10th World Congress on Structural and Multidisciplinary Optimization
May 19 -24, 2013, Orlando, Florida, USA

Acoustic Analysis and Optimization of Embedded Exhaust-Washed Structures

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1. Abstract
The configurations for high speed, low observable aircraft expose many critical areas on the structure to extreme environments of random acoustic pressure loadings. When combined with primary structural and thermal loads, this effect can cause high cycle fatigue to aircraft skins and embedded exhaust system components. By optimizing the integrated aircraft components that involve interactions between fluid and structural coupled systems, the structural stresses created from the high acoustic pressure magnitude of the frequency response functions can be reduced, therefore prolonging the fatigue life of the aircraft structure. This paper highlights an optimization technique that is utilized to reduce the acoustic related stress of a simplified engine exhaust-washed structure.

2. Keywords: acoustic, coupling, vibro-acoustics

3. Introduction
As aerospace technology continues to advance across the globe, demand is ever increasing for future capabilities of aircraft. These requests call for improvements in extended flight intervals, rapid attack and defense mechanisms, reusable launch system techniques, and improved configurations for low observability. In each of these cases, the critical sections more susceptible to failure, such as aircraft skin, embedded engine exhaust systems, etc., on aircraft structures may endure extreme environments characterized by elevated temperatures, intense acoustic effects, as well as additional structural loads introduced by high speed and prolonged flight. Although many of these disciplines have been considered in the past, most works focus only on part of the combined loading situation that these new extreme conditions pose. In regards to previous methods of aircraft design, many times specific loading conditions, such as the ones created from vibro-acoustics, are neglected because of their relatively small size compared to other structural or thermal loads. In addition, the response of aircraft components under dynamic acoustic loading has been difficult to predict. This approach is insufficient for the effective design of complex aerospace structures, such as internal ducted exhaust systems and sensitive airframe designs, because the true structural response is a combined loading effect that requires attention from all disciplines. The high cycle acoustic loads resulting from the vibro-acoustics can significantly decrease the fatigue life of aircraft components when added to primary structural or thermal loading environments. Thus, a multidisciplinary computational analysis and simulation for aerospace structures should be considered in future aircraft designs.

When an aircraft travels through the atmosphere at hypersonic speeds during sustained flight, random intense acoustic environments are introduced by the air flow, wake vortices, and the vehicle's propulsion system with varying sound pressure at different locations on the structure. The structural-acoustic pressures transmit random vibration though mechanical substructures and exhaust-washed system components of the aircraft. The addition of vibro-acoustic loading directly on the surface structures at certain excitation frequencies creates high cycle fatigue issues and premature structural failure [1]. As a result, acoustic effects become very significant to the fatigue life of critical constituents that already experience loading forces from structural, aerodynamic, and thermal conditions. Aircraft that rely on low observability from both radar cross section and infrared detection utilize the concept of embedding engines inside the airframe. Ducted paths for the expulsion of the hot exhaust gases experience extreme thermal loads, while engine noise and exhaust flow contribute wide-band acoustic loading to the same area. The substructures that surround the engine and the components of the exhaust nozzle or aft deck experience heightened acoustic excitations. Previous research investigated the premature cracking of the aft deck of the B-2 Spirit shown in Figure 1. The work concluded that nonlinear thermal stresses initiated cracking and random acoustic loading accelerated the crack growth to component failure [2].

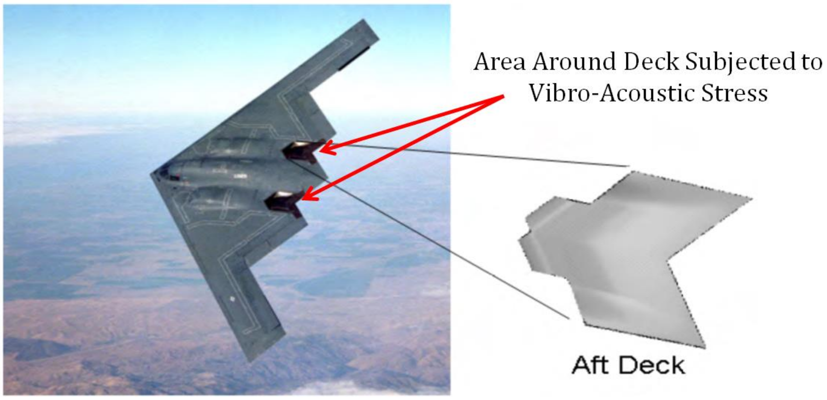

Figure 1: Location of the aft deck structure relative to B-2 aircraft [2]

