

# Balancing High Fidelity MDAO with Robust System Design

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The High Fidelity Multidisciplinary Optimization (HFMDO) application delivers physics-based multidisciplinary analysis and optimization (MDAO) capabilities that are required to develop next generation supersonic 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) has been working to deliver a modular design environment suitable to high fidelity analysis and design of coupled systems. Some of this work has involved partnering with Phoenix Integration (developer of the industry standard ModelCenter framework) to combine the specialties of MDAO and framework design. The HFMDO System has been developed using multiple, incremental builds. This paper describes Build 3.1 and Build 4.0. Build 3.1 is a culmination of previous builds that has resulted in a complete high fidelity MDAO system featuring capabilities such as multi-fidelity aerodynamics and parametric finite element model generation. Build 3.1 implements the High Speed Civil Transport (HSCT) configuration and a trade study and optimization of this supersonic vehicle configuration is also presented. Build 4.0 addresses the need to balance a high fidelity MDAO system with robust system design. Build 4.0 implements the N+2 Supersonic Transport configuration and is the final build of the HFMDO System.

## Nomenclature

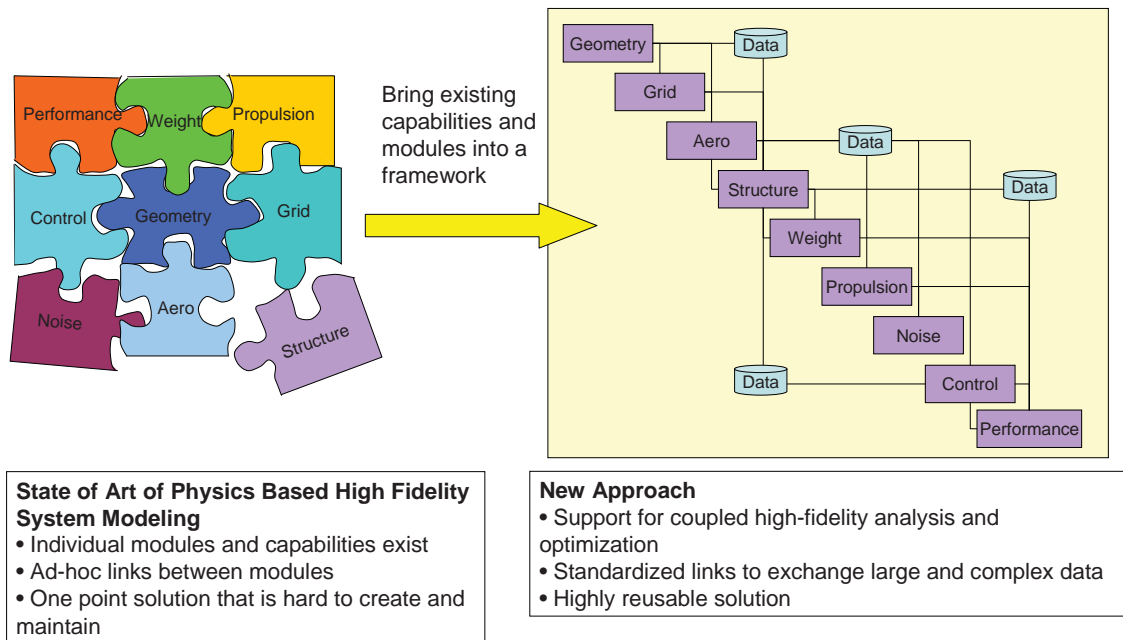
$V$	=	velocity at current Mach number and altitude
$CL_{max}$	=	Maximum lift coefficient
$C_{L\alpha}$	=	Lift Curve Slope
$L/D$	=	Lift/Drag
$Isp$	=	specific impulse
$W$	=	weight
$T$	=	thrust
TOGW	=	takeoff gross weight

## I. 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<sup>1</sup>. 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 required foundation to address varying fidelity level analyses and design problems, which are applicable to multiple configurations and incorporate physics-based models.

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

Framework software tools (e.g., ModelCenter<sup>®2</sup>) 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 (i.e. flap area, vertical tail span, etc.) by interrogating the model for use in the Aerodynamics Module. In order to avoid duplication of work, it is critical for the framework tools to provide capabilities to easily transmit complex data between modules. 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 should be updated in an automated and efficient manner as design variables are changed.

HFMDO is a multidisciplinary analysis and optimization toolset designed to address these issues for next generation vehicle applications. HFMDO develops 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. HFMDO develops a library of common objects and analysis modules based on custom data types. The initial focus was on high fidelity aerodynamic and structural analysis disciplines and the associated objects (e.g., aerodynamic database). The HFMDO system succeeded in sharing complex data by utilizing an object oriented approach in which upstream modules create objects that are used by downstream modules upon demand. Both the data and the methods reside in the object and downstream modules request the data when needed. HFMDO implements automatic mesh generation and morphing through advanced parametric geometry and grid technology for multidisciplinary modeling<sup>5</sup>. M4 Engineering has developed a parametric grid morphing tool, Geometry Manipulation by Automatic Parameterization (GMAP)<sup>6</sup> and a parametric FEA model generator for internal structures (RapidFEM<sup>7</sup>). Additionally, multi-fidelity aerodynamics has been incorporated.

With multi-fidelity aerodynamics, engineers benefit from a compromise between time (low fidelity panel methods) and accuracy (computationally intensive CFD). 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 HFMDO 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.

There have been additional issues that need to be addressed as this HFMDO system has been developed. A high fidelity system cannot be so complex that setup time precludes its use or that only one vehicle configuration can be analyzed. As such, the final build (Build 4) of the HFMDO system takes a different turn. Instead of adding enhanced functionality to the Build 3.1 System, M4 Engineering spent effort implementing a robust system design and validating that a different configuration could be implemented. The robust system design focuses on system/configuration separation and objects that make use of the new ModelCenter Data Object capability. The improved system design also allows the Aerodynamics Module to easily reside on the user's platform of choice (Windows or Linux) utilizing ModelCenter's Analysis Server feature. The N+2 configuration within the robust system design is featured in Build 4.0

## **II. HFMDO Development Approach**

Developing high fidelity MDAO currently requires extremely sophisticated skills of both engineering and software development. The approach defined herein will help engineers focus on engineering problems instead of on programming issues. This process is leading to a paradigm shift in the way high fidelity MDAO is performed.

The key elements of this toolset include an object-oriented integration framework, common objects and analysis modules based on custom data types. The HFMDO system utilizes GMAP and RapidFEM for advanced parametric geometry and grid generation technology for aerodynamic and structural models. The HFMDO system utilizes Phoenix Integration's ModelCenter framework to integrate modules and control data sharing and communication.

### **A. Incremental Build Approach**

An incremental build approach was used to develop this HFMDO system. The incremental build approach has been successful in implementing the philosophy of "Thinking big but starting small". The overall system was too complex to attempt to build in a single step. Smaller, more manageable development milestones have been established and risk has been greatly reduced. This paper specifically addresses Build 3.1 and Build 4.0. Build 3.1 culminated at the end of Year 2.5 with software and documentation being delivered April 30, 2010. Build 4.0, which is the final build of the system, culminated at the end of Year 3 with software and documentation being delivered December 31, 2010.

