

Multiphysics Approach to Design and Optimization of Hot Structures Subject to Engine Acoustic Loading

Topic Area: RQ16-15: Enabling Robust and Durable Aerospace Structures for Combined,
Extreme Environments
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Problem Statement

Ever since the advent of turbine engines, acoustic loading of the neighboring structures has been noted as a significant source of fatigue damage that tends to reduce the intended life cycle of affected components. As early as 1950's, acoustic loading was identified as a critical parameter that warrants consideration in the early design of aircrafts. Despite this observation, acoustic loads have received little attention in initial design concepts due to the complex nature of the dynamic problem that is inherent in acoustic related analysis, which can make analysis both computationally and time demanding. Additionally, acoustic loads are thought to be relatively small in magnitude when compared to structure loads imposed by aerodynamic and thermal effects. As a result, over the past 70 years there have been notable fatigue related issues as a direct consequence of poor acoustic loading considerations. To remedy the impact of these early failures, significant monetary and time expenditures are required in terms of increased frequency of unplanned inspection and repair intervals.

As aircraft designs become increasingly complex due to stealth and high speed flight requirements, the role of acoustics will become more significant and must be treated in a multidisciplinary manner in conjunction with aerodynamic and thermal loads. This is especially true for Efficient Supersonic Air Vehicles (ESAV) and Engine Exhaust Washed Structures (EEWS) that are often found in embedded engines aircraft design. Since current design practices do not lend themselves to through treatment of multi loading effects that structures may experience due to combined loading (aerodynamic, thermal, and acoustic loading), the final designs are not optimal. This lack of analysis lead to early skin failures on the upper wing section of the F-15 fighter, which is a generation 4 aircraft. It is only natural that this issue is propagated to generation 5 aircraft such as the B-2 spirit stealth bomber, where aft-deck of the embedded exhaust structure fails prematurely due to a combination of thermal and acoustic loads [1]. Above two examples clearly demonstrate a need to develop better physical understanding of the interactions between acoustic and thermal loading within the embedded exhaust structure. More specifically, work proposed herein aims to employ a coupled fluid-structure model of the exhaust structure under the acoustic and thermal loading to accomplish following tasks:

- Incorporate heat transfer analysis of the coupled fluid-structure EEWS model to ascertain the temporal distribution throughout the structure.
- Use the temperature distribution results to obtain thermal stresses, which the exhaust structure will experience.

- Perform modal analysis on the thermally loaded fluid-structure model in order to determine dynamic response of the model and the coupling nature of the fluid and structure subcomponents.
- Utilize the modal analysis results in conjunction with periodic/random dynamic loading in order to simulate stress response of the structure.
- Utilize stress results from the coupled thermal acoustic loading case in conjunction with topology optimization techniques in order to obtain superior design of the EEWS.

Accomplishing the above stated tasks will help further understanding of thermal and acoustic loading interactions. It is especially interesting to study the effect thermal buckling has on acoustic loading within the exhaust structure, which can have profound impact on fatigue performance of individual panels that comprise the complete system. The methods developed by the proposed work will give rise to novel design configurations that otherwise would not be immediately discernible by conventional design practices. Consequently, this advanced treatment of the acoustic loading effects will serve to reduce unexpected failure occurrences due to lack of physics in initial design phase. This will in turn reduce unexpected repair costs and schedule delays for future aircraft platforms.

Background

As stated in the prior section, acoustic vibrations became a significant source of loading, which the aircraft has to sustain during operation. This was the result of incorporating jet engines in the mainstream aircraft design in the 1950's. In these very early inceptions of jet engines, it became quickly evident that secondary structures that were in the vicinity of the jet engine experienced fatigue failures [2]. As these types of failures became more frequent, government agencies of that time such as National Advisory Committee for Aeronautics (NACA, today known as NASA) began to study acoustic effects of jet engine noise on surrounding components [2-4]. Majority of failures experienced were in the aircraft skin and exhaust structures near the outlet [3]. Acoustic loading driven by the jet engine noise is typically occurring in high frequency ranges that can be as high as 1000 Hz [5]. This translates to more than a million fatigue cycle loads in a single flight. Since acoustic loading is a high cycle fatigue phenomenon, majority of fatigue life is spent in initiating a crack. This is followed by a shorter period of crack growth until either the defect is discovered or failure occurs [6]. If, however a damage site is already present due aerodynamic and/or thermal loads, then fatigue life is drastically shortened since no operational life of the aircraft is spent initiating a damage site. This deleterious multi-loading interaction can cause panels to fail less than 10% into the service life [7]. These sort of fatigue cases lead NACA in the 1950's to call for acoustic analysis to be incorporated early in the design process. Failure to do so was attributed to extensive rework and repair of the affected areas, which often carried a heavy price tag [8].

