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Grid Fin Stabilization of the Orion Launch Abort Vehicle

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Wind tunnel tests were conducted by Nielsen Engineering & Research (NEAR) and Rose Engineering & Research (REAR) in conjunction with the NASA Engineering & Safety Center (NESC) on a 6%-scale model of the Orion launch abort vehicle (LAV) configured with four grid fins mounted near the base of the vehicle. The objectives of these tests were to 1) quantify LAV stability augmentation provided by the grid fins from subsonic through supersonic Mach numbers, 2) assess the benefits of swept grid fins versus unswept grid fins on the LAV, 3) determine the effects of the LAV abort motors on grid fin aerodynamics, and 4) generate an aerodynamic database for use in the future application of grid fins to small length-to-diameter ratio vehicles similar to the LAV. The tests were conducted in NASA Ames Research Center's 11x11-foot transonic wind tunnel from Mach 0.5 through Mach 1.3 and in their 9x7-foot supersonic wind tunnel from Mach 1.6 through Mach 2.5. Force- and moment-coefficient data were collected for the complete vehicle and for each individual grid fin as a function of angle of attack and sideslip angle. Tests were conducted with both swept and unswept grid fins with the simulated abort motors (cold jets) off and on. The swept grid fins were designed with a 22.5° aft sweep angle for both the frame and the internal lattice so that the frontal projection of the swept fins was the same as for the unswept fins. Data from these tests indicate that both unswept and swept grid fins provide significant improvements in pitch stability as compared to the baseline vehicle over the Mach number range investigated. The swept fins typically provide improved stability as compared to the unswept fins, but the performance gap diminished as Mach number was increased. The aerodynamic performance of the fins was not observed to degrade when the abort motors were turned on. Results from these tests indicate that grid fins can be a robust solution for stabilizing the Orion LAV over a wide range of operating conditions.

Nomenclature

C_X = Axial force, X-Axis
C_Y = Side force, Y-Axis
C_Z = Normal force, Z-Axis
C_l = Rolling moment, X-Axis
C_m = Pitching moment, Y-Axis
C_n = Yawing moment, Z-Axis

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I. Introduction

At present, the Orion launch abort vehicle (LAV), shown in Fig. 1, is not meeting performance requirements during transonic flight. The LAV is statically unstable throughout the ascent phase of any launch abort scenario and it requires the incorporation of an attitude control motor to control its trajectory as it maneuvers away from the launch vehicle during an abort. The LAV must operate in a wide range of flight conditions from a stationary pad abort to a supersonic, high-altitude abort just after first-stage burnout. For cases when the LAV must pass through the transonic range during its ascent, defined here as Mach 0.90–1.60, aerodynamic interactions between the abort motor plumes and the vehicle further degrade its stability. Under nominal conditions, the LAV can successfully traverse the transonic flight range without tumbling. However, when aerodynamic uncertainties are added to the nominal conditions, the vehicle tumbles for an unacceptable percentage of transonic abort simulations. The LAV is not structurally designed to withstand tumbling flight at these conditions and as such would be expected to break up with probable loss of crew.

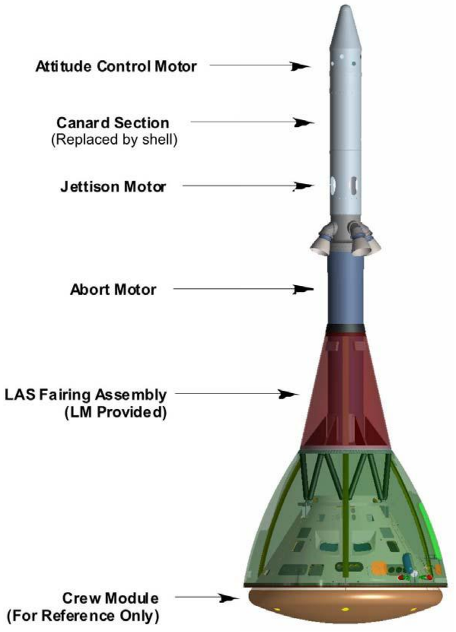


Figure 1. Orion launch abort vehicle.

To address this stability concern, the Constellation Program (CxP) Flight Performance Systems Integration Group (FPSIG) began investigating alternative approaches to stabilizing the LAV so as to move the nominal performance of the vehicle farther away from the static stability boundary during transonic flight. One technique for attaining this objective is to add deployable grid fins (also known as lattice fins) near the base of the Orion LAV. Research and development of grid fins has been ongoing since the early 1990s[1], and there are a number of current military and space applications including the Soyuz Launch Escape System shown in Fig. 2. Grid fins have the desirable characteristics that they 1) maintain a positive lift slope at larger angles of attack than conventional fins, 2) generate very little hinge moment about their root chord, and 3) can readily be folded against the vehicle's body to reduce stowed volume and aerodynamic interference.

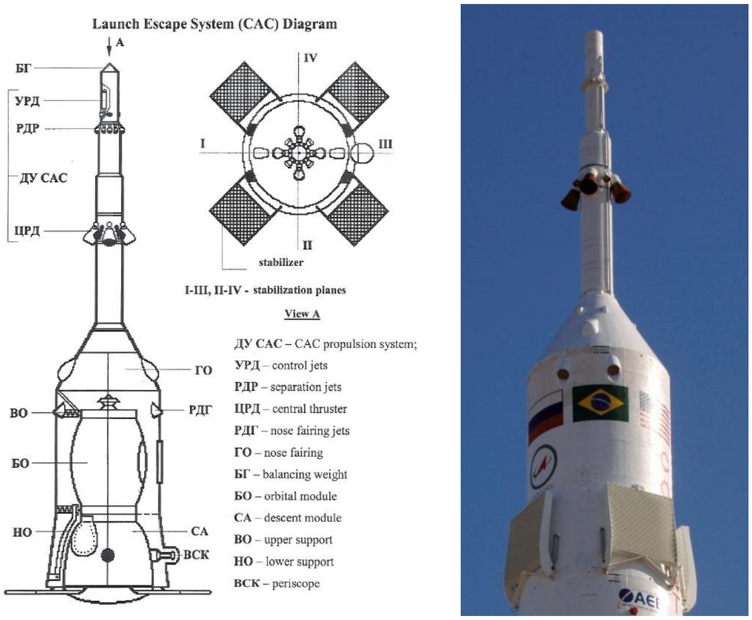


Figure 2. Deployable grid fins on the Soyuz Launch Escape System.

The majority of grid-fin research and development conducted to date has focused on their integration with relatively long, slender bodies where the flow entering the fin is typically well aligned with the fin's internal lattice structure. Because the Orion LAV has a much smaller length-to-diameter ratio, flow entering the grid fins is more three-dimensional than what is encountered on typical missile configurations or the Soyuz vehicle. Recent wind tunnel tests were successfully completed with grid fins on NASA's Max Launch Abort System (MLAS)[2] which is comparable in aspect ratio to the Orion LAV. Results from these tests were used to guide the design of the grid fins described in this report.

II. Experimental Setup

Wind tunnel tests were conducted using a 6%-scale model of the Orion launch abort vehicle as shown in Fig. 3. The model was configured with variable-thrust cold-jet abort motors and four grid fins mounted near the base of the vehicle. Data were collected with unswept and swept grid fins in both the + orientation (shown in Fig. 3) and the x orientation (all grid fins rotated 45° about the vehicle's longitudinal axis to be in line with the abort motors).

