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High Fidelity MDO Process Development and Application to Fighter Strike Conceptual Design

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As design requirements and affordability for future aircraft become increasingly demanding, aircraft design processes will be required to explore a larger design space and capture multi-disciplinary effects during conceptual design to effectively assess the benefits of new technologies. Lockheed Martin is currently participating in the ESAVE (Efficient Supersonic Air Vehicle Exploration) AFRL program which is developing MDO-based improvements to the fighter strike conceptual design process. This paper discusses the program progress to date of both conceptual design process improvements for fighter/strike aircraft and the application of the resultant MDO process to a specific design problem. The fighter/strike design process involves many coupled discipline interactions due to demanding mission performance requirements. The ESAVE program has focused on capturing the discipline interactions required for the active structures and variable cycle engine technologies. Initial results demonstrate that integration of these structural and propulsion technologies in an MDO-based framework expands the traditional fighter/strike design space and can potentially provide significant performance improvements compared to conventional conceptual design processes.

Nomenclature

AR = Aspect Ratio
DOE = Design of Experiments
DV = Design Variable
FEM = Finite Element Model
GTOW = Gross Takeoff Weight
ICE = Innovative Control Effectors
MDO = Multidisciplinary Design Optimization
OPR = Overall Pressure Ratio
RSM = Response Surface Model
SEP = Specific Excess Power
SSD = Spoiler/Slot Deflector
T/C = Thickness to Chord
TR = Taper Ratio

I. Introduction

Recently, Lockheed Martin Aeronautics Company (LM Aero) has participated in the Air Force Research Laboratory (AFRL) ESAVE multi-disciplinary optimization based design process development and application contract. The ESAVE program is comprised of two major phases as shown in Figure 1. The Basic phase focused on

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the design and development of an MDO based conceptual design process to be used to explore the design space for future US Air Force aerospace vehicles. During the Option phase, the objective is to apply the MDO process developed during the Basic phase to a fighter/strike design problem.

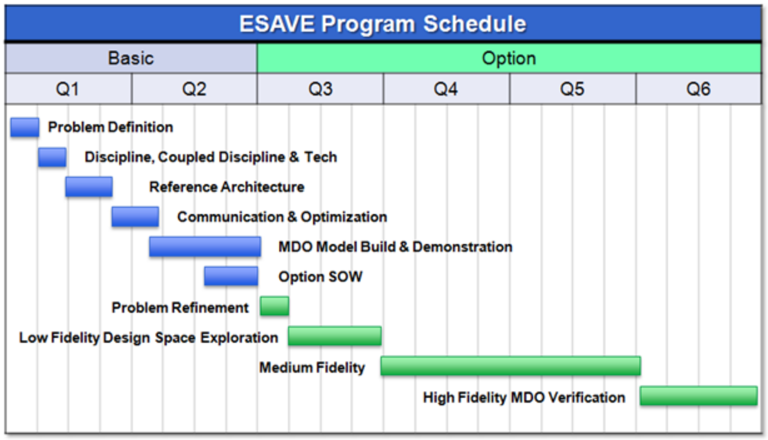


Figure 1. ESAVE Program Schedule

The MDO based conceptual aircraft design process developed under ESAVE consists of low fidelity, medium fidelity, and hi fidelity phases. This paper presents the problem definition and an overview of the low fidelity process as well as results obtained to date. The ESAVE MDO model integrates additional disciplines and higher fidelity analyses early in the design process to capture coupled discipline interactions and accurately model the impacts of new technologies while exploring the fighter/strike design space. As the design space matures fidelity is increased to capture higher order/nonlinear effects. This approach will allow expansion of the fighter/strike design space to incorporate new and innovative configurations enabled by the full integration of new technologies into the aircraft design/optimization process.

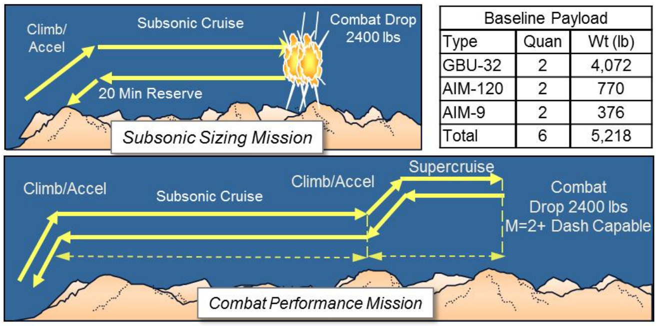
A conventional aircraft design process utilizes low fidelity analyses supported by empirical data to establish a baseline vehicle design for technology studies. Technologies are then typically applied by using "K" factors on various attributes or performance parameters to attempt to determine the sensitivity of the baseline design to a specific technologies. For example, a more efficient engine technology will be simply modeled as a "K" factor adjustment on fuel flow, or a new structural technology will be represented as a "K" factor on a structural weight predicted from historical data. This approach necessarily evaluates the non-integrated impact of new technologies on a conventional aircraft design without taking into account how the technology performance varies with other design parameters or technology combinations.

The MDO framework being developed during the ESAVE program takes a different approach. By combining commonly used parametric design processes with MDO techniques, ESAVE will explore the fighter/strike design space and develop unique sensitivities and designs for each combination of technologies under consideration. To eliminate simple "K" factors, ESAVE will pull forward higher fidelity analysis methods which capture the physics of new technologies, enabling a more accurate assessment of their impact throughout the flight envelope. In other words the MDO approach will allow each aircraft configuration in the trade space to be optimized for its combination of technologies and constraints, resulting in a true understanding of the design impacts of technologies.

II. ESAVE Problem Definition

Foundational to the Basic phase for ESAVE was understanding and defining the fighter/strike problem to be addressed by the MDO process. As of this writing there are no official Air Force requirements for the future fighter projects to use as performance goals. Working with AFRL, we agreed to leverage requirements from other AFRL next generation fighter studies in Figure 2 as a basis for defining objectives for ESAVE.