Design challenges for the modern aircraft designers have only become more daunting and influence of acoustic loads has become more prominent. This is mainly driven by the need to develop aircraft that have reduced radar, infrared, and visual signatures. Additionally, there has been a push to develop more efficient airframes, which are capable of sustained supersonic and hypersonic flight regimes. Programs such as these fall under the scope of Efficient Supersonic Air Vehicles (ESAV) directive as seen in Figure 1 [9, 10]. The pictured configuration employs an embedded engine design along with the exhaust duct work as seen in Figure 2, which is

subject to thermal and acoustic loads generated by the power plant. Embedded engine configurations have become a staple of 5th generation aircraft design and is only seen to gain popularity in the future. As a result, loading characteristics of modern aircraft are highly multidisciplinary in nature and possess many coupled interactions that are hard to quantify using conventional design tools [11]. Additionally, the severity of the operating conditions cause non-linear response within the structure due to both thermal and acoustic effects. Modeling becomes even more difficult since material and dynamic properties of the structure are load and temperature dependent [11, 12]. Couple these challenges with the complex shapes required for EEWS in order to ensure low visibility characteristics renders the design space open for manipulation very minimal. Conventional practices such as increasing panel thicknesses may reduce deformation due to acoustic loading but is detrimental to thermal performance of the structure. Additionally, added weight is typically not welcome in high performance designs. Given the interplay of loading mechanisms coupled with complex and restrictive shape requirements of the exhaust structure, new modeling techniques need to be developed in order to ensure robust designs.

During usual operation of the embedded engine aircrafts, the exhaust structure will experience loading that is mainly driven by the power plant. These loads will include a combination of acoustic and thermal loads. In general, thermal loads can be considered static while acoustic loads are dynamic and cause the structure to react through a band of mode shapes and frequencies as imposed by the acoustic nature of the turbine engine [7]. Depending on the severity of the thermal loads, the structure will experience expansion, which is resisted by surrounding structure and as a result thermal stresses are generated. These stresses, can in worst cases, cause buckling to occur in selected panels. Besides the static structural effects, thermal loading can also modify the dynamic response of the exhaust structure through deflections imparted into the structure via expansion. It can also change material properties, which will have a profound effects on the dynamic response [13]. Acoustic experiments performed on heated aluminum panels show that the natural frequencies of the test articles are reduced. Furthermore, stiffness and damping characteristics are also changed, which can lead to increased deformations due to acoustic loads. Stiffness, tends to go down until buckling occurs, which in turn can increase stiffness since the panel takes on a new shape [14]. Panels exposed to acoustic loading have three modes of vibration in a thermal environment. Before buckling occurs the panel will oscillate about its neutral point. When buckling occurs two forms of vibratory response can take place. If acoustic energy is high enough, it will be able to ‘push’ the panel from one buckled mode to the other. This is also called snap-through [5,14,15]. Conversely, if acoustic energy is not high enough for snap through to occur, the panel will simply vibrate about one of the buckled points. Instances of these behaviors can be seen in Figure 3 [15]. Each one of the modes pictured in Figure 3 will have a certain effect on fatigue performance and it is critical to understand these effects if meaningful predictions about fatigue performance are to be made.

Based on the discussion above, determining the influence of thermal loading on the dynamic response of the structure is an integral part of any posed solution to the acoustic problem. As such thermal analysis is necessary to infer the spatial temperature distribution of the exhaust structure and is shown in Figure 4. Temporal values can then be used to evaluate the thermal stress within the structure, which in turn are used to study the dynamic response of the coupled fluid-structure system due to acoustic loading. To the knowledge of the author this sort of analysis has not been carried out on EEWS. Since thermal and acoustic interactions are not well understood, design challenges for these types of structures is quite daunting and likelihood

of suboptimal design selection is likely. Therefore, to ensure sound design practices for future aircraft designs, whose requirements will only become more demanding, good understanding of thermal and acoustic interactions is integral to success.

