

Transonic Aeroelastic Analysis of the X-59 Aircraft Using FUN3D

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The Low-Boom Flight Demonstrator (LBFD), or X-59 aircraft, was designed and fabricated by the Lockheed-Martin (LM) Corporation under a contract from NASA as part of the QueSST Mission. One of the primary goals is to demonstrate that a low sonic boom is achievable via aerodynamic shaping. The aircraft successfully completed its first flight, marking the beginning of an extensive envelope expansion campaign. As part of the requisite preparation for first flight and subsequent flights, the combined NASA/LM X-59 team prepared documents towards Airworthiness Certification including various tests and analyses. Given that the aircraft will reach a maximum Mach number of 1.4, a transonic aeroelastic analysis has been generated to address any potential concerns at transonic conditions. Three different methods, all based on the FUN3D code, were used to generate these solutions: FUN3D, FUN3D/AEROM, FUN3D/Linearized Frequency Domain (LFD). Results are presented for four Mach numbers: $M=0.95$, 0.97 , 0.99 , and 1.05 .

I. Introduction

The Low-Boom Flight Demonstrator (LBFD) aircraft, also known as the X-59, was designed and fabricated by the Lockheed-Martin Company under a NASA contract as part of NASA's QueSST Mission. The primary goal of the QueSST Mission is to acquire flight test data demonstrating an achievable low boom over land in order to effect change of current supersonic flight regulations. The X-59 aircraft has been designed with a shape to significantly reduce the sonic boom signature. There are three phases to the QueSST Mission: Phase 1 consisting of design, fabrication and envelope expansion; Phase 2 consisting of sonic boom signature data acquisition from X-59 flights over land from a limited number of airfields; and Phase 3 consisting of sonic boom data acquisition from X-59 flights over residential areas near major airports.

The X-59 is currently in Phase 1 of the project. With design and fabrication complete, and with a successful first flight, the project is now moving towards subsequent envelope expansion flights. In order to address potential concerns regarding aeroelastic stability at transonic Mach number conditions, CFD-based analyses were performed.

II. Low-Boom Flight Demonstrator, X-59

An image of the Low-Boom Flight Demonstrator (LBFD), or X-59, is presented in Figure 1. The X-59 has been designed and fabricated by the Lockheed-Martin Corporation under a contract from NASA in partial fulfillment of NASA's QueSST mission. The project is currently in Phase I of the QueSST mission that consists of design, fabrication, ground tests, and first flight. The design, fabrication, and ground tests have all been completed. The project recently achieved its first flight, a critically important and significant milestone.

In a subsequent section, additional details regarding structural modeling and related structural tests are presented.



Figure 1. X-59 aircraft

III. Computational Methods

III.A. FUN3D Code

FUN3D is a CFD software suite developed at NASA Langley Research Center.¹ The primary solver is a node-centered finite volume discretization.² For aeroelastic simulations, FUN3D uses a linear elasticity analogy to deform the volume mesh and modal solver to represent the structure.³ The mode shapes from the finite element model are projected onto the aerodynamic surface with radial basis function interpolation. For time-domain aeroelastic simulations, dual time stepping is used to converge the governing equations at each time step of the backwards difference formulation scheme.

Recent work in FUN3D added a Streamline Upwind Petrov-Galerkin (SUPG) stabilized finite-element solver (FUN3D/SFE)⁴ and a corresponding Linearized Frequency Domain (LFD) solver.⁵ The LFD method linearizes the SUPG governing equations about some nonlinear equilibrium solution, either a steady jig shape or static aeroelastic solution, then solves the flow response to a harmonic perturbation input in the frequency domain. For a flutter analysis, the harmonic perturbations are the mesh motion due to movement of the mode shapes, and the frequency-domain Generalized Aerodynamic Forces (GAFs) are computed as the inner product of the linearized forces from the flow response to the harmonic input and the mode shapes. An independent LFD linear system is solved for the combination of modes being perturbed and a set of frequencies that cover the range of expected flutter frequencies. The resulting set of GAFs are then fed into a flutter (p-k, k, g-method) solver to compute the aeroelastic response.

For both the time-domain finite volume solutions and the LFD simulations, Spalart Allmaras (SA) turbulence model is utilized.⁶ For FUN3D/SFE and LFD simulations, the negative variant of SA (SA-neg)⁷ is applied.

III.B. New Method for Computing Aeroelastic Transients Using FUN3D

When performing CFD-based aeroelastic analyses, the standard procedure consists of the following steps: 1). compute a steady rigid solution about the desired flight condition (Mach number, Reynold's number); 2). compute a static aeroelastic solution at this flight condition and for each dynamic pressure of interest using the steady rigid solution (Step 1) as the initial condition; and 3). compute a dynamic aeroelastic solution at this flight condition for each dynamic pressure of interest using the corresponding static aeroelastic solution at each dynamic pressure as the initial condition.

Typically, the static aeroelastic solution (Step 2) generates the largest aeroelastic deformations as the dynamic pressure is increased. As these deformations become larger, the grid deformation scheme is pushed to limits until negative volumes are encountered and the solution is halted. As a result, some aeroelastic analyses cannot be performed above a particular dynamic pressure because if the static aeroelastic solution cannot be computed, then the dynamic aeroelastic solution (in search for potential flutter conditions) cannot be computed either.

To sidestep this issue, a new process has been developed and successfully applied to the X-59 configuration. This process relies on two fundamental innovations: 1). the use of a negative dynamic pressure, and 2). the use of an option within FUN3D that allows the setting of a desired generalized aerodynamic force (GAF) as an initial condition. The first step enables a simplified approach towards computing an estimate of the aircraft jig shape. The converged static aeroelastic forces from this first step are then used to define the generalized aerodynamic force values to define an initial condition for the dynamic aeroelastic solution.

The computation of the jig shape has consisted of first computing a static aeroelastic solution at a positive dynamic pressure. Since the CFD grid is based on the cruise shape (not the jig shape), this converged deformation is then inverted (multiplied by -1) to yield an approximate jig shape. However, this process can result in several problems including inability to converge to a static aeroelastic solution at a desired (typically high) dynamic pressure. Therefore, instead of this somewhat lengthy process, a static aeroelastic solution is computed for a negative dynamic pressure. It is important to understand that the value of dynamic pressure in most aeroelastic CFD codes is to simply scale the GAFs that are being output from the CFD computation. Therefore, there is no concern with violation of any physical issues since it is solely a scaling process. By performing a static aeroelastic solution at a negative dynamic pressure, an approximate jig shape is obtained in one solution.

