil) was used. The material of the ballute walls is assumed to be Upilex and isotropic. The Young's modulus of elasticity is 8.826×10^7 N/m^2, the density is 1468 kg/m^3, and the Poisson's ratio is 0.25. The internal pressure inside the inflated torus was held constant at 75 Pa, imposed as a pressure boundary condition on the internal surface of the torus. The ballute is assumed fixed at the spacecraft base location.

Continuum Regime Clamped Ballute Aeroelastic Predictions

Flight environments for a preliminary Titan aerocapture trajectory were provided by James Masciarelli of Ball Aerospace (Masciarelli, 2005). CFD solutions were generated for the maximum dynamic pressure (Q_{max}) trajectory condition at an altitude of approximately 531km. Flow conditions for this point are U=4266m/s, T=166K, and P=0.273Pa. The corresponding freestream Mach number is M=16.4 and the dynamic pressure is Q=51Pa. The Titan atmosphere was modeled as composed of pure N2 for simplicity. The CFD-FASTRAN code was used for the CFD flow simulations. Figure 4 shows the computed sample flow field at zero and five degrees angle of attack

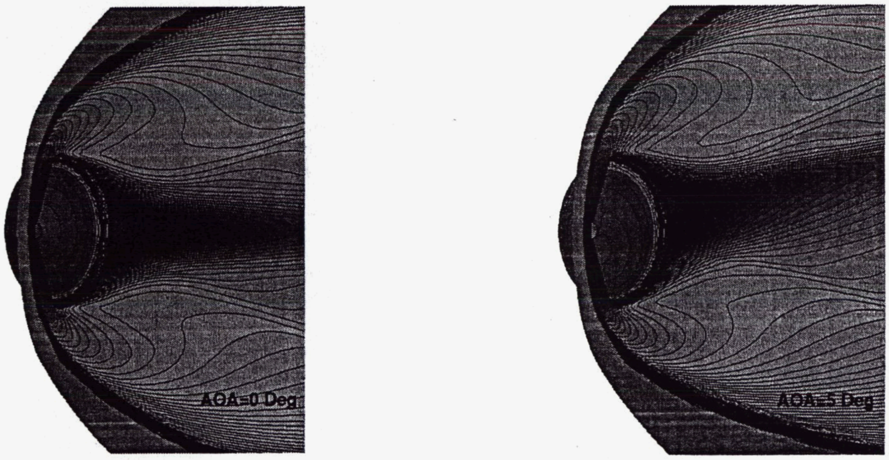


Figure 4. Clamped Ballute Flow Field Solution at Q-max Condition Symmetry Plane Mach Number and Surface Pressure Contours Shown

The sample coupled aeroelastic simulations were performed with both linear and non-linear material models and the deformed shapes were obtained through both steady-state and time-accurate evolution. The time-accurate solution executes both the flow solver and structural solver modules at every time step in the synchronized time-accurate fashion that would be required for a fully-coupled dynamic aeroelastic response simulation. The purpose for exercising all of these combinations was to demonstrate the ability of the aeroelastic system to cover the range from simulating an asymptotic, static deformation all the way to capturing a time-dependent nonlinear material response such as may occur for wrinkling and flutter of the ballute film material.

Figure 5 shows the time evolution of the ballute deformation over a few select time instances during the time-accurate simulation. The symmetry plane Mach number and surface pressure contours at various times are shown in the left column. The corresponding maximum material shear stress is shown in the right hand column.

