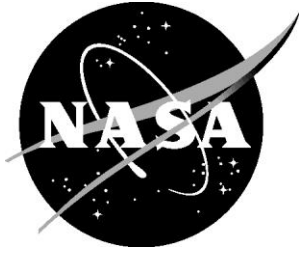


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Aeroelastic Stability Assessment Methodology and Application to Slat Noise Treatments on the High-Lift Common Research Model

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September 2024

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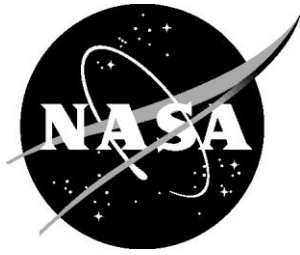
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Abstract

This work supports a larger effort at NASA to reduce airframe noise and, thus, environmental noise around airports. The leading-edge slat of conventional high-lift systems is a prominent source of airframe noise, and two technologies were previously identified as promising for noise reduction without significant aerodynamic or weight penalty: the slat cove filler (SCF) and the slat gap filler (SGF). NASA fabricated a 10%-scale semispan aircraft model for wind tunnel testing based upon the High-Lift Common Research Model (CRM-HL). NASA embarked on a test campaign with the 10% CRM-HL to determine the noise reduction effectiveness and other performance metrics of 3D SCF and SGF treatments in flow conditions representative of flight. The highly flexible SCF and SGF treatments posed a risk to the model and aeroelastic instability would compromise research integrity, so aeroelastic stability assessment was required. This work briefly describes the 10% CRM-HL, design of the SCF and SGF treatments to the model, and supporting fluid structure interaction (FSI) research. Relations for static and dynamic aeroelastic similitude are then developed for convenience of reference, and simplifications are introduced of particular utility to the cases considered in this study. The similitude relations are employed to assess the stability of the treatments under wind tunnel flow conditions based upon known behaviors from the supporting research. It is shown that the treatments are safe for test under the anticipated wind tunnel flow conditions with significant margins/factors of safety. It is furthermore demonstrated that the SCF is more susceptible to aeroelastic instability than the SGF, which has implications for flight feasibility.

Introduction

Reduction of airframe noise remains as an important goal for NASA in reducing environmental noise around airports. Airframe/nonpropulsive noise associated with transport aircraft is mainly attributed to contributions from the high-lift system and landing gear. A high-lift system increases lift at the low speeds encountered during the approach and landing phases of flight. However, unsteady flow phenomena caused by geometric discontinuities introduced by the deployed high-lift system and landing gear are important contributors to airframe noise. The relative contribution of individual sources is dependent on several factors, but model scale tests [1-3] and an aircraft flyover experiment [4] have both shown that the leading-edge slat device is a prominent source of airframe noise for transport aircraft during approach and landing.

Previous computational research and wind tunnel tests at model scale have identified noise production mechanisms associated with the flow about the leading-edge slat [1-3, 5-11], and several noise treatments have been proposed to reduce slat noise [3, 12-21]. Prior to the body of work of which the present study is a part, NASA had only evaluated slat noise treatments via computational fluid dynamics (CFD) and computational aeroacoustics (CAA), in 2D structural proof of concept tests on the benchtop, and in wind tunnel tests involving idealized, impractical representations of the treatments.

Of the proposed treatments, slat cove filler (SCF) [22] and slat gap filler (SGF) [23] devices have distinguished themselves in recent research as particularly promising for slat noise reduction. An SCF encloses the cavity in the cove of the slat to eliminate the typical recirculation region and guide the gap flow in a manner that reduces the unsteadiness and, thus, the radiated noise. An SGF blocks the gap flow entirely for all normal operating conditions but is rapidly and autonomously opened in an emergency

condition to regain the baseline high-lift configuration and performance. Concepts for both treatments are typically highly deformable to enable reconfiguration between the disparate stowed and deployed shapes.

Significant effort has been put forth to increase the technology readiness level (TRL) of SCF and SGF technologies [22-30]. The TRL advancement resulted in thin shell-type structures fabricated from a pseudoelastic shape memory alloy (SMA, specifically NiTi) material to enable the large deformation involved in structural reconfiguration. However, that work was limited to 2D in both structural implementation and flowfield. NASA embarked on development of a wind tunnel model and test campaign to push the SCF and SGF technologies to higher TRL via a 3D airframe with dynamically scaled SCF and SGF treatments in flow conditions representative of flight.

Exposure of the flexible SCF and SGF treatments to flow conditions representative of flight led to questions about their stability. The goal of this study is to document the approach used to substantiate the safety of testing the wind tunnel model at conditions corresponding to approach and landing angles of attack (AoA) and flow speeds up to Mach 0.2. Substantiation of test safety will be achieved by assessment of the static and dynamic stability of the SCF and SGF treatments at the worst-case test condition. Background information on the wind tunnel model and treatments is followed by a short description of supporting fluid structure interaction (FSI) research that will be used to perform the stability assessments. Dimensional analysis is then used to develop the scaling relations for static and dynamic aeroelastic similitude between systems in various scenarios involving fixed and varying parameters. Finally, the similitude equations are used to perform stability assessments of the SCF and SGF treatments to the wind tunnel model based upon the supporting research at different geometric scales and flow speeds.

It is anticipated that the need for stability assessment of flexible additions to wind tunnel models will become more commonplace as adaptive structures technologies, especially those enabled by SMA materials, for flight vehicles continue to advance and move into the mid-TRL range. It is hoped that this study will help in future assessments.

Background

Model description

Boeing* and NASA previously collaborated on the development of the open geometry known as the Common Research Model (CRM), which is representative of a widebody transport aircraft. The CRM was developed to serve as benchmark geometry for computational and experimental research without proprietary restrictions, and it has been widely used in the AIAA Drag Prediction Workshops [31]. More recently, Boeing and NASA developed a high-lift version of the CRM, known as the CRM-HL [32-33], to facilitate similar research progress on airframe noise reduction and other technologies associated with the high-lift configuration. The CRM-HL is also an open geometry that has been used in the AIAA Geometry and Mesh Generation Workshops [34] as well as the AIAA High-Lift Prediction Workshops [35].

The TRL of the SCF and SGF technologies was advanced through the design of treatments for the CRM-HL. The geometry of the SCF and SGF treatments to the CRM-HL was prescribed through CFD/CAA [36]

* Specific vendor and manufacturer names are explicitly mentioned only to accurately describe the model hardware and/or associated research activities. The use of vendor and manufacturer names does not imply an endorsement by the U.S. Government, nor does it imply that the specified equipment is the best available.

to maximize noise reduction potential while avoiding aerodynamic penalties. The corresponding structural configurations were developed and designed as functioning flight hardware at full scale via computational structural analysis [37] to minimize estimated articulation loads and weight penalty while remaining conservative on sizing for fail-safety. Many challenges were faced in advancing the SCF and SGF treatments to 3D while achieving flight-like structures capable of massive reconfiguration (retract-deploy) and balancing the trades just mentioned. The outcome of the structural advancement to 3D was a two-component SCF that is stress free in the deployed configuration and joined to the slat via a sliding flexure hinge at the forward/lower connection and a fixed flexure in the aft/upper connection near the slat trailing edge (TE). The SGF design was a stress-free skin conformal to the outer mold line (OML) of the main wing (termed stress-free retracted, SFR), i.e., configured as an “overleaf” to the stressed skin bearing flight loads, and articulated by a linkage housed in the forward section of the main wing and driven by the slat actuators.

NASA fabricated a 10%-scale version of the CRM-HL for testing airframe noise and high-lift technologies in the NASA Langley Research Center (LaRC) 14- by 22-foot Subsonic Tunnel (14x22). The model design included a modular main wing to allow interchangeable leading-edge (LE) assemblies. The slat noise testing incorporated three subassemblies consisting of inboard (IB) and outboard (OB) slats, slat brackets, and a leading-edge component to the main wing that allowed interchange of untreated/baseline, SCF treated, and SGF treated configurations. The treated subassemblies included features for fail-safe integration of the SCF and SGF treatments while providing boundary conditions that represented the anticipated behavior of the treatments in flight hardware.

Compromises were made in adapting the SCF and SGF designs to 10% scale and to achieve fail-safety for the 10% CRM-HL in flow. The sliding degree of freedom of the SCF was negated at the forward/lower joint to the slat, but that was deemed only important for retract/deploy functions. The treatment integration features in the wind tunnel model accurately represented the remaining behavior for flight hardware. An SGF that is stress free in the deployed (termed stress-free deployed, SFD) configuration was selected for the 10% CRM-HL because of the greatly simplified implementation relative to the SFR and the expectation of identical aerodynamic and acoustic performance between the SFR and SFD configurations. Additionally, the linkage driving the forward end of the SGF was omitted from the model and replaced by fasteners to the slat trailing edge as the mechanism protruding into the recirculating cove flow was not anticipated to contribute significantly to the radiated noise. An image of the 10% CRM-HL main wing with the resulting 3D SCF treatment on the OB slat is shown in Figure 1. Note that design of an SCF treatment for the IB slat was not possible, so the SGF treatment was implemented there. The SCF thickness assignments shown in the figure resulted from a rule-of-thumb design approach described in a later section and developed during the course of supporting research described immediately below. A similar image of the 10% CRM-HL main wing in the baseline split-slat configuration and treated with the SGF on both slats is shown in Figure 2. Another rule-of-thumb design approach was developed in analogous supporting research and used to make the SGF thickness assignments shown in the figure. Additional detail on the technology advancements for 3D SCF and SGF treatments and the manner in which they were adapted to the 10% CRM-HL can be found in [37].

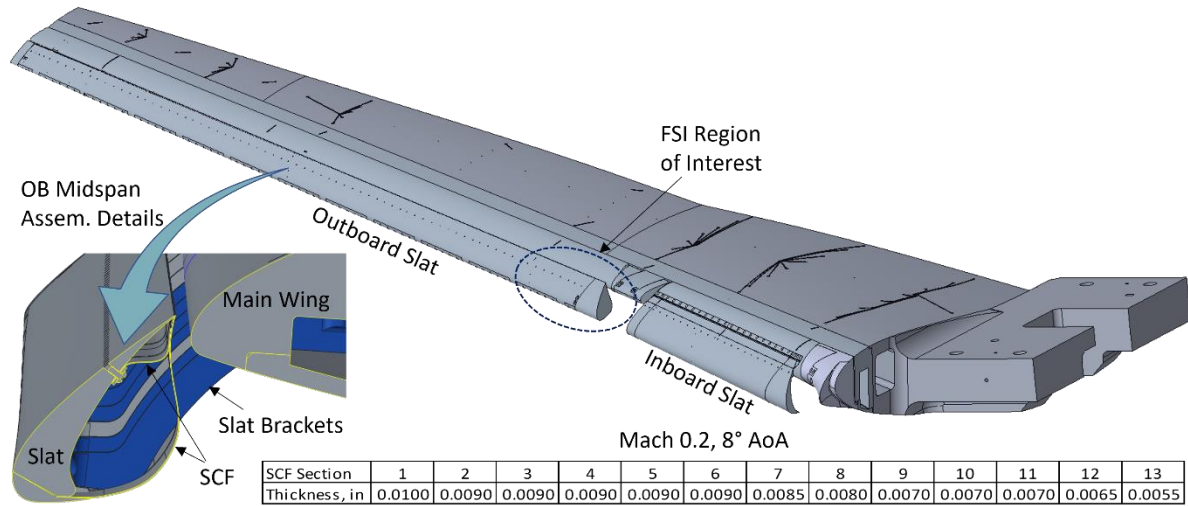


Figure 1. CAD example for the SCF treatment to the outboard (OB) slat of the 10% CRM-HL showing assembly detail at the OB slat midspan and the FSI region of interest; inboard (IB) slat treated with the SGF.

