

Parametric Study of the Forward Attachment Geometry for the Space Launch System Next Generation Booster

James M. Ramey^{*}, Ian Giles[†], Oleg Goushcha[‡], Patrick S. Heaney[§], David J. Piatak[¶],
Martin K. Sekula^{||} and Francesco Soranna^{**}

NASA Langley Research Center, Hampton, VA 23681

Launch vehicle transonic buffet environments can generate large dynamic structural loads and vibratory responses. For the Space Launch System (SLS) vehicle, the highest transonic buffet environments have been observed in the multibody region between the core and solid rocket boosters, particularly downstream of the booster forward attachment. The buffet environment is particularly sensitive to the outer mold line (OML) of the forward attachment, and even relatively minor geometry changes can have large impacts on buffet and other aerodynamic environments. The SLS program is redesigning the booster for the Block 2 vehicle to support updated mission goals and hardware requirements. This redesign necessitated changes in the forward attachment geometry, which raised concerns about the buffet and vibroacoustic environments. A preliminary study was conducted that developed multiple forward attachment geometries that satisfied the programmatic requirements, but the aerodynamic environment impacts were unclear. In March 2022, a wind-tunnel test was conducted at the NASA Ames 11- by 11-foot Transonic Wind Tunnel to study these environments generated from each of the configurations in order to select the most viable candidate. This paper will discuss this test campaign, the results from the parametric study, as well as general observations regarding OML features that impact the buffet environment. Buffet environments will be presented and compared for each configuration and comparisons presented where applicable.

Notice to Readers

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

ARC	=	Ames Research Center
ATAT	=	Ascent Transient Aerodynamics Test
BFASTST	=	BOLE Forward Attachment Trade Study Test
BFF	=	buffet forcing function
BOLE	=	Booster Obsolescence and Life Extension
CLA	=	combined loads analysis
DDS	=	dynamic data system

^{*}Research Aerospace Engineer, Aeroelasticity Branch, AIAA Member

[†]Research Aerospace Engineer, Aeroelasticity Branch, AIAA Member

[‡]Research Aerospace Engineer, Aeroelasticity Branch, AIAA Member

[§]Research Aerospace Engineer, Aeroelasticity Branch, AIAA Member

[¶]Assistant Branch Head, Aeroelasticity Branch, AIAA Senior Member

^{||}Senior Research Aerospace Engineer, Aeroelasticity Branch

^{**}Research Aerospace Engineer, Aeroelasticity Branch, AIAA Member

LaRC	=	Langley Research Center
LSRB	=	left solid rocket booster
OML	=	outer mold line
PT	=	pressure transducers
RBM	=	rigid buffet model
RSRB	=	right solid rocket booster
SLS	=	Space Launch System
SRB	=	solid rocket booster
UPWT	=	Unitary Plan Wind Tunnel
TDT	=	Transonic Dynamics Tunnel
α	=	angle of attack
β	=	slideslip angle
θ	=	azimuthal clocking angle
M_∞	=	freestream Mach number
F	=	force
$\Delta f_{xyz,rms}$	=	sectional centerline buffet forcing functions in the x,y,z directions (mean removed), root-mean-square

II. Introduction

Launch vehicle buffet environments consist of unsteady aerodynamics dominated by fluctuating pressures. Transonic buffet occurs as a launch vehicle passes through the transonic regime, from Mach numbers 0.8 to 1.2, where unsteady phenomena such as shock oscillations, boundary layer separation, turbulence, and vortex shedding are prominent flow features. The unsteady aerodynamic forces produced by these phenomena can excite both global and local vehicle structural responses [1–3].

It has been shown that the buffet environment in the multibody booster-to-core region is particularly sensitive to outer mold line (OML) changes of the booster-to-core forward attachment, and even relatively minor geometry changes can have large impacts on buffet loads [4]. Due to the unsteady and complex flowfield, wind-tunnel testing has been the most successful method of characterizing the buffet environment [5]. During these wind-tunnel tests, discrete fluctuating pressures are measured by unsteady pressure transducers distributed across the model (often hundreds of them). Buffet forcing functions (BFFs) are then computed by integrating the measured pressures along the surface of the model to develop a series of centerline orthogonal loads that correspond to rings of transducers at numerous longitudinal stations on the model. A coupled loads analysis is then conducted that includes applying the BFFs to a finite element model to identify peak loads (moments/shears) and vibratory responses of the vehicle.

Figure 1 provides an overview of the vehicle configurations of the Space Launch System (SLS) program. Starting with the Block 2 (B2) configuration, the current boosters will have been expended on previous flights and are to be replaced with an updated design. To this end, the Booster Obsolescence and Life Extension (BOLE) program is being conducted by Northrop Grumman Space Systems. The BOLE program is redesigning the SLS boosters to support the updated SLS architecture and mission goals for exploration beyond low earth orbit [6]. Amongst the various booster changes necessary to satisfy the mission goals, the forward attachment geometry was modified to accommodate a greater overall booster thrust and to allow for a larger and more operations-friendly design. However, past wind tunnel studies have noted that the unsteady flow environment is highly sensitive to the forward attachment geometry, where seemingly minor changes to the OML can result in large changes in the unsteady flow field. These observations raise buffet and vibroacoustic concerns for the updated booster design.

Several forward attachment redesigns were proposed with guidance from the SLS Aerodynamics team, but without wind-tunnel data, the final selection could not be made without large uncertainties. Therefore, a wind-tunnel test at the NASA Langley Transonic Dynamics Tunnel (TDT) was scheduled. The TDT was selected to conduct this test not only due to unique scaling and testing capabilities [7], but also a history of successful SLS buffet testing at the facility [5, 8, 9]. However, due to COVID- and tunnel maintenance-related test delays, and the approach of BOLE programmatic milestones, a decision was made to perform a more limited BOLE forward attachment buffet trade study test at another facility to aid in the downselect of this design.

This new test program, called the BOLE Forward Attachment Structure Trade Study Test (BFASTST), was conducted at the NASA Ames Research Center (ARC) Unitary Plan Wind Tunnels (UPWT) 11- by 11-foot Transonic Wind Tunnel (11-Ft TWT) and utilized components of an existing SLS wind-tunnel model [10]. Because of hardware and time constraints, delivery of full-stack buffet forcing functions was not the primary focus; rather, the local fluctuating unsteady

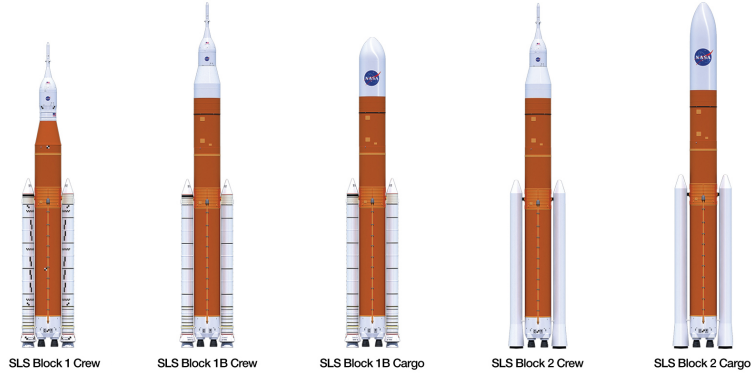


Fig. 1 SLS vehicle configurations.

pressure environments themselves would be the focus. The primary objective of BFASTST was to perform a parametric study of several options for the BOLE booster forward attachment OML geometry for the B2 Cargo SLS configuration to aid in the down-selection of an aerodynamically-viable forward attachment geometry. A viable configuration would result in buffet environments unchanged (or reduced) relative to the B1 and B1B environments.

This paper will examine all configurations tested to assess the unsteady pressure environments for each forward attachment geometry to provide guidance for the BOLE design. Design recommendations and observations of the unsteady aerodynamic buffet environment are provided for all the tested geometries.

III. Model Description

The BFASTST test article was a 2.5%-scale full-stack representation of the B2 Cargo vehicle, designated SLS-11006. As stated in the introduction, the model utilized both existing and new hardware. The existing hardware consisted of two components: the core stage and the cargo payload fairing. The core stage was based on the SLS OML established in July 2012, with updates in 2016 and 2019 for protuberance changes. The cargo payload fairing was based on the SLS OML established in March 2019 with a 60-40 ogive payload fairing and all protuberance details larger than two inches full-scale represented. The new hardware fabricated for the BFASTST test consisted of the BOLE boosters and interchangeable forward attachment hardware (detailed in Sec. III.A). The boosters were based on preliminary designs delivered by Northrop Grumman, which were updated close to the test to reflect the latest protuberance and configuration changes.

The coordinate system for this vehicle is provided in Figure 2 and is used throughout this study. The figure depicts the model looking along the longitudinal axis from the nose toward the engines of the vehicle, identifies the core and boosters, and illustrates the azimuthal clocking of the model for locating model features and pressure sensor locations.

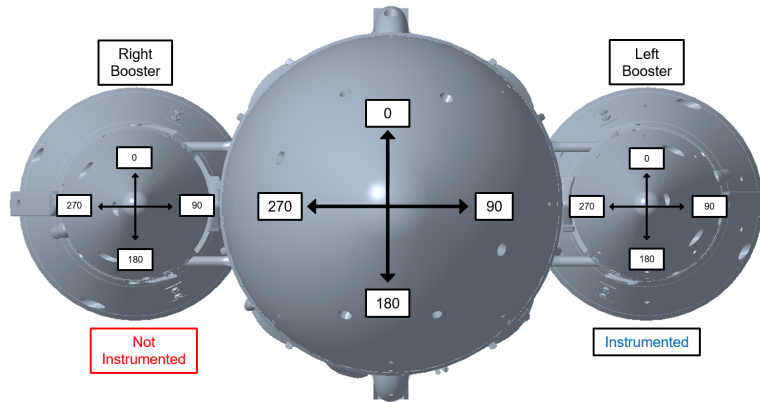


Fig. 2 BFASTST model azimuthal clocking angles.

