I. TITLE: “Adaptive Aerostructures for Revolutionary Civil Supersonic Transportation”
II. TOPIC (Strategic Thrust): “Innovation in Commercial Supersonic Aircraft” (Outcomes 1,2)
III. PRINCIPAL INVESTIGATORS: 1) PI: Dimitris Lagoudas, Texas A&M Engineering Experiment Station (TEES); 2) Co-PIs: Darren Hartl, TEES; Paul Cizmas, TEES; Rodney Bowersox, TEES; James Mabe, Boeing Research and Technology

IV. SELECTION OF RESEARCH PARTNERS:

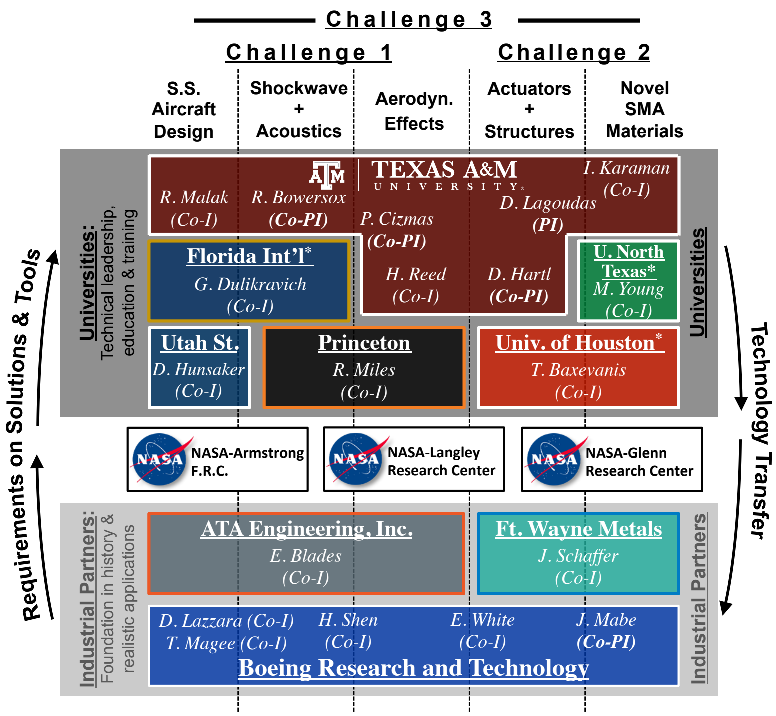


Figure 1 – Texas A&M selected essential academic and industrial partners and potential NASA collaborators. Research partner organizations are shown positioned relative to their primary technical contributions. Minority serving and high minority enrollment institutions are denoted with a (*).

This transformative research effort will explore new engineering tools and materials demonstrating that small-scale distributed structural adaptivity can enable robust low boom performance in supersonic aircraft operating in changing flight conditions. The team is described in detail in Figure 1 and was carefully chosen to tackle this unique aeronautics problem, is strong in each important technical area, and is synergistic across multiple disciplines and identified challenges. The Texas A&M leadership is natural for this effort given its many previous interdisciplinary research successes and long history of “smart materials and structures” developments and supersonics/ hypersonics exploration. Partner institutions were chosen on the basis of their technical capabilities to provide new opportunities for supporting NASA’s mission of extending inclusion to a wide range of researchers, be they students or faculty. Also included are institutions and early career faculty members with an interest in increasing their service to NASA and a recognized commitment to the education of historically underserved groups.

V. RESEARCH OBJECTIVES AND OVERALL STRATEGY

To enable commercially-viable civil supersonic transport (SST) aircraft, innovative solutions must be developed to meet noise and efficiency requirements for overland flight. The research effort will consist of a multi-disciplinary team of academic and industrial experts *exploring for the first time* the potential of **small real-time geometric outer mold line (OML) reconfigurations** to minimize boom signatures and drag in response to changing ambient conditions, thereby enabling noise-compliant SST flight. The team will exploit recent advances in supersonic computational fluid dynamic (CFD) methods, new noise prediction tools, and new design approaches to consider embedded highly energy-dense shape memory alloy (SMA) actuators for *in situ* adjustment of an SST aircraft leading to optimal low boom signature and low drag in different environments. Potential areas of application are illustrated in Figure 2 on an example Boeing N+2 concept. The university-led program will provide strategic leadership toward technology convergence that advances ARMD's research objectives with regard to Thrust 2: Innovation in Commercial Supersonic Aircraft by exploring for the first time enabling low-boom operation across a range of flight conditions via structural adaptivity, and will promote education of the next generation of engineers.

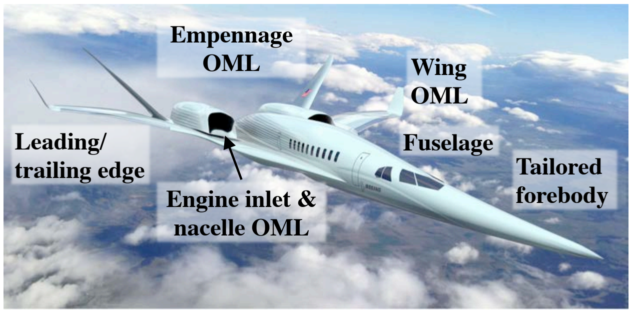


Figure 2 – Our ULI team has identified numerous adaptivity locations to feed the Challenge 1 trade studies. A Boeing N+2 concept is shown, but multiple baseline configurations will be considered.

V.1. Background Context: Many studies over the past fifty years have labored to minimize sonic boom through vehicle shaping. Early investigations [1, 2] studied the effects of airplane configuration using farfield solutions [3] of sonic boom theory (F function). Later studies [4, 5] further matured the design approach, using the F function and equivalent area for low-boom design methods. Other boom minimization investigations indicated that near-field sonic boom signatures exist and depend on the detailed geometry of the airplane. These non-asymptotic effects could be very important compared to the asymptotic far-field N-wave solutions [6]. Flight programs such as the DARPA Shaped Sonic Boom Demonstration (SSBD) program have experimentally demonstrated sonic boom modification by vehicle shaping. For the SSBD program, a modified Northrop Grumman F-5E aircraft was utilized to repeatedly demonstrate "bottom line" validation that aircraft shaping can produce a shaped sonic boom that persists in the far field [7]. Important trade-offs between boom reduction and aircraft performance were demonstrated, *supporting applicability and robustness of our concept* to practical aircraft design for tailoring sonic boom signatures. Recent efforts have focused on developing new methods and tools to better address the challenge of reducing the sonic boom generated by a supersonic aircraft, in addition to increasing the general public acceptance of supersonic flight overland.

Significant efforts have focused on designing and optimizing low boom vehicle geometries for *fixed design points*, typically nominal cruise conditions [8]. All such solutions result in *static*, *condition-sensitive* designs, which exhibit lower performance for off-design conditions. Of the new potential sonic boom reduction technologies not yet investigated, a NASA report states "*Technologies rated the highest included adaptive/inflatable*

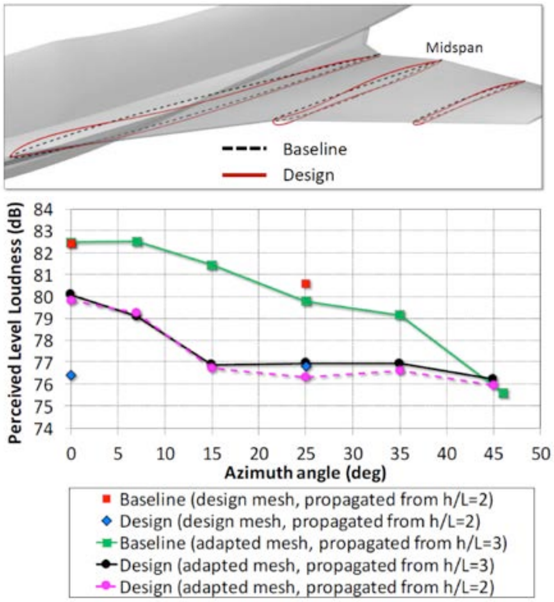


Figure 3 – Recent NASA study shows that small OML geometry changes, can lead to significant reduction in off-track loudness distribution [8].

wing elements….The reason adaptive geometry scored so high was due to the technology's broad range of potential applications." [9].

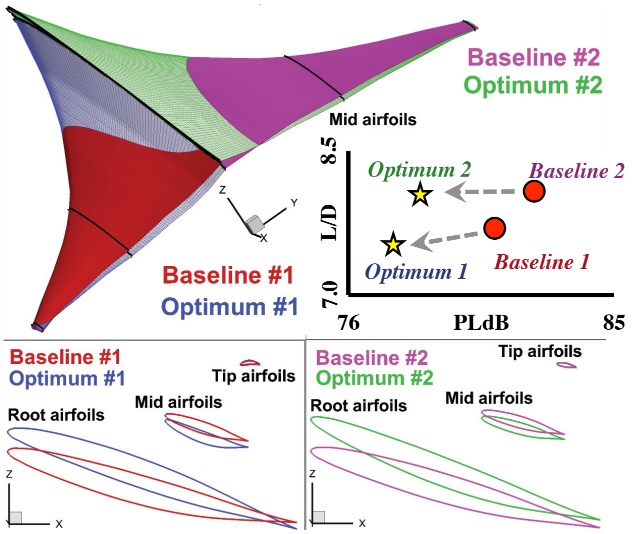


Figure 4 – Small configurational changes in optimized efficiency and sonic boom noise performance show noise performance can be enhanced without detriment to efficiency [10].

Previous research efforts have shown that small distributed changes in SST OML can substantially reduce perceived sonic boom noise (Figure 3) without negatively affecting aerodynamic performance (Figure 4). However, signatures optimized through OML shaping at a single flight condition degrade rapidly with slight changes in flight condition. Angle of attack, altitude, air density, and speed are known to significantly impact boom signature and SST flight performance, endangering true commercial viability of overland supersonic flight [10-12]. To be commercially-viable, **an SST must robustly meet boom signature limits for a range of flight conditions** and thus requires real-time adaptability.

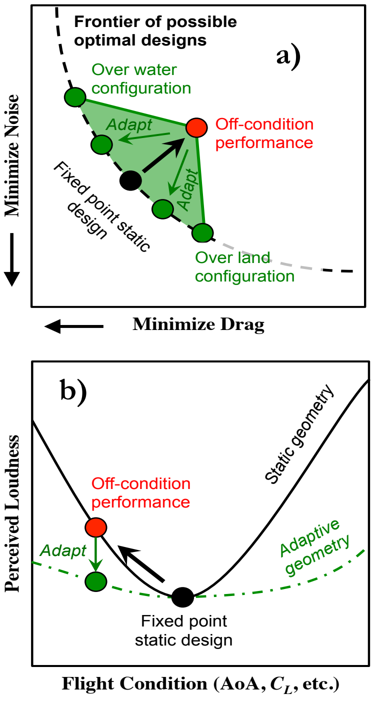


Figure 5 – Illustration of continuous adaptivity for SST flight. Small adaptations are localized or distributed and are performed real-time throughout flight, in response to changing flight conditions.

