

Force and Moment Analysis for the High Reynolds Number Wind Tunnel Test of the Space Launch System at Ascent Conditions

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A high Reynolds number test of the Space Launch System was performed at the NASA Langley National Transonic Facility (NTF). The objective of the test was to use the cryogenic testing capabilities of the NTF to acquire data over the largest range of Reynolds numbers possible with a specific focus on the Reynolds numbers closest to flight conditions. The test was performed at Mach numbers from 0.50 to 0.95, which corresponds to the ascent portion of flight for the SLS vehicle. Force and moment data showed that pitching and yawing moments were sensitive to Reynolds number effects over the full range of Mach and Reynolds numbers tested. Axial force also showed sensitivity to Reynolds number with the largest differences seen between Mach 0.50 to 0.90. Surface pressure data showed the highest sensitivity to Reynolds number in the vicinity of the solid rocket booster forward attach region.

Notice to the Reader

The Space Launch System, including its predicted performance and certain other features and characteristics, have been defined by the U.S. Government to be Controlled Unclassified Information (CUI). Information deemed to be CUI requires special protection and may not be disclosed to an international audience. To comply with CUI restrictions, details such as absolute values have been removed from some plots and figures in this paper. It is the opinion of the authors that, despite these alterations, there is no loss of meaningful technical content. Analytical methodologies and capabilities are discussed; significant and interesting technical results are still present; and meaningful conclusions are presented.

I. Nomenclature

Variables

C_A	Axial Force Coefficient
C_l	Rolling Moment Coefficient
C_m	Pitching Moment Coefficient
C_N	Normal Force Coefficient
C_n	Yawing Moment Coefficient
C_p	Pressure Coefficient
C_Y	Side Force Coefficient
D	Centerbody Reference Diameter
Re_D	Reynolds Number Based on Core Diameter
$Trip$	Boundary Layer Transition Configuration
X	Axial Station
Z	Vertical Station

α	Angle of Attack
β	Sideslip Angle
Δ	Difference

Abbreviations

ATT	Aerodynamics Task Team
CFD	Computational Fluid Dynamics
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NTF	National Transonic Facility
SLS	Space Launch System
SRB	Solid Rocket Booster
TWICS	Transonic Wall Interference Correction System

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II. Introduction

THE Space Launch System (SLS) is a launch platform developed by NASA to extend human exploration beyond Earth's orbit [1]. The SLS vehicle, seen in Figure 1, is comprised of a liquid fuel core stage common to all vehicle configurations with two solid rocket boosters (SRB) on the Block 1 configurations or evolved boosters on the Block 2 configurations. A number of upper stages can be integrated with the core stage depending on mission requirements including three configurations with the Orion Multi-Purpose Crew Vehicle for crewed missions. The SLS Aerodynamics Task Team (ATT) is responsible for providing aerodynamic databases for each of the launch vehicles throughout the entire launch from liftoff until the vehicle leaves the Earth's atmosphere.

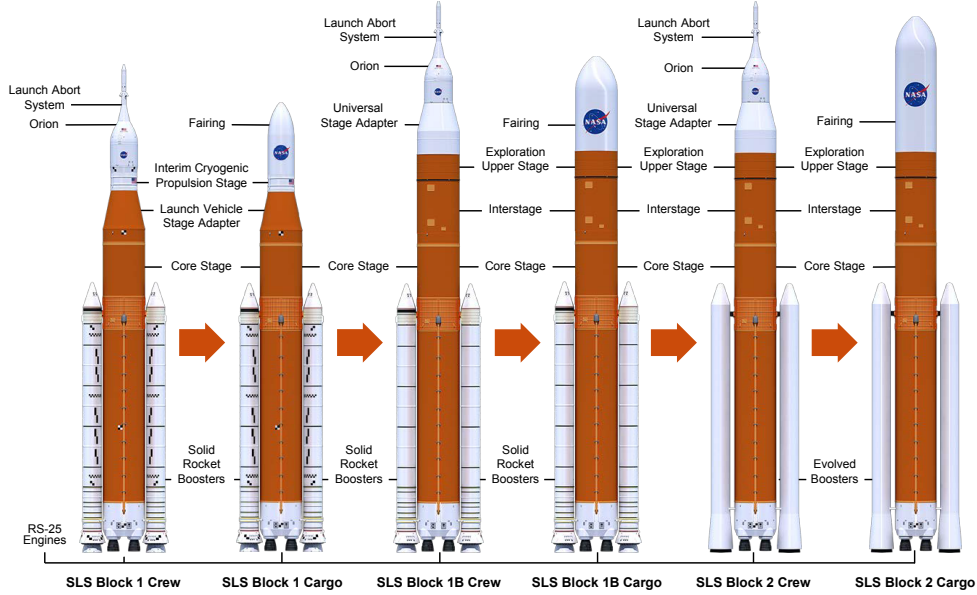


Fig. 1 Artist renderings of the SLS vehicle configurations [2].

Aerodynamic testing of the SLS vehicle utilizes wind tunnel test facilities ranging from low-speed ($Mach \leq 0.30$) for liftoff and transition testing [3–6] to high supersonic facilities (up to $Mach 5.0$) for ascent flight as the vehicle leaves the atmosphere [7–9]. Due to the scale of the SLS, most of the ground test facilities used are limited to testing at diameter based Reynolds numbers (Re_D) one to two orders of magnitude lower than flight Reynolds numbers. Typically, the SLS ATT uses computational fluid dynamics (CFD) simulations performed at flight conditions to predict the effects of Reynolds number. Simulations at flight conditions can be compared against simulations at ground test conditions to help inform database development and uncertainty quantification [10, 11]. The current test was performed to provide experimental data at Re_D closer to flight conditions to give additional insight into Reynolds number effects on the SLS vehicle and to generate data at higher Re_D to help validate CFD at conditions closer to flight. The NASA Langley National Transonic Facility (NTF) was utilized for this test, which allowed for testing up to approximately 45% of flight Re_D . The current paper will focus on the results of the NTF test while more details of the facility, model, and test hardware can be found in the companion paper by Chan et al. [12].

III. Experimental Setup

The NTF wind tunnel can achieve extremely high Reynolds numbers (flight or near-flight) for various aircraft, spacecraft, and launch vehicles using cryogenic test techniques. The tunnel is a closed-circuit, continuous-flow wind tunnel capable of operating with dry air at warm temperatures up to 120°F or with nitrogen gas from warm to cryogenic temperatures down to -270°F . The NTF can operate over an absolute pressure range of 1 to 8.3 atmospheres, a Mach number range from 0.1 to 1.2, and a maximum unit Reynolds number of 146×10^6 per foot at Mach 1. The test section has an 8.2-foot square cross-section that is 25 feet long. The test section floor and ceiling are slotted (6% open), and the sidewalls are solid. More details regarding the facility can be found in references [13–16]. The data presented in the following sections were acquired at Mach numbers ranging from 0.50 to 0.95, and Re_D ranging from 2×10^6 to 40×10^6 .

A detailed summary of the complete test conditions can be found in reference [12].

The test article was a 1.75%-scale model of the full-scale geometry of the SLS Block 1 Cargo configuration. The wind tunnel model was designed with a specific focus on acquiring force and moment data in the NTF. The 1.75% scale was selected to keep the model as large as possible, allowing for more detailed protuberances, but to stay under the 0.5% blockage ratio criteria recommended by the NTF. The test article was installed in the NTF test section using the arc sector, roll mechanism, and a traditional sting mount as seen in Figure 2. Model orientation was achieved using pitch-roll positioning, and data were acquired via move-pause acquisition. The balance used was a six-component strain-gauge balance designed for use at cryogenic temperatures. The model was also instrumented with 124 static pressure port orifices distributed among model surface, base, and cavity pressures.