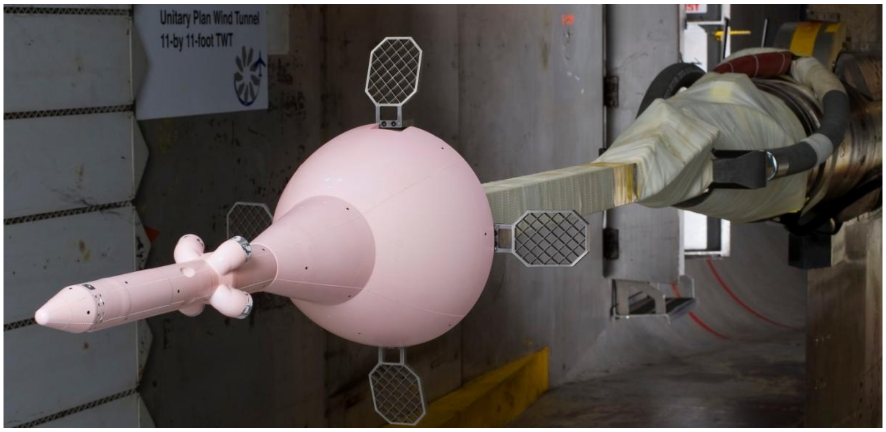


Figure 3. Photograph of the 6%-scale Orion launch abort vehicle with swept grid fins in the NASA ARC 11x11-foot transonic wind tunnel.

The swept fins were developed in an effort to improve LAV stability by increasing the distance from the vehicle's center of gravity to the fin's center of pressure, as shown in Fig. 4. Because this distance is intrinsically short for the Orion LAV, the relatively small aft movement in center of pressure provided by the swept fins can potentially yield a substantial increase in pitching moment. The swept fins were fabricated with a 22.5° aft sweep angle on the frame and internal lattice to maintain the same frontal projection as the unswept fins, as shown in Fig. 5. The full-scale area for each fin (defined to be 0.9*width*height) would be 3,030 in^2 which can be compared to the full-scale heat shield area of 30,800 in^2.

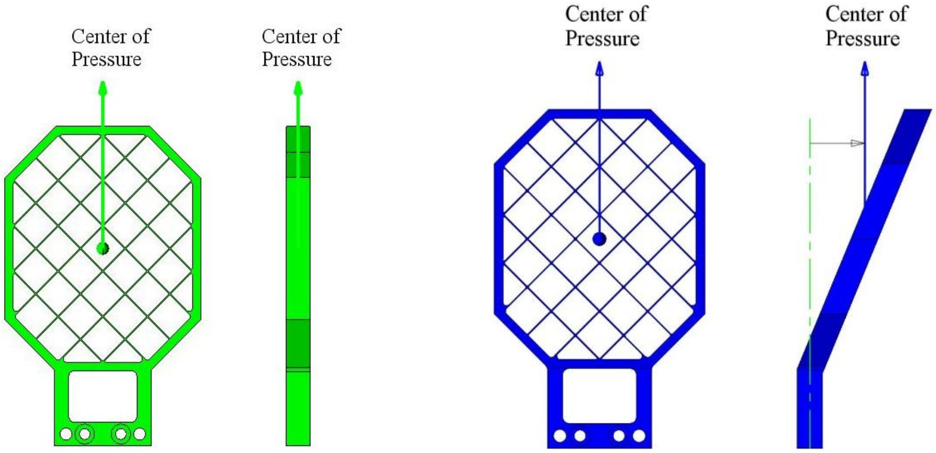


Figure 4. Center-of-pressure location for an unswept fin (left) and a swept fin (right).

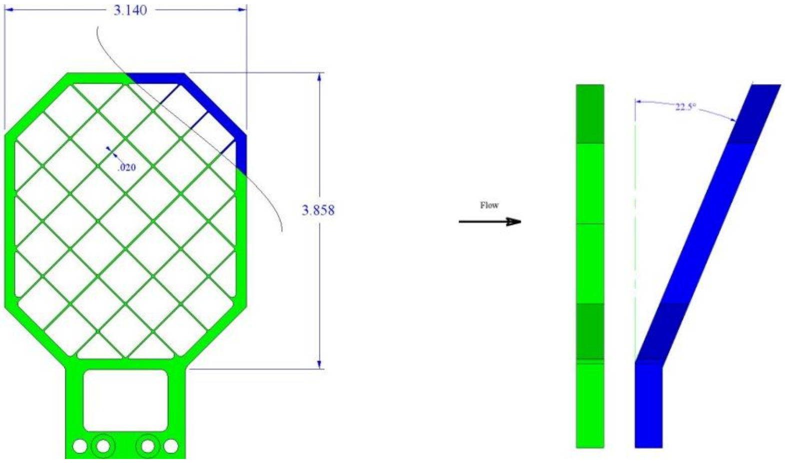


Figure 5. Streamwise (left) and cross-stream (right) views of the 6%-scale unswept and swept fins.

Initial tests of the grid fin-equipped LAV were conducted in NASA Ames Research Center's 11x11-foot transonic wind tunnel (www.windtunnels.arc.nasa.gov/11ft1.html) at Mach numbers from 0.5 to 1.3. Subsequent tests were conducted in NASA Ames Research Center's 9x7-foot supersonic wind tunnel (www.windtunnels.arc.nasa.gov/9x7ft1.html) at Mach numbers from 1.6 to 2.5. Due to sting limitations, the maximum angle of attack range varied with sideslip angle, Beta. At 0° sideslip angle, data were collected from +15° to -15° angle of attack at nominally 2° increments. For 5° sideslip angle, the angle of attack range covered was approximately ±12.5°, and for 10° sideslip angle, the angle of attack range was approximately ±10°. Tests were conducted with the abort motors off and with the abort motors on at a thrust coefficient of approximately 2.0, where the thrust coefficient is defined to be the total abort motor thrust divided by the product of the freestream dynamic pressure and the reference area. Due to excessive dynamic loading on the fins and balances, data collection with the abort motors on was limited, as is discussed below. Force and moment data were collected with a 6-component main balance internal to the LAV and with the four individual grid-fin balances shown in Fig. 6. The coordinate system used to present data in this report is shown in Fig. 7. The moment reference center (MRC) was taken to be at the virtual apex of the crew module.

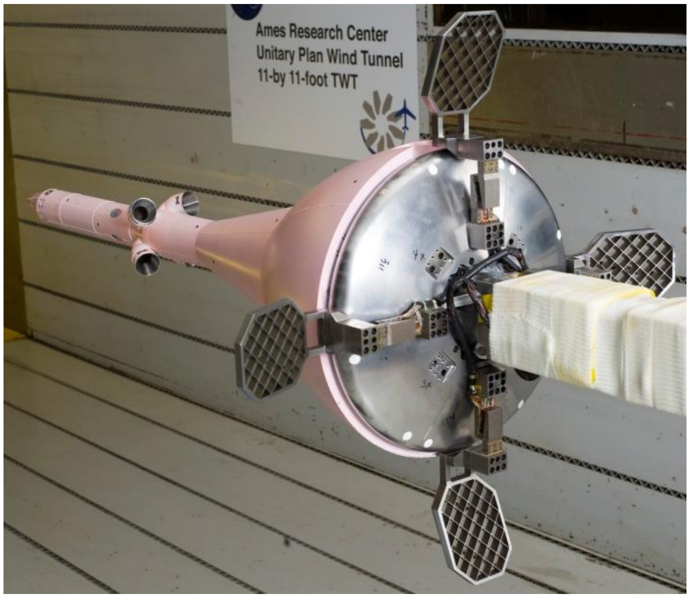


Figure 6. Photograph showing the four individual balances used to connect each grid fin to the model's heat shield.

