Developing the Aerodynamics Module for the Integrated Multidisciplinary Optimization Object System

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The Integrated Multidisciplinary Optimization Objects (IMOO) System delivers physics-based multidisciplinary analysis and optimization (MDAO) capabilities that are required to develop next generation subsonic, supersonic, and hypersonic aircraft. The software tools and approaches accurately model prediction of vehicle performance, interdisciplinary couplings, and system-level evaluation of the benefits and risks. M4 Engineering (experts in high fidelity MDAO processes) is working with NASA Glenn (who is currently developing a Python-based MDAO framework called OpenMDAO) to combine their specialties to deliver a modular design environment suitable to the high fidelity analysis and design of coupled systems. The key elements of this toolset include an object-oriented integration framework, common objects, and analysis modules that based on custom data types. The IMOO system utilizes Geometry Manipulation by Automatic Parameterization (GMAP) and RapidFEM for advanced parametric geometry and grid generation technology for aerodynamic and structural models. Both GMAP and RapidFEM are in-house applications developed by M4 Engineering. M4 Engineering is developing the IMOO System using multiple, incremental builds each with their own unique example problem. The Aerodynamics Module is the software component in IMOO that enables calculation of the aerodynamic performance of an arbitrary vehicle design, as well as pressure loads on the vehicle surface. It uses a unique blending of the results between Low Fidelity and High Fidelity results to generate an accurate Mid Fidelity Aerodynamic Database quickly.

Nomenclature

$C_{L\,max}$	= Maximum Lift Coefficient
L/D	= Lift / Drag
AR	= Aspect Ratio
C_{D0}	= Zero Lift Drag
$C_{L\alpha}$	= Lift Curve Slope
y	= Spanwise Direction, positive to the right (starboard)
C_p	= Coefficient of Pressure
α	= Alpha, Angle of Attack

INTRODUCTION

RECENTLY there have been significant efforts to bring physics-based models into the conceptual/preliminary design phase of aerospace systems. Physics-based models allow for a higher fidelity analysis. An example of this is the Integrated Hypersonic Aeromechanics Tool (IHAT) developed by a team that included M4 Engineering[1]. However, these existing systems do not provide the capabilities required for designing the next generation air and space vehicles. The individual modules are implemented in a manner that prevents them from being easily reused as configurations and the design problems change. Since the modules are tied together using scripting languages in a rather ad-hoc approach, it is difficult to understand and modify the workings of the system. A system should deliver a suite of capabilities that can be utilized as required depending on the configuration and the problem being solved. As a system becomes more modular, modules can be more easily swapped in and out based on the user's needs without excessive system redesign. A modular framework that is highly configurable (Figure 1) provides the

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required foundation to address design problems using varying levels of fidelity, which are applicable to a wide range of configurations, by incorporating physics-based models and object-oriented programming.

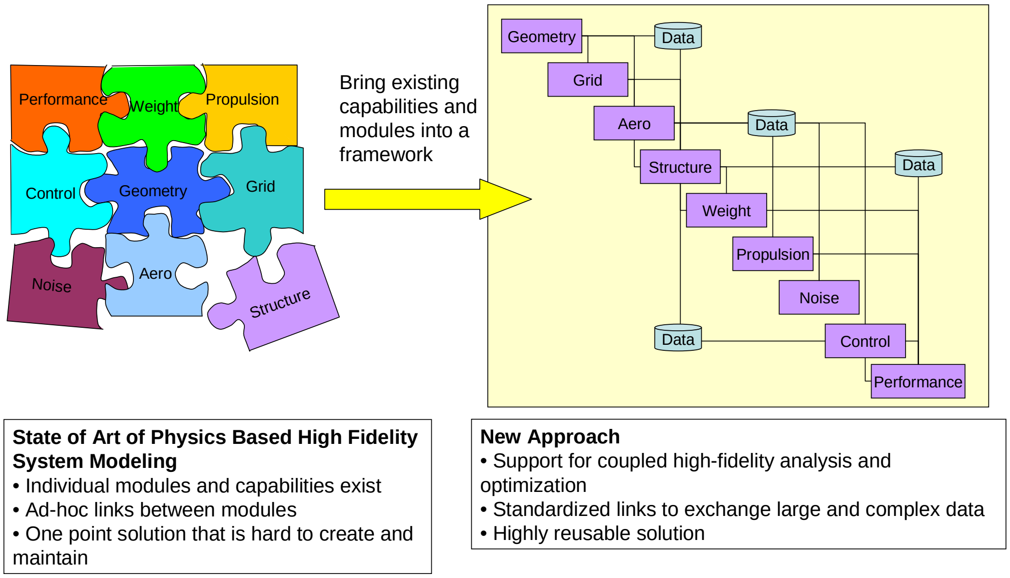

Figure 1: Create high fidelity, physics-based analysis and design capability that is modular and

Framework software tools (e.g., OpenMDAO[2]) standardize the common tasks of analysis code execution, job scheduling, the use of distributed computing resources, and the transfer of data from one analysis code to another. Unfortunately, framework tools have been less successful in high fidelity applications. This is because the development of high fidelity MDAO processes gets increasingly difficult as more and more complex data and information need to be exchanged. As an example, consider the interaction between aerodynamics and geometry. When the Geometry Module is executed, a Geometry Calculations object is instantiated. Subsequently, this object is passed downstream to the Aerodynamics Module. This object contains various methods designed to calculate important geometric quantities (e.g., flap area, vertical tail span, etc.) by interrogating the baseline and/or morphed model for use in the Aerodynamics Module. This object must be able to differentiate between a wing and a horizontal tail, and determine relevant parameters such as planform area, wetted area, and Aspect Ratio. Another capability that is key to the success of physics-based modeling is the accurate modeling of geometry and the automatic generation of quality grids and meshes. The analysis of coupled systems requires consistent conversion of geometry data to external grids and internal structural meshes. The automatic mesh generation should be flexible enough to handle large geometry variations and be adaptable to different configurations. Lastly, in order to perform meaningful trade studies and optimization in a reasonable amount of time, the analysis models must be updated in an automated and efficient manner as design variables are changed.

The IMOO System is a multidisciplinary analysis and optimization toolset designed to address these issues for next generation vehicle applications. It uses enhanced versions of the HFMDO[3] and MOOL[4] modules to create a more capable system. IMOO utilizes an object-oriented integration framework that allows users to efficiently link high fidelity analysis modules. This framework significantly reduces the problem setup time by simplifying the definition of interdisciplinary coupling, allowing the creation of complex data objects and eliminating laborious manual data conversion. IMOO develops a library of common objects and analysis modules based on custom data types. Custom data types help avoid duplication of work. It is critical for the framework tools to provide capabilities to easily transmit complex data between modules. These objects reduce the need for file parsers by defining standard object interfaces. The Aero Database Object is a custom data type that has a "lookup" method that can determine the value of any aerodynamic performance parameter (e.g. C_L, C_D) based on a Mach Number, angle of attack α, etc. It is passed from the Aerodynamic Module to the Structural Module, where it can also be used to interpolate on a Pressure Distribution, which can then be mapped to the Structural FEM.

The initial focus is on high fidelity aerodynamic and structural analysis disciplines and the associated objects (e.g., Aero Database). The IMOO system succeeds in sharing complex data by utilizing an object-oriented approach in which upstream modules create objects that are used by downstream modules on demand. Both the data and the methods reside in the object and downstream modules may request the data when needed. An example of this is mesh generation. IMOO implements automatic mesh generation and morphing through advanced parametric geometry and grid technology for multidisciplinary modeling[5]. M4 Engineering has developed a parametric grid morphing tool, Geometry Manipulation by Automatic Parameterization (GMAP[6]), and a parametric FEA model generator for internal structures (RapidFEM[7]). These tools are integrated into the framework environment so that engineers can quickly integrate FEA/CFD analyses, morph geometry, re-mesh, apply loads, and generate useful results. Through careful automation of the analysis process, the IMOO system allows configurations to be rapidly assessed, allowing many variations to be considered in a relatively short time. This facilitates the implementation of numerical optimization techniques that can be used to help determine the optimal design. An example application demonstrates the use of this new MDAO framework and analysis modules for the high fidelity MDAO of a relevant supersonic fixed wing vehicle configuration as seen in Figure 2.

