NASA/CR–2014-218537

Supersonic Wing Optimization Using SpaRibs

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October 2014

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Prepared for Langley Research Center
under Contract NNL09AA00A

October 2014

Acknowledgment

The authors acknowledge the support of NASA's Fundamental Aeronautics Program's Supersonic Project for this research and the technical guidance of Marcia Domack.

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Abstract

This research investigates the advantages of using curvilinear spars and ribs, termed *SpaRibs*, to design a supersonic aircraft wing-box in comparison to the use of classic design concepts that employ straight spars and ribs. The objective is to achieve a more efficient load-bearing mechanism and to passively control the deformation of the structure under the flight loads. Moreover, the use of *SpaRibs* broadens the design space and allows for natural frequencies and natural mode shape tailoring. The *SpaRibs* concept is implemented in a new optimization MATLAB-based framework referred to as ***EBF3SSWingOpt***. This optimization scheme performs both the sizing and the shaping of the internal structural elements, connecting the optimizer with the analysis software. The shape of the *SpaRibs* is parametrically defined using the so called *Linked Shape* method. Each set of *SpaRibs* is placed in a one by one square domain of the natural space. The set of curves is subsequently transformed in the physical space for creating the wing structure geometry layout. The shape of each curve of each set is unique; however, mathematical relations link the curvature in an effort to reduce the number of design variables. The internal structure of a High Speed Commercial Transport aircraft concept developed by Boeing is optimized subjected to stress, subsonic flutter and supersonic flutter constraints. The results show that the use of the *SpaRibs* allows for the reduction of the aircraft's primary structure weight without violating the constraints. A weight reduction of about 15 percent is observed.

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Table of Contents

List of Figures

List of Tables

1. Introduction

To optimize supersonic aircraft wing structures, different aspects of the design need to be addressed, such as 1) the internal structural layout, 2) the size of the structural components, 3) the aerodynamic loads developed for the given flight conditions, and 4) the aeroelastic response of the structure. In particular, the study of the interaction between the structure and the aerodynamics is critical for designing supersonic transport aircraft and must be considered in an optimization framework that aims to devise more efficient wing structures. In this research, the curvilinear spars and ribs (*SpaRibs*) design concept, envisioned several years ago at Virginia Tech, is implemented in a multidisciplinary optimization framework including structural, static aerodynamic, and flutter analysis in an effort to reduce the weight of a baseline supersonic transport aircraft, given structural and aerodynamic/aeroelastic constraints. The optimization framework includes a geometry modeling module, a steady aerodynamic analysis module, an aeroelasticity analysis module, and an optimization module.

The geometry modeling module generates the curvilinear spars and ribs. The steady aerodynamic analysis module computes the flight loads and the associated stresses for different flight conditions, and the aeroelasticity analysis module predicts the flutter velocity for two flight conditions: 1) subsonic flow at 20,000 ft., and 2) supersonic flow at 40,000 ft. The framework also incorporates both topology optimization and size optimization. The former optimizes the internal structural layout using the *SpaRibs,* and the latter optimizes the thickness of each structural component given the fixed optimum global structural layout. The results show a reduction of the weight of the wing/tail load bearing structure of about 15 percent.

The project accomplishments are briefly outlined, and the obtained results are described below, along with a comparison with the baseline structure.

1.1. Research Objectives

The aim of this research is to introduce new design concepts to optimize the structural layout of supersonic wings. In particular, the concept of *SpaRibs* is introduced. The *SpaRibs* are curvilinear stiffening members used in place of the classic straight spars and ribs. The purpose of introducing this new design concept is to take advantage of the structural deformation couplings (bending-bending-torsion, axial-bending) provided by the curvature and to design more efficient and lighter structures. The use of curvilinear internal structures allows for an enlarged design space which gives the designers more flexibility to tailor the structure according to the load path and vice-versa. The objectives of this research can be summarized as

- introducing the use of *SpaRibs* to improve the design of supersonic wing structures;
- developing a new design framework for the optimization of supersonic wing structure, which includes the use of *SpaRibs;*
- developing an efficient parameterization capable of describing the shape and topology of the wing internal structure;
- implementing the optimization framework and the parameterization using commercially available analysis software as VisualDOC, MSC.NASTRAN and MSC.PATRAN.

2. Project Status

The current supersonic wing optimization tool (***EBF3SSWingOpt***) has proven its efficiency in optimizing the weight of a wing box using *SpaRib*s as compared to using the classic straight spars and ribs (refs. 1–9). The method has been applied with success for designing various wing box configurations (refs. 1–9). Structural weight reduction has been observed in every single case considered. More information about the applications of ***EBF3SSWingOpt*** framework for wing box optimization can be found in references 1–9 (see section 4). This cutting edge optimization tool links together different analysis software available on the market and allows the designer to carry out an optimization task in a very efficient and a completely automatic fashion. The current capabilities are briefly enumerated and described as follows:

- Geometry modeling module improvement
- Trim analysis and flight loads calculation
- Aeroelasticity analysis
- Optimization framework

2.1. Geometry Modeling Module Improvement

A new parameterization for the *SpaRibs* has been introduced. The parameterization uses six parameters or design variables to describe each set of *SpaRibs* placed in a quadrilateral wing box. Each element of a set is characterized by its own curvature. However, the shapes of the *SpaRibs* belonging to the same set are coupled together. The curves defining the shape of the *SpaRibs* are placed in the normalized space and subsequently transformed in the physical space as presented in Figure 2-1**.**

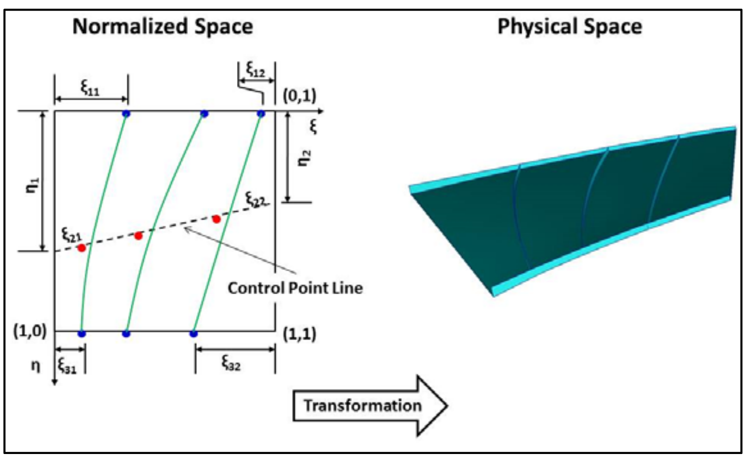


Figure 2-1: Linked shape parameterization.

The parameterization has been implemented in the optimization framework using MSC.PATRAN geometry generation routines. An example of internal *SpaRibs* layout automatically generated using MSC.PATRAN session file is presented in Figure 2-2.

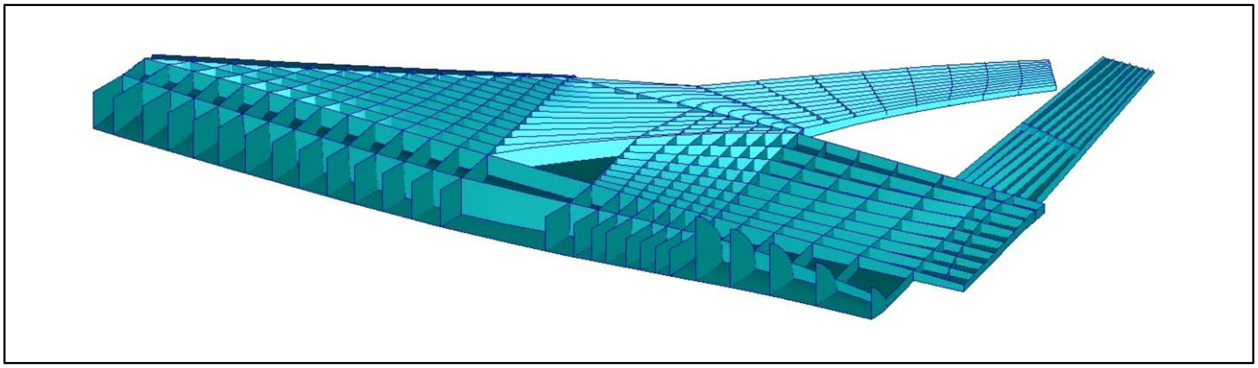


Figure 2-2: Example of internal wing structure configuration generated with *EBF3SSWingOpt*.