Of interest, for this particular aircraft, it was easier to generate static aeroelastic solutions at a particular negative dynamic pressure than at the same, positive dynamic pressure without encountering negative volumes in the grid deformation scheme. For the cases where negative volumes were encountered using a negative dynamic pressure, the strategy consists of computing a solution for as large a negative dynamic pressure as possible, then scaling the resultant GAFs to a larger, desired dynamic pressure. For example, if the desired solution is at a dynamic pressure of 1.0 psi (144 psf), the solution is performed at a dynamic pressure of -1.0 psi. If this solution executes without any numerical issues, then the next step can be performed. However, if the solution at -1.0 psi does not converge, a solution at a dynamic pressure of -0.5 psi is generated. If this solution executes without an issue, then the resultant GAFs are scaled to the desired dynamic pressure (multiplied by 2). These scaled GAFs are then defined as the GAF initial condition option in order to perform the dynamic aeroelastic solution. By setting these GAF initial conditions, the solution assumes that it is already at (or near) the converged static aeroelastic solution so very little, if any, additional grid deformation is required. If there is little to no grid deformation performed, the issue of negative volumes due to large static aeroelastic deformations is completely sidestepped.

This method works extremely well and has been validated with the more traditional solutions but, clearly, only if traditional solutions are possible at desired dynamic pressures without encountering negative volumes. In many instances, this method provided the only way that both static and dynamic aeroelastic solutions could even be generated at particular dynamic pressures. The results presented in a later section of this paper under the "Full FUN3D Solutions" category where computed in precisely this manner.

III.C. AEROM

In structural dynamics, the realization of discrete-time state-space models that describe the modal dynamics of a structure has been enabled by the development of algorithms such as the Eigensystem Realization Algorithm (ERA)⁸ and the Observer Kalman Identification (OKID)⁹ Algorithm. These algorithms perform state-space realizations by using the Markov parameters (discrete-time impulse responses) of the systems of interest. These algorithms have been combined into one package known as SOCIT developed at NASA Langley Research Center.

There are several algorithms within the SOCIT that are used for the development of unsteady aerodynamic discrete-time state-space models. The PULSE algorithm is used to extract individual input/output impulse responses from simultaneous input/output responses. For a four-input/four-output system, simultaneous excitation of all four inputs yields four output responses. The PULSE algorithm is used to extract the individual sixteen (all combinations of four inputs and four outputs) impulse responses that associate the response in each of the outputs due to each of the inputs. Once the individual sixteen impulse responses are available, they are then processed via the ERA in order to transform the sixteen individual impulse responses into a four-input/four-output, discrete-time, state-space model. A brief summary of the basis of this algorithm follows.

A finite dimensional, discrete-time, linear, time-invariant dynamical system has the state-variable equations

$$x(k+1) = Ax(k) + Bu(k) \quad (1)$$

$$y(k) = Cx(k) + Du(k) \quad (2)$$

where x is an n -dimensional state vector, u an m -dimensional control input, and y a p -dimensional output or measurement vector with k being the discrete time index. The transition matrix, A , characterizes the dynamics of the system. The goal of system realization is to generate constant matrices (A , B , C , D) such that the output responses of a given system due to a particular set of inputs is reproduced by the discrete-time state-space system described above.

For the system of Eqs. (1) and (2), the time-domain values of the discrete-time impulse responses of the system are also known as the Markov parameters and are defined as

$$Y(k) = CA^{k-1}B + D \quad (3)$$

with A an ($n \times n$) matrix, B an ($n \times m$) matrix, C a ($p \times n$) matrix, and D an ($p \times m$) matrix. The ERA algorithm begins by defining the generalized Hankel matrix consisting of the discrete-time impulse responses for all input/output combinations. The algorithm then uses the singular value decomposition to compute the (A , B , C , D) matrices.

In this fashion, the ERA is applied to unsteady aerodynamic impulse responses to construct unsteady aerodynamic state-space models. The AEROM software includes the necessary SOCIT routines as well as additional routines to manage the data flow and model generation.

The application of AEROM for the development of an aeroelastic ROM consists of two parts: the creation of the unsteady aerodynamic ROM and the creation of the structural dynamic ROM. The combination of the unsteady aerodynamic ROM with the structural dynamic ROM yields what is referred to as the aeroelastic simulation ROM.

An outline of the AEROM development process is as follows:

1. Generate the number of orthogonal functions (such as Walsh functions, for example) that corresponds to the number of structural modes;
2. Apply the generated input functions simultaneously via one CFD execution resulting in GAF responses due to these inputs; these responses are computed directly from the restart of a steady rigid CFD solution (not about a particular dynamic pressure);
3. Using the simultaneous input/output responses, identify the individual impulse responses using the PULSE algorithm (within SOCIT);
4. Transform the individual impulse responses generated in Step 3 into an unsteady aerodynamic state-space system using the ERA (within SOCIT);
5. Evaluate/validate the state-space models generated in Step 4 via comparison with CFD results (i.e., ROM results vs. full CFD solution results);

A schematic of steps 1-4 of the AEROM process outlined above is presented as Figure 2. Using modal information (generalized masses, modal frequencies, and modal dampings), a state-space model of the structure is generated. This state-space model of the structure is referred to as the structural dynamic ROM (see Figure 3). Once an unsteady aerodynamic ROM and a structural dynamic ROM have been generated, they are combined to form an aeroelastic simulation ROM (see Figure 4). Then root locus plots are extracted from the aeroelastic simulation ROM.

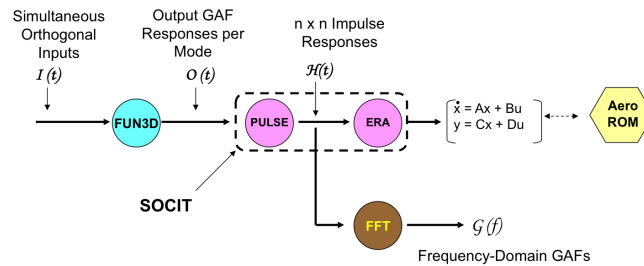


Figure 2. Improved process for generation of an unsteady aerodynamic ROM (Steps 1-4).