It was also important to develop a geometric baseline for the ESAVE aircraft concept to support parametric studies. Modern fighter designs like F-22 and F-35 are typically highly integrated and not very amenable to wide-ranging geometric excursions desired for ESAVE. To make the problem tractable, we have chosen a modular layout for the ESAVE fuselage arrangement as shown in Figure 3 which enables wide variations in aero surface arrangements in the core geometric model without disrupting the basic fuselage layout.



Baseline Payload		
Type	Quan	Wt (lb)
GBU-32	2	4,072
AIM-120	2	770
AIM-9	2	376
Total	6	5,218

Figure 2. ESAVE Sizing Missions and Payload

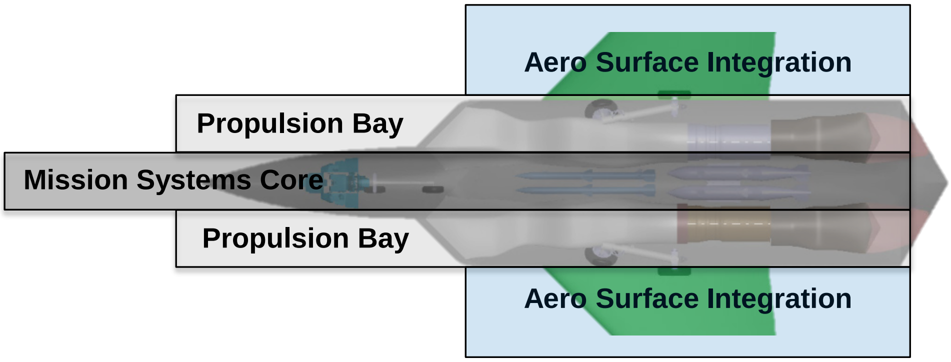


Figure 3. Modular Approach Enables Flexible Aero Surface Positioning Across Design Space

Another essential element of the problem definition was to choose which configuration classes to analyze in ESAVE. The Advanced Tactical Fighter competition, which led to the F-22, demonstrated the great diversity in possible configurations (1 tail, 2 tail, 4 tail, trapezoidal wing, diamond wing, etc.) considered for modern fighter design. For the ESAVE program AFRL has chosen to address the challenge of tailless fighter design featuring a 2 panel trapezoidal wing. While the number and range of the design variables for the planform is discussed later in section III, Figure 4 represents the "center point" or "baseline" configuration for the ESAVE low fidelity design exploration. The configuration shown displays the modular fuselage approach with the wing design at the midpoint of all the design variables.

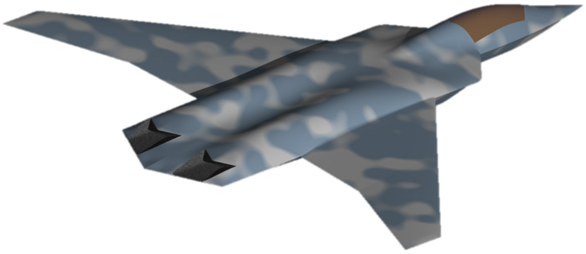


Figure 4. ESAVE Low Fidelity Centerpoint Configuration

III. Trade Study Approach

The ESAVE trade space encompasses different technology suites and performance requirements applied to a tailless strike/fighter configuration. A configuration's technology suite refers to the set of individual technologies (Table 1) whose impacts are analyzed and accounted for during the MDO process. Its performance requirements describe the vehicle's capabilities in the context of fighter/strike missions (Table 2).

Each unique combination of technology suite and performance yields a distinct ESAVE configuration. The configurations are generally optimized to maximize the radius of a subsonic, base-to-base mission (Figure 2), although supersonic mission radius and gross takeoff weight (GTOW) are alternative objective functions. The parameters adjusted to do so include both global and local design variables (Table 3). There were 12 global design variables, which are inputs to the multidisciplinary analysis described in Section IV, optimized to size each configuration. Seven of these define an aft-swept, 2-panel wing and 5 define the engine scale and cycle "Panel Break" and "Wing Break" define the spanwise and chordwise location, respectively, of the break in the trailing edge between wing panels. The "Engine Design Variable"(s) refer to GE proprietary cycle parameters exposed for the optimization. Finally, the local design variables are iterated offline within the indicated disciplinary analysis.

Table 1. ESAVE Technologies

Discipline	***Technologies***
Configuration	Compact Weapons
	Compact Launchers
Aerodynamics	Subsonic Laminar Flow
	Supersonic Laminar Flow
Propulsion	Variable Cycle Engine
	Advanced High Speed Inlet
Structures	Active Aeroelastic Wing
	Active Flutter Suppression
S & C	ICE Effectors (SSD)

Table 2. Performance Requirements (MDO Constraints)

Enforced Within Analysis	Payload	Per Figure 2
	Load Factor (max. g's)	9
	Static Margin	5% Unstable
	SupercruiseCruise Mach	1.6+
Enforced by Sizing Optimization	Max (Dash) Mach	2.0+
	Spec. Excess Power (SEP)	5th Gen. class
	Supersonic Radius	NGTA Mission

Table 3. ESAVE MDO Design Variables

Global Design Variables			Local DV's (Discipline)
DV's		Bounds	
Wing DV's	LE Sweep	35 – 55 deg.	Wing Thickness Distribution (Aero)
	Aspect Ratio	3 – 5	
	Taper Ratio	0.15 – 0.25	Wing Camber Distribution
	Panel Break (% Exposed Span)	30 – 50%	Inlet Capture Area (Propulsion)
	Wing Break	0.0 – 0.6	Control Surface Sizes (S&C)
	Wing T/C	0.02 – 0.04	Structural Topology (Structures)
	Wing Reference Area	800-1200 sq. ft.	
Engine DV's	Engine Scale	0.7 – 0.9	
	Engine Design Variable #1	0-1	
	Engine Design Variable #2	0-1	
	Engine Design Variable #3	0-1	
	Engine Design Variable #4	0-1	

IV. Analysis Approach

An essential requirement of the ESAVE program is to capture coupled physics early in the design process. While complex military aircraft are host to many different interacting disciplines, an early task in the program was to identify specific high value coupled interactions the ESAVE MDO process would capture within scope. Given the well understood importance of empty weight and propulsion technology in fighter performance, LM chose to focus on the disciplines and fidelities necessary to capture the impact of active aeroelastic structures and variable cycle engine technologies (shown in Figure 5) which show high potential as enablers to meet the demanding missions chosen by AFRL. This paper will discuss the analysis approach used to model these MDO sub-problems and the trade study approach used to explore the design space opened up by the MDO-based design process.