A. Forward attachment geometry

The forward attachment geometries were based on designs delivered in March 2021, and updated based on an October 2021 delivery, after a trade study (and feedback from NASA) conducted by Northrop Grumman from June 2020 through March 2021. Figure 3 shows commonly used terms when referencing components of the geometry. There were seven configurations, which are presented in Fig. 4. Of the configurations, four represented candidate design options of the forward attachment geometry provided by Northrop Grumman for direct assessment (collectively referred to as *Candidate* for the remainder of the paper), one reference configuration based on the current SLS forward attachment geometry, and two test-specific, research configurations designed to study the impact of specific OML features (referred to as *Research* for the remainder of the paper):

- 1) Candidate configurations
 - 1) **Baseline**: Original March 2020 concept.
 - 2) **Two-Sided**: March 2021 concept based on a previously designed umbilical but modified to have a rectangular crossover with four connectors.
 - 3) **One-Sided**: March 2021 concept based on a previously designed umbilical.
 - 4) **Heritage**: March 2021 concept based on current SLS geometry, with modifications to clear the thrust-post and allow for new crossover feed-through.
- 2) Reference configuration
 - 1) **Legacy**: Current SLS forward attachment geometry. Designed to isolate booster OML impacts and establish an appropriate comparison case.
- 3) Research configurations
 - 1) **Thrust-Post-Only**: Modified Baseline configuration, removing the forward crossover wings.
 - 2) **Fwd-Crossover-Only**: Modified Baseline configuration, removing the thrust-post structure.

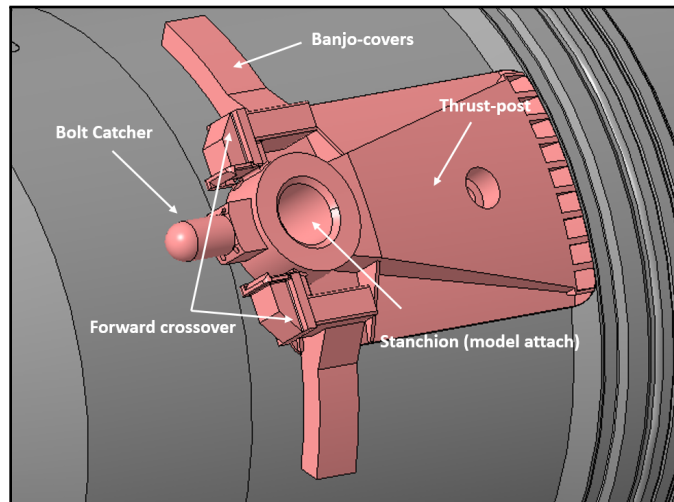
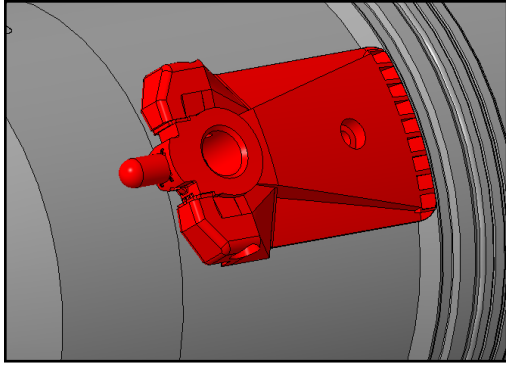
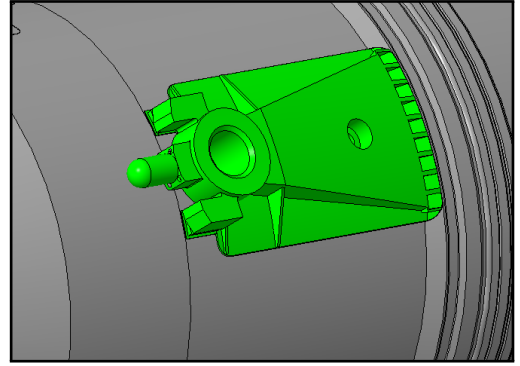


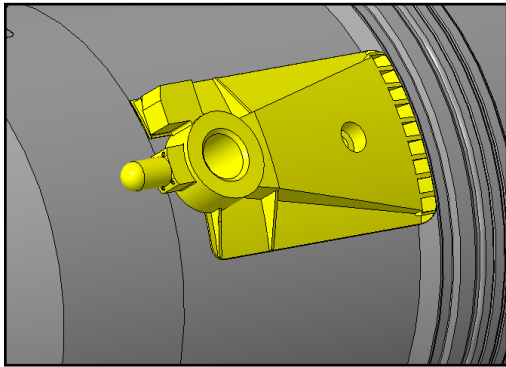
Fig. 3 Commonly used terms for the forward attachment geometry.



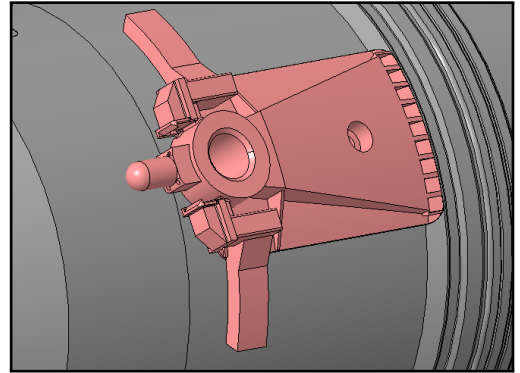
(a) Baseline (Candidate).



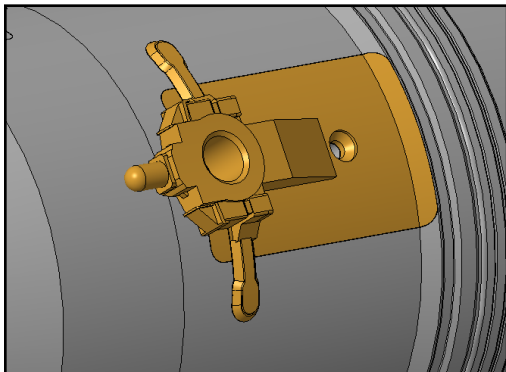
(b) Two-Sided (Candidate).



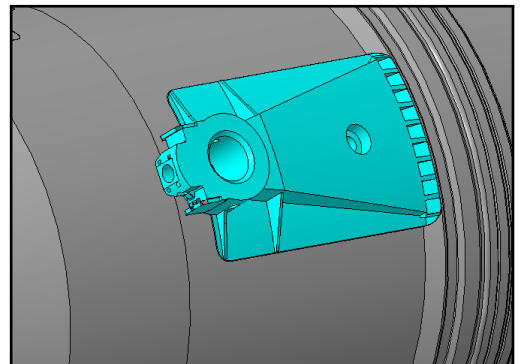
(c) One-Sided (Candidate).



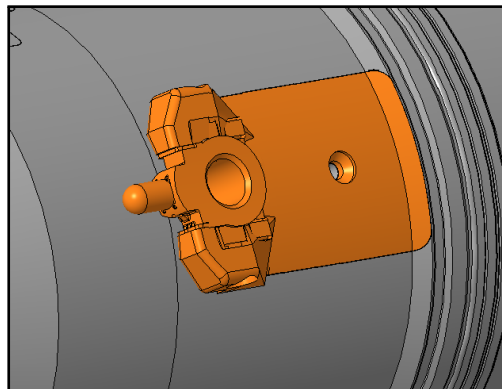
(d) Heritage (Candidate).



(e) Legacy.



(f) Thrust-Post-Only (Research).



(g) Fwd-Crossover-Only (Research).

Fig. 4 Forward attachment configurations tested during BFASTST.

B. Instrumentation

The model was populated with Kulite[®] unsteady pressure transducers (PTs) to acquire aeroacoustic and buffet data. A total of 161 sensors were installed in holders integrated into the model skins and individually contoured to the model surface. The holders were based on a Kulite[®] B-screen design that consisted of ten 0.008 in. diameter holes equally spaced in a 0.048 in. diameter circular pattern. Factory calibrations of the PTs were used for the test. Due to the age of the sensors (as they were recovered from previous test campaigns of this model), sensor health checks were regularly performed. The wind tunnel circuit pressure was reduced to six known pressures where data were taken. A check calibration curve was generated for each sensor, where faulty transducers were flagged. In addition, throughout the test, each sensor was spot checked for inconsistent characteristics. The data used for this report were reanalyzed to identify and remove faulty sensors.

Eighty-seven sensors were installed in the core and an additional seventy-four sensors were installed in the left solid rocket booster (LSRB). This distribution can be seen in the unwrapped view in Fig. 5, where θ represents the azimuthal clocking-angle. Due to previously established conventions, the station numbers start at 20. However, most core and LSRB stations are not coincident, both having independent model- and full-scale x -coordinates. Only stations 23, 24, and 25 for the core and LSRB share the same longitudinal location.

To characterize the peak unsteady pressure and aeroacoustic environments, many sensors were located on the core and LSRB around the forward attachment in locations identified by computational fluid dynamics (CFD) and previous tests as key locations to observe the vortices shed by the forward attachment hardware. The LSRB contains a tightly-spaced sensor array directly downstream of the forward attachment to capture the changes in the environments with respect to M_∞ , α , and β . To estimate buffet forces, azimuthally-distributed rings of pressure sensors were located longitudinally along both bodies. The sensor rings allowed for the calculation of integrated centerline sectional forces and future evaluation by the coupled loads analysis team. For comparison purposes, the sensor rings were located to match previous tests, and were labeled as presented in Fig. 6. The core stations are demarcated in blue while the LSRB stations are in red.