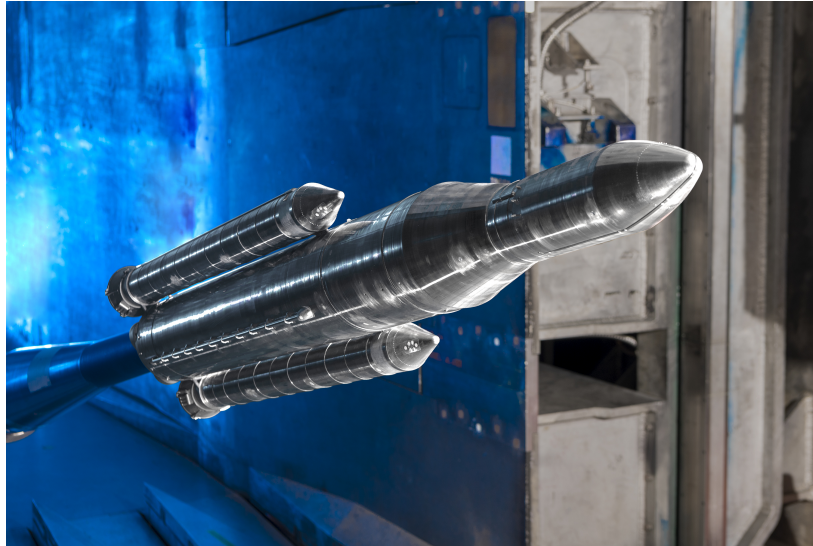


Fig. 2 1.75%-scale SLS Block 1 Cargo model installed in NTF test section.

Three trip dot configurations were used during testing. All runs in Nitrogen mode ($Re_D \geq 4 \times 10^6$) used a trip dot height selected for the high Reynolds number runs following the Braslow and Knox guidelines [17]. The Nitrogen mode trip dot configuration is denoted as $Trip = 2$. At low Reynolds numbers in air mode, two trip schemes were used. The first was free transition (no boundary layer tripping devices), indicated as $Trip = 0$. The second was trip dot heights selected for low Reynolds numbers, indicated as $Trip = 1$. More details of the trip dot placement and sizing can be found in reference [12].

IV. Data Corrections and Analysis

Several corrections were made to the force and moment data and the tunnel freestream conditions. These included standard facility corrections such as blockage effects and flow angularity. The NTF also applied corrections for wall interference using the Transonic Wall Interference Correction System (TWICS), which applies corrections to Mach number, dynamic pressure, pitch angle, lift coefficient, drag coefficient, and pitching moment coefficient. Corrections specific to SLS were also made including base and cavity pressure corrections, Mach setpoint corrections, and roll dependent bias corrections. More details regarding the corrections applied can be found in references [8, 12, 18].

Response surfaces were generated to help simplify the Reynolds number effect comparison process. A unique response surface was computed for each force and moment coefficient at each Mach number and Re_D using thin-plate splines in Matlab [19]. The response surfaces were computed with angle of attack and sideslip angle (α and β) as the two independent variables and a single force or moment coefficient as the dependent variable. Using thin-plate splines allowed data from multiple runs to be combined into a single representative dataset without the need for significant preprocessing of the data to combine or average repeated data points.

After generating the response surfaces, differences between the measured test data and the response surface model were computed. The differences encompass the within-test repeatability uncertainty and the response surface modeling error. The balance accuracy was characterized prior to the test as part of the balance calibration, and this information was

used to compute a balance measurement uncertainty. The response surface modeling error and balance measurement uncertainty were root-sum-squared to compute a 95% confidence measurement uncertainty, represented as error bars in the figures that follow.

Figure 3 shows the data for four repeat pitch sweeps (symbols) acquired at Mach 0.90, $Re_D = 30 \times 10^6$, and $\beta = 0^\circ$. C_N , C_Y , and C_A are the fully corrected normal, side, and axial force coefficients, respectively. C_m , C_n , and C_l are the fully corrected pitching, yawing, and rolling moment coefficients, respectively, computed about the balance moment center. As expected, normal force and pitching moment coefficients show strong dependence on angle of attack, while side force and yawing moment coefficients remain near zero. Axial force coefficient shows weak dependence on angle of attack, and rolling moment coefficient remains near zero as the SLS is nearly planar symmetric (the exceptions being relatively small protuberances).