Technical Development and Proposed Work

Multidisciplinary nature of the proposed work will require it to be discretized into sections that will build upon each other to produce a complete body of work. The first step will include the thermal analysis in order to determine the temperature distribution throughout the exhaust structure. This will be necessary in order to account for the thermal stresses which will act on the structure. Additionally, the increase in temperature will also affect the material and dynamic properties of the model, which must be accounted for to maintain proper fidelity of the model. Once thermal contributions have been identified, modal analysis can be carried out in order to calculate the resonant frequencies and critical modes shapes that will dominate the response of the structure. Subsequently the modal analysis can be used in conjunction with a dynamic excitation force (periodic/random) to estimate displacements and stresses within the structure. Stress results can then be used to derive topology optimization results capable of sustaining the harsh operating environment found with the EEWS.

After the implementation of the thermal analysis one of the most critical aspects of the proposed work will be accurate dynamic response of the coupled fluid-structure EEWS model. Modal analysis has been already carried out within our research group on simple EEWS representations as seen in Figure 5 [11]. Work done by Vogel [11] extensively studied the dynamic response of the fluid-structure interactions of the model shown in Figure 5. Simulation results show that coupling interactions played a significant role in the modal response of the system. Failure to account for the exhaust volume inside the EEWS cavity affected the modal shapes and natural frequencies significantly enough to impact proper stress response of the model under dynamic loading. Given this prior work, the plan is to utilize this model and modify it to include thermal effects. This method of analysis will make it easier to identify the impact thermal loading will have on the modal response of the system. Effects such a buckling, frequency shifting, stiffness impacts, and modal shape changes should be clearly identifiable. Once thermal effects on the modal response have been fully characterized, the plan is to move to a more representative EEWS model, which will be comprised of more complex shapes indicative of real world EEWS designs as seen in Figure 6. It has been stated in the prior work that shape complexity induces more pronounced fluid-structure interactions. Furthermore, curved structures tend to have higher coupling tendencies between flexural and membrane modes. This effect will be studied accordingly.

Following the modal analysis and verification, the results can be used to simulate displacement and stress response of the models proposed above. Initially as simple periodic loading condition will be implemented. This will lend itself to easier interpretation of the results at the initial stage. Following this, random loading inputs shall be implemented to compare and contrast the response of the structure with respect to the periodic loading case. Attempt will be made to acquire random acoustic loading generated by a jet engine. Furthermore, test are planned at AFRL which are intended for studying acoustic response of airframe panels. If available, loading histories from the test can be utilized for model simulations. Moreover, any future test results can be used to verify the accuracy of the multi-physics models developed.

Ultimate goal is to utilize the developed model and the subject stress predictions in conjunction with an optimization routine to achieve optimal EEWS designs that maintain proper function during operation. Work proposed herein will focus on predominantly utilizing topology optimization in an attempt to search for an optimal design. By definition topology optimization is characterized by a systematic method that seeks to find the best material distribution within the defined boundary [16]. Topology optimization is considered an iterative technique where material is either added or removed until an optimum design is achieved based on a cost function and supporting problem constraints. Many topology optimization techniques exist in the literature which include but are not limited to; Solid Isotropic Material with Penalization (SIMP), homogenization method, level set method, and cellular division method, which is inspired by biological processes [17-20]. Each of the aforementioned methods have advantages and drawbacks, which have been effectively summarized by Deaton and Grandhi [21]. In work done by Vogel [11], modal results were used in conjunction with a periodic loading sequence to perform a panel thickness optimization on the model shown in Figure 5. Due to the spatial and multi-modal considerations, the design space may have multiple local optima which make the optimal solution dependent on the initial design configuration. To circumvent this problem a hybrid optimization technique was implemented, which combines global and local search algorithms in order to obtain an optimum design. Details of the implemented method can be found in reference [22]. Since the proposed work will have similar spatial and multi-modal dependencies hybrid optimization techniques such as presented above will be thoroughly investigated for implementation in topology optimization.