2.2. Trim Analysis and Flight Loads Calculation

In static aeroelastic problems, the interaction of aerodynamic forces and structural deformation on a flexible aircraft results in a redistribution of the aerodynamic loading as a function of airspeed. The aerodynamic load causes structural deformation and stress redistribution, which is needed by the structural analyst.

For static aeroelastic analysis, the flight loads calculation is performed by integrating MSC.NASTRAN solution sequence SOL 144 in ***EBF3SSWingOpt*** and by retrieving the aerodynamic loads data to use for the structural analysis. MSC.NASTRAN includes the Doublet Lattice Method and ZONA51 method for the computation of the aerodynamic loads at subsonic and supersonic regimes, respectively. Both methods are based on linearized aerodynamic potential theory, which neglects both the thickness of the wing and the viscous effects.

The aerodynamic panel grid used for the analysis is automatically generated by ***EBF3SSWingOpt***. To transfer the aerodynamic load onto the structure, the structural and the aerodynamic grids are connected by splining interpolation. A set of spline nodes is defined for each aerodynamic panel. The aerodynamic forces can be interpolated using the spline nodes. The structural nodes corresponding to the *SpaRibs* caps, and leading and trailing edges were selected as spline nodes. Different load conditions were considered for the flight loads calculation.

2.3. Aeroelasticity Analysis

Flutter analysis is critical for large supersonic transport aircrafts since the flexibility of the structure and the severe load conditions can lead to flutter instability. Flutter speeds were included as constraints in the optimization. Flutter speed prediction is a process of determining the flutter boundary for a structure that is moving in a fluid. MSC.NASTRAN implements several flutter analysis methods such as the K-Method and the PK-Method. The K-method computes eigenvalues and eigenvectors for user-specified reduced frequencies. PK-method computes eigenvalues and eigenvectors for user-specified velocities. The PK-method was used to plot the velocity-damping (v-g) diagram. Flutter will occur if the damping value becomes positive. The PKNL method is the PK-method without looping on all combinations of density, Mach number, and velocities. Thus, only the matched points are analyzed. The PKNL method is appropriate for finding matched flutter points. The PKNL method was selected in MSC.NASTRAN solution sequence SOL 145 to solve the flutter problem in this particular case. Figure 2-3 shows the flight envelope of the Boeing N+2 supersonic aircraft concept.

There are two schemes to search the aircraft flutter point. The first scheme is checking the flutter speed at a fixed altitude and different velocity values. The second scheme is finding the flutter dynamic pressure at a certain Mach number and various air densities. In the former case the flutter dynamic pressure is computed using the velocity and air density at the matched points. In this research, a sequence of matched points with a same Mach number but various air densities is used for the flutter analysis. Two flight conditions were considered: a subsonic regime at 20,000 ft and a Mach number equal to 0.836, and a supersonic regime at 40,000 ft and a Mach number equal to 1.8.

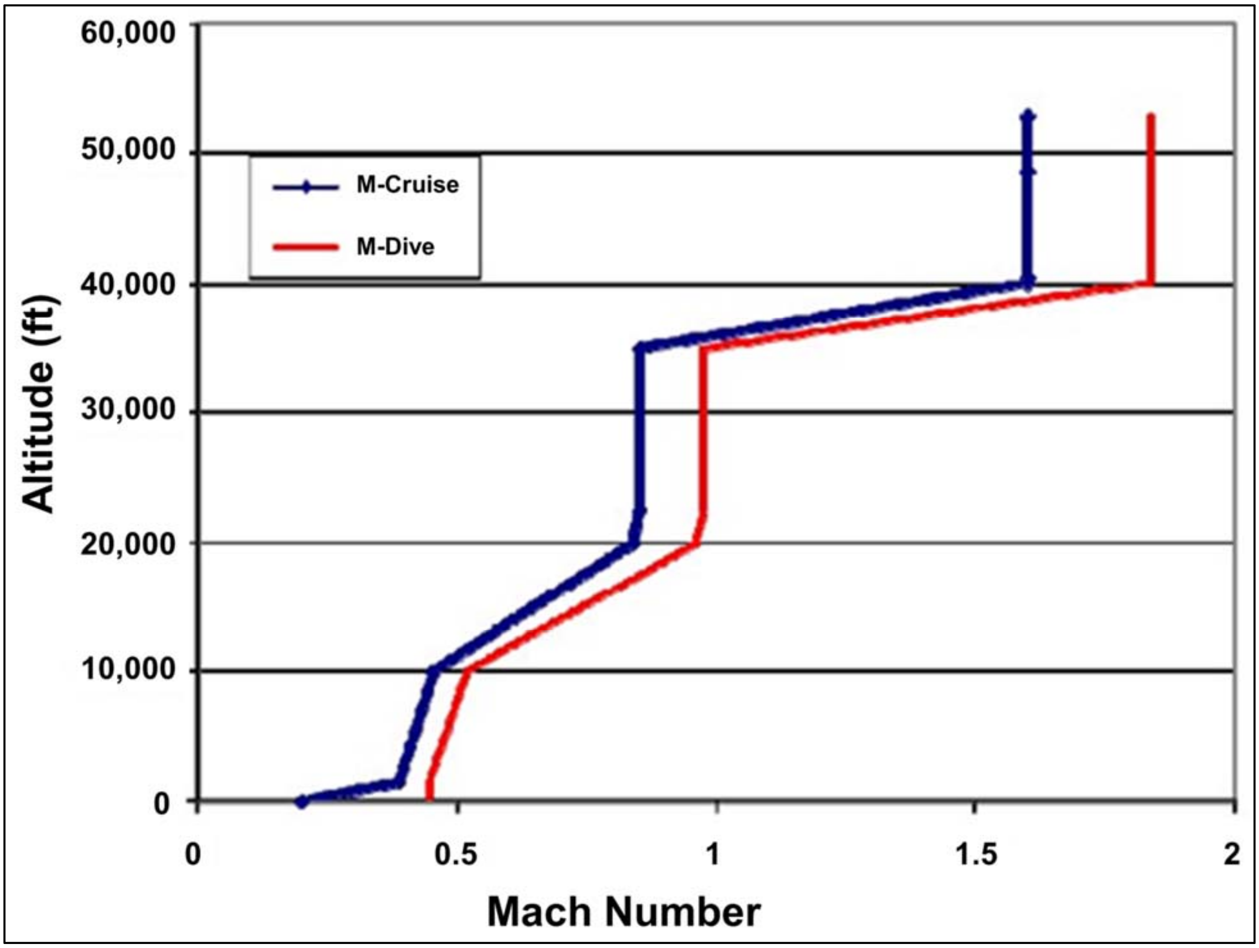


Figure 2-3: Flight envelope of Boeing HSCT aircraft concept.

2.4. Optimization Framework

The optimization framework is presented in Figure 2-4. The optimal topology configuration is computed in the first optimization step; the optimal thickness of the skin panels and *SpaRibs* is computed in the second optimization step. The objective of each step of the optimization is to reduce the weight of the structure. Once the responses are computed, the optimizer checks the convergence criterion of the optimization method used and eventually restarts the process with a new design variables vector if the convergence is not achieved. The topology and size loops are executed sequentially, and convergence must be achieved in both steps separately.