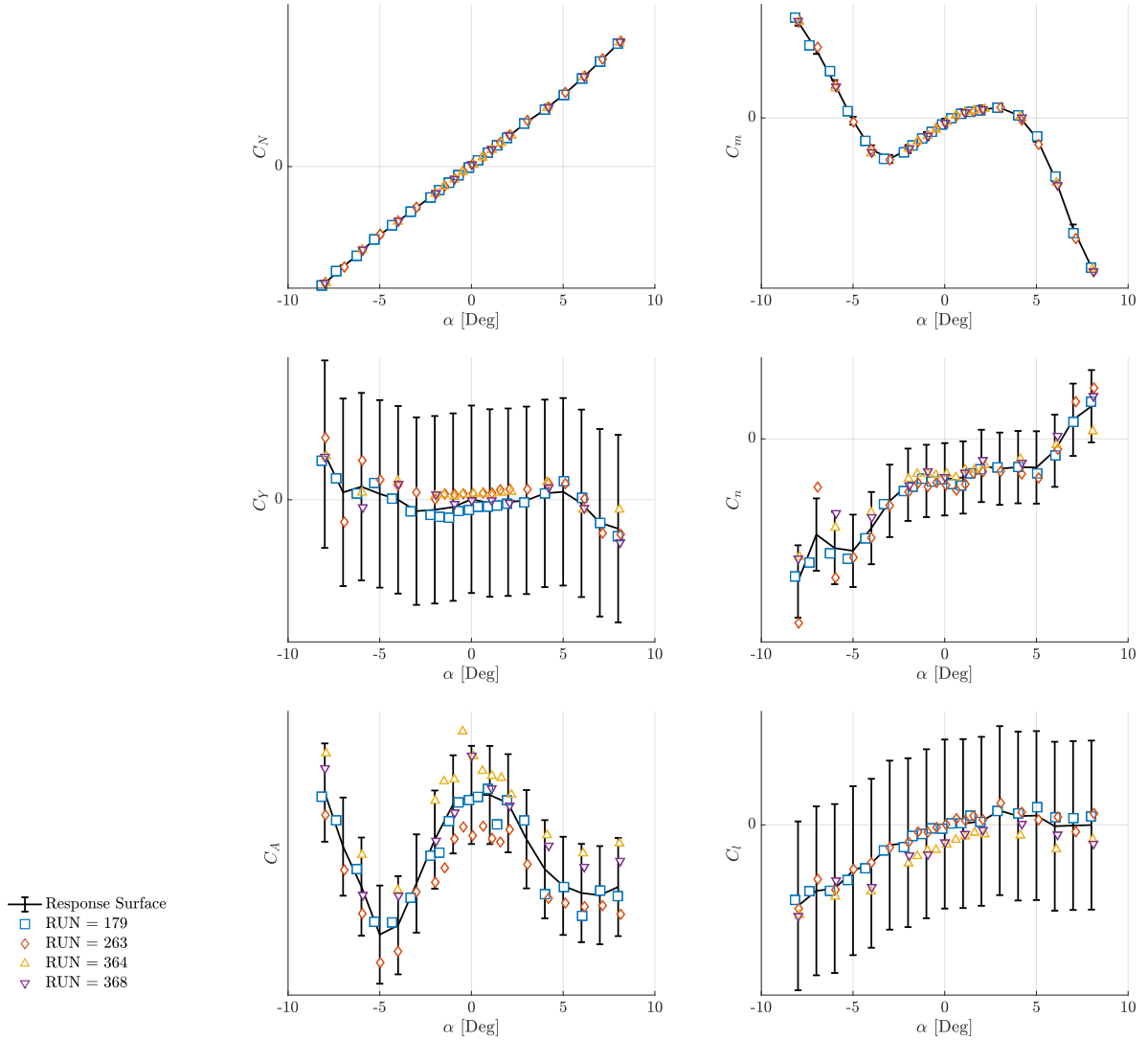


Fig. 3 Example response surface fit for repeated pitch sweeps at Mach 0.90 and $Re_D = 30 \times 10^6$.

Figure 3 also shows computed response surface fits (solid line) with the corresponding error bars. Good repeatability is shown for normal force and pitching moment coefficients, with the error bars being smaller than the plotted symbols. The error bars for the side force, yawing moment, and rolling moment coefficients appear large at first, but recall that the measured values are nearly zero. Axial force coefficient is a useful case for evaluating the error bar calculation as there was higher variation in the axial force reading compared to the other balance components resulting from the complexity

of testing in the cryogenic environment. Here, the response surface model captures the mean trend in the data, and the error bars capture a majority of the scatter in the repeated data points.

V. Results

A. Force and Moment Coefficients

Figure 4 shows the effect of Reynolds number and trip scheme when pitching the model at Mach 0.80. Note that the Re_D values listed in the legend for the figures that follow are in millions ($\times 10^6$). Normal force coefficient shows no significant dependence on the trip scheme or Reynolds number. Pitching moment coefficient does show a significant dependence on Reynolds number. The pitching moment coefficient curves near $\alpha = 0^\circ$ are the same within the uncertainty bounds for all cases presented here. The largest differences in magnitude are seen around $\alpha = \pm 4^\circ$, and an increase in slope of the curve is seen beyond $\alpha = \pm 4^\circ$. Evaluating the trends with respect to increasing Reynolds number, it does not appear that the data have reached a Reynolds number threshold. That is, the trends here indicate that increasing Reynolds number beyond $Re_D = 40 \times 10^6$ could result in further shifts in the pitching moment coefficient profiles.

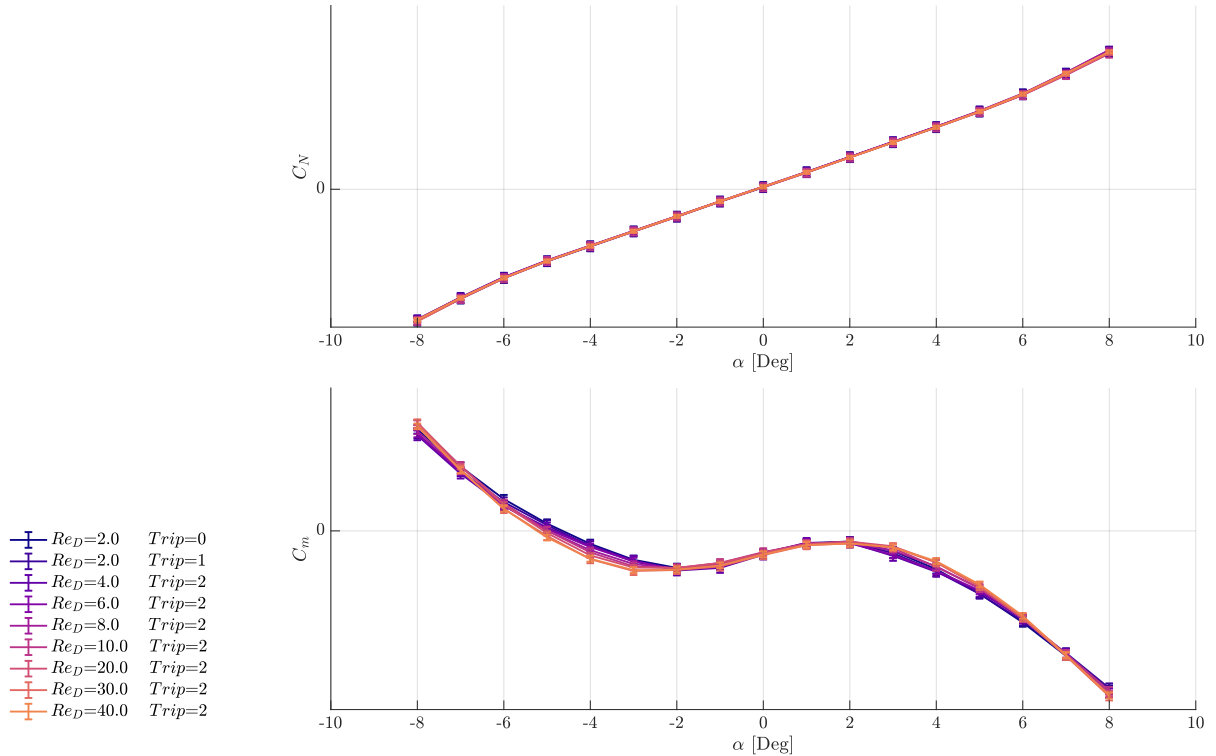


Fig. 4 Reynolds number effects for pitch sweeps at Mach 0.80.

Figure 5 shows the effect of Reynolds number and trip scheme when yawing the model at Mach 0.80. Side force coefficient shows no significant dependence on the trip scheme or Reynolds number. Yawing moment coefficient does show dependence on Reynolds number. The yawing moment coefficient curves near $\beta = 0^\circ$ are nearly the same within the uncertainty bounds for all cases presented here. The differences in magnitude are seen to increase as sideslip angle increases with the largest differences at $\beta = -8^\circ$ with the slope decreasing with increasing Reynolds number. Evaluating the trends with respect to increasing Reynolds number, it does not appear that the data have reached a Reynolds number threshold. That is, the trends here indicate that increasing Reynolds number beyond $Re_D = 40 \times 10^6$ could result in further shifts in the yawing moment coefficient profiles.