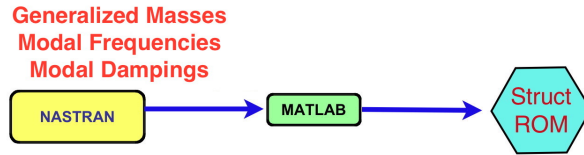


Figure 3. Process for generation of a structural dynamic state-space ROM.

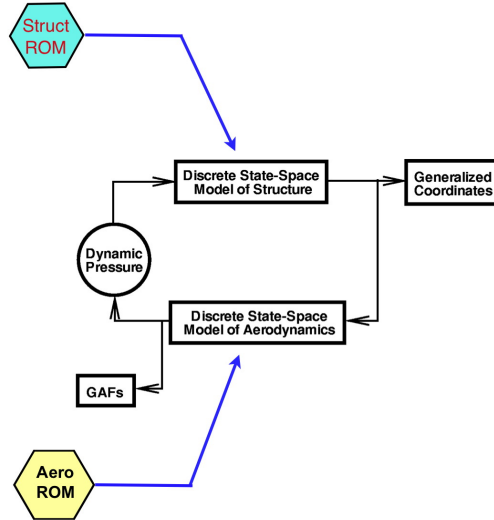


Figure 4. Process for generation of an aeroelastic simulation ROM consisting of an unsteady aerodynamic ROM and a structural state-space ROM.

Details of the AEROM software are available in the References.¹⁰

IV. Structural Models and Related Tests

Presented in Figure 5 is a detailed image of the finite element model (FEM) and all the various subcomponents of the structure. The primary components are presented along with their corresponding labeling within the FEM. The accuracy of the FEM is, of course, critical for all subsequent analyses including structural loads, structural margins, aeroelastic and aeroservoelastic (ASE) analyses. Structural tests were performed to validate the FEM including Proof (stiffness) test, Ground Vibration Test (GVT), and Structural Coupling Test (SCT), as well as other related tests. Some critical results from these tests are presented in this section.

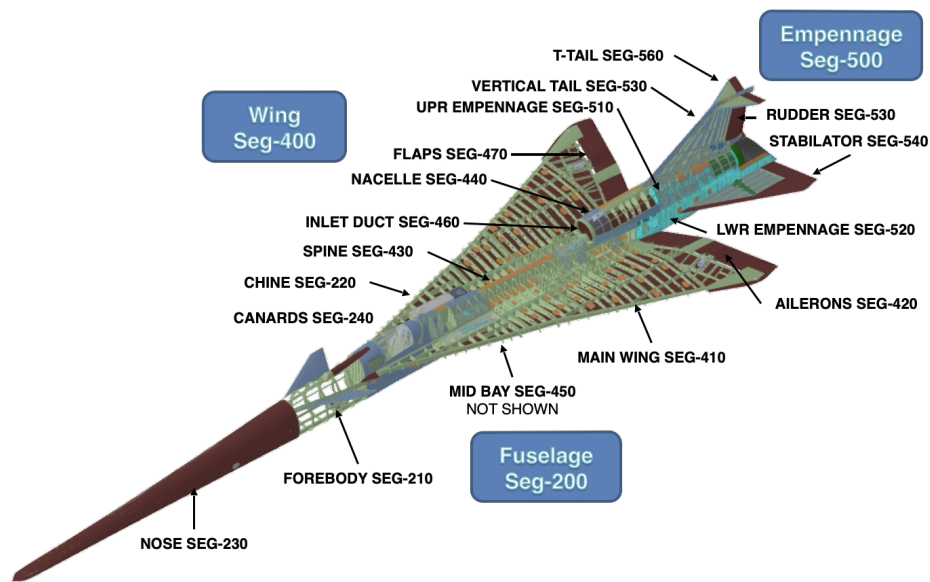


Figure 5. Finite element model (FEM) and related segment details.

Presented in the following figures are the three more significant mode shapes and associated frequencies for aeroelastic and ASE interests. Figure 6 is the fuselage first vertical bending mode, of critical importance to ASE-related interactions. Presented in Figure 7 is the antisymmetric stabilator rotation mode and presented in Figure 8 is the antisymmetric aft fuselage torsion mode, with both modes important for aeroelastic (flutter) interactions.

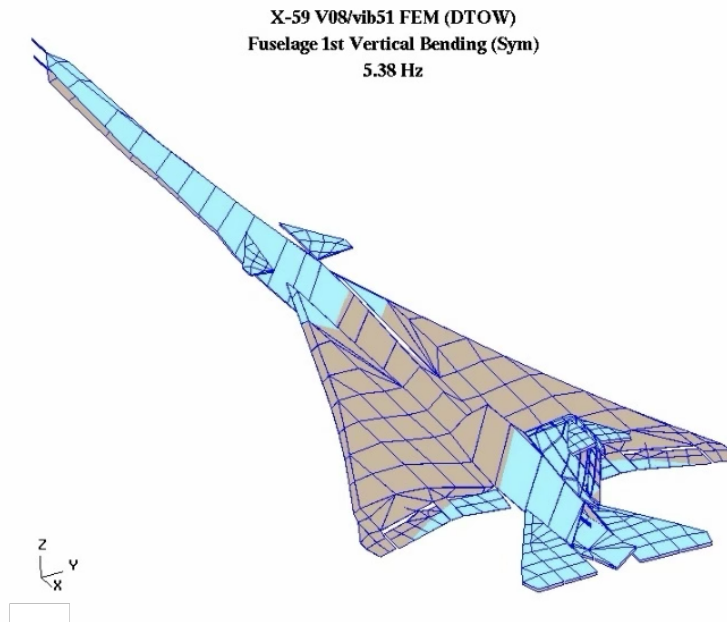


Figure 6. Fuselage first vertical bending mode from FEM version V08/vib51 for the Design Take-Off Weight (DTOW) condition.