V.2. Overall Research Strategy: A multi-disciplinary team of academic and industrial experts will explore the potential of small OML (geometric) reconfigurations to enable noise-compliant SST flight. The team will first combine improved supersonic CFD methods, boom propagation models, and new atmospheric sensing techniques into a new multi-disciplinary design framework. The framework will consider advances in low-volume energy-dense solid-state SMA actuators to determine embedded solutions for in-flight adjustment of an SST aircraft that enable optimal low boom and low drag configurations across all environments from takeoff to landing. This concept is schematically illustrated in **Figure 5**. Such a novel multi-disciplinary structurally integrated approach will provide a truly innovative and commercially-viable technology for enabling community-accepted SST aircraft. This team will focus primarily on the novel concept of small-scale distributed adaptivity (SSDA), approximately defined as localized deformation with magnitudes on the order of 5% average chord.

Beyond their potential for transition into full-scale commercial production platforms, the SMA actuation technologies (*e.g.,* new material compositions, processes, component forms) and analysis tools developed will also enable real-time reconfigurable flight test components and wind tunnel models for SST design validation and system development. For example, SMA actuators for reconfigurable test hardware have been demonstrated in full-scale flight tests by the Boeing Company, as later described [13].

The investigation is inherently high risk/high reward and is well suited to university-led research. New tools will be developed to explore what kinds of small-scale distributed adaptations can truly affect SST flight performance. A detailed study will determine whether SMA materials with the appropriate temperature and force/displacement characteristic exist and whether SMA-based actuators are economically viable at the system level. It is unclear that the near term outcome of increased community acceptance of SST flight and midterm outcome of increased efficiency will outweigh the costs of new materials, certification, local/global design complexity, maintenance, and other considerations. The team will consider these barriers.

The overall research strategy is to pursue three critical areas: the design of configurations for reducing boom, material development and modeling, and technology feasibility demonstration in a relevant environment. Initially, the team will identify potential applications where structure or geometry adaptivity provides a benefit in noise or drag across the entire flight envelope (see Figure 2). For selected applications/structural locations, required OML geometry changes will be determined based on analysis of boom ground signature and drag reduction using new design tools and trade studies and atmospheric sensing techniques. Designs will be developed and evaluated against requirements on loading, stroke length, and operational temperature. New alloy formulations will be developed tailored for both autonomous and controlled actuation modes. As the SMA material development matures, integrated system-level factors will be investigated. Optimized designs for small-scale distributed adaptivity applications of maximum benefit will then be matured and tested, moving toward demonstration of the innovative technology approaches at a TRL 4-5 and showing that sonic booms can be reduced by reconfiguration on demand.

V.3. Teaming Strategy and Educational Activities: Figure 1 captures the essential elements of the teaming strategy for the effort. As the lead institution, Texas A&M covers the full breadth of research challenges. Sub-groups of this Texas A&M team have a long history of successful NASA University Research, Engineering and Technology Institutes (URETIs; http://tiims.tamu.edu/about.html) and DoD Multidisciplinary University Research Initiative (MURIs). Lagoudas, Karaman, and Hartl have collaborated with Boeing on the development of SMA alloys and actuators for conventional subsonic applications for over a decade with great success. As the primary industry partner, the Boeing Research and Technology team also covers the full range of technical topics.

The management of the project will be performed by the PI with the help of Darren Hartl as the operations director. The PI has extensive experience with managing large grants, most recently a NASA URETI, and Dr. Hartl has valuable experience working with NASA projects, and recently spending time at AFRL and Boeing. Three co-PIs (Cizmas, Hartl, Mabe) will coordinate the three focus areas and with the PI, will set scientific priorities and oversee deliverables to NASA. Dr. Bowersox (co-PI), will oversee the TRLs of the individual projects, securing smooth transitions from low to high TRL. Our industry partners will form the nucleus of an industry advisory board and they will evaluate technology commercialization paths from the research outcomes.

Other partner organizations have been strategically selected to increase technical depth/ expertise in certain areas, with priority given to academic investigators that are either early in their careers or previously unfunded by NASA (Young, Baxevanis, Hartl, Hunsaker) and also established *Minority Serving Institutions* (MSIs) and Department of Education designated *significant minority enrollment institutions* (see Figure 1). The academic institutions will lead the engineering science aspects of the research, transferring new technological capabilities to the industrial partners with a background in the successful development and deployment of novel shape memory and supersonic applications. They will provide essential guidance regarding real-world requirements. Given that the current effort parallels NASA's own internal research, we desire and expect that appropriate NASA centers will be invited to contribute to the program and we imagine that students from all participating academic institutions will have the opportunity to gain valuable research experience at these sites.

This teaming arrangement also provides a unique opportunity for dynamic education and training of future engineering practitioners and researchers to maintain U.S. technological leadership. Across the team, student and post-doc funding has been given budget priority. All six academic institutions are committed to interchange students where appropriate to both promote collaborative research progress and to permit novel experiential education opportunities; senior faculty such as Helen Reed and Richard Miles will be critical to this effort. Special efforts will be made to provide exchange opportunities to students from minority serving institutional partners; their highly diverse student body provides an advantage in recruiting both undergraduates and graduates from underrepresented groups participate in this effort. It is expected that directed studies courses will be established for teams of undergraduate students to contribute to the design and development of experimental prototypes and capabilities (*e.g.*, actuated wind tunnel models), and an additional five undergraduates will be supported at Texas A&M annually for multi-disciplinary engagement across researchers. Perhaps more importantly, previously established and successful relationships between academic and industrial partners will be leveraged to enable both targeted internships for students and the placement of practicing engineers in the academic environment. Students will have the opportunity to work with and learn from world leaders in supersonic platform design and active materials and adaptive structures development.

V.4. Novelty and Impact on ARMD Strategic Thrust 2: Adapting supersonic aircraft geometry in real-time in response to changing environmental or flight conditions will enable satisfaction of sonic boom and efficiency requirements across a much wider operating range than current static designs allow. This directly supports ARMD's Strategic Thrust 2 research focus on enabling vehicle designs that meet the Near-term Outcome of acceptable sonic boom noise as well as Mid-term Outcomes such as improved efficiency. This project uses a high level of technology convergence combining aerodynamics, noise, structures, sense and control, and materials technologies. Validated and integrated tools for evaluation and optimization of adaptive geometries to minimize boom and increase efficiency will be developed. New shape memory alloy formulations and processing methods will be developed that meet the specific in-service requirements of supersonic platform integration. Potential adaptive geometry applications for supersonic aircraft will be identified. The design and analysis tools will be used to evaluate the benefits of and develop design solutions for selected embodiments. Key components will be built and demonstrated in the lab and wind tunnel. In addition, the practicality of using this technology for adaptive hardware and components for wind tunnel models test hardware will also be shown.

The team takes primary responsibility for maintaining high levels of technical quality throughout the project. Publication across a diverse range of peer-reviewed journals and organized special sessions/symposia at applicable conferences (*e.g.,* AIAA SciTech) are available forums being considered for dissemination of the result and allow peer assessment of team progress. Further, a workshop with external invitees is being planned for Year 3 to allow critical review of progress.

VI. TECHNICAL CHALLENGES AND PROJECT MILESTONES

Three technical challenges have been identified to meet the overall project objective of developing and demonstrating SMA technology for in-flight tailoring of sonic boom, drag, and aircraft trim. These three represent technical barriers for which there is a quantifiable measure of success that will be met via sustained research effort (see Figure 6).

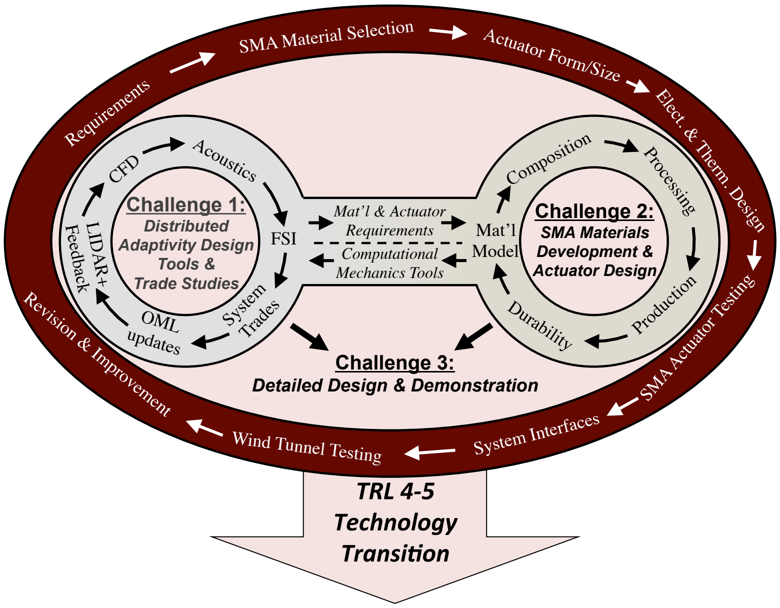


Figure 6 – Teams addressing the three challenges will work in a synergistic manner. Challenge 3 incorporates the developments of Challenges 1 and 2.

1. Develop and/or incorporate integrated multi-disciplinary validated tools to enable the quantitative understanding of *in situ* small-scale distributed adaptivity (SSDA) and its impact on flight performance and sonic boom noise.
2. Design and demonstrate new producible and certifiable SMA materials, systems, and components that will enable in-flight OML/aerostructural modifications and SSDA.
3. Demonstration of SMA technology for high-performing SSDA applications. These demonstrations would include analysis, benchtop testing, and wind tunnel testing.

VI.1. Overall Project Milestones:

Five annual project-level milestones will be used to gauge the overall progress of the program. Summarized in Figure 7, each is also included in the associated challenge-specific technology maturation plots to follow.

- **1 year** after project start (FY18Q4): "*Existing structural, aerodynamic, and sonic boom propagation tools verified and validated.*" •The program utilizes a number of existing analysis tools for supersonic flow, sonic boom propagation, structural and actuator analysis. Because of the dependency of meaningful progress on the predictions of these tools and their integration into a design exploration/optimization framework, their individual accuracies must be characterized early in the effort. •Exit: *All tools should be individually validated against known or new*

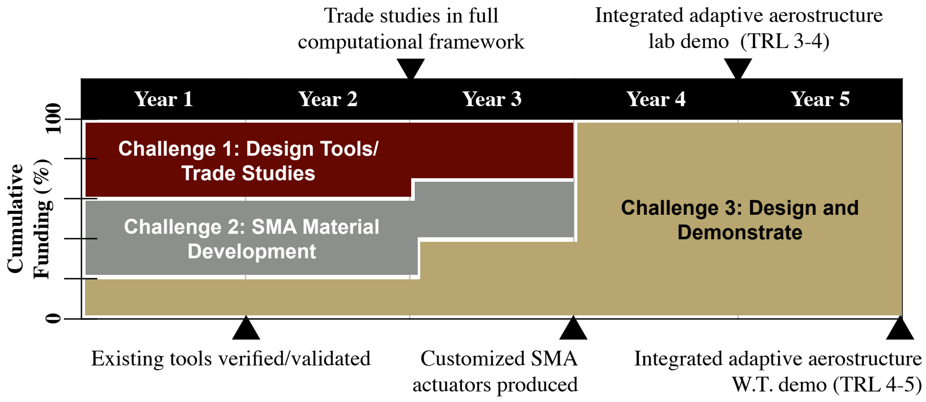


Figure 7 – Project-wide focus will evolve over period of performance; annual milestones track progress toward technology demonstrator and TRL increase.

benchmark problem to within 5% error. •Deliverables: Annual report, technical interchange charts; Accuracy of each tool at the end of year one will be summarized in project report. •Supports Challenges 1 and 2.