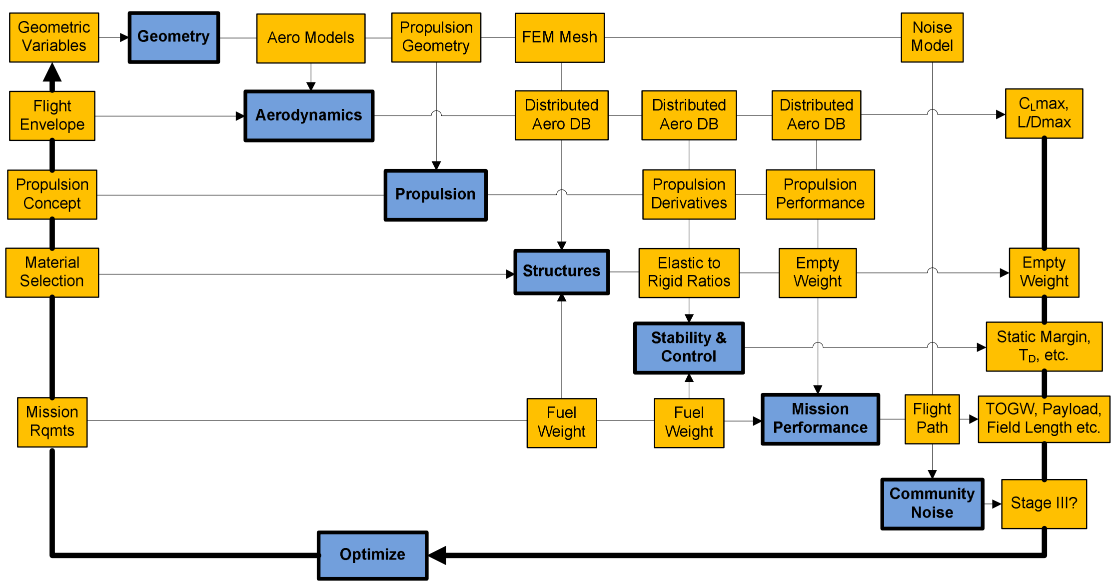

Figure 2: Supersonic Fixed Wing Vehicle Process.

AERODYNAMICS MODULE DESIGN

The purpose of the Aerodynamics Module is straightforward: to calculate the aerodynamic performance of a candidate vehicle over the expected flight envelope. However, the Aerodynamics Module is one of the most challenging modules to design. The implementation of computational fluid dynamics (CFD) in the Aerodynamics Module is one of the unique features of the Aerodynamics Module, offering a level of fidelity not obtainable by panel methods alone (as is common in current MDAO tools). Since the calculation of aerodynamic flows using CFD is a computationally demanding task, the Aerodynamics Module is expected to be the slowest module to execute in a vehicle design process. In order to alleviate this, it was crucial to offer alternatives to the resource-intensive utilization of CFD. This led to the design of a mid fidelity approach to the Aerodynamics Module, which combines the results of high fidelity CFD tools with those of low fidelity panel methods to ensure that the best answer is obtained in an acceptable amount of time. The module allows the option of running entirely low fidelity (panel method), entirely high fidelity (CFD), or a combination of the two. In the low fidelity or high fidelity mode, the Module runs a list of conditions in the appropriate code and uses the results to populate an aerodynamic database. In the mid fidelity mode, a low fidelity database is constructed, and the values are corrected to match a reduced list of high fidelity conditions.

The top-level architecture of the Aerodynamics Module is illustrated in Figure 3. Its primary tasks are to update a pre-existing baseline grid to conform to the outer mold line (OML) geometry of the current design, calculate the aerodynamic forces on the OML, and generate a corresponding aerodynamic database. The software programs selected for use in the Aerodynamics Module are Panair[8] and S/HABP[9, 10] for low fidelity aerodynamics, Cart3D[11] and Usm3D[12] for high fidelity aerodynamics, and Digital Datcom[13] to calculate $C_{L\,max}$ and stability derivatives. GMAP is used for mesh morphing. Furthermore, the Aero Module is packaged as a Python class, which allows for the use of the module in different ways (i.e., with and without Datcom) by simply setting "runDatcom" to False.

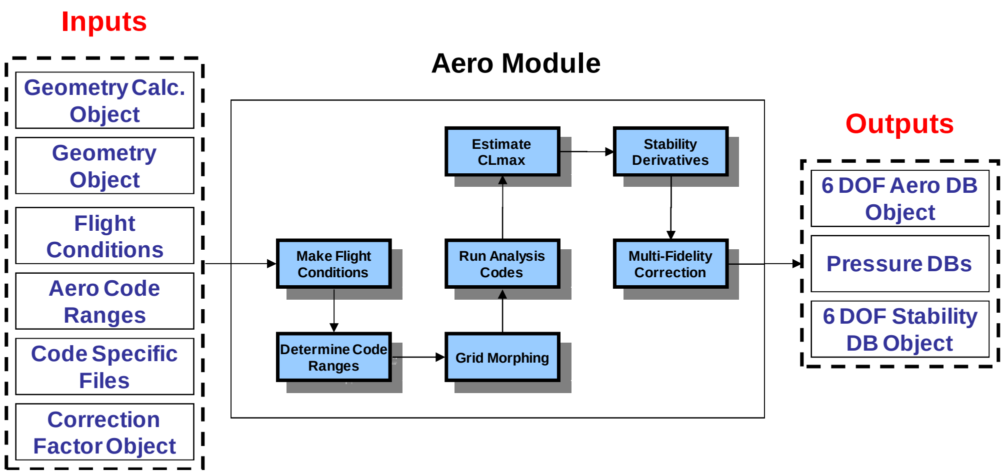

Figure 3: Flow Chart of Aerodynamics Module

Grid Generation

The first step in the Aerodynamics Module's execution process is to generate updated geometry based on the design variables. The IMOO Geometry Module, which uses GMAP, is responsible for generating the updated geometry. The GMAP morphing models may be parameterized using either a custom-tool or by selecting from a library of tools and modifying the baseline values to properly size the tool. GMAP models may be parameterized with design variables such as Wing Area S_{ref}, Aspect Ratio AR, sweep angle Λ, as well as pitch, roll, and yaw control angles. An example of a GMAP morphing tool is shown below in Figure 4.

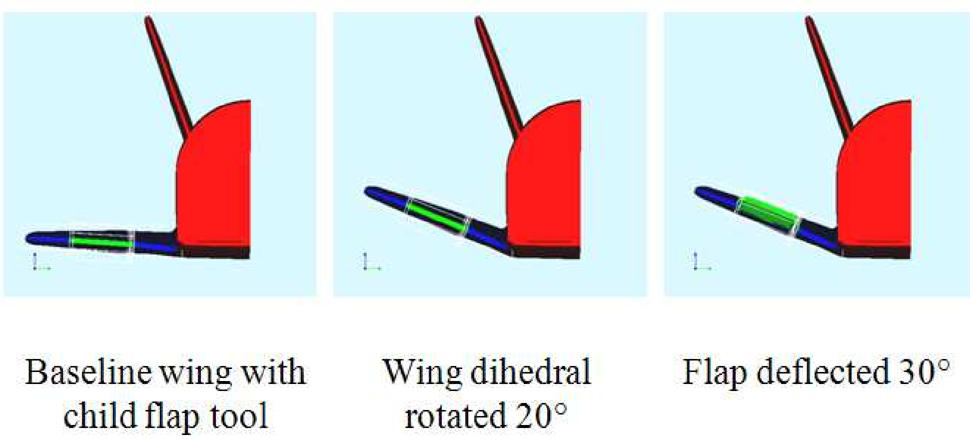

Figure 4: A flap deflection tool is attached to a wing dihedral rotation tool. When the dihedral is changed, the flap tool automatically rotates along with the rest of the wing.