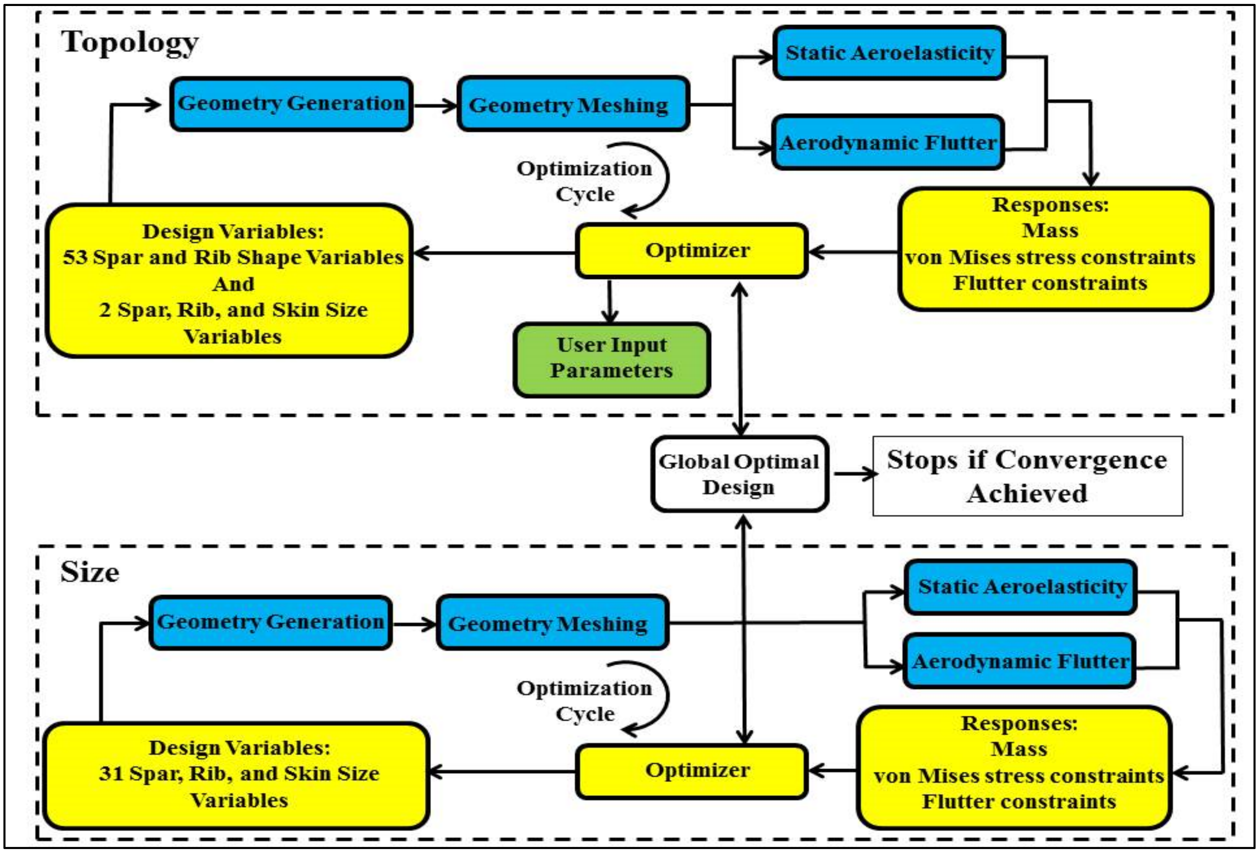


Figure 2-4: Optimization framework.

The topology optimization determines topology and the size design variables to be specified for computing the responses of the aircraft structure. In the first phase, the topology design variable vector is used to generate an aircraft configuration, including the geometry definition of the *SpaRibs* and skin panels and the finite element model for aerodynamic and structural analysis. At this stage, the thickness of the structural components is fixed.

The size optimization loop designs the thickness of the structural components given the topological configuration computed in the first step. The final output of the optimization process is a wing structure with optimal topology and optimal size, for that particular configuration of *SpaRibs*, and that satisfies strength and flutter constraints.

3. Results and Discussion

This section presents the results obtained using the curvilinear *SpaRibs* to optimize the HSCT aircraft concept developed by Boeing. The baseline N+2 Boeing configuration is at first described and subsequently compared with the design developed using ***EBF3SSWingOpt*** framework.

3.1. Baseline N+2 Configuration

Figure 3-1: Boeing N+2 HSCT aircraft concept.Figure 3-1 presents the baseline aircraft layout (ref. 13). The aircraft is characterized by an 86.1 ft wing span and a fuselage length of about 154 ft; 30 passengers can be transported at a cruise velocity equivalent to Mach 1.6 at an altitude of 50,000 ft for a maximum range of 3200 nm.

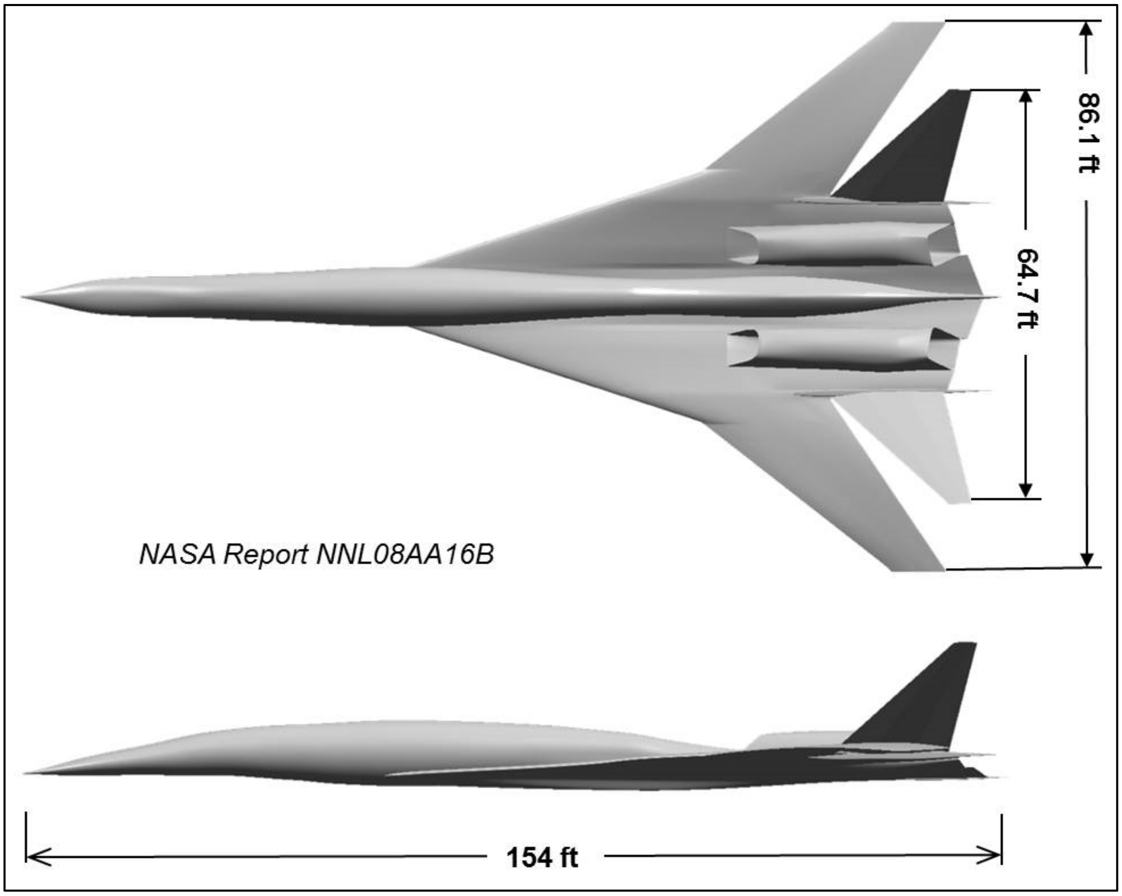


Figure 3-1: Boeing N+2 HSCT aircraft concept.

The wing, tail, and fuselage structures are specified as fabricated from a titanium alloy material, while the secondary structures and control surfaces are fabricated from honeycomb and composite materials. Straight spars and ribs are used for the wing and tail internal structure layout which is outlined in Figure 3-2.