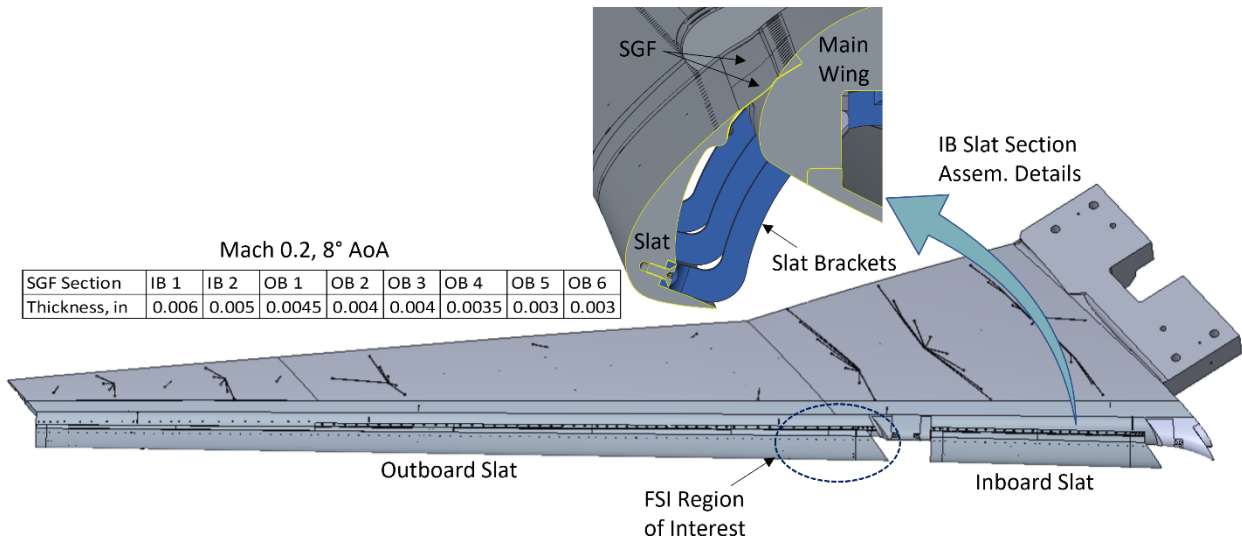


Figure 2. CAD example for the SGF treatment to the IB and OB slats of the 10% CRM-HL showing assembly detail at an IB section of the IB slat and the FSI region of interest.

It can be shown through dimensional analysis and similitude, some of which will be described and developed later in this document, that a scaled wind tunnel model tested at the same Mach and Reynolds[†] numbers and with the same fluid properties as the flight vehicle will satisfy all requirements for dynamic scaling as long as the shape and orientation relative to the flow are the same, the construction is similar, and the materials used are consistent. The following factors are relevant to the current study and important for establishment of dynamic scaling between nominal flight and expected wind tunnel conditions.

[†] Reynolds number considerations will be discussed in the Dimensional Analysis and Similitude section.

1. All wetted dimensions of the 10% CRM-HL are 10% of the corresponding full-scale geometry flight vehicle, including the thickness of flexible SCF and SGF treatments to the slat.[‡]
2. Flow during testing of the CRM-HL in the 14x22 will be nominally at reference conditions for a flight vehicle in terms of fluid properties and flow speed representative of approach and landing, i.e., sea level standard atmosphere and flow speeds up to $M=0.2$.
3. The shape of the CRM-HL, including the SCF and SGF treatments, is the same as the corresponding full-scale geometry, and the test angles of attack will be representative of flight.
4. Integration of the SCF and SGF treatments into the slat and main wing of the 10% CRM-HL is similar to construction of a functioning system at full scale. However, the 10% CRM-HL construction includes fasteners that would not be present in a flight vehicle between the SCF/SGF treatments and the wing components for fail-safety due to the research nature of the wind tunnel testing.
5. The material used to fabricate the SCF and SGF treatments is consistent with that required for a flight vehicle, i.e., pseudoelastic NiTi.

According to the above enumerated factors, the SCF and SGF treatments to the 10% CRM-HL meet the requirements for dynamic scaling, which means that their static and dynamic response to the flow will be representative of a flight vehicle. The fastening systems, mentioned in factor 4 above, render the SCF and SGF treatments incapable of detaching from the main model components. However, it is still of interest for model safety and research integrity that the flexible SCF and SGF treatments do not exhibit any static or dynamic instability behavior. To that end, stability of SCF and SGF treatments is assessed below.

Supporting Research

The aeroelastic stability assessment provided in this document was completed prior to testing the SCF and SGF treatments to the 10% CRM-HL in the NASA LaRC 14x22, but it was not available prior to treatment design. Therefore, rules of thumb were used to arrive at conservative sizing for the thickness of the shell-type SCF and SGF structures [37], as shown in Figures 1 and 2, and representative thickness values will be presented in the SCF and SGF stability assessment sections. Nonetheless, the SCF and SGF treatments were highly flexible due to the requirement for reconfiguration between highly disparate retracted and deployed configurations and to the goals of minimizing articulation load and weight penalty, both performed in computational structures simulation at full scale. Thus, there were concerns about static and dynamic aeroelastic stability under the planned tests at flow conditions representative of approach and landing: airflow at Mach 0.2 and sea level atmospheric conditions.

Two supporting research activities were established to understand the fluid structure interaction (FSI) behavior of the SCF and SGF treatments in flow. The first activity was performed in collaboration with Texas A&M University (TAMU) and was a combined computational and experimental study focused on the SCF treatment utilizing their 4-foot by 3-foot wind tunnel. The goal of the work was to explore the aerodynamic, aeroacoustic, and FSI behavior of a flexible SCF treatment in flow and with high-lift system articulation. The physical model represented a freestream parallel slice at the midspan of the outboard slat of the CRM-HL (v2.0, which is similar to, but not identical to the final version) at 6.25% scale; the small scale being due to the tunnel size. The CRM-HL (v2.0) was a predecessor to the final version of the CRM-

[‡] The upper and lower trailing edges of the leading-edge slat for the CRM-HL are excepted from the linear scaling rule because linear scaling to 10% would result in an impractical trailing-edge thickness. Consequently, the slat trailing edges of the baseline 10% CRM-HL are double that of linear scaling, and the baseline geometry must be modified to remove interference between the slat and main wing to render the slat operable, which was done to perform the computational structures simulations and analysis.

HL (termed v2.1), and the earlier version had a greater chord/thickness ratio for the leading-edge slat. The SCF implementation was also an earlier vintage having a conventional hinge at the forward/lower connection to the slat and a fixed flexure configured as a lap joint at the slat TE. The physical model included an articulating leading-edge slat and trailing-edge flap, and tests were performed up to flow speeds of Mach 0.1. Computational models were correspondingly pseudo-2D, i.e., uniform cross section of finite spanwise length and termed 2.5D, at 6.25% scale to match the experiments. Full-scale simulations with Mach 0.2 flow were also performed in collaboration with the University of Bristol. The geometry associated with the computational models having a span of one element/grid (FEA/CFD) is shown in Figure 3. For reference, the SCF at 6.25% scale had an unsupported curvilinear length of just under 2", a baseline thickness of 0.003", and a minimum thickness of 0.002". The minimum thickness was limited by material availability but was still anticipated to exhibit signs of instability at flow speeds achievable (up to Mach 0.1) in the wind tunnel experiments. CFD, computational structures, and FSI studies were performed via a framework consisting of SC/Tetra (flow solver) and Abaqus (structural solver), and various computational results at 6.25% scale were correlated to experimental measurements. Additional details about this research activity can be found in [24-27, 38], and specific cases from that work will be described in more detail and used in the present aeroelastic stability assessment later in this document.

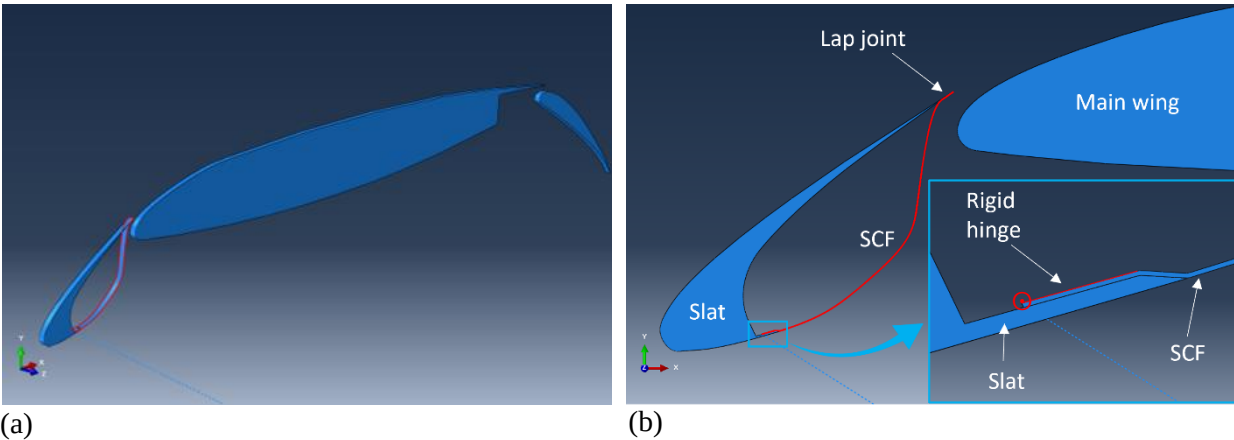


Figure 3. Geometry for the 2.5D computational model with SCF treatment at 6.25% scale: (a) perspective view and (b) detail of the SCF integration with the slat.

The second supporting research activity was purely computational and was performed in collaboration with ATA Engineering, Inc. (ATA). The goal of the work was to build 3D computational models of the 10% CRM-HL (v2.1) with the SCF and SGF treatments and substantiate the safety of testing the model in the NASA LaRC 14x22 through aeroelastic stability assessments of the treatments at the expected flow conditions. The FSI framework consisted of Loci/CHEM (flow solver) and Abaqus (structural solver), although a similar framework consisting of FUN3D and Abaqus was developed utilizing the Simulia Co-Simulation Engine as another component of the work. A preliminary FSI assessment was done on SCF and SGF treatments to a 2.5D model at the outboard slat midspan to refine the methodology before embarking on 3D assessments. The 2.5D SCF case was the same as that described above for the TAMU supporting research activity. The 2.5D SGF case was analogously constructed at the outboard slat midspan of the CRM-HL (v2.0) using the same approach for geometric definition as that for the 3D SGF treatment to the CRM-HL (v2.1). One distinguishing factor for the 2.5D SGF is that a pinned (simply supported) boundary was applied to the forward edge to model the rotational freedom anticipated for a mechanized system, as opposed to the encastre (clamped) boundary incorporated in the 3D SGF to model the fastened joint with the slat TE. The resulting geometry for the 2.5D SGF computational model is shown in Figure 4, which

incorporated an SGF with an unsupported curvilinear length of approximately 0.25” and a nominal thickness of 0.002” at 6.25% scale.

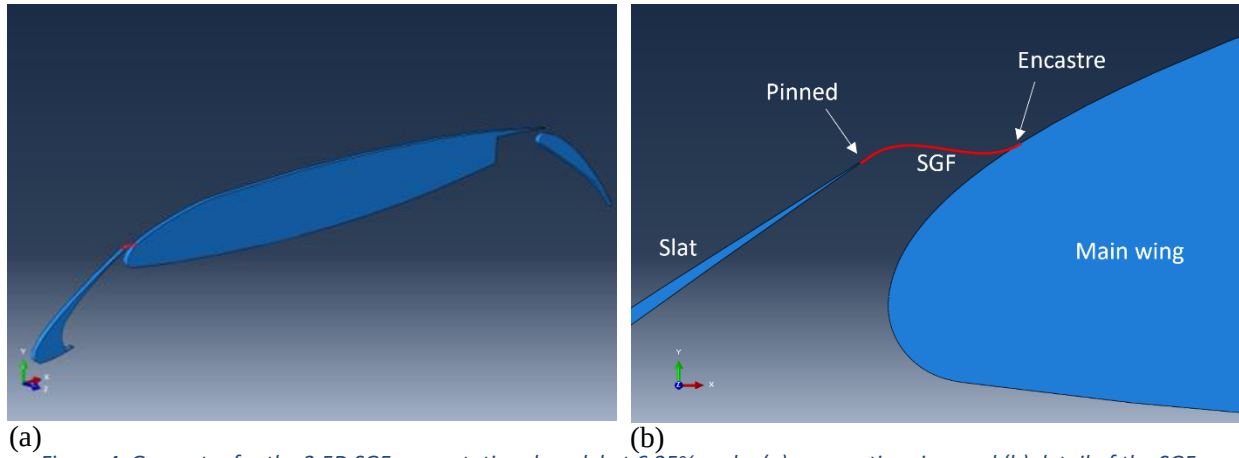


Figure 4. Geometry for the 2.5D SGF computational model at 6.25% scale: (a) perspective view and (b) detail of the SGF integration into airframe.