Build 1 established the development framework, integrated prototype modules and provided a proof-of-concept demonstration. This first build was comprised of the Geometry, Aerodynamics, Propulsion, and Structural Modules implemented in ModelCenter. ModelCenter provided the infrastructure for the object-oriented integration framework. The Build 1 milestone also included morphing-based updates to aerodynamic and structural models. The morphing functionality was implemented through the GMAP application. Lastly, Build 1 included analysis of a High Speed Civil Transport (HSCT) configuration.

Build 2 was comprised of the Geometry, Aerodynamics, Propulsion, Structural, Stability & Control, and Mission Modules integrated in ModelCenter. The Geometry, Aerodynamics, and Structural Modules were enhanced whereas the Stability & Control and Mission Modules were added. RapidFEM was included as a Geometry Module option to perform automatic finite element model (FEM) generation and the automatic execution of a full NASTRAN analysis after the RapidFEM meshing is complete. ModelCenter was updated to include a new DataObject functionality. Lastly, Build 2 utilized all of the feature upgrades and new modules as well as pre-existing functionality to execute an updated analysis of the HSCT configuration within the enhanced ModelCenter/Analysis Server environment.

Build 3.0 added the Noise Module and multi-fidelity aerodynamics to the Build 2 System. The Noise Module calculates the noise footprint of the vehicle. Multi-fidelity aerodynamics allows a compromise between time and accuracy. It uses a unique blending of the results between Low Fidelity and High Fidelity results to generate an accurate Mid Fidelity Aerodynamic Database quickly.

Build 3.1 used an enhanced RapidFEM application to add parametric automatic finite element model generation to the Build 3.0 System. RapidFEM uses entirely parametric or explicit 2-D definitions of the structural topology along with CAD renderings of the 3-D vehicle outer mold line to mesh and assemble a complete vehicle finite

element model. In addition, the flight event and structural optimization parameters are assembled. The resulting complete model and analysis deck are used within an integrated HFMDO System to determine the finite element based optimized vehicle weight.

Build 4.0 is comprised of the Geometry, Aerodynamics, Propulsion, and Structural Modules implemented in ModelCenter. It was necessary to use fewer modules to reduce risk and ensure that configuration dependent features were not tightly integrated into the system model. This effort supported the objective of system/configuration separation allowing for different configurations to be analyzed. The example configuration was updated to the N+2 Supersonic Transport to validate that different configurations could be easily analyzed within HFMDO without excessive user setup time. This Build 4 milestone also included enhancements to ModelCenter and Analysis Server for improved support of data object and file data type. The Custom Data Type infrastructure was updated to support file and file array members so that files could be transferred as an attribute of an object. To support creation and maintenance of complex models, capability to store and share commonly used class definitions using a server was added. A full description of the HFMDO modules and their features is discussed in Section III.

## **B. Design Process**

The Supersonic Vehicle Design Process is shown in Figure 2. This standard Design Structure Matrix format shows the analysis modules as blue boxes on the diagonal of the matrix, and the data items used by or generated by the modules are shown as yellow boxes. The far left column of yellow boxes represents inputs to the entire process, and the far right column represents outputs from the process. Otherwise, the outputs of a module are shown on the same row as the module, and the inputs are shown on the same column (for example, FEM Mesh is an output of the Geometry Module and an input to the Structural Module).

Module execution is shuffled to get as much information as possible into the upper-right triangle of the matrix, which represents a feed-forward path, where the module generating the data is executed prior to the module using the data. Feedback paths are possible, but require special consideration (e.g., iteration to convergence). Feedback paths require an initial guess at the data to get started, and the estimate is updated as the modules are executed. The ordering of the modules should be tailored such that the number, relative impact, and ease of developing initial starting guesses for the feedback communication paths is minimized. Note that Figure 2 only shows the most significant interactions between modules.

In this process, the Geometry Module takes the geometric variables and generates an updated CFD model (through mesh morphing), a FEM mesh (through parametric geometry & meshing), and information for the Propulsion Module (through simple equations). The Propulsion Module calculates the thrust loads (for structural analysis) and propulsion performance for use in mission simulation, takeoff/landing analysis, and stability & control. The Aerodynamics Module calculates the vehicle aerodynamic coefficients and distributed pressures at various flight conditions for use in performance simulation and loads calculation. The Structural Module calculates loads and structural sizing to estimate structural weight, which is passed to the Mission Performance Module to estimate the takeoff gross weight (TOGW). The Stability & Control Module determines available control authority for sufficient trim and adequate static stability characteristics. The Mission Module, which only calculates Takeoff/Landing parameters, will verify that the vehicle can take off and land on the required fields. The resulting takeoff flight paths are passed to the Airport Noise Module to calculate the noise footprint of the vehicle.



Object Name	Value / Path
Geometry	
ConfigPathBase	C:\work\hfmdo\hf...
WorkPathBase	C:\work\hfmdo\hf...
StageName	cruise
WingArea	1.23529e+006
AR	1.5
Sweep	66.0693
Taper	0.07446
Omega	0.61016
Eta	0.61934
Theta	0.76537
RapidFemOption	RapidFEM with an...
GeometryObject	<view...>
GeometryObject._gmapPath	gmap
GeometryObject._morphingTool...	C:\work\hfmdo\hf...
GeometryObject._rapidFemPath	rapidfem
GeometryObject._configPath	C:\work\hfmdo\hf...
GeometryObject._workPath	C:\work\hfmdo\hf...
GeometryObject.tank1	None
GeometryObject.tank2	None
GeometryCalcObject	<view...>
GeometryCalcObject._morphing...	C:\work\hfmdo\hf...
GeometryCalcObject._configPath	C:\work\hfmdo\hf...
GeometryCalcObject._workPath	C:\work\hfmdo\hf...
GeometryCalcObject._reference	

Figure 3. HFMDO Objects are transferred using Data Object capability of ModelCenter.

## B. HFMDO Modules

### 1. Geometry Module

The Geometry Module generates a finite element mesh based on an OML and a sketch file, modifies a user-supplied mesh by moving its grid points based on changes in supplied design variables, and calculates various geometric properties of the mesh. The Geometry Module takes in two basic types of inputs: configuration information (where input models are located), and geometric design variables (e.g., Sweep, Wing Area, Aspect Ratio, etc.). It generates two objects: a Geometry Object and a Geometry Calculations Object. These two objects are passed to other modules in the system, so that those downstream modules can call methods on the objects to morph geometry (Geometry Object), generate a FEM (Geometry Object), or calculate geometric values (Geometry Calculations Object), such as the length of the vehicle, the area of the wing, and the Aspect Ratio. This allows models to be easily generated as necessary, rather than requiring that all information is defined at the beginning of the execution process.