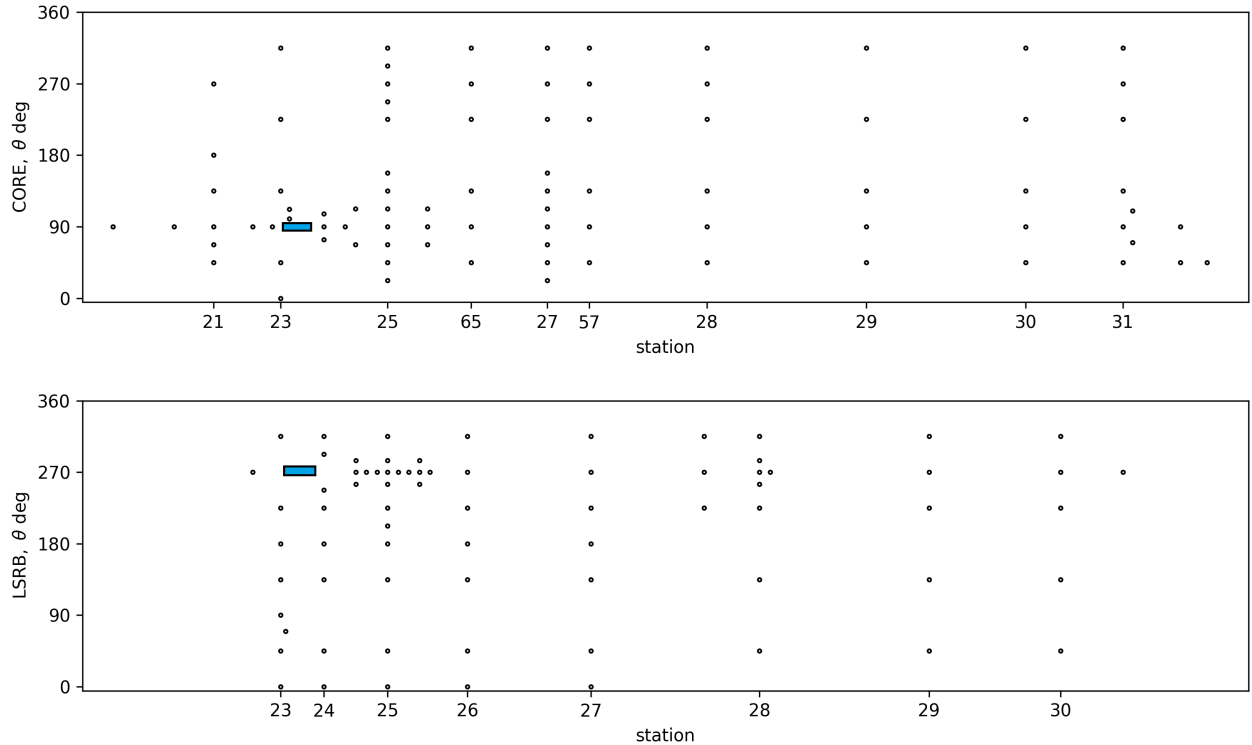


Fig. 5 Unwrapped view of the instrumentation on the core and LSRB. Forward attachment location with respect to each body represented by blue rectangles.

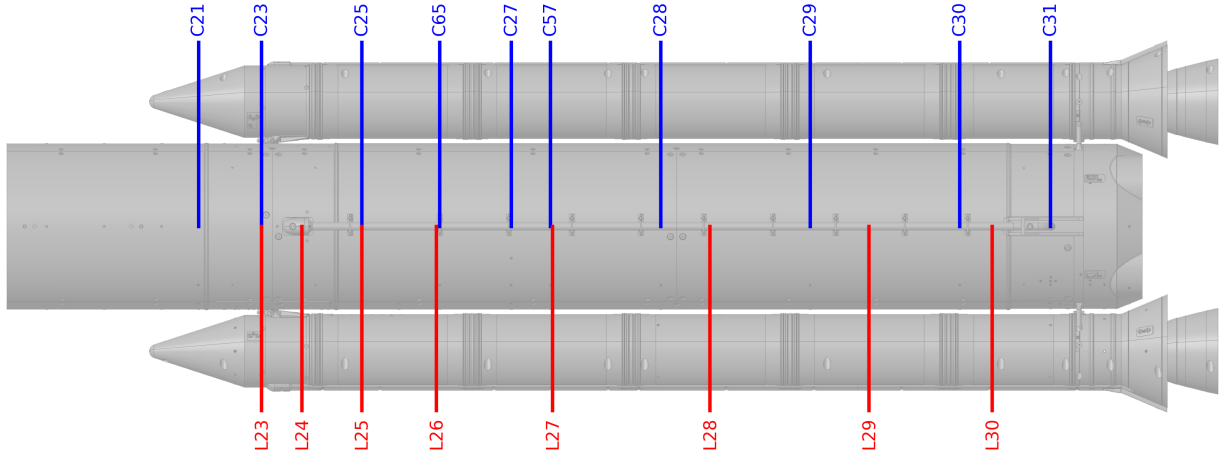
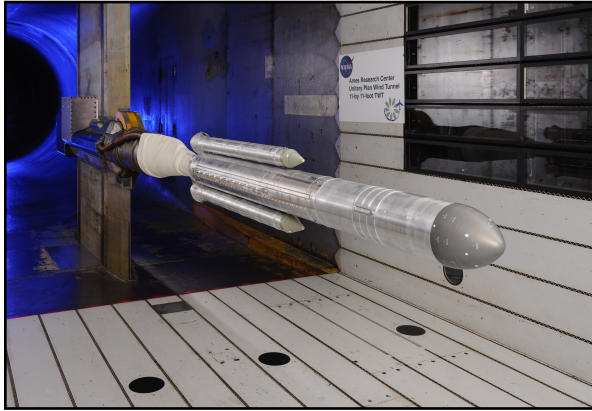


Fig. 6 BFASTST buffet sensor rings.

IV. Data Sources

This report references data from BFASTST and the Ascent Transient Aerodynamics Test (ATAT). Both tests were conducted in the ARC UPWT 11-Ft TWT [11]. The 11-Ft TWT is a closed-return variable-density wind tunnel with a test section that is 11-by-11 feet in cross section. The facility operates at a Mach range of 0.20 - 1.40, and unit Reynolds Numbers up to 9.6 million per foot. Test photos for each of these models are shown in Fig. 7. Both tests used the facility-owned dynamic data system (DDS) to acquire dynamic data at 10 kHz to resolve buffet frequencies with a 15 sec duration to allow enough time for the measurements to statistically converge. A brief description of each test campaign will be provided in this section.



(a) SLS Block 1B Cargo 2.5%-scale RBM tested during the ARC UPWT BFASTST. [Photo: NASA]



(b) SLS Block 1B Cargo 2.5%-scale RBM tested during the ARC UPWT ATAT. [Photo: NASA]

Fig. 7 SLS Rigid Buffet Models analyzed in this study.

A. BOLE Forward Attachment Trade Study Test

The BFASTST test was conducted from March 7th through March 16th, 2022 with wind-on testing beginning on March 10th. Each forward attachment configuration was tested at the same test conditions: a Mach sweep and a series of sideslip angle, β , sweeps at various angles of attack, α , for selected Mach numbers. Unit Reynolds number was maintained at $Re = 3 \times 10^6/\text{ft}$ throughout the testing. The Mach number sweep included 55 points at $\alpha = \beta = 0^\circ$ for variable increments in Mach depending on the region. The Mach sweep is provided graphically in Fig. 8, and the α vs.

β combinations are graphically represented in Fig. 9. The testing of each model configuration included approximately 115 runs with more than 800 data points total. Overall, 966 runs were performed consisting of nearly 5,000 data points, with the representative test matrix and attitude schedules for each configuration shown in Fig. 10.

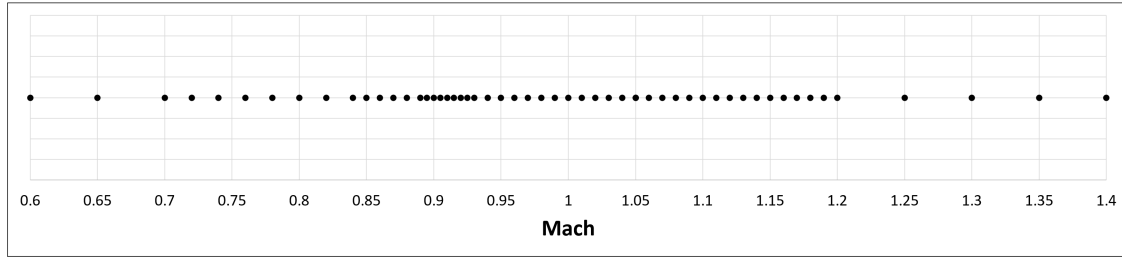


Fig. 8 BFASTST Mach sweep.

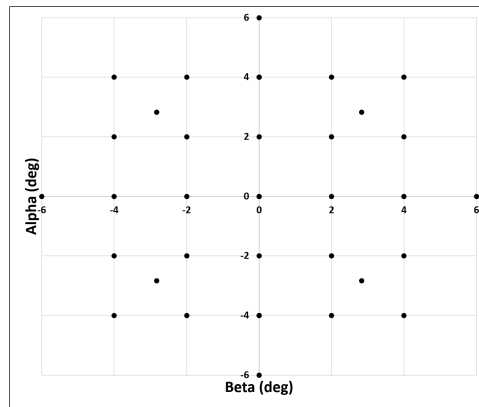


Fig. 9 BFASTST α vs. β .