FSI simulation and analysis of the full semispan CRM-HL was impractical for 3D assessment due to the computational expense. Reynolds Averaged Navier Stokes (RANS) CFD solutions for the semispan CRM-HL were computed using FUN3D and Loci/CHEM, and very large eddy simulations (VLES) were later computed via Simulia Powerflow to better understand the flowfield, gain confidence in the accuracy of the solutions, and provide boundary conditions on a subdomain approach for the FSI computations to reduce the computational expense. 3D FSI analysis of the treatments was focused on the inboard end of the outboard slat, as shown in Figures 1 and 2, where the aerodynamic loading was found to be the worst case due to the influence of the nacelle and pylon. 3D FSI assessment via the subdomain approach was later pared down to focus on the SGF case due to time limitations, anticipation of better acoustic performance than the SCF from computational aeroacoustic (CAA) predictions, and availability of the extensive 2.5D SCF FSI work performed by TAMU (described above). Additional details about the Loci/CHEM-Abaqus and FUN3D/Abaqus FSI frameworks, the subdomain approach, and the FSI models themselves, along with accompanying results, are available in [39-40]. A stability assessment of the 3D SGF treatment will be demonstrated later in this document via similitude with the 2.5D case; however, results from the 3D FSI assessment of the SGF case will also be briefly discussed.

Stability and Scaling Considerations

The previous sections established the highly flexible nature of the SCF and SGF treatments and their potential susceptibility to aeroelastic instability in the presence of wind tunnel test conditions. Static instability, or divergence, would result in the flexible airframe treatment (SCF or SGF) undergoing large deformation into an alternate equilibrium configuration that is undesirable for aerodynamic and/or aeroacoustic reasons, thereby degrading performance and/or defeating the purpose for addition of the treatment to the airframe. Dynamic instability, or flutter, would typically initially manifest as large amplitude limit cycle oscillations (LCO) that would be detrimental to the aerodynamics and/or aeroacoustics of the airframe. Above a critical flow speed, those oscillations could become divergent and lead to catastrophic failure of the flexible treatment. Dynamic stability is of greatest concern with regard to safely testing the wind tunnel model.

It is desirable to compare the FSI behavior of 2.5D SCF and SGF systems from the previously mentioned supporting studies [24-27, 39-40] at various scales and flow speeds to understand the implications for stability of the 3D treatments developed for the 10% CRM-HL. Development of scaling relations between the cases is required for similitude to be used for that assessment.

Dimensional Analysis and Similitude

Similitude is often used to design experiments at small scale, such as in a wind tunnel, that adequately represent the physics of system behavior at full scale. Similitude can also be used with computational data and can relate physical behavior between scales. A combination of experimental and computational data is used in this study, and similitude is used to relate behavior at various scales.

Rigorous aeroelastic similitude requires meeting various constraints and matching a multitude of nondimensional parameters derived either via the Buckingham π Theorem [41] or by nondimensionalizing the governing equations. The latter method is used by Molyneux [42] to study similitude of aeroelastic models in great detail, and a specific example application of the process is given by Heeg et al. [43] for the case of static aeroelastic scaling. Molyneux provides the scaling relations for the most general and demanding case corresponding to dynamic aeroelastic similitude (flutter assessment) in hot, high-speed flow, and then discusses simplifications for a variety of flow regimes and specific test conditions. The scaling relations required for the present study can be interpreted from Molyneux's work, but some will be rederived here for greater understanding, clarity, and ease of reference for the specific cases of interest here: subsonic testing of flexible airframe treatments to an otherwise idealized scaled model at sea level atmospheric conditions and approach/landing Mach numbers.

Dynamic aeroelastic similitude requires consideration of the equations governing the aerodynamics, the structural response, and the dynamic behavior of the coupled system. Aerodynamic similitude requires matching of Mach and Reynolds numbers as well as geometric similarity of the "wetted" surface, its orientation relative to the flow, and its deformation. The equilibrium (force-deflection) equation for the structure requires that the ratio of aerodynamic load to structural restorative forces be maintained along with the distribution of structural stiffness, i.e., structural construction should be similar. Structural vibration equations of motion require the mass ratio (structural mass to surrounding fluid mass) or, equivalently, the ratio of aerodynamic to restorative forces and the reduced frequency (ratio of speed of oscillations to flow speed) to be maintained. Usage of the ratio of aerodynamic to restorative forces in structural dynamic similarity makes the dynamic similitude more similar to and partially satisfied by static similitude, and that approach will be used in this study (as opposed to mass ratio).

While some guidelines for design are required, relaxation of some of the above requirements and constraints for similitude is often justified and sometimes required, even if not justified, because higher-fidelity information is not available. The following assumptions and simplifications to similitude are justifiable in this work.

1. In the case of the subject wind tunnel test of the 10% CRM-HL, the flow conditions must simulate approach and landing flight conditions. Thus, sea level atmospheric conditions and a flow speed of Mach 0.2 is representative of flight and is conservative from the standpoint that sea level conditions provide the greatest pressure load for a given flow velocity.
2. Reynolds number matching is one aspect of similitude that is often difficult to accomplish. It is generally accepted that Reynolds number is of minor importance for the aeroelastic effects of main lifting surfaces. Although this is likely a poor assumption for boundary layer effects on the

aerodynamics and aeroacoustics, it is not possible to match flight Reynolds number in the NASA LaRC 14x22, so Reynolds number matching will be neglected in this work.

3. The cantilevered support of the semispan 10% CRM-HL and the vertical orientation of the model justify neglecting Froude number matching, i.e., gravitational effects are ignored.
4. In the process of SCF and SGF treatment stability assessment later in this document, similitude is drawn between cases of different geometric scale and flow speed. However, the flow speeds involved are similar such that compressibility effects are negligible and turbulence effects are comparable. These cases are 2.5D of short spanwise extent such that gravitational effects are negligible. Thus, Reynolds and Froude number scaling are ignored, and reasonable Mach number differences are allowed in those cases.

Static Aeroelastic Similitude

The governing parameter for static aeroelastic similitude arises from the static equilibrium or force-deflection equations for a structure, which can be expressed in the following generic form:

$$\delta = \frac{P}{EI} \quad (1)$$

where δ is the deflection, P is the applied force, and $E\tilde{I}$ represents the structural stiffness. E is the Young's modulus of the material and $\tilde{I}$ is a geometric parameter similar to the traditional area moment of inertia but typically composed of cross-sectional and planform dimensions that results in a dimension of length. The flexible structures under study in this case closely resemble plates or shells such that the structural stiffness is proportional to the product of the material and geometric contributions to stiffness, i.e., $E\tilde{I} \propto Eh^3L^2$, where h is the structural thickness dimension and L is a generic length dimension characteristic of the planform area of the structure. The thickness is held distinct from the other structural dimensions because it will be useful in the discussions and developments to follow. The load in cases of interest to this work is aerodynamic and proportional to the dynamic pressure q acting on the wetted surface of the structure, which can be represented by $P \propto \rho_f V^2 L^2$ where ρ_f is the mass density of the fluid and V is the flow velocity. The parameter for static aeroelastic similitude can then be written as the following ratio:

$$\delta \propto \frac{\rho_f V^2 L^2}{E\tilde{I}} \quad (2)$$

Nondimensionalizing the proportionality relation in Equation (2) to the generic length dimension L results in

$$\delta' = \frac{\delta}{L} \propto \frac{\rho_f V^2 L}{E\tilde{I}} \quad (3)$$

which represents the ratio that must remain invariant regardless of geometric, material, or flow changes for static aeroelastic similitude to be maintained. Thus, assigning subscripts T and R to represent target and reference scale, respectively, it follows that

$$\delta'_T = \delta'_R, \quad \left(\frac{\delta}{L} \right)_T = \left(\frac{\delta}{L} \right)_R, \quad \left(\frac{\rho_f V^2 L}{E\tilde{I}} \right)_T = \left(\frac{\rho_f V^2 L}{E\tilde{I}} \right)_R \quad (4)$$

which can be rearranged as

$$\frac{\delta'_T}{\delta'_R} = 1, \quad \frac{\delta_T}{\delta_R} = \frac{L_T}{L_R}, \quad \frac{(E\tilde{I})_T}{(E\tilde{I})_R} = \frac{q_T L_T}{q_R L_R} \quad (5)$$

Introducing scale factors λ , defined as the ratios of target scale parameters to reference scale parameters (e.g., model-scale wind tunnel parameters to full-scale flight vehicle parameters), static aerodynamic similitude in Equations (5) requires

$$\lambda_{\delta'} = 1, \quad \lambda_{\delta} = \lambda_L, \quad \lambda_{E\tilde{I}} = \lambda_q \lambda_L \quad (6)$$

where λ_{δ} , λ_L , λ_q , and $\lambda_{E\tilde{I}}$ are the scale factors for deflection, geometric dimension, dynamic pressure, and structural stiffness, respectively. Equations (6) demonstrate that deflection scales with geometric dimension, as would be expected, and structural stiffness scales with the product of dynamic pressure and geometric dimension. The latter scaling equation offers options for manipulation to maintain similitude in situations of parametric constraint.

The rightmost Equation (6) can be rewritten to permit manipulation of parameters as follows:

$$\lambda_{E\tilde{I}} = \lambda_E \lambda_I = \lambda_q \lambda_L \quad (7)$$

General static aeroelastic similitude

where λ_E and $\lambda_I = \lambda_h^3 \lambda_L^{-2}$ are the Young's modulus and geometric parameter scale factors, respectively. Several useful scaling rules can be derived from Equation (7) for various scenarios of specific interest for similitude between a target scale (e.g., wind tunnel model) and a reference scale (e.g., flight vehicle).

1) Consider the case of the 10% CRM-HL for which the test conditions will be the same as flight, i.e., sea level atmospheric properties and flow speeds up to Mach 0.2. Thus, fluid property, flow velocity, Mach number, and dynamic pressure matching are assured (i.e., $\lambda_{\rho_f} = \lambda_v = \lambda_M = \lambda_q = 1$), and Reynolds number matching will be neglected as discussed previously. Then the static aeroelastic similitude equation becomes

$$\lambda_E \lambda_I = \lambda_E \lambda_h^3 \lambda_L^{-2} = \lambda_L \quad \rightarrow \quad \lambda_E = \left(\frac{\lambda_L}{\lambda_h} \right)^3 \quad (8)$$

Static aeroelastic similitude, matched fluid properties and flow speed

Although a material with a suitable Young's modulus, i.e., $\lambda_E \approx 1$, could be substituted for the expected stress-strain range in the wind tunnel tests, it is desirable to use the same superelastic SMA material (NiTi, $\lambda_E = 1$) as that envisioned for the flight vehicle to increase TRL and because the unique material properties could manifest behaviors that are unforeseen in this application. Note from Equation (8) that material matching ($\lambda_E = 1$) requires the structural thickness to be scaled with the other geometric dimensions

($\lambda_h = \lambda_L$). Indeed, NiTi sheet in thickness values at 10% of those sized for flight were specified for the 10% CRM-HL, so the model meets the requirements for static aeroelastic similitude.

In any case for which material matching and/or uniformity of geometric scale is not possible or desirable, Equation (8) indicates that static aeroelastic similitude can still be maintained by judicious material and/or geometric scale selections to result in a Young's modulus scale factor equal to the cube of the ratio of geometric dimension scale factors.