### 2. Aerodynamics Module

The Aerodynamics Module calculates aerodynamics (in the form of an Aero Database Object) for a vehicle using the low-fidelity, potential flow code, Panair, the high fidelity, inviscid, unstructured code, Cart3D, and the high-fidelity, viscous or inviscid, unstructured code, Usm3D. This module uses the Geometry Object to call GMAP to morph a baseline mesh as design variables change. The greatest strength of the Aerodynamics Module lies in its mid fidelity capability, which blends the low fidelity results with the high fidelity results to generate an accurate mid fidelity database in a short amount of time. Additionally, the Aerodynamics Module calculates  $CL_{max}$  for the vehicle as well as the stability derivatives of the vehicle (in the form of a Stability Derivative Database Object) using the empirical code, Datcom.

The Aero Module is capable of running multiple aerodynamic analysis codes: Panair, Cart3D, and Usm3D may be executed. The Aerodynamics Module accomplishes its analyses by first building a structured list of flight conditions to run. Each analysis case must be placed in a “box”, which defines which code is going to run the analysis point. A request to the Geometry object is made to morph the grid before the aerodynamic code (Panair, Cart3D, or Usm3D) is run. The aerodynamic program code (such as the Panair code) is responsible for taking a list of models and flight conditions to run. The results are returned and the next analysis code may be run.

The resulting Aero Database and Stability Derivative Database are objects, which have the capability of interpolating on the results and querying any previously analyzed cases. The resulting pressure databases are not objects, but may be viewed by a standard viewer. Although the pressure databases are not objects, the Aero Database Object has methods that operate on the pressure databases and can perform operations on those files. An example of an operation that is supported is interpolation.

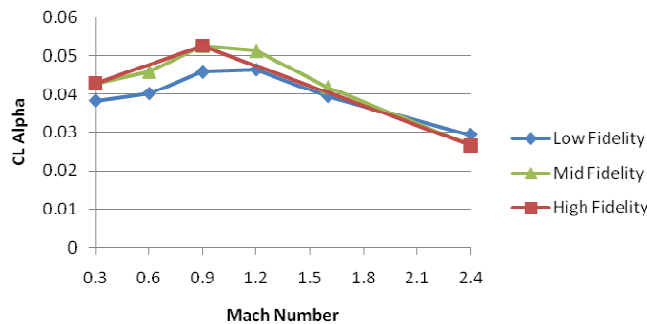


The Cart3D N+2 aerodynamic model shown in Figure 4 was created by taking the STL mesh and converting it into Cart3D format.



**Figure 4. Cart3D Aerodynamic Mesh.**

In order to demonstrate the Aerodynamics Module’s mid fidelity capability, 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 5. 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 5.  $C_{L\alpha}$  vs Mach for Low, Mid, and High Fidelity Results**

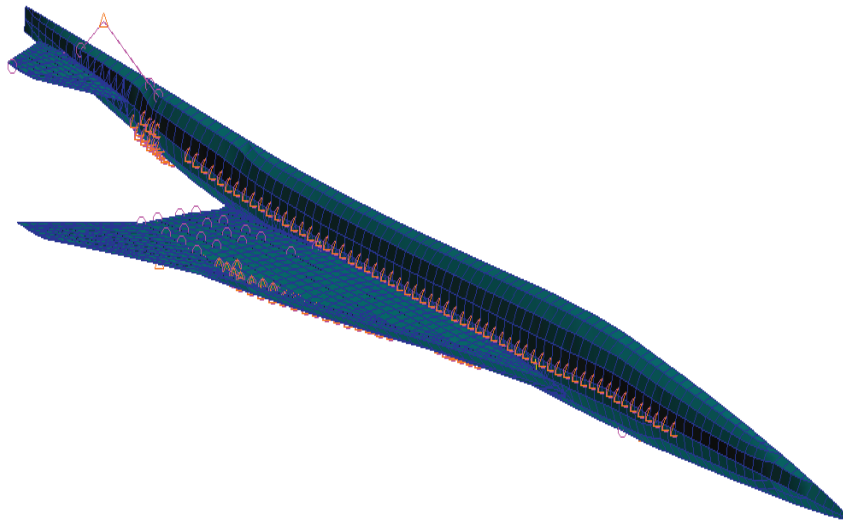
### 3. Propulsion Module

The Propulsion Module calculates the overall performance of an engine under a given flight condition. The Propulsion Module is based on NPSS and utilizes an NPSS engine model of a small business jet. This engine model has the same cycle as the engine used in the High Speed Civil Transport (HSCT) and was scaled up to the HSCT engine thrust level.

### 4. Structural Module

The Structural Module uses MSC/Nastran to analyze either a pre-made structural bulk data file (bdf) or a bdf assembled using M4 Engineering’s RapidFEM software. The module can use a fully stressed design (FSD) technique or Nastran’s gradient optimization technique to determine the weight optimized structural sizing for the model. Lastly, the module will determine mass properties of the structure and property regions as well as provide a margin summary of the optimized structure. As design variables change (i.e., a trade study execution), the Structural Module can invoke RapidFEM by utilizing the Geometry Object to generate a new finite element model; or the Structural Module can use the Geometry Object to call GMAP<sup>5</sup> to morph an existing finite element model.

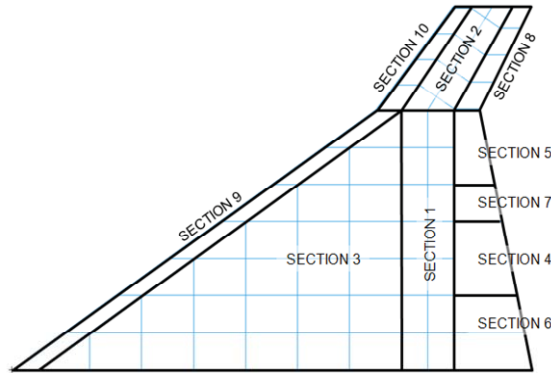
The Structural Module executes the RapidFEM capability with the Geometry Object as the pre-processor to create the finite element model including distributed fuel and payload weight with the linear aero model and analysis conditions. Figure 6 shows the model generated by RapidFEM. The outer mold line of the S4T wind tunnel test model was scaled to full size and used as inputs to RapidFEM. The internal structure was parametrically defined as a reasonable layout of ribs and spars in the wing/tail and floor and bulkheads in the fuselage. The parametric description of the structural layout significantly decreases the time necessary to modify the layout (e.g., the number and distribution of the wing ribs) based on results from trade studies performed with the system. The fuel and payload were added based on the mass properties described in [8]. The following combinations of model input and optimization techniques have been executed: 1) User supplied FEM running Fully Stressed Design (FSD) optimization, 2) User supplied FEM running gradient based optimization (Nastran Solution 200) and 3) RapidFEM generated FEM running gradient based optimization.