The ESAVE analysis framework incorporates Response Surface Models (RSM's) to capture high-fidelity analysis results within an automated optimization process and provide smooth functions conducive to optimization. The low-fidelity ESAVE framework includes two RSM's. One is a set of neural networks to predict installed engine

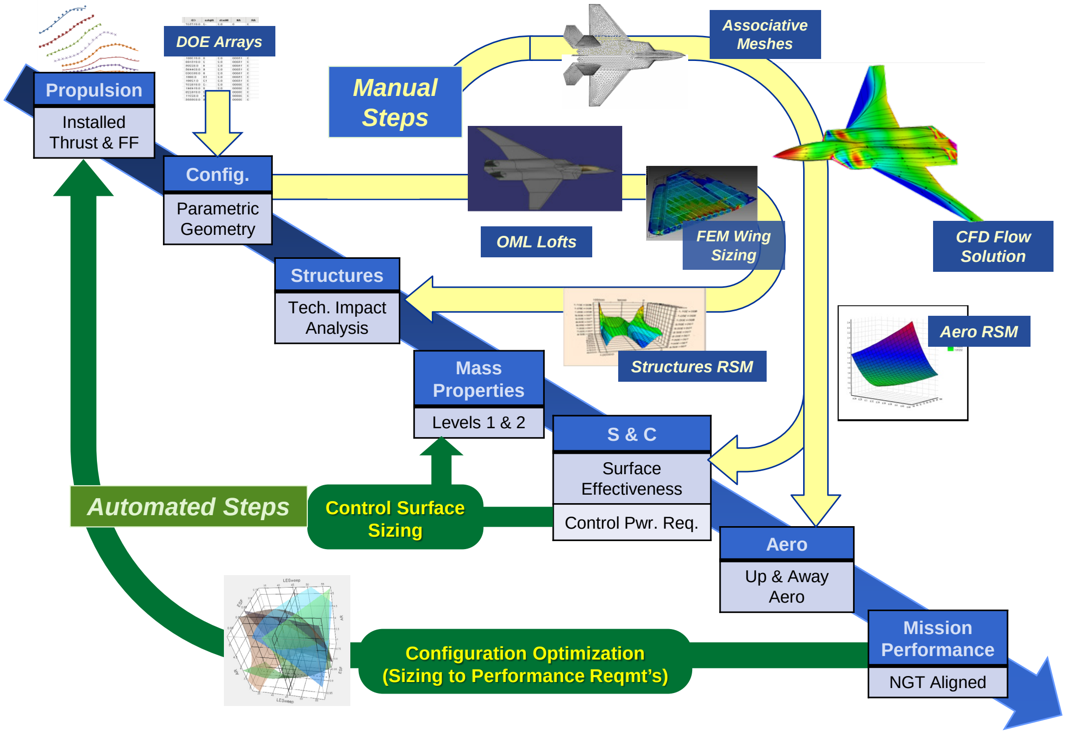


Figure 5. ESAVE MDO Process Development Focuses on Aeroelastic and Propulsion Technologies

thrust & fuel flow as a function of 4 engine cycle design variables; the other relies on polynomial approximations to predict wing weight based on planform, t/c and structural technologies. The medium-fidelity framework will include an additional set of neural networks to predict inviscid aerodynamic force and moment coefficients as functions of wing planform and flight condition.

RSM's are the key conduit by which multidisciplinary interaction effects are accounted for during trade studies (Figure 6). Of critical importance is the Structures RSM, built from results of the FEM-based wing optimization process (described in Section IV-A). Unique control power requirements and aerodynamic loads are computed specifically for each design Design of Experiments (DOE) array. Furthermore, technology impacts are analyzed by relaxing or removing constraints on the structural sizing process. Therefore, the structural weights predicted by this RSM account for the interaction between aerodynamics, structures, and controls – a key goal of the ESAVE framework.