Multidisciplinary optimization of airframe structures typically considered aerodynamic and structural disciplines in iterative design processes in the past. Most investigations involved linear structural analysis for static displacements and stresses under multiple flight load conditions. In addition, these procedures used integration of aerodynamic loads computed through panel and computational fluid dynamics to study steady and unsteady flight conditions. The limited number of disciplines that were considered in preliminary designs served well for aircraft in the past. With the current demand for new air vehicle platforms, including the Efficient Supersonic Air Vehicle (ESAV) concept, the technical challenges are much more critical for a reliable and cost effective operation under new and adverse stipulations. Notable challenges include the need for structural design, based on finite element analysis procedures that can account for the acoustic pressures created from the presence of airframe vibro-acoustics caused by high-lift devices and landing gear and acoustic pressure in engine exhaust washed systems caused by the implementation of embedded engines [3]. Figure 2 shows the exhaust duct configuration of a high speed, low observability concept aircraft and depicts the problematic areas of loading to which this type of vehicle would be susceptible. By analyzing acoustics loads that would be present in a multidisciplinary design of an aircraft, critical components can be redesigned or reinforced using optimization techniques and the fatigue life of system can be improved.

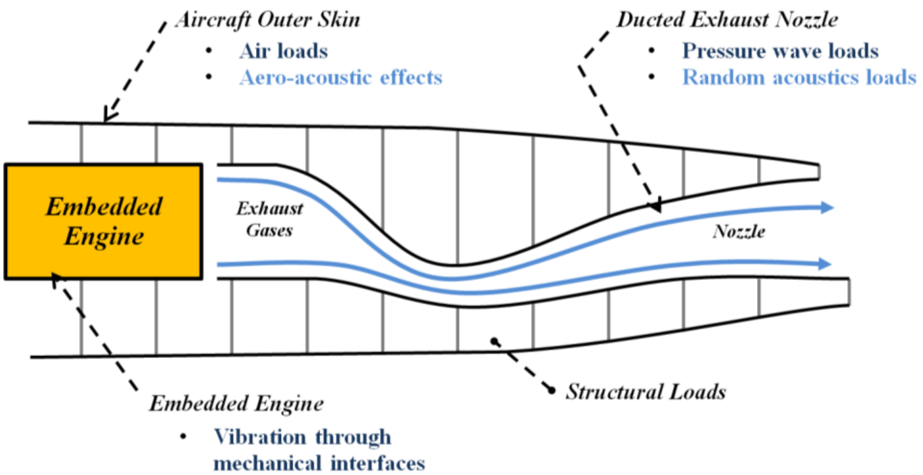

Figure 2: Schematic of high speed, low observability aircraft exhaust duct with combined loading sources

This research investigates the acoustic excitations generated from the acoustic pressure produced by structurally integrated embedded engines. The goal of this work is to study the effects of the aircraft components involving the interactions between fluid and structural coupled systems, and to optimize these structures in order to decrease the internal acoustic signature. By optimizing the integrated aircraft components that involve interactions between fluid and structural coupled systems, the structural stresses created from the high acoustic pressure magnitude of the frequency response functions can be reduced, therefore prolonging the fatigue life of the aircraft structure. This paper highlights an optimization technique that is utilized to reduce the acoustic related stress of an engine exhaust-washed structure.

Previous investigations have allowed for a comprehensive study of the current representation of the ducted exhaust system model. In this work, the structural-fluid coupling effects of the system had a significant effect on the mode shapes of the model, requiring future models to include the fluid domain in the analysis. Preliminary optimization results showed that the structural thickness can be altered in order to reduce the maximum acoustic pressure observed within the system [4]. Gradient based methods, such as SQP, as well as an adaptive/hybrid optimization search algorithm were utilized to optimize the structure in order to reduce the acoustic pressure and mass of the system. With the dynamic frequency dependent loads and stresses that are seen in this problem, a new optimization formulation was implemented utilizing a critical point constraints technique in which areas prone to experience larger stresses are monitored.

4. Problem Description

Acoustic pressure waves that induce structural vibrations have been major fields of research interest. In the separate works by Akl et al. [5], Pretlove [6], Hong and Kim [7], and Kinsler et al. [8], the structural-acoustic problem was studied using numerical expressions for the two domains. It is apparent in this literature that the two connecting domains, the flexible structure and acoustic cavity, can be adequately coupled together and that the entire system can be studied as a whole. In most of these related vibro-acoustic works, the main objective was to study the changing effects of acoustic pressure and acoustic noise. In this work we are primarily concerned with the structural effects and impact from an acoustic source load. Therefore, we have to relate the acoustic pressure to structural stresses, and couple these effects with the structural vibrations present in the system in order to effectively model the response.

In most real applications, the vibro-acoustic systems that are studied involve complex shapes and require a fine discretization to capture the geometry. So although analytical functions are the basis for solving the structural-acoustic problem, they cannot be practically used for describing the spatial distribution of the primary variables. Instead, numerical approaches are utilized. The finite element analysis tool that is used in this work is Abaqus 6.10 [9] for its widely accepted standards and capacity to incorporate dynamic and vibration responses.