The interface between the Aerodynamics Module and the Geometry Module has been designed in such a way as to limit the problems associated with degenerate volumes. Even for the high fidelity CFD codes Cart3D and Usm3D, the user must only provide surface meshes as input. Thus the user must only be concerned with creating a reasonable morphed surface mesh rather than a morphed volume mesh. A volume mesh is built based on the surface mesh as part of the standard execution process. This allows for much greater flexibility when creating morphing tools.

Low Fidelity Analysis

Based on the desired goals of each analysis, there exist cases where the greatest aerodynamic accuracy is not needed in order to model a vehicle. It may be beneficial in these cases to obtain low fidelity aerodynamic data in a very short amount of time and at little computational cost. To this end, Panair and S/HABP are available within the Aerodynamics Module. Panair and S/HABP are capable of producing basic lift, drag, moment, and aerodynamic center location data. Panair solves the surface potential equations, while S/HABP uses empirical equations, such as the Newtonian impact method. These methods are meant for relatively simple (yet arbitrary) geometries, which do not rely heavily on vortex action for their aerodynamic performance. Together, Panair and S/HABP provide acceptable results across the subsonic, supersonic and hypersonic flight regimes. The surface meshes can be generated by a competent user within a short time frame when compared to generation efforts for meshes suited to Navier-Stokes solutions. Additionally, where solutions of Navier-Stokes equations in volume grids may take a significant amount of time (on the order of hours) and computational resources, a typical Panair solution will take a couple of minutes on a single processor, while a typical S/HABP run can be expected to take no more than about 30 seconds.

High Fidelity Analysis

If the intended analysis requires a detailed prediction of the flow about a vehicle, a high-order computational fluid dynamics method must be used. Within IMOO, high fidelity aerodynamic solutions can be obtained through the use of either Cart3D or Usm3D. Cart3D solves the inviscid Navier-Stokes equations, while Usm3D is capable of solving inviscid or viscous solutions. Cart3D's greatest strength is that it can take a triangulated surface mesh and automatically generate a volume grid based on a user-defined number of mesh refinements. Cart3D has been found to be extremely robust and well-suited to solving problems with large geometry changes. In addition, both Cart3D and Usm3D are well-suited to parallelization, which is shown below in Figure 5.

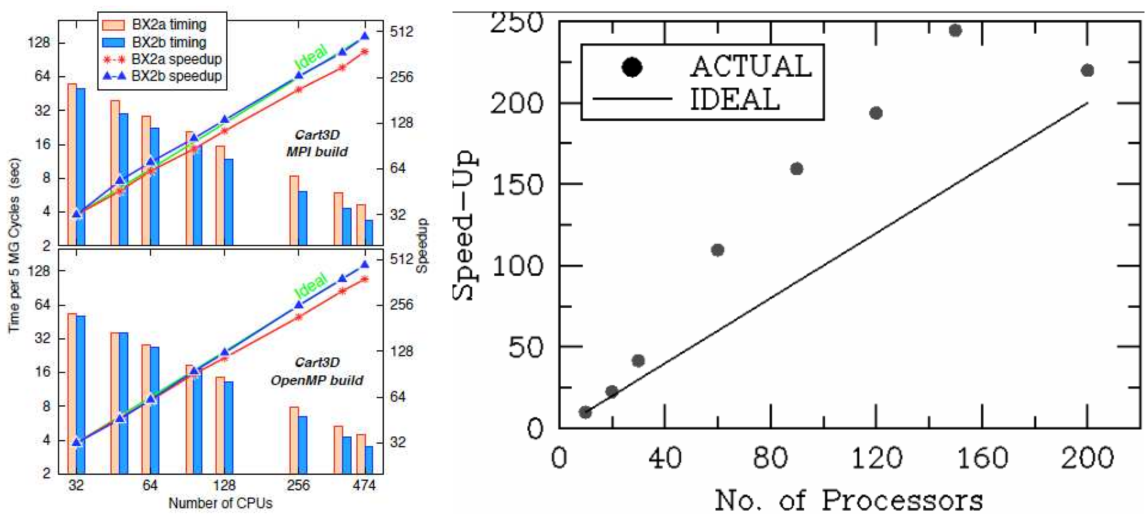

Figure 5: Comparison of execution time and parallel speedup of Cart3D solver module using both MPI and OpenMP communication libraries (left). Speed-up for a Usm3D business jet model is better than ideal performance due to increased cache efficiency (right)[11].

Mid Fidelity Analysis

The mid fidelity option was implemented to provide the flexibility needed to obtain the highest fidelity solution possible for a given time constraint. In the mid fidelity mode, a low fidelity database is constructed, and the values are corrected to match a reduced list of high fidelity conditions. The user selects the number of high fidelity points to use in a given analysis and provides the specific conditions for those points. The Aerodynamics Module calculates a low fidelity database over the defined trajectory envelope, an anchor database using low fidelity calculation over the user-chosen high fidelity trajectory points, and a high fidelity database using CFD over the high fidelity trajectory points. Interpolation is performed on the anchor and high fidelity data, and the low fidelity data is subsequently corrected using an additive correction:

$$f_{Mid_{Fi}}(x_i) = f_{Low\ Fi}(x_i) + g\big(f_{High\ Fi}(x_j) - f_{Low\ Fi}(x_i), x_i\big)$$
$$-\big\{g\big(f_{High\ Fi}(x_j), x_j\big) - g\big(f_{Low\ Fi}(x_i), x_j\big)\big\}$$

where x_i are the low fidelity trajectory points over which the low fidelity database is generated, x_j are the user-chosen high fidelity trajectory points, f_{Low_Fi} represent the calculated low fidelity data, f_{Low-Fi} the low fidelity anchor data, f_{High_Fi} the high fidelity data, f_{Mid_Fi} the corrected mid fidelity data, and g represents the interpolation function used to interpolate the data. Thus, the greater the number of high fidelity points used, the higher the degree of correction provided to the low fidelity data. The tradeoff for this method is the increased computational resources required for the CFD calculation of the high fidelity data points.

Configuration Setup

For each configuration to be analyzed, the following input files are required by the IMOO Aerodynamics Module:

Required Files for all Aerodynamic Codes
- Regions.txt – ASCII file containing patch-region information for skin-friction drag calculation

Required Panair Files
- Panair.inp – ASCII surface mesh geometry and boundary conditions

Required S/HABP Files
- shabp.inp – ASCII surface mesh geometry and boundary conditions

Required Cart3D Files
- Cart3d.i.tri – ASCII surface mesh geometry
- inpt.cntl – contains boundary conditions and flow solver information
- COMMANDS history

Required Usm3D Files
- front – ASCII surface mesh geometry
- cogsg – Binary surface mesh geometry
- d3m – OML connectivity
- bc – boundary conditions
- inpt – flow solver information
- mapbc – patch-boundary information
- restart – optional file used to improve convergence speed (optional)
- COMMANDS history

The design goal of the IMOO Aerodynamics Module was to use standard input files for each software code to allow the user to focus on the design problem, rather than worrying about the format of their input. Therefore, without modifying any inputs it is possible to validate the system's results for a single point while running outside the system. The system is designed in order to ensure confidence in the results that the system is creating.

All the analysis codes (Panair, S/HABP, Cart3D, and Usm3D) include a regions.txt input file, which defines the major physical regions or components of the vehicle. Region types could include fuselage, engines, inboard wing, and the outboard wing sections as shown in Figure 6.