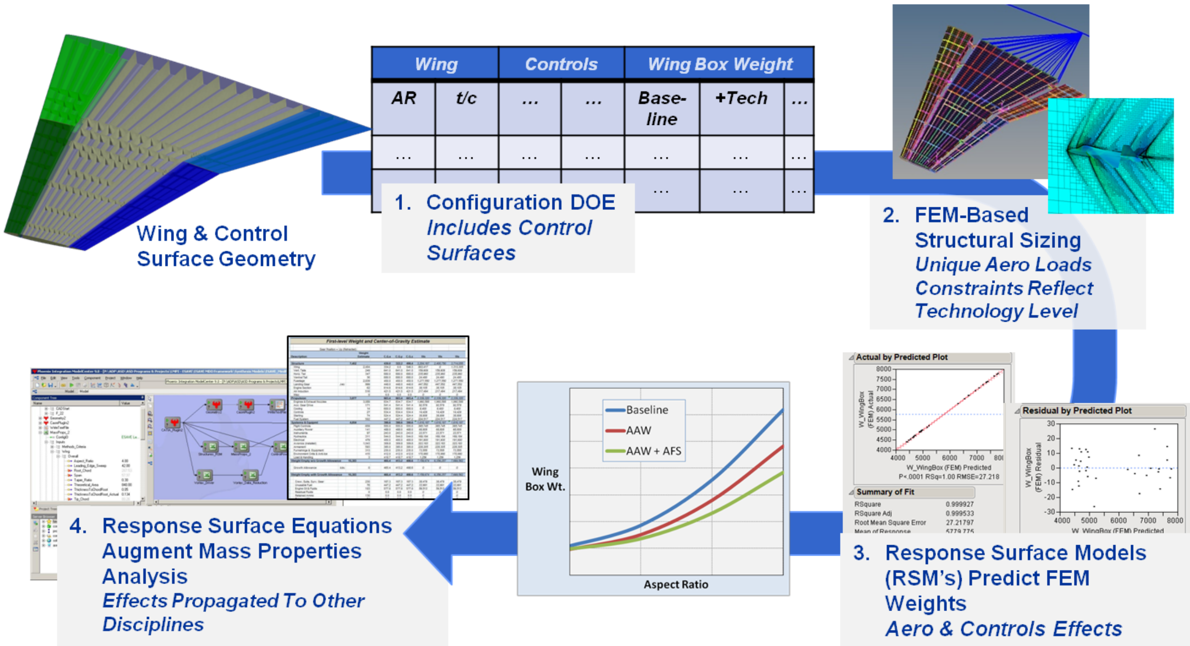


Figure 6. Structures RSM Generation

A. Aero/Structures/Controls Analysis

Future aircraft configurations employing advanced technologies such as Active Aeroelastic Wing (AAW) and Active Flutter Suppression (AFS), exceed the bounds of historical mass properties databases, requiring a physics-based analysis approach to provide realistic airframe weight sensitivities with respect to design variables. Finite Element Model (FEM) based weights provide a means of filling the gap between unprecedented aircraft configurations and historical databases. Though they do not provide a complete prediction of airframe weight, since details such as fasteners, sealants, and adhesives are often omitted, they can provide valuable sensitivity information in terms of quantifying the impact of configuration changes and technology selection on airframe weight. In ESAVE, our approach to enabling physics-based, structural weight sensitivities during conceptual design is to augment traditional weight estimation methods that are calibrated to the F-22 with response surface equations derived from FEM-based analyses. These equations capture the effect of planform changes and model the effect of advanced aeroservoelastic technologies. This section will discuss two key aspects of this approach, model generation and physics based assessments of the technologies used as the basis for the response surfaces, as well as present some results obtained to date.

1. Model Generation Process

To meet the challenging modeling requirements of exercising high-fidelity methods during the conceptual stage of vehicle design, LM Aero has developed a process that leverages streamlined model generation in concert with grid morphing to rapidly construct the required FEMs to populate a DOE array. The process, illustrated in Figure 7,

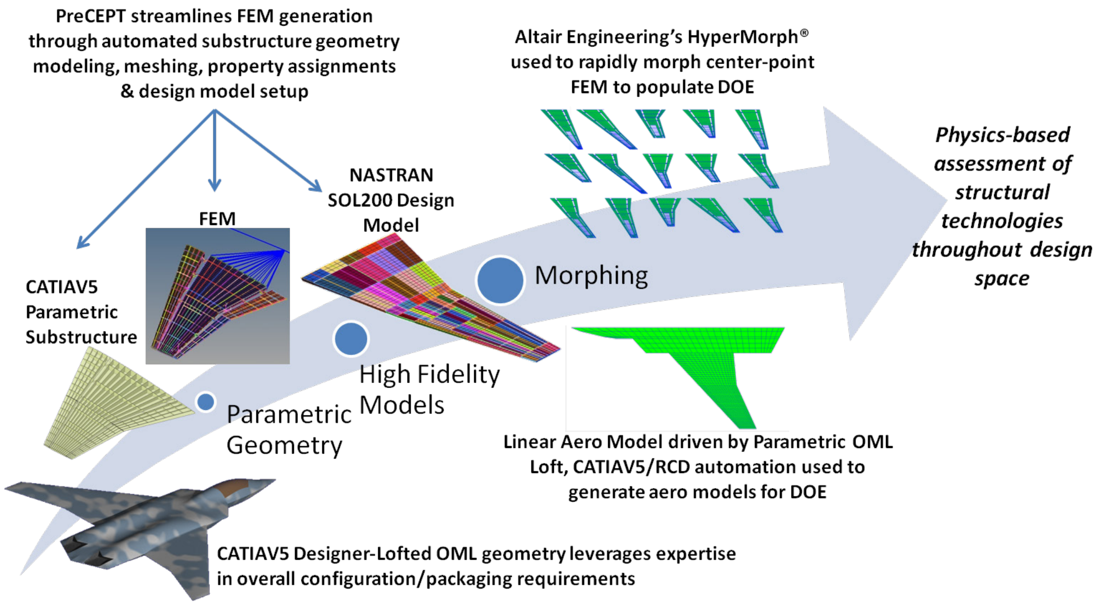


Figure 7. ESAVE Low Fidelity Structural Model Generation Process enables Physics-Based Structural Technology Assessment during Conceptual Design

begins with geometry defined within CATIAV5. An in-house developed tool, PreCEPT[1], is used to rapidly generate substructure geometry suitable for finite element modeling within CATIAV5. PreCEPT implements a smart product modeling approach that allows the analyst to construct a parametric model from a palette of pre-defined components. It utilizes an API provided by CATIA V5 to rapidly build parametric, associative geometry. A scripting capability is also supported, enabling knowledge capture and facilitating structural trade studies. PreCEPT also leverages integration with Altair Engineering's HyperMesh to reduce the time required for meshing, and material, property, and boundary condition assignments, as well as the development of loads and structural optimization design models needed for structural sizing.

With a completed FEM, Altair Engineering's HyperMorph is used to rapidly modify the initial FEM to capture planform changes represented by the members of the DOE. CATIA V5/Modelcenter integration is used to modify the CATIAV5 model and generate inputs needed by the morphing process. A custom LM Aero tool within CATIAV5 is driven by the same process to generate linear aero models for each member of the DOE. The morphing process keeps the topology of the FEM and linear aero models intact, enabling the reuse of the splines between these models for all configurations generated by the morphing process. Figure 8 contains a composite image of the resulting 34 FEMs in the DOE.