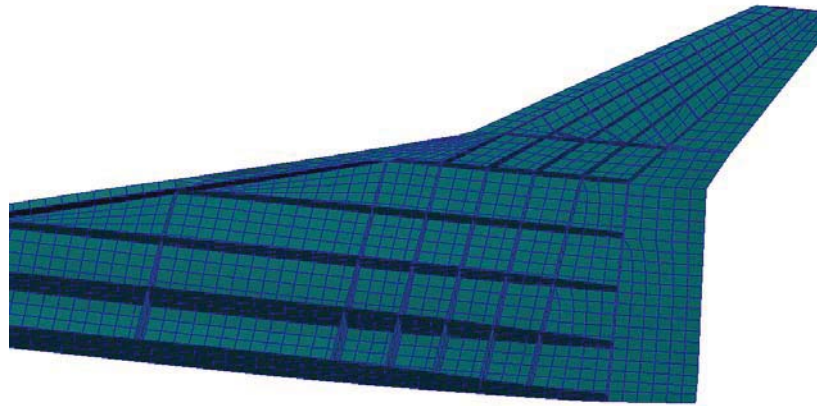
**Figure 6. RapidFEM Generated HSCT Structural Model.**

Build 3.1 demonstrated a significant step forward in making models of airframe structures with the Structural Module utilizing the enhanced RapidFEM tool. Previously, RapidFEM required the analyst to explicitly define the planform. In Build 3.1 using RapidFEM's new smart structure, the entire planform can be described parametrically and altered with minimal input. Components can be divided into sections by type of layout. Structural properties can also be defined based on a map of the structure. The wing structure options include spar orientation, rib orientation, and distribution. The spar can be parallel to the leading edge, parallel to the trailing edge, or root and tip of spar at constant percent chord. The rib orientation can be perpendicular to the leading edge, perpendicular to the trailing edge, or constant span. The distribution can be fixed number, fixed spacing or a specified distribution. The fuselage structure options include the floor, bulkhead, and frame. Only one floor can be defined in a section with smart inputs and the placement is either flat (constant Z) or constant percent height. The bulkhead is located at specific fractions of the section length and they are flat (constant X). The frames can be ring or rail. The frame distribution can be fixed number, fixed spacing, or a specific distribution. Figure 7 shows how a wing with a complicated planform can be divided into sections. Figure 8 shows a FEM of the HSCT wing generated using RapidFEM's parametric definition of the planform.





**Figure 7. Complicated Planform Divided into Sections**



**Figure 8. RapidFEM Generated FEM showing Wing Internal Structure**

### 5. *Stability and Control Module*

The Stability & Control Module is primarily responsible for the analysis and design of the stability and control characteristics of a user-supplied aircraft model for a number of critical flight conditions. The module uses Matlab Stability and Control Toolbox (MASCOT) to perform a low fidelity stability and control assessment of the aircraft model. The module determines available control authority for sufficient trim and adequate static stability characteristics.

The Flight Critical Condition (FCC) Set No. 1 horizontal flight condition is tested. The S&C Module utilizes the Aerodynamics Module's DATCOM database to calculate the aerodynamic coefficient and derivative data required for the S&C analysis. As DATCOM solves only subsonic problems, the Set No. 1 flight conditions are set to Mach = 0.8, alt = 35,000 feet, and attack angle  $\alpha = 0^0$ . The Set No.1 S&C analysis is treated as a three degree of freedom (3 DOF) problem. Six degree of freedom (6 DOF) lateral analyses are not performed.

### 6. *Mission Module*

The Mission Module is responsible for calculating the takeoff and landing performance characteristics of a given aircraft configuration. Note that this implementation of the Mission Module uses TAKEOFF, which is a stand-alone version of Flight Optimization System (FLOPS). TAKEOFF only analyzes takeoff and landing performance. It has been validated that the Mission Module successfully wraps TAKEOFF and outputs the results in a convenient form for the user without degrading the accuracy of the initial TAKEOFF stand-alone program results.

### 7. Noise Module

The Noise Module is responsible for calculating effective perceived noise levels for sideline, approach, and takeoff flyover. It also predicts whether or not the aircraft meets the standards specified by FAR 36 accounting for its engine, airframe, flight path, landing gear deployment, and flap settings. The Noise Module uses Aircraft Noise Prediction Program (ANOPP) to perform its calculations. The output is a Pass/Fail flag for FAR 36 Stage III Certification.

## IV. Demonstration Application and Results

### A. System Setup – Build 3.1

Each of the modules within the system was developed in Python. ModelCenter was used in order to integrate the modules into a system framework. To do this, scriptWrapper files were developed to link the Python code from the modules into ModelCenter components. The Build 3.1 System is shown in Figure 9.

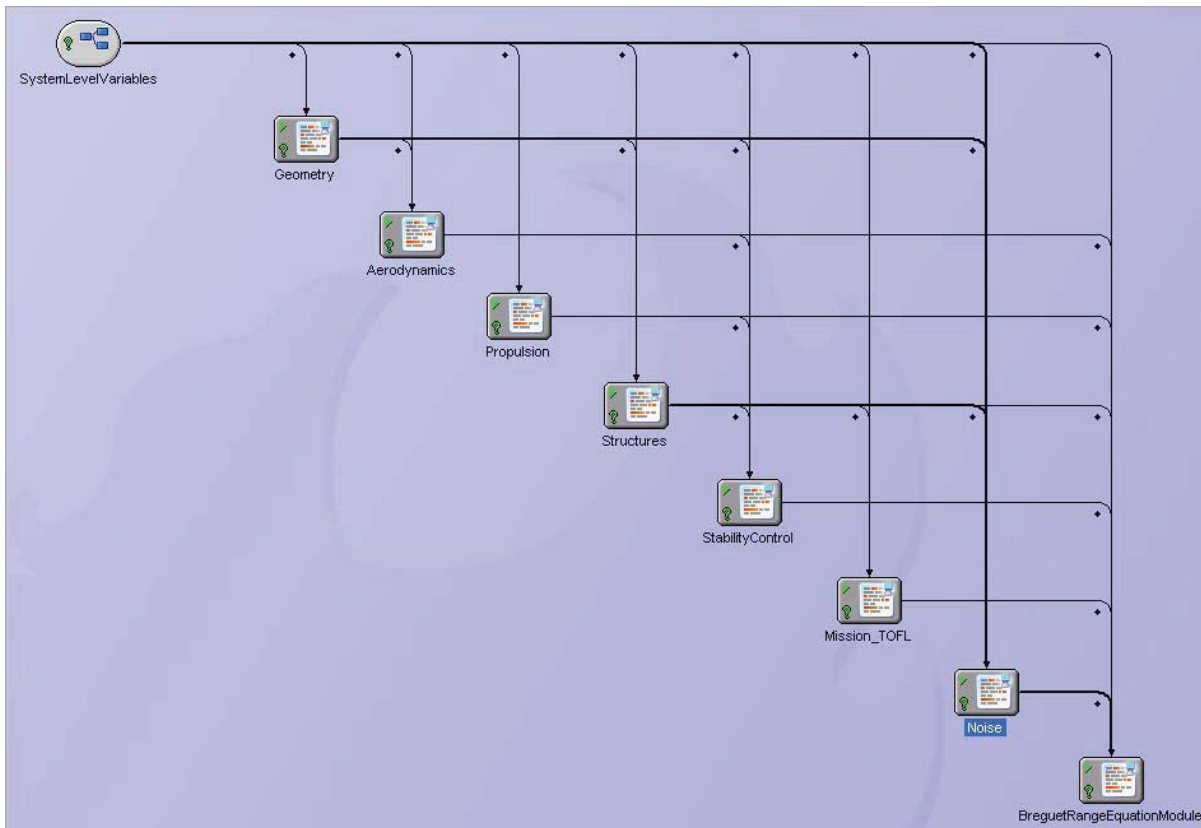


Figure 9. Build 3.1 HFMDO System Integrated in ModelCenter.

