Problem Statement **Multidisciplinary Size, Shape, and Topology Optimization of Thermoelastic Structures Under Combined Loading**

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Meeting demands for aircraft versatility, mission capability, and combat survivability is becoming increasingly difficult. The ability to remain undetected is one of the most important factors in meeting these demands. Modern aircraft and future aircraft relay on low observabled technology to accomplish. An essential component of low observable technology is embedded engine integration. An embedded engine uses exhaust ducting, known as exhaust washed structure (EWS), which is part of the aircraft structure itself to route exhaust to the rear of the vehicle. The low observability design criterion for EWS creates strict geometric requirements on their design. This restraint on thermal expansion causes high thermal stresses to develop making the EWS susceptible to thermal buckling and fatigue.

In the modern day, there exists a need for high performing, reliable hot structures for use in the extreme thermal environments found on hypersonic vehicles, atmospheric reentry platforms, and low-observable embedded engine aircraft. To date, structures designed to operate in these environments represent highly non-optimal solutions and have frequently failed due to a lack of understanding of fundamental interactions of different physics in this complex design domain. This is evidenced in the repeated failures of thermal protection panels on NASA's Space Shuttle and a hot exhaust structure known as the aft-deck on the Air Force's B-2 Spirit bomber. As such, the coupled effects of heat transfer, structural mechanisms, and thermoelasticity are seen as detrimental with regards to design. However, as in the case of aeroelastic tailoring, the possibility exists to study the basic physics at work in this environment and exploit coupling to develop superior performing designs. By using multiphysics topology, shape, and sizing optimization, we propose to tailor thermoelastic behavior of high temperature structures such as aircraft exhaust-washed structures and hypersonic thermal protection systems (TPS). Specifically, in this work we will:

* Extend the capability of an existing in-house topology optimization code to include heat transfer effects with proper sensitivity analysis to capture thermal design dependency.
* Incorporate state-of-the-art stress-based design methods for topology optimization that are more suitable for thermoelastic responses than classical methods.
* Benchmark the in-house topology optimization code against a novel cellular division-based method for application to the thermoelastic tailoring of hot structures.
* Deliver a coupled thermal-structural optimization capability suitable for thermoelastic tailoring and design of next generation hot structures.

These tasks will produce new design methodologies to tackle several challenging thermoelastic design criteria including thermal stresses, thermal buckling, and excessive expansion, which often behave non-intuitively and are not well addressed by conventional design practices. Such developments are critical in order to reduce both acquisition cost and life-time maintenance expenditures for a broad class of aerospace hot structures.

This issue caused cracking and failure on the B-2 bomber’s aft-deck well in advance of the aft-decks intended life. This issue costs the Air Force significant funds in replacement and retrofitting. A more accurate optimized technique needs developed to more accurate predict these thermal stresses during EWS design.

# Background & Relevance to Previous Work

Research into thermal structures first appeared in the late 1940’s with the advent of supersonic flights. This field focuses on heat trasnfer as well as the effects of temperature on engineering materials. Temperature affects structures through altering the material properties and can introduce stresses in the material if thermal expansion or contraction is restrained or if a temperature gradient is present.

The study of thermal structures was developed significantly in the 1950’s by Boley and Weiner, and Gatewood. Boley and Weiner used a mathematical approach and provided the coupled governing energy equation for heat transfer and elastic equilibirum equations for linear thermoelasticity. Limited analysis of nonlinear thermal structures was also described. Gatewood used an application approached focused in aerospace components. Analytical solutions are provided for basic geometry, but the majority of discussion focused on assembled structures such as skin-stringer combintions and joints in two dimenions.

Thornton helped address two topics significant to modern thermal structurs in 1996. Geometric nonlinearity in thermal structures is examined with approximate solutions to large displacement beam and shells structures. He also introduced discretized numerical analysis methods, including the finite element method (FEM), for use in thermal structure design. Advances in the computational ability of computers has made FEM techniques much more viable and these have been introduced in commercial programs such as ANSYS, Abaqus, and Nastran.

The design of aerospace structures for elevated temperature environments has been a critical area of research since the early 1950’s and the onset of supersonic flight. As flight speeds increased, designers realized that the elevated temperatures resulting from high speed aerodynamic phenomena and the effects on aircraft structural performance would place a “thermal barrier” on supersonic flight. In response, a new area of research emerged known as *thermal structures* to help overcome this barrier with advances in aerospace materials and innovative structural designs [1].  
 In the present day, thermal structures continue to be a driving facet of modern military aircraft designs due to the desire for low-observability and the use of embedded engines. The design of these structures is complicated by the extreme combined environment in which they must operate. This environment leads to nonlinear structural responses due to material and geometric nonlinearity and both large temporal and spatial temperature gradients.

When structural components are subjected to elevated temperatures or a spatial/temporal temperature gradients, they undergo some amount of thermal expansion. If this expansion is restrained by rigid fixivity to surrounding structures or strict geometric layout requirements, deformation, thermal loading, and potentially damaging thermal stresses will occur. Two basic design rules for thermal structures are to minimize temperatures and gradents, and accommodate thermal expansion. Neither of these rules can be easily applied in embedded engine integration due to the low observability critereon. For example, Figure 2 shows a notional cross section of a low observable exhaust structure configuration. The geometric shape of the nozzle surface is determined primarily by low observable and propulsion efficiency design constraints. Every structural component in this region is subject to elevated temperatures from the hot exhaust and thus undergoes some amount of expansion. Thermal stresses are generated and must be addressed in the structural design. The major challenge for the designer is how to develop this exhaust structure, the geometric shape of which is fixed, and the surrounding substructure that must support it. In doing so, it is imperative to accommodate thermal expansion in some way to reduce stresses and prevent excessive thermal loading from being transferred to surrounding structures.