2) Alternatively, if no constraint is placed on dynamic pressure ($\lambda_q \neq 1$), aerodynamic similitude can still be maintained, i.e., Mach number matching, by judicious fluid and/or test condition choices. Then, scaling all geometric dimensions uniformly, i.e., $\lambda_h = \lambda_L \rightarrow \lambda_i = \lambda_L$, results in the following for static aeroelastic similitude

$$\lambda_{Ei} = \lambda_E \lambda_L = \lambda_q \lambda_L \rightarrow \lambda_E = \lambda_q \quad (9)$$

Static aeroelastic similitude, uniform geometric scaling

Thus, the material for the model could be selected to achieve a Young's modulus scale factor that matches the dynamic pressure scale factor achievable in the facility. Conversely, dynamic pressure could be adjusted to compensate for a material limitation. This case is not relevant to the present study but is useful to note as an option.

3) It is often most difficult to scale the thickness dimension of a model due to limitations in machining or in material availability, e.g., sheet metal thickness. In such cases, it may be desirable to scale the thickness dimension separately from the other geometric dimensions to write the static aeroelastic similitude Equation (7) as follows:

$$\lambda_E \lambda_i = \lambda_E \lambda_h^3 \lambda_L^{-2} = \lambda_q \lambda_L \quad (10)$$

General static aeroelastic similitude

If the material used in the model is consistent with the flight vehicle, as is the case for the SCF and SGF treatments to the 10% CRM-HL, then $\lambda_E = 1$ and Equation (10) can be rearranged to result in the following:

$$\lambda_h^3 = \lambda_q \lambda_L^3 \rightarrow \lambda_h = \lambda_q^{\frac{1}{3}} \lambda_L \quad (11)$$

Static aeroelastic similitude, matched materials

Thus, this converse case to 2) shows that the ratio of thickness to planform geometric scale factors should equal the cube root of the dynamic pressure scale factor for static aeroelastic similitude to be maintained.

Recall that dynamic pressure scales with the product of gas density and flow speed squared; $\lambda_q = \lambda_{\rho_f} \lambda_v^2$.

Thus, for similitude between cases having the same sea level atmospheric conditions, i.e., $\lambda_{\rho_f} = 1$, $\lambda_c = 1$, and thus $\lambda_q = \lambda_M^2$, the static aeroelastic similitude equation can be simplified to the following:

$$\lambda_h = \lambda_M^{\frac{2}{3}} \lambda_L \quad (12)$$

Note that Equation (12) suggests a change in Mach number between cases, which violates the requirements for aerodynamic similitude. However, this form of the equation will be useful and justified in later discussions in light of item 4 of the justifiable assumptions and simplifications to similitude.

Dynamic Aeroelastic Similitude

Dynamic aeroelastic similitude requires satisfaction of additional constraints beyond static aeroelastic similitude. The governing parameter for dynamic aeroelastic similitude is the reduced frequency or Strouhal number scale factor. The Strouhal number in aerodynamics is the ratio of oscillatory behavior to the flow speed:

$$St = \frac{fL}{V} \quad (13)$$

Strouhal number for vortex shedding in flow

where f is typically taken to be the frequency of vortex shedding, L is a characteristic length (i.e., of the body in flow) perpendicular to the flow direction, and V is the flow velocity. For cases involving bodies exhibiting oscillating movement, f is typically taken to be the frequency of oscillation and L becomes the amplitude of the oscillation A .

$$St = \frac{fA}{V} \quad (14)$$

Strouhal number for oscillating body in flow

The Strouhal number must remain invariant to maintain dynamic aeroelastic similitude. Thus, by a procedure analogous to that demonstrated by Equations (4) and (5), it follows that

$$St_T = St_R \quad \left(\frac{fA}{V} \right)_T = \left(\frac{fA}{V} \right)_R \quad (15)$$

and rearrangement results in

$$\frac{St_T}{St_R} = 1 \quad \frac{\left(\frac{fA}{V} \right)_T}{\left(\frac{fA}{V} \right)_R} = \frac{V_T}{V_R} \quad (16)$$

Scale factors can then be introduced to rewrite Equation (16) as follows

$$\lambda_{St} = 1 \quad \rightarrow \quad \lambda_f \lambda_A = \lambda_V \quad (17)$$

General dynamic aeroelastic similitude

Thus, the flow speed must scale with the product of the frequency and amplitude of oscillation for dynamic aeroelastic similitude to be maintained. However, frequency and amplitude of oscillation are parameters that cannot be directly controlled, so it is desirable to express Equation (17) in terms of quantities that can be adjusted.

Recall from the static aeroelastic similitude section that manipulation of material and geometric dimensions can offer options to maintain similitude where constraints on other parameters make it difficult. It will be convenient in the following discussion to define scaling relations for the characteristic resonant frequency of structural vibration. Recalling that stiffness for beam, plate, and shell-type structures is proportional to $E\tilde{I}$ or Eh^3L^2 , the following relationship can be written to represent the proportionality of resonant frequency to the stiffness and mass of the structure:

$$f = \sqrt{\frac{k}{m}} \propto \sqrt{\frac{Eh^3}{\rho_s h L^4}} \quad \rightarrow \quad \lambda_f = \left(\frac{\lambda_E}{\lambda_{\rho_s}} \right)^{\frac{1}{2}} \frac{\lambda_h}{\lambda_L^2} \quad (18)$$

Structural resonant frequency scale factor

where E is Young's modulus, ρ_s is the mass density per unit volume of the structural material, and h is the structural thickness that has been left distinct from the other geometric dimensions L to facilitate independent manipulation. Additionally, note that the amplitude of vibration scales according to the same ratio of aerodynamic load to structural stiffness as the static aeroelastic similitude case:

$$A \propto \frac{\rho_f V^2 L^2}{E\tilde{I}} \quad \rightarrow \quad \lambda_A = \frac{\lambda_q \lambda_L^4}{\lambda_E \lambda_h^3} \quad (19)$$

Structural oscillation/vibration amplitude scale factor

Substituting from Equations (18) and (19) into Equation (17) results in a dynamic similitude relation between fundamental parameters:

$$\lambda_v = \left(\frac{\lambda_E \lambda_{\rho_s}}{\lambda_{\rho_f}^2} \right)^{\frac{1}{2}} \left(\frac{\lambda_h}{\lambda_L} \right)^2 \quad (20)$$

Dynamic aeroelastic similitude in terms of primary parameters

Again, useful scaling rules can be obtained from Equations (17) – (20) for various scenarios of interest for similitude between target and reference scales.

1) Consider the present case of the 10% CRM-HL where the fluid properties, flow speed, and thus Mach number and dynamic pressure match that of flight ($\lambda_v = \lambda_{\rho_f} = 1$). Then, Equation (20) can be rewritten as follows:

$$\lambda_E \lambda_{\rho_s} = \left(\frac{\lambda_L}{\lambda_h} \right)^4 \quad (21)$$

Dynamic aeroelastic similitude, matched fluid properties and flow speed

Again, it is desirable to use the same superelastic SMA material (NiTi) as that envisioned for the flight vehicle ($\lambda_E = \lambda_{\rho_s} = 1$) from which Equation (21) dictates uniformity in geometric scaling ($\lambda_h = \lambda_L$). Recalling that thickness of the SCF and SGF treatments for the 10% CRM-HL are scaled with the other dimensions, it is concluded that the model also meets the requirements for dynamic aeroelastic similitude.

Equation (21) dictates the scaling requirement for dynamic aeroelastic similitude in cases of matched fluid properties and flow speed but material matching or uniformity of geometric scaling are not possible. It can be seen that this is a rather complex requirement; furthermore, it must be balanced with the scaling relation in Equation (8) for static aeroelastic similitude.

2) Releasing the constraint on fluid properties and flow speed ($\lambda_{\rho_f}, \lambda_v \neq 1$) but maintaining matched Mach number and uniformity of geometric scaling ($\lambda_h = \lambda_L$) results in the following simplified form of Equation (20)

$$\lambda_{\rho_f}^2 \lambda_v^2 = \lambda_{\rho_f} \lambda_q = \lambda_E \lambda_{\rho_s} \quad (22)$$

Dynamic aeroelastic similitude, uniform geometric scaling

which gives some guidance on scaling between flow and structural material to retain dynamic similitude, albeit still quite complex and likely difficult to achieve in practice. Scaling relations for the oscillation frequency and amplitude from Equations (18) and (19) are similarly complex.

Reintroducing the matched fluid properties and flow speed ($\lambda_v = \lambda_{\rho_f} = 1$) allows the relation for dynamic aeroelastic similitude from Equation (22) to be further simplified, and Equations (18) and (19) indicate that the scale factors for resonant frequency and oscillation amplitude become reciprocals as follows:

$$\lambda_E \lambda_{\rho_s} = 1 \quad \rightarrow \quad \lambda_f = \frac{1}{\lambda_A} = \frac{\lambda_E}{\lambda_L} \quad (23)$$

Dynamic aeroelastic similitude, uniform geometric scaling, matched fluid properties and flow speed

The dynamic aeroelastic similitude relation is satisfied by matched materials, but it could also be satisfied by a material choice having a fortuitous product of Young's modulus and mass density scale factors. Furthermore, the resonant frequency/oscillation amplitude between models of the same size scale directly/inversely with the Young's modulus of the materials used. Conversely, the resonant frequency/oscillation amplitude scale inversely/directly with the geometric size between models having matched materials.

3) Releasing the geometric scale factors to scale independently ($\lambda_h \neq \lambda_L$) but enforcing matched materials ($\lambda_E = \lambda_{\rho_s} = 1$), along with the unconstrained fluid properties and flow speed ($\lambda_{\rho_f}, \lambda_v \neq 1$), results in another relatively complex form of dynamic aeroelastic similitude from Equation (20)

$$\lambda_{\rho_f} \lambda_v = \left(\frac{\lambda_h}{\lambda_L} \right)^2 \quad (24)$$

Dynamic aeroelastic similitude, matched materials

Reintroducing matched fluid properties and flow speed ($\lambda_v = \lambda_{\rho_f} = 1$) brings us back to case 1) directly above and again the scale factors for resonant frequency and oscillation amplitude are reciprocals:

$$\frac{\lambda_h}{\lambda_L} = 1 \quad \rightarrow \quad \lambda_f = \frac{1}{\lambda_A} = \frac{1}{\lambda_L} \quad (25)$$

Thus, as demonstrated in 1) for this case, dynamic aeroelastic similitude requires uniformity in geometric scaling and inverse/direct scaling of the resonant frequency/oscillation amplitude with the geometric scale factor.

Analogous to case 3) under static aeroelastic similitude, matched fluid properties ($\lambda_{\rho_f} = 1$, sea level atmospheric conditions) results in matched speed of sound and Mach number scaling solely with flow speed. Under these conditions, Equation (24) can be rewritten as

$$\lambda_V = \lambda_M = \left(\frac{\lambda_h}{\lambda_L} \right)^2 \quad (26)$$

Again note that Equation (26) suggests a change in Mach number between cases, which violates the requirements for aerodynamic similitude. However, this form of the equation will be useful and justified in later discussions via item 4 of the justifiable assumptions and simplifications to similitude.

SCF Stability Assessment

The SCF is considered the more susceptible of the two treatments (SCF and SGF) to static and dynamic instability due to its much larger unsupported length and to its exposure to high speed, attached flow on one side. Additionally, supporting research on the SCF design and the TAMU study of FSI behavior showed that the geometry/shape of the SCF is critical for achieving desirable flow characteristics/noise reduction and that the flowfield and structural configuration are strongly coupled. A typical flowfield around the airframe treated with a rigid SCF treatment is shown in Figure 5 for the 2.5D model at 6.25% scale, 8 degrees angle of attack (AoA), and Mach 0.044 (15 m/s) freestream flow speed. Note that the streamlines indicate attached flow on the entirety of the slat/SCF OML, and the pressure coefficient inset indicates positive net pressure over the SCF except for a small region near the trailing edge. The steady pressure on the SCF at the indicated flow speed is approximately 0.01 psi (73 Pa), which scales to about 0.2 psi (1,520 Pa) at the target flow speed of Mach 0.2 for the CRM-HL at 10% scale. Three cases of known information relevant to SCF stability are explored and assessed below using the similitude equations developed above. All of the cases for stability assessment are from 2.5D FSI results.