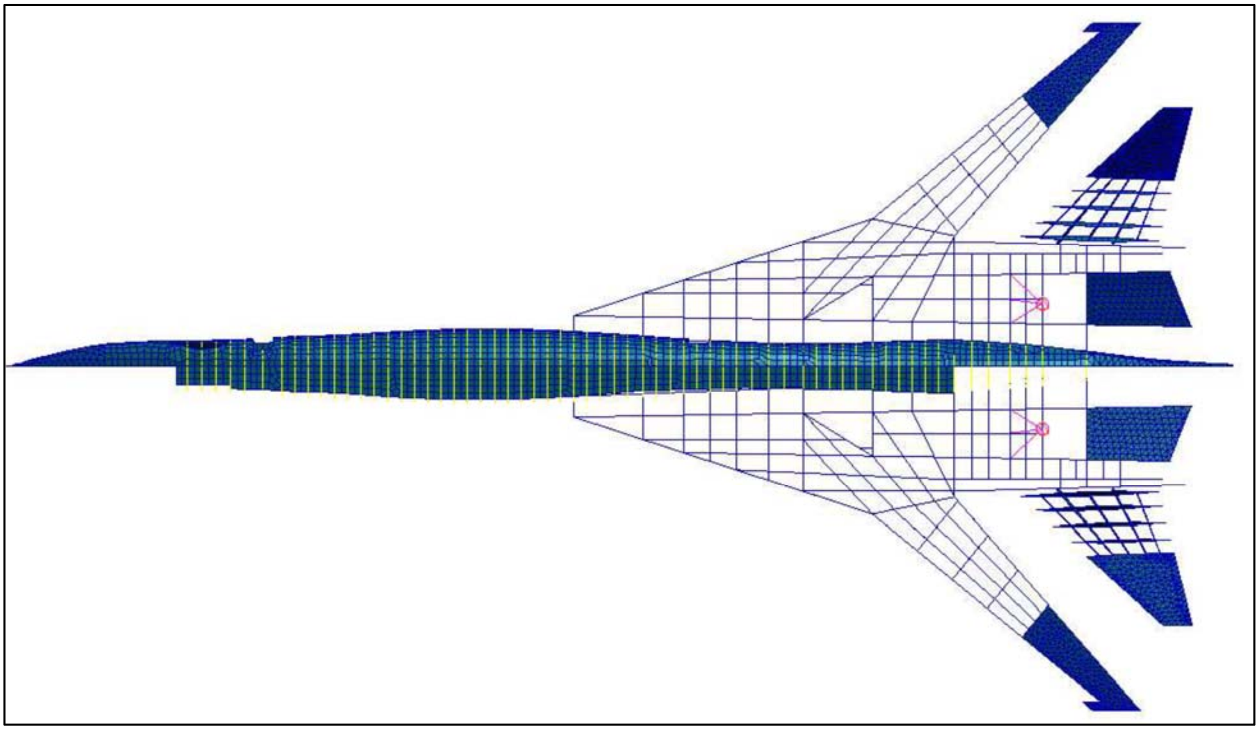


Figure 3-2: Boeing N+2 aircraft internal configuration.

3.1.1. Optimization Results for the Baseline Aircraft

This baseline aircraft configuration was optimized under static aerodynamic constraint and under flutter constraints by the Boeing Company (refs. 10 and 13). The results are summarized in Table 3-1. The weight of the load bearing structure optimized to satisfy only the strength constraint is 39,305 lb. If the flutter constraint is considered, the weight of the structure increases by 18.5 percent. In other words, to satisfy the flutter constraint a penalty of 18.5 percent on the structure weight must be paid. For more details about the flutter behavior of the baseline structure, please see reference 10.

Table 3-1: Weight summary for Boeing N+2 aircraft concept. Optimization performed by Boeing Company.

	Strength Optimization	Strength and Flutter Optimization
Mass (lb)	39,305	46,587

The data presented in Table 3-1 refer to the whole structure of the aircraft concept developed by Boeing. This includes the wing, the tail, and the fuselage. The mass is subdivided as follows: wing-tail assembly 25,560 lb, fuselage assembly 13,745 lb. The ***EBF3SSWingOpt*** optimization framework is only applied to re-design part of the wing and part of the tail structure. For consistency, the data relative to the portion of the structure re-designed during the optimization process are presented in Table 3-2.

Table 3-2: Weight summary for Boeing N+2 aircraft concept. Data refer to the portion of the structure that was actually optimized.

	Strength Optimization	Strength and Flutter Optimization
Weight (lb)	12,780	15,182 to 16,421

The data given in Table 3-2 refer to the half structure presented in Figure 3-3. The mass of the structure subjected only to the strength constraint is computed from the finite element model provided by Boeing, using MSC.NASTRAN mass estimator. The weight of the structure optimized for strength and flutter is extrapolated from the weight computed using the strength constraint, since the finite element model for this case is not available. The range of weight is estimated to be between 15,182 lb and 16,421 lb, where 15,182 lb is computed by adding the 18.5 percent penalty to 12,780 lb and 16,421 lb is computed subtracting the weight of the fuselage from 46,587 lb and dividing by 2 to account for the half structure. In other words the lower boundary is computed assuming that the weight penalty is equally shared between wing, tail, and fuselage structure, while the upper boundary is computed assuming that the weight penalty affects only the wing and tail structure leaving the fuselage weight unchanged.

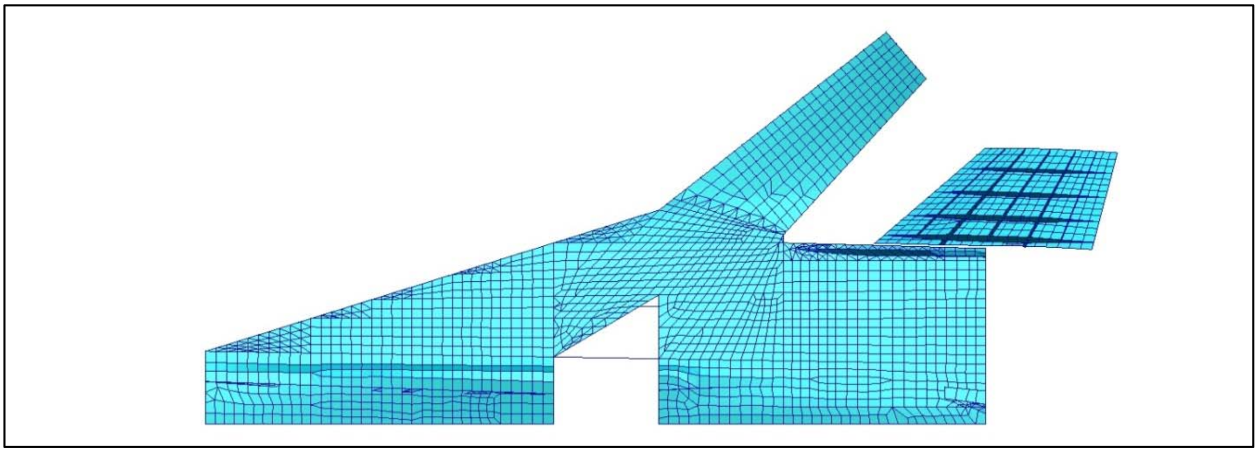


Figure 3-3: Portion of the structure of the wing and tail re-designed using *EBF3SSWingOpt*.

3.2. N+2 Aircraft Concept Optimized with *SpaRibs*

The N+2 supersonic aircraft concept developed by Boeing was optimized using ***EBF3SSWingOpt*** framework by the Virginia Tech unitized structures group. The internal structure layout is replaced by a new layout characterized by curvilinear *SpaRibs*. Optimization of the structural weight was conducted under structural stress and both subsonic and supersonic flutter constraints. The optimization includes the re-design of the load bearing structure of the wing and of the tail; the fuselage structure, the control surfaces, and the wing and tail tips are not optimized using ***EBF3SSWingOpt*** and are kept fixed throughout the process.

3.2.1. Stress Constraint Formulation

The stress constraint is formalized using the modified Kreisselmeier-Steinhauser criterion, following the relation

$$KS_\sigma(\sigma) = \frac{1}{\rho}\ln\left(\frac{1}{\sum_{i=1}^{N} A_i}\sum_{i=1}^{N} A_i e^{\rho\left(\sigma_{vm_i}/\sigma_y\right)^{1/2}}\right) < 1$$

where ρ is a coefficient set to the value of three, A_i is the area of the i^{th} finite element in the model, σ_{vm_i} is the von Mises stress in the i^{th} finite element of the model, and σ_y is the yield stress of the material. For more information about the Kreisselmeier-Steinhauser stress criterion and its application please see references 11 and 12.

3.2.2. Flutter Constraint Formulation

Two flutter constraints are used during the optimization process: one for subsonic cruise regime and one for supersonic cruise regime (ref. 10). The constraints are formulated as follows:

$$F_{Subsonic} = 1.2\frac{Q_{cr_{Subsonic}}}{Q_{fl\ Subsonic}} < 1$$

$$F_{Supersonic} = 1.2\frac{Q_{cr_{Supersonic}}}{Q_{fl\ Supersonic}} < 1$$

where Q_{cr} is the critical dynamic pressure computed using MSC.NASTRAN, and Q_{fl} is the actual dynamic pressure associated to the flight condition considered. A safety factor of 1.2 is also applied. If the flutter analysis shows that the critical dynamic pressure value is outside the range investigated, the flutter constraint value is considered to be zero. From reference 10 the critical flutter velocities for subsonic and supersonic regimes are chosen to be 867 ft/sec at 20,000 ft (M = 0.836) and 1782 ft/sec at 40,000 ft (M = 1.8), respectively. The corresponding flutter dynamic pressure values are 3.31 psi and 6.19 psi, respectively.