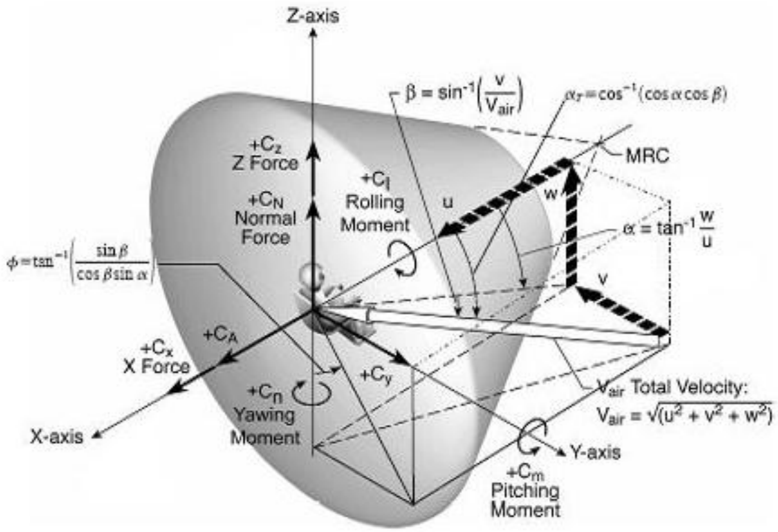


Figure 7. Coordinate system used for overall vehicle data, and location of the moment reference center.

III. Data Presentation and Discussion

The following sections provide a discussion of results from the 11x11-foot transonic wind tunnel and the 9x7-foot supersonic wind tunnel. Data for the complete Orion LAV are presented as aerodynamic increments where force or moment coefficient data (as measured by the main balance) for the vehicle with the grid fins off are subtracted from similar data with the fins on. Because the fin-on and fin-off data sets were not collected at identical angle of attack values, the increment data could not be created by simple subtraction. Alternatively, the data were created by first generating a 3rd-order polynomial fit to the fin-on data and another 3rd-order polynomial fit to the fin-off data. The two curve fit equations were evaluated at selected reference angle of attack points and the resulting values from each equation were subtracted.

Additional data are presented below to document the contributions to overall vehicle aerodynamics from the four grid fins. These "fin contribution" force and moment coefficient data were obtained from the individual fin balances and were transformed into the vehicle coordinate system. A limited set of force and moment coefficient data is also presented below for each of the four grid fins, individually. In all cases, the reference length used for the coefficient data is 11.88 inches and the reference area is $\pi*(11.88/2)^2$ in^2.

A. Orion LAV Stability Augmentation with Grid Fins

The primary objective of this test program was to assess if grid fins could provide stability augmentation to the Orion LAV. To quantifying this, pitching-moment coefficient increment data (fin-on minus fin-off) are plotted as a function of angle of attack for the vehicle with unswept and swept grid fins. In these figures, the pitching moment was computed about the vehicle's moment reference center (MRC). Typical pitch-plane stability data at Mach 0.5 and Beta = 0° are shown in Fig. 8 with the grid fins in the + orientation and the abort motors off. Under these conditions, the baseline vehicle without grid fins was observed to be statically unstable (data not shown), but the addition of unswept or swept grid fins made the vehicle stable about nominally 0° AOA. At this Mach number, the swept grid fins are shown to provide increased stability as compared to the unswept fins. Similar data collected at Mach numbers up to 2.5 indicate that the addition of grid fins always provided significant stability improvement to the baseline vehicle. Pitch stability was always better with the swept fins as compared to the unswept fins except for the highest Mach number investigated, as can be seen in Fig. 9. Pitching-moment increment data shown in Fig. 10 and Fig. 11 indicate that with the fins in the + orientation, the LAV abort motors had little adverse influence on vehicle stability augmentation from the grid fins.

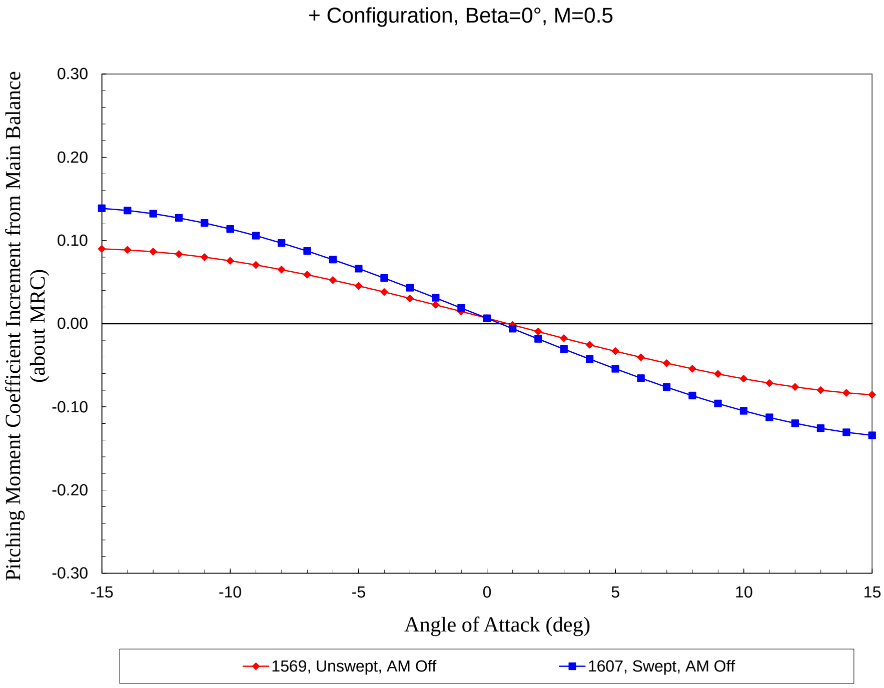


Figure 8. Pitching-moment coefficient increment about the MRC for the vehicle with unswept and swept grid fins in the + orientation at Mach 0.5 with the abort motors off.

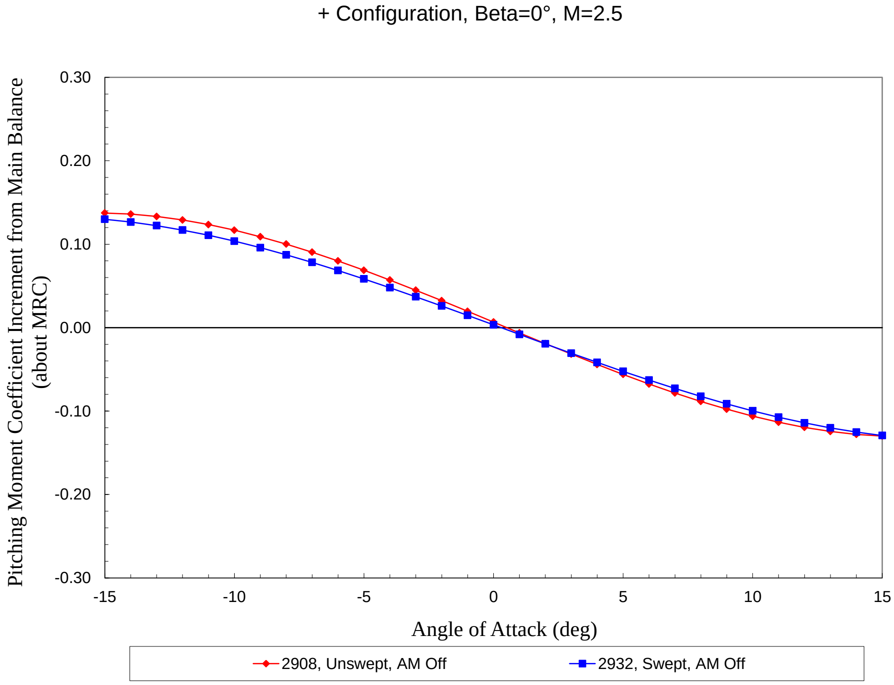


Figure 9. Pitching-moment coefficient increment about the MRC for the vehicle with unswept and swept grid fins in the + orientation at Mach = 2.5 with the abort motors off.