Figures 6 and 7 show the effect of Reynolds number and trip scheme when pitching and yawing the model at Mach 0.90, respectively. The effect of Reynolds number and trip scheme at Mach 0.90 are similar to the effects seen at Mach

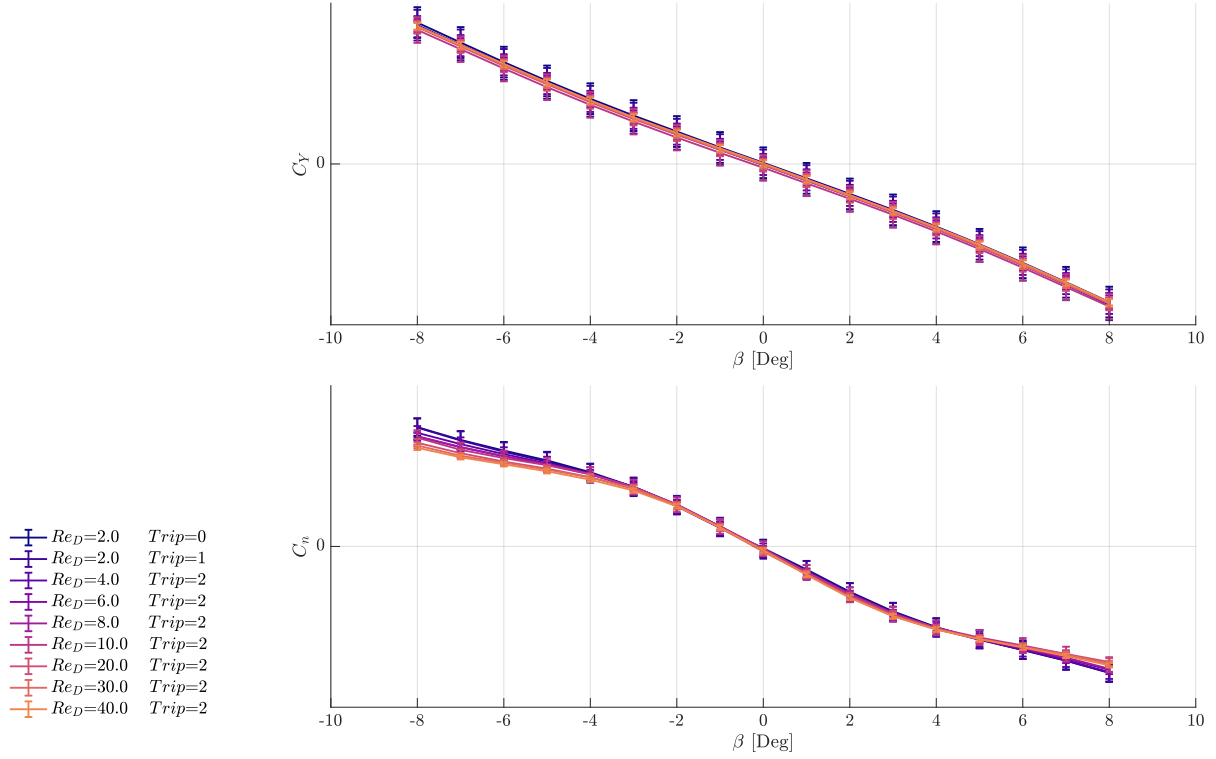


Fig. 5 Reynolds number effects for sideslip sweeps at Mach 0.80.

0.80. Normal and side force coefficients show no significant dependence on Reynolds number. Pitching and yawing moment coefficients both show dependence on Reynolds number, specifically at the larger angles of attack and sideslip angles.

Figure 8 shows the effect of Reynolds number and trip scheme when pitching the model at Mach 0.95. Similar to the lower Mach numbers investigated, normal force coefficient shows no significant dependence on the trip scheme or Reynolds number. Pitching moment coefficient does show a dependence on Reynolds number, but these effects are less significant than at lower Mach numbers. Note a slight offset in the $Re_D = 30 \times 10^6$ case at $\alpha = 0^\circ$ that shifts the curve down relative to the lower Reynolds number data. Without this offset, the $Re_D \geq 10 \times 10^6$ cases have nearly identical behavior indicating that, at least for the first derivatives, a critical Re_D threshold may have been reached. Unfortunately, the facility was not able to run beyond $Re_D = 30 \times 10^6$ at Mach 0.95 to verify this.

Figure 9 shows the effect of Reynolds number and trip scheme when yawing the model at Mach 0.95. The effects are similar to those seen at lower Mach numbers. Side force coefficient shows no significant dependence on Reynolds number. Yawing moment coefficient does show dependence on Reynolds number, specifically at the larger sideslip angles.

Figure 10 shows the effect of Reynolds number and trip scheme on axial force coefficient as a function of Mach number. For all cases tested here, the typical drag rise near Mach 1 is evident. In general, higher Reynolds number values have a lower axial force coefficient. The two $Re_D = 2 \times 10^6$ cases have the highest axial force coefficient with the trip dots ($Trip=1$) decreasing axial force coefficient slightly at the lower Mach numbers evaluated. There is then a small step between the Re_D cases at 2×10^6 and the cases at 4, 6, and 8×10^6 . Beyond $Re_D = 8 \times 10^6$, there is another decrease in axial force coefficient, with the cases at 10, 20, 30, and 40×10^6 all having similar axial force coefficient values at Mach 0.80 and 0.90. This trend starts to reverse at Mach 0.95 where the $Re_D = 10 \times 10^6$ case has the lowest axial force coefficient and increasing Reynolds number increases the axial force coefficient with the 30×10^6 case nearly returning to the 2×10^6 levels.

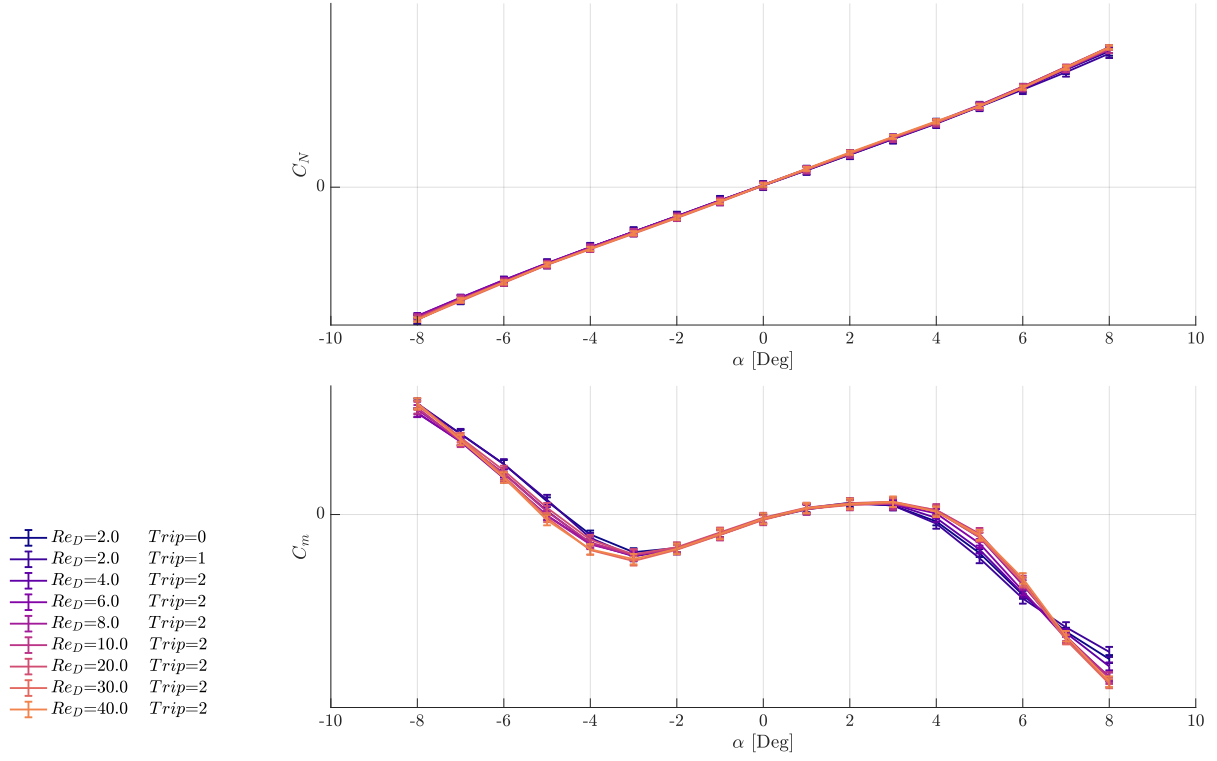


Fig. 6 Reynolds number effects for pitch sweeps at Mach 0.90.