3.2.3. Optimization Results

This aircraft configuration is optimized and subjected to strength and flutter constraints as described previously. The strength constraints are computed for different flight conditions as prescribed by Boeing. The results are visualized in Table 3-3. The mass refers to the half structure presented in Figure 3-4.

Table 3-3: Mass summary for Boeing N+2 aircraft concept optimized with *SpaRibs*. Data refer to the portion of the structure that was actually optimized.

	Strength Optimization	Strength and Flutter Optimization
Weight (lb)	N/A	12,340

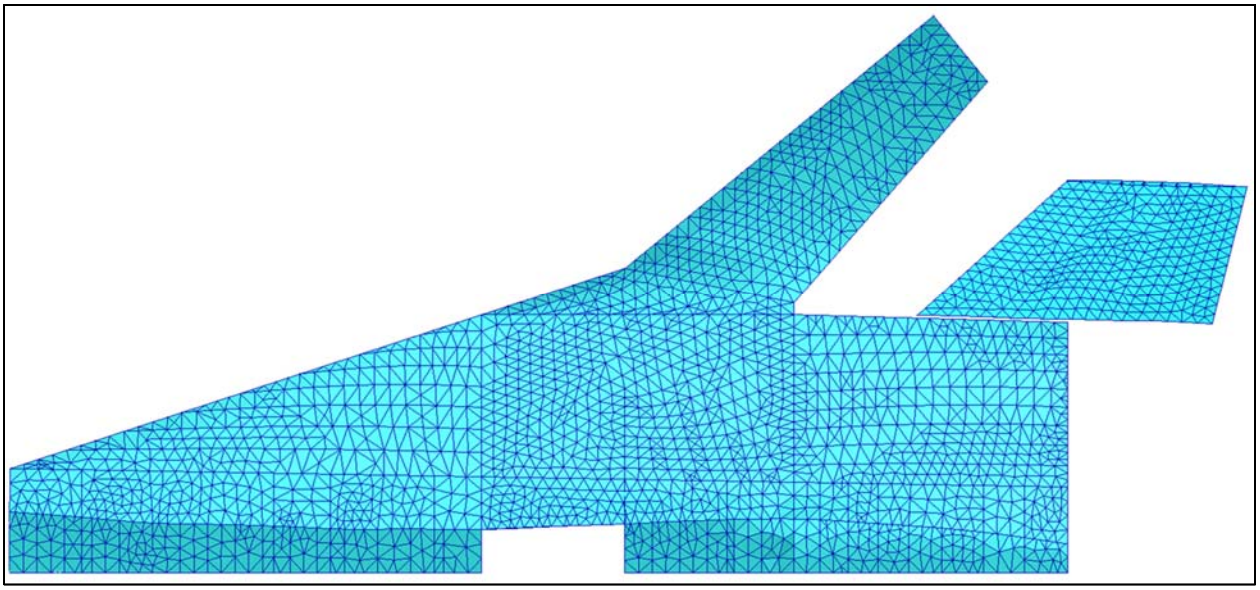


Figure 3-4: Finite element mesh of the portion of the structure of the wing and tail re-designed using *EBF3SSWingOpt*.

Table **3-4** and

Table 3-5 present the constraint coefficients computed according to the relations presented above. The strength and subsonic and supersonic constraints are satisfied.

Table 3-4: Kreisselmeier-Steinhauser coefficients for different flight conditions. The constraint is amply satisfied for every case considered. The coefficients refer to the configuration shown in Figure 3-5.

Maneuver	KSσ(σ)
2.5G Pull Up at M = 0.836	0.89
1.2G Pull Up at M = 1.6	0.34
-0.5G Push Over at M = 0.836	0.17
Roll at M = 0.836	0.53
1.5G Pitch Up at M = 1.6	0.33

Flutter does not occur in the flight range investigated, therefore, the flutter constraint coefficients are zero. This means that the structure actually flutters outside the flight envelope, and the flutter velocity and critical dynamic pressure requirements are satisfied.

Table 3-5: Flutter constraint coefficients of configuration in Figure 3-5. Both flutter constraints are satisfied.

Flutter Constraint Parameter	Value
$F_{Subsonic}$	0.0
$F_{Supersonic}$	0.0

3.2.4. Topology Optimization

The first part of the optimization process is the design of the *SpaRibs*. This task involves the use of 53 design variables which define the number of *SpaRibs* required and their shape. The optimum configuration computed at this stage is shown in Figure 3-5 along with the baseline internal structure for comparison.

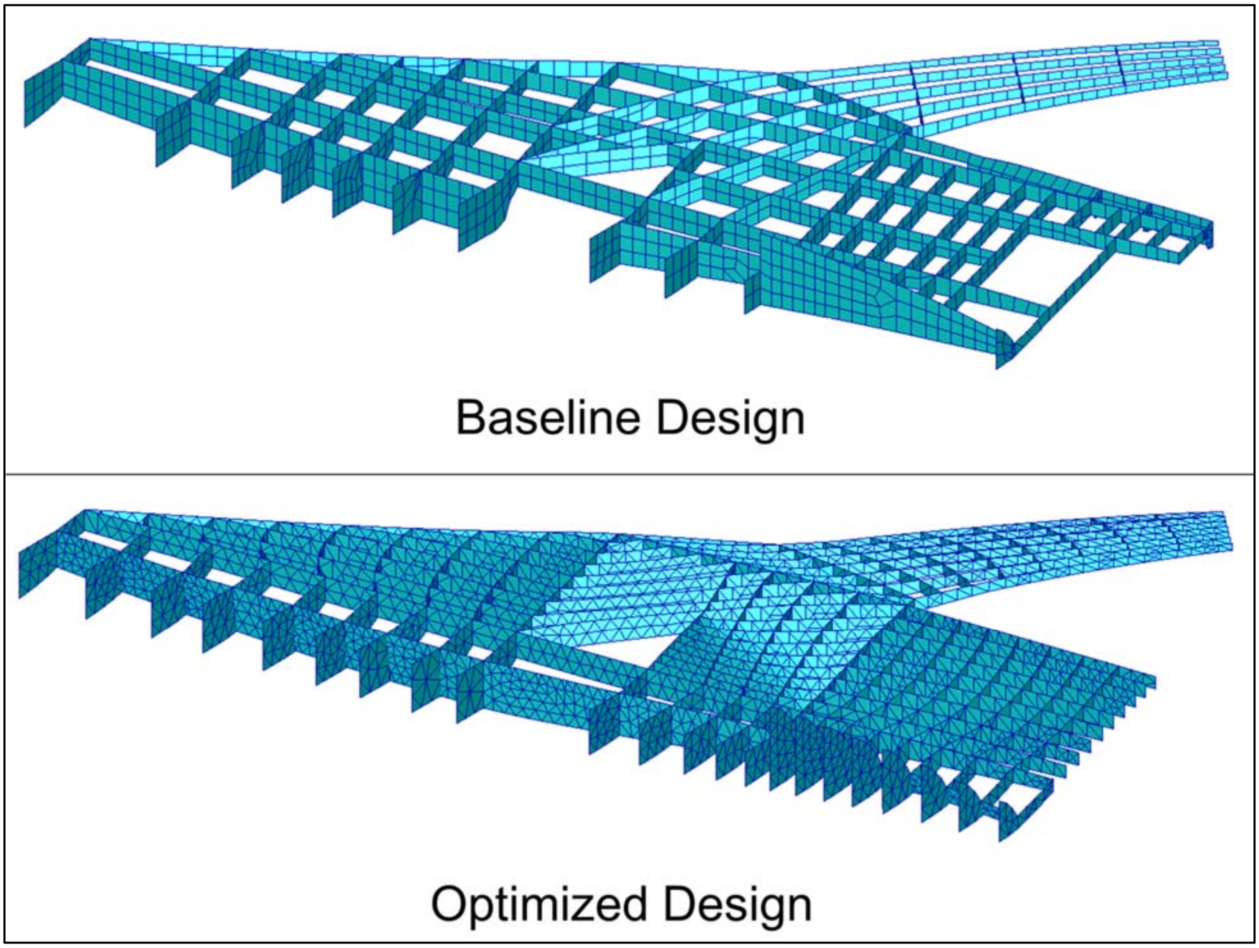


Figure 3-5: Optimum topology computed at the first optimization step.