A simplified model representation of the complex embedded exhaust-washed structure (EEWS) is used to gather a better understanding of the physical acoustic phenomena occurring in this type of environment. This model retains most of the components from a real model, but reduces the complexity so the results can be better dissected. The simplified model representation of the embedded exhaust-washed structure can be seen in Figure 3 below.

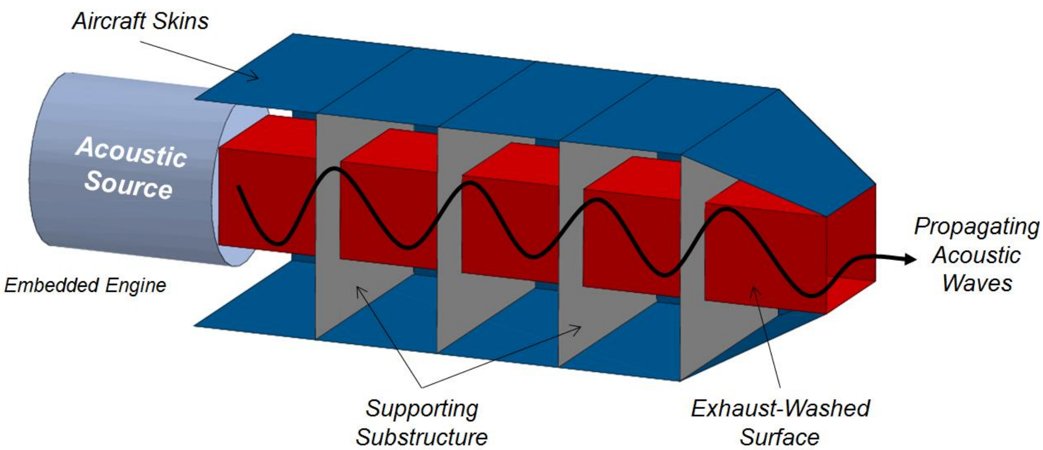

Figure 3: Simplified engine exhaust-washed structure

As shown above, the curved geometry of an actual EEWS is represented by a rectangular cross-section duct, and the complicated supporting structures are simulated by using a reduced number of square panels. The acoustic source is simulated by using a dynamic distributed pressure load on the front surface of the exhaust system. The surrounding aircraft skins and other mechanical interfaces are approximated by applying simply supported constraints on all of the edge nodes of the substructures as well as the front and rear edges of the ducted exhaust path. In this setup, an acoustic cavity measuring 0.75 x 1.0 x 5.0 meters is enclosed by five structural walls. At the rear of the duct, infinite acoustic elements are created to represent an exit to an unbounded domain. Four substructural panels, with the same material properties as the main structure, are connected to the duct structure at one meter intervals. The material used for the structure in this analysis is typical Aluminum 2024 and the fluid used in this analysis is standard air at 20 °C and 1 atmospheric pressure. The damping coefficient given for the aluminum material is $\zeta = .004$ or 0.4%. The meshed structure and air (although coupled together in the analysis) are shown separately in Figure 4.

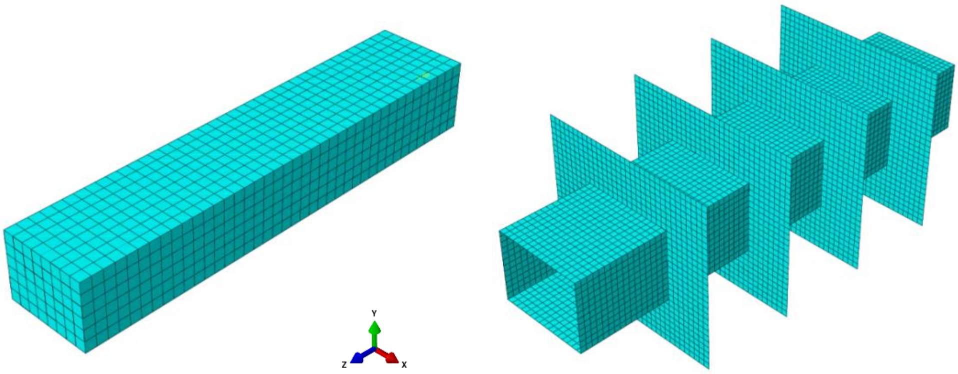

Figure 4: Meshed fluid (left) and structure (right)

The boundary conditions, as specified previously, are simply supported conditions on all four edges of each substructure as well as all four edges of the front and the rear edge of the duct. The dynamic pressure load on the front surface (fixed thickness during optimization) is simply a sinusoidal loading function with a magnitude of 1500 Pa to simulate the acoustic pressure from the embedded engine.

