Aeroelastic Optimization of Wing Structure Using Curvilinear Spars and Ribs (SpaRibs) and SpaRibMorph

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Abstract

Conventional aircraft wing structures consist of skins over a network of substructure elements that are approximately straight and orthogonal (ribs and spars). New manufacturing techniques such as additive manufacturing, Electron Beam Free Form Fabrication, Friction Stir Welding, and other variants have dramatically changed the cost-complexity tradeoff, and have made it worthwhile to consider the case where the underlying structure is not made of straight, regular members. The introduction of curvilinear spars and ribs (SpaRibs) has the potential to significantly increase performance, especially where the possibility of a fine tailoring of stiffness axes is beneficial, such as buckling and aeroelasticity. This paper describes a set of tools and techniques for defining, modeling, analyzing, and optimizing aircraft structures with SpaRibs, and begins to investigate the resulting performance benefits.

Nomenclature

ATW2	=	Aero-structures Test Wing #2 (composite, straight ribs/spars)
ATW4	=	Aero-structures Test Wing #4 (aluminum)
ATW4a	=	Baseline model for the ATW4 (aluminum, straight ribs/spars)
ATW4b	=	SpaRib-Optimized model for the ATW4 (aluminum, SpaRibs)
EBF3	=	Electron Beam Free Form Fabrication
EBF3GLWingOpt	=	Software for generating SpaRibs
FSW	=	Friction Stir Welding
NASA	=	National Aeronautics and Space Administration
RapidFEM	=	Software for generating Aero-structural finite element models
SpaRib	=	Curvilinear Ribs and Spars
SpaRib-Morph	=	Software for generating SpaRibs
P_i	=	Penalty for Optimization
$V_{flutter}$	=	Flutter Speed
W_i	=	Weighting Factors for Optimization
M	=	Wing Mass
m_0	=	Baseline Wing Mass

I. Introduction

Classical structural design of aircraft wing boxes uses components such as straight spars, straight ribs, and quadrilateral wing skin panels with straight stiffeners. The components are typically connected by fastening or bonding, making the use of straight, or nearly straight internal structure a manufacturing requirement. A new design philosophy, using curvilinear stiffening members (SpaRibs and stiffeners), pioneered by Kapania and his group at Virginia Tech [1; 2; 3; 4; 5] , has been introduced based on emerging manufacturing technologies such as Electron Beam Free Form Fabrication (EBF3) [6] and Friction Stir Welding (FSW) [7] .

Using these innovative technologies, the wing structure is manufactured as an integrated part instead of using mechanically fastened or bonded structural components. Compared to the conventional straight spars and ribs, the

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curved SpaRibs have ability to offer tailored stiffness properties, such as coupling between bending and torsion. Also, the curvilinear stiffeners have shown potential in improving the buckling resistance of local panels [8; 9; 10]. The concept of curved stiffening members enlarges the design space and leads to the possibility of a more efficient aircraft design.

The goal of the following research is to demonstrate the advantage of using curvilinear spars and ribs (SpaRibs) for the structural design of aircraft wing structures. This investigation starts with the NASA ATW2 configuration, and optimizes the orientation, layout, and curvature of the internal structure. The NASA ATW2 is a composite configuration, previously flight tested on the underbelly of a test aircraft [11], was used as the basis for the wing structure. In the interest of demonstrating the feasibility of SpaRibs, specifically using an additive manufacturing technique such as 3D printing, two variants of the ATW4 have been established: 1) The ATW4a, which follows the structural layout of the ATW2, but is made from aluminum instead of composite, and 2) the ATW4b, which is also aluminum, but has an optimized internal structure of SpaRibs. All configurations (ATW2, ATW4a, ATW4b) have a boom mounted to the wing tip that is used to tailor the flutter behavior.

The topology of the wing structure is optimized using SpaRibs with considerations for strength, flutter, and the flight test envelope. An overview of the optimization process can be seen in Figure 1. The framework for the optimization is essentially a nested optimization process with two levels. The upper level optimizer controls the topology variables of the configuration. This includes the number of SpaRibs, their starting and ending points, and their shape. These variables determine the shape of the configuration and are used to generate a mesh. The lower level optimizer controls the structural sizing (e.g. thickness, composite ply angles) to satisfy stress, buckling, and flutter constraints.

The process for a single topology begins with the FEM generation step, which is a critical component. A baseline aero-structural model is perturbed using SpaRib-Morph to bend straight ribs and spars into curved ribs and spars (SpaRibs). Then a sizing optimization for minimum weight using quasi-static flight loads (typically including a 2.5g pullup and 1g pushover maneuver) is performed. Skin and SpaRib thicknesses are varied to meet the stress constraints. For the ATW4, this sizing optimization step is skipped as the model is sized for minimum gage.

Upon convergence of the stress/buckling iteration, a flutter analysis is performed to determine the flutter speed. The flutter analysis can optionally include aeroservoelastic control laws, and a further optimization to satisfy flutter constraints can be introduced at this step, although this is not a focus of the current results. In the context of an aircraft design, the objective function would typically be to minimize the weight, possibly with penalties associated with failing to satisfy some other design constraints. In our case, we are evaluating the aeroelastic benefit of the SpaRib technologies, so our objective is to optimize the topology such that we get the highest possible flutter speed, subject to being no heavier than a baseline configuration (with conventional rib/spar internal structure). In this case, we construct a composite objective function:

$$F = \frac{1}{V_{flutter}} + W_{mass} P_{mass}$$

$$P_{mass} = max(0, m - m_0)$$

Where F is the objective to minimize, W_i are the weighting factors, P_{mass} is the mass penalty, m is the wing mass, m_0 is the baseline wing mass, and $V_{flutter}$ is the flutter speed. The mass penalty ensures that designs with more mass than the baseline are penalized. It is assumed that the sizing optimization loop results in designs where the stress and buckling constraints are satisfied, and stress/buckling problems are reflected in a high structural weight.