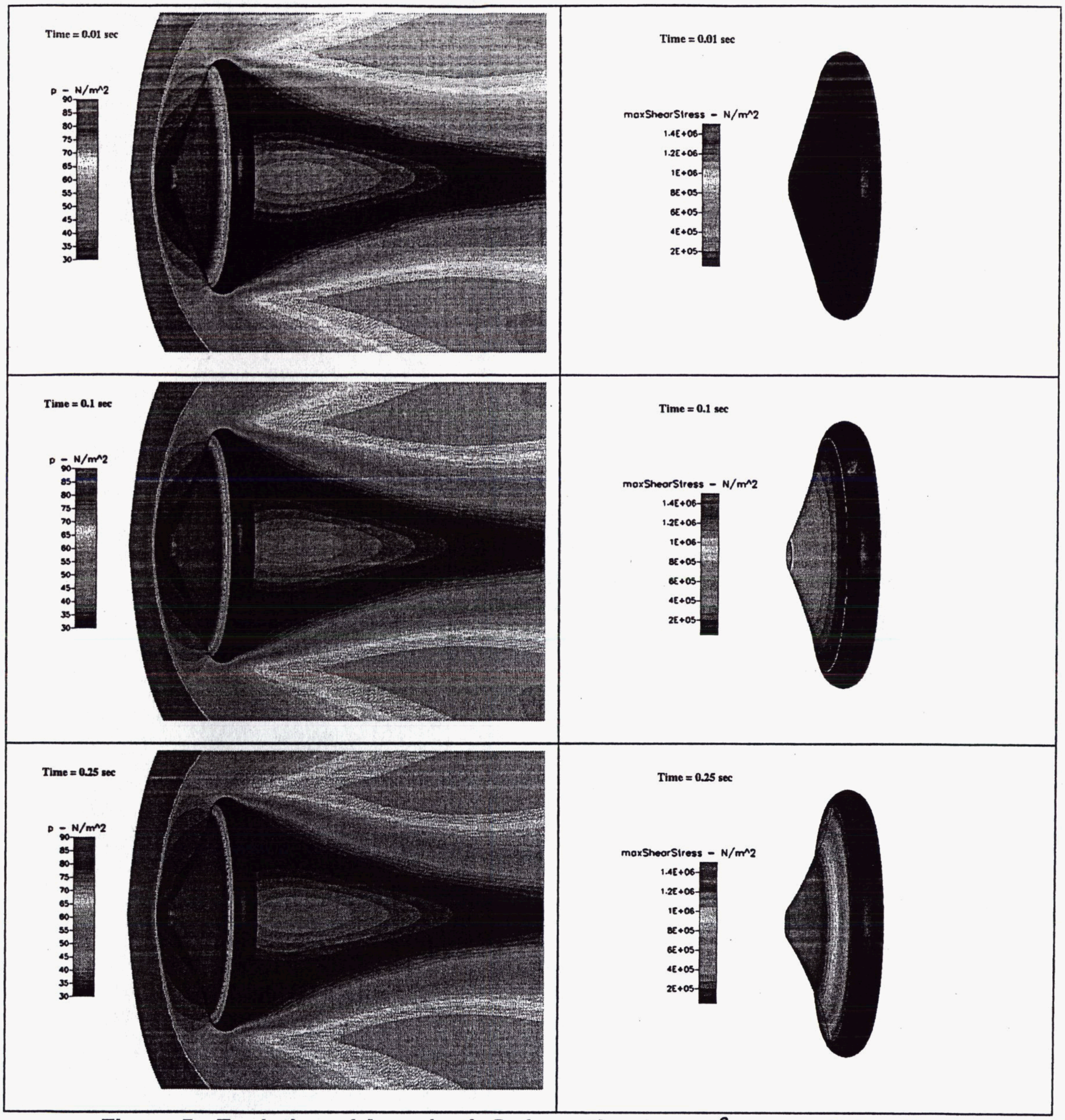


Figure 5. Evolution of Aeroelastic Deformation for $\alpha=0^\circ$ at max-Q Condition. Left Column: Symmetry Plane Mach Number Contours and Surface Pressure Contours. Right Column: Material Shear Stress Levels

Figure 6 shows the final axial displacement of the ballute structure reached under the loads imparted at the simulated condition. The initial, undeformed shape of the structure is superimposed on the side view for comparison. Significant stretching of the material and large curvature of the conical ballute surface occur. The resulting maximum shear stress in the material is also shown in Figure 6. Maximum shear stress occurs at the base of the spacecraft where the fabric is attached. Ball Aerospace engineers confirmed agreement of shape and deformation levels predicted here with their observations.