Config ID	Attitude Schedule			Ref/ft x 10 ⁶	Type																
	α , deg	β , deg	Φ , deg			0.60	0.70	0.80	0.85	0.87	0.88	0.89	0.90	0.91	0.92	0.94	0.95	1.05	1.10	1.20	1.40
SLS-11006, Baseline	0	0	-90	3.0	sweep																
	0	A1	-90	3.0	polar																
	-4	A2	-90	3.0	polar																
	4	A2	-90	3.0	polar																
	-2	A3	-90	3.0	polar																
	2	A3	-90	3.0	polar																
	-2.83	A4	-90	3.0	polar																
	2.83	A4	-90	3.0	polar																
	6	A5	-90	3.0	polar																
	-6	A5	-90	3.0	polar																

(a) Test matrix.

Attitude Schedules	No.	Positions, deg
A1	9	0, -6, -4, -2, 0, 2, 4, 6, 0
A2	7	0, -4, -2, 0, 2, 4, 0
A3	5	-4, -2, 0, 2, 4
A4	2	-2.83, 2.83
A5	1	0
A6	19	0, -6, -5.5, -5, -4.75, -4.5, -4.25, -4, -2, 0, 2, 4, 4.25, 4.5, 4.75, 5, 5.5, 6, 0
B1	10	-5.5, -5, -4.75, -4.5, -4.25, 4.25, 4.5, 4.75, 5, 5.5

(b) Attitude schedule.

Fig. 10 BFASTST test matrix and attitude schedule.

B. Ascent Transient Aerodynamics Test

ATAT was conducted in September 2019 to determine the acoustic and buffet environments on the Block 1B Cargo SLS vehicle (in addition to other configurations). As mentioned in Sec. III, BFASTST and ATAT utilized many of the same test parameters, including the test article (with the exception of the boosters), pressure sensors, mount hardware, and facility. By design, the two tests included similar test conditions and model attitudes. The main differences between the two tests are as follows:

- 1) **Forward attachment geometry:** The Legacy forward attachment was the common forward attachment configuration tested during both ATAT and BFASTST. A comparison of the model-scale attachment geometries for these two tests is provided in Fig. 11. Despite the OMLs for these model components being based on the same vehicle CAD file, the geometries include some differences due to limitations of model manufacturing methods employed and required accommodations for a stanchion, the model component passing through the forward attachment insert that physically attaches the boosters to the core. The BFASTST model included a smaller, redesigned stanchion and forward attachments were made of laser-sintered inconel pieces, with tolerances of ± 0.005 in. The ATAT model employed a larger stanchion and the forward attachment was made of 3-D printed PLA material. The combination of a larger stanchion and manufacturing method resulted in the crossover of the ATAT attachment to be 5% wider (0.027 in.) than the BFASTST component and included a larger forward-facing area at the base of the bolt catcher. These model OML discrepancies probably contributed to the differences in the measured fluctuating pressures between the two tests. Furthermore, the ATAT components included small increases in the bolt catcher diameter and slightly longer thrust post - geometric differences that are probably of lesser impact on the measured buffet environment.

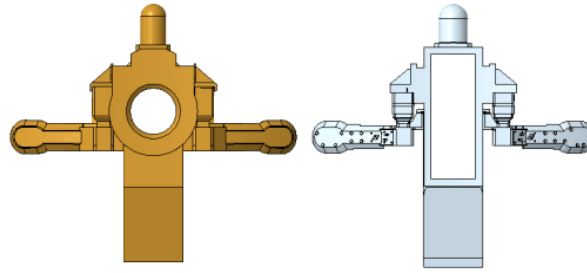


Fig. 11 BFASTST Legacy (left) vs. ATAT (right) forward attachment geometries.

- 2) **Booster geometry:** The OML of the BOLE booster has changed compared to the Block 1B geometry, most notably being an approximate 1.5-inch increase in full-scale diameter than the current booster and more pronounced field joints. These differences can be seen in Fig. 12, which presents a cross sectional comparison of the ATAT and BFASTST boosters. The blue area represents the wall of the ATAT booster model, while the grey represents the BFASTST geometry. The field joint differences can clearly be seen, with the ATAT being significantly smaller than the BFATST design. The BFASTST model also has ramps that lead up to the field joints, seen in the picture. These features would be expected to lead to differences in the fluctuating pressure magnitudes when BFASTST Legacy results are compared to those from the ATAT test.

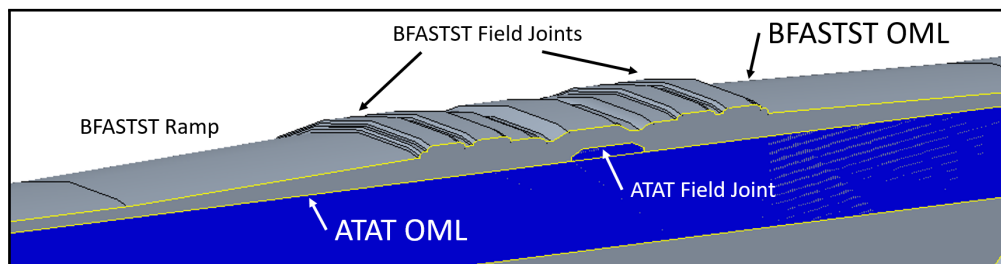


Fig. 12 OML differences between BFASTST booster (gray) and ATAT booster (blue).

- 3) **Sensor distribution:** The sensor distribution on the booster is denser on the BFASTST test relative to the ATAT test. For a direct comparison between the two tests, this report will only consider common sensors for assessment of differences between ATAT and BFASTST.

V. Analysis Methodology

Several analysis and data visualization approaches have been employed to assess the unsteady aerodynamic environment influenced by the forward attachment utilizing the time-correlated pressure time histories measured by each pressure transducer. The model-scale unsteady pressure data have been scaled to full-scale using rigid buffet scaling laws and the vehicle trajectory conditions. The following sections contain descriptions of the analyses performed on the data.

A. Fluctuating pressure environment analysis

Trends in the fluctuating component of the pressure coefficient, $\Delta C_{p,rms}$, are examined for the BFASTST configurations. For succinctness throughout this document, root-mean-square (rms) will imply that the mean of the signal is removed, i.e., it represents the standard deviation. The rms is a measure of the unsteadiness associated with the buffet environment. Due to the complexities in assessing spectral content on measured buffet environments, the comparative frequency content of fluctuating pressures between configurations is not considered in this work. There are two assessment methods employed:

- 1) **Maximum global vehicle $\Delta C_{p,rms}$:** This metric identifies the sensor with the highest value of $\Delta C_{p,rms}$ over the entire vehicle for each configuration and plots that value over the tested Mach number range at $\alpha = \beta = 0^\circ$. This analysis will give an overall assessment at the highest fluctuating environment and allow for a direct comparison between all of the configurations.
- 2) **Contour plots of $\Delta C_{p,rms}$:** This approach plots $\Delta C_{p,rms}$ corresponding to the sensor with the highest value of $\Delta C_{p,rms}$ over the core or the LSRB for each configuration as a function of Mach number and either α or β . This analysis shows the trends of peak $\Delta C_{p,rms}$ over the Mach number and attitude space, and provides insight into how the peak buffet environment changes for each configurations.

B. Fluctuating buffet force analysis

The buffet environment associated with each BFASTST forward attachment configuration can be assessed by calculating the centerline sectional buffet forcing functions (BFFs) that are computed by azimuthally integrating a ring of unsteady pressure time-histories and assuming a unity longitudinal integration length. The rms values of sectional BFFs in the lateral (y) and vertical (z) directions ($\Delta f_{y,rms}$ and $\Delta f_{z,rms}$) will be presented to compare the longitudinal distribution of these forces and to identify locations and magnitudes of peak loads.

These sectional BFFs were developed using the *Unified Buffet Methodology* analysis software developed at NASA LaRC to support BFF development. For more detail on this software and the development methods, see Ref.[12]. The sectional BFFs were developed for all sensor rings as shown in Fig. 6.

VI. Results and Discussion

This section is divided into two subsections. The first compares the Legacy configuration to previous results obtained during the ATAT test. Comparisons of the BFASTST Legacy configuration to previous test results will isolate the impacts of the new BOLE Block 2 booster geometry from the impacts of each BFASTST forward attachment configuration. These comparisons will help anchor the BOLE measurements to B1/B1B environments in order to assess if BFASTST Block 2 configurations results in reduced or increased buffet environments, from the standpoint of fluctuating pressure magnitudes.

The second subsection will contain the results from each BFASTST configuration. Comparisons will be drawn to identify the lowest buffet environments, and each attachment design will be further compared against a reference case:

- 1) **Legacy (reference) configuration vs. Candidate configurations:** Each of the Candidate BFASTST configurations will be compared to the Legacy configuration in order to identify the configuration that result in the lowest buffet environments. The Candidate configurations that reduce the lowest buffet environment magnitudes within critical Mach numbers and defined vehicle attitudes will be indicated.
- 2) **Baseline configuration vs. Research configurations:** The Thrust-Post-Only and the Fwd-Crossover-Only

configurations will be compared against the Baseline configuration to determine how these major components of the forward attachment geometry individually affect the buffet environments. The Baseline configuration is used as the reference because the Thrust-Post-Only and Fwd-Crossover-Only configurations are subcomponents of the Baseline configuration: the Thrust-Post-Only configuration removes the forward crossover and the Fwd-Crossover-Only configuration removes the thrust-post. The goal of this analysis is to identify key features of the OML that impact the buffet environment that may help guide future OML developments.