The optimized structure is characterized by a higher number of internal elements in every section of the wing. No constraint was prescribed on the number of *SpaRibs* to be placed in the wing structure, therefore, the optimizer drives the number of the internal stiffening element to the optimum. If constraints on the number of *SpaRibs* were to be prescribed, the value of the corresponding design variables could be fixed and the optimizer would find the best shape of the *SpaRibs* for that particular configuration.

3.2.5. Size Optimization

The second phase of the optimization process is the sizing of the internal components and the skin panels. This task involves 31 design variables. The optimal size is presented in Figure 3-6. The maximum component thickness is reduced to about 0.3 inches from the 1.1 inches of the baseline. In general a thickness reduction of the skin panels is observed. The reduction is more pronounced in the outer, center, and forward portion of the wing structure. The forward wing is characterized by thicker spars and ribs.

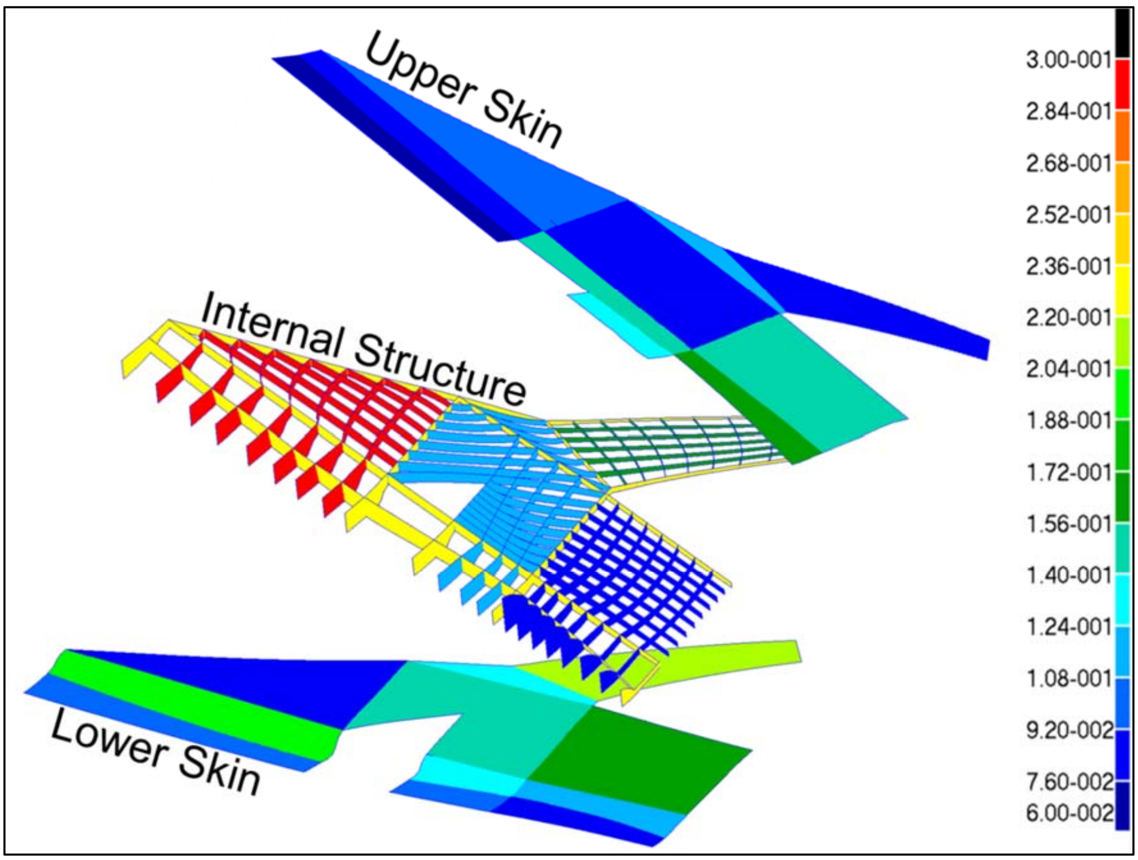


Figure 3-6: Thickness (in) distribution of the optimized structure.

3.2.6. Static Stress Analysis

The static stress analysis was performed for every load case listed in

Table 3-4. The most severe maneuver from the stress point of view is the 2.5 g pull-up maneuver at Mach 0.836. The von Mises stress distribution in the structure is plotted in Figure 3-7.

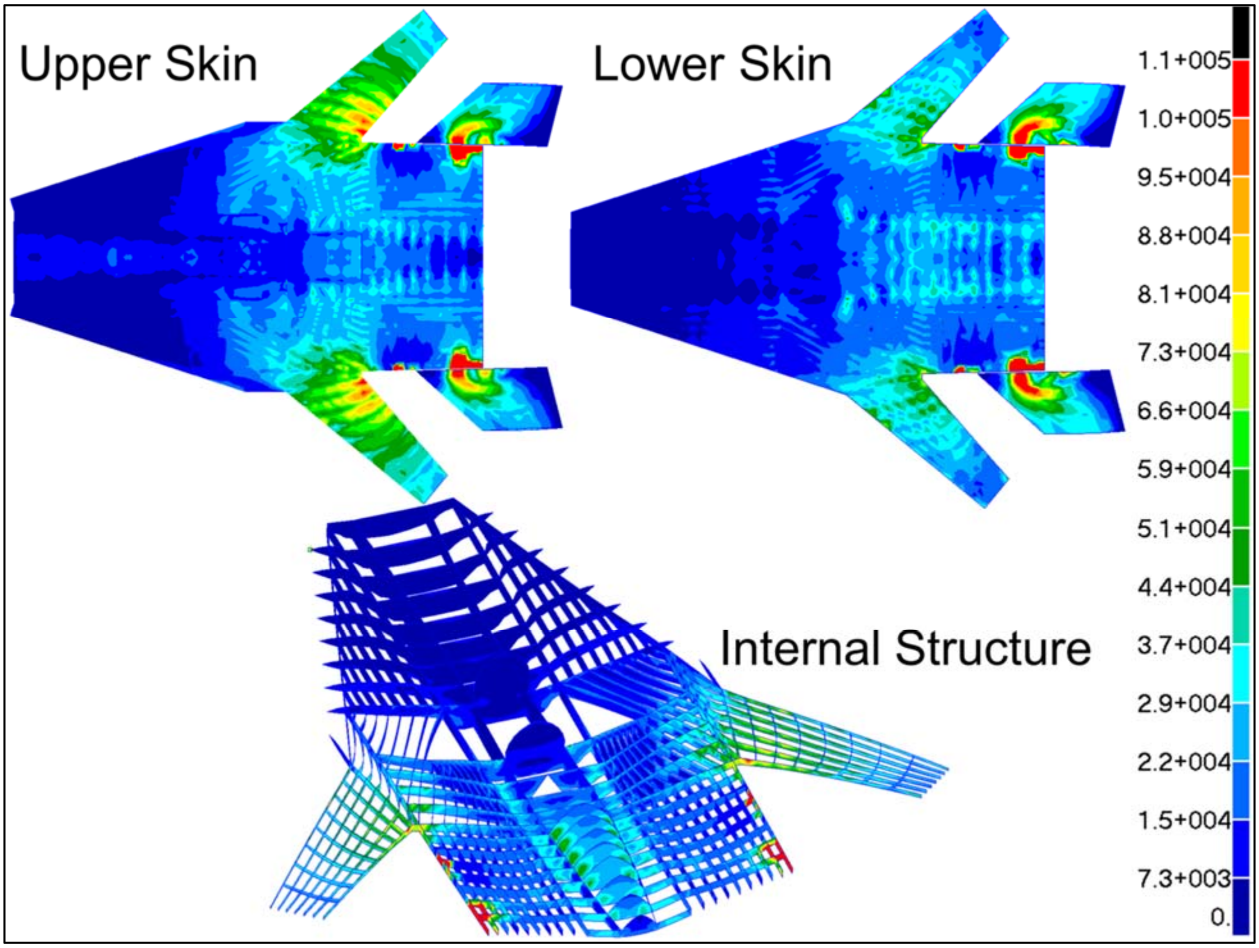


Figure 3-7: Von Mises stress distribution associated to the 2.5 G pull-up maneuver at Mach number equal to 0.836. Stresses in the upper and lower skin and in the internal structure are plotted