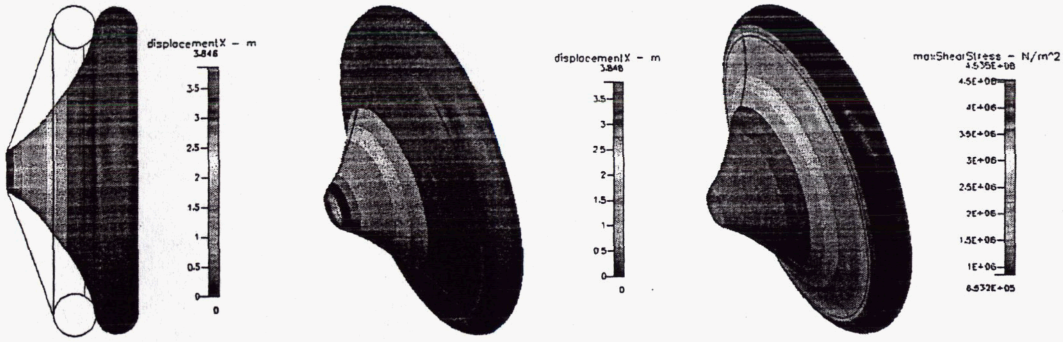


Figure 6. Predicted Asymptotic Aeroelastic Deformation for Zero Angle-of-Attack Axial Displacement and Material Shear Stress Shown

All simulation variations resulted in identical asymptotic deformation. Unsteady behavior was not observed. The present structural model is not detailed enough to capture any local dynamic or nonlinear structural behavior, should it occur, and no attempt was made to refine the model for this demonstration. The simulations were performed at a zero angle of attack resulting only in axial movement of the torus. Simulations at off-zero angles would result in more complex transverse displacement of the torus with non-axisymmetric stretching and stress patterns. Wrinkling and flutter of the film will more likely occur under those conditions. A much more detailed structural model would be required for resolving such phenomena. The simulations performed nevertheless demonstrate that the simulation environment is indeed capable of modeling static and dynamic deformations of thin, flexible ballute structures.

Demonstration of DSMC Fluid-Structure Coupling

The goal of this task was to demonstrate the feasibility of integrating a rarefied flow solver in the multi-disciplinary aeroelastic simulation framework. The DAC code (DSMC Analysis Code) developed at the Johnson Space Flight Center (LeBeau, 2001) has been the main rarefied flow solver for ballute analyses and was consequently selected for this demonstration. DAC has an advanced Cartesian grid generation and adaptation ability that allows near-automatic discretization of complex geometries.

Simulations were performed with the DAC code at rarefied flight conditions for the sample ballute configuration. Flight conditions for a Knudsen number of Kn=0.1 were extracted from the Titan aerocapture trajectory provided by James Masciarelli of Ball Aerospace. The resulting freestream conditions for a pure N_2 atmosphere are U=6500m/s, T=200K, with a number density of 6.3e+17 molecules/m^3. The Knudsen number is based on the maximum ballute diameter of 27.66m as the characteristic dimension. Figure 7 shows the rarefied flow field results obtained with the DAC code for a Knudsen number of Kn=0.1 for the clamped ballute configuration.

A procedure was established for coupling the DAC code with the CFD-FEMSTRESS structural module through MDICE using the same structural model utilized in the continuum flow demonstration case. A loosely coupled approach was selected for this demonstration that uses a file I/O mechanism for the exchange of surface conditions. An output data file for plotting the surface grids and the corresponding forces generated by the post-processing utility of the DAC code was utilized as the fluid side MDICE interface source. A small utility program module was created that reads the output of the DAC plotting file and supplies the fluid side data for the fluid/solid interface, i.e. the unstructured surface grid and the pressure forces from DAC to MDICE.

This step constitutes a very inefficient, loosely coupled file I/O process. The three modules used in this loosely coupled system were the DAC data module, the FEMSTRESS code, and the MDICE module. A script file was created that contains the commands that call the MDICE modules to control the simulation. The process was executed for a single fluid-structure interaction step to simply demonstrate the feasibility and identify the steps to integrate DAC into the MDICE system. A full rarefied flow aeroelastic deformation analysis was not carried to completion due to the limited computational resources available for a rather expensive full DAC simulation.