It was noted as far back as the 1950's that high sound pressure levels (SPL) can cause nonlinear modal response within the structure. These nonlinearities were evident in the panel tests carried out by Lassiter and Hess [4] where frequency response functions developed skewed response shapes with increasing SPL's as seen in Figure 7. Asymmetric peaks were contributed to increase/decrease in panel stiffness. Additional effects of nonlinearities are response broadening and frequency shifting to higher values as was pointed out by [7, 8]. Curve broadening has been attributed to change in damping of the system and curve peak shift is credited to stiffness changes within the structure. Additionally, strain response is typically over-predicted if linear analysis is used in the nonlinear regime. All the aforementioned influences are seen in Figure 8. Nonlinear impact to frequency and strain response will have a significant impact on fatigue performance of the acoustically loaded structure. Therefore, as part of future work it will be noteworthy to explore nonlinear impact to the proposed work. Presently, reduced order modeling is a highly utilized method to perform nonlinear modal response while maintaining computational times to reasonable levels [5,7,22]. Such a method or equivalent can be employed herein to study impacts of modal nonlinearities.

Relevance to Previous Work

Work proposed herein plans to expand on previous work done on the acoustic problem within our research group [11]. In past, fluid-structure interactions were studied and found to be significant. However, thermal effects and random loading effects are still to be analyzed. Ultimate goal is to unify thermal and acoustic loading under a single multidisciplinary approach, which is the goal of the proposed work. Additionally, significant amount of effort has been expended within our group on the thermoelastic problem of EEWS [10,12]. Furthermore, my advisor Dr. Ramana Grandhi is a published leader in the optimization community with over 200

authored papers. Given the past experience and expertise we are well suited to work on and tackle the problem presented by thermal and acoustic loading interactions.

Timeline

Timeframe below outlines the schedule of the proposed work. Throughout the course of the project I expect great deal of collaboration between my advisor, AFRL personnel, and myself. Since this work is performed at the PhD level schedule details are provided beyond the first year.

2016 Q1: Incorporate thermal analysis on the simplified fluid acoustic model in order to obtain thermal stresses present in the structure. Thermal stress results will then be added to the model for further simulation work.

2016 Q2: Perform modal analysis on the simplified EEWS model to ascertain the impact thermal effects may have on the dynamic response of the structure. The results will be used to fully characterize the impact thermal influence by contrasting the results with prior work which did not possess thermal inputs. This step will be critical moving forward.

2016 Q3 (summer): Intent is to spend the summer working full time at the WPAFB. While there, lessons learned from the simplified fluid-solid model to perform thermal and modal analysis on more representative complex shape EEWS model. Effects of structure complexities with respect to thermal effects will be fully investigated.

2016 Q4: Thermal-modal analysis and quantification performed over the summer will be used in conjunction with periodic and random loading signals to generate displacement and stress results from the simple and complex shape models under thermal effects.

2017 Q1: Stress results from the fluid-solid coupled EEWS model will be used to perform topology optimization in an attempt to generate optimal structures that will sustain combined thermal and acoustic effects. Method for topology optimization has not been defined yet but hybrid methods will be given priority based on previous experience with fluid-structure optimization results. Results will be documented and methodologies delivered to AFRL.

2017 Q2: Study non-linear modal effects due to loading conditions. This may be performed by reduced order modeling techniques or equivalent method.

2017 Q3: Since modeling and analysis will be well defined at this stage, efforts can be shifted to study uncertainty quantification of the acoustic loading envelope and material properties of the model.

2017 Q4: Using all the work outlined above simulations, which include uncertainty quantification can be utilized to generate stress spectrums for the EEWS. These spectrum can be converted into fatigue loading block cycles via rainflow counting methods that can be used for fatigue life estimation.

Expected Results and Significance

It is expected at the end of the project to obtain significant findings on thermal and acoustic interactions which govern lifecycle limits of EEWS. Results of this work will provide multiphysics modeling techniques and tools to be used in design and simulation of component reactions to thermal and acoustic loading environments. This not only applies to embedded exhaust structures but has potential to be modified for use on hypersonic vehicle skin analysis,

where thermal and acoustic loading due to high speed airflow are significant. The newly gained knowledge can help save the Air Force millions of dollars by preventing inadequate designs from reaching maturity only to fail soon after service life begins.