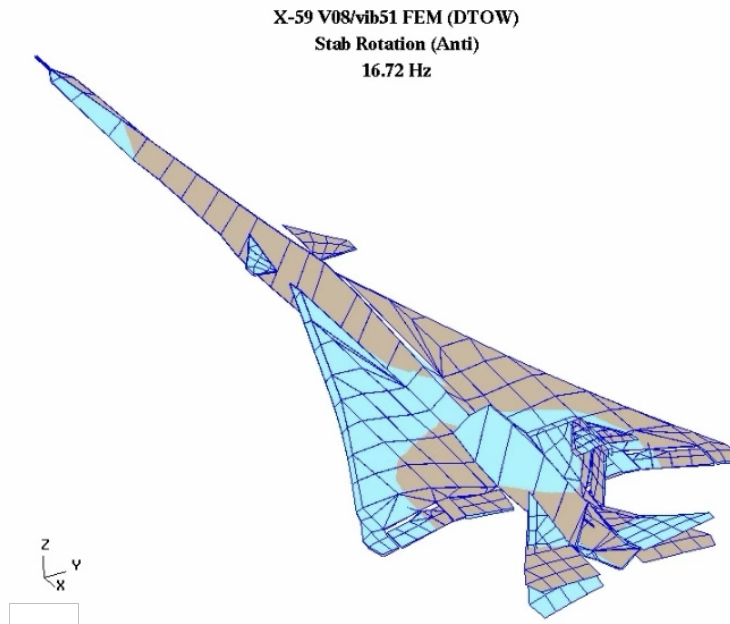


Figure 7. Antisymmetric stabilator rotation mode.

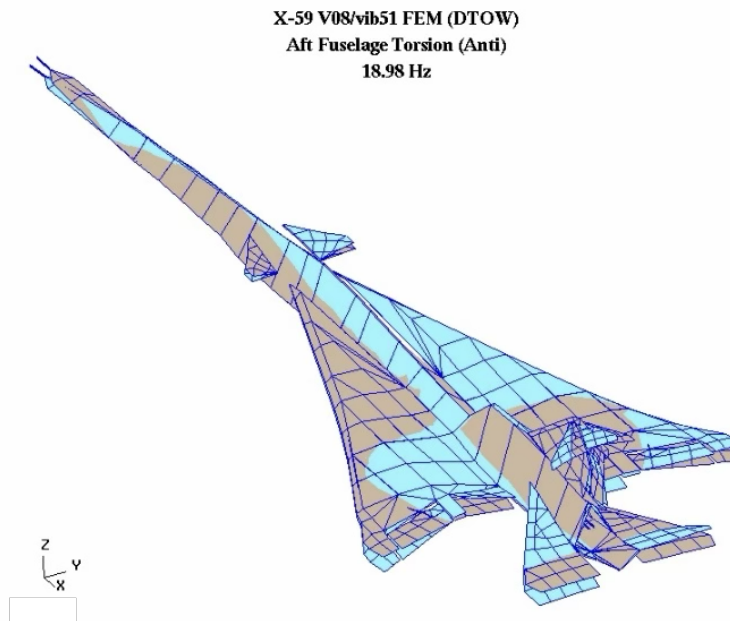


Figure 8. Antisymmetric aft fuselage torsion mode.

Presented in Figure 9 is a sample result from the Proof test performed at the Lockheed-Martin Ft. Worth Structures facility. During this test, 19 critical flight loads were applied to the airframe via hydraulic actuators. The resultant loads and deflections on the aircraft were measured and recorded for comparison with FEM predictions. As can be seen, the FEM predictions were in good agreement with the measured values, exhibiting linear structural behavior with no degradation of response. These Proof test results were the first step towards validation of the FEM.

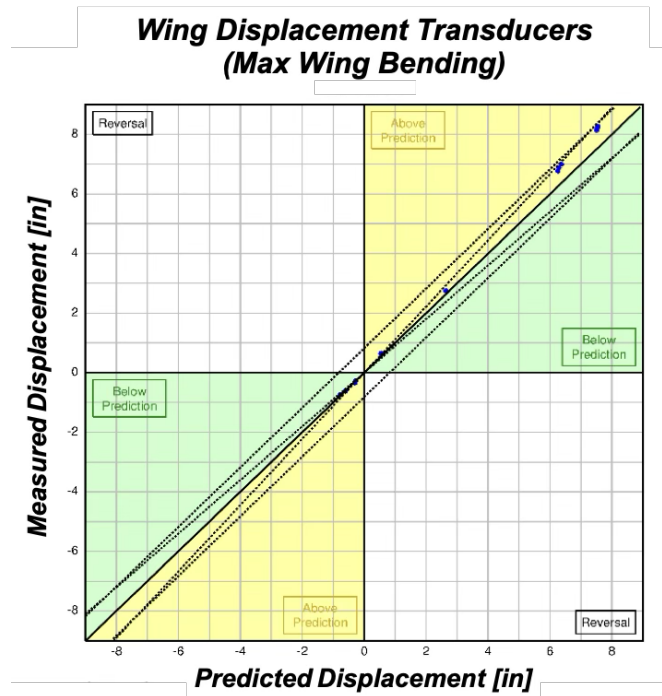


Figure 9. Comparison of predicted versus measured displacement using data from Proof test.

Presented in Figure 10 is a table comparing predicted modal frequencies (FEM) with those measured during the GVT. As can be seen, for the critical modes presented above, the difference between predicted and measured frequencies is less than five percent, an excellent result further confirming the quality and validity of the FEM.

Mode Shape	Sym/Anti	GVT Measured Frequency (Hz)	Post-GVT Predicted Frequency (Hz)	Pre-GVT Predicted Frequency (Hz)	Post-GVT % diff from GVT	Pre-GVT % diff from GVT
Fuselage 1st Bending	Sym	5.60	5.83	5.95	4.1%	6.3%
Fuselage 1st Bending	Anti	7.01	7.50	7.86	7.0%	12.1%
Wing 1st Bending	Sym	9.52	9.45	9.65	-0.7%	1.4%
VT 1st Bending	Anti	10.71	10.67	10.76	-0.4%	0.5%
Fuselage 2nd Bending	Sym	11.00	11.44	11.65	4.0%	5.9%
Fuselage 2nd Bending	Anti	13.86	13.10	13.14	-5.5%	-5.2%
Wing 1st Bending	Anti	14.64	13.41	13.40	-8.4%	-8.5%
Stabilator Rotation	Anti	17.32	17.31	16.08	-0.1%	-7.2%
Stabilator Rotation	Sym	18.00	17.69	16.52	-1.7%	-8.2%
Fuselage 3rd Bending	Sym	18.56	19.55	19.85	5.3%	7.0%
Aft Fuselage Torsion / Stab Bending	Anti	20.70	19.91	19.66	-3.8%	-5.0%
Flap rotation	Sym	22.39	23.25	32.33	3.8%	44.4%
Flap rotation	Anti	22.39	23.37	32.77	4.4%	46.4%

Figure 10. Table presenting a comparison for a subset of predicted (FEM) and measured vibration frequencies from the Ground Vibration Test (GVT).