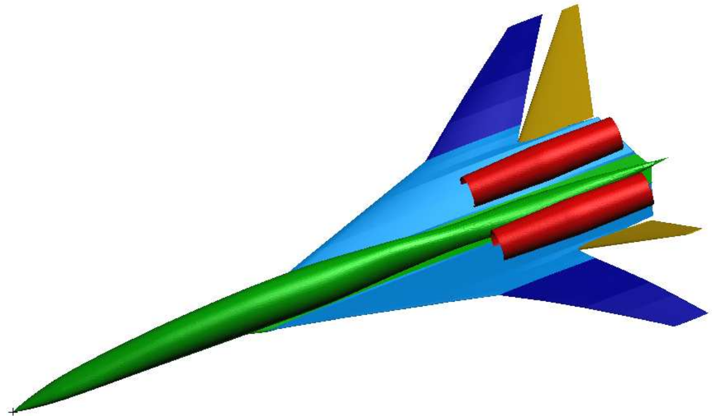

Figure 6: Supersonic N+2 Cart3D Model After Setting Regions

Once the updated aero model has been created, the Aerodynamics Module continues its analysis by running either Panair, S/HABP, Cart3D, or Usm3D. In the case of Panair and SHABP, only the baseline mesh file is required to run the analysis. Once supplied with the proper files, Panair and S/HABP perform their calculations in a matter of seconds. Low fidelity output consists of an aerodynamic database of forces and moments in either three- or six-degrees-of-freedom (DOF), depending on whether a half or full model is used. Plot3D files containing local pressure coefficients on the OML are also produced.

High fidelity results are obtained in a similar manner to low fidelity results, but with inputs tailored for Cart3D and Usm3D. Cart3D uses a method to take surface triangulation and create a full volume mesh. In addition, the user must log their command history in the COMMANDS file, which is later used by the system to reproduce their mesh generation procedure. If parallel processing is required, the user need only to setup the COMMANDS file to use multi-processors or distributed computing to take advantage of that feature. Allowing the user to specify the COMMANDS file for Usm3D/Cart3D ensures that future updates will automatically be supported.

In the case of Usm3D, the system uses Usm3D input files generated during the process of linking the geometry to the surface grid to ensure that no degenerate volumes are constructed. This is a standard procedure when creating a Usm3D mesh. At this point the user must log their commands and build the volume grid. This command history file is later used by the system to reproduce their execution process after morphing.

Upon convergence, aerodynamic data are extracted from the output files and inserted into the Aero Database for further use by IMOO downstream modules, and a standard Cart3D or Usm3D output file (q-file) of the surface mesh is created for graphical analysis and future load mapping applications. Again simple output formats (i.e.,triq for Cart3D, Tecplot for Usm3D) are used to ensure system compatibility.

Output

Outputs from the Aerodynamics Module include the following:

1. An Aerodynamic Performance Database Object containing force and moment coefficients as functions of flight condition (Mach, angle of attack, altitude, and control surface deflection). In addition, relevant information about the codes that were used to perform the analysis is stored in the database.
2. A multi-file Distributed Aero Database containing standard Plot3D (for Panair and S/HABP), Cart3D, and Tecplot (for Usm3D) formatted grid and function files with pressure coefficients

The real strength of the Aero Database Object lies in the convenient format the database is stored in. The data is stored as a Python object that has various methods that can be used to print the data as well as query the data contained in the database. The lookup method takes a flight condition as an input and using either interpolation or extrapolation, the results at any flight condition in the flight envelope can be found. In addition to interpolating over standard floating point data, the user can use the "interpolatePressureDB" method of the Aero Database and obtain an interpolated Distributed Pressure Database, which may be used as part of a structural analysis.

VALIDATION TEST CASES

HSCT

In order to ensure that development satisfied the requirements of a supersonic aircraft and to provide for eventual system-level validation of the IMOO System, a Validation Test Case configuration was identified early in the program. The configuration selected is the High Speed Civil Transport[14] (HSCT). The HSCT program was started in 1990 and ended in 1999. An illustration of the configuration is shown in Figure 7. The design variables used in the IMOO model of the HSCT are Wing Area, Aspect Ratio, Sweep Angle, Taper Ratio, Spanwise Location of Break Chord, Leading Edge Position of Break, Break Chord,-and Tip Chord Ratio.

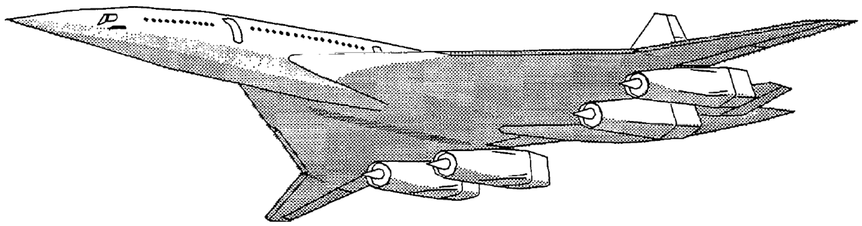

Figure 7: HSCT Configuration

Initially, the test case serves as a development aid. It provides the necessary inputs for testing each module as development is underway. Once development is complete, the complete HSCT configuration is analyzed in the IMOO System, and the analysis results are compared with the HSCT preliminary design data, providing validation of IMOO's analysis capabilities. Finally, a configuration-level optimization of the HSCT is performed, providing validation of the IMOO System's ability to improve the overall performance of a given configuration.

The Panair, Cart3D, and Usm3D models are shown for the HSCT Vehicle below in Figure 8, Figure 9, and Figure 10 respectively.

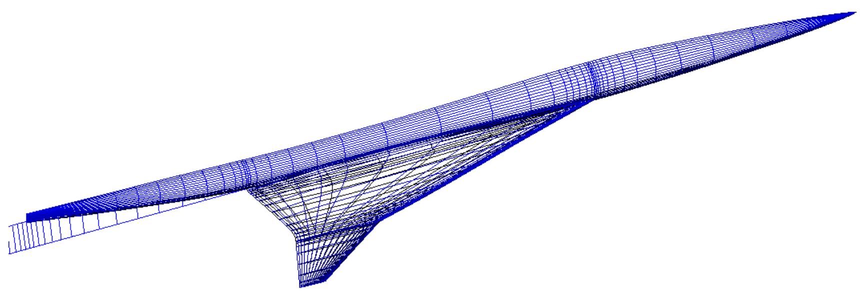

Figure 8: HSCT Panair Model (Body-Wing wake shown, Wing wake not shown)

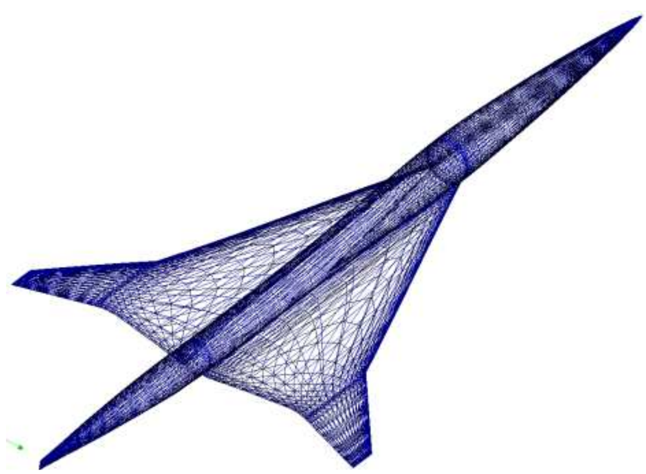

Figure 9: HSCT Cart3D Model

A cutting plane of the Usm3D mesh at $y = 0$ after generating the surface grid (and bounding box) is shown below in Figure 10.