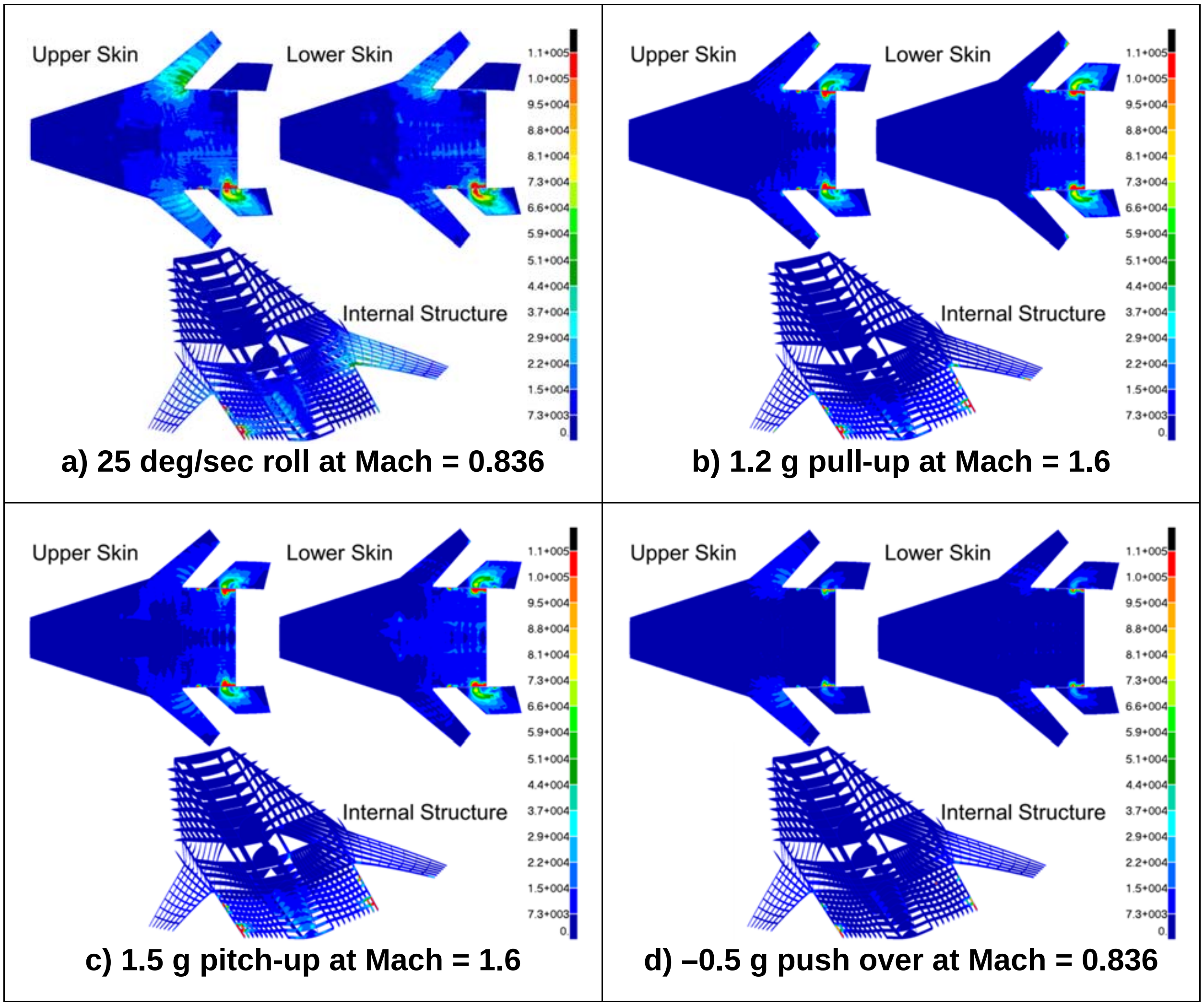
The yield stress of the titanium alloy[1] chosen for the design is 110,000 psi.

High stress concentration is observed in correspondence of the tail connection with the rear section of the wing and at the attachment of the outer wing with the center wing section. The stress concentration in the former location is expected, since all the aerodynamic load acting on the large tail surfaces are transmitted to the rest of the structure by only three structural components modeled as rigid bar elements. The stress concentration in the latter location is explainable by the fact that the load acting on the outer wing produces a high-bending moment in that particular region of the structure. Moreover, the loads coming from the control surfaces are transmitted to the outer wing trailing edge spar through rigid bar elements.

[1] Titanium alloy physical characteristics widely change depending on the alloy composition and thermal treatments. In particular, the yield stress can vary from about 100,000 psi to over 200,000 psi. In absence of more precise indications, a lower grade alloy has been chosen as reference for the design to avoid contamination of the results due to the “optimistic” estimation of the material properties.

The high stress regions amount to only about two percent of the total wing surface, and, therefore, can be considered local effects caused by the use of the rigid bar elements to connect the various parts of the structure. A more accurate modeling of the structure and a localized optimization should solve the issue effectively. The forward section of the wing is practically unstressed for this flight maneuver.

Figure 3-8 shows the von Mises stress distribution for the remaining maneuvers. The most critical maneuver, after the 2.5 g pull-up at Mach 0.836, is the roll at Mach 0.836 at a turning rate of 25 degrees per second. This kind of maneuver generates an asymmetric aerodynamic load on the wings. The portions of the wing characterized by high stress are the tail-wing connection and the outer wing-center wing attachment, as observed in the previous case. The 1.2 g pull-up maneuver and the 1.5 g pitch-up maneuver at a Mach number equal to 1.6 have similar stress distribution with higher stresses localized in the tail and rear wing region. Finally, the push over maneuver at a Mach number equal to 0.836 and a load factor equal to –0.5 is characterized by a very low stress level throughout the whole structure. In conclusion, the strength design is driven by the pull-up maneuver at 2.5 g and by the roll maneuver at a Mach number equal to 0.836. The most critical regions of the structure, from the stress point of view, are the tail surfaces, the rear wing, and the outer wing.



a) 25 deg/sec roll at Mach = 0.836

b) 1.2 g pull-up at Mach = 1.6

c) 1.5 g pitch-up at Mach = 1.6

d) –0.5 g push over at Mach = 0.836

Figure 3-8: Von Mises stress of the aircraft structure

3.2.7. Flutter Analysis

The flutter analysis is performed using the PKNL method available in MSC.NASTRAN. The results show that flutter does not occur for the flight conditions studied. In particular, the flutter modes damping is always negative for the range of dynamic pressure considered. Figure 3-9 shows the structural damping as a function of the dynamic pressure for the subsonic and supersonic regimes, respectively. The damping value is always negative; therefore, flutter does not occur.

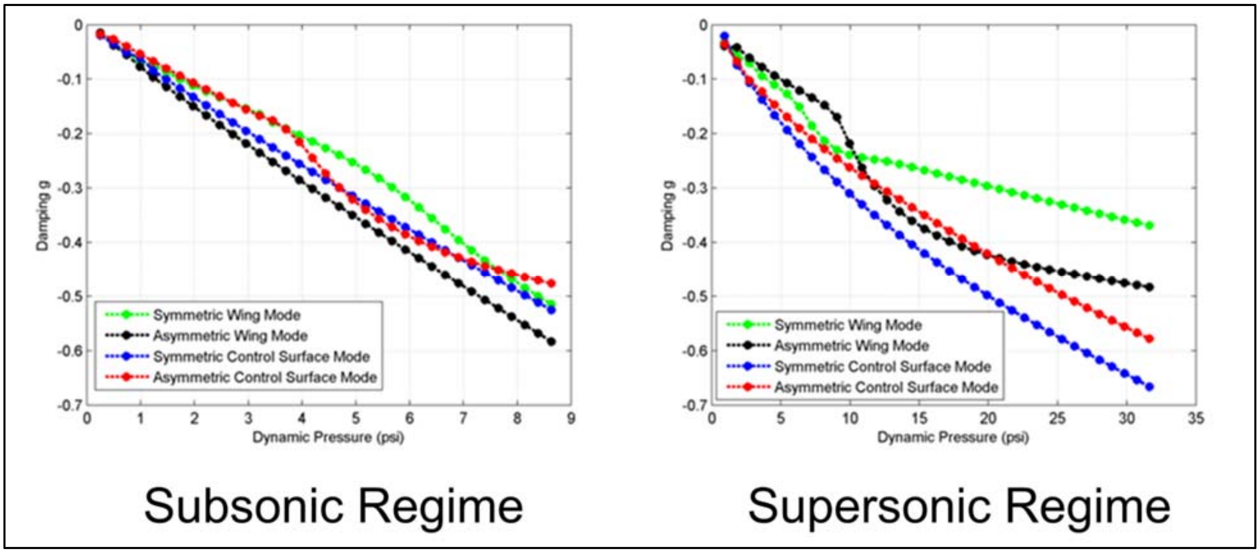


Figure 3-9: Flutter analysis results.