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Figures

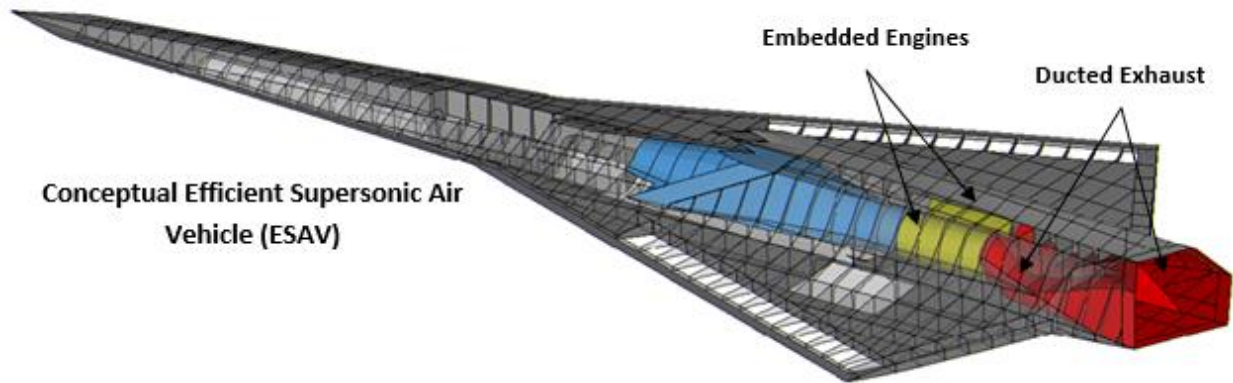


Figure 1: Embedded engine design configuration for the ESAV concept pictured above.

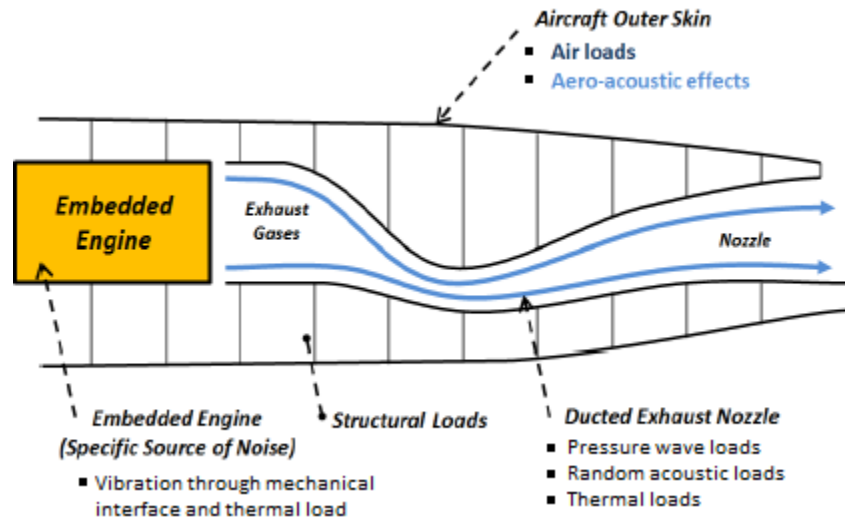


Figure 2: Typical exhaust nozzle design with the embedded engine shown.

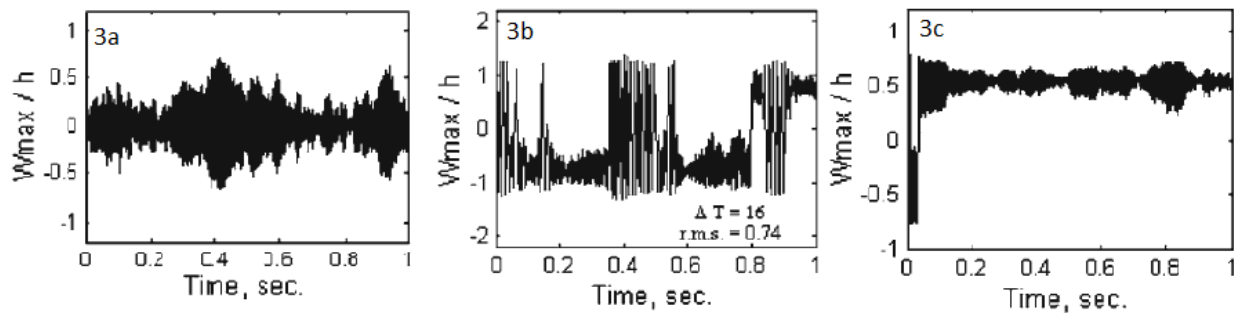


Figure 3: Dynamic response of aluminum panels subjected to thermal loading. 3a) non-buckled panel subject to acoustic loading. 3b) Post-buckled panel showing snap-through. 3c) Post-buckled panel vibrating about a buckled position.