A. Legacy configuration vs. ATAT

This section will provide a comparison of the BFASTST Legacy configuration data to the ATAT test and will establish the impacts of the booster and forward attachment OML differences discussed in Sec. IV.B. An overview of the maximum $\Delta C_{p,rms}$ levels on the core between the ATAT test and the Legacy configuration for a Mach number sweep ($\alpha = \beta = 0^\circ$) is provided in Fig. 13. Sensor data from the LSRB is not presented in this section due to the sensor location differences between ATAT and BFASTST tests. All peak rms values occurred at one of two sensors directly downstream of the forward attachment on $\theta = 90^\circ$. The trends are similar between tests with the ATAT $\Delta C_{p,rms}$ magnitudes being higher than the Legacy configuration for all Mach numbers. In addition, the ATAT peak occurs at approximately the same Mach number, but has a notably broader peak.

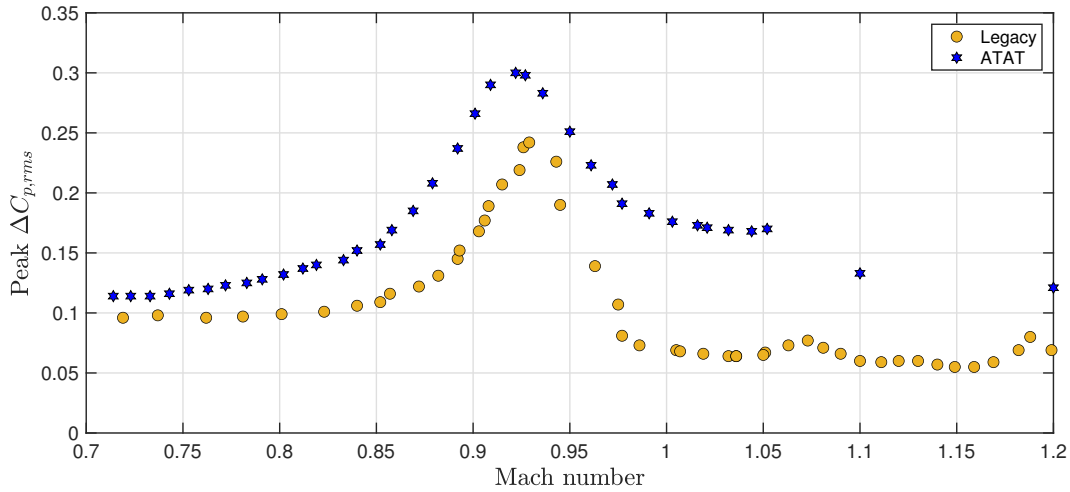
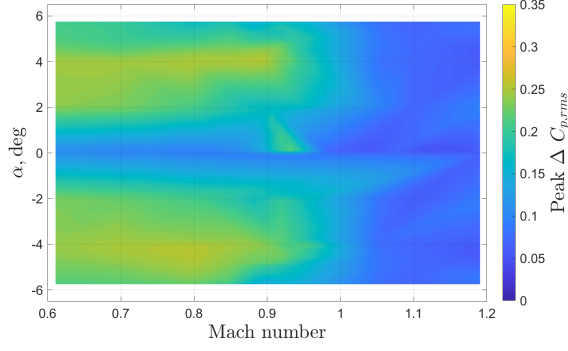


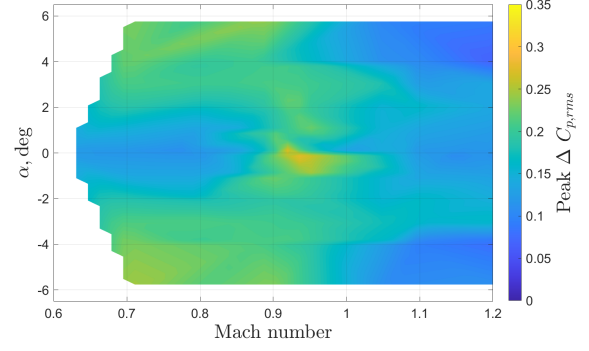
Fig. 13 Comparison of maximum core $\Delta C_{p,rms}$ between the Legacy configuration and ATAT.

Further examination of the test-to-test differences in $\Delta C_{p,rms}$ is provided in Fig. 14, which shows the maximum $\Delta C_{p,rms}$ for the core as a function of Mach number and α . The borders are irregular for the ATAT plots because data were not available at those conditions. For the BFASTST Legacy configuration, the highest peak magnitudes for the contour plots (Fig. 14) exist at $\alpha = \pm 4^\circ$. A low magnitude trough exists for $\alpha = 0^\circ$, except for a peak at $M_\infty = 0.92$ (this trend corresponds to the data shown in Fig. 13). For ATAT, the peak at $M_\infty = 0.92, \alpha = \beta = 0^\circ$ is much stronger than the BFASTST Legacy configuration, and is the largest $\Delta C_{p,rms}$ magnitude on these plots. The large fluctuation magnitudes still exist for ATAT, but are generally lower in level to the BFASTST Legacy configuration. In addition, the ATAT magnitudes tend toward higher angles of attack at lower Mach numbers while shifting lower around $M_\infty = 0.92$. This behavior is not present in BFASTST, where the large fluctuations stay at $\alpha = \pm 4^\circ$ and largely drop off at supersonic Mach numbers. This analysis shows that while Fig. 13 is useful for a broad overall view at zero vehicle attitude, there are additional flight condition/vehicle attitude dependencies that differ between the two tests.

Another approach to assessing the unsteady aerodynamic environment is to compute sectional BFFs, which integrate the unsteady pressures at each station into orthogonal forces at the centerline of the core or booster. These sectional BFFs model the net aerodynamic forces acting at a particular vehicle station. The rms values of the sectional BFFs ($\Delta f_{yz,rms}$) developed for the core for $M_\infty = 0.92, \alpha = \beta = 0^\circ$ and $M_\infty = 0.92, \alpha = 4^\circ, \beta = 0^\circ$ are provided in Fig. 15. These conditions were chosen based on the peak $\Delta C_{p,rms}$ magnitudes. Lines have been provided to illustrate the relationships clearer, but due to the nature of discrete measurements, may not be indicative of the loads between transducer stations.

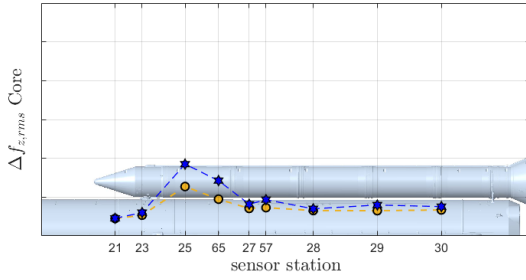
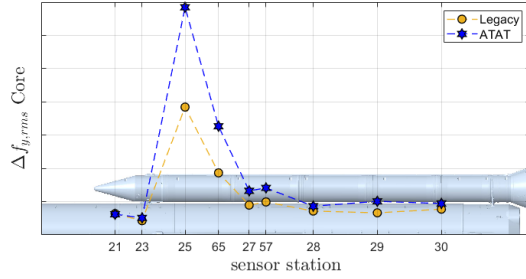


(a) Legacy configuration.

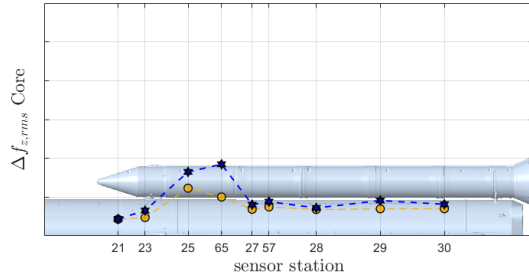
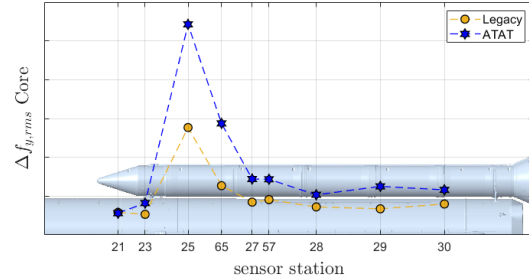


(b) ATAT.

Fig. 14 Comparison of maximum core $\Delta C_{p,rms}$ as a function of M_∞ and α between the Legacy configuration and ATAT.



(a) $M_\infty = 0.92, \alpha = \beta = 0^\circ$



(b) $M_\infty = 0.92, \alpha = 4^\circ, \beta = 0^\circ$

Fig. 15 Comparison of core $\Delta f_{yz,rms}$ between the Legacy configuration and ATAT.

There is a substantial difference between the $\Delta f_{y,rms}$ levels of the ATAT test and the Legacy configuration, particularly in the peak magnitudes around model station 25. The ATAT sectional BFFs generally envelope and are higher than those of the Legacy configuration; furthermore, the ratio between the Legacy configuration and ATAT peak levels are higher for $\Delta f_{y,rms}$ than $\Delta C_{p,rms}$ levels. The $\Delta f_{z,rms}$ peak levels are lower than the $\Delta f_{y,rms}$ peak levels at stations 25 and 65, but generally share similar comparative percent differences to $\Delta f_{y,rms}$ levels at each sensor station. The differences are less apparent as the magnitudes are generally lower.