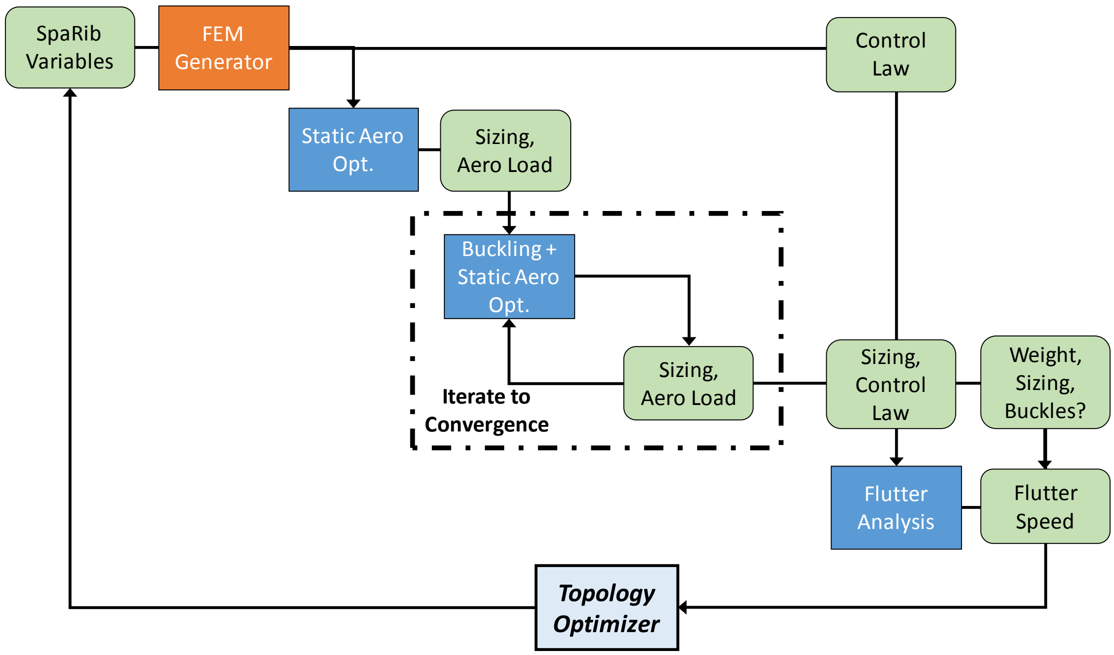

Figure 1: Optimization process overview

II. SpaRib Parameterization Methods

In order to address the different scenarios in which SpaRibs may be used in aircraft optimization, a family of modeling and optimization tools have been developed:

- EBF3GLWingOpt directly constructs the geometric surfaces representing SpaRibs, and meshes them in a commercial FEA preprocessing package, and has the associated advantages [2; 3; 12].
- SpaRib-Morph updates an existing finite element model by modifying the internal structure, making it useful in cases when small changes to an existing configuration are desired.
- SpaRib-ContourIntersector uses a set of generalized functions (e.g., spars are defined at the ¼ and ¾ line at key points, but may "dragged" at specific points) to create a RapidFEM sketch that can be meshed [13].
- RapidFEM is a toolset that constructs an aeroelastic model (e.g. flaps, hinge stiffness, aero panels) directly from outer mold line geometry and a 2D "sketch" describing the internal structure. The software is integrated into OpenVSP as a software plugin [14].

These different approaches provide a toolkit for optimizing SpaRib configurations in different environments and different constraints. Since the results models and results presented here were developed with the RapidFEM and SpaRib approaches, these will be discussed in some detail below.

RapidFEM [15] is a software program developed to automatically generate geometry and finite element models of complex built-up structures for rapid concept evaluation and structural optimization. In this process, top-level geometry in a simplified format is provided to the RapidFEM program along with information about the structural layout. The required geometric operations are then performed to divide the surface into numerous patches, each of which represents a single structural component, which are then used to mesh the geometry. This process has been used to develop the baseline ASE models for the ATW4a configuration as shown in Figure 2 and Figure 3.