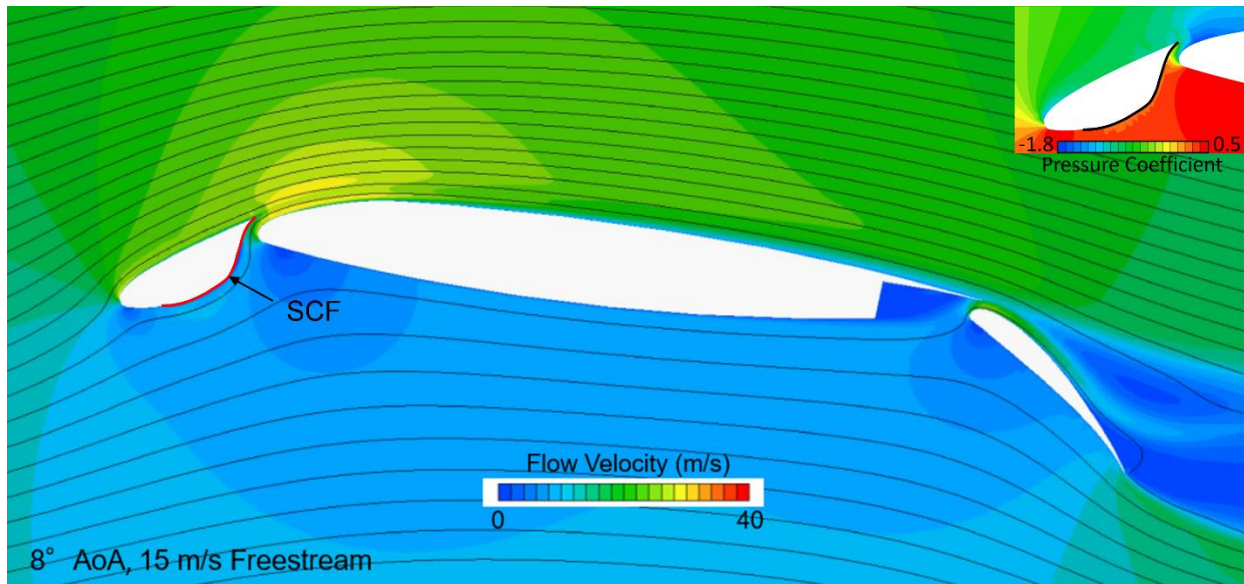


Figure 5. Flow velocity contours and streamlines for the 2.5D SCF at 6.25% scale, 8 degrees AoA, and Mach 0.044 (15 m/s) freestream flow speed, from Scholten [27].

Rule of Thumb Regarding Steady Deflection

TAMU performed supporting work that included extensive computational FSI studies of the CRM-HL (v2.0) at 6.25%, and at full scale in collaboration with the University of Bristol. The results provided insight on static and dynamic stability of the 2.5D model. A general rule of thumb that came out of that work suggested that an SCF that exhibited a static deflection significantly greater than the structural thickness was suspect for aeroelastic instability.

Aerodynamic loads for sizing the SCF treatment to the 10% CRM-HL (v2.1, the final version) were provided by 3D unsteady Powerflow VLES CFD computations performed by NASA LaRC researchers on a semispan configuration incorporating OML geometry representative of an SCF treatment designed in the same manner as that for the 2.5D TAMU model [36]. The flowfield associated with the 3D CRM-HL (v2.1) exhibited significant spanwise flow features that loaded the SCF components in a highly nonuniform manner, that is not consistent with the 2.5D cases studied by TAMU, characterized by the greatest load occurring in a very localized region at the outboard end of each SCF section [37]. Thus, the thickness of each SCF section for the 10% CRM-HL was sized to keep the maximum static deflection under one thickness of the corresponding structure under this non-uniform load condition. The thickness assignment, by this rule of thumb, for the SCF section at the midspan of the outboard slat for the 10% CRM-HL was 0.0085", as shown in Figure 1. Note that this would not be a conservative design if the aerodynamic load was uniform, but sizing the thickness for the entire structure to meet the deflection metric at the most highly loaded location makes it somewhat conservative. Additional margin/factor of safety was not applied because the thickness assignments were already near the maximum considered acceptable for scaling up to flight hardware.

Scaling Up from Stability Boundary at 6.25%

An experimental FSI study of the 2.5D CRM-HL (v2.0) at 6.25% scale accompanied the computational FSI work and focused the study at flow speeds compatible with tunnel operations (up to Mach 0.1 or 35 m/s at

sea level atmospheric conditions). Extensive correlation of the computational and experimental results was performed, and good agreement was obtained [25-26]. It is because of the extensive work/observations at 6.25% scale and Mach 0.1, and because of the availability of corroborating experimental data, that this lower-speed case will be used for stability assessment of the 3D 10% CRM-HL (v2.1) at Mach 0.2 despite violation of strict aerodynamic similitude, as will be justified subsequently.

Results of the 2.5D computational FSI work at 6.25% model scale with an SCF treatment of 0.002" thickness are shown in Figure 6 [27]. Figure 6a shows the response at the location exhibiting the maximum displacement magnitude versus solution time. The first 1.25 seconds correspond to a RANS CFD solution to render the flowfield approximately steady and the remaining time shown corresponds to a URANS solution of increasing flow speed. It can be seen that the mean value of displacement increases with flow speed, but the vibratory displacement about that mean varies only slightly until the critical flow speed is reached. The displacement mean value changes and the vibratory amplitude increases abruptly and dramatically at the critical flow speed. Figure 6b shows the same displacement trend vs flow speed, which indicates that the critical flow speed is approximately 34 m/s or Mach 0.099 at sea level atmospheric conditions.

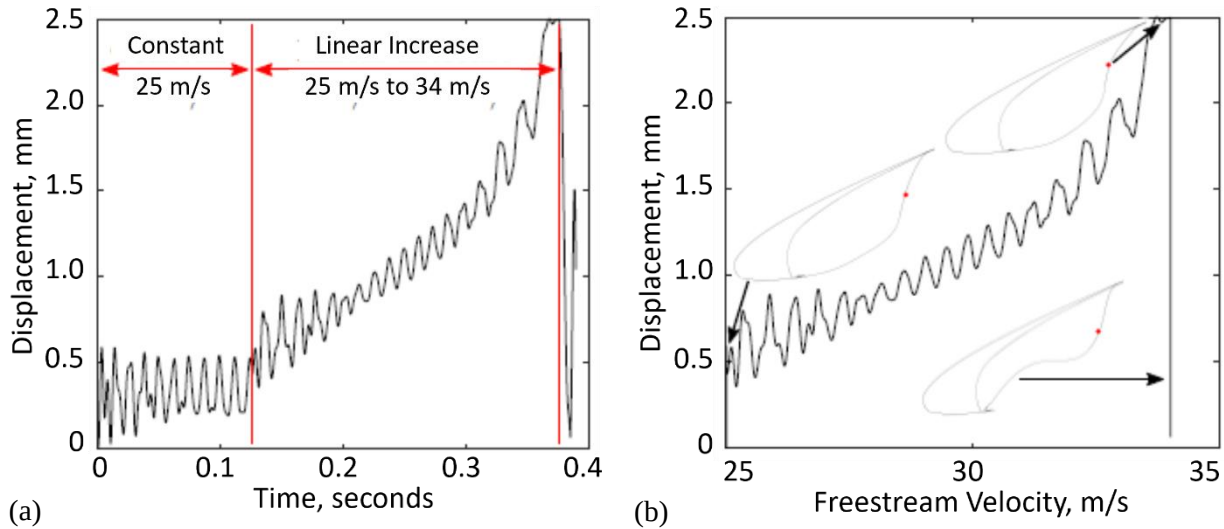


Figure 6. FSI response of a 0.002"-thick SCF treatment to the 2.5D CRM-HL (v2.0) at 6.25% scale: (a) max displacement vs time, (b) max displacement vs freestream flow speed, from Scholten [27].

Additional insight can be interpreted from the fundamental natural frequency of the 0.002"-thick SCF at 6.25% scale as determined by eigenvalue analysis of the structural system under the aerodynamic load at varying freestream flow speeds, as shown in Figure 7. The fundamental frequency exhibits a monotonic decline with increasing flow speed. A stable solution could not be achieved for flow speeds greater than 34 m/s, but a polynomial fit to the computed values for fundamental natural frequency suggests that the frequency goes to zero at a flow speed of approximately 35 m/s. For reference, the unloaded/undeformed case exhibits a fundamental natural frequency of 165 Hz, so it can be seen that the aerodynamic load has significant influence on the fundamental frequency even at the lowest flow speed (20 m/s) considered in the analysis.

The displacement and frequency results can be attributed to nonlinearity in the structure and in the coupling of the structure to the flow, as can be explained by observing the structural configuration in

Figure 3 and the aerodynamic load in Figure 5. The stiffer response at lower flow speeds is due to the predominantly convex curvature of the SCF effectively supporting the aerodynamic load. However, even at the lower flow speeds, destructive coupling exists such that deflection of the SCF causes flowfield changes that increase the aerodynamic load. Additionally, compressive stress develops in the SCF and reduces the structural stiffness due to the deflection working against immovable in-plane boundaries. These trends continue with increasing flow speed until the critical speed is reached and the structure snaps to an alternate equilibrium configuration that would likely become the start of LCO. Continued increase in flow speed would result in flutter.

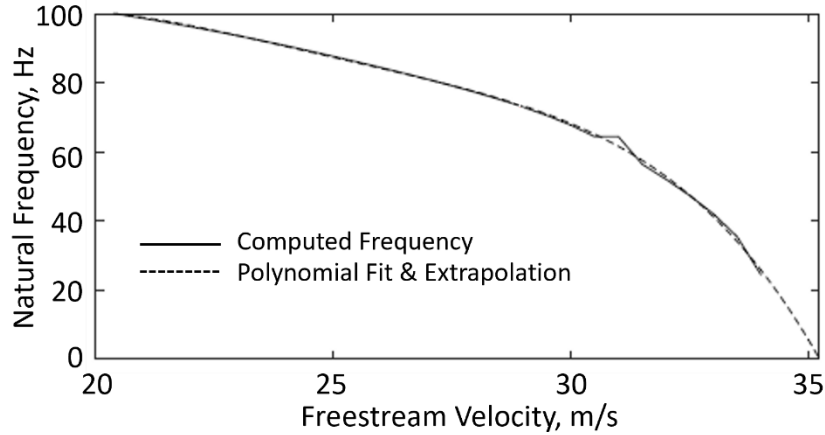


Figure 7. Fundamental natural frequency of the 0.002"-thick SCF treatment to the 2.5D CRM-HL (v2.0) at 6.25% scale under aerodynamic load at increasing freestream speed, from Scholten [27].

It is desirable to determine the SCF thickness at 10% scale for the CRM-HL (v2.1) that exhibits a stability boundary at the intended flow speed of Mach 0.2. Alternatively, it is desirable to know at what flow speed the SCF treatment to the 10% CRM-HL, sized by rule of thumb, will show aeroelastic instability. Some of the requirements for static and dynamic aeroelastic similitude are satisfied in comparing the 10% CRM-HL (v2.1) to the 6.25% CRM-HL (v2.0), but similitude is not strictly met for the following reasons:

- The 10% CRM-HL (v2.1) case has a lower chord/thickness ratio than its v2.0 counterpart, and the 10% model is 3D with sweep and taper to the structural configuration as well as 3D features in the flowfield that are not present in the 2.5D 6.25% case [37]. However, the higher chord/thickness ratio of the 2.5D 6.25% case presents a worst-case estimate of stability due to its greater compliance. Also, the 3D SCF treatment is spanwise segmented, and the section that is to be compared to the 2.5D case (midspan of the outboard slat) has mild geometric nonuniformity over its finite spanwise length. The 3D flow effects will be addressed in a later discussion.
- The structural construction is also slightly different in that the 6.25% case used a lap joint between the SCF and the slat TE and incorporated a conventional hinge near the slat cusp. In contrast, the 10% case employed a “reverse auxiliary” component for connection near the slat TE and a flexural hinge near the slat cusp [37]. These differences are considered to be secondary because the test configurations planned for the 10% CRM-HL at the slat TE bound the 6.25% case in terms of stiffness. Furthermore, the conventional hinge in the 6.25% assembly represented a worst-case for stiffness and stability.
- Finally, the Mach numbers for these two cases are different. However, both Mach numbers are in the low subsonic range such that flow character is similar and compressibility effects can be ignored.