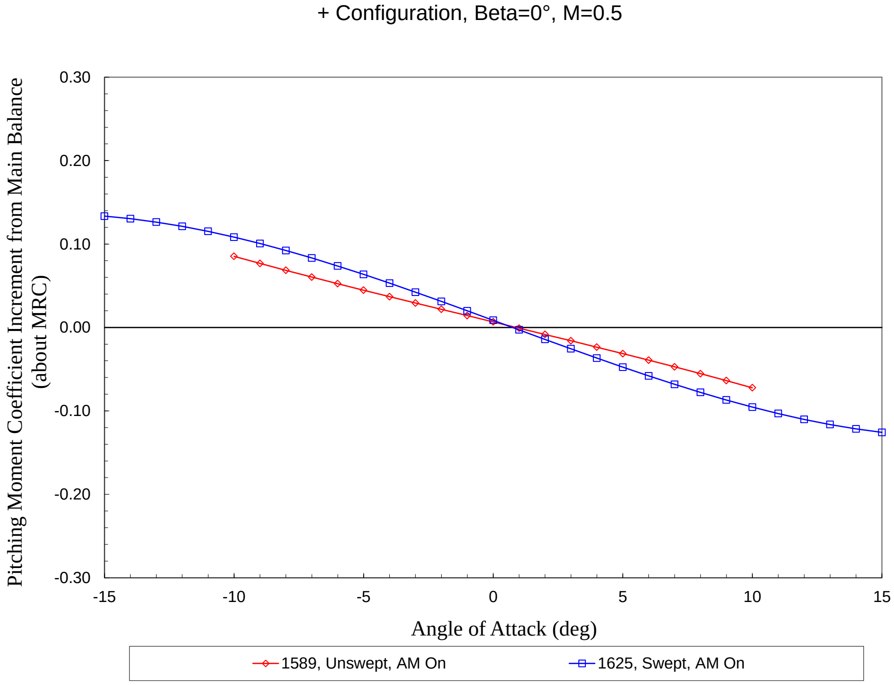


Figure 10. Pitching-moment coefficient increment about the MRC for the vehicle with unswept and swept grid fins in the + orientation at Mach 0.5 with the abort motors on.

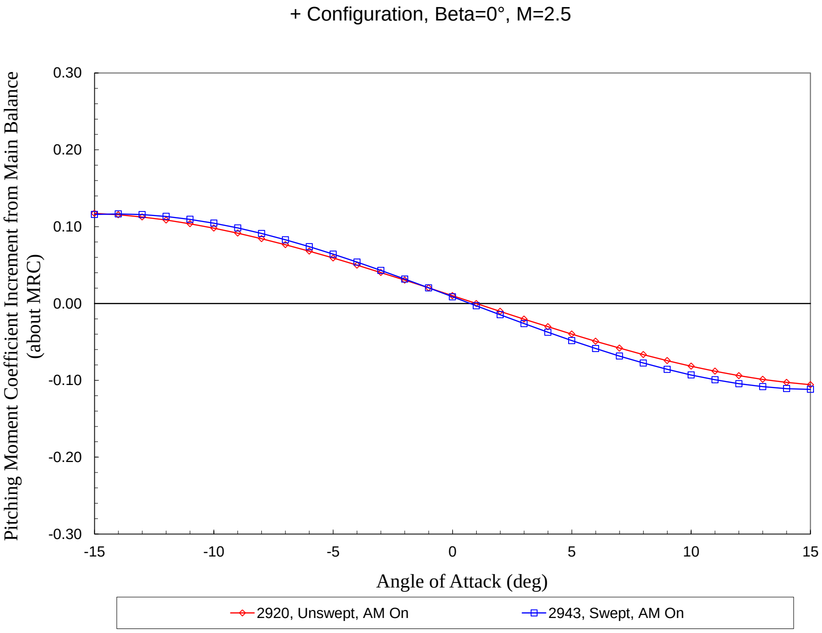


Figure 11. Pitching-moment coefficient increment about the MRC for the vehicle with unswept and swept grid fins in the + orientation at Mach 2.5 with the abort motors on.

B. Effects of Mach Number and Abort Motors on Grid Fin Performance

To continue investigating the influences of Mach number and the abort motors on grid fin aerodynamics, fin-contribution data from the four fin balances were analyzed. As shown in Fig. 12, the pitching-moment coefficient (in the vehicle coordinate system about the MRC) generated by the four swept grid fins is independent of Mach number over the range of subsonic, transonic, and supersonic conditions investigated. Similar data collected with the unswept grid fins, shown in Fig. 13, do show a slight increase in pitch stability with increasing Mach number.

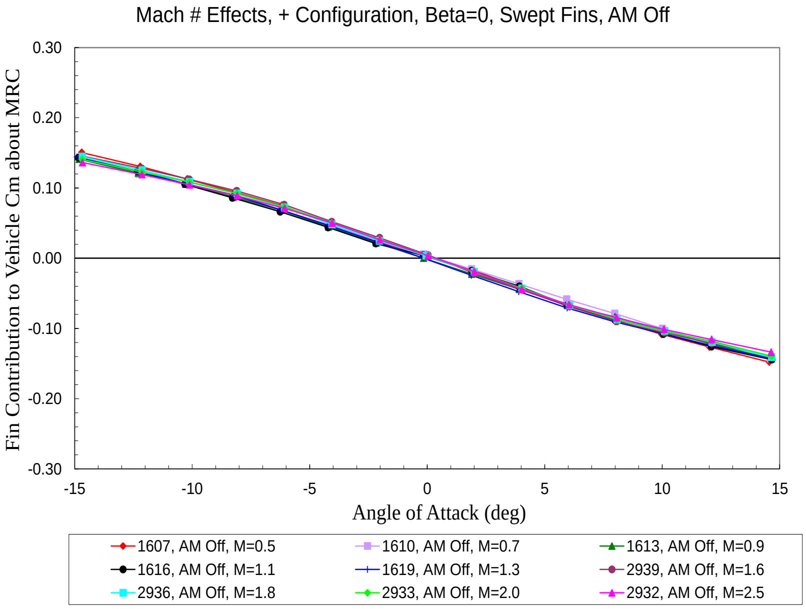


Figure 12. Mach-number effect on pitching-moment coefficient contribution from all four swept grid fins (about the vehicle's moment reference center) as measured by the individual fin balances with the abort motors off.

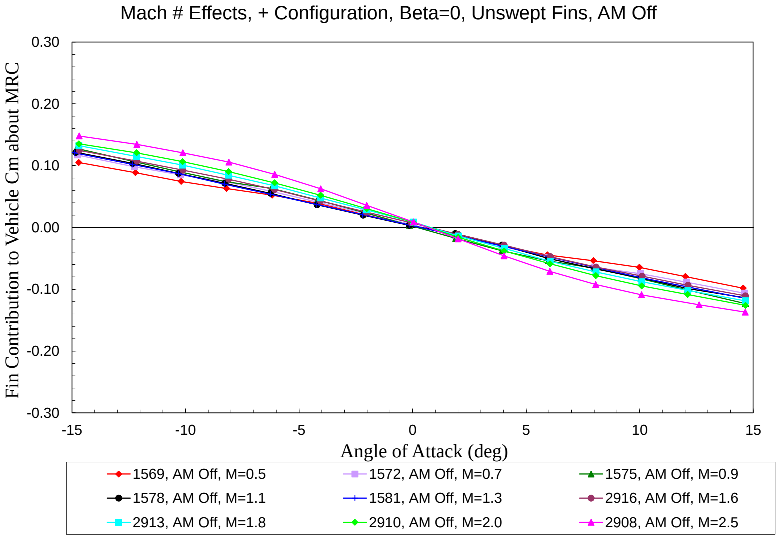


Figure 13. Mach-number effect on pitching-moment coefficient contribution from all four unswept grid fins (about the vehicle's moment reference center) as measured by the individual fin balances with the abort motors off.