The Structural Coupling Test (SCT) consists of a test of the open- and closed-loop interactions of the control system with the structural dynamics of the aircraft. This test was concluded in early 2024 with all results indicating good comparisons between the ASE computed/predicted results and the results measured during the SCT. For brevity, those results are not included in this paper.

V. Computational Results

A subset of results from time-domain FUN3D solutions (referred to as "Full Solutions"), AEROM solutions, and LFD solutions, at several transonic Mach numbers, are presented in this section.

V.A. Linear Aeroelastic Analyses

Linear aeroelastic analyses were performed using two methods: NASTRAN/doublet lattice method analyses performed by Lockheed-Martin, and ZAERO analysis method performed by NASA. While both of these methods are based on linear aeroelastic methods, there was some concern early in the program if modeling of the noseboom could affect results. In the NASTRAN/doublet lattice method, bodies of revolution such as the nosecone and fuselage are modeled as flat plates (boxes), the standard approach for this method. In the ZAERO method, the nosecone and fuselage were modeled as bodies of revolution to investigate this concern. Analyses indicated that there was no significant difference between the two methods. Both methods continued to be used throughout subsequent analyses.

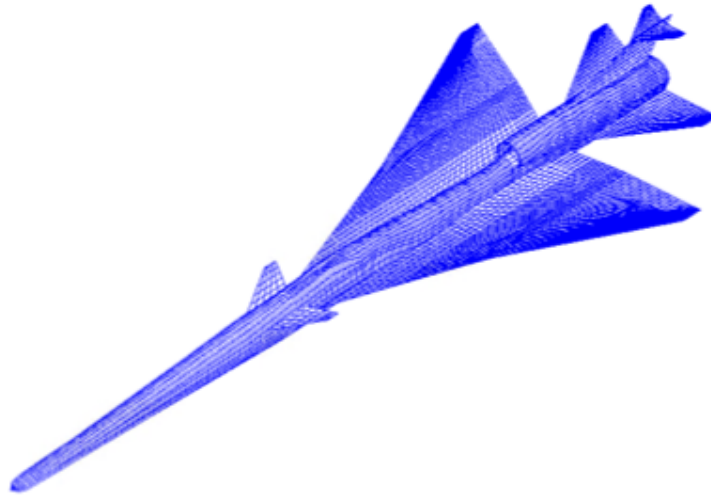


Figure 11. The ZAERO code aerodynamic panel layout.

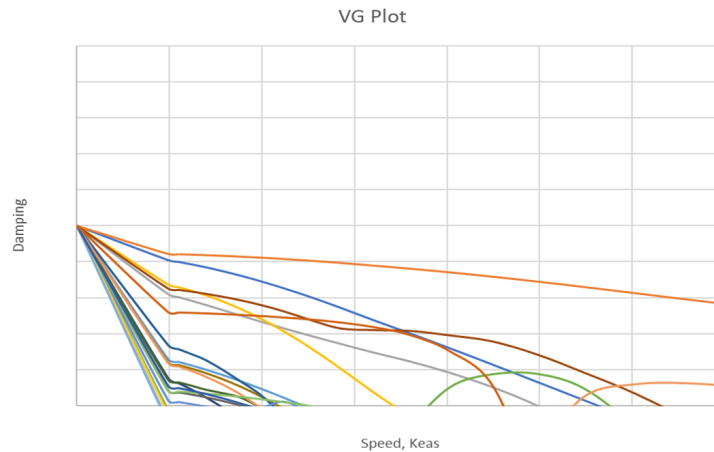


Figure 12. The V-g-f plot at $M=2.0$ based on ZAERO aerodynamic model.

Presented in Figure 11 is the panel layout defined for the ZAERO analyses consisting of about 10k panels. This panel layout was refined over time, improved to better capture unsteady aerodynamic variations across the geometry and for improved comparisons with other methods. Presented in Figure 12 is the V-g-f plot at

M=2.0 using ZAERO GAFs and the g-method. As can be seen, there are no instabilities within the range presented. Solutions using ZAERO were computed at the following Mach numbers: 0.9, 0.95, 0.97, 0.99, 1.05, 1.20, 1.40, 2.0. At all Mach numbers analyzed, no aeroelastic instabilities were identified.

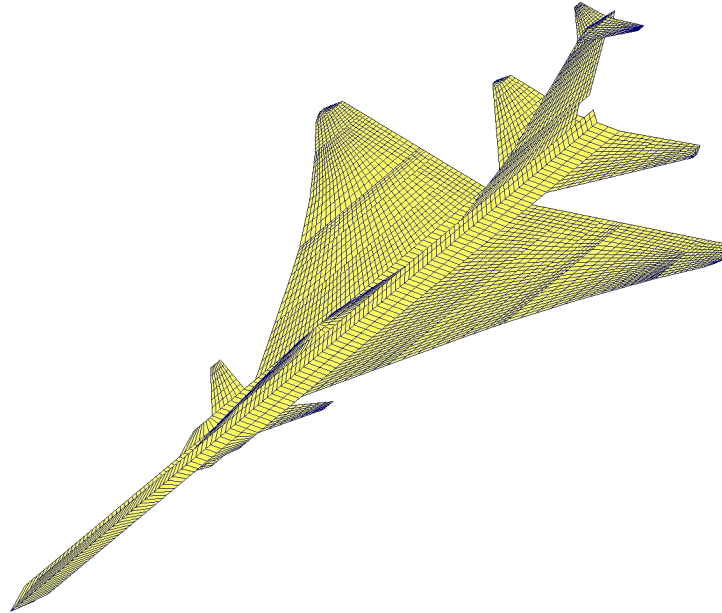


Figure 13. The doublet lattice aerodynamic box layout.