The nine main components in the system model are:

1. SystemLevelVariables
2. Geometry
3. Aerodynamics
4. Propulsion
5. Structures
6. StabilityControl
7. Mission\_TOFL
8. Noise
9. BreguetRangeEquationModule

The Breguet range equation shown in Eq. (1) was used to calculate the range from a variety of system level outputs:

- Range – Range computed from Breguet range equation
- V – Velocity at current Mach number and altitude
- L/D – Lift/Drag
- Isp – Specific Impulse
- W – Weight

$$Range = V \frac{L}{D} I_{sp} \ln \left( \frac{W_{initial}}{W_{final}} \right) \quad (1)$$

## B. HSCT Example Problem

The ModelCenter framework is responsible for coordinating the execution of the HFMDO System. This includes ensuring that all the required modules are executed in the correct order, that the required data are transferred from one module to the next, and that the overall trade study or optimization process is carried out efficiently. Two types of execution options are used: Single Point Analysis and Parametric Trade Study. Single Point Analysis is a single run through the HFMDO system to evaluate the performance of the current design. Parametric Trade Study allows the user to define ranges for the system design variables; and, the HFMDO system loops over the defined ranges, evaluating each design point. This allows the sensitivity of the design to variations in continuous-valued design variables to be quickly evaluated.

For the HSCT example problem, three trade studies were examined in which a geometric design variable was varied. The three geometric design variables studied were Sweep, Wing Area, and Aspect Ratio. These design variables were plotted against Range, L/D, and TOGW. Table 1 summarizes the data collected from the studies. Note that the red boxes represent a design point in which the NASTRAN optimization did not converge on a final value.

**Table 1. Trade Study Results**

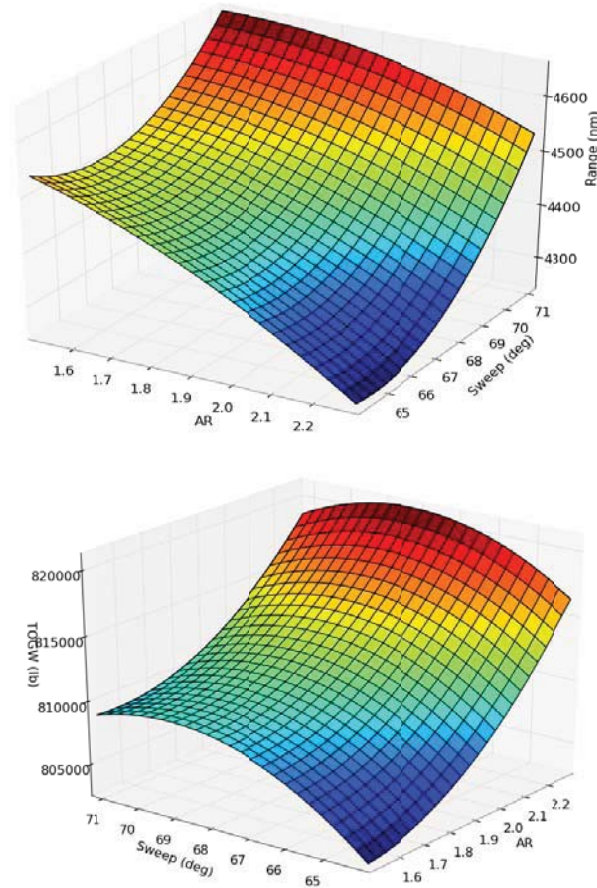
Parameter	Sweep Study					Wing Area Study					Aspect Ratio Study				
	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 5 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 5 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 5 Values
Wing Area (in <sup>2</sup> )	1235285	1235285	1235285	1235285	1235285	1000000	1200000	1400000	1600000	1800000	1235285	1235285	1235285	1235285	1235285
AR	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	2.008	1.500	1.775	2.050	2.325	2.600
Sweep (°)	64	66.5	69	71.5	74	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1	66.1
Taper	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074
Omega	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610
Eta	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
Theta	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765
Range (nm)	4426.285	4370.087	4469.28	4608.483	5136.197	4582.913	4381.694	4217.641	3961.499	3784.423	4536.131	4372.226	4320.612	4295.128	4092.792
L/D	11.11151	11.23811	11.42715	11.80713	12.54938	11.20378	11.22286	11.21739	11.19442	11.03413	11.46009	11.33027	11.2066	11.07546	10.94114
Isp (s)	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45	3618.45
TOGW (lb)	802952.3	814497.2	811711.6	812695.8	790324	790581.1	812557	831097.1	862446.1	879408.9	805978.2	818234	818673.9	815819.1	833668.5
1/2 TOGW (lb)	401476.1	407248.6	405855.8	406347.9	395162	395290.6	406278.5	415548.5	431223.1	439704.5	402989.1	409117	409337	407909.6	416834.3

## C. HSCT Optimization Problem

By utilizing the HFMDO system, an optimization problem to maximize range was posed. This problem sought to maximize range subject to constraints on vehicle weight and takeoff field length. The design space for this problem was created by varying wing sweep and aspect ratio. A total of 16 cases were run to obtain enough data to generate response surfaces for range, takeoff gross weight, and takeoff field distance. The data obtained from these design points are summarized in Table 2. The response surfaces created from the 16 design points are shown in Figure 10.

**Table 2. Summary of Data used in Optimization Problem**

Parameter	Baseline Values	Sweep Study - AR - 1.5				Sweep Study - AR - 1.775				Sweep Study - AR - 2.008				Sweep Study - AR - 2.325			
		Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values
Wing Area (in <sup>2</sup> )	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285	1235285
AR	2.008	1.500	1.500	1.500	1.500	1.775	1.775	1.775	1.775	2.008	2.008	2.008	2.008	2.325	2.325	2.325	2.325
Sweep (°)	66.1	64	66.5	69	71.5	64	66.5	69	71.5	64	66.5	69	71.5	64	66.5	69	71.5
Taper	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074
Omega	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610	0.610
Eta	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619	0.619
Theta	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765	0.765
Range (nm)	4317.02	4545.556	4538.085	4546.422	4613.649	4451.34	4367.067	4509.875	4664.881	4426.285	4370.087	4469.28	4608.483	4215.315	4261.888	4407.393	4454.687
L/D	11.2166	11.37151	11.47569	11.5873	11.7427	11.24017	11.35184	11.49737	11.82395	11.11151	11.23811	11.42715	11.80713	10.9907	11.09933	11.32339	11.73424
Isp (s)	3618.45	3618.454	3618.454	3618.454	3618.454	3618.454	3618.454	3618.454	3618.454	3618.45	3618.45	3618.45	3618.45	3618.454	3618.454	3618.454	3618.454