- **2 years** after start (FY19Q4): "*Analysis tools combined into optimization/trade study framework and first trade studies completed.*" •Once the various analysis tools have been validated and combined into an optimization framework, trade studies will be performed to explore the SMA technology design space. • Exit: *Trade studies should be completed on at least two baseline geometries where SMA structural adaptation is investigated* •Deliverables: Annual report, technical interchange charts; baseline designs and promising perturbations (adaptations) will be provided to the Challenge 2 and Challenge 3 teams. •Supports Challenges 1 and 3 (Challenge 2 receives results).
- **3 years** after start (FY20Q4): "*Produce two distinct SMA actuators having different forms and operational (i.e., transformation) temperatures.*" •One of the novelties of the overall effort is the use of distributed, highly energy dense SMA actuators. While the coupled design tools and prototype development can consider other actuation schemes in a straightforward manner, the demonstration of completely customized SMA actuators for supersonic applications is essential for successful transition of this particular technology. •Exit criteria and deliverable*: two actuator prototypes will be developed and shared with NASA collaborators (NASA-Glenn Advanced Metallics Branch)*; annual report and technical interchange charts •Supports Challenge 2.
- **4 years** after start (FY21Q4): "*Laboratory demonstration of an adaptive actuator/structure subsystem under representative loading conditions.*" •Using a design optimized by the Challenge 1 team and a custom SMA actuator from Challenge 2, the experimentalists will develop and demonstrate a geometrically adaptive aerostructural subsystem for sonic boom shaping. This will increase the TRL of this technology to 3-4. • Exit: *Displacement error at aerodynamically critical locations should not exceed 5% relative to computationally determined target design.* •Deliverables: Annual report, technical interchange charts; benchtop prototype available to share with NASA collaborators. •Supports Challenge 3.
- **5 years** after start (FY22Q4): "*Wind tunnel demonstration of adaptive actuator/structure subsystem.*" •Continued coupled analysis and optimization considering the results of prior experimental efforts in Year 4 and considering improved understanding of both computational tools and alloys/actuators will drive the team toward this final sub-system demonstration in a wind tunnel environment under supersonic conditions (NASA-LaRC 4'x4' Unitary or NASA-Ames 9'x7' or Boeing Polysonic tunnel required). This will increase the TRL of this technology to 4-5 • Exit: *Displacement error at aerodynamically critical locations should not exceed 5% relative to computationally determined target design.* •Deliverables: Annual report, technical interchange charts; wind tunnel prototype will be available to share with NASA collaborators as appropriate. •Supports Challenge 3.

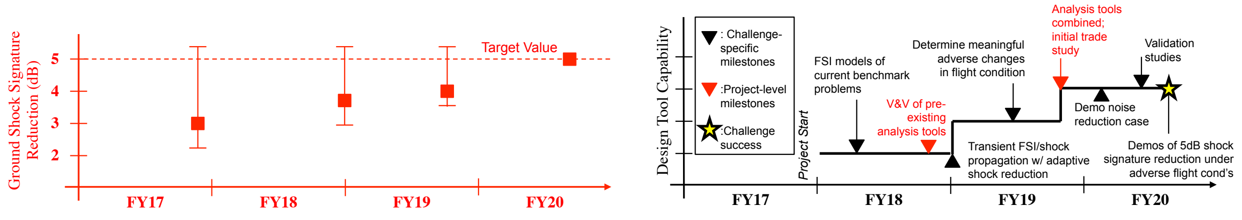
VI.2. Challenge 1: Distributed Adaptivity Design Tools Development and Trade Studies:

Statement: "Develop system-level convergent multi-disciplinary design optimization tools for distributed structural adaptivity to demonstrate multiple examples of system-feasible options that reduce ground boom signature by 5PLdB under common off-design flight conditions (late FY20)." Perceived boom reduction is the primary goal of this research effort and was selected as the Challenge 1 metric. The target value of 5 PLdB was taken after Figure 4. The technology performance and technology maturity plots for Challenge 1 are shown in Figure 8.

VI.3. Challenge 2: Materials Development and Integrated Solid-State Actuation Design:

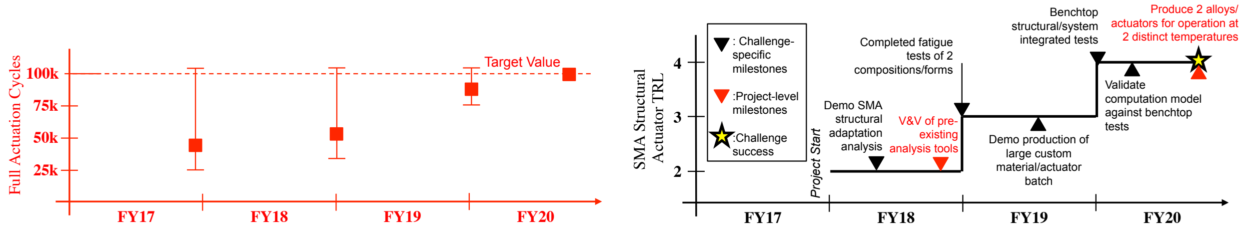
Statement: "Identify a menu of shape memory alloy actuator options (composition, processing, and form) having validated computational models and capable of providing structurally required forces and displacements at application specified temperatures for more than 100k full actuation cycles (late FY20).” It has been widely demonstrated that SMA actuators can produce the forces and displacements necessary to provide aircraft structural adaptivity [14]. It is their durability that must be proven for widespread aerospace adoption and is taken as a metric. Based on previously published SMA actuator fatigue efforts [15, 16], 100k cycles is a bold yet attainable goal. The technology performance and technology maturity plots for Challenge 2 are shown in Figure 9.

VI.4. Challenge 3: Detailed Design and Demonstration: Statement: “Design, fabricate, and demonstrate at least one concept incorporating system-level complexities and capable of adapting geometry under representative flow conditions to within 5% displacement error at critical locations relative to the computationally determined target geometry (mid FY22)”. While perceived boom reduction is the overarching goal, no experiments allowing direct assessment of such a metric are within the scope of the program. The ability of demonstrated prototypes to match actuated/adapted geometries associated with computed boom reductions is a more meaningful progress metric. The technology performance and technology maturity plots for Challenge 3 are shown in Figure 10.



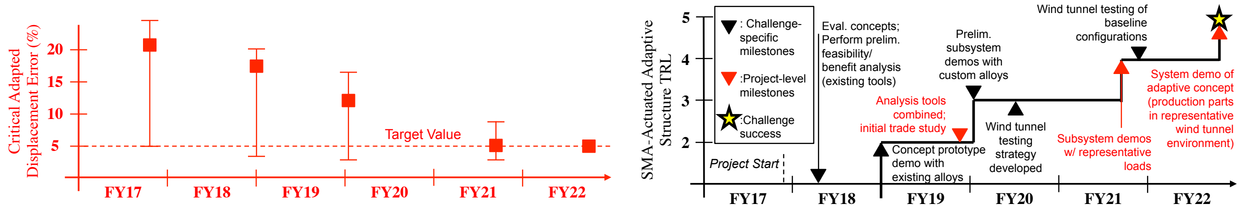
(a) (b)

Figure 8 – The Challenge 1 technology maturation plan produces the validated tools needed to achieve a 5 PLdB reduction.



(a) (b)

Figure 9 - The Challenge 2 technology maturation plan produces new shape memory actuators cable of providing substantial work density at customizable temperatures for 100k cycles.



(a) (b)

Figure 10 - The Challenge 3 technology maturation plan considers demonstration prototypes that increase the TRL of the subject technology to 4-5.

VII. TECHNICAL APPROACH

To successfully address the coupled technical challenges listed above, a research team having a range of backgrounds and technical strengths and led by a Tier 1 research institution will work as a unit to address this highly multi-physical, multi-disciplinary research, development, and design problem.

VII.1. Challenge 1: Distributed Adaptivity Design Tools Development and Trade Studies

(Florida International, Princeton, Texas A&M, Utah State; ATA, Inc., Boeing; Led by Dr. Paul Cizmas, TEES): Supersonic aircraft design involves complex multi-disciplinary coupling with competing design objectives, namely sonic boom mitigation and aircraft performance. Other important goals must be investigated to define a feasible configuration, such as structural integrity with minimal weight, stability constraints, payload sizing, noise, fuel efficiency, environmental impact, takeoff/landing performance, and range. The most common approach to this design problem is to conduct multi-disciplinary design optimization and develop a single fixed OML that best meets the design objectives. The Boeing collaborators, for example, are well experienced in such studies [17-22]. This new ULI program, however, targets the added capability of choosing specific OML shapes for separate operating conditions and alleviates the conventional multi-point performance compromises via the incorporation of SMA (or other) structural actuators. SSDA will be utilized to enable sonic boom mitigation and robustness, and aerodynamic performance improvements. This involves multi-disciplinary considerations associated with application of SMA actuation to supersonic flight and opportunities to identify improved design methods at the sub-system and vehicle system level. A multi-tier study providing indications for developing new methods that mitigate design trade-offs in supersonic configurations and expand their performance beyond the state-of-the-art. The overall design exploration and optimization framework is shown in Figure 11.

In addressing the challenge statement of Challenge 1 and Challenge 3, our team will first identify adaptive geometries that will most benefit boom mitigation and drag reduction by evaluating publicly available supersonic configurations, such as the NASA low-boom configuration 25D, to quantify their performance trade-offs and determine possible adaptivity solutions. Design trade-offs for boom mitigation and aircraft performance will also be compared between SMA actuation and conventional actuation systems. The comparison will aim to quantify which actuation approach, or combination thereof, most effectively and efficiently improves the design objectives from a multi-disciplinary system perspective.