Only a limited amount of data was collected with the abort motors on due to excessive dynamic loading on the fins and balances. With the fins in the + orientation, the abort motor plumes nominally pass between the fins, but the expanding plumes do impinge on the fins to some degree. It was observed that the magnitude of the dynamic loading decreases as the Mach number increases. It was also observed that as the vehicle AOA increases or decreases from 0°, the lower or upper plumes, respectively, impinge on the two horizontal fins and increase the dynamic loading.

Data collected with the abort motors on, shown in Fig. 14, indicate that the motors (operating with a thrust coefficient of 2.0) had virtually no effect on the pitching-moment coefficient generated by the swept fins in the + orientation. The abort motors did have a slight effect on the unswept fins, serving to make the pitching moment relatively independent of Mach number as shown in Fig. 15. A limited set of data was collected in the 9x7-foot tunnel with the abort motors on and the unswept fins in the x orientation. The data shown in Fig. 16 indicate that while the abort motors did not significantly degrade stability augmentation provided by the fins, the plumes did alter the qualitative shape of the pitching moment curves.

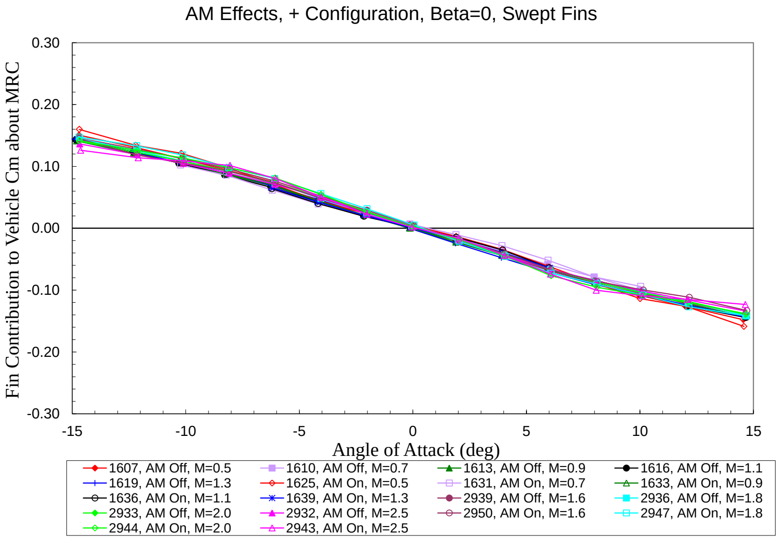


Figure 14. Pitching-moment coefficient contribution from all four swept grid fins (about the vehicle's moment reference center) as measured by the individual fin balances with the abort motors off and on.

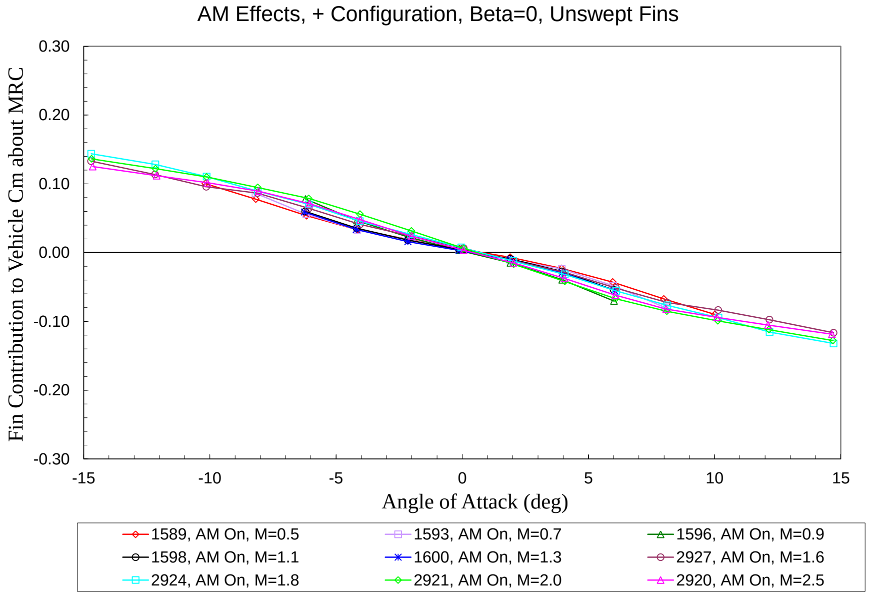


Figure 15. Pitching-moment coefficient contribution from all four unswept grid fins (about the vehicle's moment reference center) as measured by the individual fin balances with the abort motors on.

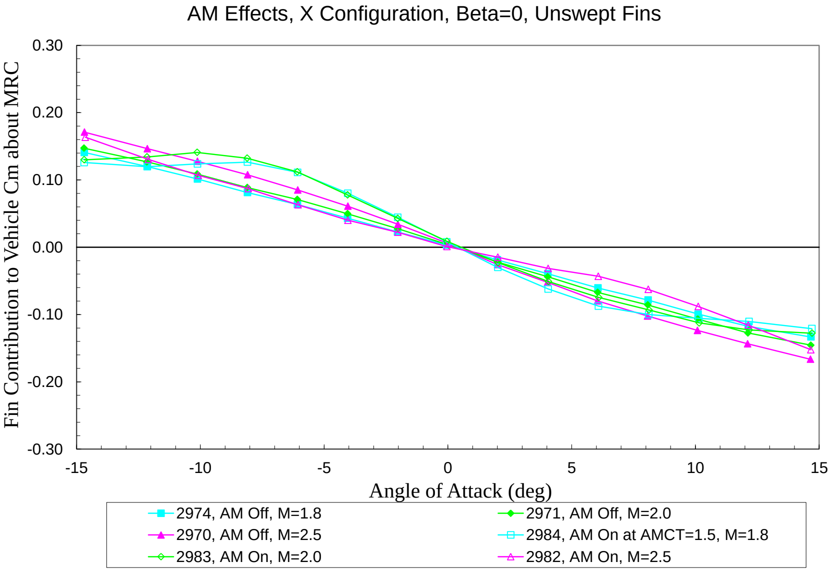


Figure 16. Pitching-moment coefficient contribution from all four unswept grid fins (about the vehicle's moment reference center) as measured by the individual fin balances.

Tests were run with the fins in the + and the x orientations to assess if there was a performance bias. The data collected indicate that there was not a significant difference in stability augmentation between the two orientations. This observation is supported by higher Mach number data collected with the swept grid fins, Fig. 17.

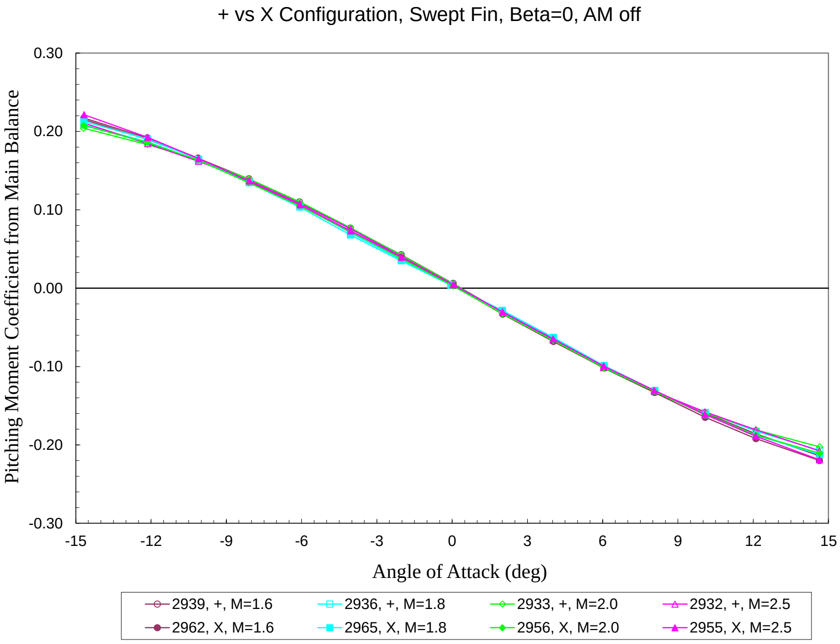


Figure 17. Pitching-moment coefficient about the moment reference center with swept grid fins in the + and the x orientations.