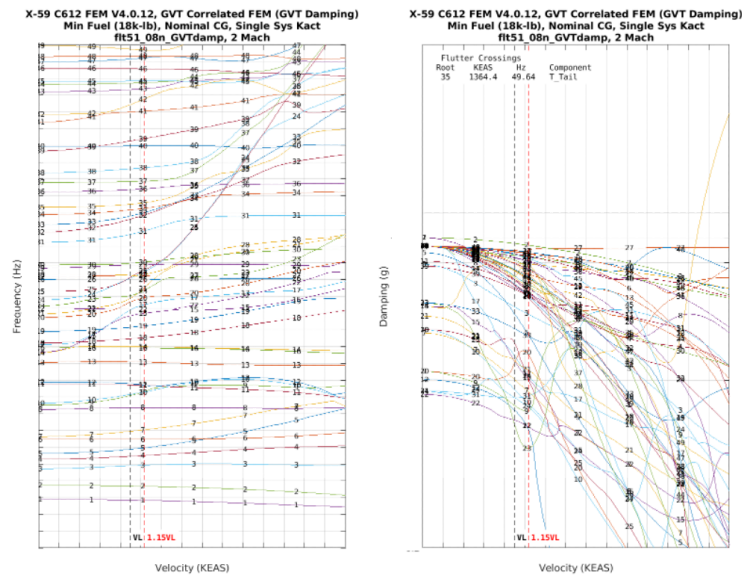


Figure 14. The V-g-f plot at M=2.0 based on doublet-lattice aerodynamic model.

Presented in Figure 13 is the box layout defined for the NASTRAN/doublet lattice analyses performed by Lockheed-Martin. This box layout includes about 4100 boxes, refined in regions to capture relevant transients and improve correlations. Presented in Figure 14 is the V-g-f plot at M=2.0 using doublet lattice GAFs and the p-k method for a larger range of velocities. Consistent with the ZAERO results, there are no instabilities within the flight envelope, with the exception of an instability that is significantly outside of the aircraft's flight envelope. Solutions using doublet lattice were computed at the following Mach numbers: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 0.95, 1.05, 1.1, 1.2, 1.3, 1.4, 1.55, 1.6, 1.7, 2.0. Lockheed-Martin also computed some ZAERO results at a smaller subset of Mach numbers.

Results using both linear methods, ZAERO and doublet lattice, presented consistent results indicating no aeroelastic instabilities anywhere within the flight envelope of the aircraft.

V.B. Full FUN3D Solutions

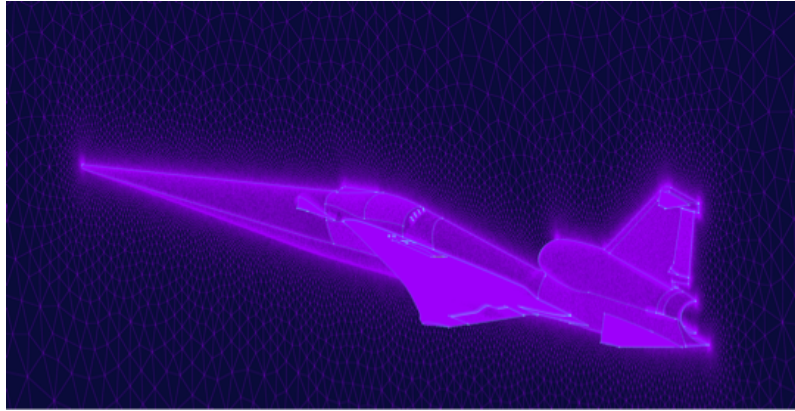


Figure 15. Unstructured grid consisting of 31 million grid points.

Presented in Figure 15 is the unstructured grid consisting of 31 million grid points used for all subsequent FUN3D solutions. This section covers the full FUN3D solutions using the newly developed method to sidestep the sometimes challenging issue of negative volumes due to large deformations of a dense CFD grid. As the focus of the application of CFD-based methods was application at transonic conditions, only the following Mach numbers were investigated: 0.95, 0.97, 0.99, 1.05, and 1.40. For brevity, only a small subset of solutions will be presented at particular Mach numbers. To be clear, for this set of solutions, there were no aeroelastic instabilities identified across these transonic Mach numbers.

Presented in Figure 16 is a plot of the pressure distribution on the upper surface of the aircraft at $M=1.05$, where transonic flows are evident. This Mach number presents the strongest transonic condition with the remainder of the Mach numbers indicating reduced transonic effects.

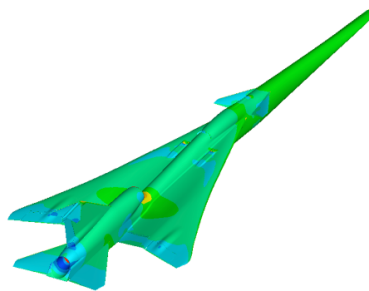


Figure 16. Pressure coefficient contour plot for $M=1.05$.

A small subset of the FUN3D solutions is presented in the following figures. Figure 17 presents the aeroelastic generalized coordinate responses for flexible modes 9 and 40 at $M=0.95$ and a dynamic pressure of 216 psf. This condition is consistent with an actual flight condition, indicating stable response. The responses for all 40 flexible modes included in the analysis was also stable across the board.

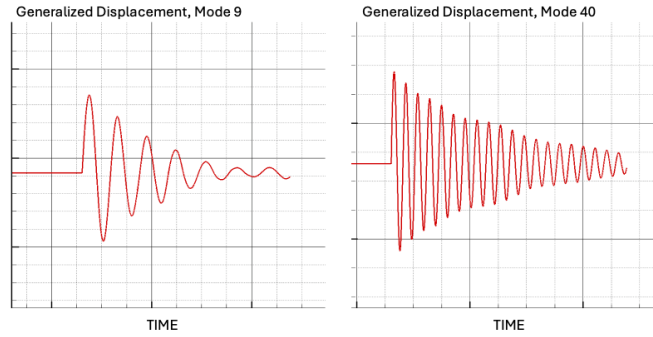


Figure 17. FUN3D aeroelastic generalized coordinates for $M=0.95$ at $Q=216$ psf for flexible modes 9 and 40.

Figure 18 presents the aeroelastic generalized coordinate responses for flexible modes 12 and 28 at $M=1.05$ and a dynamic pressure of 360 psf. Again, this reflects an actual flight condition, indicating stable response across the board. It is important to mention that these solutions were possible by the implementation of the new method presented above using modified initial conditions based on the static aeroelastic result. If not for this method, these solutions would have resulted in unconverged (failed) solutions.