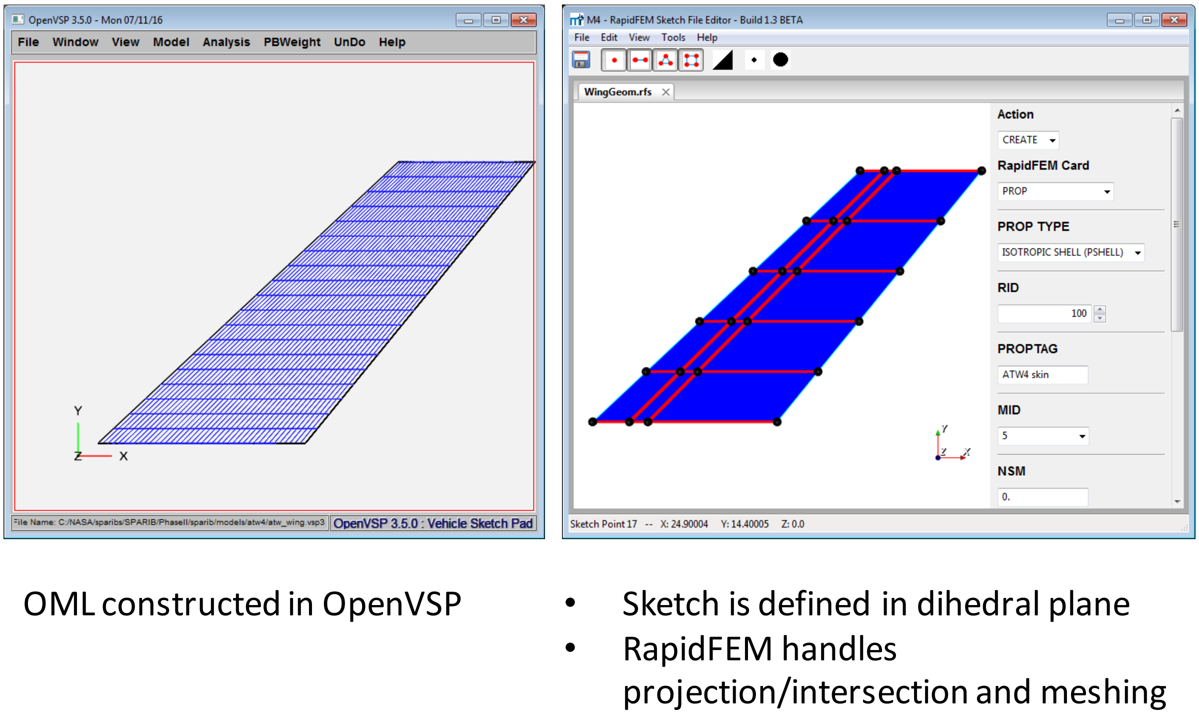

Figure 2: Outer Mold Line and 2D Sketch of the ATW4a configuration.

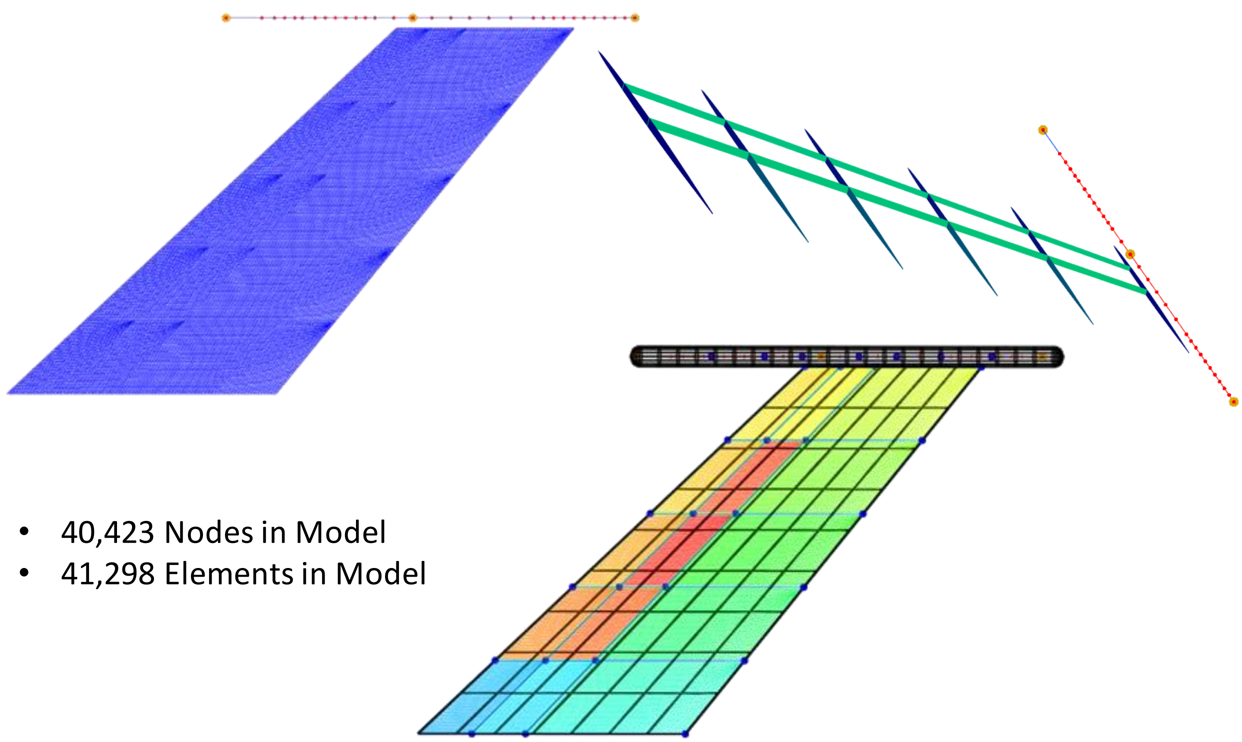

Figure 3: Resulting structural and aerodynamic models for ASE analysis.

In the context of this paper, RapidFEM has been applied to generate the ATW4 baseline configuration. The element size and baseline aero mesh were generated. This model was used as a starting point for the analysis and used for establishing a baseline flutter speed.

III. Baseline ATW4 Configuration

The demonstration problem for the SpaRib optimization process is a representative transonic configuration.

A. ATW2 Configuration

The NASA ATW2 configuration is a composite transonic wing that has flight test data and is used as a common point of comparison for the effects of various structural changes on the flutter speed. The ATW2 was flight tested on the underbelly of a test aircraft [11]. This configuration was selected as a starting point as it had severe flutter problems with a large room for improvement.

B. ATW4 Configuration

The ATW4 configuration was designed and has the same airfoil and planform as the ATW2 configuration. However, the ATW4 is made of aluminum instead of composites to enable 3D printing. 3D printing was desired in order to reduce cost and use a manufacturing process similar to EBF3/FSW, which would be used by SpaRibs for a full scale configuration. Note that foam core was used on ATW2 to aide in manufacturing. As it does not contribute significantly to stiffness and was no longer required for manufacturing, the foam core was removed for the ATW4.

As the wing is rigidly attached to a test aircraft, there is not a standard set of maneuver conditions for structural analysis. As such, bending and torsional unit load cases was defined in order to validate that there is no stress penalty to using SpaRibs.

C. Development of the ATW4 Model

The ATW2 was initially converted to use aluminum. As the initial model did not flutter and there were no static load cases defined, a weight minimization optimization processes was performed with an assumed 10° angle of attack static load case. A constraint on the stress margin was added to ensure that the margin was greater than or equal to the composite configuration. After optimization, it was found that the thickness of the ribs, spars, and skin were globally set to minimum gage.