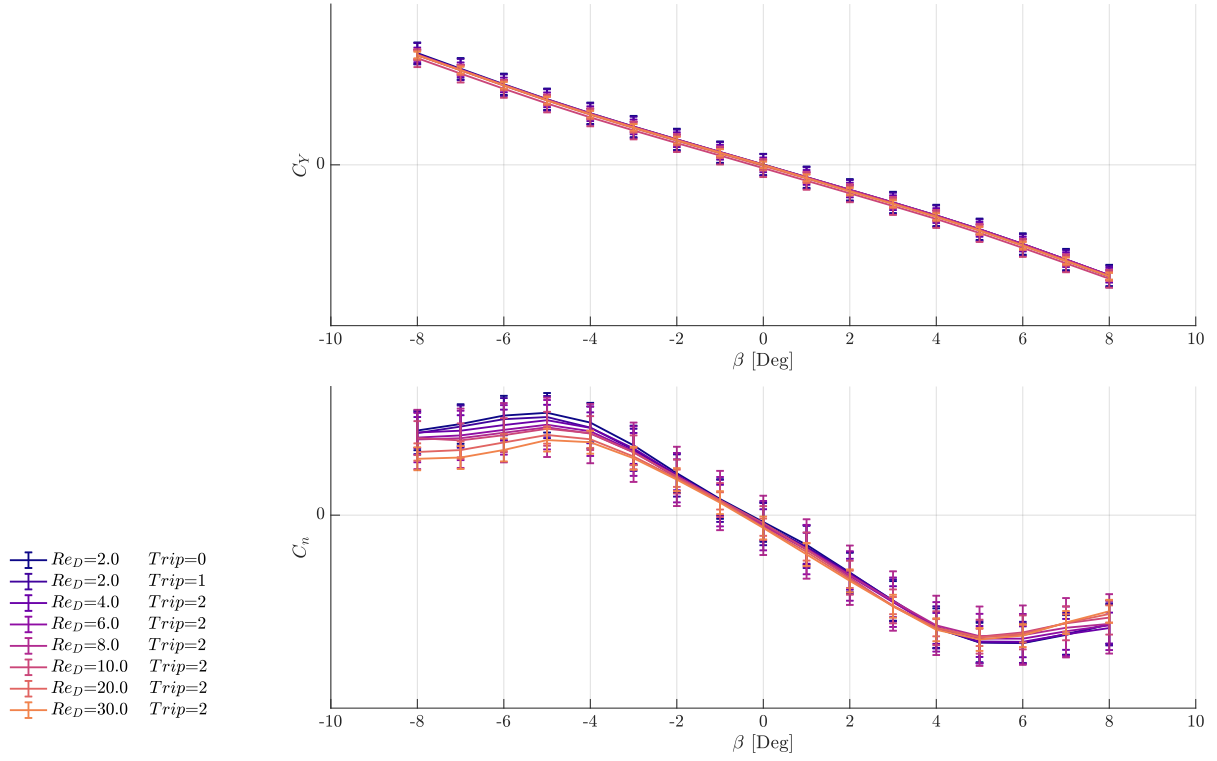


Fig. 7 Reynolds number effects for sideslip sweeps at Mach 0.90.

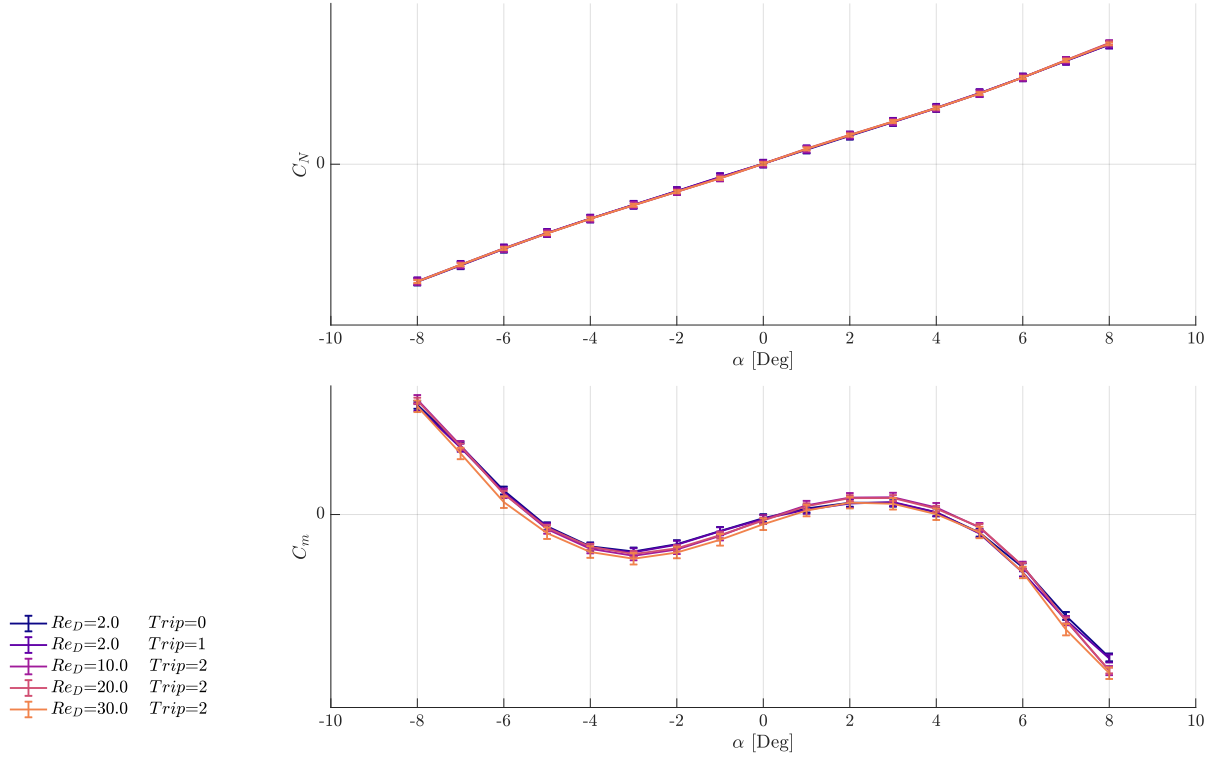


Fig. 8 Reynolds number effects for pitch sweeps at Mach 0.95.