3.3. Result Comparison

The baseline and the optimized structure performance are compared. Table 3-6 summarizes the structural performance for the baseline and the *SpaRibs*-optimized design.

Table 3-6: Comparison of the optimized structure performance.

	Baseline	**Optimized with *SpaRibs***
Weight (lb)	15,182 to 16,421	12,430 (**18.1% to 24.3% Reduction**)
Stress Constraints	Satisfied	Satisfied
Subsonic Flutter	**Not Satisfied**	Satisfied
Supersonic Flutter	Satisfied	Satisfied

The use of the *SpaRibs* allows for a mass reduction of the structure between 18.1 percent and 24.3 percent, depending on how the baseline weight is estimated. Furthermore, both the subsonic and supersonic flutter constraints are met.

3.4. Conclusion

The ***EBF3SSWingOpt*** framework was applied for the optimization of the N+2 supersonic Boeing aircraft concept. The results obtained are considered preliminary and not final. Nonetheless, the weight reduction achieved and the fact that all constraints were satisfied shows the efficiency of the design process and the advantage of the use of curvilinear *SpaRibs*.

Further improvements can be achieved after running a new optimization process, which includes the thickness of each skin panel as a design variable. As of now, the size optimization only accounts for 31 design variables, and various skin panels are grouped together and are characterized by the same thickness. Adding thickness design variables should allow for a better material tailoring of the structure and further reduction of the weight. Moreover, local buckling analysis performed on the skin panels would be possible and efficient.

The formulation of the stress constraints may also be improved upon. As of now, the stress constraints are formulated using the Kreisselmeier-Steinhauser criterion. According to the Kreisselmeier-Steinhauser formula, presented in section 3.2.1, a coefficient which represents an “average” stress distribution can be computed from the von Mises stress value of every finite element of the mesh. Although this criterion is reliable and is widely used to formulate stress constraints in optimization problems, there is the possibility that the level of stress exceeds the ultimate strength of the material in some localized region of the mesh. These regions are usually localized in correspondence of sharp corners of the mesh or rigid connections between parts of the mesh. This requires checking the optimized configuration and eventually re-sizing the high-stress regions separately. This might lead to a slight increase in the weight if thicker elements are required to reduce the stresses.

4. List of Related Publications

This is a list of conference and journal papers related to this research.

1. Locatelli, D., “Optimization of Supersonic Wing-Box Using Curvilinear *SpaRibs*”, Doctorate Thesis, Virginia Polytechnic Institute and State University, 2012.

2. Locatelli, D., Mulani, S. B., and Kapania, R. K., “Supersonic Wing Box Weight Optimization Using Curvilinear Spars and Ribs (SpaRibs)”, *Journal of Aircraft*, 2011, 48 (5), 1671–1684.

3. Mulani, S. B., Locatelli, D., and Kapania, R. K., “Algorithm Development for Optimization of Arbitrary Geometry Panels using Curvilinear Stiffeners”, *51st AIAA/ASME/ASCE/ASC Structures, Structural Dynamics & Materials Conference,* Orlando, Florida, April 12–15, 2010.

4. Locatelli, D., Mulani, S. B., and Kapania, R. K., “Supersonic Wing Box Weight Optimization Using Curvilinear Spars and Ribs (SpaRibs)”, *51st AIAA/ASME/ASCE/ASC Structures, Structural Dynamics & Materials Conference,* Orlando, Florida, April 12–15, 2010.

5. Mulani, S. B., Locatelli, D., and Kapania, R. K., “Grid-Stiffened Panel Optimization using Curvilinear Stiffeners”, *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics & Materials Conference,* Denver, Colorado, April 04–07, 2011.

6. Locatelli, D., Mulani, S. B., and Kapania, R. K., “A Multidisciplinary Analysis Optimization Environment for Wings Having SpaRibs”, *53rd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics & Materials Conference,* Honolulu, Hawaii, April 23–26, 2012.

7. Locatelli, D., Mulani, S. B., and Kapania, R. K., “Parameterization of Curvilinear Spars and Ribs (SpaRibs) for Optimum Wing Structural Design”, *53rd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics & Materials Conference,* Honolulu, Hawaii, April 23–26, 2012. Accepted for publication on *Journal of Aircraft,* 10.2514/1.C032249.

8. Locatelli, D., Mulani, S. B., Liu, Q., and Kapania, R. K., “Optimal Supersonic Wing Structure Design Using Curvilinear Spars and Ribs (*SpaRibs*)”, *AeroMat 2012 Conference and Exposition*, Charlotte, NC, USA, June 18–21, 2012.

9. Locatelli, D., Tamijani, A. Y., Mulani, S., Liu, Q., and Kapania, R. K., “Multidisciplinary Optimization of Supersonic Wing Structures Using Curvilinear Spars and Ribs (SpaRibs)”, *54th AIAA/ASME/ASCE/AHS/ASC Structures Conference*, Boston, Massachusetts, 8–11 April 2013.

10. Mulani, S. B., Slemp, W. C. H., and Kapania, R. K., “EBF3PanelOpt: An optimization framework for curvilinear blade-stiffened panels”, Thin-Walled Structures 63 (2013) 13–26.

5. References

1. Locatelli, D., "Optimization of Supersonic Wing-Box Using Curvilinear *SpaRibs*", Doctorate Thesis, Virginia Polytechnic Institute and State University, 2012.

2. Locatelli, D., Mulani, S. B., and Kapania, R. K., "Supersonic Wing Box Weight Optimization Using Curvilinear Spars and Ribs (SpaRibs)", *Journal of Aircraft*, 2011, 48 (5), 1671–1684.

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10. Chen, D., Britt, R. T., Roughen, K., and Stuewe, D. "Practical Application of Multidisciplinary Optimization to Structural Design of Next Generation Supersonic

Transport", 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, 13–15 September 2010, Fort Worth, Texas.

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13. "N+2 Supersonic Concept Development and System Integration", Technical Report, Contract NNL08AA16B, Submitted by Boeing Company, Final Draft, July 2009.

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
01- 10 - 2014	Contractor Report	

4. TITLE AND SUBTITLE
Supersonic Wing Optimization Using SpaRibs

5a. CONTRACT NUMBER
NNL09AA00A

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Locatelli, David; Mulani, Sameer B.; Liu, Qiang; Tamijani, Ali Y.; Kapania, Rakesh K.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
984754.02.07.07.15.07

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA/CR-2014-218537

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 39
Availability: NASA CASI (443) 757-5802

13. SUPPLEMENTARY NOTES
Langley Technical Monitor: Marcia S. Domack

14. ABSTRACT
This research investigates the advantages of using curvilinear spars and ribs, termed SpaRibs, to design a supersonic aircraft wing-box in comparison to the use of classic design concepts that employ straight spars and ribs. The objective is to achieve a more efficient load-bearing mechanism and to passively control the deformation of the structure under the flight loads. Moreover, the use of SpaRibs broadens the design space and allows for natural frequencies and natural mode shape tailoring. The SpaRibs concept is implemented in a new optimization MATLAB-based framework referred to as EBF3SSWingOpt. This optimization scheme performs both the sizing and the shaping of the internal structural elements, connecting the optimizer with the analysis software. The shape of the SpaRibs is parametrically defined using the so called Linked Shape method. Each set of SpaRibs is placed in a one by one square domain of the natural space. The set of curves is subsequently transformed in the physical space for creating the wing structure geometry layout. The shape of each curve of each set is unique; however, mathematical relations link the curvature in an effort to reduce the number of design variables. The internal structure of a High Speed Commercial Transport aircraft concept developed by Boeing is optimized subjected to stress, subsonic flutter and supersonic flutter constraints. The results show that the use of the SpaRibs allows for the reduction of the aircraft's primary structure weight without violating the constraints. A weight reduction of about 15 percent is observed.

15. SUBJECT TERMS
Curvilinear Spars Ribs; SpaRibs; Structural optimization; Supersonic wing structure

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER ***(Include area code)***
U	U	U	UU	31	(443) 757-5802