The potential causes of the $\Delta C_{p,rms}$ and $\Delta f_{yz,rms}$ differences between the Legacy configuration and ATAT have been described in Sec. IV.B. As was shown, the differences in booster OML, including a smaller core-booster gap and larger field joints, could contribute to lower fluctuation levels. This difference is hypothesized to be the biggest factor impacting the test-to-test comparisons, but further examination is needed to isolate the specific cause. Also, the ATAT forward attachment includes differences in geometry required to accommodate the model attachment hardware, which could contribute to this increase in levels.

This comparison between the previous test and the Legacy configuration helps to provide context regarding how the buffet environment of the BFASTST Legacy configuration compares to past test data that have been used to develop BFFs for the Block 1B vehicle. The Legacy configuration will be used as the reference for comparing the Candidate configurations, since it removes the influence of the BOLE boosters and isolates the effect of the forward attachment hardware on the buffet environments.

B. BFASTST configuration comparisons

1. Maximum global vehicle $\Delta C_{p,rms}$

Figures 16 and 17 compare the maximum vehicle $\Delta C_{p,rms}$ on the core and LSRB during the Mach sweep ($\alpha = \beta = 0^\circ$) for all configurations tested during BFASTST. Figure 16 also contains the ATAT data for ease of comparison. Just as in the test-to-test comparisons, the maximum fluctuating pressure levels are dominated by the 90° azimuth sensors on the core and 270° azimuth sensors on the booster, which face the gap between the core and booster and measure pressures in the wake of the attachment hardware, with station 25 typically measuring the highest pressure fluctuations.

All the Candidate configurations follow approximately the same trends for both the core and LSRB with respect to Mach number, with some minor variations. First, the Mach number corresponding to the peak maximum $\Delta C_{p,rms}$ for all configurations varies from $M_\infty = 0.90$ to $M_\infty = 0.95$. Second, the One-Sided configuration has higher peak core $\Delta C_{p,rms}$ at lower Mach numbers than other configurations, except the Baseline configuration. This outlier is likely due to the asymmetry of this configuration and impact on the core, as this behavior is not seen on the LSRB. Finally, the LSRB peak magnitudes are higher than the core, particularly for the Heritage configuration, likely due to sensor density along $\theta = 270^\circ$. Later results discussed in Sec. VI.B.3 suggest that the Heritage configuration in particular may shift the peak environment downstream and between sensors for the core. Because of this shift, the LSRB, which has a higher sensor density behind the forward attachment, may be more likely to track the peak $\Delta C_{p,rms}$ environment.

Despite the Candidate configurations displaying similar trends, the rms magnitudes do vary greatly, particularly near $M_\infty = 0.92$, where peak fluctuations are typically measured. The Baseline configuration generally has the highest fluctuating levels, while the Heritage and One-Sided configurations have the lowest. Once again, the LSRB generally has higher peak environments as compared to the core, due to the aforementioned sensor density.

Examining the Research configurations, the Fwd-Crossover-Only configuration has the highest fluctuating pressure levels of any configuration, even exceeding the levels measured during the ATAT test. The Fwd-Crossover-Only configuration also has high $\Delta C_{p,rms}$ levels at lower Mach numbers, the highest of all configurations. Conversely, the Thrust-Post-Only configuration has some of the lowest fluctuating pressure levels, most clearly evident on the LSRB. The dip in core peak $\Delta C_{p,rms}$ measurements in the Fwd-Crossover-Only configuration around $M_\infty = 0.88$ is most likely a missed peak fluctuating environment on the core due to lack of sensor density, and could potentially be influenced by the lack of a thrust-post structure.

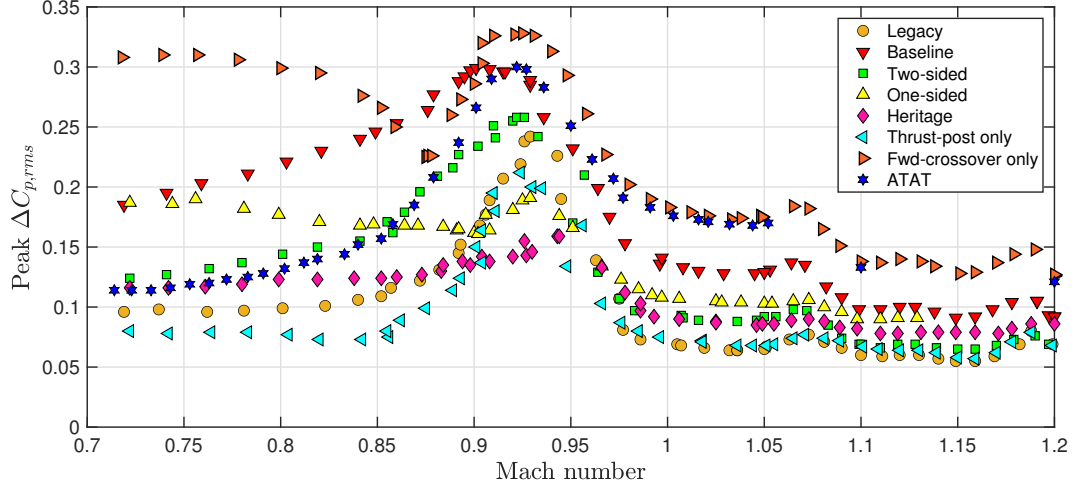


Fig. 16 Effect of forward attachment geometry on maximum core $\Delta C_{p,rms}$ as a function of M_∞ , $\alpha = \beta = 0^\circ$.

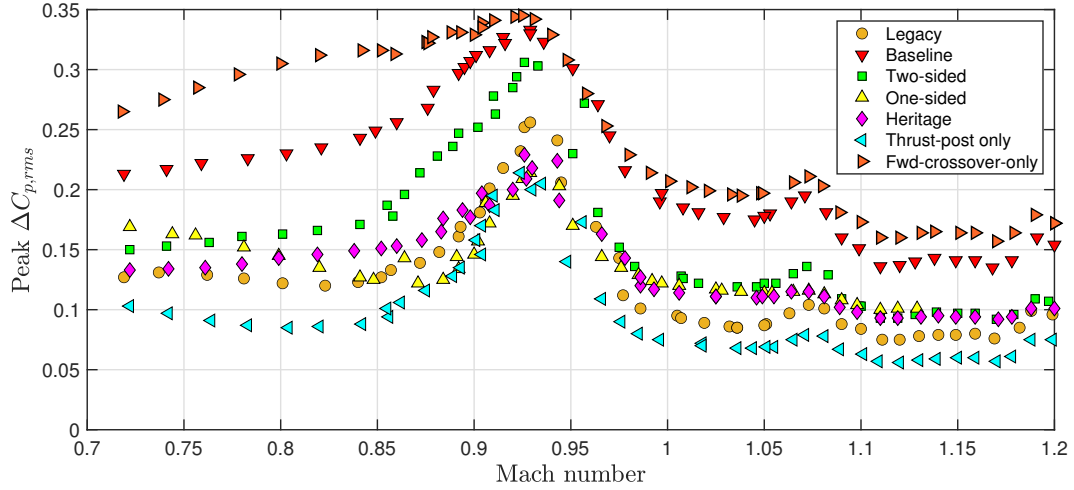


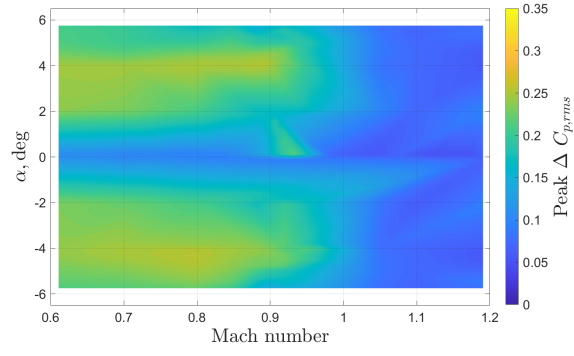
Fig. 17 Effect of forward attachment geometry on maximum LSRB $\Delta C_{p,rms}$ as a function of M_∞ , $\alpha = \beta = 0^\circ$.

2. Contour plots of $\Delta C_{p,rms}$

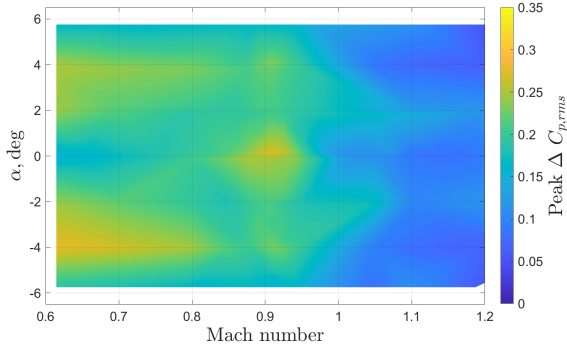
To further illustrate the differences in $\Delta C_{p,rms}$ between the configurations, Figs. 18 and 19 show the peak $\Delta C_{p,rms}$ contour plots for the core and LSRB as a function of Mach number and α . Most of the peak $\Delta C_{p,rms}$ magnitudes are located near the $\theta = 90^\circ$ clocking angle, but with some limited cases of $\theta = 73^\circ$ or 106° .