5. Design and Optimization Approach

5.1. Prior Investigations

In recently documented studies [4], it was evident that the exhaust system model must be studied using a coupled analysis if correct natural frequencies, mode shapes, and/or frequency response functions are to be obtained from the whole system. This was accomplished by performing a frequency analysis on coupled and uncoupled models of the system and using modal indicators to determine the actual impact of the structural-acoustic interaction. Another important aspect of the work comes from the parametric study on varying the structural thickness in this structural-acoustic coupled environment. The frequency response functions were obtained from a location at the rear of the exhaust structural, near a corner boundary condition (shown by the red dot at the far left of Figure 5). The study shows that at this acoustic nodal location, the increase of material thickness decreases the acoustic pressure magnitude. However the tendency observed does not define the frequency output at all nodal locations of the system. For example, an additional study was conducted where a nodal location was observed at the center of the top panel in segment one. In this study, it was determined that increasing the model thickness actually increased the acoustic pressure at the boundary of the structure, a reverse effect of the previous nodal location. To further explore this panel, stress values were extrapolated from the acoustic pressure, as shown on the image to the right of Figure 5. This research concluded that that fluid and structural damping properties, as well as the compliability of the panel, promotes damping of the acoustic pressure and related stress in the frequency response function of the system. This effect is apparent in nodal locations where the structure can more easily expand/contract, and is less evident in more rigid locations near supports or boundary conditions.

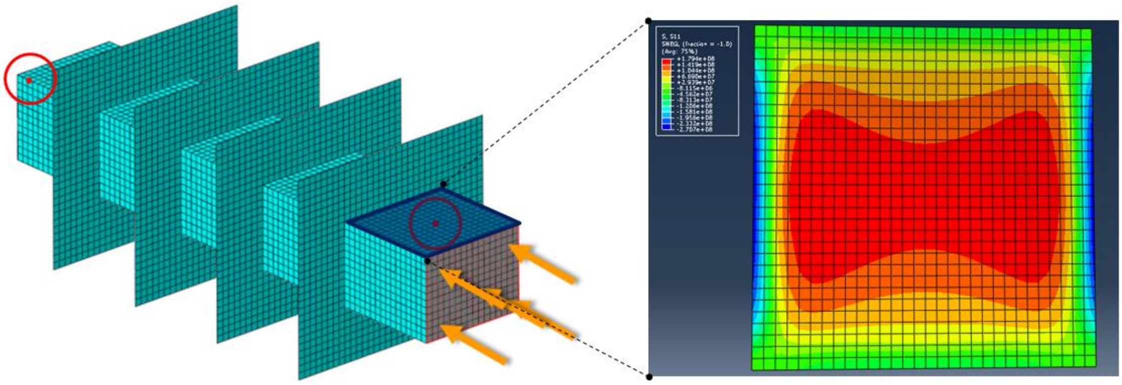

Figure 5: Locations of conflicting acoustic load tendencies

The conflicting acoustic effects at differing nodal regions add more complexity to this already challenging dynamic coupled problem. Re-designing the structure to minimize acoustic loading effects at one nodal region can result in the acoustic related stress to significantly increase at another region. This introduces the need for optimization in this problem, where the correct optimization schemes can exploit the controversial behavior of this acoustic design effect. Utilizing optimization, the mass of the system can be minimized while constraining the stress magnitudes at all critical locations in the system.

5.2. Design Goal

On a low observable aircraft, the embedded engine structures have been meticulously designed and tested for exact specifications. For this reason, much of the geometry and location of the exhaust ducted path itself is fixed and unlikely to drastically change. However, the areas located between the exhaust duct and the aircraft skins, which contain the substructure supports, do not influence the exhaust flow and could be redesigned. It has been proven that the location, shape, and thickness of these members influence the acoustic pressure distribution throughout the exhaust duct system [4]. Although the area and shape of the inside wall of the exhaust duct is most likely fixed, the opposite surface (within the subspace between the aircraft skin and the exhaust washed structure) can be supported or reinforced. Using this thickness optimization ideology, the initial or baseline design will change through the process and determine where more material should be added and where material should be taken away.