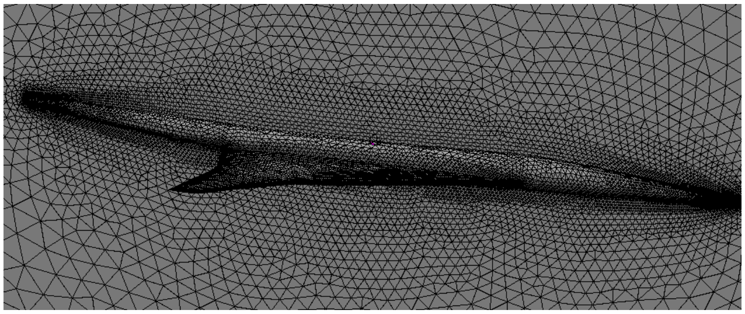

Figure 10: HSCT Usm3D Model

After the models are created, the Aerodynamics Module can then be run. In addition to loads calculations, the pressure distributions for the different flight conditions are found. The pressure distributions for Panair, Cart3D, and Usm3D are shown in Figure 11, Figure 12, Figure 13 respectively.

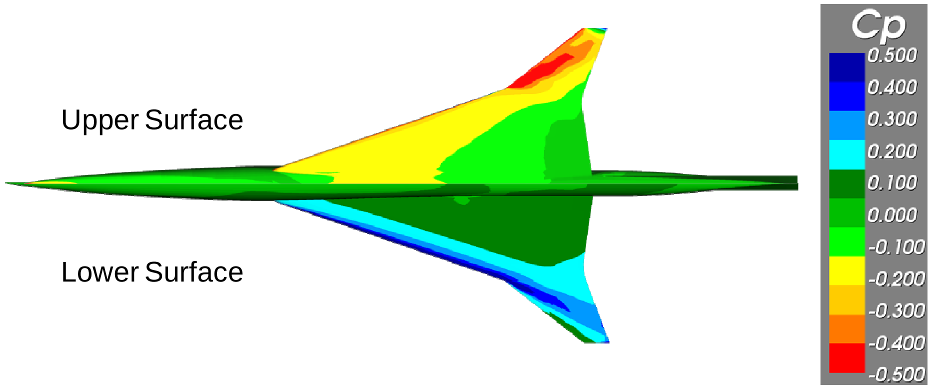

Figure 11: HSCT C_p for Mach=2.4, Alpha=10˚

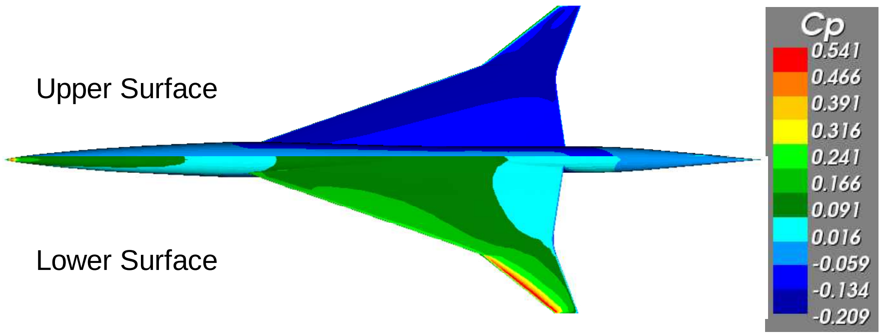

Figure 12: Cart3D C_p Distribution for at Mach=2.4, Alpha=10˚

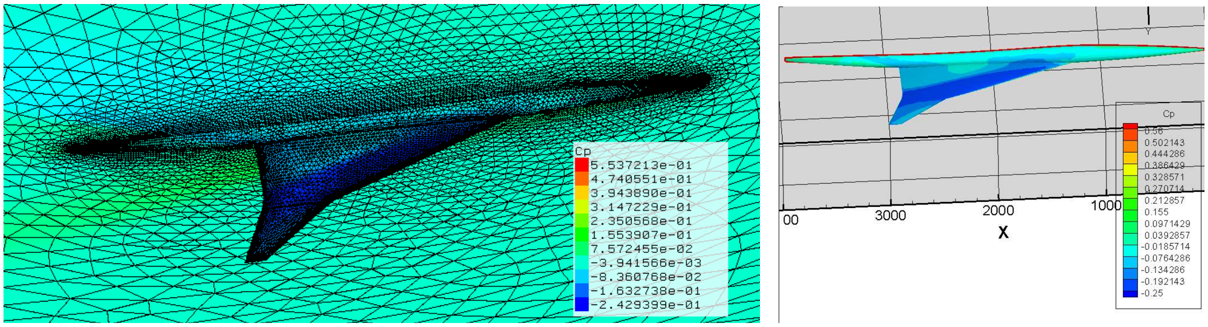

Figure 13: Usm3D C_p Distribution before (left) and after mapping to surface grid (right) (Mach=2.4, Alpha=10˚)

As seen in Figure 14, the L/D is 8.5, and is lower than the expected 9.281 as seen in Figure 15. However, the HSCT design clearly assumes local tailoring, detailed design, and nonlinear optimization of the aircraft to decrease the drag coefficient and achieve the goals of the design.

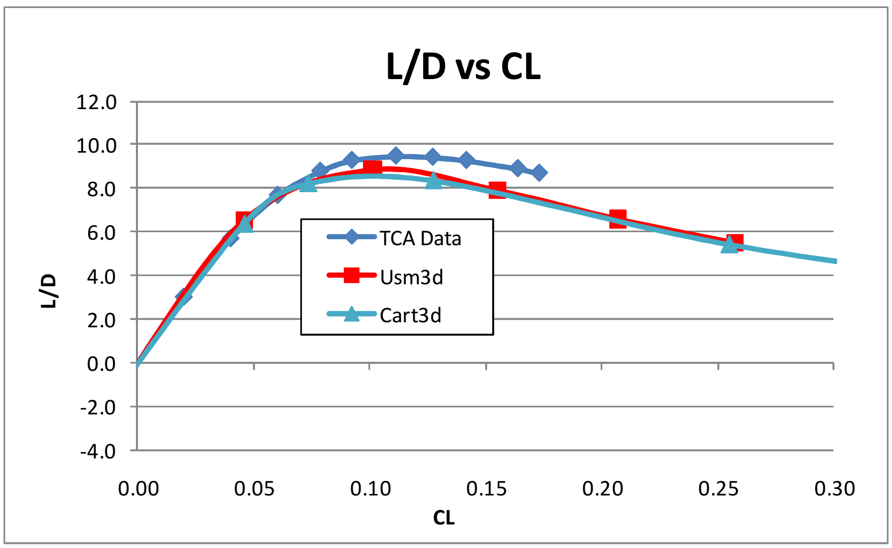

Figure 14: L/D vs C_L

$C_{D technology}$ =	-.00121	Bookkept as improvements of 20% C_{Dexcr}, 16% of linear theory zero lift wave drag, and 14.9% of linear theory C_{Dlift}. Technology projection represents the expected effects of: - local tailoring - detail design - Non-linear optimization - etc.
$C_{D projected}$ =	.01078	Projected cruise level, L/D = 9.281

Figure 15: Technological Drag Reduction[14]

The previous validation succeeded in proving the integration of the analysis codes. The desired approach to running the Aerodynamics Module is to use the Mid Fidelity option, which has greater accuracy with reduced analysis time.

Sixty low fidelity (Panair) and eighteen high fidelity (Cart3D) cases were analyzed. The resulting low, mid, and high fidelity curves for $C_{L\alpha}$ vs Mach are shown below in Figure 16. Notice that the low fidelity data captures the trend well, while the high fidelity results are better, but poorly capture the trend. The mid fidelity data captures both the trend of the low fidelity data, as well as providing more reasonable estimates of the value of $C_{L\alpha}$ at points in between the high fidelity data points.