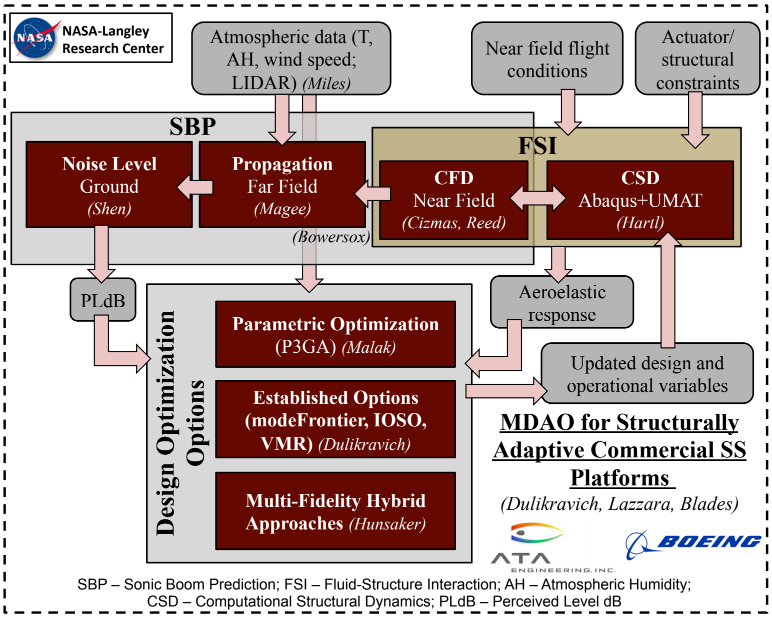


Figure 11 – Overall design exploration and optimization framework for meeting Challenge 1, including partition of effort and possible NASA collaborators.

A range of design problems will be studied, starting with simple canonical unit problems and then progressing to more complicated system-level configuration design problems to fully understand the contributions of SSDA. To isolate the sensitivity of a boom signature to localized actuation, an actuated axisymmetric body may suffice. Such a study will require use of a variety of methods, disciplinary models, computational tools and optimization approaches to investigate supersonic aircraft design optimization with SMA technology. Throughout these investigations, whether focused on the entire configuration or its components, a combination of low and high fidelity methods will be used as appropriate when analyzing the impact of localized actuation across a flight profile, including computational fluid dynamics (CFD), non-linear thermally coupled computational structural dynamics (CSD), sonic boom propagation methods, SMA actuation models, compliant and advanced adaptive structures, thermoelasticity, dynamic models, and others. Overall, the problem statement for Challenge 1 will be addressed by considering four distinct thrusts described below. Specialized peer review will be provided via publication in topical journals (*e.g.,* Journal of Aircraft, Journal of Mechanical Design) and special AIAA SciTech sessions on "Small-Scale Distributed Adaptivity in Supersonic Aircraft."

VII.1.A. Thrust 1: Design Methods and Framework *(Blades, Dulikravich, Hunsaker, Malak):*

Design studies led by Dulikravich will be performed of conventional and SMA-based SSDA sub-systems and their integration into a supersonic vehicle, while considering a number of multi-disciplinary design analysis and optimization (MDAO) perspectives. This will involve Dulikravich, Malak, and Hunsaker applying suitable design parameterizations with conventional and state-of-the-art MDAO methods to uncover particular details of a constrained, multi-objective design space with SMA actuation [23-26]. In some studies, for example, gradient-based aerodynamic shape design with CFD adjoint information will be utilized, whereas in other studies surrogate models, evolutionary methods and hybrid approaches may be implemented to resolve design trends in a broader design space, as successfully done by Hunsaker [27]. Important discipline performance constraints will also be studied generally to incorporate aspects of feasible vehicle design when applying SMA actuation. The systems focus of the Challenge 1 team is essential, as a system composed of independently-optimized subsystems is unlikely to be optimal with respect to system-level considerations. While MDAO methods are capable of simultaneously considering several disciplines and/or subsystems to find an optimal design [28-35], they can result in a single "point solution" providing limited engineering insight. Although this research will use various MDAO methods as appropriate, they will be part of a broader trade study strategy that focuses on building knowledge that will be valuable in overcoming the challenges of detailed test and engineering (c.f., Challenge 3 of this proposal) through use of the novel advanced techniques of Malak such as parametric optimization [36, 37] and machine-learning-based techniques for technical feasibility assessment [38].

Parametric optimization results in a flexible range of optimal solutions as a function of the parameters, rather than a more restrictive point solution. Consider the far-field atmospheric conditions, which change uncontrollably during flight yet greatly influence optimally quiet structurally adaptive supersonic aircraft configurations. Atmospheric conditions represent an input parameter variable to be carefully explored. The novel Predictive Parameterized Pareto Genetic Algorithm (P3GA) [39-42] has been developed and will be used herein to solve multi-objective parametric optimization problems efficiently for both input and response parameter variables [39,49]. It is the only known algorithm that supports parametric optimization with black-box functions—an important capability for this project. Before conducting detailed optimizations of any kind, we desire first to understand the feasibility envelope for SMA-based distributed actuation. Typical algorithmic approaches for identifying the feasible region require accessible analytical problem formulations [39] or are not tractable for high-dimensional problems since they sample the entire search space [40-42]. The research team will use a recently-developed constraint satisfaction algorithm that leverages machine-learning-based methods to handle many-dimensional "black-box" problems [46-48]. This technique will be applied to establish a feasibility envelope for SMA actuation concepts.

Lastly, the deterministic analysis and design optimization will be extended to robust design under uncertainty by quantifying the uncertainty introduced by SMA actuation and its impact on supersonic aircraft performance and boom signature shaping. This effort will leverage existing work in uncertainty quantification for different aircraft disciplines and seek both sub-system and vehicle-level robust design with SMA actuation, thus enabling a higher likelihood of achieving a mature technology-readiness level (TRL). Outputs from these designs will serve as critical inputs for the experimental efforts associated with Challenge 3.

VII.1.B. Thrust 2: Sonic boom analysis and prediction *(Bowersox, Magee, Shen, Lazzara):* An objective of this project is to achieve minimal sonic boom levels on the ground for a practical range of flight and atmosphere conditions by applying the SMA-driven adaptive structures and related technologies to supersonic vehicle design. Reliable prediction of sonic boom signatures and loudness metrics on the ground is a critical element throughout the program. The current state of the art of sonic boom prediction developed in part by Shen and Lazzara divides the prediction process into the near-field and far-field stages, as shown in Figure 12 [50-52]. The near-field prediction, typically based on a Euler/Reynolds-averaged Navier—Stokes (RANS) CFD method, captures the Mach waves at a certain distance away from the vehicle. For the far-field predication, the near-field solution is propagated to the ground with a quasi-one-dimensional model along a ray path determined by acoustics ray tracing at each relevant azimuth direction. The propagation model accounts for the effects of geometric spreading, nonlinearity, molecular relaxation and thermal-viscous attenuation. The variation of thermodynamic parameters, wind and humidity in the atmosphere have a strong influence on the propagation of the sonic boom waveform (see Thrust 4).

The computational expense of the near-field solution vastly exceeds that of the far-field solution. Accurate predication of ground signatures using the quasi-one-dimensional model requires a near-field solution sufficiently far-away from the flight path. This may create a serious challenge to the affordability and accuracy of the CFD process. There is evidence that the common practice of using 2-3 airplane body lengths for the radius of the near-field CFD domain may not be sufficient; a study of the impact of near-field distance on ground signature will be carried out for relevant configurations. Boeing researchers will work with Bowersox to evaluate Different Euler/RANS solvers [53] and gridding strategies and identify the approach most suitable for sonic boom prediction, aerodynamic design, and optimization. A near-field prediction method based on a high-fidelity space marching process [54] will also be used. For far-field propagation predictions and cross validations,

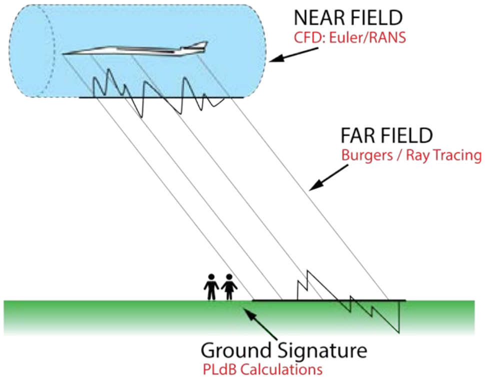


Figure 12 – Near-field and far-field effects will be considered in a coupled manner.

NASA's sBOOM code [55], Wyle Lab's PCBOOM code [56], and Boeing's Zephyrus code [57] will be utilized. NASA and Boeing sonic boom metrics calculation codes [58, 59] will calculate the loudness of ground sonic boom signatures.

The sonic boom prediction process will be integrated into the MDAO process for SMA-based distributed actuation. Sonic boom near-field and full carpet ground signatures and loudness will be objective functions. Variations in flight and atmosphere conditions will be integrated into the design space. Standard atmosphere profile and atmosphere profiles representative at major destination cities and flight corridors at different seasons will be included in addition to *in situ* LIDAR data. Past meteorological data will be used for generation of sonic boom loudness statistics.

VII.1.C. Thrust 3: Aeroelastic analysis *(Cizmas, Blades, Reed):* At supersonic speeds, small OML geometric changes can have a significant effect on (1) aerodynamic forces and moments, (2) boundary layer, and (3) heat fluxes [60]. The aeroelastic stability of SMA-enabled SSDA must be explored to avoid triggering deleterious phenomena. The prescribed time variation of the geometric changes and the variation of the stiffness of adaptive geometries will be explored using a fluid-structure interaction (FSI) simulation that couples the near-field CFD model to the finite element-based computational structural dynamics (CSD) model described in VII.B.2 to follow.

The ability to fully analyze and optimally design air vehicles with inherent nonlinear features is limited by the computational cost of the CFD solver [61]. Standard CFD models based on RANS solvers include the relevant fluid nonlinearities but are computationally too expensive for aeroelastic trade studies. The computational cost is further increased if the prediction of laminar-to-turbulent transition is necessary. Whether the flow is laminar or turbulent has a sizeable impact on the drag (range, fuel consumption) of the vehicle. If long near-full-chord laminar runs could be achieved on the wings, it has been estimated by Reed and others that the cruise drag on a quiet-supersonic-platform- (QSP-) class vehicle could be reduced by ~20-25% [62]. A turbulent wedge produced by the turbulent boundary layer on the fuselage can contaminate the laminar flow on the wing. If this is the case, it is estimated that a 10% drag reduction could be obtained with laminar flow factored in to the design. If necessary, Reed will lead the use of an in-house state-of-the-art nonlinear parabolized stability equation solver that was successfully used to predict the instability point for various 3-D high-speed configurations [63-67].

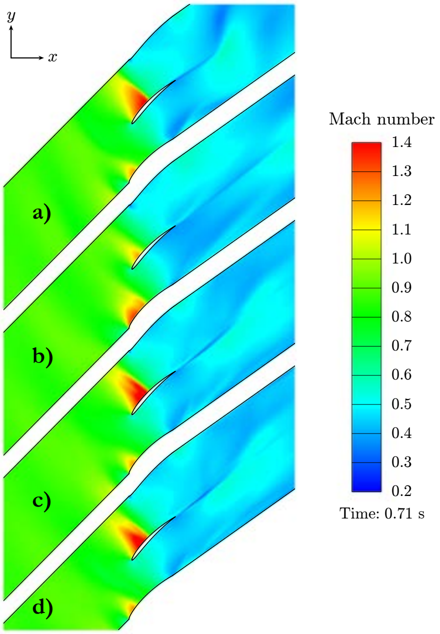


Figure 13 - Mach number contour plots on an airfoil plunging with an amplitude h_0 = 0.05c, k = 0.375: (a) full-order model; (b) standard POD model with 7 static basis functions; (c) dynamic POD model with dynamic average, 6 static basis functions; and (d) dynamic POD model, dynamic average, 3 dynamic basis functions [PC15].