5.3. Objective Function and Constraints

The cost function and constraints in this optimization setup are directly dependent on goals described in the previous section. For this analysis, the objective function is to minimize weight of the structure subject to constraints on the structural elements' stress values. Initially a constraint was put on the acoustic pressure seen at the boundary of the fluid and structural domain, but since the primary goal is concerned with the effects that this pressure has on the structure, the definition was modified to constrain stresses on the structure. Utilizing this methodology allows the optimization statement to not only account for the acoustic pressure acting on the structure, but also the mechanical vibrations that travel through the duct walls. However, the stress constraints depend on the frequency and spatial locations of the problem because of its dynamic and coupled nature. Another issue that stress constraints cause in this complex problem is that the optimization setup used is computationally affected by the number of total constraints. After mesh convergence, the current model of the exhaust duct requires approximately 7500 structural elements, which translates to 7500 elemental stress constraints that must be placed on the finite element model. Utilizing a critical point constraint technique, will not only account for the stress dependence on the frequency and spatial regions, but significantly reduce the number of constraints used in the problem formulation. Through extensive studies conducted on the duct model, the regions of elevated stress on the exhaust duct were discovered and monitored using the critical point constraints technique. For visual purposes, these elements are highlighted on the last segment of the exhaust duct shown in Figure 6 (applied to all segments of the duct). The stresses in the substructures are not monitored in this analysis, because the elemental stress is very dependent on the boundary conditions. Since only simply supported boundary conditions are used as an approximation, the stresses that result from these conditions on the substructural panels will be inaccurate. The same stress spikes will be seen at the front of the structure near the approximated load. Since realistically there will be no plate at the front of the exhaust duct, the stress that arise are unreliable. However, the stresses obtained from the duct itself, away from the substructural edge boundary conditions and front loading of the system, will be more true to the actual stress response.

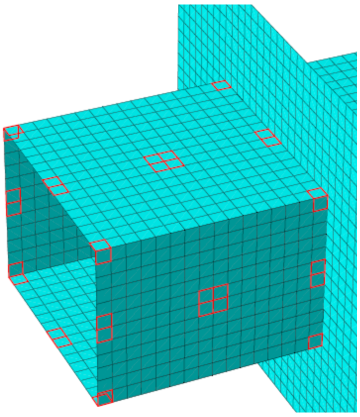

Figure 6: Critical Point Constraint Regions

Another set of bounds applied on this problem deals with the frequency range of interest. From previous analyses of the frequency response for this type of structure, the maximum pressure peaks occur anywhere from 12 Hz to 90 Hz. Although the engine will most likely operate at much higher frequency ranges, this analysis is to develop the tools in order to accomplish a structural-acoustic optimization of a system in a multidisciplinary loading environment. For this reason, the analysis will be constrained to a frequency range of 0-120 Hz. To accurately capture the peak acoustic pressures, even with structural damping applied to the model, a frequency step size of 0.1 Hz should be used. The frequency response function was plotted for the baseline design, and can be seen in Figure 7.

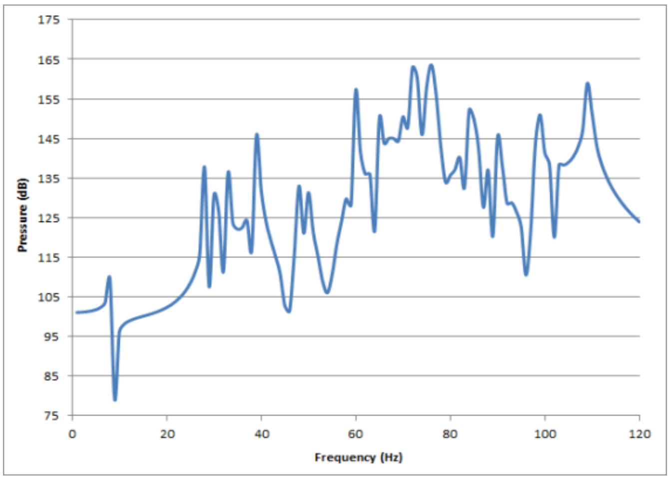

Figure 7: Frequency response function of baseline design

5.4. Design Variables

The design variables in this optimization setup, like previously specified, are the structural thicknesses on sections of the exhaust duct. Each element of the duct and substructures could potentially be a thickness design variable, but this approach would be improbable to manufacture. Therefore, for this optimization problem the design variables that were chosen are the thickness of the duct walls and the four separate substructures shown in Figure 8. By utilizing the model's symmetry and design variable linking techniques, t1 and t2 were established for the horizontal and vertical walls of the duct.

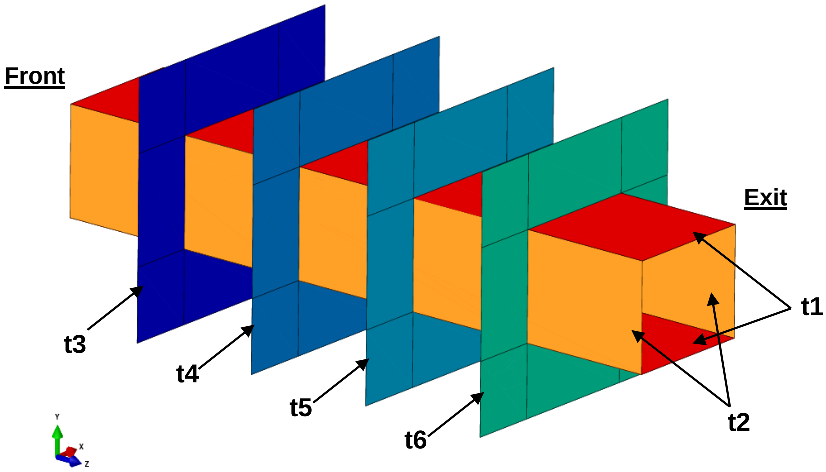

Figure 8: Design variables shown in different colors

5.5. Problem Statement

The optimization problem statement containing the objective function, constraint functions, and the side bounds on the design variables is shown below