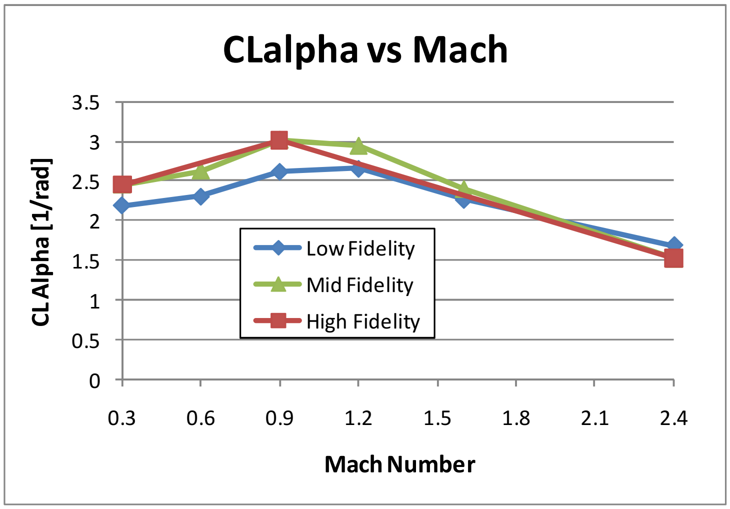

Figure 16: $C_{L\alpha}$ **vs Mach for Low, Mid, and High Fidelity**

The resulting curves for low, mid, and high fidelity for C_{D0} vs Mach are shown below in Figure 17. Notice that the low fidelity data captures the trend well, while the high fidelity results at the analyzed points are slightly higher. The transonic drag rise that occurs above Mach 0.9 is completely paved over as no points were analyzed between Mach 0.9 and Mach 2.4. Depending on the analyses required, this is potentially a serious problem. The mid fidelity results shift the low speed results slightly upwards to improve the low speed results, but also captures the wave drag spike.

Obviously, there is no guarantee that the Mach 1.2 results are correct, but it is clear that the results are better than if linear interpolation was used based on the high fidelity data. The mid fidelity capability used by the Aerodynamics Module requires no extra inputs (assuming the user has already created a low fidelity and high fidelity model) and the results are much improved. Were a Mach 1.2 case to be run as well, the supersonic profile would be improved, but the judgment of which Mach Numbers to include depends on the problem that the user is analyzing.

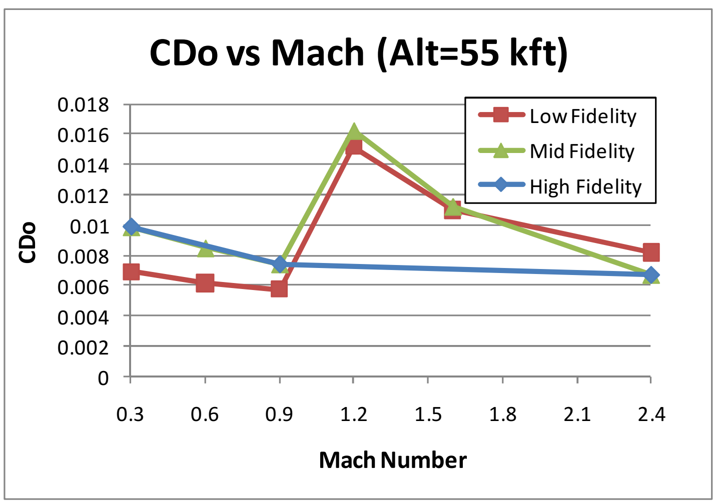

Figure 17: C_{D0} **vs Mach for Low, Mid, and High Fidelity**

The initial Multi-Fidelity capability performed well for calculating data such as $C_{L\alpha}$ and C_{D0}, and it showed poor performance when interpolating over the Drag Coefficient. The Drag, which is a quadratic function of angle of attack, is poorly captured by linear interpolation. The Database class was enhanced to support cubic spline interpolation, which greatly improved the accuracy of the interpolation of the Drag Coefficient. This is shown in Figure 18.

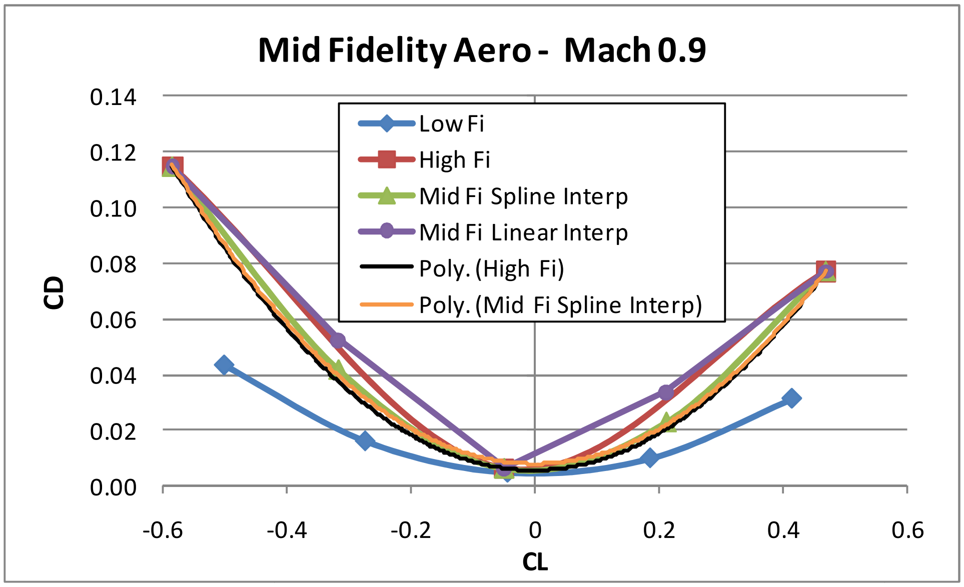

Figure 18: Comparison of Linear Interpolation vs Spline Interpolation

HWB N2A

The HWB N2A (Blended Wing Body) configuration is the product of a joint venture program between NASA and Boeing[15] and is a larger, cargo aircraft similar to the X-48B configuration. The HWB N2A program provided an enormous wealth of data on flaps, stability and control, propulsion integration, and noise data, making it an excellent, well-documented configuration for validation of the IMOO Aerodynamics, Stability and Control, and Noise Modules.

With the lessons learned from modeling the HSCT configuration, setting up the HWB N2A (a blended wing body configuration) within IMOO was straightforward once the geometry was modeled. This time, a better quality mesh was used, which included the BWB's vertical fins. The mesh is shown in Figure 19.

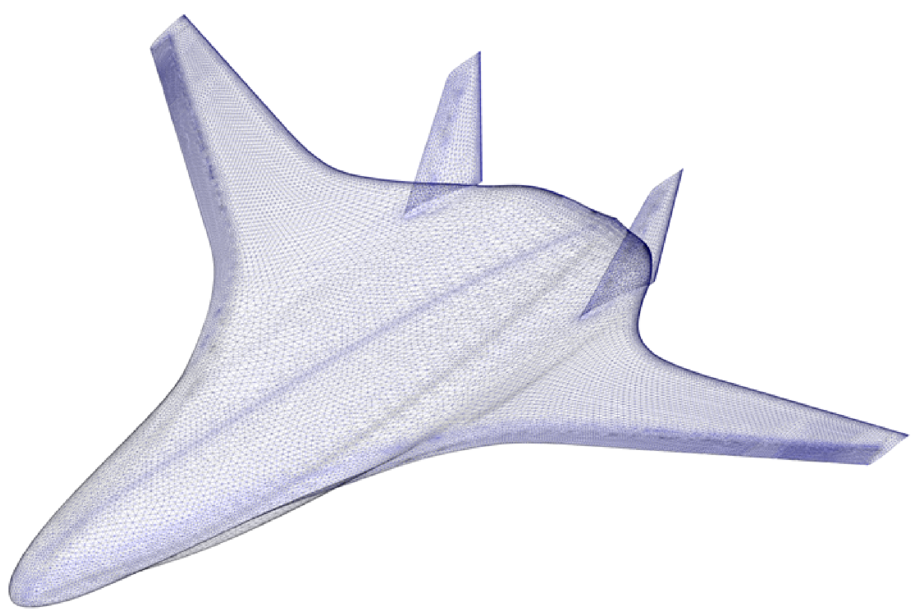

Figure 19: HWB N2A (BWB) Cart3D Model

The pressure distribution for Mach=0.80, Alpha=5° is shown below in Figure 20.