In this situation, the designer is faced with a complex and non-intuitive design response to variability within the design domain resulting from the design dependency of thermal loading. This means that the amount and direction of thermal loading within a structure actually depends on its size, shape, and overall configuration. For example, it has been demonstrated by the authors' that adding material by increasing the thickness of a structure subjected to elevated temperature more thermal load is generated because the added material also undergoes thermal expansion if sufficiently restrained [4]. In many thin structure configurations, like those that make up EWS and TPS components, which can be idealized as a thin curved shells as shown in Figure 3, this leads to an increase both thermal stresses and reaction load that must be carried by adjoining structures. This behavior is quite contrary to what one would expect with structural material addition (usually a stress decrease) and is demonstrated in Figure 4 (a) and (b).

It should also be noted that thermal loading in a structure is also design dependent from a heat transfer standpoint as well. The application of thermal loads to a structural model requires a heat transfer analysis to capture the true physics in the domain as shown in Figure 5. Results of this analysis are utilized to determine the temperature distribution throughout the structure. Thus, a change in the structural layout also affects the heat transfer processes and resulting temperature distributions. It is obvious that to predict and ultimately tailor hot structures, two effects must be accurately captured in both design responses and sensitivity analysis: (i) design dependency of heat transfer processes and (ii) design dependency of thermal loads due to an elevated temperature.

Optimization techniques applied to thermal structure design has been very limited and mostly used only in academic work to date. While some commercial software has the ability to solve linear steady-state thermal-structrues problems, the desgin capabilities are significantly less than analytical techniques. Optimality criteria has been developed for minimum-mass problems with temperature constraints, approximation methods for the combined thermal-structural problem, and a fully stressed design (FSD) technique for minimum-mass sizing of thermoelastic structures. Topology optimization use has been limited to thermal micro-mechanical actuation.

The absence of appropriate design methodologies for new aerospace thermal structures related to low observability aircraft and sustained hypersonic flight vehicles is one reason for this research. Topology optimization is ideal for this application. However, the majority of research into this technique has been limited to entirely mechanical problems.

The proposed work aims to investigate and develop topology optimization formulations suitable for thermal-structural design environments. These developments will then be applied to aerospace thermal structures design problems, specifically exhuast-washed structures, to develop structural systems with improved thermoelastic performance.

Dr. Ramana Grandhi and his research group at Wright State University have extensive experience in design optimization. Dr. Grandhi is the director for the Ohio Center of Excellence for Product Reliability and Optimization, CEPRO. He and his groups also have extensive experience directly involved with structural optimization for use in extreme thermal environments such as those experienced by exhaust structures. Past programs include cited works regarding the topology optimization of both exhaust-washed structures for stealth aircraft and thermal protection systems for space vehicles. Dr. Grandhi is a published leader in not only the structural optimization community, but also in area of reliability-based design, where he is co-author of a textbook on the subject [21].

A Ph.D candidate working under Dr. Grandhi, Joshua Deaton, has developed several finite element exhaust structure models based on the ESAV configuration. Additionaly, he has developed a sizing optimization technique capable of performing optimization that efficiently accounts for the effects of changes within a structure in both heat transfer and structural analyses [4]. His work has also included extending these capabilities to topology optimization although this is still in the beginning stages [20]. An example of this work is shown in Figure 7. His research will be directly used for the researched proposed here.

# Methodology & Procedure

The design challenges presented by EWS are particularly well addressed using multidisciplinary design optimization techniques, which can simultaneously manage multiple competing responses and arrive at a suitable configuration [17].

The research is divided into systematic steps which each successive step being dependent on the results of the previous step. First, the characteristics responses of thermal structures will be examined. This research will determine the exhaust structure thermoelastic response using the finite element method provided by commercial programs. A heat transfer model of an EWS is analyzed. A structural model of the same EWS is then created an analyzed. This allows insight to be gained regarding the intuitive responses and the non-intuitive, often nonlinear, responses.

The results of the characteristic thermal structure analysis will be explored to identify regions within the design domain where geometric nonlinearity is most significant. There are two types of nonlinearity in structural analysis: material and geometric. Material nonlinearity occurs when there isn’t a linear relationship between material stress and strain and this often occurs in cases of thermal loading.

## Anticipated Efforts Beyond One Year

# Expected Results & Significance

Results of this work include multiphysics thermoelastic design tools that can be used to design hot structures for future aircraft, particularly embedded engine platforms and hypersonic thermal protection systems. The design tools could also be used to evaluate and provide solutions to thermal stress problems in current aircraft. A better understanding of the complex thermal-structural design space and tailoring of thermoelastic responses of these capability critical components would save the Air Force millions throughout the life of an embedded engine platform or hypersonic vehicle.

There are no commercial design programs or academic and research codes that have the capability to rigorously treat the EWS design problem. The programs developed during this research would be useful in the design of any structural component that must operate in a combined thermal-structural environment, including those where thermal expansion is restrained. This design scenario is found in several non-defense applications including commercial airline engines and braking systems, nuclear reactors, electric generators and other power generating machinery, and micro-electronic-mechanical systems. Thus, new design tools developed here could benefit Ohio companies in the commercial aerospace, alternative energy, and electronics design and manufacturing sectors.

# Literature References

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