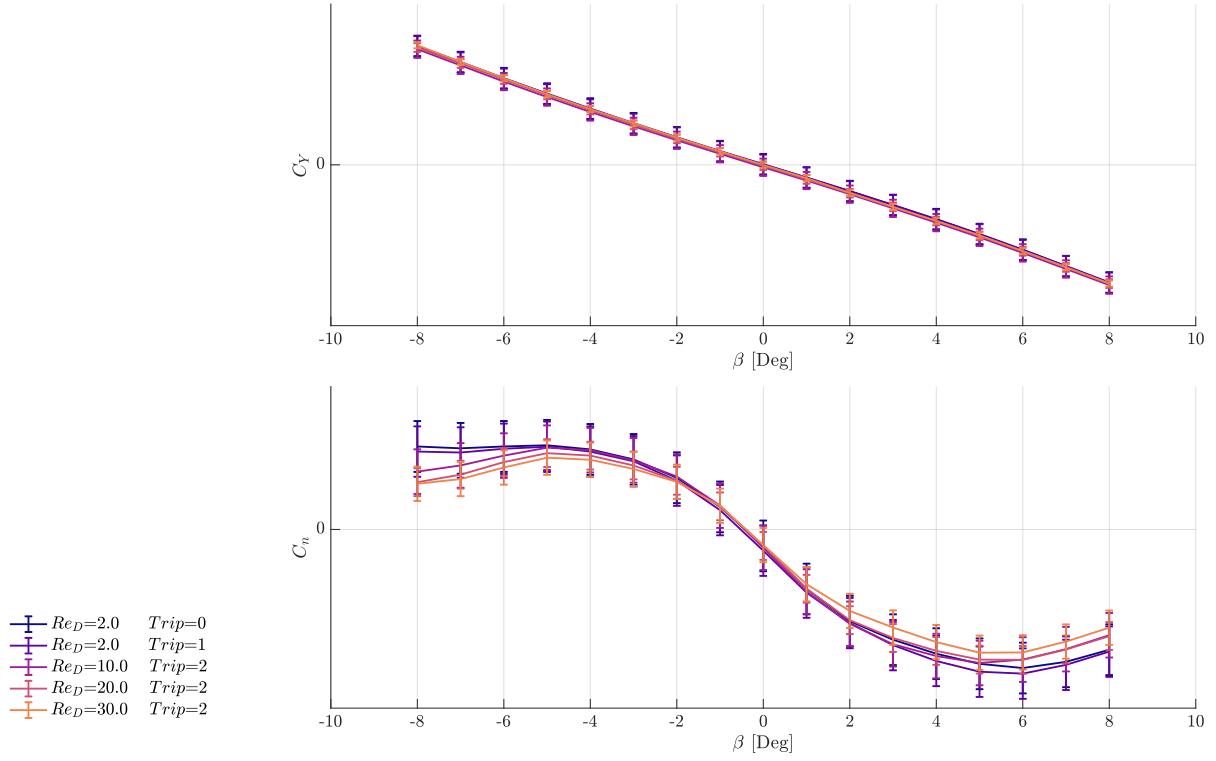


Fig. 9 Reynolds number effects for sideslip sweeps at Mach 0.95.

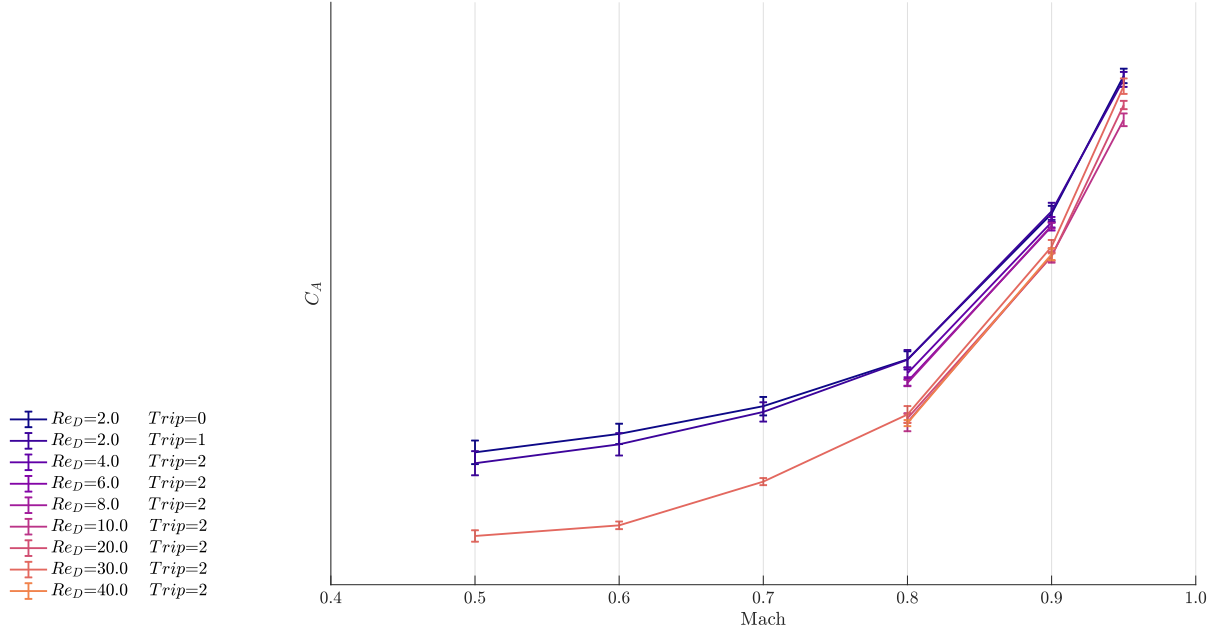


Fig. 10 Reynolds number effects for Mach sweeps at $\alpha = 0^\circ$ and $\beta = 0^\circ$.

B. Surface Pressure Coefficients

Pressure taps were distributed across the model and can be used to help gain insight into the regions of the vehicle that are contributing to the Reynolds number effects seen in the integrated force and moment data. Figure 11 shows an example of the surface pressure data acquired at Mach 0.90, $Re_D = 30 \times 10^6$, $\alpha = -4^\circ$ and $\beta = 0^\circ$ and provides an overview of how the pressure taps were distributed on the model. Each colored dot overlaid on the graphical representation of the SLS model represents a single pressure tap colored by the measured surface pressure coefficient. Some flow features, such as the low pressure region in the wake of the SRB forward attach hardware, can be identified from this type of qualitative data representation, but making detailed comparisons between different test cases can be difficult.

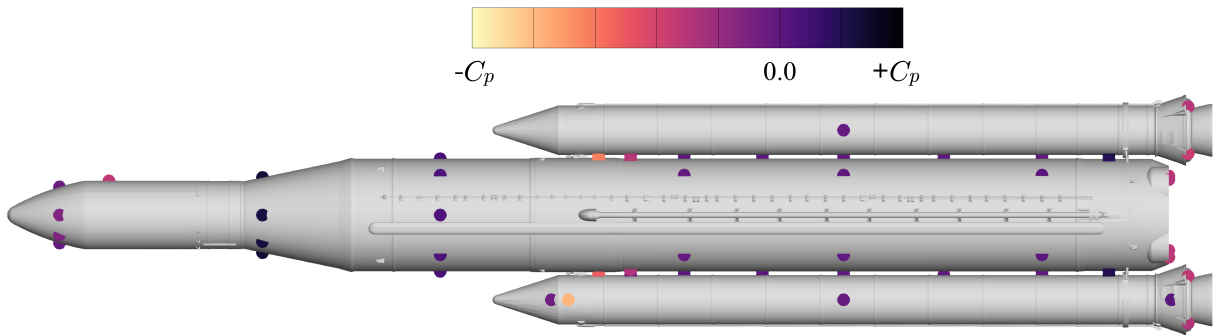


Fig. 11 Surface pressure coefficients for Mach 0.90, $Re_D = 30 \times 10^6$, $\alpha = -4^\circ$, and $\beta = 0^\circ$.