The initial design of the ATW4 resulted in a flutter speed that was significantly higher than the ATW2's [11]. In order to more closely match the ATW2's flutter speed and behavior as closely as possible, the concentrated masses in the boom were tailored. This aluminum-based configuration with a tailored boom (shown in yellow in Figure 4) and is known as the ATW4a.

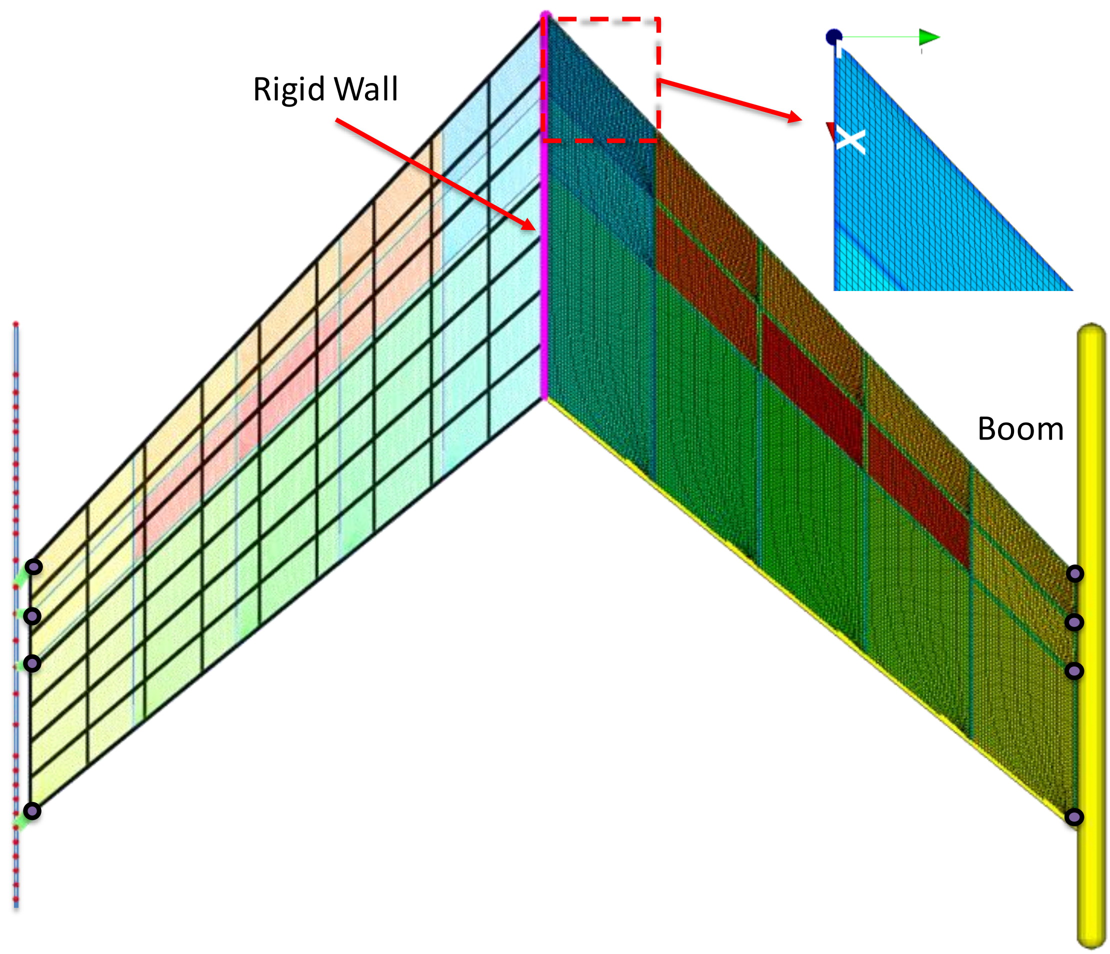

Figure 4: Baseline (ATW4a) fine mesh. Aero Mesh on Left Side, Structural Mesh on Right Side.

A fine model was required in order to retain adequate nodal density on the ribs and spars and quality on the SpaRib panels after morphing. The rigid wall is modeled as a constraint on all the boundary degrees of freedom as opposed to a single node representing the average motion as in the case of the coarse ATW4 mesh.

IV. Analysis of Baseline ATW4 Configuration

The ATW4 configuration was analyzed using the following process. This process verification step ensured that the results of the process does not introduce errors.

A. Null SpaRib-Morph

SpaRib-Morph design variables (to be discussed later) are defined in parametric coordinates relative to their nominal location. Thus, for a null morph, all design variables are 0.

B. Remeshing

When subjected to extreme morphs, SpaRib-Morph runs into multiple issues. In the worst case, SpaRib-Morph will create structure that intersects itself without creating additional joints. Additionally, element quality is degraded with highly tapered/skewed elements being a common problem. Both problems were addressed using Patran's MeshOnMesh capability, coupled with model checks and corrections based on PyNastran [16] and scripts for quality checks. In all cases, triangular shell elements were used for the structural model. A comparison was made to a model with quadrilateral shell elements (generally preferred for accuracy) and it was found that the triangle mesh model was sufficiently accurate for this study.

C. Flutter Analysis

During optimization, a Nastran flutter analysis [17] is performed. The flutter speed is programmatically extracted (see Figure 5) and returned as the objective function (to be maximized) in the SpaRib optimization process.