Four basic ideas are currently being pursued by Cizmas for reducing computational cost while retaining the essence of nonlinear flow phenomena: (1) time linearization [68-70], (2) harmonic balance [71], (3) proper orthogonal decomposition (POD) [72, 73] and (4) Volterra series [74]. Of these, POD appears to be the most desirable approach for nonlinear aerodynamic simulations. Using POD, computational cost is reduced by a factor of more than 100

[75]; a new POD method based on the zeta-variable showed speed-ups exceeding 500. The traditional POD method, however, does not allow for grid deformation [76-78], which is needed for predicting the effect of SMA-enabled adaptive geometries on sonic boom. Recently, the Cizmas group developed a dynamic POD method that allows mesh deformation [79]. This method uses an index-based dynamic average and dynamic basis functions that vary continuously with respect to parameters associated with the flow unsteadiness and/or mesh deformation, and they are optimal, subject to the prescribed form. The dynamic POD method, [80] shown in Figure 13, will be used in concert with the methods of Blades (ATA Engineering) to determine whether deleterious aeroelastic effects occur during SMA-based actuation.

VII.1.D. Thrust 4: Look-down solar-blind LIDAR *(Miles):* The coalescence of shock waves into the sonic boom arriving at the ground is affected by the temperature profile of the atmosphere below the aircraft, and that can vary significantly over the flight envelope. If that profile is known in real time, then dynamic shape morphing methods may potentially be employed for the optimum reduction of the sonic boom signature. Accurate atmospheric profiles from careful studies can also be important during the design optimization process. The use of Light Detection and Ranging (LIDAR) is a proven method for atmospheric profiling and will be explored. The measurement of temperature profiles, aerosol and particle scattering must be removed. This has been achieved by Miles using atomic and molecular filtered Rayleigh scattering methods [81]. A novel and enabling filtering approach has been shown [82] to provide a robust method of measuring temperature profiles without contamination from particles and aerosols. However, to date only systems that can be flown at night and are ineffective during the day have been demonstrated.

A look-down, solar-blind Filtered Rayleigh LIDAR system will be developed, based on the use of a mercury filter at 253.7 nm, which falls into the solar-blind region of the spectrum. This component of sunlight is absorbed by the ozone layer. Thus, there is virtually no solar background. This wavelength is far from the transmission region of the eye, so no retinal damage can occur in persons on the ground. The look down configuration is much better than the standard look-up configuration for atmospheric profiling since the density gradient of the air offsets the $1/r^2$ reduction of the scattering signal with distance. In previous work a 253.7 nm Differential LIDAR (DIAL) system was used to measure mercury contamination in the air over a chemical processing plant at distances up to 1 km [83].

For this effort, isotopically pure mercury 202 vapor filters will be used by Miles and the temperature profile will be determined by the Rayleigh scattering from the air molecules as detected through these filters [84]. Proof of concept work will be conducted in the laboratory using an existing injection locked Ti:sapphire laser and mercury cells. In this way, a very specific and novel experimental technique will be developed to truly enable, via the acquisition of accurate and important data, the kind of in-flight adaptivity of supersonic aircraft for minimal perceived sonic boom noise. The use of Raman LIDAR and rotational Raman with a mercury vapor filter to measure atmospheric humidity will also be explored [85, 86].

VII.2. Challenge 2: Materials Development and Integrated Solid-State Actuation Design (*Texas A&M, Univ. of Houston, Univ. North Texas; Boeing, Fort Wayne Metals, Led by Dr. Darren Hartl, TEES*): An enabling technology for the adaptive aerostructures concept is the development of reliable and tunable shape memory alloy (SMA) actuators [NASA GRC-E-DAA-TN25074]. SMA-based actuators are compact, lightweight, rugged actuation systems, providing up to 10 times more actuation energy density than any known alternative and thus a means for affecting conventional control surfaces in volumes previously too small to be. Challenge 2 addresses the problems of developing, modeling, and producing application-specific, durable, and customized SMA materials and components for implementation into a supersonic adaptive aerostructural concept .

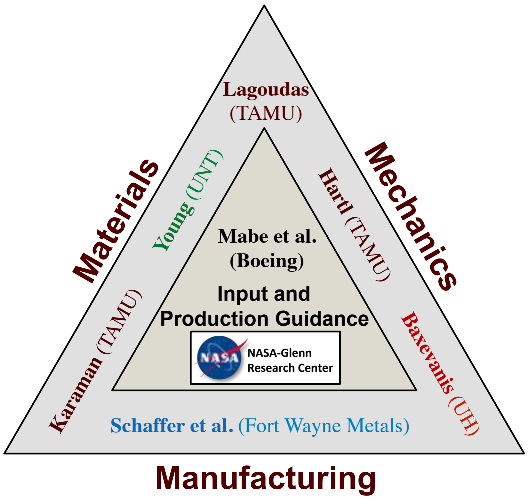


Figure 14 – The three thrusts and collaborators associated with meeting the objective of Challenge 2 (NASA-Glenn proposed *as possible collaborator).*

The approach for this challenge will be divided into three distinct but wholly interdependent thrusts described below. Each thrust will leverage the unique capabilities and background of a subset of the investigator team, and all three will be both supported and advised by the OEM partner (Boeing) to maximize technology transfer toward eventual real-world production of the novel concepts. This partition of effort is summarized in Figure 14. Progress will be indicated as candidate material systems prove to provide the actuation characteristics needed under the thermal conditions required and scale-up is demonstrated. Success of this effort will be confirmed when final actuator components are experimentally integrated into candidate morphing surfaces and demonstrated to a TRL of 3-4 with 100k actuation cycles.

It is important to note that two potential actuation modes will be initially investigated for this research effort: "Autonomous systems" will include SMA actuators controlled by changes in ambient temperatures or loads (*e.g.,* temperature changes due to altitude change); "controlled systems" will include SMA actuators directly driven/controlled through the application of thermal energy, as shown in the past successful example in Figure 15. These two modes might require SMA material systems with vastly different transformation temperature ranges and, thus, different material compositions and processing approaches, as described below.

Specialized peer review will be provided via publication in topical journals (*e.g.,* Journal of Intelligent Materials and Structures, D. Hartl Associate Editor; Smart Materials and Structures, D. Lagoudas, Associate Editor) and in special issues proposed to the same. Special sessions are expected at the ASME SMASIS conference (D. Hartl, symposium co-Chair).

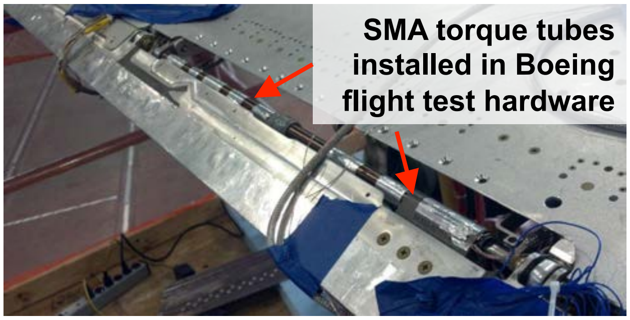


Figure 15 - Example of SMA torsion actuation installed on a Boeing 737 for full-scale flight testing [87]. Many other component types are possible and will be explored.

VII.2.A. Thrust 1: Solution-Specific SMA Materials Development *(Karaman, Lagoudas, Young, Mabe, Schaffer):* Recent advances by our team in understanding new alloy formulations and processing approaches allows for the tailoring of alloys based on application requirements. For this thrust, Texas A&M and

University of North Texas researchers will work with Boeing engineers to investigate potential SMAs and processing methods that lead to optimal mechanical and functional properties for the selected applications of interest. An established approach considering microstructural and bulk material actuation characterization methods will be employed. Boeing researchers have committed to work with other members of the ULI team to mature the technology for this project, alloy and material processing to optimize the SMA properties for the selected application and actuation mode and to demonstrate durability.

SMAs can undergo large recoverable shape changes under high stresses as a result of reversible (*i.e.*, thermoelastic) martensitic transformation. SMAs with transformation temperatures higher than 100°C, *i.e.*, high temperature SMAs (HTSMAs), have recently attracted significant attention in aeronautics and general transportation industries because of their promise as an enabling technology for high temperature solid state actuators [88]. Higher transformation temperatures allow for faster cyclic response in these fundamentally thermally driven system (*i.e.*, hotter SMA components cool faster) and also prevent auto-actuation when air vehicles are exposed to high ambient operating temperatures.

A wide range of HTSMAs exists [88]; in addition to the high transformation temperatures, potential HTSMAs must also exhibit acceptable recoverable transformation strain levels, long term stability, resistance to plastic deformation and creep, and adequate environmental resistance. These criteria become increasingly more difficult to satisfy as their operating temperatures increase due to greater involvement of thermally activated mechanisms in their thermomechanical responses. In spite of these challenges, progress has been made through compositional control, alloying, and the application of various thermo-mechanical processing techniques to the point that several likely applications have been demonstrated in alloys such as NiTiX (X=Hf, Zr, Pd, Au and Pt). In these NiTiX systems, the Karaman group at Texas A&M, the Young group at the University of North Texas, and others have demonstrated stable, repeated reversible martensitic transformation / actuation up to 350°C [88-100].

Among the HTSMAs that can demonstrate multiple actuation up to 400°C, NiTiHf and NiTiZr alloys are the most promising candidates on which our team has performed extensive previous work, demonstrating their actuation behavior under multiple thermo-mechanical cycles. Figure 16 demonstrates the stability of the NiTiHf response, which is attributed to the suppression of plastic deformation during martensitic transformation with the help of nanoprecipitates. As shown in Figure 17, the controlled formation of nanoprecipitates allows for fine tuning of transformation temperatures, and the team plans to perform this control primarily via heat treatment time and temperature exploration. However, the full materials design space for HTSMAs remains largely unexplored. Considering possible alloying additions to increase the transformation temperatures, variations in composition, nano-precipitate formation as a result of different heat treatment temperatures and times, there are clearly a vast number of potential alloying options.