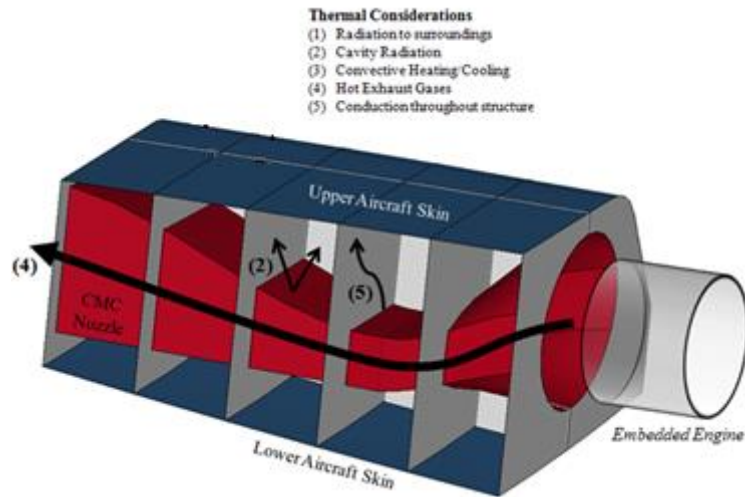


Figure 4: Thermal modeling considerations for EEWS.

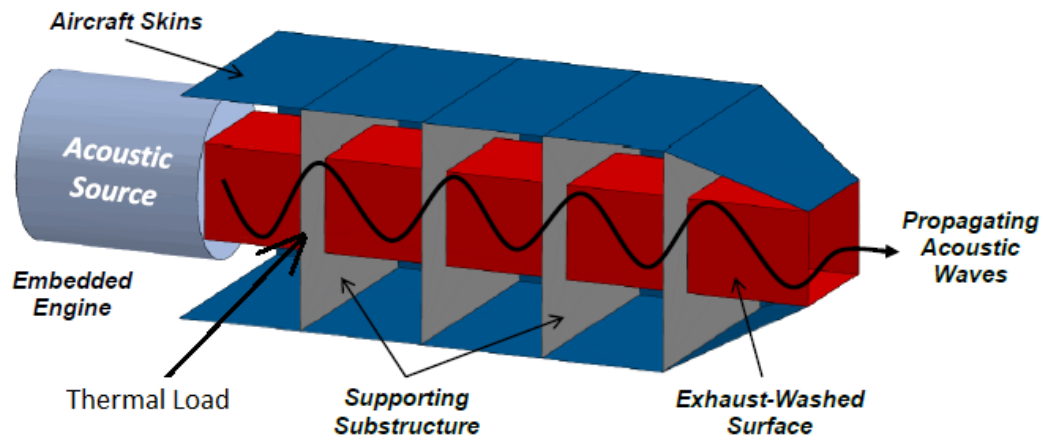


Figure 5: Simplified representation of the EEWS.

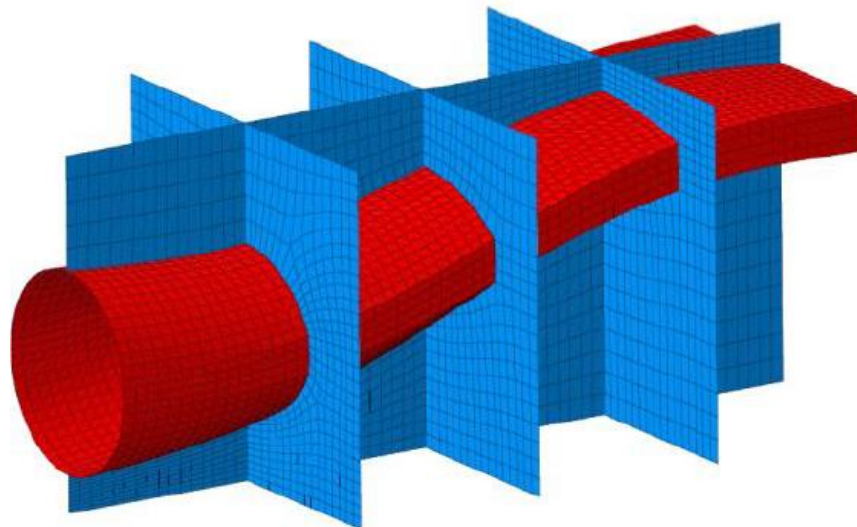


Figure 6: More representative shape for the EEWS.