Scaling from 6.25% Mach 0.099 to 10% Mach 0.2

Considering the above arguments in support of ignoring the identified similitude violations and applying the condition for static aerodynamic similitude from Equation (12), the thickness scale factor for similitude between the 6.25% scale case at Mach 0.099 and the 10%-scale case at Mach 0.2 is as follows:

$$\lambda_h = \lambda_M^{\frac{2}{3}} \lambda_L = 2.02^{\frac{2}{3}} \cdot 1.6 = 2.557 \quad \rightarrow \quad h_{10\%unstableM\ 0.2} = 0.0051'' \quad (27)$$

Thus, an estimate for the SCF thickness at the midspan of the outboard slat for the 10%-scale CRM-HL that will exhibit a static stability boundary at Mach 0.2 is 0.0051 inches. Recall that the thickness assigned to the midspan section of the outboard slat on the 10% CRM-HL is 0.0085 inches, which represents a factor of ~4.6 in stiffness over the 0.0051-inch thickness estimated to be unstable at that flow speed.

Dynamic aeroelastic similitude between the 6.25% case with a 0.002"-thick SCF at Mach 0.099 and the 10% SCF at Mach 0.2 is now considered. The thickness scale factor in this case corresponds to Equation (26)

$$\lambda_h = \lambda_M^{\frac{1}{2}} \lambda_L = (2.02)^{\frac{1}{2}} \cdot 1.6 = 2.27 \quad \rightarrow \quad h_{10\%unstableM\ 0.2} = 0.0045'' \quad (28)$$

which results in a thickness estimate of 0.0045 inches for an SCF that will exhibit a dynamic stability boundary at Mach 0.2. The thickness assignment to the midspan of the outboard slat on the 10% CRM-HL represents a factor of ~6.7 in stiffness over the 0.0045-inch thickness estimated to be dynamically unstable at Mach 0.2.

Scaling from 6.25% Mach 0.099 to 10% Stability Boundary

It is also instructive to estimate the critical flow speed (stability boundary) for the 0.0085"-thick SCF at the midspan of the outboard slat on the 10% CRM-HL from the critical flow speed for the 0.002"-thick 2.5D SCF at 6.25% scale. Rearranging the condition for static aeroelastic similitude in Equation (12) allows estimating of the critical flow speed for the 0.0085"-thick as follows:

$$\lambda_M = \left(\frac{\lambda_h}{\lambda_L} \right)^{\frac{3}{2}} = \left(\frac{4.25}{1.6} \right)^{\frac{3}{2}} = 4.33 \quad \rightarrow \quad M_{10\%0085unstable} = 0.43 \quad (29)$$

This estimate is clearly outside of the bounds of similitude because the flow character at Mach 0.43 is significantly different from that at the lower Mach numbers of 0.2 and 0.099 as experience has shown that the flow character changes significantly at around Mach 0.3. However, this calculation indicates that there is a Mach 0.23 margin of flow speed above the intended test condition of Mach 0.2 for which the 10%-scale SCF will be statically stable, which corresponds to a factor of safety of 4.6 in dynamic pressure (aerodynamic load).

The condition for dynamic aeroelastic stability in Equation (26) affords another method to estimate the critical flow velocity for the 0.0085"-thick SCF on the 10% CRM-HL as follows:

$$\lambda_M = \left(\frac{\lambda_h}{\lambda_L} \right)^2 = \left(\frac{4.25}{1.6} \right)^2 = 7.06 \quad \rightarrow \quad M_{10\%0085unstable} = 0.7 \quad (30)$$

which represents a much greater excursion into differing flow character and margin of safety of Mach 0.5 in flow speed above the Mach 0.2 test condition (or factor of safety of 12 on aerodynamic load) for dynamic stability of the 0.0085”-thick SCF at the midspan of the outboard slat on the 10% CRM-HL.

All of the stability assessments for the SCF treatment to the 3D 10% CRM-HL (v2.1) from the 2.5D 6.25% CRM-HL (v2.0) FSI results indicate substantial margins and factors of safety with the lowest factor of safety at 4.6. It is therefore concluded that the SCF treatment is safe for testing in the 14x22 at flow speeds up to Mach 0.2. The generous margins/factors of safety achieved are likely at least partly due to the application of the rule of thumb design method based upon the highly localized maximum deflection under the nonuniform aerodynamic load associated with the SCF configuration.

SGF Stability Assessment

The SGF treatment is considered less susceptible to aeroelastic instability because neither side of the structure is exposed to attached flow. Also, in contrast with the SCF case, it was found from supporting research on the SGF design and the ATA study of FSI behavior that the shape of the SGF transition between the slat TE and the main wing is relatively unimportant and that the flowfield and structural configuration are not strongly coupled. The SGF has a large recirculation region on the bottom, in the cavity between the slat cove wall and the main wing, and a smaller one on top created by the adverse slope of the SGF extending from the slat TE to the main wing. An example of the flowfield around the rigid geometry treated with an SGF is shown in Figure 8 for the 2.5D model at 6.25% scale, 6 degrees AoA, and Mach 0.073 (25 m/s) freestream flow speed. Although the flow is separated on both surfaces of the SGF, which results in relatively uniform mean pressure in both regions, the pressure differential is approximately 0.17 psi (1,172 Pa) at the flow speed shown and about 1.3 psi (8,695 Pa) at the target flow speed of Mach 0.2 for the 10% CRM-HL. The SGF loads are also fluctuating due to the recirculation, so the load is not insignificant.

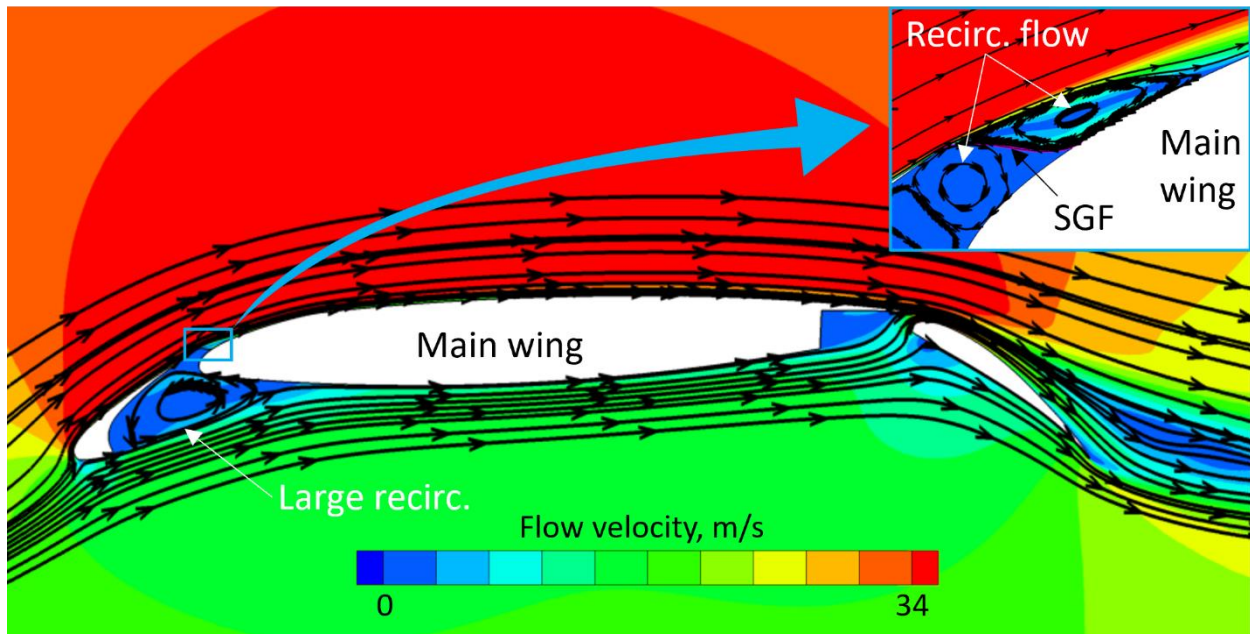


Figure 8. Flow Mach number contours and streamlines for the 2.5D SGF at 6.25% scale, 6 degrees AoA, and Mach 0.073 (25 m/s) freestream flow speed.

Rule of Thumb Regarding Steady Deflection

FSI study of the SGF case was performed in collaboration with ATA Engineering in both 2.5D on the 6.25% CRM-HL (v2.0) and 3D on the 10% CRM-HL (v2.1) [39-40]. Although results from only the 2.5D case were available in time for stability assessment of the 3D SGF treatment to the 10% CRM-HL, some results from the 3D computations will follow discussion of the 2.5D case in the subsequent sections. Experience gained from ATA's supporting work, and its relation with the parallel activity performed by TAMU on the 6.25% CRM-HL (v2.0) treated with the SCF, suggested that a more generous deflection allowable was justified for the SGF case relative to the SCF because the SGF has detached flow on both sides, the fluid-structure coupling is weak, and the deflected shape of the SGF does not impose a direct influence on the high speed flow unless the deflection is very large, i.e., the deflection puts the SGF surface above the trailing edge of the slat. A somewhat arbitrary maximum allowable deflection of twice the structural thickness was deemed conservative from experience and was established as the rule of thumb for design of the SGF treatment.

Analogous to the SCF case, aerodynamic loads for sizing the SGF treatment to the 10% CRM-HL (v2.1) were provided by 3D unsteady Powerflow VLES CFD computations on the semispan model. The 3D flowfield again showed spanwise variation on the SGF treatment, but to a much lesser extent than the SCF case. The thickness assignments to the SGF sections in Figure 2 were sized to keep the max deflection of each section under the two-thickness limit with the nonuniform aerodynamic load. In contrast to the SCF sizing, the SGF thickness assignments performed in this manner were already considered acceptable for scaling up to flight, so a more aggressive metric was not sought.

2.5D Case at the Midspan of the OB Slat

Recall that the 2.5D model was developed for a freestream parallel section at the midspan of the CRM-HL (v2.0) at 6.25% scale for the ATA study. The midspan of the outboard slat on the 10% CRM-HL (v2.1) is at a break between two SGF sections. The SGF sections adjacent to the outboard slat midspan had thickness assignments, by the rule of thumb, of 0.004 and 0.0035 inches, respectively (see Figure 2). The thickness for the SGF section at the midspan was taken to be the average of the two adjacent sections or 0.00375" for comparison to FSI study of the 2.5D model.

Scaling Up from Stability Boundary at 6.25%

ATA conducted FSI analysis for a variety of cases with SGF thickness values of 0.002" (baseline) or 0.003" and subjected to Mach 0.2 flow at sea level atmospheric conditions as the baseline or nominal case. Plots of the displacement response versus time at the node of maximum amplitude for the SGF from a few of the cases are shown in Figure 9 [40]. The responses shown were achieved by 1) computing a RANS CFD solution on the rigid geometry as an initial condition for steady/quasistatic cosimulation, 2) performing a RANS CFD and quasistatic computational structural dynamics (CSD) cosimulation to steady state as an initial condition (corresponding to time=1.0 in Figure 9) for time-accurate cosimulation, and 3) URANS CFD and time-accurate CSD cosimulation along with an impulsive load perturbation introduced after a short time lag. The increased dynamic pressure cases indicated by 4x and 6x q were achieved by adjustments of static pressure and air density, at constant temperature and flow speed (Mach 0.2), to simulate increased loads of commensurately higher speed flows without changing the flow character, e.g., Reynolds number and compressibility. The 0.003" thickness resulted in a fundamental frequency 50% greater than the baseline because frequency scales directly with thickness when all other parameters remain

unchanged, see Equation (18) with ($\lambda_E = \lambda_{\rho_s} = \lambda_L = 1$). Additionally, a fundamental frequency half that of the baseline was produced via a Young's modulus valued at 25% of the baseline (termed soft E) as frequency scales with $\sqrt{E}$, see Equation (18) with ($\lambda_{\rho_s} = \lambda_h = \lambda_L = 1$). The focus of this analysis was comparison of the nominal case with the varied cases to explore stability.