2. Aeroservoelastic Technologies Assessment

To capture realistic weight trends, the DOE of 34 FEMs are sized using MSC.Nastran SOL200 to strength and aeroelastic criteria selected from fighter aircraft historical data. Table 4 contains the list of load cases used, with a description of the maneuver, Mach number where the maneuver is performed, and the criteria for which the load case was selected. Some duplication appears in this

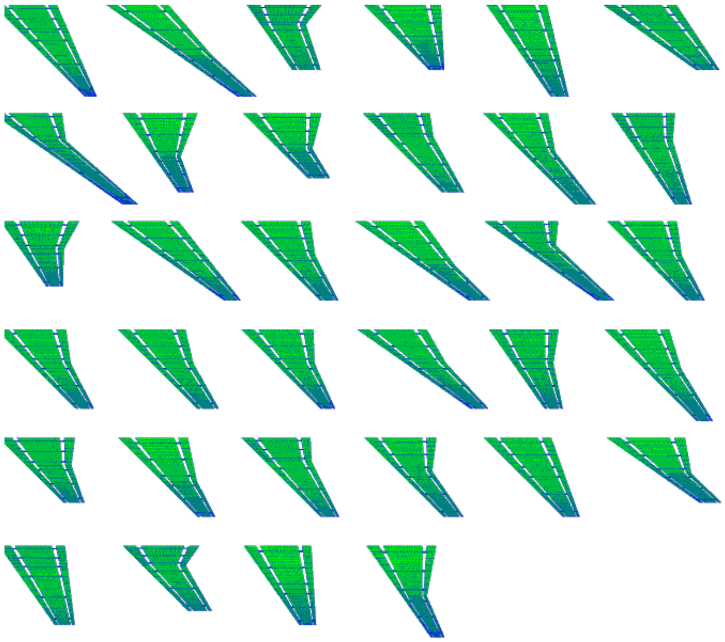


Figure 8. DOE of Wing Configurations used for Advanced Technology Assessments

Table 4. Load Cases Used in Structural Sizing Process

LC	Description	Mach	Criteria
1	-3G Symmetric Push Over	1.5	Min Bending, Min Shear
2	9G Symmetric Pull Up	0.95	Max Bending, Max Shear
3	9G Symmetric Pull Up	0.8	Max Torsion, Max Shear
4	Max Roll Rate	0.9	Min Torsion
5	Max Roll Rate	0.95	Max Torsion
6	Max Roll Rate	1.1	Max Torsion
7	Steady Roll Rate	2+	Static Aeroelastic Roll Effectiveness
8	Steady Roll Rate	0.9	Static Aeroelastic Roll Effectiveness
9	Steady Roll Rate	0.6	Static Aeroelastic Roll Effectiveness
10	Flutter	0.9,1.1,1.2	Flutter Margin

table, since the maximum or minimum for a particular criteria may occur at a different condition as the configuration changes. Each load case is introduced as an aeroelastic analysis (SOL144) within MSC.Nastran SOL200 in order to capture flexible effects on the final trim state and resulting loads on the vehicle. Composites structures are assumed. Stress and strain allowables, as well as minimum gauge constraints, are also applied during the sizing process.

The impact of technologies is assessed by removing load cases to effective relax the criteria used to size the vehicle, with the assumption that the technology being assessed will compensate for the relaxed constraint. Two main technologies being assessed under the ESAVE effort are AAW and AFS. AAW has the potential to reduce wing weight by using the control surfaces to deform the wing such that the net lift of the wing contributes to the required maneuver, rather than solely relying on the control surfaces as the effector[2]. AAW is modeled by removing the wing stiffness requirement for the high speed roll cases and optimizing the control surface schedule to minimize wing root bending while satisfying the required trim state. AFS uses control surfaces deflections to counter the flutter mechanism, thereby saving weight by relaxing the stiffness requirement to passively stabilize the flutter mechanism. AFS is modeled by removing the flutter constraint during optimization. The subset of the load cases used to model each technology and combinations thereof is shown in Table 5. Each FEM in the DOE is sized by four different structural optimizations to represent a baseline design, an AFS only design, an AAW only design, and finally an AFS + AAW design. The FEM weight for each design is multiplied by a calibration coefficient to account for non-modeled weight and the resulting weights are then used to develop a response surface equation for each technology being assessed.

3. Results

The DOE array used to construct the ESAVE structures RSM contained 34 designs, including the center point and 12 axial points or "face centers" characterized by one DV at its upper or lower bound while all others were centered. The remaining designs were located along the edges or at the corners of the 6-dimensional hypercube

Table 5. Advanced Structural Technologies Modeled by Relaxing Load Cases

Strength Criteria (Symmetric)			Strength Criteria (Asymmetric)			Static Aeroelastic Criteria			Flutter	Tech Assessment
LC1	LC2	LC3	LC4	LC5	LC6	LC7	LC8	LC9	LC10	
x	x	x	x	x	x	x	x	x	x	Baseline (No Advanced Technology)
x	x	x	x	x	x	x	x	x		Active Flutter Suppression
x	x	x	x	x	x					Active Aeroelastic Wing + Active Flutter Suppression
x	x	x	x	x	x				x	Active Aeroelastic Wing