C. Grid Fin Axial Force

The increment in axial-force coefficient from installation of the unswept and swept grid fins is shown in Fig. 18. These data indicate that the grid fins generate significant increases in vehicle axial force, with the increment from the unswept fins being greater. Axial force contributions from the four grid fins (as measured by the fin balances) are presented in Fig. 19 and Fig. 20 with the fins in the + orientation and the abort motors off and on. At 0° AOA the effect of the abort motor plumes on fin axial force diminishes as the Mach number increases due to reduced plume expansion. As the vehicle AOA increases or decreases from 0°, the lower or upper plumes, respectively, impinge on the two horizontal fins and increase the measured axial force.

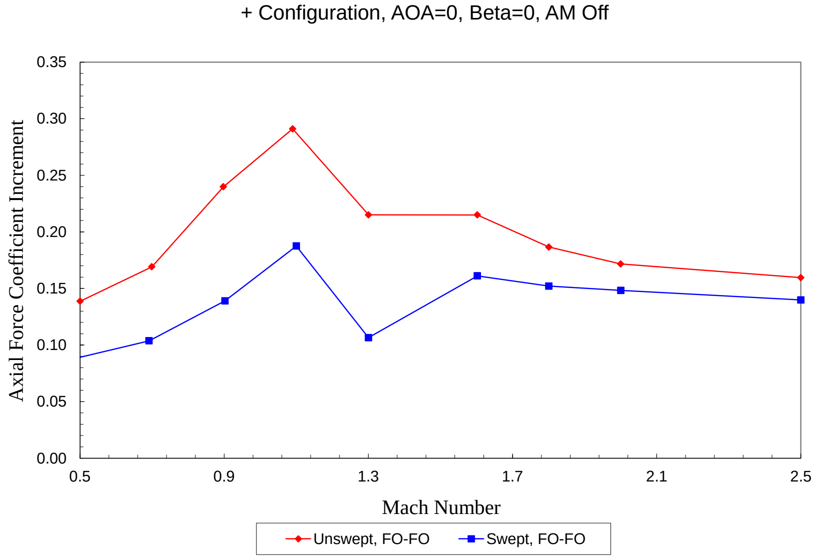


Figure 18. Axial-force coefficient increment (fin-on minus fin-off data) for the vehicle with unswept and swept grid fins in the + orientation.

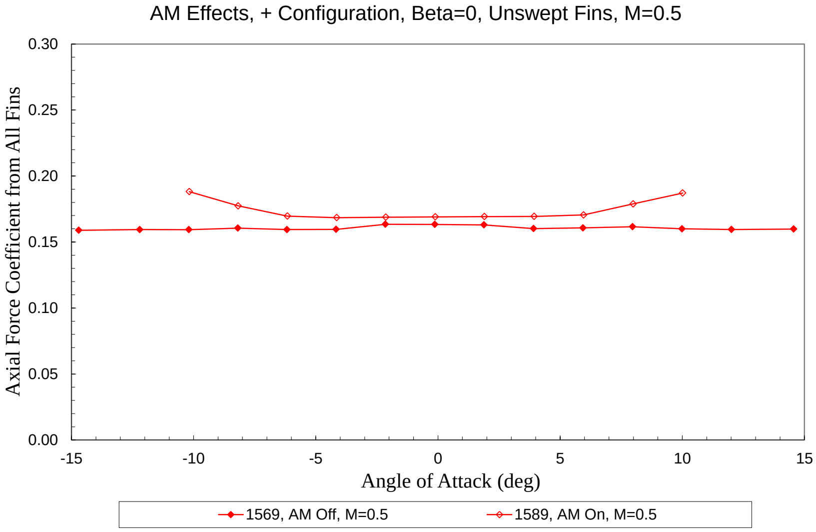


Figure 19. Axial-force coefficient from the unswept and swept grid fins in the + orientation at Mach = 0.5.

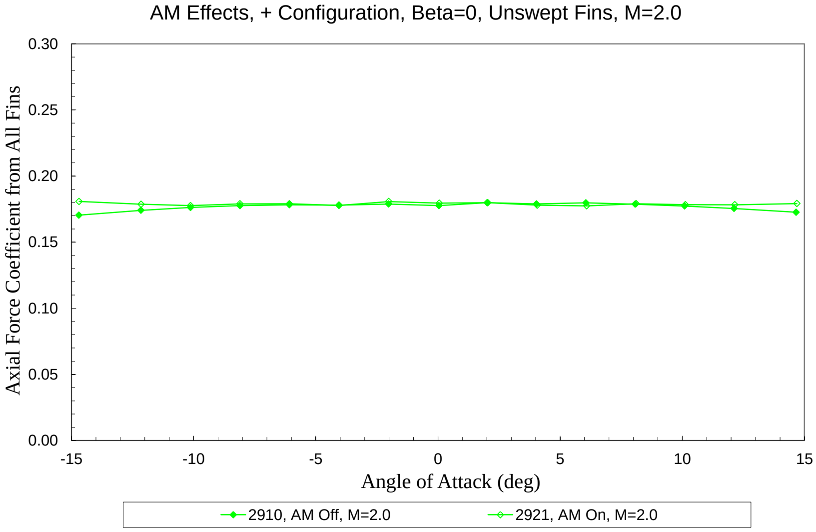


Figure 20. Axial-force coefficient from the unswept and swept grid fins in the + orientation at Mach = 2.0.

With the fins in the x orientation, the abort motors significantly increase the measured axial-force contribution as shown in Fig. 21. At low AOA values, the fins are directly downstream of the plumes and the increased dynamic pressure results in a large increase in the total axial force on the fins. As the AOA increases/decreases, the upper/lower two fins begin to emerge from the plumes, and the total measured force decreases.

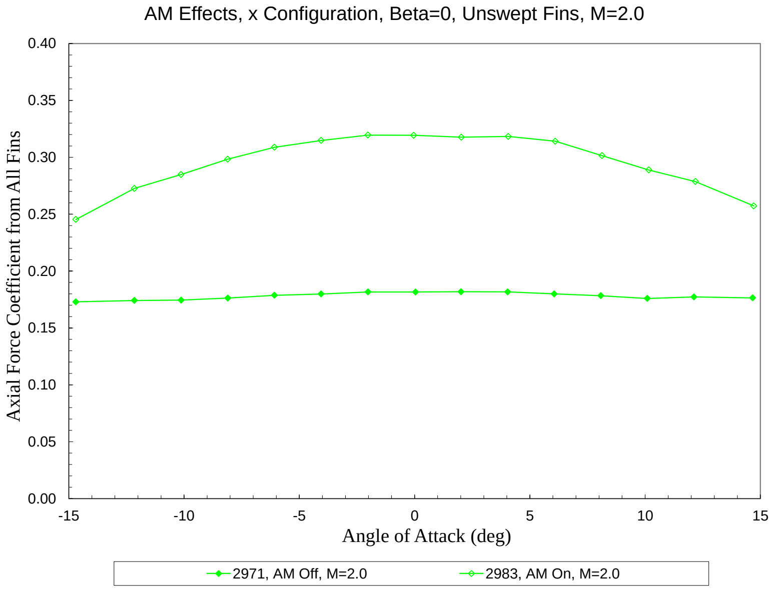


Figure 21. Axial-force coefficient from the unswept and swept grid fins in the x orientation at Mach = 2.0.