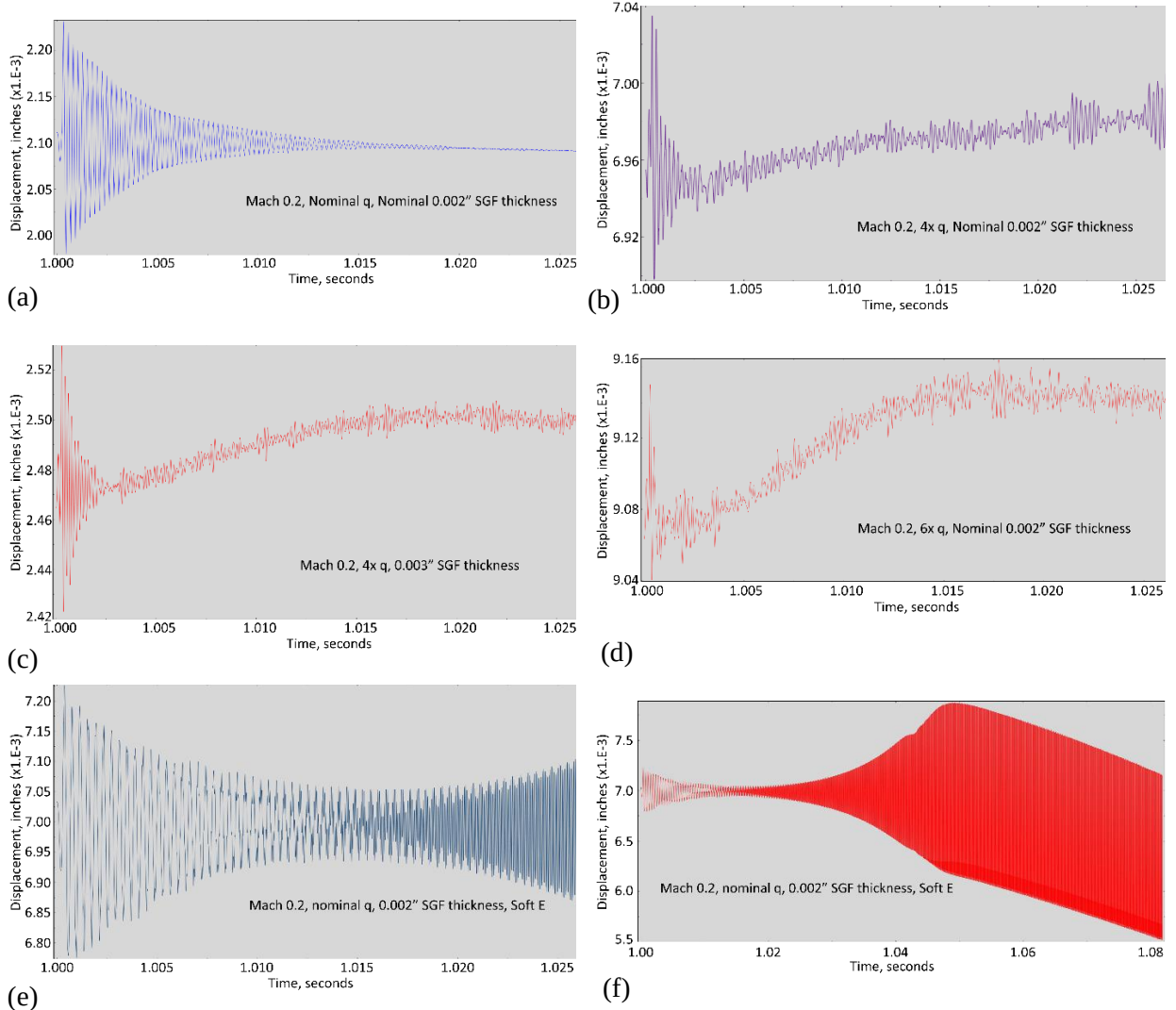


Figure 9. Max displacement vs time for 2.5D freestream parallel SGF at 6.25% scale and Mach 0.2 flow: (a) nominal q, 0.002" thick, (b) 4x q, 0.002" thick, (c) 4x q, 0.003" thick, (d) 6x q, 0.002" thick, (e) nominal q, 0.002" thick, soft E, and (f) same as e) but longer run time, from Shah et al. [40].

Note from Figure 9d that, even at six times the nominal dynamic pressure, the mean of the maximum displacement is only about four times the SGF thickness. In all cases, the mean value of the maximum displacement response from the time-accurate cosimulation differs from the converged displacement of the steady/quasistatic cosimulation. In the nominal q and thickness case, the displacement mean value drifts to a slightly lower value while in all higher-q cases the mean value increases. This behavior was not interrogated for detailed physical understanding at the time, but it is clear that inertial effects and/or unsteadiness in the flow are important and cause the solution to converge to a slightly different equilibrium

relative to the steady/quasistatic solution. Additionally, note that the vibratory displacement response is very small in all but the Soft E case, and there is no evidence of divergent or flutter behavior. The soft E case in Figure 9e has very different character marked by slow initial decay in the perturbed displacement response followed by growth in the response amplitude. The case was run to longer execution time, shown in Figure 9f, where it was found that the coupled response eventually went into LCO with a decaying mean value and oscillation amplitude, the latter not being obvious in the figure. ATA Engineering also performed Partial Floquet analysis on the displacement responses and found that there was stable damping in all physical modes for all cases, including the LCO response of the soft E case.

Again, the fundamental natural frequency provides additional understanding of the coupled response behavior. The fundamental natural frequency for the baseline, the 0.003"-thick, and soft E cases are shown in Figure 10 vs increasing dynamic pressure ratio relative to the baseline at sea level atmospheric conditions. In contrast with the nonlinear softening behavior of the SCF case with increasing flow speed, both SGF cases exhibit mild to moderate stiffening with increasing q . This behavior can be explained by observing the structural configuration in Figure 4 and the aerodynamic load interpreted from Figure 8 for the SGF case. The aerodynamic load works against a predominantly concave curvature that tends to create tensile stress with the immovable in-plane boundaries and stiffens the structural response with increasing aerodynamic load. These observations highlight another fundamental difference between the FSI behavior of the two treatment types. The SCF case exhibits destabilizing nonlinearity in the coupled response and stronger coupling, whereas the weaker coupling in the SGF case exhibits nonlinearity that is stabilizing over the load range examined.

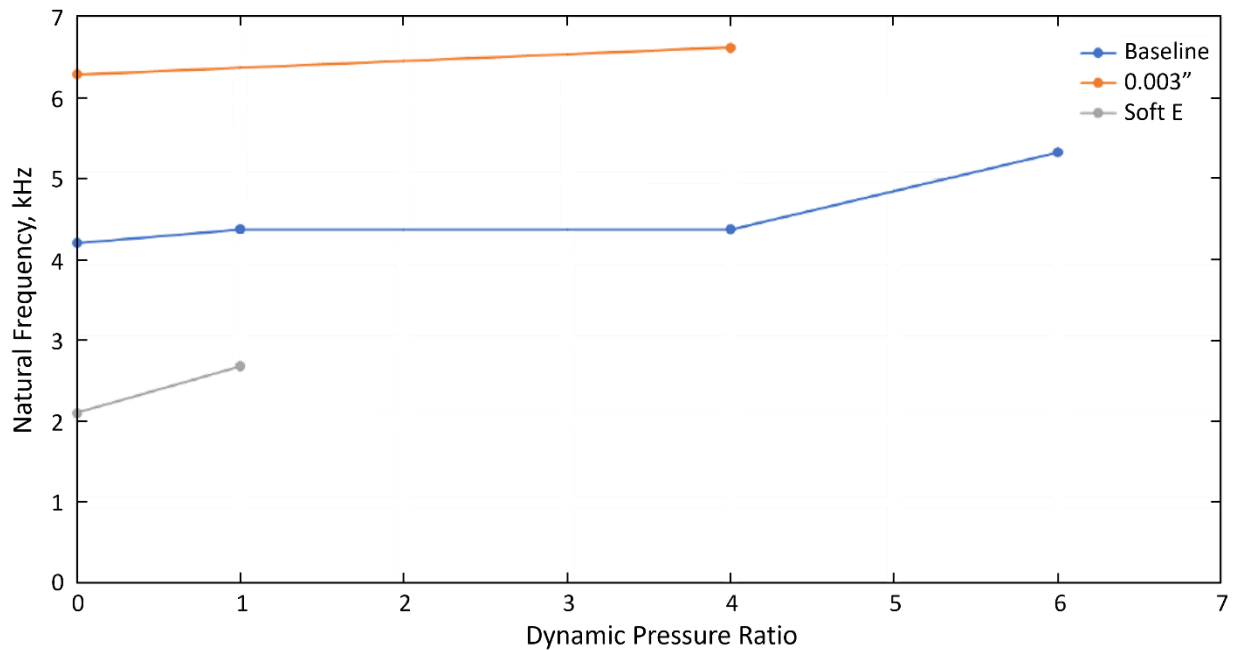


Figure 10. Fundamental natural frequency of the baseline (0.002"), 0.003"-thick, and soft E SGF treatments to the 2.5D CRM-HL (v2.0) at 6.25% scale at varying dynamic pressure ratios relative to the baseline at sea level conditions, from Shah et al. [40].

As above for the SCF case, the SGF thickness for the 10% CRM-HL (v2.1) that exhibits a stability boundary at the intended flow speed of Mach 0.2 can be determined by similitude to the results above for the 2.5D 6.25% CRM-HL (v2.0). Estimates of the flow speed for which the SGF treatment at 10% scale, sized by rule of thumb, will exhibit aeroelastic instability will not be sought via similitude to 6.25% scale for reasons

that will be articulated below. Also similar to the SCF case, some requirements for strict similitude are not met. Those factors and justification for neglecting them are as follows:

- The 3D aspects of the 10% CRM-HL (v2.1) are again ignored on the basis of the geometric uniformity of the SGF section at the outboard slat midspan and weak nonuniformity in the aerodynamic load from 3D flow effects.
- The pinned support conditions for the forward end of the SGF in the 2.5D 6.25% CRM-HL (v2.0) case produces a more compliant structure as compared to the fixed support incorporated in the 10% CRM-HL (v2.1) to represent the fastened joint in that model. Thus, the 6.25% case provides a conservative result in comparison.

Scaling from 6.25% 6x Nominal q to 10% Mach 0.2 6x Nominal q

Having established that the 0.002"-thick 2.5D SGF at 6.25% scale exhibits statically and dynamically stable response to at least six times the nominal dynamic pressure of sea level atmospheric conditions at Mach 0.2, it is simple to assess the stability of the SGF treatment designs for the 10% CRM-HL by similitude. First, the 0.002" SGF thickness known to be stable to at least 6x the nominal q at Mach 0.2 for the 2.5D 6.25% model can be scaled directly to the midspan of the outboard slat at 10% on the 3D CRM-HL by uniform geometric scaling, which results in an SGF thickness of 0.0032 inches. The 0.00375" thickness assignment to the midspan of the 10% CRM-HL is now understood to be very conservative.