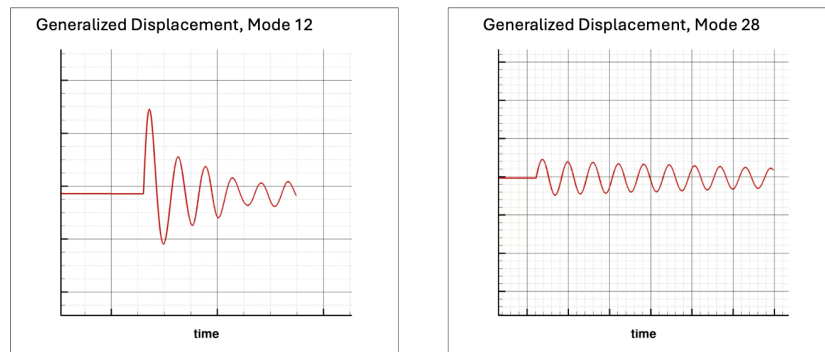


Figure 18. FUN3D aeroelastic generalized coordinates for $M=1.05$ at $Q=360$ psf for flexible modes 9 and 40.

V.C. AEROM Solutions

In this section, a comparison between the AEROM solutions and the full FUN3D solutions is presented for a subset of results. Presented in Figure 19 is a comparison between the AEROM generated solution and the full FUN3D solution at $M=0.99$ and a dynamic pressure of 216 psf for flexible modes 7 and 18. As can be seen, the comparison presents excellent correlation between the two methods. It should be repeated that, once the AEROM model is generated for a particular Mach number, it is valid for a broad range of dynamic pressures, providing significant computational efficiency over full FUN3D solutions.

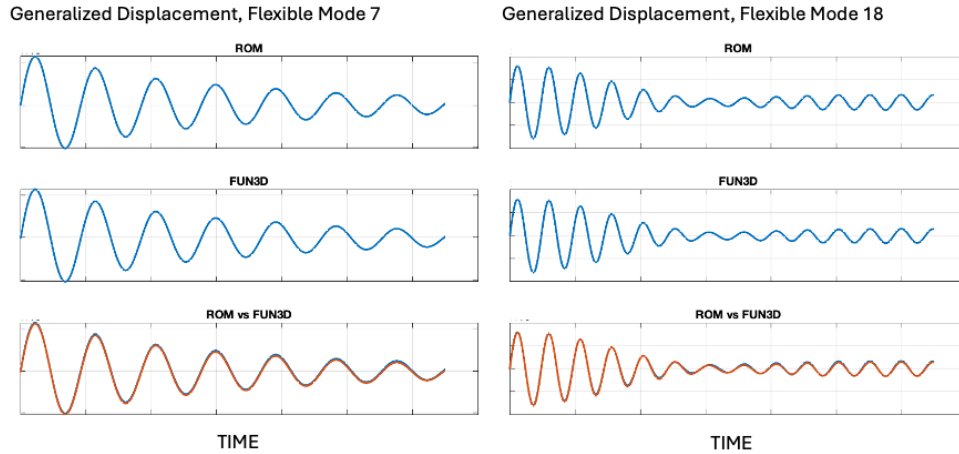


Figure 19. Comparison of AEROM and FUN3D aeroelastic generalized coordinates for $M=0.99$ at $Q=216$ psf for flexible modes 7 and 18.

In addition to computing the generalized coordinates at any dynamic pressure, the AEROM model also computes the corresponding GAFs at that condition. Presented in Figure 20 is a comparison of the AEROM and the full FUN3D solution GAFs at the same Mach number and dynamic pressure for the same modes. Again, the comparison is excellent and confirms the validity and accuracy of the AEROM generated.

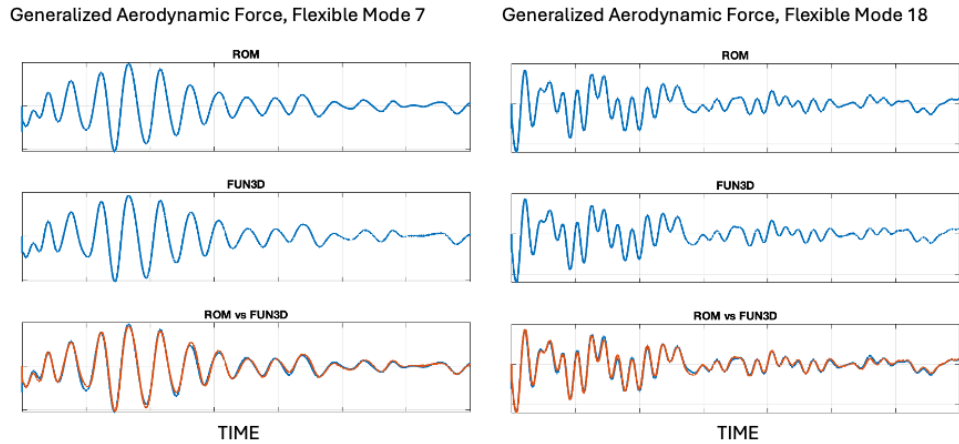


Figure 20. Comparison of AEROM and FUN3D aeroelastic generalized aerodynamic forces for $M=0.99$ at $Q=216$ psf for flexible modes 7 and 18.

Finally, the AEROM model also generates an aeroelastic root locus for any desired range of dynamic pressures, including modal damping values. In Figure 21, the aeroelastic root locus plot for all 40 flexible modes is presented for $M=0.99$, ranging from a dynamic pressure of 0 to 432 psf. This root locus plot includes the corresponding modal damping values measured during the GVT. As can be seen, all roots lie in the left half plane, indicating full stability at this Mach number for this range of dynamic pressures. The maximum dynamic pressure presented is beyond the actual flight envelope of the aircraft, indicating a robust stability margin.

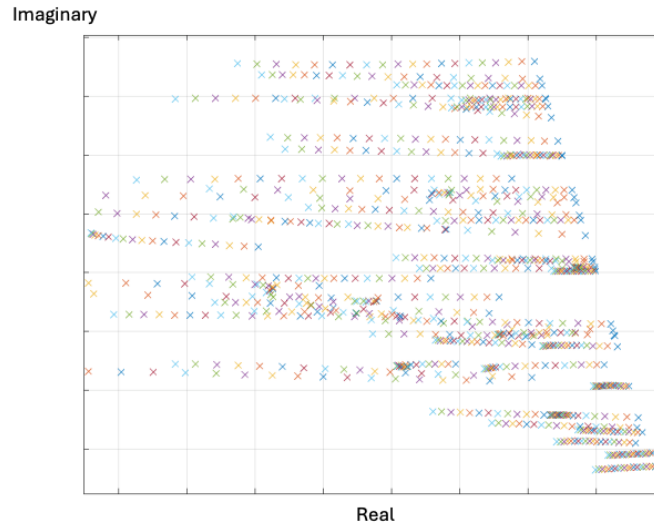


Figure 21. AEROM-generated aeroelastic root locus plot for $M=0.99$, from $Q=0$ to $Q=432$ psf, for 49 flexible modes including GVT-measured structural damping values.