$$\text{Minimize:} \quad h(x) = \text{Total Mass}$$

$$\text{Subject to:} \quad g_1(x) = \sigma / 100\ \text{MPa} - 1 \leq 0\ \text{MPa}$$

$$\text{Design Variables:} \quad x_i = [t_1, t_2, t_3, t_4, t_5, t_6]$$

$$\text{Side Bounds:} \quad 1\ \text{mm} \leq x_i \leq 10\ \text{mm}$$

Where σ is the Von Mises stress of the critical elements and t is the corresponding thickness for each design variable.

6. Solution Approach

The optimization process utilized in this research combines two different optimization schemes. This first method utilizes an adaptive global search technique from the optimization package developed by Red Cedar Technology. Then the second method takes this information and applies gradient based functions to locally optimize the structure. In this way, the dynamic and frequency dependent structural-acoustic problem can be effectively optimized to reduce the vibro-acoustic stress while minimizing weight.

6.1. Computing Sensitivities

The Abaqus FEA model is originally ran at the initial design point to obtain the function value. The initial baseline variable dimensions are: $t_1 = t_2 = \cdots = t_6 = 5.0\ mm$, which are values at the mid-point between the side bounds. The FEA can be conducted again by taking a small variation in the design variable range in order to obtain the gradients by the forward finite difference method. These gradients are utilized in the sequential quadratic programming method of optimization that is initiated for finding a better design solution.

6.2. Optimization Process

For this research, the design variables were initialized and the objective function and constraints were evaluated using Abaqus (structural-acoustic coupled FEA). The optimization process flowchart, shown in Figure 9, then requires the gradients to be evaluated, optimize algorithms, and redesign the problem. For small changes, function approximations are used on the constraints until this inter-loop optimization problem converges. From this point the process goes back to the black box to validate the solution. This process is continued until a previously designated convergence criterion is satisfied, and then the optimization process exits with a feasible and improved design. In this research, the dynamic and frequency dependent system is difficult to represent with a function, so the optimization software HEEDS and its internally built functions are used to optimize the problem, as shown by the red dashed lines in Figure 9.