Scaling from 6.25% 6x Nominal q to 10% Mach 0.2

Additional insight can be gleaned from Equation (11) for static aeroelastic similitude between two cases having differing dynamic pressures and with thickness scaled separately from other dimensions. Assuming the 6x nominal dynamic pressure to be the stability boundary for the 6.25% scale 2.5D SGF at 0.002" thickness, the SGF thickness required for a stability boundary at 10% scale and the nominal dynamic pressure can be calculated as follows:

$$\lambda_h = \lambda_q^{\frac{1}{3}} \lambda_L = 0.167^{\frac{1}{3}} \cdot 1.6 = 0.881 \quad \rightarrow \quad h_{10\%unstableM 0.2} = 0.0018" \quad (31)$$

Another estimate can be interpreted from Equation (20) for dynamic aeroelastic similitude under the conditions of matched materials ($\lambda_E = \lambda_{\rho_s} = 1$), and matched flow speed ($\lambda_v = 1$), but with fluid density scaled to produce varying dynamic pressure at a constant Mach number of 0.2. Fluid density scales directly with the dynamic pressure under these conditions. Thus, an estimate for the SGF thickness at the outboard slat midspan of the 10% CRM-HL to have a stability boundary at the nominal q of Mach 0.2 flow can be calculated from the assumed stability boundary at 6x nominal q for the 0.002"-thick SGF on the 2.5D model at 6.25% scale as follows:

$$\lambda_h = \lambda_{\rho_f}^{\frac{1}{2}} \lambda_L = 0.167^{\frac{1}{2}} \cdot 1.6 = 0.654 \quad \rightarrow \quad h_{10\%unstableM 0.2} = 0.0013" \quad (32)$$

Critical flow speeds for the SGF at the midspan of the 10% CRM-HL will not be calculated via similitude to the 6.25% case because of the dynamic pressure method used to achieve increased loads.

Scaling from 6.25% Soft E Mach 0.2 to 10% NiTi Mach 0.2

Finally, it will be instructive to consider the soft E case for similitude to the 10% CRM-HL. Although the soft E case at 6.25% scale with a thickness of 0.002" was observed to have stable damping by Partial Floquet

analysis, and decaying mean value and oscillation amplitude that might eventually drop the response out of LCO, the response is clearly undesirable and could represent a reasonable case for a stability boundary. Recall structural stiffness is proportional to Eh^3L^{-2} , which indicates that the soft E case results in a factor of four loss of structural stiffness relative to NiTi at the same thickness and planform dimensions. The thickness for an NiTi material case at 10% planform scale exhibiting the equivalent stiffness, i.e., load-deflection behavior, to the soft E case at 0.002" thickness and 6.25% planform scale can then be determined from static aeroelastic similitude in Equation (8) as follows

$$\lambda_h = \lambda_E^{-\frac{1}{3}} \lambda_L = 4^{-\frac{1}{3}} \cdot 1.6 = 1.01 \quad \rightarrow \quad h_{10\%unstableM0.2} = 0.002" \quad (33)$$

A similar assessment for the soft E case can be performed from the dynamic aeroelastic stability perspective via Equation (20). The soft E case has a Young's modulus 25% of that for NiTi but with equivalent mass density. An estimate for the NiTi thickness at 10% planform scale that would exhibit LCO behavior equivalent to the soft E case at a thickness of 0.002", 6.25% planform scale, and at the same nominal q can be determined by simplification and rearrangement of Equation (20) for dynamic aeroelastic similitude as follows.

$$\lambda_h = \lambda_E^{-\frac{1}{4}} \lambda_L = 4^{-\frac{1}{4}} \cdot 1.6 = 1.131 \quad \rightarrow \quad h_{10\%unstableM0.2} = 0.0023" \quad (34)$$

The stability assessments for the SGF treatment to the midspan of the outboard slat on the 10% CRM-HL (v2.1) from similitude to the 2.5D 6.25% soft E case at nominal q and the NiTi case at 6x q seem to disagree. However, recall that both the static and dynamic similitude equations cast the structural stiffness as proportional to Eh^3L^{-2} with no other influence. It can be seen in Figure 9 that the mean deflection of the soft E case is similar to the nominal case at 4x q, so it can be concluded that their respective load to stiffness ratio is similar. Also, note from Figure 10 that the nominal case does not show significant nonlinearity until loaded at dynamic pressures above 4x q. Thus, it is hypothesized that the soft E case is still in the linear load-deflection range at nominal q whereas the nominal case at 6x q is influenced by stress stiffening that is not captured by Eh^3L^{-2} proportionality in similitude. It is concluded from this argument that, although similitude to the soft E case is more conservative, it might not be best for assessing stability of the 10% CRM-HL or flight hardware that can be designed to exploit the stabilizing nonlinear load-deflection behavior of the SGF configuration and the very large deformation capability of NiTi materials. Critical flow speeds for the SGF at 10% scale will also not be determined from similitude to the soft E case at 6.25% because of the preceding arguments.

Taking the more aggressive approach of setting 6x q of Mach 0.2 sea level flow as a stability boundary for the nominal 0.002" SGF case at 6.25% scale and deriving stability assessments for the 10% CRM-HL by similitude results in SGF thickness estimates of 0.0018" and 0.0013" for static and dynamic similitude, respectively. It is concluded that the baseline SGF thickness assignments for the 10% CRM-HL, made by rule of thumb and resulting in an outboard slat midspan SGF thickness of 0.00375", are vastly overconservative as they represent factors of 9 and 24 in stiffness over the 0.0018" and 0.0013" thicknesses estimated to be unstable at 10% scale and nominal q of Mach 0.2 sea level flow. The true stability boundary of this SGF design is yet to be determined, and it is likely that the minimum thickness for the SGF treatment on a flight vehicle would be dictated by other factors such as debris strike.

3D Case at the IB End of the OB Slat

Although 3D FSI assessment of the SGF treatment was not available in time for substantiation of safety in the wind tunnel, a brief description of the problem definition, results, and implications for stability assessment are given here for completeness. Additional detail can be found elsewhere [39-40].

An FSI computational framework consisting of the CFD solver Loci/Chem, structural solver Abaqus, and the SIMULIA Cosimulation Engine was employed. A 3D RANS solution was achieved on the rigid 3D semispan CRM-HL geometry at 10% scale to establish initial flow conditions. A subdomain approach was used to study the SGF treatment at the inboard end of the outboard slat because of the complex flow conditions and high aerodynamic loading there due to the influence of the nacelle and pylon. A quasistatic cosimulation was performed on the subdomain to determine the static equilibrium configuration. Then a time accurate cosimulation was performed with the URANS CFD computations starting from the converged RANS solution as an initial condition. A perturbation in aerodynamic load was introduced to excite the SGF structure, and the cosimulation solution was continued to observe the ensuing response. Finally, system identification was performed to determine coupled response quantities, and partial Floquet analysis was performed to assess stability.

The results of the 3D FSI assessment for the SGF treatment showed stable response at the nominal dynamic pressure corresponding to Mach 0.2 flow at sea level conditions and at a high-q condition corresponding to 1.88x nominal dynamic pressure. These results corroborate the findings from similitude to the 2.5D cases, but a true stability boundary for the SGF treatment remains to be determined.

Summary and Conclusions

Previous adaptive structures work has shown that highly flexible structural treatments, known as a slat cove filler (SCF) and slat gap filler (SGF), integrated with the leading-edge slat of transport aircraft have great potential for noise reduction without significant aerodynamic penalty or weight addition. Shape memory alloy (SMA) materials, and in particular Nickel Titanium (NiTi), have been identified as enabling for SCF and SGF treatments. NASA fabricated a wind tunnel model at 10% scale based upon the CRM-HL geometry to facilitate aerodynamic and aeroacoustic research on high-lift systems. Interchangeable leading-edge assemblies enabled testing of multiple SCF and SGF concepts at flow speeds representative of approach and landing (Mach 0.2). Dynamically scaled SCF and SGF treatments were designed for testing on the 10% CRM-HL in the NASA LaRC 14- by 22-foot Subsonic Tunnel, and the aeroelastic stability of the treatments had to be demonstrated as part of the Model Systems Report (MSR).

Supporting fluid structure interaction (FSI) research was ongoing at the time of SCF and SGF treatment design for the 10% CRM-HL, but the aeroelastic stability assessment described in this document was not available. The thickness assignments for the SCF and SGF treatments were made by rules of thumb developed by experience gained up to that time and were purposefully conservative but reasonable for representation of flight hardware. Progress in the supporting research between treatment design and the required stability assessment for the MSR was limited to 2.5D (spanwise uniform geometry of small finite span) FSI analysis. The 2.5D FSI work included both computational and experimental results for an SCF configuration corresponding to the midspan of the outboard slat at 6.25% scale and flow speeds up Mach 0.1 (35 m/s), which were limitations imposed by the wind tunnel for the experimental results. The analogous 2.5D FSI work for the SGF case was limited to computations and was performed on the same 6.25% scale outboard slat midspan, but incorporated Mach 0.2 flow and a range of dynamic pressures up

to 6x the nominal of the Mach 0.2 flow, which was enabled by fluid density and pressure adjustments at constant temperature and Mach number.

Relations for static and dynamic similitude are well known, but some were rederived for clarity and ease of reference in the present work. Simplified forms were presented as a reference for cases where manipulation of parameters associated with materials, component dimensions, fluid properties, or flow speed might offer opportunities for similitude when some of the parameters are constrained. The similitude relations were used in the case of the SCF treatment to determine thickness estimates at 10% scale and Mach 0.2 that correspond to a stability boundary identified at Mach 0.099 for a 0.002"-thick SCF at 6.25% scale, with the violation of constant Mach number being justified by the similarity in flow character and lack of compressibility effects at the two flow speeds. Conversely, estimates of the critical flow speed for the SCF at 10% scale as designed by the rule of thumb were determined by similitude with the Mach 0.099, 0.002"-thick SCF at 6.25% scale. All SCF stability assessment results indicate there is a factor of safety of at least 4.6 in the thickness assignments made by rule of thumb for the 10% semispan CRM-HL.

A stability boundary for the 6.25% SGF case was not identified in the completed work. Stability to at least 6x the nominal dynamic pressure of Mach 0.2 flow was demonstrated for a 0.002"-thick NiTi SGF at 6.25%, and similitude relations were used to estimate a commensurate SGF thickness at 10% scale. Similitude was also used to estimate an SGF thickness at 10% and nominal q of Mach 0.2 flow by assuming that 6x q represented a stability boundary for the 0.002"-thick SGF at 6.25%. A reduced modulus case (soft E) that exhibited limit cycle oscillations at 6.25% scale, 0.002" thickness, and nominal q was also assessed as an example of an undesirable condition for similitude to the 10% CRM-HL. The soft E case was found to produce a more conservative SGF thickness at 10% scale and nominal q than setting the NiTi case at 6x q as an assumed stability boundary. However, it was determined that the soft E case lacked the nonlinearity exhibited by the NiTi case over the greater load range, thereby negating exploitation of nonlinear structural response supported by a material (NiTi) capable of very large deformation. The SGF stability assessment results demonstrated that the thickness assignments made by rule of thumb for the 10% semispan CRM-HL are extremely conservative with a factor of safety of at least 9. Best estimates of the minimum SGF thickness required for flight conditions suggest a gauge so light that factors other than aerodynamic load are likely to dictate the thickness.

The results of this study confirmed the early observation that the SCF treatment is more susceptible to aeroelastic instability than the SGF. In addition to the stronger fluid-structure coupling of the SCF case, the coupled response of the SCF exhibited destabilizing nonlinearity, whereas the nonlinear coupled response for the SGF was stabilizing over the load range studied. It is likely that the SCF design by rule of thumb was found aeroelastically conservative only because it was sized to the highly localized maximum deflection under the nonuniform aerodynamic load of that configuration. However, the SCF thickness assignments were at the high end of that considered acceptable for flight hardware and considerable thinning was desired. In contrast, the SGF rule of thumb design produced thickness assignments considered reasonable for flight hardware, but the stability assessment demonstrated them to be excessively conservative. These outcomes underscore the great importance of aeroelastic analysis for successful design in such cases, in addition to safety considerations.

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