V.D. LFD Solutions

The LFD method was applied and results obtained at two Mach numbers: 0.97 and 1.05. These solutions require a significant amount of memory and compute time so only these two Mach numbers were investigated. As described above, the method generated locally linearized GAFs using FUN3D at transonic conditions. Once the GAFs are computed, they can be used in any flutter determinant solution (such as p-k or g-method) to compute the requisite V-g-f flutter boundary plots. Since LFD results were compared with those from ZAERO, the g-method that is available in ZAERO was used.

As a first step, a comparison between LFD-generated and ZAERO-generated GAFs is performed. The objective is to ensure that the GAFs appear reasonable and physically viable before performing the flutter analysis. Although some GAFs may not match each other well, that is not necessarily crucial if those particular GAFs are not critical for the aeroelastic/flutter analysis. Presented in Figure 22 is a comparison of the magnitudes between the linear ZAERO GAFs and the LFD GAFs at $M=1.05$ for GAF(7,7) and GAF(9,9). The comparison indicates good correlation for the (7,7) GAFs and consistent correlation for the (9,9) GAFs. The comparison for all GAFs was similar to this specific comparison, with some GAFs matching very well and other GAFs having similar trends without exact matching. It should be expected that there will not be identical comparison between GAFs given that there will be differences between the purely linear (ZAERO) method and the CFD-based (LFD) method.

The more significant part of this comparison consists of a comparison of the V-g-f flutter plots generated using both the ZAERO GAFs and the LFD GAFs. This comparison is presented in Figure 23 indicating a good similarity between the results using both methods and with no instabilities throughout this range of speeds within the flight envelope.

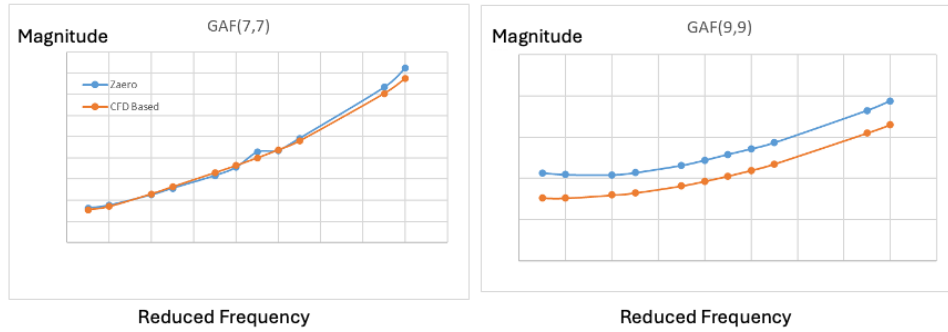


Figure 22. Comparison of ZAERO and LFD generalized aerodynamic forces for $M=1.05$, diagonal components for flexible modes 7 and 9.

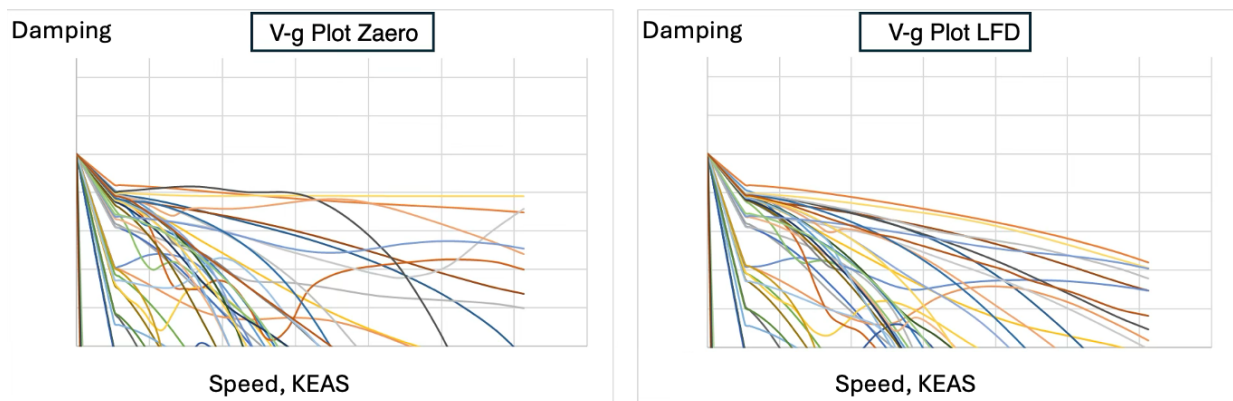


Figure 23. Comparison of ZAERO and LFD generalized aerodynamic forces for $M=1.05$, diagonal components for flexible modes 7 and 9.

VI. Concluding Remarks

This paper presented the results of transonic aeroelastic analyses of the X-59 aircraft using linear and non-linear (CFD-based) aeroelastic results at several Mach numbers and dynamic pressures. These flight conditions are aligned with flight conditions for the subsequent envelope expansion mission. The results presented included time-domain full FUN3D aeroelastic analyses, including generalized coordinates to demonstrate stability at those conditions. A new method was introduced that significantly enabled the computation of static and dynamic aeroelastic results while avoiding the challenge of numerical problems resulting from large static aeroelastic deformations. These results demonstrate the effectiveness of this new method as well as the consistent aeroelastic stability of the aircraft across several transonic Mach numbers and varying dynamic pressures. Results presented also included aeroelastic transients (generalized coordinates and generalized aerodynamic forces) using the AEROM computational tool. The AEROM results compared exceedingly well with the full FUN3D solutions indicating the good quality and high accuracy of the AEROM model generated as well as the aeroelastic stability at these conditions. Finally, results from the LFD method included a comparison of GAFs from the ZAERO method as well as V-g-f plots generated using the GAFs from each method. Results again indicate excellent comparison between these two methods with regards to the V-g-f flutter analysis plots that indicate no aeroelastic instability was identified by either method across several flight conditions.

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