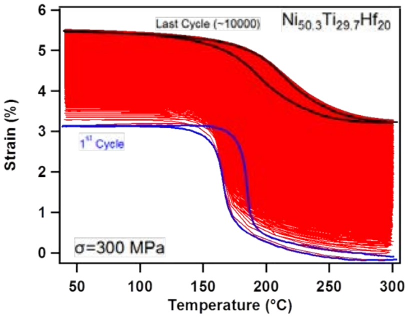


Figure 16 - The evolution of strain vs. temperature response over 10k cycles for $Ni_{50.3}Ti_{29.7}Hf_{20}$ *HTSMA under 300 MPa showing excellent durability under a very high load*

The team of Karaman, Young, and co-workers (in collaboration with Boeing and with input from Fort Wayne Metals) will focus on synthesizing, characterizing, and understanding the response of thes NiTiHf and NiTiZr HTSMA systems. The ultimate goal is the ability to select, produce, and process a nearly optimal alloy for any given SMA actuation need within the space of possible actuators for supersonic aerostructural reconfiguration. Toward this goal, the materials development teams expects to employ a number of critical characterization methods, including differential scanning calorimetry (DSC), dual beam focused ion beam (FIB) / scanning electron microscopy (SEM), synchrotron radiation X-ray diffraction (SR-XRD), transmission electron microscopy (TEM) and/or local electrode atom probe (LEAP). The University of North Texas team in particular will perform SR-XRD on NiTi-Hf,Zr samples at elevated temperature to observe phase evolution and its effect on processability.

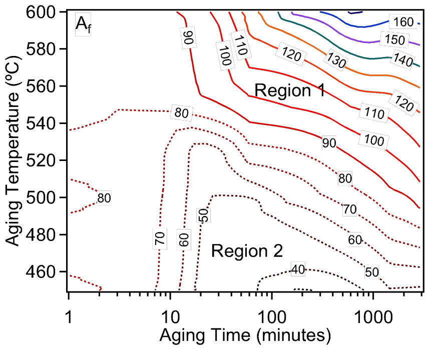
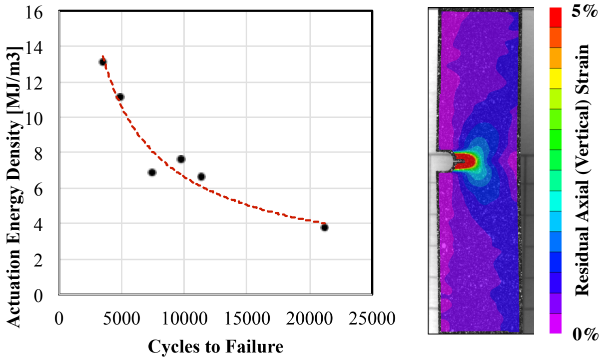


Figure 17 - Effect of aging temperature and time on the austenite finish temperature of $Ni_{50.3}Ti_{34.7}Hf_{15}$ *shape memory alloy. Large changes in transformation characteristics are achieved through the formation of nano-precipitates.*

Regarding produced actuation components, one of the primary concerns is the durability under cyclic loading. Repeated actuation with the maximum recoverable strain of 3-5% in most common polycrystalline SMAs results in gradual accumulation of TRansformation-Induced Plasticity (TRIP) and eventual failure due to low cycle fatigue. This behavior is characteristic of SMAs and is defined as "thermo-mechanical" or "actuation" fatigue. To date there is a lack of actuation fatigue testing standards, understanding of the damage mechanisms, and a method for accurately predicting the lifetime of actuator parts. Prior experimental investigation into the durability of SMAs by Lagoudas and The Boeing Company has led to the characterization of many preliminary material systems to date, including HTSMAs with transformation temperatures of up to 400°C [15,16,101-103], as shown in Figure 18. Similar and improved characterization studies will be performed in the current effort and a novel actuation fatigue model incorporating damage mechanics inherent to the SMA system will be expanded and improved [103].



a) **b)**

Figure 18 – Prior SMA actuation fatigue results of the kind to be leveraged herein: a) Work density/fatigue life plot for NiTiHf loaded from 200-500MPa, b) Accumulated residual strain near an actuator stress concentration just prior to failure.

VII.2.B. Thrust 2: Mechanics, Modeling, and Component Design for Durability

(Hartl, Lagoudas, Baxevanis): The overall SMA/HTSMA materials and actuator analysis and design framework depends on the incorporation of a single constitutive model that captures all the pertinent thermal and mechanical effects of interest and utilizes a single set of model parameters with a unique calibration across scales. To this end, the models developed by Lagoudas, Hartl, and coworkers [104-110] will be extended. They are phenomenological and consider the average thermo-mechanical response of a given material representative volume element. A Gibbs free

energy potential will be chosen, and a thermodynamically consistent constitutive model will be derived by assuming specific forms for the energy of phase mixing and of the thermodynamic transformation criteria [110].

In particular, the anisotropic elastic and transformation responses observed at the crystalline (*i.e.*, granular) scale are included, which allows, via micromechanics or direct numerical simulation, the consideration of the effects of precipitate properties as well crystallographic texture on the macro-scale response. In the new approach [111], transformation and reorientation surface fits are pre-calculated to anisotropic systems at the *crystalline* scale, [112] resulting in a two orders of magnitude performance improvement over past approaches (see Figure 19). For the analysis and design of components for use at the system scale (*i.e.*, in actual engineering applications), Computational Structural Dynamics (CSD), based on a finite element analysis (FEA) approach, is utilized by Hartl [113, 114].

With a constitutive modeling scheme in place, approaches for accelerating the development cycle of SMAs will be investigated, based on design requirements for actuation force, displacement and stable actuation response by integrating into the modeling the microstructure that controls the thermomechanical and functional properties of SMA. Members of the team (Baxevanis, Karaman, Lagoudas) recently developed a microscale-informed model to predict the effective thermomechanical response of processed (precipitation hardened) alloys [115, 116]. This predictive capability will be adopted to account for additional alloying elements leading to high temperature phase transformations and it will also be expanded to include transformation-induced plastic response [117]. Homogenization schemes for upscaling the microstructural information to evaluate the effective actuation strain, hysteresis, and cyclic response will be developed using a computational finite element approach [115, 116]. The entire problem will be solved as a nested boundary value problem, while boundary conditions on the representative micro-volume element will allow the incorporation of the length scales associated with the transformation and transformation induced plasticity kinetics. The outcome of the methodology is to correlate composition and heat treatments to actuation properties, including actuation strain at various stress levels and transformation temperatures, thus resulting in a continuum of SMA actuator material made to design specifications.

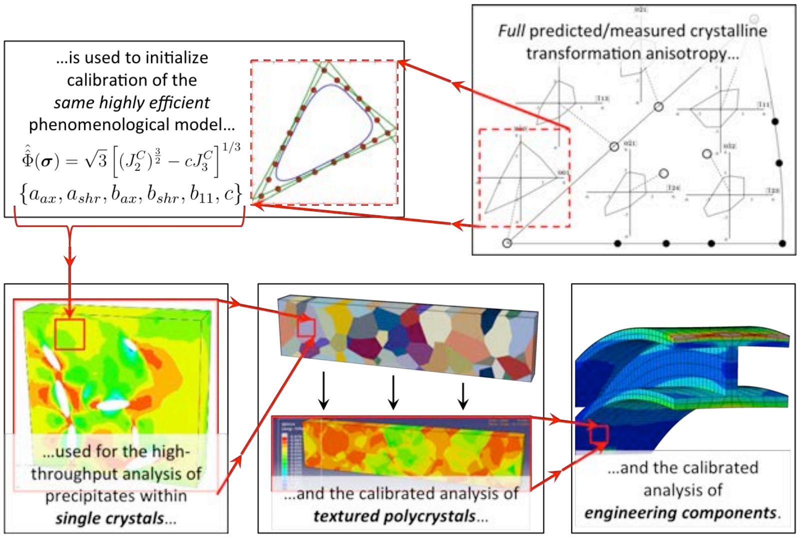


Figure 19 - Computational methodology for high-throughput analysis across scales. A constitutive model for the HTSMA is first calibrated using derived crystallographic information. This information allows prediction of polycrystalline response for the calibration of engineering structural models for Computational Structural Dynamics (CSD).

Finally, with regard to computational modeling of SMA component durability and fatigue, Lagoudas and Baxevanis recently proposed a new and accurate model for the actuation fatigue life prediction of various SMA material systems under the constant-stress loading condition

[118]. Models were initiated to examine stress state in different orientations in space and can therefore incorporate some effects of multiaxiality and non-proportionality by considering cracks that form and run on a *critical plane* [119-121]. The objectives of the current research focus on the mechanics and modeling of SMA/HTSMA fatigue and durability are to test critical plane fatigue prediction approaches against actuation lifetime data from SMAs under multiaxial loading and create efficient algorithms for fatigue life estimation under complex non-proportional loading as might occur in a general actuation component in real service. The most prominent will be further evaluated with simulations of single crystals with cracks along different crystallographic orientations and with simulations of polycrystalline samples to validate models given complex loading sequences, where the maximum difference in crack tip displacement during a loading cycle appears to provide the driving force for fatigue crack growth among virtually all stages [122-124]. A criterion for variable amplitude loading will also be developed as a generalization of its counterparts for constant multiaxial amplitude loading, by introducing a cycle counting method (*e.g.*, rainflow method [125]) and a damage accumulation model (*e.g.*, the Miner rule [126]).

VII.2.C. Thrust 3: Custom and Novel Material and Actuator Production and Certification (*Karaman, Mabe, Schaffer*): A critical and novel aspect of the current research effort is the intentional focus placed on potential producibility of the actuation concepts at a commercial scale. For that reason, the expertise of Schaffer and co-workers at Fort Wayne Metals (FWM) has been recruited. They have previously collaborated with Boeing researchers on SMA actuator development, and success toward satisfying the objectives of Challenge 2 is expected to substantially advance the cause of SMA actuation for aerospace applications, especially in the supersonic regime.

As previously described, custom tuning of SMA actuator components is critical to project success but this may depend on many factors related to the local OML-component design criteria including load, temperature, and durability constraints. Fort Wayne Metals is an integrated supplier of application-tuned shape memory alloys from melt through application in high precision medical device and aerospace technology, and will be able to leverage its history and capabilities in critical tuning of SMA and provide top-down interaction with every step of SMA production from metals procurement and melt consolidation, breakdown and final forming, and thermomechanical training and characterization. Early prototype engagement is key to understanding and overcoming early design obstacles, such as alloy homogenization, fabrication and defect control for mechanically durable design at a production scale. The material production and actuator fabrication team plans to mitigate challenges associated with unexpected findings in the development of scaled metals processes by leveraging solutions to analogous issues in SMA alloy consolidation through finish processing.

Fort Wayne Metals, being a capable supplier of SMA components on a large scale, will enable an efficient design iteration cycle via the following efforts: *i*) Prototype alloys prepared through multiple melt modalities (Vacuum Arc Melting, Vacuum Arc Remelting, Vacuum Induction Melting). Large melts (50-200 lb) are possible; a range of materials including conventional $Ti_{50}Ni_{50}$ and TiNiHf compositions can and will be produced; *ii*) Near net shaping and structure-property development by thermo-mechanical processing, including hot forging, hot rolling, cold drawing, interpass annealing, and stress-annealing, will be performed in preparation for the final forming of actuation components; *iii*) FWM-produced actuation components are expected to include SMA rod torque elements, wire strands and cables, torque tube prototypes, and strip formed material for iterative characterization and process tuning between FWM and Texas A&M, UNT, and Boeing.