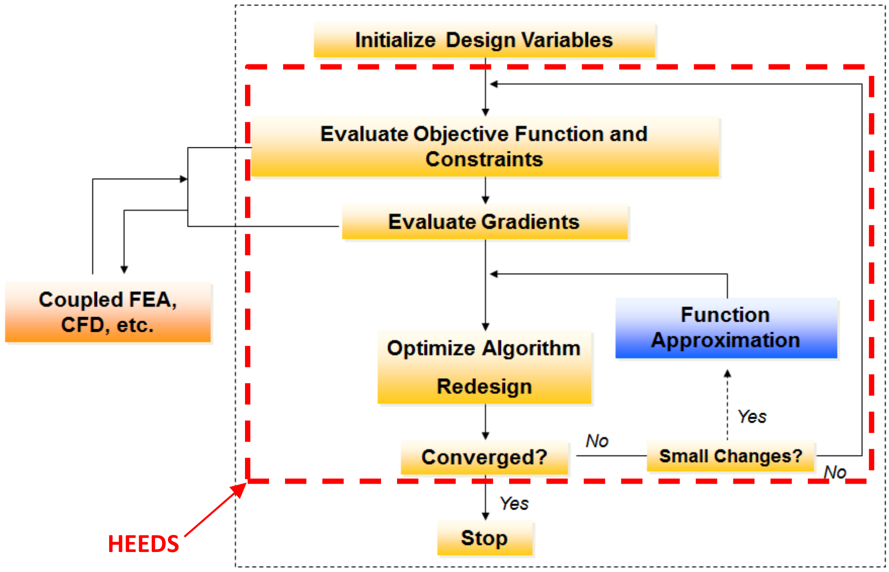

Figure 9: Optimization process

6.3. Optimization Approach

The optimization technique used in this research is a hybrid method combining global and a local optimization methods. The first optimization method used is SHERPA (Systematic Hybrid Exploration that is Robust, Progressive, and Adaptive) developed by HEEDS (Hierarchical Evolutionary Engineering Design System) of Red Cedar Technology. HEEDS is an optimization package that automates the iterative design process and uses an adaptive search strategy to efficiently find optimized solutions [11]. In the SHERPA scheme, the algorithm uses the elements of multiple search techniques simultaneously (not sequentially) in a unique blended manner in attempts to take advantages of the best attributes from each methods. In these optimization methods, each participating approach contains internal tuning parameters that are modified during the search according to the knowledge obtained from the design space. In this way, SHERPA learns about the design space and adapts in order to effectively search all types of design spaces. This type of optimization is especially beneficial for solving this dynamic and frequency dependent problem because the multi-modality of the design space causes difficulties for most typical optimization algorithms. Once the SHERPA method is used to find a global optimum for the design, these parameters are fed into a sequential quadratic programming (SQP) optimization method. Using this technique, the SQP method utilizes gradient information from the problem and locally converges to an optimum solution.

7. Results

7.1. Objective Function and Constraint Values at Initial Design Point

As previously specified, there are six design variables in this analysis, each of which corresponds to a specific thickness as labeled in Figure 8. The initial design variables are all equal to 5.0 mm thick, which results in a baseline design with a mass of 405 kg and a maximum stress value of 165.53 MPa. From this baseline study the Von Mises stress constraint is violated, and is nearly 1.5 times larger than the maximum allowable stress.

7.2. Optimization Results

The hybrid optimization technique starts with the global SHERPA approach. The plots shown in Figure 10 represent the objective function history and the constraint history of the analysis. The blue line on this plot corresponds to the best design progress during optimization, and the red line depicts the constraint value.

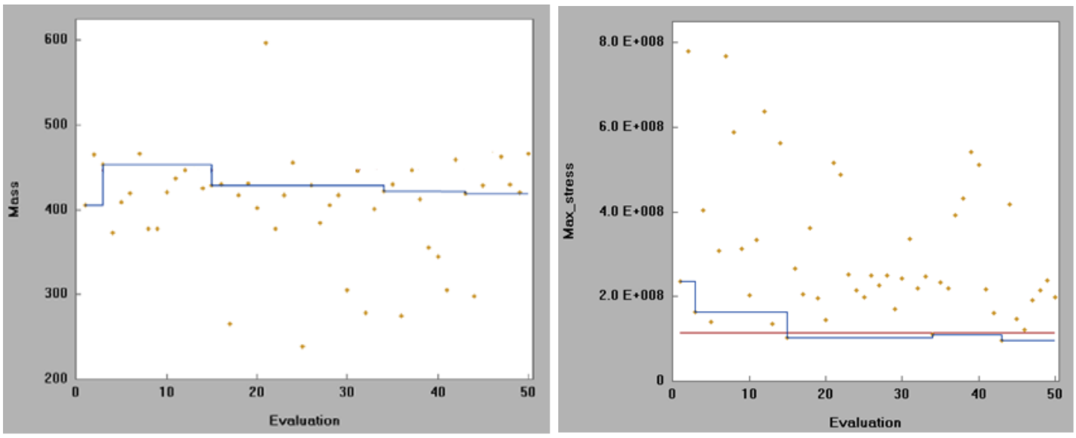

Figure 10: Objective function and constraint histories

From this analysis, it can be observed that it took approximately 15 iterations to find a feasible solution that satisfied the stress constraint. The process continued to globally search for an optimum solution while minimizing weight through the remainder of the evaluations. Near the end of the evaluation process, an improved set of variables were found to minimize the weight and satisfy the stress constraints. Since all design variables for this problem are constrained within the same bounds, they can be shown on the same plot in Figure 11. Each colored "best design" line corresponds to the same colored variable data point specified in the legend.