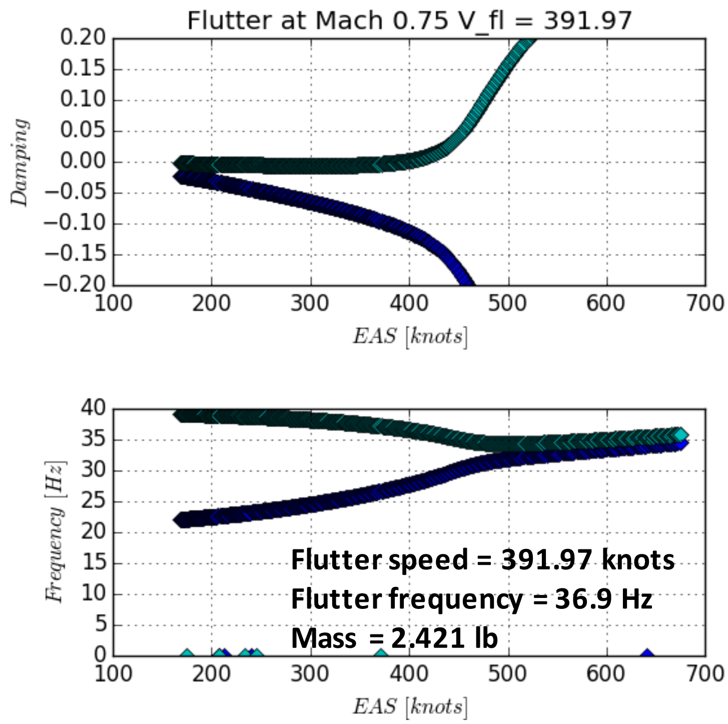

Figure 5: Flutter Speed for Baseline (ATW4a) Wing. First Bending and First Torsional Modes are shown.

V. Optimized ATW4 Configuration

The demonstration problem for the SpaRib optimization process is a representative transonic configuration.

A. Selection of Optimizer

Previous attempts [13] at optimizing a SpaRib configuration have shown that large changes to the internal structure are likely necessary to improve flutter performance. A genetic algorithm was chosen to allow exploration of a large design space and be fault tolerant without when impossible designs are considered. The Python module DEAP [18] was used in this optimization process.

B. Generating SpaRibs Using SpaRib-Morph

SpaRib-Morph [19], a tool developed by M4 Engineering, for the analysis of SpaRib-like structures is very capable in making smooth changes the internal structure. A thin plate spline is used to smoothly drag the neighboring nodes and create curved ribs and spars from straight ribs and spars. As such, the structure remains continuous and no elements are introduced or removed. The boundaries may be also fixed or converted into parametric coordinates to allow for slider boundaries.

For the ATW4b optimization, 28 design variables, 2 at each internal node (16 total) and 1 at each free node (12 total). The design variables are shown in Figure 6. Nodes are free to move in the spanwise and chordwise directions if they are an internal node, but are only allowed to slide in either spanwise or chordwise directions if they are a boundary node.

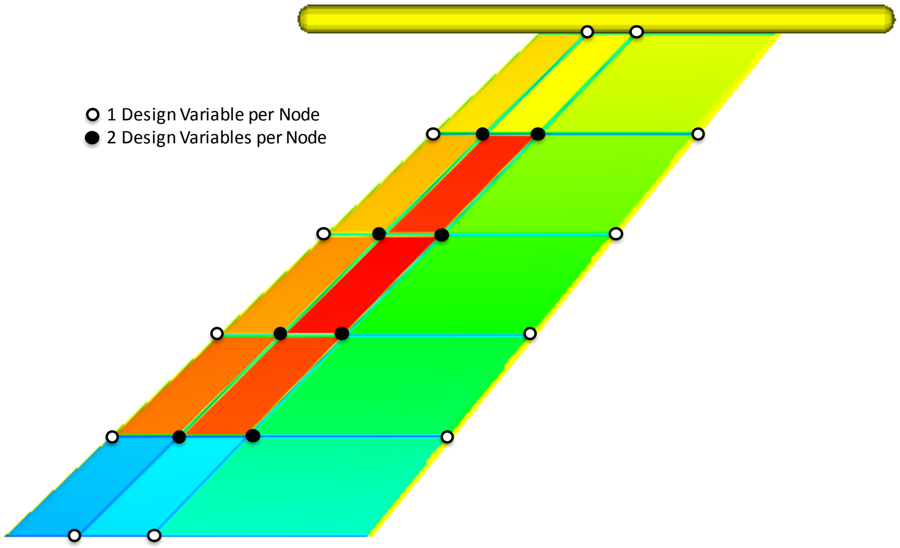

Figure 6: 28 design variables are placed at critical locations along the wing.

C. SpaRib Optimization

The optimization history for the ATW4 is shown below in Figure 7. Note that two different meshes were used to speed up the analysis.

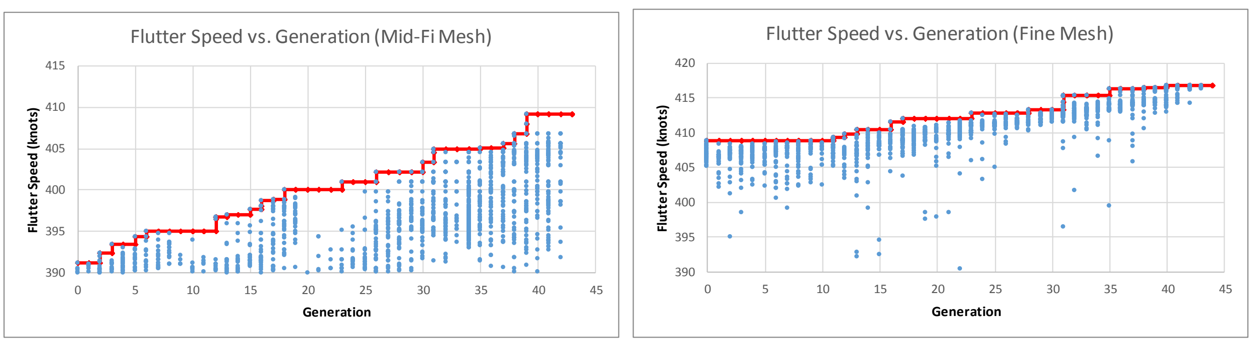

Figure 7: Optimization history for ATW4 using SpaRibs.