D. Individual Fin Aerodynamic Data

The following discussions focus on aerodynamic coefficients from each of the four fins, individually. Pitching moment data from the unswept grid fins in the + orientation are presented in Fig. 22 in the vehicle coordinate system about the vehicle's moment reference center. The fin numbering convention has Fin 1 at the top of the vehicle with fin number increasing clockwise around the vehicle when looking upstream. As would be expected, pitching moments from the two horizontal fins are very similar over the angle of attack range. In this configuration, a majority of the pitch stability comes from the two horizontal fins, with some contribution coming from the windward vertical fin at large (positive or negative) AOA values.

Corresponding normal force coefficient data are shown in Fig. 23. The two horizontal fins demonstrate a relatively linear variation in normal force with AOA. At 0° AOA, the two horizontal fins generate no normal force, as would be expected, but the upper and lower fins generate sizeable normal forces that are oriented radially outward. These latter forces are due to the radially diverging flowfield over the "stubby" LAV body interacting with the lattice structure within the grid fins. At -15° AOA, the normal force on the top fin is still positive indicating that the average flowfield over the fin is still radially outwards, despite the large negative AOA. It is significant to note that these radial forces would not be present in grid-fin databases derived with long, slender missile bodies.

Axial forces on the upper and lower fins generate pitching moments about the vehicle's moment reference center. However, because the axial force from each fin is relatively constant with AOA, their respective pitching moment contributions cancel resulting in no significant impact on vehicle stability. Virtually all of the pitching moment contribution from the four fins results from the normal force generated, as shown in Fig. 24.

With the swept grid fins installed, the pitching moment contributions from the two horizontal fins, as shown in Fig. 25, are qualitatively similar to those from the unswept fins (Fig. 22), but are greater in magnitude due to the aft shift in center of pressure. The magnitude of this shift is shown in Fig. 26 for the two cases currently being discussed.

A significant difference between the swept and unswept fins is the normal force generated by the two vertical fins at 0° AOA. For the unswept fins, the normal force is radially outwards as discussed above, but for the swept fins, the force is radially inwards as shown in Fig. 27. This reversal in radial force direction is likely due to a combination of effects including 1) the flow deflecting radially outwards by the swept framework of the grid fin and 2) the swept fins operating in a region where the radial flowfield from the LAV body is less substantial.

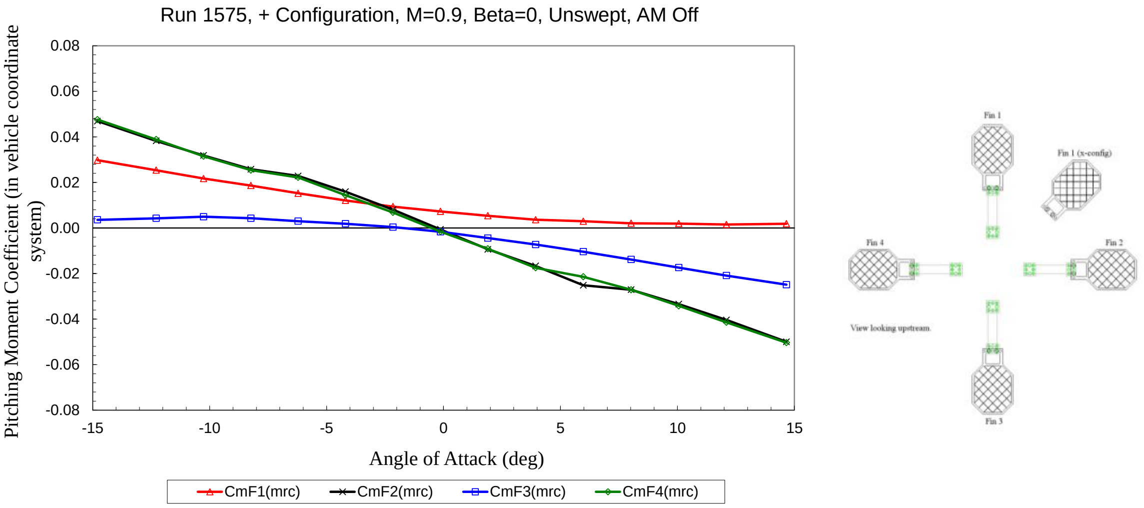


Figure 22. Pitching-moment coefficient (in the vehicle coordinate system about the MRC) from each individual grid fin as measured with each fin's balance. Fin numbering system shown to right of graph.

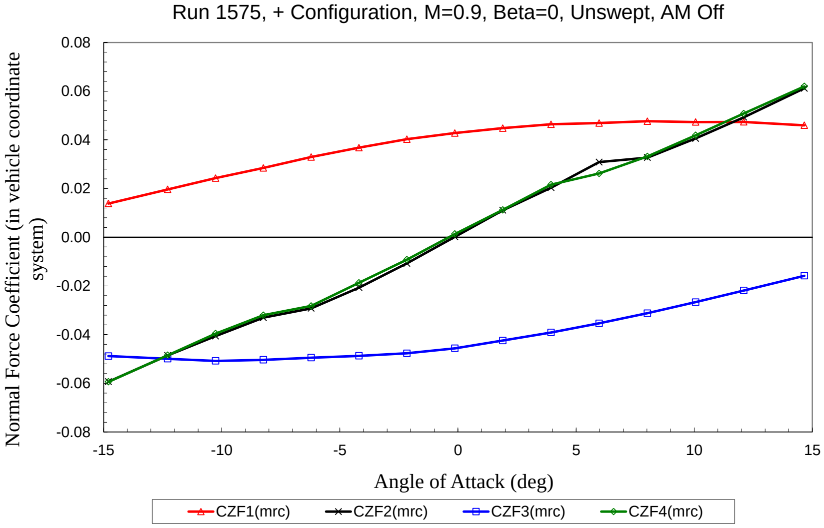


Figure 23. Normal force coefficient (in the vehicle coordinate system) from each individual grid fin as measured with each fin's balance.

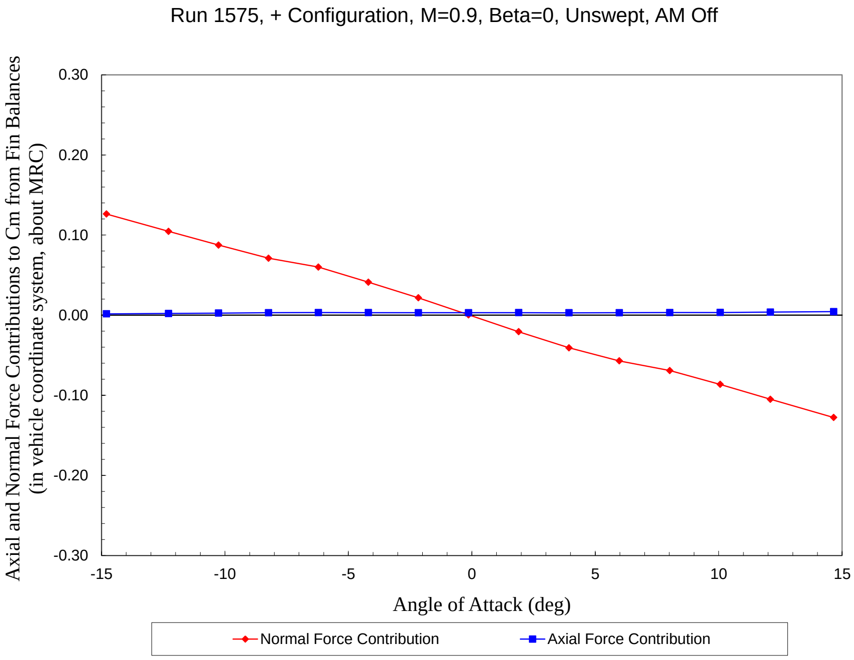


Figure 24. **Normal- and axial-force contributions from all four fins to the vehicle's pitching moment.**