The core $\Delta C_{p,rms}$ levels as a function of Mach number and α are displayed in Fig. 18. In general, the Legacy, Baseline, and Thrust-Post-Only configurations share similar trends, with relatively high magnitudes at $\alpha = \pm 4^\circ$, and a significant peak at $M_\infty = 0.92$, $\alpha = \beta = 0^\circ$. The Two-Sided configuration shares a similar profile to these configurations, but exhibits the relatively high magnitudes at $\alpha = \pm 2^\circ$. The effect of the One-Sided configuration asymmetry on $\Delta C_{p,rms}$ is clearly visible in Fig. 18d. When the forward crossover is on the leeward side, at negative α angles, the intensity of the shedding is emphasized, while this is largely muted in positive (windward) α angles. The Heritage configuration appears to have the lowest $\Delta C_{p,rms}$ levels, with peak amplitudes noted at $\alpha = \pm 6^\circ$ instead of $\alpha = \pm 4^\circ$ and no significant peak at $M_\infty = 0.92$, $\alpha = \beta = 0^\circ$. The Fwd-Crossover-Only configuration shows significant $\Delta C_{p,rms}$ levels throughout the α range below $M_\infty = 0.90$, and has the highest $\Delta C_{p,rms}$ levels of all configurations at the $M_\infty = 0.92$, $\alpha = \beta = 0^\circ$ peak including strong magnitudes at $\alpha = \pm 2^\circ$ through the transonic and supersonic conditions.

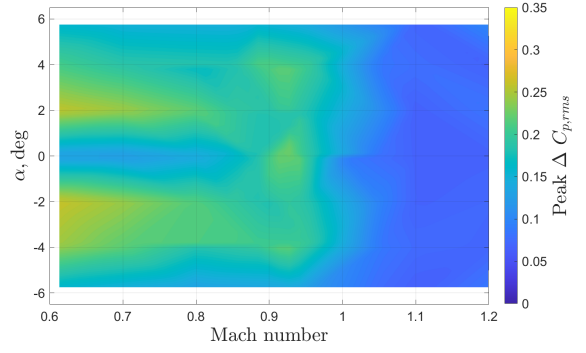
The LSRB $\Delta C_{p,rms}$ levels as a function of Mach number and α are shown in Fig. 19. The Baseline, Two-Sided, Heritage, Thrust-Post Only, and Fwd-Crossover-Only configurations all exhibit similar trends in $\Delta C_{p,rms}$ magnitudes as their core counterpart, albeit with some magnitude differences. The Legacy configuration has reduced magnitudes at the $\alpha = \pm 4^\circ$ and the asymmetry in the $\Delta C_{p,rms}$ of the One-Sided configuration is less pronounced than what was measured on the core. The Baseline, Two-Sided, and Heritage configurations measure a general increase in $\Delta C_{p,rms}$ both as a function of Mach number and angle of attack.



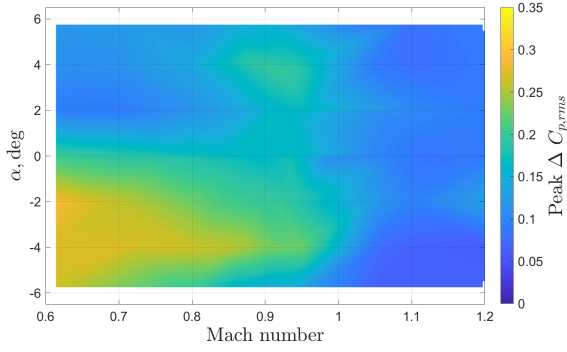
(a) Legacy configuration.



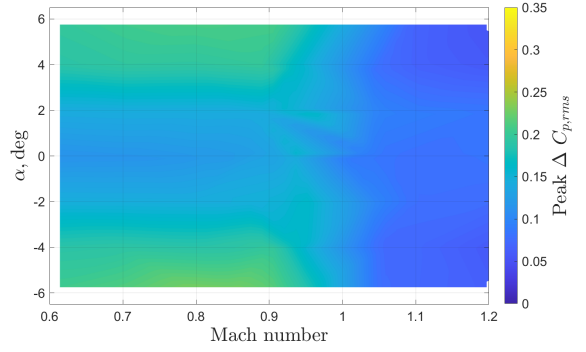
(b) Baseline configuration.



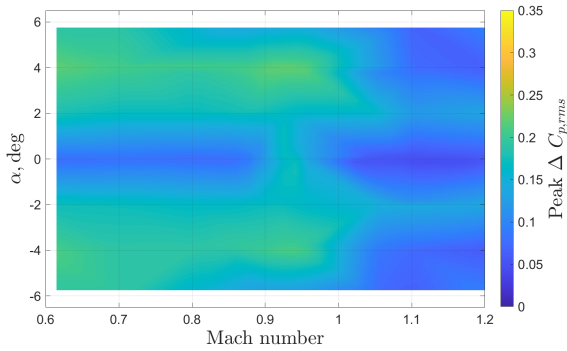
(c) Two-Sided configuration.



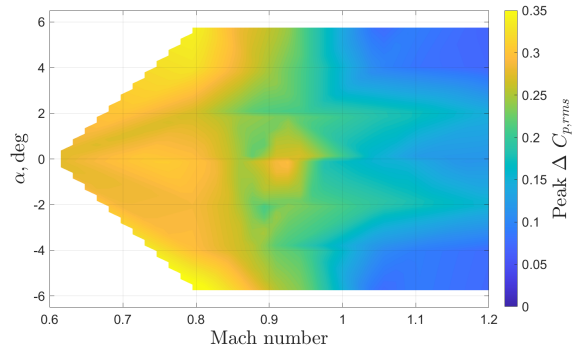
(d) One-Sided configuration.



(e) Heritage configuration.

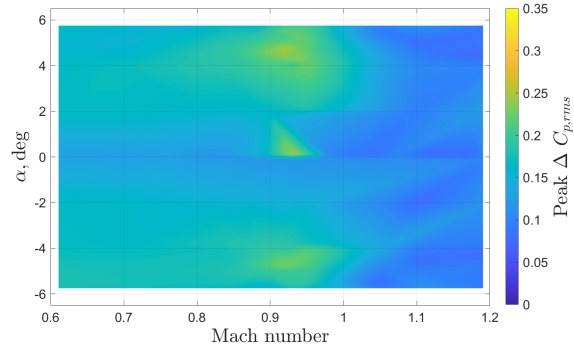


(f) Thrust-Post-Only configuration.

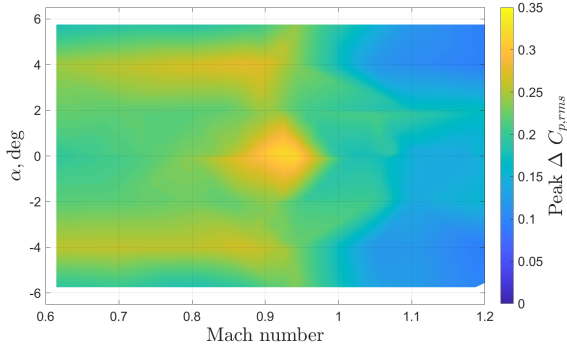


(g) Fwd-Crossover-Only configuration.

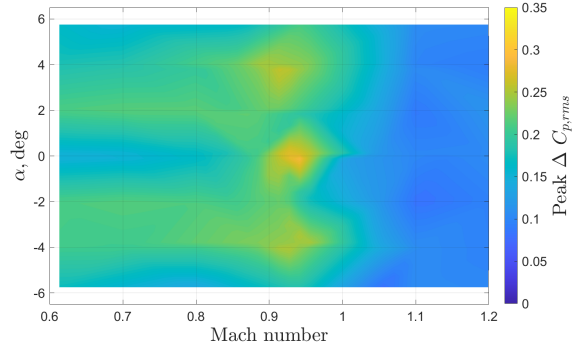
Fig. 18 Comparison of maximum BFASTST core $\Delta C_{p,rms}$ as a function of M_∞ and α .



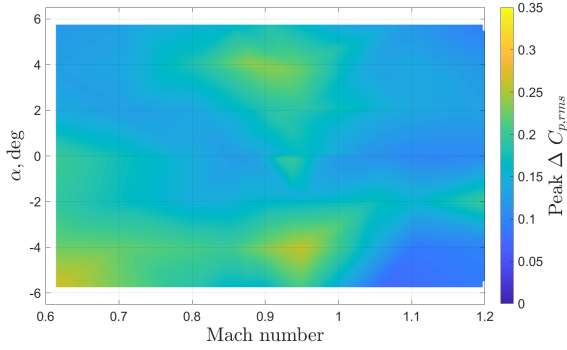
(a) Legacy configuration.



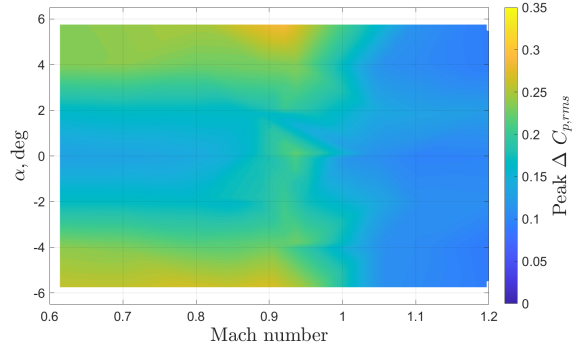
(b) Baseline configuration.



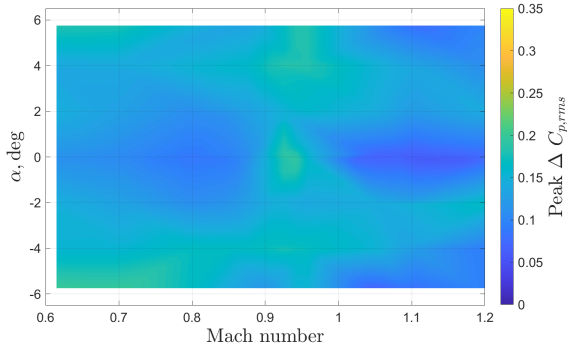
(c) Two-Sided configuration.