The final optimized SpaRib configuration is shown in Figure 8. The flutter speed is increased from 391.93 knots to 415.79 knots, for an increase in the flutter speed of 6.08% with only a slight mass penalty of 0.66% due to the small increase in length of the ribs and spars.

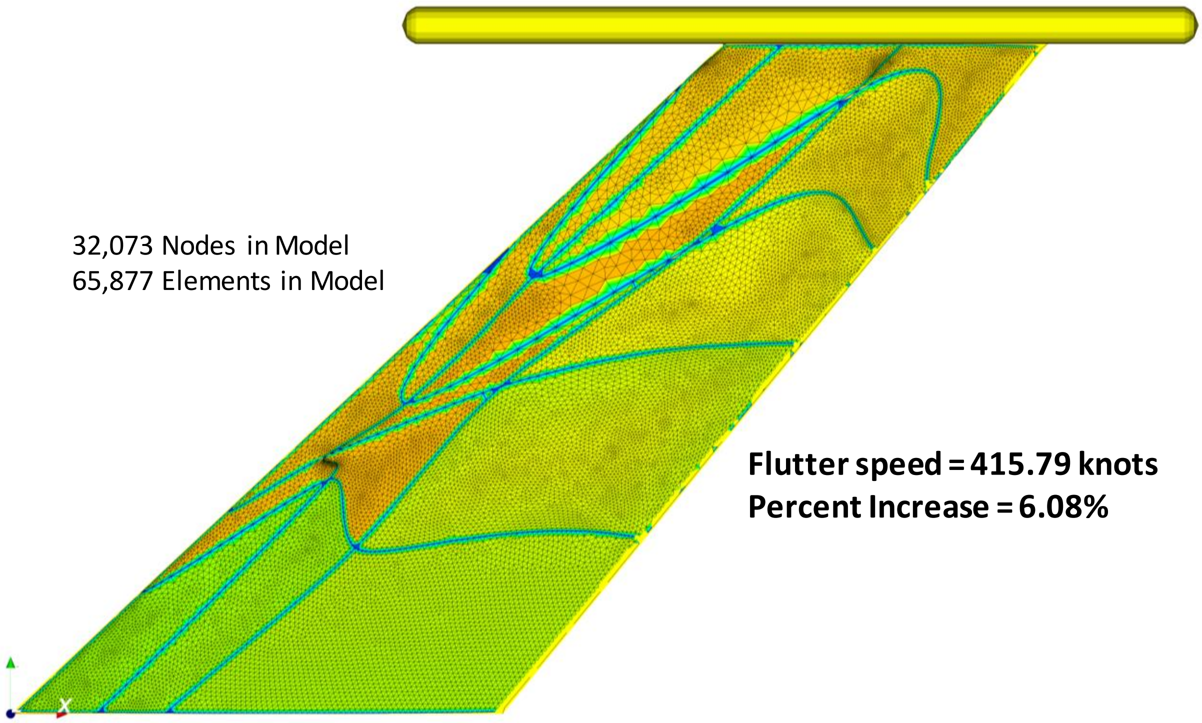

Figure 8: Optimized SpaRib (ATW4b) configuration.

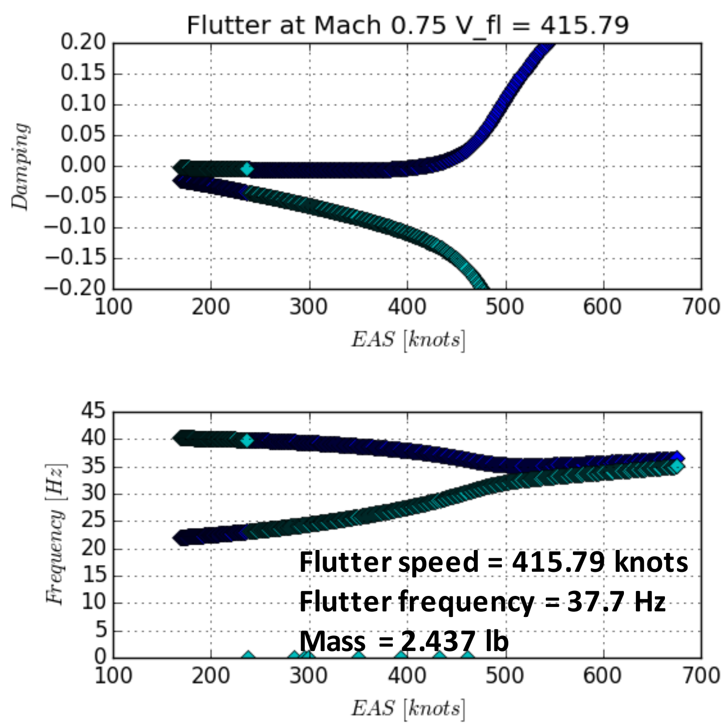

Figure 9: Flutter Speed for Optimized SpaRib (ATW4b) Wing. First Bending and First Torsional Modes are shown.

D. Comparison of Baseline ATW4 (ATW4a) with SpaRib-Optimized Configuration (ATW4b)

The ATW4a and ATW4b flutter behavior are compared in Figure 10. While there is a slight mass penalty (0.66%), the benefits are clear; the flutter speed is increased by 6.08%.