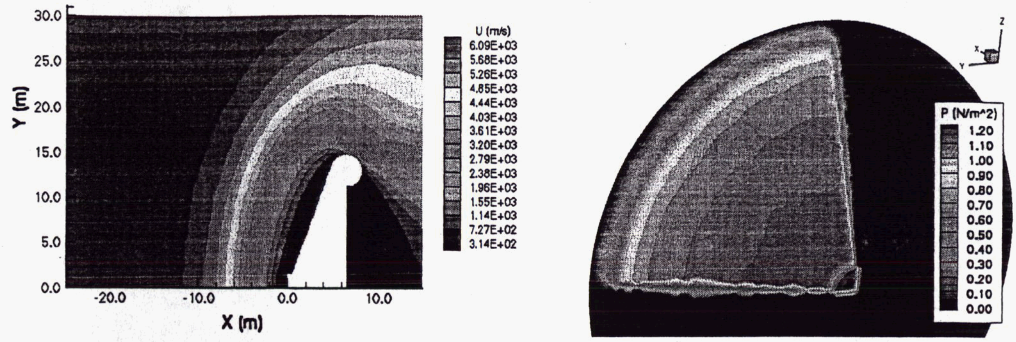


Figure 7. DAC DSMC Results for Knudsen Number Kn=0.1;
Left: Axial Velocity Profiles. Right: Surface Pressure;
Simulation Was Performed for 90-Degree Quadrant at Zero Angle-of-Attack

Work is now underway to directly couple the DAC code with the MDICE environment. The implementation plan includes the development of a modified post-processing module to the DAC code that directly accesses the solution and transfers the surface loads to the structural solver via MDICE functions. The solution adaptive function of the DAC grid generation and adaptation utilities will also be modified to accept the new deformed surface and adapt the Cartesian grid to both, the slightly different solid surface and the changes occurring in the flow field. The updated (deformed) surface definition will then be fed back into the DAC analysis cycle while the MDICE interface modules and the structural modules remain in wait mode.

Selection of Analysis Modules for NASA Ballute Applications

After demonstrating the capabilities of the multi-disciplinary simulation system for ballute applications, steps were taken towards including NASA-preferred and selected software modules. A number of engineers and researchers actively involved in ballute aerobrake technology development were consulted to solicit recommendations for software tools to be integrated. The objective is to port trusted and proven software modules that have already been applied in ballute development and to couple them with government and industry preferred structural and thermal modules through the multidisciplinary environment.

The multi-physics modules selected for coupling into the environment include the FUN3D Navier-Stokes flow solver (Gnoffo, 2004) containing the aerothermal models of the LAURA code and the DAC DSMC code. Both of these codes have been applied with great success in aerobrake and ballute analysis and constitute NASA's most capable and trusted fluid analysis tools for ballute flow field simulations. These codes will be equipped to interact with the MSC-NASTRAN and ABAQUS structural analysis codes inside the MDICE environment. These two codes have been widely applied in complex, non-linear structural and aeroelastic simulations and have been identified as the tools with the most advanced capabilities to correctly model the complex physics and structural behavior observed for thin-film inflatable structures (Bartels, 2005). Adopting the state-of-the-art codes from the fluid and the structural analysis sides and combining them into a tightly integrated new simulation tool is what MDICE does best. The individual analysis modules will be equipped with the required interface calls to exchange data through MDICE and allow process control for a coupled simulation.

FUTURE WORK

The CFD, DSMC, and structural analyses codes that were identified in this study will be integrated in the MDICE simulation system to create an operational aeroelastic ballute simulation capability. The specific codes selected for integration are:

- The FUN3D Navier-Stokes flow solver containing the LAURA aerothermodynamic models
- The DAC DSMC code for rarefied flow
- The MSC-NASTRAN structural analysis code
- The ABAQUS structural analysis code

Upon integration of each module in the MDICE framework, the codes will be tested in stand-alone mode to verify that the integration process has not altered their functionality. The coupled aeroelastic simulation capability will then be established between the various permutations of these modules and their interaction will be tested. Once full functional status has been established, the coupled aeroelastic capabilities will be tested and validated against benchmark solutions and against wind tunnel data. The specific process required to integrate each of the module selected are described in the following sections.