To evaluate the Reynolds number effects in a more quantified manner, a direct difference between the $Re_D = 2 \times 10^6$ ($Trip = 1$) and $Re_D = 30 \times 10^6$ pressure tap data were taken to compute the pressure coefficient differences (ΔC_p) as defined in equation 1.

$$\Delta C_p = C_{p, Re_D=30 \times 10^6} - C_{p, Re_D=2 \times 10^6} \quad (1)$$

The pressure coefficient differences for Mach 0.90, $\alpha = 0^\circ$, and $\beta = 0^\circ$ are plotted as scatter plots in Figure 12. Figure 12(a) shows the ΔC_p data for all the pressure taps plotted as a function of the vehicle X-axis (along the length of the vehicle). The largest differences can be seen just aft of the cargo fairing shoulder; just downstream of the forward attach hardware where the SRBs connect to the centerbody; and the region that contains the aft attach hardware and SRB aft skirts.

Figures 12(b) and 12(c) show ΔC_p as a function of Z-axis in the left and right booster gaps, respectively, at the forward attach hardware. Note that the dependent variable (Z/D) is on the vertical axis and the independent variable (ΔC_p) is on the horizontal axis to help orient the data to physical space. $Z/D = 0$ is along the centerline of the vehicle core stage such that the top of the vehicle corresponds to positive Z/D values and the bottom corresponds to negative Z/D values. Here, the ΔC_p data are fairly uniform, without strong top-bottom or left-right gradients. These data will be used as a baseline for comparison at pitch and sideslip angles.

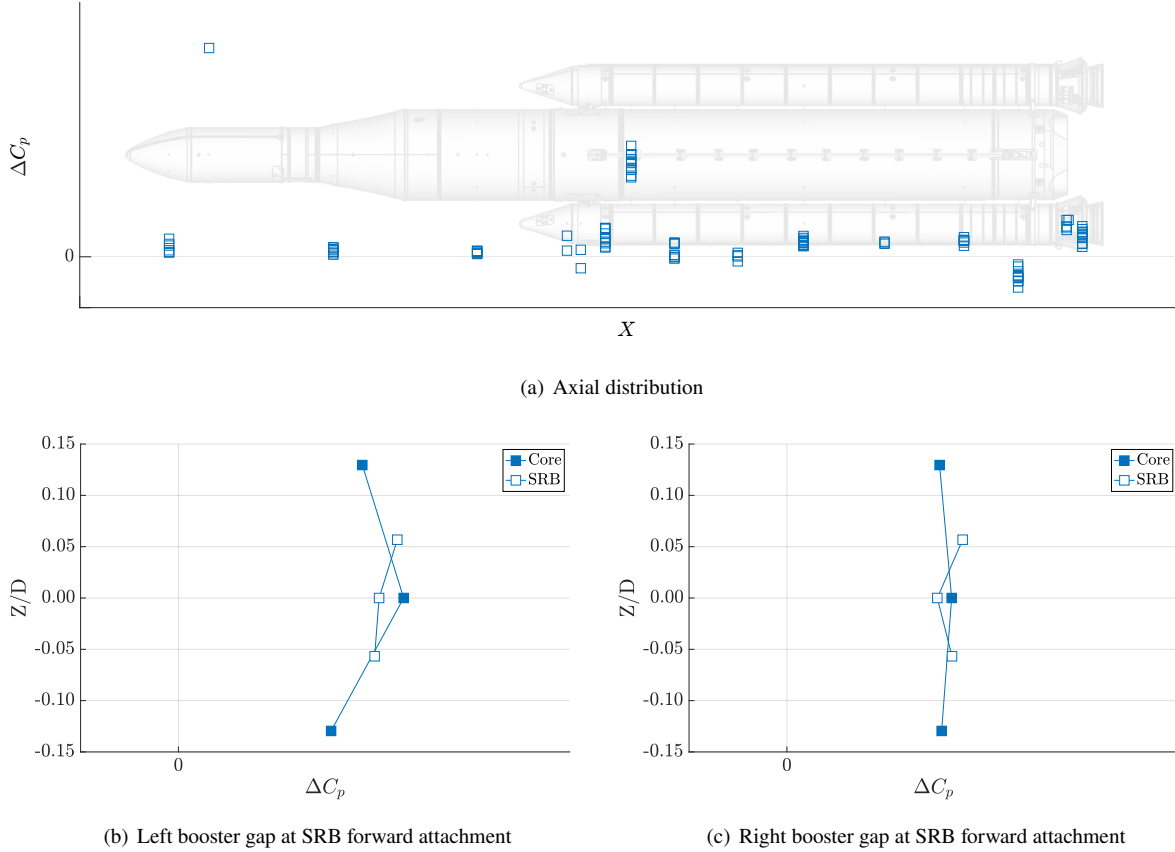
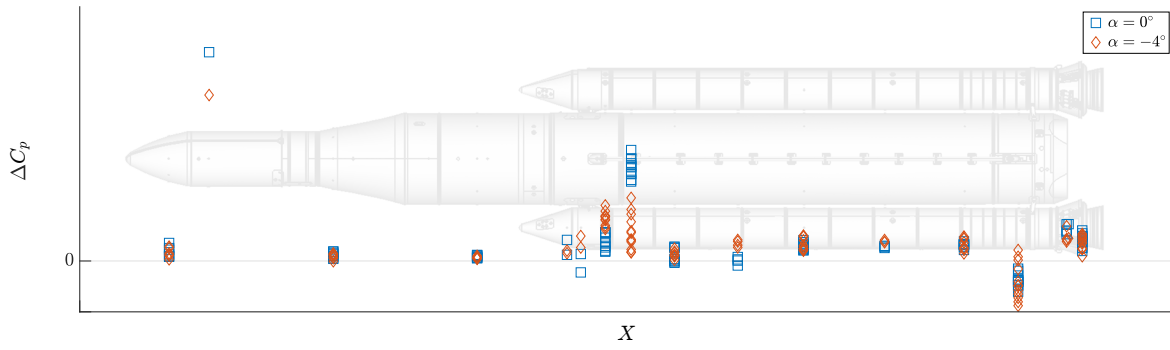


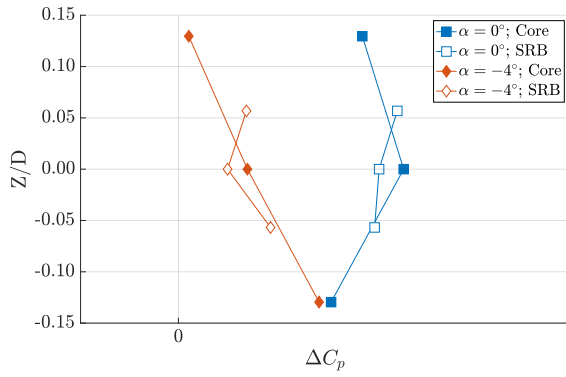
Fig. 12 Surface pressure coefficient difference between $Re_D = 2 \times 10^6$ and $Re_D = 30 \times 10^6$ at Mach 0.90, $\alpha = 0^\circ$, and $\beta = 0^\circ$.

Figure 13 shows ΔC_p for Mach 0.90 and $\beta = 0^\circ$ at angles of attack of 0° and -4° . The largest differences are again evident near the forward attach hardware, but now an asymmetry is apparent between the top and bottom of the vehicle. The scatter plots shown in Figures 13(b) and 13(c) help highlight this where the top of the model shows smaller ΔC_p values than the bottom of the model. This asymmetry likely indicates that the wake behind the forward attach hardware develops differently at different Reynolds numbers. This wake region then impacts the flow field downstream of the forward attach hardware. Because these effects are localized to the aft half of the vehicle, the resulting impact to the integrated forces and moments can be seen most clearly in pitching moment (see Figure 6).