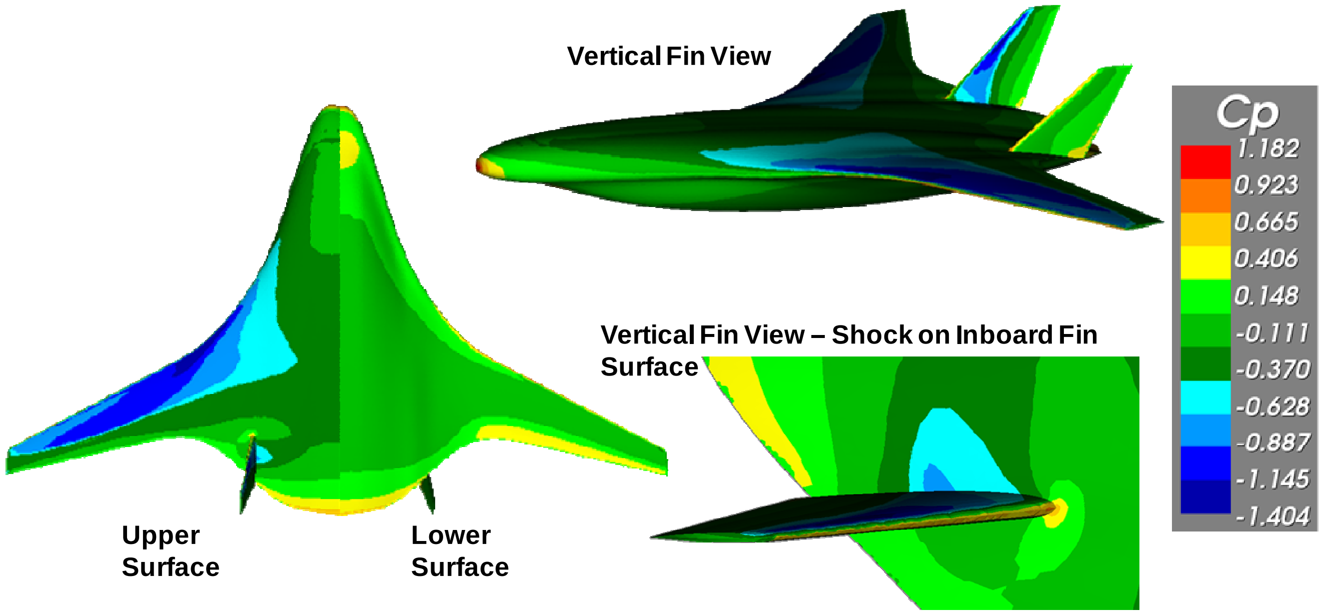

Figure 20: C_p Distribution (Mach=0.80, Alpha=5°).

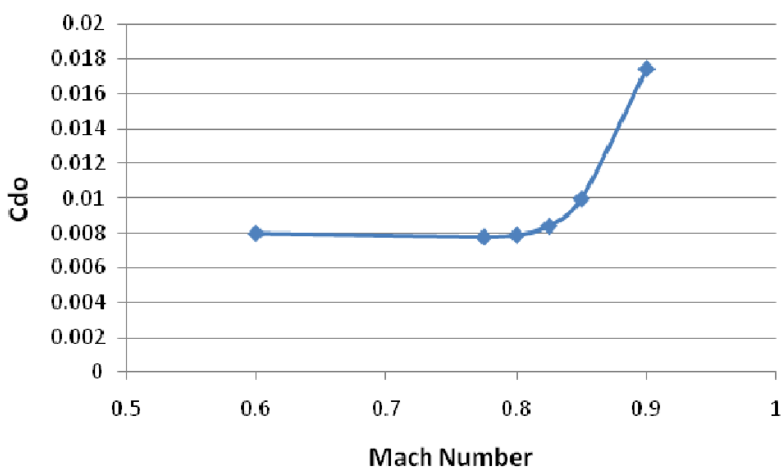

Figure 21: Transonic Drag Rise

Cart3D captures a transonic drag rise as shown in Figure 21. The BWB cruise point as defined in HWB N2A report[15] is Mach=0.79. The transonic drag rise was expected to be very close to this point. This validation increased our confidence with the Cart3D's capability to accurately model transonic effects.

The L/D_{max} in the HWB N2A report[15] is 21.61. This L/D from the report assumes no vertical fins. As Cart3D is an inviscid code, skin friction drag was added[16,17,18]. After correcting for this effect, the L/D_{max} decreased from 22.1 to 17.3. With local tailoring of geometry, the shocks on the wing and fins can be reduced, which will improve the L/D ratio.

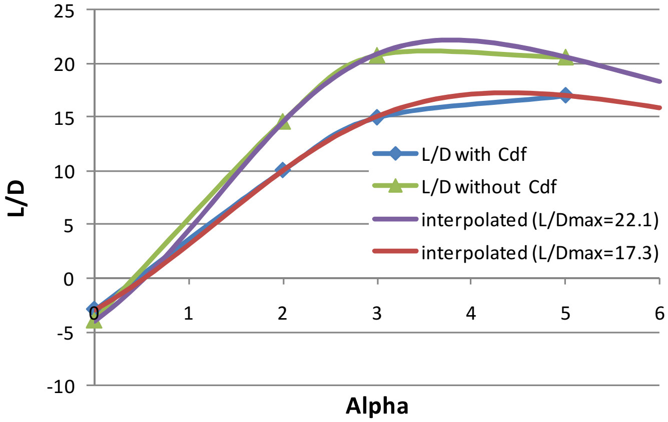

Figure 22: L/D vs Angle of Attack (Mach=0.8)

High Alpha RLV – Configuration F

The High Angle of Attack (40°-80°) reusable launch vehicle (RLV) was designed for quick access to space[19]. The RLV aerodynamics model is shown in Figure 23 for a nominal flight condition. This S/HABP model was received from AFRL and is validated below.

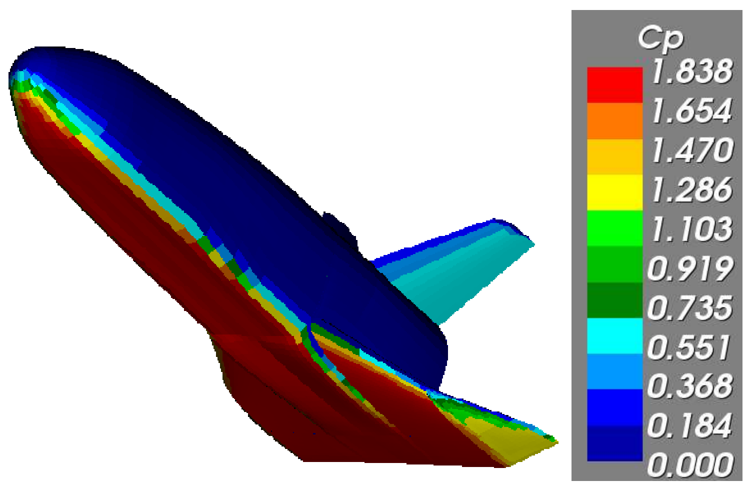

Figure 23: Cp Distribution (Mach=14, Alpha=40˚)

In order to validate the RLV model, the Normal Force, Axial Force, and Aerodynamic Center were investigated. The skin friction drag and base drag contributions were also validated. The resulting skin friction drag and base drag contributions are small.

The Normal Force Coefficient (CZ) is shown in Figure 24. From 40 degrees AOA until approximately 65 degrees AOA, the SHABP Aero Module calculated data (shown in blue) matches the Wind Tunnel data [20] and is shown in green/pink. Even at 75 degrees AOA, the RLV model results nearly match the wind tunnel data. It is believed that the deviation occurs due to high angle of attack shielding effects that are not considered.