The successful transition of SMA based adaptive technology to production applications will depend on acceptance and approval by regulatory agencies. The US Code of Federal Regulations (CFR) in Title 14 (Aeronautics and Space), Part 25 provides guidance on the establishment of airworthiness certification for materials. Recently a team of aerospace companies, including Boeing, Embraer, and Rolls-Royce and materials suppliers, including SAES, ATI, Johnson-Matthey, and Fort Wayne Metals have submitted two new standard test methods for SMA materials and components to ASTM for approval and publication [127]. These are the first ever regulatory agency-accepted material specification and test standards for shape memory alloys employed as actuators for commercial and military aviation applications. They will provide a clear path towards regulatory acceptance and approval of SMA actuator systems for commercial production.

VII.3. Challenge 3: Detailed Design and Demonstration *(Entire team, Led by James Mabe, Boeing):* The underlying purpose of Challenge 3 is to provide the evidence that major technology risk elements have been addressed such that our novel small-scale distributed adaptivity concept has reached sufficient maturity for a future supersonic commercial aircraft. The design, fabrication, and demonstration of one or more system-level concepts capable of adapting geometry to the required accuracy level (*e.g.,* 5% displacement error) under representative flow conditions will be addressed. Our approach is as follows: design and demonstration of the actuation and structural system for this ULI program will start at the component level and progress through increasing levels of technology readiness and system complexity. While several critical components and sub-systems may be shown to individually have a TRL of 4-5 earlier on in the program, a capability demonstration for the entire technology including a fully integrated system, from aerodynamic surface to aircraft integration, will be demonstrated in the final year. This effort is divided into two principal thrusts, described below. Specialized peer review opportunities will be shared with those identified in both Challenge 1 and Challenge 2 above, given the interdisciplinary nature of this Challenge.

VII.3.A. Thrust 1: Understanding of Required Design Elements: The system-level design of the adaptive structure must take into account not only the actuator (SMA or conventional) but also the connecting and supporting aircraft elements. The fundamental system-level requirements are the geometry changes needed to meet aerodynamic and noise objectives. With a defined geometry, primary system requirements will be determined such as the actuator force, displacements, and load/stress/strain distributions required to make the necessary geometry changes. Additional requirements include the rate of geometry change, size and weight envelopes for each component, power availability, control methods and accuracy, failure modes, and environmental conditions. The necessary elements of a complete adaptive aerostructure system will be included in the full system demonstration and are discussed below.

Outer Mold Line (OML) Surfaces: The OML is the aerodynamic surface that interacts with the flow and changes geometry to meet aerodynamic and noise objectives. It may undergo linear or angular motion or 2D or 3D shape changes. Examples include a single piece composite panel that bends or morphs, an assembly of rigid pieces connected by hinges or compliant joints, or a flap or group of flaps. There are two primary design requirements: *i)* the OML must maintain sufficient

stiffness to hold the desired shape against pressure loads; *ii*) the OML must possess sufficient ***compliance*** such that the mechanical work required from the actuator does not result in excessive size, weight and power (SWAP). Clearly high stiffness and high compliance are fundamentally competing requirements. One approach to this problem is the application of OML skins with highly tailored and highly directional (anisotropic) stiffness and compliance coupled with compact high force SMA actuators.

Load Bearing Structure: This portion of the system transfers loads between the OML surfaces, the actuator, and the air vehicle base structure. (*e.g.*, spars, ribs, or wing box). The OML section can also be load bearing (*e.g.,* wing skin, SMA component). Conversely the OML geometry can be changed by modifying the attached load bearing structure. As with the OML skins, the load bearing structure must be selectively stiff and strong to carry lift loads and selectively compliant to enable actuation without excessive actuator SWAP.

Actuators: These devices (*e.g.,* SMA, hydraulic, electric) provide a controlled force and motion output. Forces can be linear or rotary, and in the case of SMA actuation may be 2D/3D and distributed. The advantage of SMA actuators is their mechanical work output per unit weight, which is up to an order of magnitude higher than conventional actuation systems. SMA actuators are flexible in terms of packaging within highly constrained volumes. There are two primary design challenges: *i*) development of SMAs that meet the temperature, load and displacement requirements of supersonic aircraft applications (Challenge 2); *ii*) complex system integration issues such as thermal management. The result must be a highly integrated and balanced design of the actuator/structure/skin system.

Mechanical or Structural Integration: The mechanical integration of the actuation system into the vehicle involves transfer of the actuator load output to the aerodynamically loaded OML. The key design issues include matching of the actuator output to the adaptive OML section given displacement and shape needs. Boeing's Variable Geometry Chevron (VGC) shown in Figure 20 [128] is an example of coupling an SMA actuator to the more rigid structure to achieve the desired in flight shape changes. FEA design and optimization tools developed by Texas A&M since the 2005 flight test, which identified designs that reduced morphing error to an ideal goal by 2mm on average, is shown in Figure 20b [129] and will be extended herein (Challenge 1) for structural optimization to minimize actuation size and weight while meeting boom and aerodynamic geometry requirements.

Power Source: The preferred power source on next generation aircraft is electrical. This is also the preferred power source for SMA actuators. In the important case that SMA actuators are found to be infeasible, hydraulic, including Electrohydraulic Actuators (EHA), will be explored.

Environmental Interface: The impact of the ambient environment (*e.g.,* thermal, humidity, vibration, fluids) can impact system performance. Temperature, aeroelastic loads and contamination dominate the design requirements for the OML skins. Thermal energy management drives the design of the SMA actuator. Environmental impacts will be investigated in detailed design with some included in demonstrations.

Sensors and Control System: Sensors inform the control system and may include position, distributed shape, loads, power, and health. We expect that commercial off-the-shelf (COTS) sensors meet the design requirements for the adaptive system. If specific sensor technology shortfalls are uncovered they will be documented for future programs. Boeing has significant experience with development of control system approaches for SMA actuators [130]. Our team will invite NASA collaborators (*e.g.,* NASA Langley) to ensure that design requirements do not exceed the capabilities of currently proven control approaches; insufficient control system capabilities will be documented and mitigations identified.

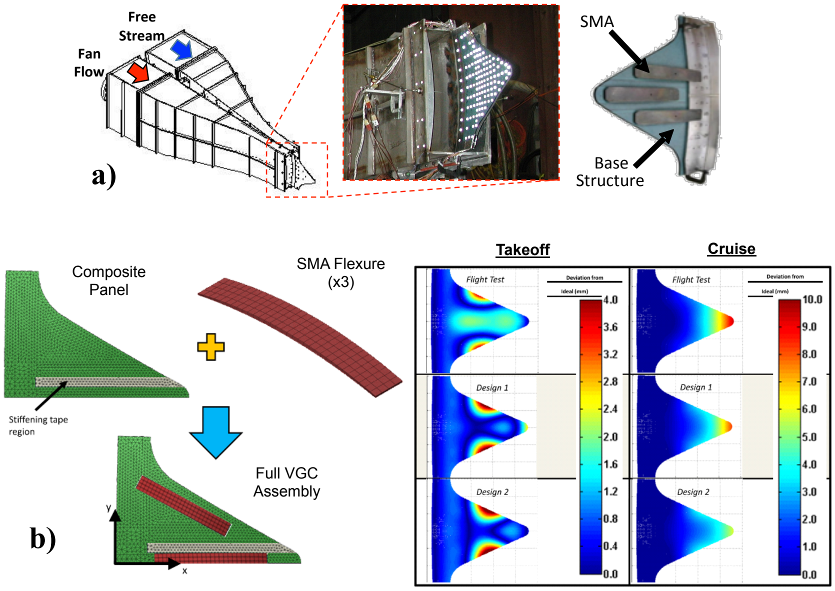


Figure 20 – Boeing Variable Geometry Chevron (VGC), whereby SMA actuators were designed to couple with nozzle structure to yield specified in-flight geometries: a) Full scale adaptive geometry nozzle segment tested in simulated takeoff and cruise free stream and fan nozzle flows; b) SMA actuator and OML structural morphing optimization study [128, 129, 131]

V.II.3.B. Thrust 2: Technology Demonstrator Development: Each of the elements described above constitute a complete adaptive structures system and will be included in the development of detailed designs, hardware fabrication, and technology demonstrations. Demonstrations will progress through several stages over the duration of the project. Starting with an assessment of the feasibility of applications identified in Challenge 1, leading to proof-of-concept testing of critical elements and subsystems, and culminating in a test of a complete adaptive structures system in a relevant environment (as shown in Figure 10). Major stages of application assessment, design, build and test are described below.

Actuation Sizing and Feasibility Assessment: To support technical and manufacturing feasibility studies and to assess the relative value of the novel adaptive structures applications, in the first year of the program an adaptive supersonic aerostructure system evaluation tool will be developed, based on mechanical energy management. The tool will estimate system design parameters including actuator size, weight, quantity, power consumption, thermal load, and system level impacts for each potential application identified by the challenge team and will consider both SMA and conventional actuation systems. Inputs to the tool will be based on shape change designs developed in response to Challenge 1 for improved aerodynamic and sonic boom performance. Input criteria will include overall shape change dimensions including local displacements, planform area of change, total volume change, aerodynamic and structural loads, actuation rates, and available actuation size and weight integration envelopes. The tool outputs will be validated against well-defined adaptive structures problems that have undergone detailed engineering studies and tests, for example the Boeing Variable Geometry Chevron or Adaptive Trailing Edge.

Component level design demonstration in laboratory and wind tunnel: During years 2-3 of the program, component level demonstrations of initial concepts such as variable leading edge shapes, variable camber, and trailing edge devices will be designed, built, and tested in both laboratory and wind tunnel environments. At this stage requirements are simplified and demonstration assemblies will be made from COTS parts, 3D printing, simplified fabrication or machining, and available SMA materials or conventional actuators. This early experimental laboratory and wind tunnel testing supports later model validation and component build-up. Our approach will be to develop an experimental validation and test plan early in the program, specifying the experiments needed to validate SMA technology. Such a plan will include the test objectives for each test, define the experimental hardware including instrumentation requirements, develop a run matrix, select/recommend a test facility, and develop a set of test exit criteria. Initial development testing is planned for low cost university facilities and wind tunnels, such as the TAMU SHR tunnel (see "Test Facilities") with significant student involvement. Here sub-system SMA components will be used to demonstrate the ability to actuate a surface in a supersonic flow field. Several SMA-actuated surfaces representative of the typical geometric adaptations for off-design boom tailoring will be possible test geometries.

Outcomes from the small-scale sub-system wind tunnel testing include increased maturity for actuator/structure design for tailored aerodynamic adaptations. High-fidelity flow field analysis utilizing Schlieren imaging, particle image velocimetry (PIV) and surface pressure measurements will be used as needed. These data will be used to *train undergraduate and graduate students*, aide in the development of the modeling design tools, and provide input to the full-scale system level supersonic wind tunnel demonstrations.