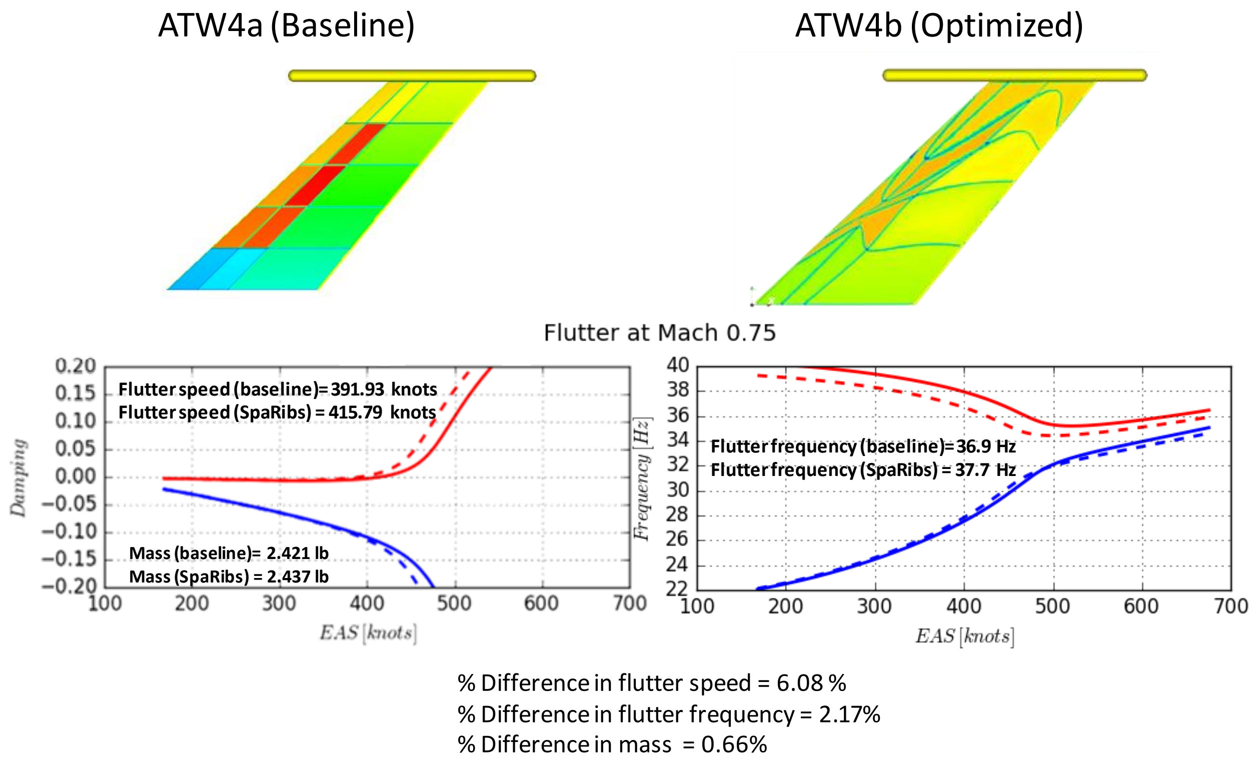

Figure 10: Difference in flutter speed between baseline ATW4a and SpaRib-optimized ATW4b.

While a SpaRib structure may have improved flutter performance, it must also not decrease static strength. As no load static cases existed for this configuration, two load cases were defined. Both cases, a 10 lb tip load (see Figure 11) and a 7.07 in-lb torsional moment (not shown) have a very similar stress pattern. In fact, instead of being worse, the SpaRib-optimized structure actually has 4.5% lower bending stress!

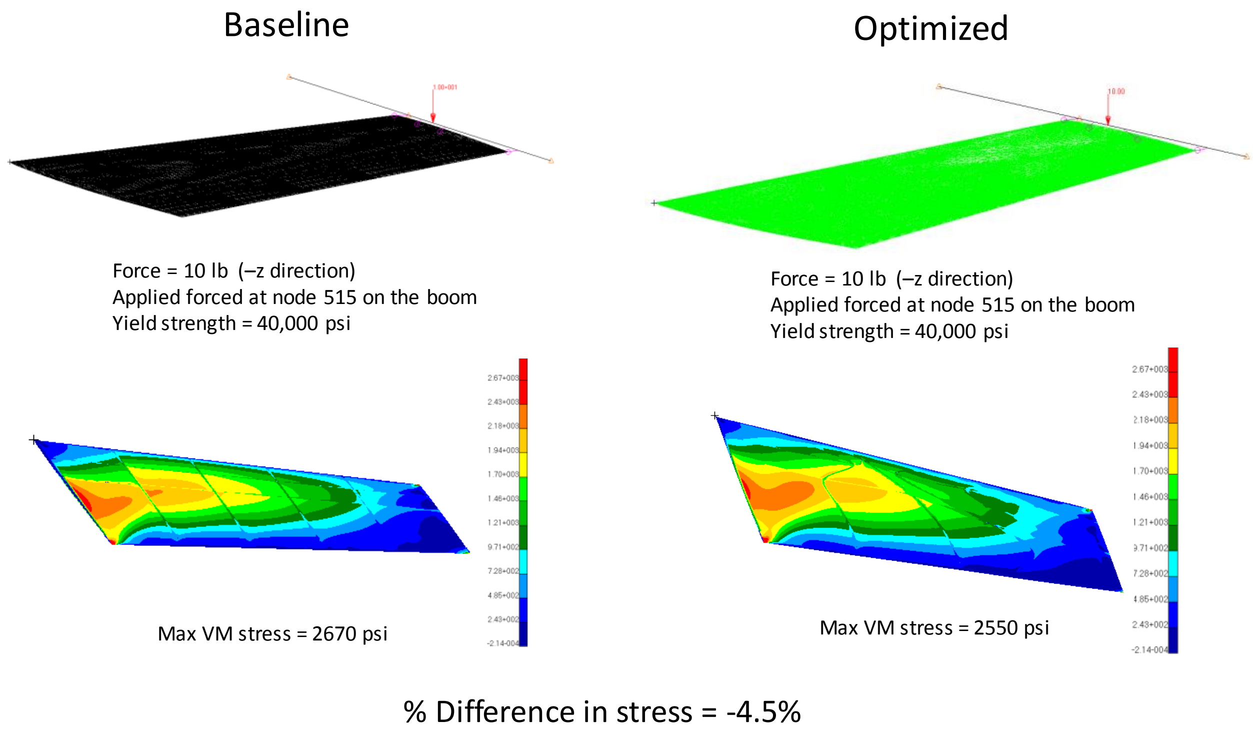

Figure 11: Difference in stress between baseline ATW4a and SpaRib-optimized ATW4b.