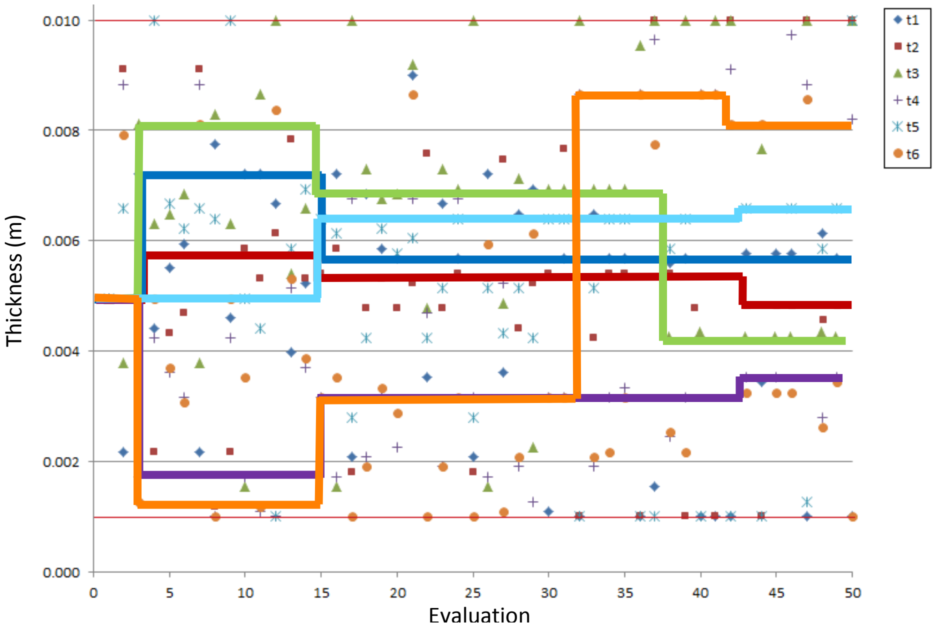

Figure 11: SHERPA "Best Design" variable history

Once the variables were approximated using the global optimization technique, these data points become the starting points for the SQP method for local optimization. Since there are numerous local optima in the multi-modal design space, the sequential quadratic programming method requires the global approximate solution in order to converge on the best design. In the thickness variable history shown in Figure 12, it can be observed that the SQP optimization locally converges on a solution in a relatively small number of iterations. The results from using this hybrid optimization method can be seen in Table 1.

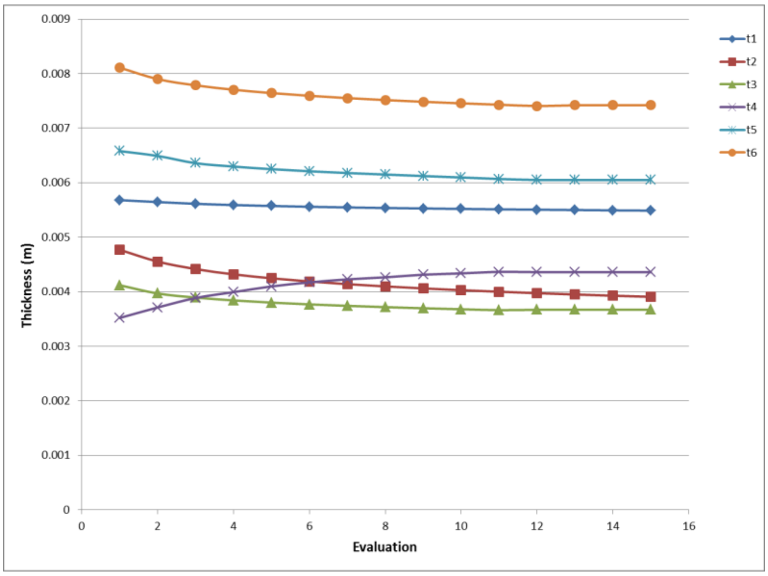

Figure 12: SQP variable history

Table 1: Optimization Results

	Thickness (mm)		
Variable	**Initial**	**SHERPA**	**SQP**
t1	5.00	5.68	5.48
t2	5.00	4.77	3.91
t3	5.00	4.12	3.67
t4	5.00	3.52	4.36
t5	5.00	6.58	6.05
t6	5.00	8.11	7.42

Responses	**Initial**	**SHERPA**	**SQP**
Max Von Mises Stress (Mpa)	165.53	79.25	99.57
Mass (kg)	405.00	436.0	407.03

8. Conclusions

Through the hybrid structural-acoustic optimization method implemented in this research, the mass of the system was reduced while constraining the stress at the critical locations. By utilizing the HEEDS global optimization scheme, an approximate set of thickness variables were obtained. These variables resulted in a stress magnitude that satisfied the constraint, although the mass did increase from the baseline design. Then by implementing a sequential quadratic programming optimization algorithm that utilized the previous data gained from the global optimization technique, an even better design was obtained. The local optimizer was able to reduce the mass of the global answer by approximately 30 kg, and this mass was nearly equivalent to the original mass of the baseline design. The major improvement was that the stress constraint was now satisfied, along with the weight reduction.

With this optimization approach one can see that there is a structural tendency in this particular problem. It can be seen that the top and bottom sections of the duct become thicker than the left and right sides. This could be due to the fact that these areas are larger than the side areas, and have more effect in reducing the stress at the corner locations observed. Another observation from these results is that as the substructural panels get farther away from the acoustic pressure source, the thickness increases. This could be as a result of the system to compensate for the larger modes that are observed at the outlet of the duct system.

In this research, it is important to use a hybrid optimization approach because of the nature of the structural-acoustic problem. The dynamic system is dependent on time and frequency, and very sensitive to small steps especially around peak stresses. Utilizing a critical point constraints technique and the hybrid optimization approach that accounts for both global and local optimization schemes, allows a better solution to be obtained in a design space that contains multiple local solutions.

9. Acknowledgements

The authors would like to acknowledge the support provided by the Air Force Research Laboratory through the Collaborative Center for Multidisciplinary Sciences.

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