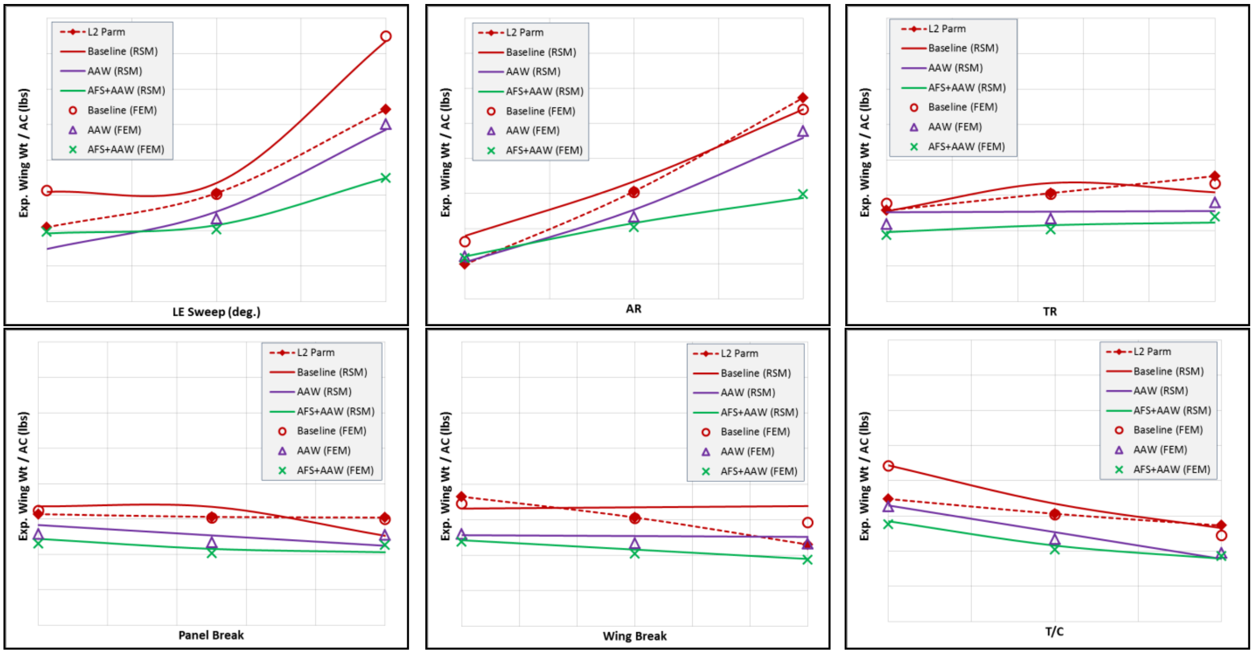


Figure 9. FEM-Based RSM Exposed Wing Weight Predictions

corresponding to the 6 wing DV's. Stepwise regression was used to fit 2nd order polynomial approximations to the exposed wing weight predicted by the FEM-based structural sizing process. The resultant RSM predicted 3 unique values of exposed wing weight (Figure 9): a "baseline" that assumed no aero/structural technologies, a 2nd reflecting the use of Active Aeroelastic Wing (AAW), and a 3rd reflecting the use of AAW and Active Flutter Suppression (AFS+AAW) together.

The baseline FEM-based RSM generally aligned with the weight trends predicted by LM parametric methods. Based on investigation of the FEM results, highly swept wings subjected to the high load factors associated with strike/fighter vechicles are sized by torsion, so roll constraints become the critical drivers of structural sizing. Lower-swept wings, conversely, are sized by their root bending moment. Consequently, while the average exposed wing weight among 35°-sweep and 45°-sweep configurations was nearly equal, several 55°-sweep configurations exhibited markedly higher wing weights (Figure 10). A more important result, and a central component of the ESAVE framework, is that the response surfaces quantify the weight reduction possible using AFS and AAW

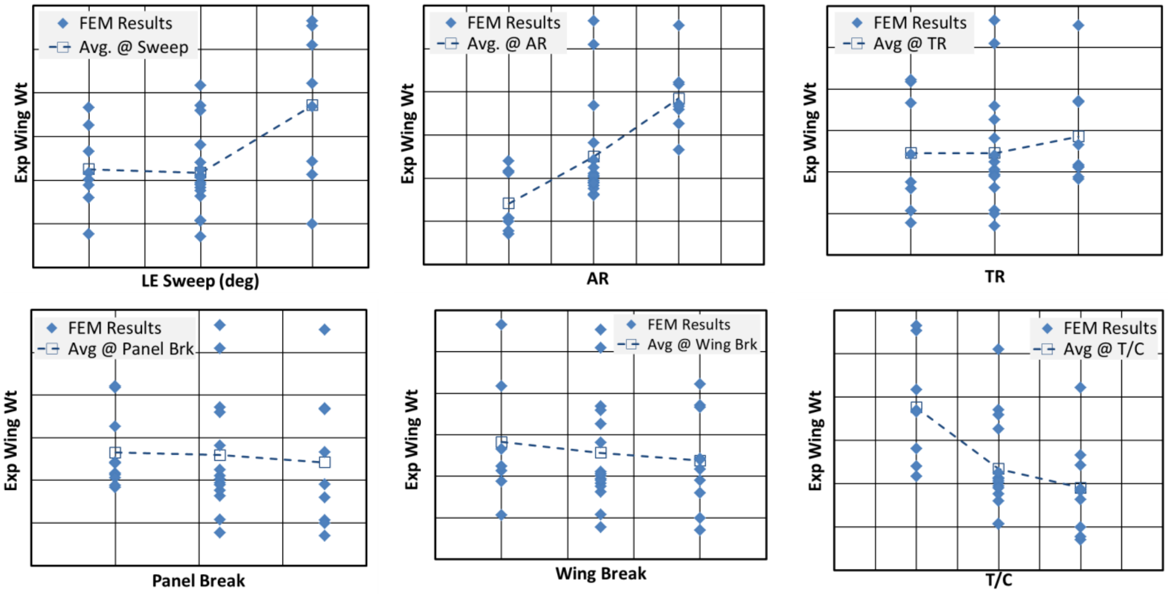


Figure 10. Structures DOE Baseline FEM Results

technologies as a function of the wing planform (Figure 9).