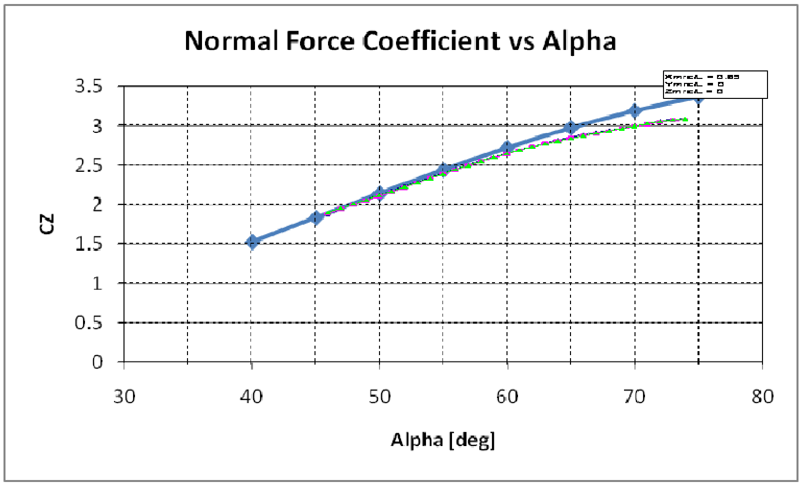

Figure 24: Normal Force Coefficient vs Alpha (Mach=14)

The Axial Force coefficient (CX) shown in Figure 25 calculated by the Aero Module (shown in blue) deviates from the Wind Tunnel data and is shown in green/pink. However, the magnitude of CX is small and therefore the contribution of CX to Lift and Drag is significantly smaller than the contribution due to CZ.

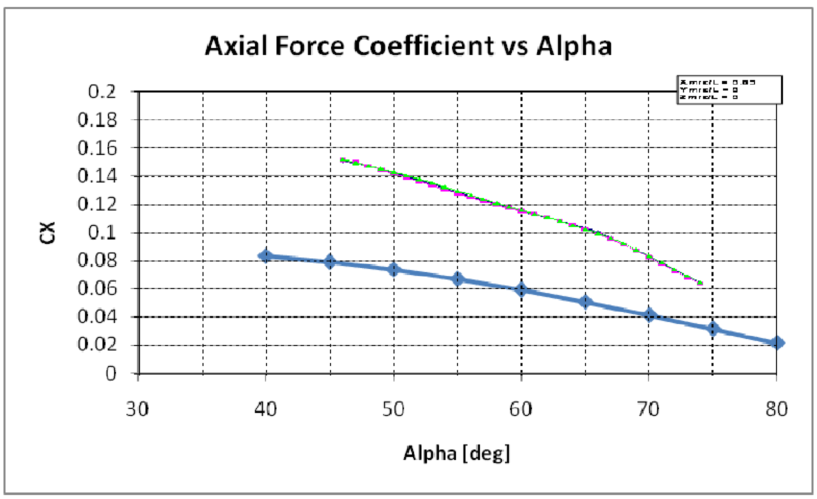

Figure 25: Axial Force Coefficient vs Alpha (Mach=14)

The Center of Pressure and Aerodynamic Center is shown below in Figure 26. The Aerodynamic Center is near the CG (taken to be 419 inches).

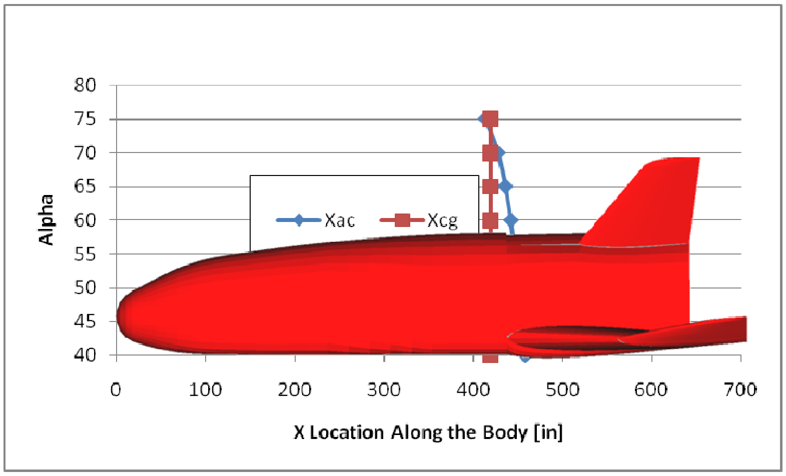

Figure 26: Center of Pressure Location Variation with Angle of Attack

The L/D shown in for an RLV at reasonable angles of attack is roughly 1.0. The trend for the High Alpha RLV is reasonable.

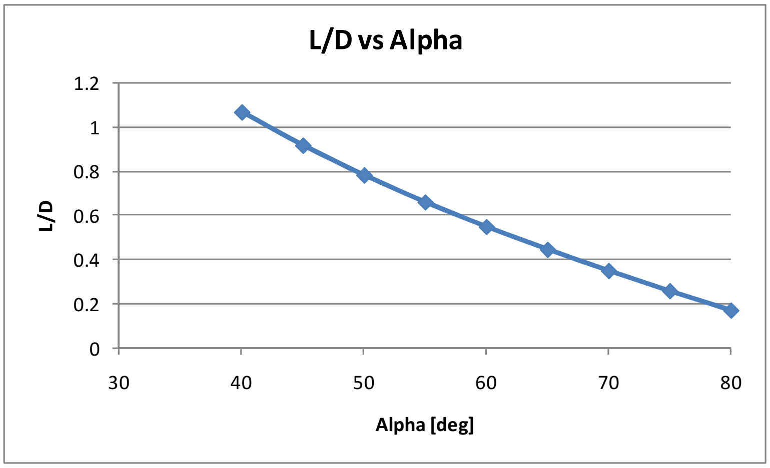

Figure 27: L/D vs Alpha

FUTURE WORK

Work on the IMOO Aerodynamics Module is on-going as this is the end of year one of a two year project. The future work will include investigation of other configurations, such as the N+2 Supersonic Transport, and complete integration and improved modularity within the OpenMDAO framework.

CONCLUSION

An Aerodynamics Module is being developed and tested as a key component of the Integrated Multidisciplinary Optimization Objects System. This module incorporates varying levels of fidelity from low fidelity methods (empirical equations and panel methods) to high fidelity methods (inviscid and viscous CFD) to determine the flow around arbitrary shaped subsonic, supersonic, and hypersonic vehicles, as well as a method for obtaining mid fidelity results. Validation results against the HSCT, BWB N2A configurations show very good correlation.

The IMOO system, when mature, will offer substantial improvements in the capability to perform high fidelity analysis and optimization of subsonic, supersonic, and hypersonic flight vehicles. Efforts to maximize the time-efficiency of CFD calculations and the implementation of a mid fidelity option utilizing a database calibration scheme have effectively enabled higher fidelity aerodynamic predictions in reasonable turn-around times.

Many important lessons have been learned in this development effort. Several are highlighted below:

- When applicable, a half model is used to reduce the grid size.
- It is much easier to create a Cart3D model as compared to creating a Panair model or Usm3D model. Cart3D models are also more robust when morphing.
- To minimize grid size and numerical complexity, only an inviscid solution is typically calculated. Viscosity contribution to lift and drag is estimated using a flat-plate model, and added to the coefficients in the aerodynamic performance database as part of the post-processing step.
- Parallel processing is used to the fullest extent to minimize runtime.
- The mid fidelity option offers a good compromise between low and high fidelity methods, combining the benefits of minimal computational resources and accuracy.
- The use of Python Objects enables a high level of data abstraction, which reduces the conceptual complexity of the system to the developer, maintainer, and ultimately users of the software.

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