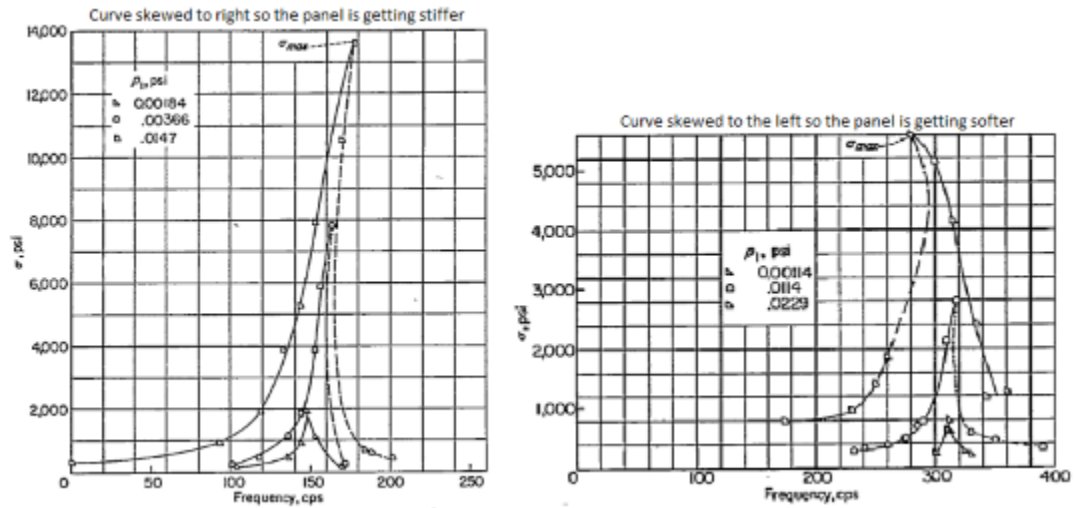


Figure 7: Asymmetric frequency response curves due to increased sound pressure levels

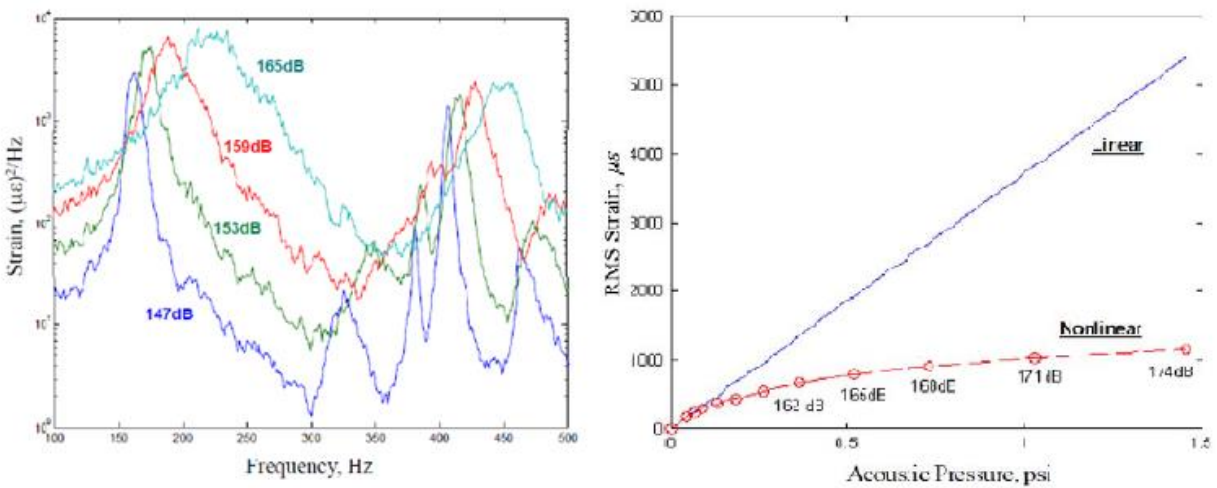


Figure 8: Frequency response function peak shifts and broadening due to nonlinear effects.