The aero-structural-controls sub-problem supports the MDO conceptual design process throughout all three fidelity levels of the process developed under ESAVE. During the low fidelity phase, MSC.Nastran linear aerodynamics are used to compute aeroelastic solutions to capture the sensitivities of advanced technologies on airframe weight to global design variables such as planform aspect and taper ratio. During the medium fidelity phase, Euler CFD loads will be introduced to the sizing process to inject additional fidelity into the sizing process. Finally, for the highest fidelity phase, a full-vehicle FEM with more load cases and better representation of carry-thru structures will be constructed to verify weight and technology benefits predicted in the Medium fidelity phase.

B. Propulsion Integration Analysis

Propulsion integration has been a key multi-disciplinary challenge for fighter/strike aircraft since their inception. Complexity has continually increased as survivability requirements demand increasingly tight integration of the propulsion system with aerodynamics, stability & control, and mission systems. With the emergence of variable cycle engine (VCE) technology, the conceptual design process must look beyond evaluating engine size and bypass ratio as major propulsion design parameters. The variable cycle technology introduces new engine cycle parameters (which vary by vendor) that must be evaluated in an integrated fashion across the mission spectrum to determine the optimum engine cycle for next generation fighter /strike aircraft. In addition the future fighter/strike design space will include higher Mach numbers than F-22, which will open the inlet design space to include advanced high speed inlets. The variable mass flow capabilities of VCE technology will enable inlet mass flow matching, cooling, and nozzle vectoring technologies which will require an integrated MDO approach to evaluate the vehicle level performance and S&C trades.

The MDO approach taken for ESAVE leverages variable cycle engine data and expertise provided by GE Aviation. To enable integration of 4 critical VCE design variables into the design space, GE provided a DOE of 25 installed engine decks to characterize their performance impacts. Response Surface Models predict thrust and fuel flow based on those VCE design variables, allowing optimizers to seamlessly traverse the design space. Several combinations of polynomial and neural network approximations were investigated. A set of neural networks, each tailored to a portion of the flight envelope, provided an excellent fit (Figure 11) to the engine performance data.

Another essential performance aspect of the propulsion integration for current and future aircraft is power and thermal management. Current fighters require increasing amounts of subsystem power and cooling while the application of composites and survivability constraints limit conventional means of dispersing heat. In addition the advent of directed energy weapons will potentially require an order-of-magnitude increase in power and cooling for operation. While detailed subsystem modeling is currently beyond the scope of the ESAVE effort, our goal is to include first order evaluation of the potential propulsion integration impacts of emerging power and thermal management systems for future fighter/strike aircraft.

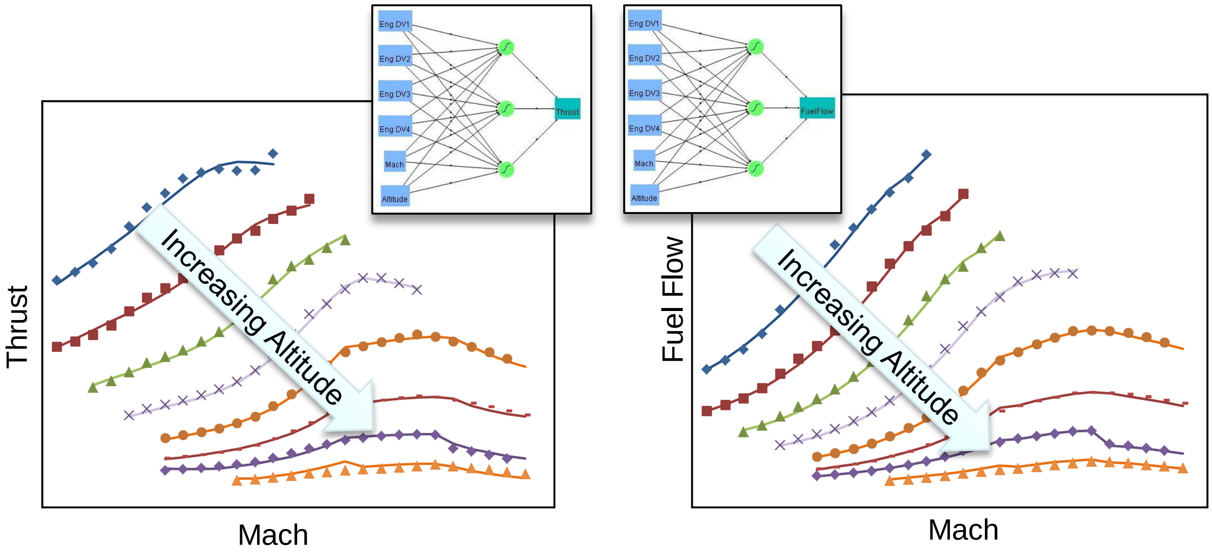


Figure 9 - Neural Network RSM of GE DOE provides an accurate and well behaved model of VCE design space.

V. Initial Results and Trade Study Plans

Optimization studies using the ESAVE integrated multidisciplinary analysis model are underway and were ongoing at the time of publication. Initial runs focused exclusively on the propulsion-related design variables and demonstrated that the ability to optimize the engine cycle "in the loop" yields improved performance compared to adjusting engine scale alone. Subsequent runs entailed 11 of the 12 ESAVE global DV's to optimize mission performance. Wing area was not active during optimization studies to date because the baseline configuration's wing loading is reasonable for fighter/strike aircraft. Whereas the FEM-based structures RSM was in work at the time of publication, these studies relied on parametric weights. The results are summarized in Table 6, which contains information on 5 configurations (letters refer to column headings):

A. Baseline ("as-drawn") configuration: all design variables at midpoints
B. Engine Scale adjusted to meet Specific Excess Power (SEP) constraints
C. Engine cycle & scale optimized to maximize subsonic radius, subject to SEP constraints
D. Engine & Wing (planform & t/c) optimized to maximize *subsonic* radius (constraints on SEP's, supersonic radius, and Dash Mach))
E. Engine & Wing (planform & t/c) optimized to maximize *supersonic* radius (constraints on SEP's, subsonic radius, and Dash Mach))

The numbers in **bold** in Table 6 indicate the elements of the MDO problem formulation (objective function, constraints, and design variables) that were active in the generation of each configuration. Specifically, only engine scale factor (ESF) was adjusted to yield configuration "B"; engine scale plus the 4 engine cycle DV's were optimized to generate configuration C; and all 11 global design variables were active in optimizing the performance of configurations D & E. The remaining (gray) values in the table reflect design variables that were held constant and constraints that were not enforced ("fallout" performance) during the corresponding run.