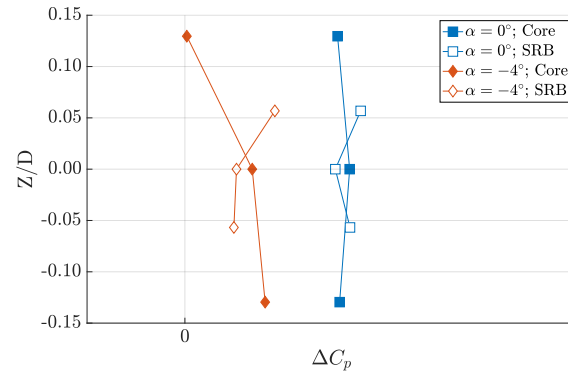
Figure 14 shows ΔC_p for Mach 0.90 and $\alpha = 0^\circ$ at sideslip angles of 0° and -7° . The largest differences are again seen near the forward attach hardware, but now an asymmetry can be seen between the left and right sides of the vehicle. The scatter plots shown in Figures 14(b) and 14(c) help highlight this where the left booster gap shows ΔC_p similar to the baseline case while the right booster gap shows smaller differences. This asymmetry likely indicates that the



(a) Axial distribution



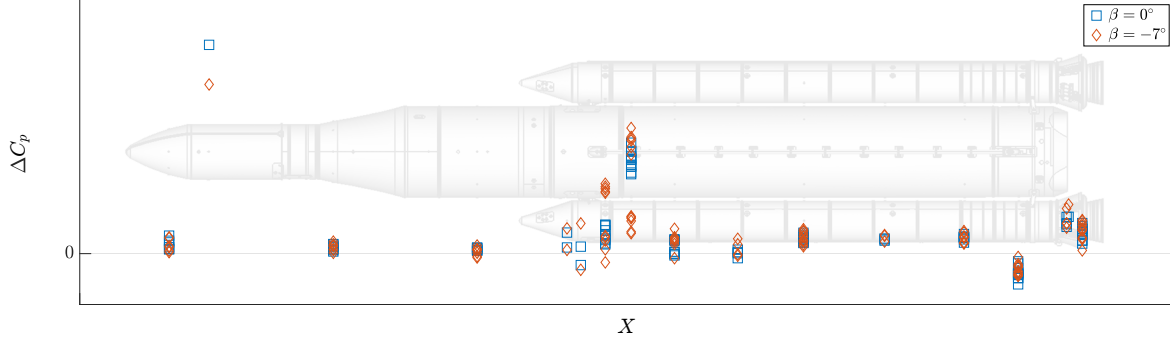
(b) Left booster gap at SRB forward attachment



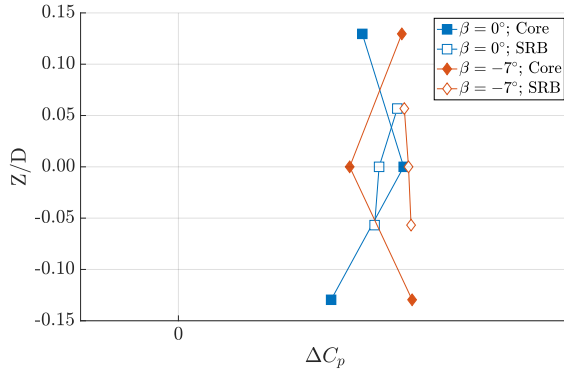
(c) Right booster gap at SRB forward attachment

Fig. 13 Surface pressure coefficient difference between $Re_D = 2 \times 10^6$ and $Re_D = 30 \times 10^6$ at Mach 0.90 and $\beta = 0^\circ$.

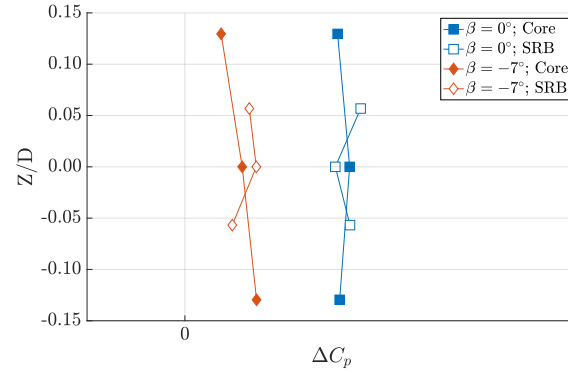
wake behind the forward attach hardware develops differently at different Reynolds numbers. This wake region then impacts the flow field downstream of the forward attach hardware. Because these effects are localized to the aft half of the vehicle, the resulting impact to the integrated forces and moments can be seen most clearly in yawing moment (see Figure 7).



(a) Axial distribution



(b) Left booster gap at SRB Forward Attachment



(c) Right booster gap at SRB forward attachment

Fig. 14 Surface pressure coefficient difference between $Re_D = 2 \times 10^6$ and $Re_D = 30 \times 10^6$ at Mach 0.90 and $\alpha = 0^\circ$.

VI. Summary and Conclusions

A high Reynolds number test of the SLS Block 1 Cargo vehicle was performed at the NASA Langley NTF. Using the transonic, cryogenic testing capabilities of the NTF, data were acquired at Mach numbers ranging from 0.50 to 0.95 at diameter based Reynolds numbers of 2×10^6 to 40×10^6 . The highest Reynolds numbers evaluated were approximately 45% of the the flight Reynolds number for the full-scale vehicle. These data have provided insight into the effect of Reynolds number on the SLS family of launch vehicles, and will provide a database to be used to further validate CFD simulations at flight conditions.

The results from the force and moment measurements showed that normal and side force coefficients did not have significant dependence on Reynolds number for the Mach numbers tested. Pitching and yawing moment coefficients did show significant dependence on Reynolds number effects over the full range of Mach numbers investigated, with the largest effects seen at larger (both positive and negative) angles of attack and sideslip. The trends seen in both the pitching and yawing moment coefficients indicated that a Reynolds number effect threshold may not have been reached, and increasing Reynolds number beyond the NTF testing limit of $Re_D = 40 \times 10^6$ could result in larger Reynolds number effects. Although not investigated in the current paper, the Reynolds number effects seen in pitching and yawing moment coefficients have the ability to impact both the performance of the vehicle as well as the development of the flight control systems that use these data as an input.

Axial force coefficient also showed significant dependence on Reynolds number. In general, the axial force coefficient was lowest at higher Reynolds numbers with a threshold appearing to be reached above $Re_D = 10 \times 10^6$ for Mach 0.50 to 0.90 such that axial force coefficient was nearly the same for all cases at $Re_D \geq 10 \times 10^6$. At Mach 0.95, this trend started to reverse at the highest Reynolds numbers with the largest values of axial force coefficient at $Re_D = 2 \times 10^6$ and 30×10^6 and the lowest values of axial force coefficient at $Re_D = 10 \times 10^6$. Axial force will impact the performance of the vehicle during ascent, and a reduction in axial force could result in increased performance and the ability to launch larger payloads.

Surface pressure measurements were used to help identify the regions on the vehicle that were potentially contributing to the Reynolds number effects seen in the integrated forces and moments. One of the most sensitive regions on the vehicle was seen near the SRB forward attach hardware where separated flow develops downstream of the attachment hardware. As the attach hardware is near the center of the vehicle, changes in how the flow develops in the forward attach region will affect how the flow develops along the aft portion of the vehicle. These differences on the aft portion of the vehicle are likely the reason that pitching and yawing moment coefficients saw the largest Reynolds number effects.

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