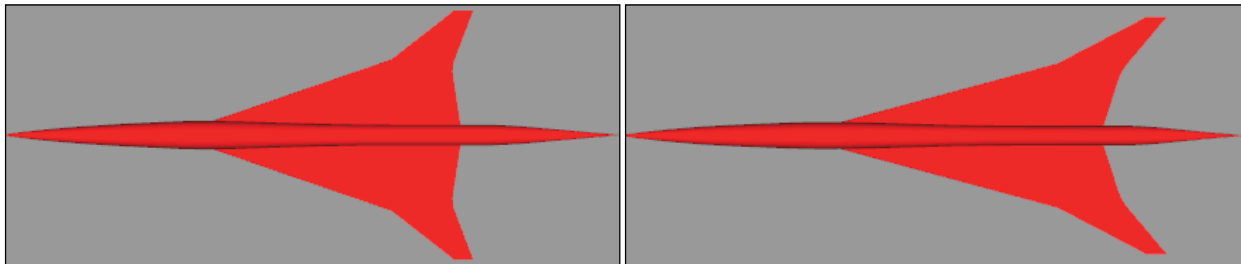
**Figure 10. Generated Response Surfaces**

By observing the response surfaces above, one can see that when aspect ratio increases the TOGW increases, range decreases, and TOFL is minimized at an aspect ratio of approximately 1.9. This trend is intuitive because when the aspect ratio increases, the wing bending moment increases causing the weight to increase thus making the vehicle heavier for a fixed amount fuel and reducing the overall range. However, the trend shown for varying sweep is unexpected. When either decreasing or increasing wing sweep from the nominal value (66°), one would expect TOGW to increase and range to decrease. This trend is believed to be due to the introduction of “noise” in the data resulting from the embedded NASTRAN optimization. With careful adjustment of the NASTRAN optimization parameters, this effect could be mitigated. Due to time constraints, this improvement remains as future work.

A summary of the constraints and final optimized design values are shown in Table 3. Figure 11 shows a comparison of the baseline and optimized configuration vehicle models. It is important note that there remains room for improvement in the quality of the result, which could be obtained by modifying the NASTRAN optimization parameters.

**Table 3. Summary of Optimization Results**

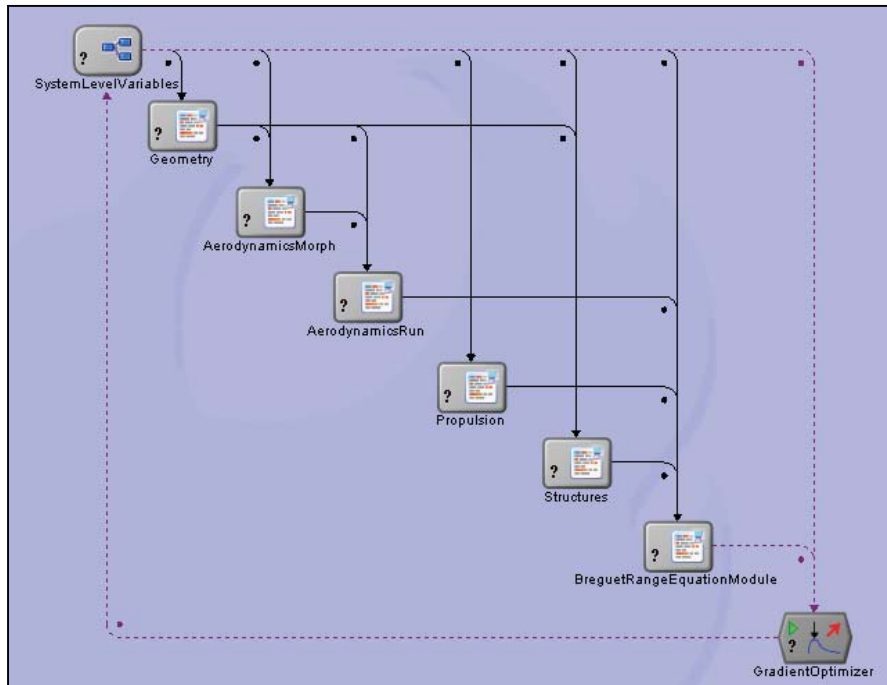
AR	Sweep (deg)	Range (nm)	TOFL (ft)	Weight (lb)	Weight Constraint (lb)	TOFL Constraint (ft)
1.777	71.500	4662.5	12500.0	809376	821800	12500



**Figure 11. Left: Baseline Model, Right: Optimized Model.**

**D. System Setup – Build 4.0**

Each of the modules within the system was developed in Python. ModelCenter was used in order to integrate the modules into a system framework. To do this, scriptWrapper files were developed to link the Python code from the modules into ModelCenter components. The system is shown in Figure 12.



**Figure 12. Build 4.0 HFMDO System Integrated in ModelCenter**



The seven main components in the system model are:

1. SystemLevelVariables
2. Geometry
3. AerodynamicsMorph
4. AerodynamicsRun
5. Propulsion
6. Structures
7. BreguetRangeEquationModule

### E. N+2 Example Problem

The following results (see Figure 13) were obtained by executing a baseline analysis, an Eta trade study, and a Taper trade study of the N+2 configuration. Note that the baseline analysis was executed with mid-fidelity aerodynamics capability. Two Cart3D volume models (~3.1 and 9 millions cells) were generated and used as input to create the mid-fidelity model. For the trade studies the low-fidelity Cart3D model was used. Note that the user is able to select the desired fidelity level model and analysis based on time and accuracy requirements. These examples validate all functionality.

Parameter	N+2 Data										
	Baseline Values	Eta Study					Taper Study				
		Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 5 Values	Run 1 Values	Run 2 Values	Run 3 Values	Run 4 Values	Run 5 Values
Wing Area (in <sup>2</sup> )	557186	557186	557186	557186	557186	557186	557186	557186	557186	557186	557186
AR	1.923	1.923	1.923	1.923	1.923	1.923	1.923	1.923	1.923	1.923	1.923
Sweep (°)	64.9	64.9	64.9	64.9	64.9	64.9	64.9	64.9	64.9	64.9	64.9
Taper	0.079	0.079	0.079	0.079	0.079	0.079	0.060	0.065	0.070	0.075	0.080
Omega	0.443	0.443	0.443	0.443	0.443	0.443	0.443	0.443	0.443	0.443	0.443
Eta	0.482	0.450	0.500	0.550	0.600	0.650	0.482	0.482	0.482	0.482	0.482
Theta	0.514	0.514	0.514	0.514	0.514	0.514	0.514	0.514	0.514	0.514	0.514
Range (nm)	2969.44	2985.992	2899.773	2903.523	2822.478	2741.881	2897.107	2911.685	2908.663	2926.793	2954.134
L/D	11.8952	11.91667	11.87838	11.81871	11.76226	11.70389	11.36866	11.46289	11.59169	11.722	11.85763
Isp (s)	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182	3619.182
TOGW (lb)	198511	198060.5	201220.3	200445.9	203349.4	206383.5	196061.9	196442.9	197891.8	198486.2	198751.1

Figure 13. Baseline, Eta Trade Study, and Taper Trade Study Results for the N+2 Configuration

#### 1. N+2 Eta-Taper Carpet Study (Cart3d)

The following results were obtained by executing a Carpet Plot study within ModelCenter for the N+2 configuration in which the Eta and Taper design variables were varied. The following figures show the variation of the Range (Figure 14), L/D (Figure 15), and TOGW (Figure 16) for the Carpet Plot study.