The benefits of engine cycle optimization are evident through comparison of columns B & C inTable 6. These configurations reflect changes to the baseline to meet 5 constraints on Specific Excess Power (SEP1 – SEP5), each of which corresponded to a critical point in the flight envelope (all have been normalized to 100 in this paper). The

Table 6. ESAVE Preliminary Optimization Results

		A (Baseline)	B (Engine Scale only)	C (Engine Cycle Opt.)	D (Subsonic Perf.)	E (Supersonic Perf.)
Objectives & Constraints (normalized; all constraint lower bounds = 100)	Subsonic Radius*	100	**92.9**	**103.3**	**107.0**	**99.5**
	Supersonic Radius*	100	95.8	101.2	**102.1**	**103.6**
	SEP1**	97.2	**108.8**	**109.0**	**112.5**	**109.1**
	SEP2**	97.8	**109.5**	**108.0**	**114.9**	**109.8**
	SEP3**	98.3	**126.5**	**125.4**	**123.3**	**125.2**
	SEP4**	73.8	**100.2**	**100.0**	**99.78**	**99.9**
	SEP5**	90.2	**104.1**	**100.4**	**114.2**	**105.7**
	Max. Mach w/ AB (2+) **	104.0	104.0	104.0	**104.0**	**104.0**
Design Variables	Engine Scale Factor (ESF)	0.8	**.905**	**0.846**	**0.854**	**0.839**
	Engine DV #1	0.5	0.5	**1.0**	**1.0**	**0.62**
	Engine DV #2	0.5	0.5	**0.0**	**0.0**	**1.0**
	Engine DV #3	0.5	0.5	**0.785**	**0.635**	**0.59**
	Engine DV #4	0.5	0.5	**0.0**	**0.0**	**0.0**
	LE Sweep (deg.)	45	45	45	**35**	**43.0**
	AR	4	4	4	**5**	**3.0**
	TR	0.2	0.2	0.2	**0.15**	**.15**
	Panel Break	42.5%	42.5%	42.5%	**0.3**	**0.309**
	Wing Break	0.3	0.3	0.3	**0.60**	**0.60**
	Wing T/C	0.03	0.03	0.03	**0.04**	**0.04**
	Wing Sref (ft^2)	800	800	800	800	800
	GTOW*	100.0	101.9	100.03	99.03	96.42

* Normalized such that Baseline performance = 100
** Normalized such that constraint lower bound = 100

baseline configuration did not meet any of these 5 constraints. Simply increasing engine scale to remedy this problem (column B) results in a heavier engine and less efficient cruise; performance consequences were a 1.9% increase in GTOW, 7.1% decrease in subsonic range, and 4.2% decrease in supersonic radius compared to the baseline. Conversely, by optimizing the 4 engine cycle parameters in addition to ESF, it was possible to not only meet the SEP constraints but also improve subsonic radius by 3.1% over the baseline (column C).

Additional cases optimized the engine and wing concurrently to tailor the ESAVE concept to different missions. The first (column D) aimed to maximize the radius of a subsonic, ground-to-ground roundtrip mission using a fixed amount of fuel and subject to the same 5 SEP constraints used during engine cycle optimization. Additional constraints ensured that the supersonic radius was no worse than the “as-drawn” (baseline) vehicle and that a Dash Mach (normalized to 100 in this paper) could be attained. The resultant configuration achieved a 6.9% increase in subsonic radius compared to the baseline by using a high-aspect ratio, low-sweep wing for efficient cruise and by adjusting the remaining wing DV’s to reduce wing weight (the combined effect of moving Taper Ratio, Panel Break, and Wing Break to their respective bounds was to shift more wing area and lift inboard, thereby reducing root bending moment and structural weight). This also yielded 2.1% increase in supersonic radius.

The last configuration (column E) was optimized to maximize supersonic radius (again based on a fixed fuel weight) while constrained to ensure that subsonic radius did not fall below its baseline value (reversing the roles of the 2 radii from the previous case). It did so by increasing wing sweep and reducing aspect ratio, achieving a 3.6% increase in supersonic radius compared to the baseline while slightly violating the subsonic radius constraint. As was the case in every run, the engine was sized by the fourth Specific Excess Power constraint (SEP4), which corresponds to a supersonic flight condition. The higher wing sweep and reduced aspect ratio of this configuration reduced supersonic drag and wing weight, respectively, enabling that constraint to be met at a reduced engine scale.

Future ESAVE optimization and trade studies will continue to refine the MDO problem formulation to establish the trade-offs between subsonic and supersonic performance. More importantly, completion of the structures RSM will incorporate higher-fidelity wing weights into the process. Finally, vehicle-level technology impact assessments will be performed by re-optimizing the vehicle while accounting for the technologies in Table 1.

Conclusion

This paper has discussed the progress of the ESAVE implementation of a MDO based design process for evaluating the design space of future fighter/strike concepts. This program has focused on bring forward higher fidelity analysis capability to address MDO subproblems in two promising technology areas for future fighters, aeroservoelasticity and variable cycle engines. A process for performing FEM based structural analysis for a DOE of wing designs to evaluate aeroelastic technologies and developing an RSM for use in the MDO model has been presented. In addition a method for incorporating variable cycle engine design parameters into the MDO process through RSM techniques has been discussed. Initial results of the application of higher fidelity MDO to a tailless fighter design problem indicate that both technologies can expand the design space for future fighter/strike concepts and potentially lead to new and innovative configurations. The completed ESAVE MDO framework will be used additional technologies at higher fidelity levels as the program progesses.

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