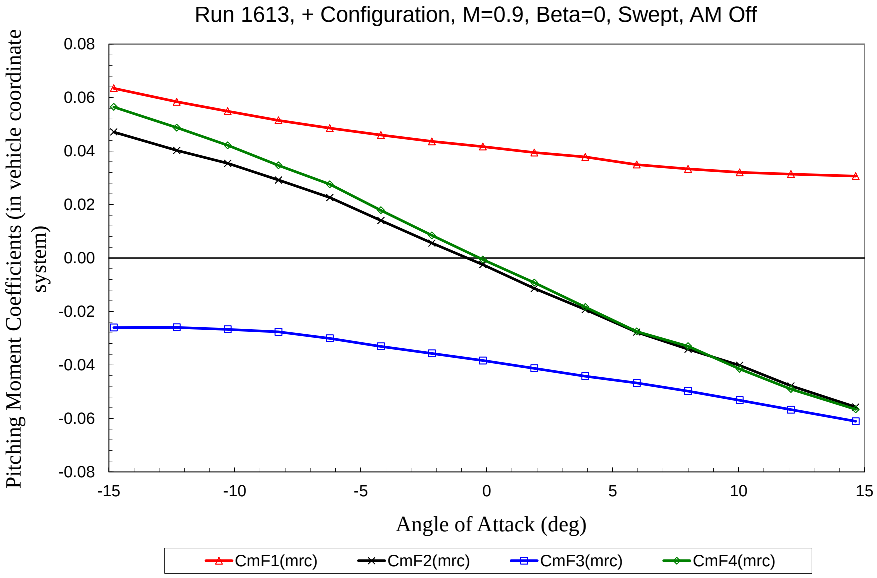
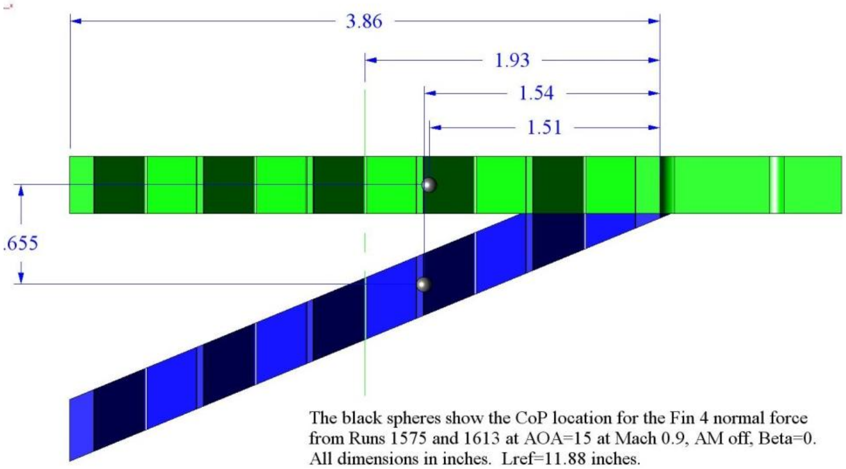


Figure 25. **Pitching-moment coefficient (in the vehicle coordinate system about the MRC) from each individual grid fin as measured with the fin's balance.**



The black spheres show the CoP location for the Fin 4 normal force from Runs 1575 and 1613 at AOA=15 at Mach 0.9, AM off, Beta=0. All dimensions in inches. Lref=11.88 inches.

Figure 26. Computed center of pressure locations for the normal force from fin 4 at 15° angle of attack for the swept and unswept fins.

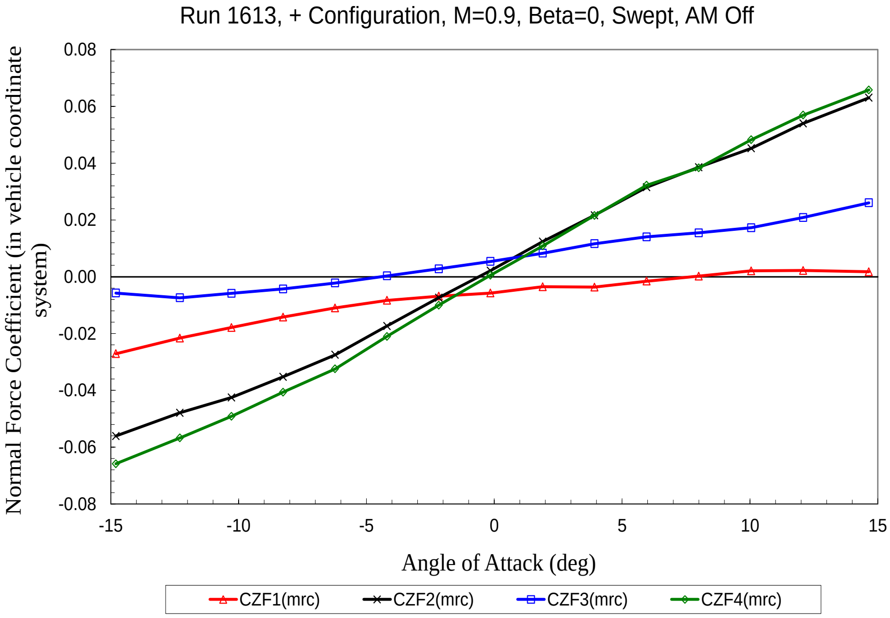


Figure 27. Normal force coefficient (in the vehicle coordinate system) from each individual grid fin as measured with the fin's balance.

IV. Conclusions

Nielsen Engineering & Research and Rose Engineering & Research collaborated with the NASA Engineering & Safety Center to conduct a series of wind tunnel tests on a 6%-scale model of the Orion launch abort vehicle (LAV) equipped with stabilizing grid fins. These tests were conducted in NASA Ames Research Center's 11x11-foot transonic wind tunnel and 9x7-foot supersonic wind tunnel over a range of Mach numbers from 0.5 through 2.5. The primary objectives of this program follow:

- Quantify LAV stability augmentation provided by grid fins attached near the base of the vehicle from subsonic through supersonic Mach numbers,

- Assess the benefits of swept grid fins versus unswept grid fins on the LAV,
- Determine the effects of the abort motor plumes on the aerodynamic performance of the grid fins in the + and the x orientations, and
- Generate an aerodynamic database for use in the future application of grid fins to small length-to-diameter ratio vehicles similar to the LAV.

A summary of conclusions derived from the wind tunnel data includes the following:

- Both unswept and swept grid fins provided significant improvement in pitch stability as compared to the baseline vehicle.
- The swept grid fins typically provided improved pitch stability as compared to the unswept fins. The relative benefit of the swept fins over the unswept fins diminished as the Mach number was increased.
- Despite initial concerns that fin performance would degrade during transonic conditions, there was little observed variation in fin performance with Mach number.
- There was no significant difference in aerodynamic performance with the fins in the + orientation versus the x orientation.
- Based on data that could be collected with the abort motors on, there was no significant degradation in grid fin performance due to the abort motor plumes.
- The grid fins' ability to perform consistently over a wide range of operating conditions provides a robust solution for stabilizing the Orion LAV.
- A grid-fin aerodynamic database was generated and is available under limited distribution.
- A flight dynamic trajectory analysis, conducted by the Orion Launch Abort System Office, indicates that the addition of grid fins to the Orion LAV substantially improves performance during transonic abort scenarios. Details of this analysis are ITAR restricted and are available under limited distribution.
- Further research is needed to determine the feasibility of integrating a grid-fin system with the Orion vehicle.

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