Range (nm)				
Eta\Taper	0.061	0.067	0.074	0.080
0.48	2867.93	2845.43	2845.58	2962.87
0.54	2776.32	2825.65	2858.23	2802.96
0.59	2787.03	2735.42	2725.5	2808.72
0.65	2552.56	2322.98	2827.45	2720.1

Figure 14. Range values for Eta vs. Taper

L/D				
Eta\Taper	0.061	0.067	0.074	0.080
0.48	11.3906	11.5261	11.6988	11.9511
0.54	11.396	11.5363	11.6908	11.8022
0.59	11.3544	11.4815	11.5619	11.8208
0.65	11.261	11.3001	11.551	11.6595

Figure 15. L/D values for Eta vs. Taper

TOGW (lb)				
Eta\Taper	0.061	0.067	0.074	0.080
0.48	197487	199854	201667	199342
0.54	201473	200812	201038	204646
0.59	200552	204249	205590	204586
0.65	210674	224262	200890	206918

Figure 16. TOGW values for Eta vs. Taper

From this data, second order response surfaces were generated. These response surfaces were used within an Excel spreadsheet-based goal-seek problem. Higher order response surfaces were generated within ModelCenter using the same data from the Carpet Plot study. Figure 17, Figure 18, and Figure 19 compare the second order response surfaces to the higher order response surfaces.

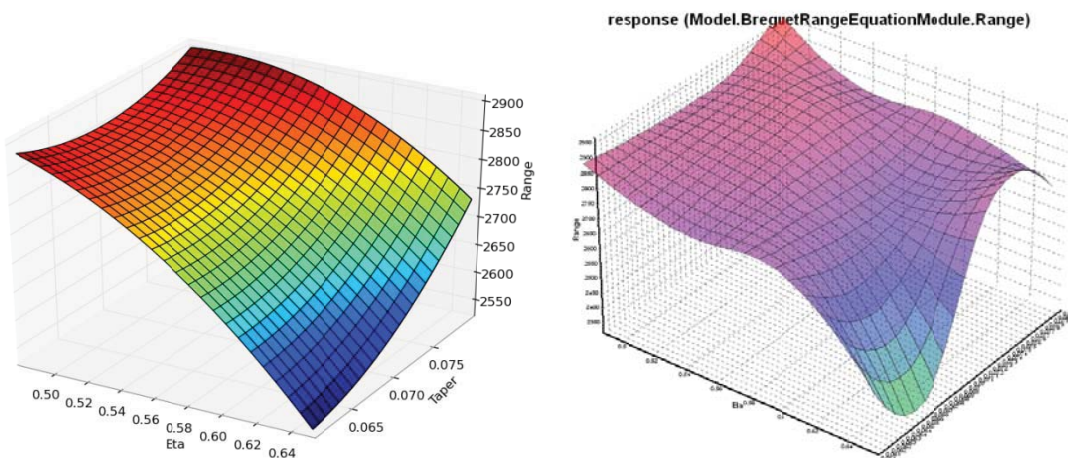
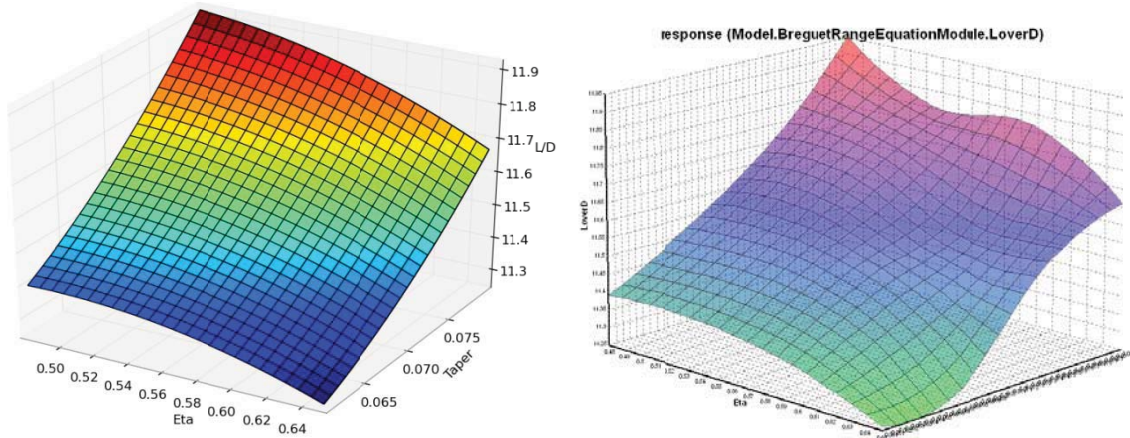
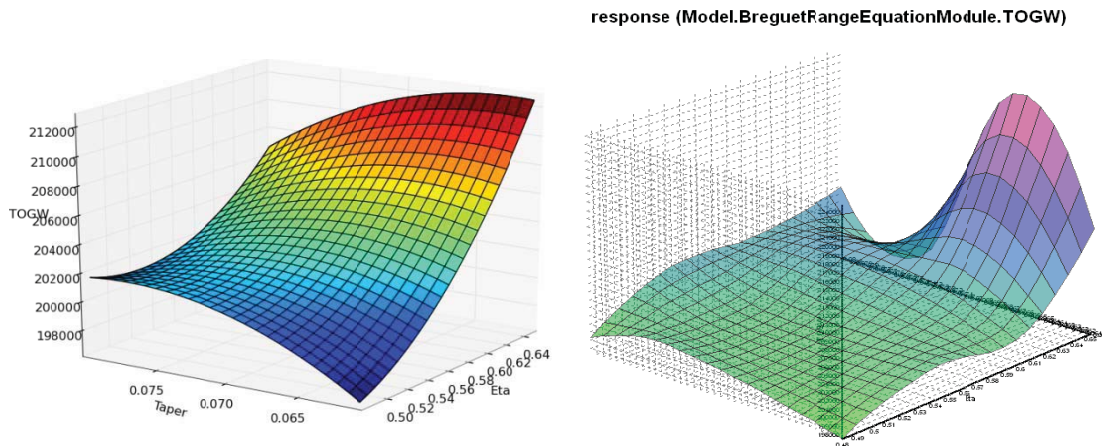


Figure 17. Second Order (left) and Higher Order (right) Response Surfaces for Range-Eta-Taper



**Figure 18. Second Order (left) and Higher Order (right) Response Surfaces for L/D-Eta-Taper**



**Figure 19. Second Order (left) and Higher Order (right) Response Surfaces for TOGW-Eta-Taper**

## 2. *N+2 Eta-Taper Design Explorer Optimization*

The last example problem consists of an optimization of the N+2 configuration using ModelCenter’s Design Explorer Tool. Figure 20 summarizes the optimization problem executed.