Integration of FUN3D with MDICE

The NASA/LaRC FUN3D code will be integrated for continuum regime flow predictions. The synthesis of the physical models within the structured grid codes LAURA (with focus on external, hypersonic flow simulations) and VULCAN (with focus on internal, scramjet flow simulations) into the unstructured flow solver FUN3D (with focus on perfect gas flow simulations with adjoint-based design and optimization capabilities) has been performed under the High Energy Flow Solver Synthesis (HEFSS) project. This capability now exists as a generic gas model option utilizing HEFSS modules within the code FUN3D (Gnoffo, 2004). The FUN3D code also features built-in grid motion and adaptation capability with the grid conservation formulation required for time-accurate moving grid simulations (Biedron, 2005). The FUN3D code therefore contains all the essential components required for an aeroelastic coupling through the MDICE environment.

Integration of DAC (DSMC Analysis Code) with MDICE

The DAC code (DSMC Analysis Code) developed at the Johnson Space Flight Center (LeBeau, 2001) has crystallized as the main rarefied flow solver for ballute analyses and was consequently selected for full integration into the MDICE environment. Implementation of the modifications identified to fully integrate the DAC code into the MDICE environment is underway. We anticipate that rarefied regime simulations will be performed primarily for static deformation analysis and will not require a time-accurate DSMC solution.

Integration of Structural Analysis Modules With MDICE

The MSC.NASTRAN and ABAQUS structural analysis codes are planned to be integrated into the MDICE environment to conduct non-linear aeroelastic simulations. Both, the MSC.NASTRAN and ABAQUS codes have found the most widespread application in heretofore uncoupled aeroelastic structural analyses. Special emphasis is currently being placed in development of these two structural analysis codes to improve simulation capabilities for thin-walled aerothermoservoelastic structure simulations. This capability is essential for accurately simulating the non-linear aeroelastic shape responses such as wrinkling and flutter anticipated for ballute structures (Bartels, 2005).

Integration of Spacecraft Thermal Management Tools:

The impact of environmental heating from solar radiation, and surface re-radiation to space and to other vehicle components will be a significant factor in thermal management of ballute spacecraft structures. Analysis tools identified for consideration include SINDA, TSS, and TAK. The availability of either one of these tools and the level of complexity of integrating the tools in a coupled simulation environment will be addressed in future work.

SUMMARY AND CONCLUSIONS

This study demonstrated the feasibility and the merits of developing and utilizing a multi-disciplinary and multi-physics simulation environment for flexible ballute aeroelastic simulations.

A computational model for an aft-attached clamped ballute based on a Ball Aerospace concept was created consisting of a structural and a fluid domain. Fully coupled aeroelastic solutions were demonstrated with CFD and structural codes already integrated into an existing multi-disciplinary computing environment, MDICE.

Rarefied flow field solutions were generated for a clamped ballute model using the rarefied flow solver DAC (DSMC Analysis Code). The process of loosely coupling (through file I/O) the DSMC code with a finite element structural code through MDICE was demonstrated and steps required for fully coupled integration of the DAC code were identified.

Engineers from NASA and industry active in ballute technology development were consulted to solicit recommendations for specific multi-disciplinary modules to be integrated into the simulation environment. Subsequently, a roadmap was generated for integrating the selected modules in a tightly coupled multidisciplinary simulation toolset, including validation and verification of the functionality of each component in the simulation environment.

The resulting multidisciplinary environment will provide a high-fidelity aeroelastic fluid-structures coupling capability that will fill the gap in NASA aeroassist simulation capability to evaluate aeroelastic effects for ballutes in both, the continuum and the rarefied flow regime. This capability will provide a crucial element for risk reduction in aerocapture technology development, and will directly support ongoing aerocapture ballute technology development programs by providing a wide level of aerodynamic, aerothermal, static aeroelastic, and dynamic aeroelastic predictions for ballute configurations

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