The obvious question that remains is how is this achieved? For this configuration, Modes I and II interact to cause flutter. As seen in Figure 12, for this design, SpaRibs does not affect the first bending frequency (Mode I). A 1.05 Hz increase in the first torsional frequency (Mode II) drives the increase in flutter speed.

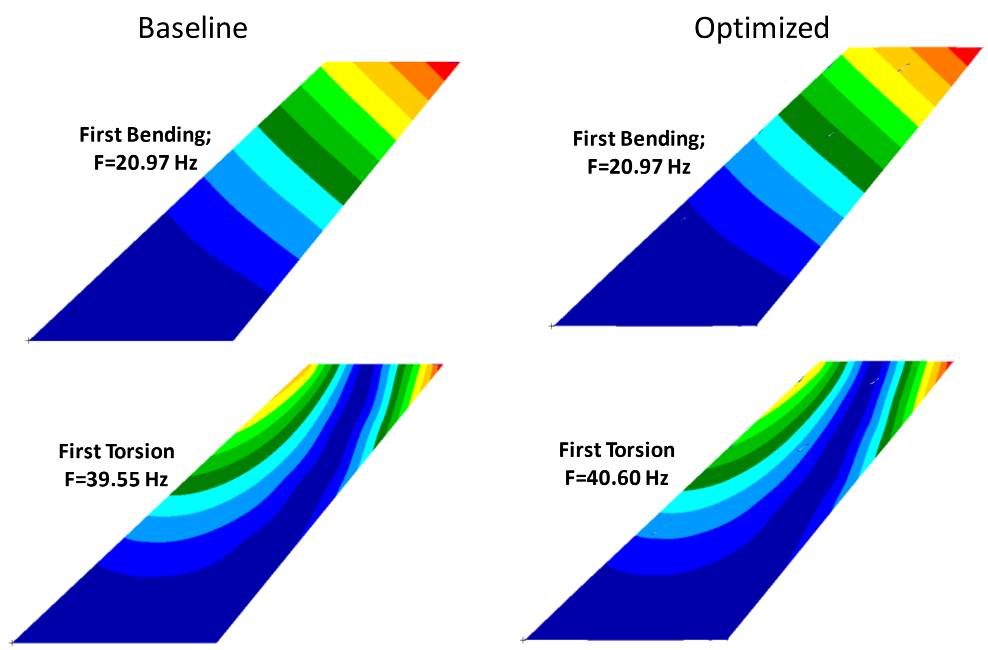

Figure 12: Difference in modal frequencies between baseline ATW4a and SpaRib-optimized ATW4b.

When comparing the baseline ATW4a and SpaRib-optimized ATW4b models on a quantitative basis, some more (possible) insight is seen. For this configuration, the percent increase in critical flutter mode (first torsion; Mode II) modal frequency almost directly corresponds to the increase in flutter frequency. Additionally, the percent increase in the gap between the first and second modes is quite close to the increase in flutter speed. While this result is vehicle specific and somewhat obvious (increasing the gap between the critical modes that interact to cause flutter improves flutter speed, which can be accomplished with just a modal solution), it's a good validation.

Mode	Frequency (Hz)		Delta	% Change	Difference with Next Mode		% Increase
	Baseline	Optimized			Baseline	Optimized	
1	20.97	20.97	-0.001	0.00%	0	0	0.0%
2	39.55	40.60	1.052	2.66%	18.58	19.64	5.7%
3	128.50	137.96	9.46	7.36%	88.95	97.36	9.5%
4	192.00	196.56	4.56	2.38%	63.50	58.60	-7.7%
5	272.97	279.81	6.84	2.51%	80.97	83.25	2.8%
6	289.48	286.88	-2.6	-0.90%	16.51	7.07	-57.2%
7	345.27	334.39	-10.88	-3.15%	55.79	47.51	-14.8%
8	448.19	458.62	10.43	2.33%	102.92	124.23	20.7%
9	550.92	499.85	-51.07	-9.27%	102.73	41.23	-59.9%
10	598.59	540.09	-58.5	-9.77%	47.67	40.24	-15.6%
Mass (lb)	2.42	2.44	0.016	0.66%			
V Flutter (Knot)	391.97	415.79	23.82	6.08%			
Freq Flutter (Hz)	36.90	37.70	0.8	2.17%			

Figure 13: Summary of the baseline ATW4a and SpaRib-optimized ATW4b configuration.

As to what's really going on in this analysis, a few consistent trends for the various SpaRibs models have been seen. Highly curved ribs and sweeping the spars afterwards increases the torsional frequency, while leaving the bending frequency unchanged, which increases the flutter speed. Some of this effect is due to increased mass, but as the mass penalty is low, not to mention stress is decreased by 4.5%, but most of it is not. For the ATW4, SpaRibs show a clear 6.08% benefit over conventional structure.

VI. Conclusion / Future Work

The use of curvilinear internal structure arranged in non-conventional ways is enabled by new manufacturing technology. As these new manufacturing approaches mature, the cost-complexity tradeoff of aerospace structures will completely change, making previously unlikely structural layouts possible. In this paper, we have presented a set of approaches for defining, modeling, analyzing, and optimizing aircraft structures using this new paradigm. This "opening of the design space" has the potential to lead to revolutionary structural concepts and configurations that may have improved performance over conventional rib/spar configurations.

We have clearly demonstrated the usefulness of SpaRibs on certain configurations. A flutter speed improvement of 6.08% was achieved. Further development of aero-structural modeling tools (e.g., OpenVSP, PBWeight, and RapidFEM) as well as SpaRib methods, will allow even further benefits from SpaRibs to be realized. In future work, a ground vibration test and possible flight test demonstration will demonstrate the usefulness of SpaRibs in a test environment.

VII. Acknowledgment

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