Objective	Goal
Range	Maximize

Constraint	Lower Bound	Upper Bound
TOGW	-	205000
L/D	11.4	11.6

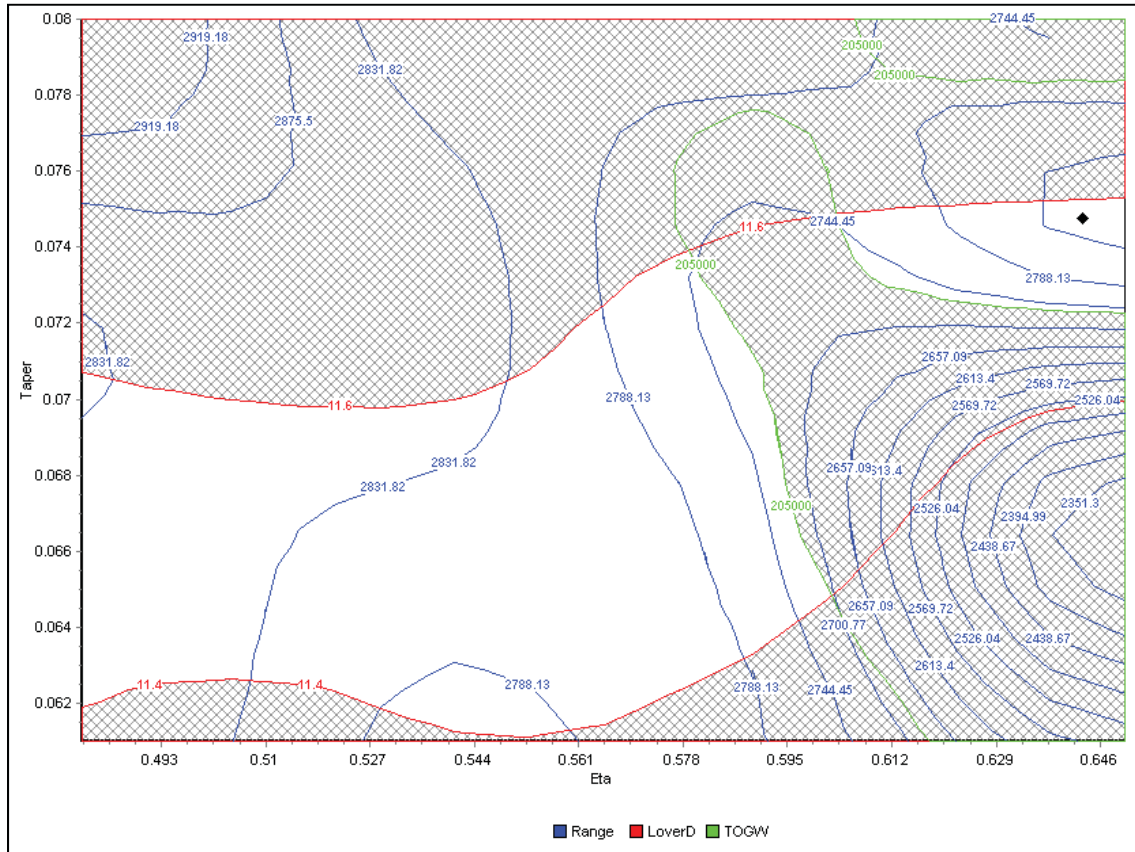
  

Design Variable	Lower Bound	Upper Bound
Eta	0.48	0.65
Taper	0.061	0.08

**Figure 20. Summary of Design Explorer Optimization Problem Information**

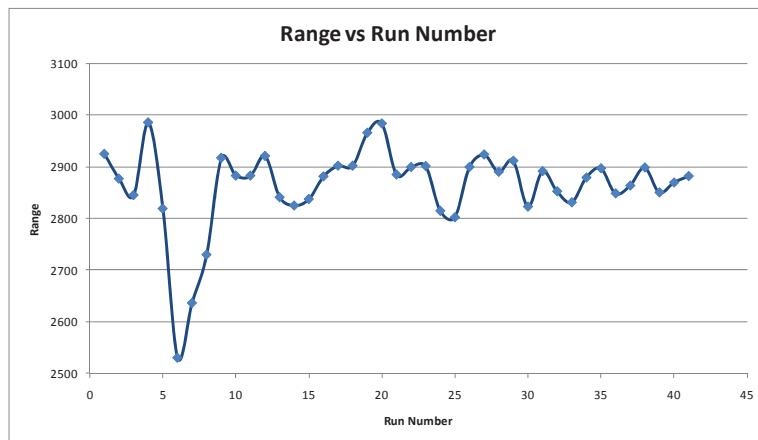
Using ModelCenter’s profile predictor capability, Figure 21 was created from the Carpet Plot study to determine a feasible optimization problem for HFMDO Build 4. First, contours (blue) for the Range (objective to be

maximized) response surface as a function of Eta and Taper were created. Second, an upper bound for TOGW (green constraint) was imposed on top of the Range contours. Finally, an interval for L/D (red constraint) was imposed on top of the Range-TOGW contours as shown in Figure 21. By visually inspecting this figure, an approximate optimal solution within the design space can be seen corresponding to an Eta value of 0.643 and a Taper value of 0.0748.



**Figure 21. Range-TOGW Constrained by L/D**

Figure 22 illustrates the Design Explorer optimization run converging to an approximate Range value of 2881 nm.



**Figure 22. Results of Design Explorer Optimization**



## V. Conclusion

The development of the HFMDO analysis tool is complete and integrated into the ModelCenter framework. High fidelity analysis systems are inherently complex. Benefitting from the accuracy of a high fidelity system sometimes involves excessive overhead and computer resources. It may also result in a system that is so complex that its use is prohibitive. This HFMDO effort achieves the goal of overcoming these issues. New work was incorporated to improve the robustness of the system and improve the ability to add different configurations. Capabilities have been implemented to define, create, and transfer custom data objects using ModelCenter and Analysis Server. The Aerodynamics Module can reside on the user's platform of choice (e.g., Windows or Linux). The HFMDO system showcases the integration of the Geometry, Aerodynamics, Propulsion, Structural, Stability & Control, Mission and Noise Modules, as well as the BreguetRangeEquation Module. The system supports different configurations (HSCT and N+2) and the example problems utilize automated mesh morphing using GMAP and automatic finite element model generation using RapidFEM. RapidFEM also allows for dynamic parametric structural layout (e.g., changing the number of spars). Multiple aerodynamic codes are supported to provide both low fidelity panel methods and high fidelity CFD. This ability allowed for the creation of the multi-fidelity aerodynamics feature. Several industry-standard codes (i.e. NPSS, NASTRAN, MASCOT, ANOPP) are supported within the system. The HFMDO System utilizes the new DataObject functionality within the ModelCenter framework to implement the geometry object, geometry calculations object, and the aerodynamic database object.

Analyses are streamlined using an object-oriented approach, which allows for simplification, as well as generalization of data. This ultimately reduces the need for file parsers by simplifying the organizational structure of the data and thus reducing the risk that errors will be introduced. There is an opportunity for reuse of the analysis tools to various aircraft configurations (subsonic/supersonic/hypersonic) due to the ease of use of the enhanced ModelCenter integration framework. The HFMDO system performs a completely automated optimization of the vehicle using the available optimization techniques inherent in the ModelCenter framework.

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