Sub-system level design and demonstration (TRL 3-4): In years 3 and 4 of the project sub-system design will be built and tested to integrate a more complete set of the adaptive system elements. Design and test of integrated components such as SMA actuators coupled to a compliant panel working against simulated loads with sensors for feedback control will be tested on the bench top. The size and weight of all parts should meet full-scale requirements as system functionality is demonstrated with an identified path towards size and weight targets and an increasing accuracy of geometry changes. Multiple actuator designs will include sufficient actuator elements and sub-systems to demonstrate the necessary structural, mechanical, and electrical integration. Sensors and control system will be integrated. Power and thermal loads within system availability will be demonstrated. Critical components will be shown to meet environmental conditions such as vibration and thermal loads.

Full System level demonstration in relevant environment (TRL 4-5): A significant step in maturing SMA actuated adaptive structures technology for commercial supersonic applications will be to conduct validation wind tunnel tests [17] showing that controlled geometry changes can alter the shock wave signature (near field) and drag of an aircraft. Our Challenge 3 adaptive system/actuation effort will culminate in a system level demonstration reaching TRL 5. The details of this demonstration will be strongly dependent upon the output of the first two technical challenge efforts and will leverage previous adaptive structures wind tunnel testing, such as the DARPA Smart Aircraft and Marine Propulsion demonstration (SAMPSON) program, where a full scale SMA actuated variable geometry *supersonic* inlet compression ramp illustrated in Figure 21 was demonstrated in wind tunnel testing at NASA LaRC [13]. Also relevant is the Boeing VGC nozzle test shown in Figure 20a [131]. In each example, full scale

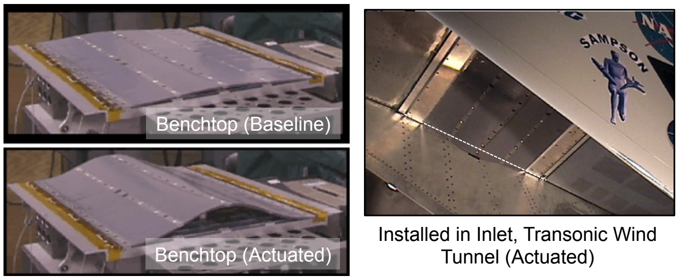


Figure 21 - SAMPSON SMA actuated compression ramp in F-15 inlet; wind tunnel demonstrated to TRL 5 [13]

adaptive structure systems actuated by SMA actuators demonstrated controlled geometry changes under realistic aerodynamic loads.

The primary objective of Year 5 tests is to demonstrate active manipulation of aerodynamic surface(s) in a relevant environment using SMA actuators. Due to wind tunnel model size limitations and the small geometric adaptation magnitudes targeted (at full scale), achieving the model precision to accurately capture boom signatures from the wind tunnel-scale full aircraft models is not feasible. Alternatively, to demonstrate the TRL of the multi-disciplinary SMA-based approach, a simplified subsection of a full-scale actuated system will be tested in a supersonic wind tunnel facility. To study impacts on drag under high-lift conditions, a wind tunnel model of a given shape will undergo force and moment measurements across a range of angle-of-attack conditions to capture baseline performance. Subsequently, SMA material could be added as appropriate to drive deformation to a variety of shape combinations at the different flight conditions to validate lower drag shapes at fixed lift and trim. These tests could also be modified to focus on adaptations for aerodynamic separation and delayed boundary layer transition relative to simulated results.

These tests would culminate in validation test(s) in a larger supersonic wind tunnel facility. Potential facilities would include the NASA Langley UPWT (preferred), NASA Glenn 8' x 6' supersonic wind tunnel, NASA Ames 9' x 7' UPWT supersonic wind tunnel, and the Boeing Polysonic Wind Tunnel (see "Test Facilities"). Wind tunnel selection will be coordinated with appropriate NASA Program Management to satisfy all technical and cost requirements. Once the data have been gathered and analyzed, a post-test report would be written for each test and would include a summary of test objectives, methodology and experimental setup, runs completed, uncertainty analysis, key findings/results and conclusions. A final SMA validation report would be constructed after all of the wind tunnel testing is complete. This report would detail the key findings and accomplishments of the SMA validation test program. The report provides the engineering documentation that the program has reduced the transition risk of our novel small-scale distributed adaptivity concept such that the technology is ready for consideration in design of future supersonic commercial aircraft and showing that sonic booms can be reduced by reconfiguration on demand.

VIII. COST SHARING

No cost sharing is proposed for this effort.

IX. PUBLICALLY AVAILABLE INTELLECTUAL PROPERTY

It is our expectation that all technologies and intellectual property developed in the course of this research effort will be shared with NASA and published in the open literature.

X. TEST FACILITIES

Multiple test facilities will be utilized for the effort, cutting across all three Technical Challenges. These facilities will support a logical technology development path, beginning with small-scale element fabrication and testing up to near-full-scale component/sub-system testing in a relevant environment.

X.1 Texas A&M University Facilities

Supports Technical Challenges 1,2,3: *Preliminary SMA element and component fabrication/testing; small-scale supersonic experimental validation for innovative multi-disciplinary design tools; preliminary supersonic feasibility demonstrations of fluid/structure interaction of actuated supersonic structures using SMA.*

X.1.A SMART Materials and Structures Lab: The Texas A&M University Shape Memory Alloy Research Team (SMART) Materials and Structures Laboratory consists of approximately 2,000 square feet of work and experiment space and includes a wide range of instruments for structural and functional property characterization. An abridged list of capabilities related to the current proposal includes: MTS Axial, Closed Loop, Servo Hydraulic Test Systems (20 to 100 KIP); An MTS Insight Test System with custom Thermcraft furnace having optical-grade window and Thermcraft controller hardware; Perkin-Elmer Pyris Differential Scanning Calorimeter (DSC); VIC-2D and VIC- 3D Digital Image Correlation Systems; Testo Thermal Imaging System with 320x240 FPA detector and 662F total temperature range; Three Boeing-designed and fabricated fully automated SMA torque tube training machines; Four-component scale SMA actuation fatigue testing frames.

X.1.B Materials Development and Characterization Center: The Materials Development and Characterization Center (MDC2), a 2,600 square foot facility provides multi-ferroics material fabrication equipment including a vacuum arc melting and suction casting systems up to 200 gr. capacity, large vacuum glove box for nano-particle and powder handling, powder consolidation and sintering instruments, a spark plasma sintering system, conventional deformation processing instruments including a cold and hot rolling system, an extrusion press, a cold swaging machine, 3 servo-hydraulic thermo-mechanical testing systems with temperature capability up to 1700ºC in different environments (air, vacuum, inert gas, and steam), several heat treatment furnaces in different environments, Bruker x-ray diffraction instrument with in situ stress and field capability and other customized equipment for the study of advanced materials.

X.1.C Supersonic High Reynolds Number Wind Tunnel: The Supersonic High Reynolds Number (SHR) wind tunnel at Texas A&M University is a blow-down facility with a 5”x5” cross section. With a ~10 minute run time, this facility provides an excellent platform for fluid/structure interaction testing, actuated surfaces, optical diagnostics, and morphing geometries. A Mach 2 fixed geometry nozzle is currently in place but a Mach 1.6 nozzle can be designed and fabricated if desired, to support the effort.

X.1.D Computational Resources: The available facilities include the Texas A&M University High Performance Research Computing Facility, which provides hardware, software and technical support for a 17340-core 337 TFLOPs IBM/Lenovo commodity cluster and a 8,512-core 326 TFLOPs Lenovo commodity cluster. In addition, the Texas A&M faculty have access to the 1.25 PFLOPs Cray x86 HPC cluster hosted at the Texas Advanced Computing Center.

X.2 Boeing Facilities

Supports Technical Challenges 2,3: *Larger-scale SMA element and component fabrication/testing; system-level testing under simulated aerodynamic loading; full concept system demonstrations and validations in supersonic wind tunnel facility*

X.2.A Advanced Aeromechanical Control Effector Systems Laboratory: Boeing support for the ULI program will center around the Advanced Aeromechanical Control Effector Systems (AACES) Laboratory that is part of the Flow Control team within Aeromechanics/Flight & Vehicle Technology in BR&T St Louis. It develops and demonstrates advanced fluidic and structural control effector technology and systems and their application to meet business unit needs for platform performance and efficiency. The lab has a broad range of capabilities including: a subsonic wind tunnel, advanced flow diagnostics, smart material actuator fabrication, advanced mechanical characterization and heat treatment.

X.2.B Boeing Polysonic Wind Tunnel: If the NASA supersonic wind tunnel facilities are unavailable for the culminating validation demonstrations, the Boeing 4’x4’ Polysonic Wind Tunnel (PSWT) facility in St. Louis, MS, may be utilized. This facility has an operating Mach number range of 0.45 to 5.58, with a Reynolds number range of 1 to 45×10^6/ft. With up to two minute run times, the Boeing PWST is a capable alternative to the NASA facilities to demonstrate the innovative SMA-based geometric adaptation technologies.

X.3 NASA Facilities

Supports Technical Challenges 3: *Full concept system demonstrations and validations in supersonic wind tunnel facility*

X.3.A LaRC 4-Foot Supersonic Unitary Plan Wind Tunnel: The versatile 4-Foot Supersonic Unitary Plan Wind Tunnel (UPWT) boasts a robust set of measurement tools and testing techniques for an enhanced understanding of complex fluid dynamics, as well as applied aerodynamics research. This facility has a Mach range of 1.5 to 4.6, utilizing two different test sections, achieving Reynolds numbers of 0.5 to 11×10^6/ft. This facility can be used to perform full concept system demonstrations and validations of an SMA-actuated morphing aerostructure. The LaRC UPWT is our primary facility choice to perform these culminating validation experiments at the end of the program.

X.3.B Ames 9'x7' Supersonic Wind Tunnel: The 9×7 SWT is a closed-return, variable-density tunnel with an asymmetric, sliding-block nozzle. Excellent optical access supports advanced flow visualization techniques, including pressure-sensitive paint, particle image velocimetry, oil flow interferometry, infrared thermography, and Schlieren imaging. This facility has a Mach range of 1.55 to 2.55, with a Reynolds number range of 0.9 to 5.6×10^6/ft. Many low boom tests have been performed in this facility, utilizing pressure rails to acquire the near-field acoustic signature for model validation and boom extrapolation. This larger supersonic facility may be used for the culminating validation experiments if the LaRC UPWT is unavailable.

X.3.C Glenn 8'x6' Supersonic Wind Tunnel: The 8- by 6-Foot Supersonic Wind Tunnel is NASA's only transonic-propulsion wind tunnel, serving industry, academia, and NASA's own community of aerospace researchers. The facility operates either in an aerodynamic closed-loop cycle, testing aerodynamic performance models, or in a propulsion open-loop cycle that tests live fuel-burning engines and models. Optional diagnostics include Schlieren photography, sheet laser visualization, pressure-sensitive paint, pressure measurements, high-speed video, and others. This facility has a Mach number range of 0.25 to 2.0, with a Reynolds number range of 2.6 to 4.8×10^6/ft. This would be the third choice NASA facility to be used for the program, if the LaRC UPWT and Ames 9'x7' SWT are unavailable.

XI. NASA SUPERCOMPUTING RESOURCE USAGE

It is expected that the computational resources of Texas A&M will be more than sufficient for the computational efforts described herein.