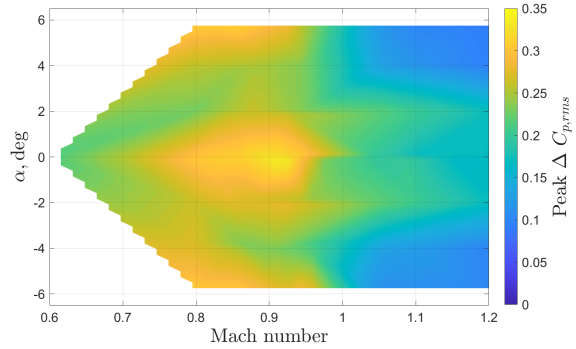
(d) One-Sided configuration.



(e) Heritage configuration.



(f) Thrust-Post-Only configuration.



(g) Fwd-Crossover-Only configuration.

Fig. 19 Comparison of maximum BFASTST LSRB $\Delta C_{p,rms}$ as a function of M_∞ and α .

3. Fluctuating BFF analysis

The rms values of the sectional BFFs ($\Delta f_{yz,rms}$) for the core and LSRB are shown for $M_\infty = 0.80, 0.92, 1.05$, and 1.20 at $\alpha = \beta = 0^\circ$ and $\alpha = 4^\circ, \beta = 0^\circ$ in Figs. 20 through 27 for all configurations. These conditions were chosen as a mixture of representative subsonic ($M_\infty = 0.80$, Figs. 20 and 21) and supersonic ($M_\infty = 1.20$, Figs. 26 and 27) environments, as well as the overall peak magnitude condition ($M_\infty = 0.92$, Figs. 22 and 23) and a local supersonic peak magnitude ($M_\infty = 1.05$, Figs. 24 and 25). Lines are not plotted in these figures as they were in Fig. 15 as there is no desire to imply envelopment.

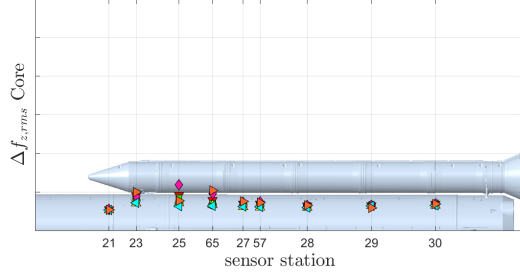
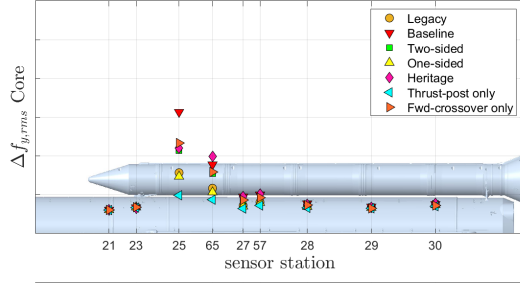
Overall, the peak $\Delta f_{y,rms}$ and $\Delta f_{z,rms}$ occur at $M_\infty = 0.92$, either at $\alpha = 0^\circ$ or $\alpha = 4^\circ$, depending on the configuration. BFF levels are generally higher at subsonic conditions as opposed to supersonic conditions, where the BFFs decrease significantly. The trends for $\Delta f_{z,rms}$ levels are similar to the $\Delta f_{y,rms}$ trends, but with significantly lower peak magnitudes and somewhat lower rms magnitudes at each sensor station. The higher $\Delta f_{y,rms}$ magnitudes across the vehicle are associated with the wake of the forward attachment in the multibody region. Furthermore, the LSRB trends follow most of the $\Delta f_{y,rms}$ and $\Delta f_{z,rms}$ trends for the core, only with slightly lower magnitudes. The peak $\Delta f_{y,rms}$ and $\Delta f_{z,rms}$ appear to occur further forward on the booster due to station locations, as station 24 does not exist for the core (see Fig. 6).

The Candidate designs experience higher peak $\Delta f_{y,rms}$ magnitudes at most examined conditions than the Legacy (reference) configuration. When comparing the maximum $\Delta f_{y,rms}$ magnitudes across all conditions examined, every Candidate configuration produces higher $\Delta f_{y,rms}$ than the Legacy configuration. The Legacy configuration produces its highest $\Delta f_{y,rms}$ at $M_\infty = 0.92, \alpha = \beta = 0^\circ$ on the core (Fig. 22a). This value is exceeded by the Baseline and Two-Sided configurations at that same condition, and is exceeded by the One-Sided and Heritage configurations at $M_\infty = 0.92, \alpha = 4^\circ, \beta = 0^\circ$ (Fig. 22b). The Legacy configuration is also generally lower at all other stations throughout the vehicle. This relationship is consistent for each examined condition. This lower magnitude relationship of the Legacy configuration (peak and longitudinal) indicates that most of the Candidate designs may result in higher buffet environments than the current SLS design. If the Legacy configuration met the structural or mechanical requirements of the BOLE program, these results would indicate that the forward attachment hardware should not be changed from that design.

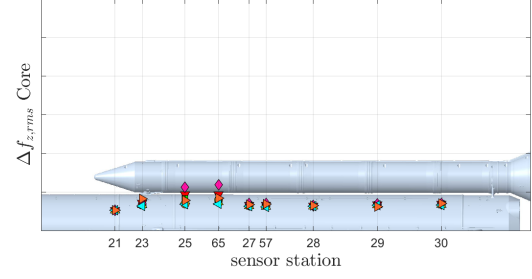
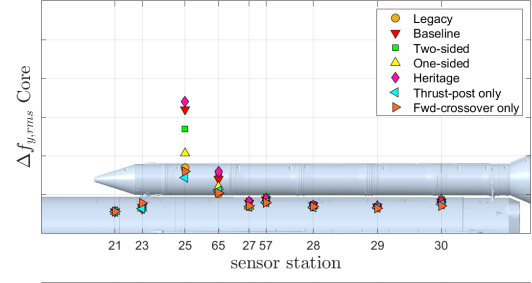
Worth special consideration amongst the Candidate configurations is the Heritage configuration. All other configurations consistently experience the highest BFF magnitudes at station 25, and then decrease longitudinally down the vehicle. This relationship is not true for the Heritage configuration; this is seen clearest in Fig. 22a, where $\Delta f_{y,rms}$ magnitudes for the Heritage configuration is lowest for all configurations at station 25, but is the highest for all configurations at station 65. In fact, the Heritage configuration generates the highest $\Delta f_{y,rms}$ and $\Delta f_{z,rms}$ magnitudes of all configurations at station 65 at all conditions. Furthermore, the Heritage configuration consistently has some of the highest BFF magnitudes at all the instrumented vehicle stations downstream of station 25. These high BFF levels and spatial distribution patterns for the Heritage configuration could indicate that the peak sectional forces for this configuration could occur between station 25 and 65, and thus the Heritage peak could have been missed.

Comparing the Research configurations (Fwd-Crossover-Only and Thrust-Post-Only) to the Baseline configuration, the highest $\Delta f_{y,rms}$ magnitude occurs at $M_\infty = 0.92$ on the core at model stations 25 and 65 (Fig. 22a). At $\alpha = \beta = 0^\circ$, the Fwd-Crossover-Only configuration has the highest sectional BFFs, with relatively similar levels for the Baseline configuration and the Thrust-Post-Only configuration being much lower. The Thrust-Post-Only configuration consistently has the lowest levels of all configurations, including the Baseline.

The lower $\Delta f_{yz,rms}$ magnitudes from the Thrust-Post-Only configuration, along with the lower $\Delta C_{p,rms}$ magnitudes, suggest that the thrust-post appears to reduce buffeting levels, or, at a minimum, does not increase the levels significantly itself. The thrust-post could be acting as a splitter plate or fence behind the forward attachment. Such splitter plates have been shown to suppress vortex shedding in wake structures downstream of cylindrical bodies [13, 14]. While the flowfield downstream of the forward attachment is much more complex, and at higher Reynolds numbers, than these examples, further exploration of a similar structure to the thrust-post (such as a fairing) could yield beneficial results. On the other hand, the Fwd-Crossover-Only configuration is a significant driver in the overall buffet levels experienced by the vehicle. The crossover width may be a key parameter for affecting the magnitude and frequency of the fluctuating pressure environment. However, other yet-to-be-determined design considerations may be just as important.

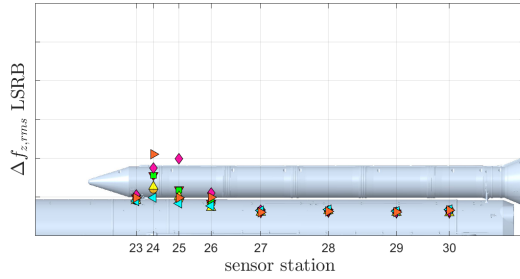
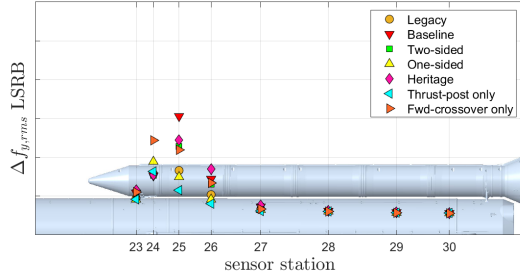


(a) $\alpha = \beta = 0^\circ$.

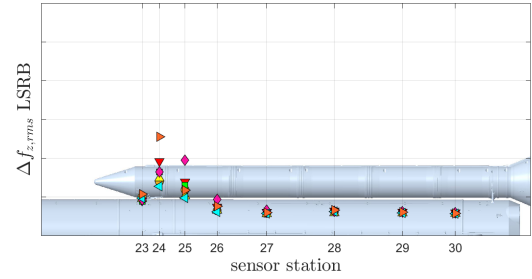
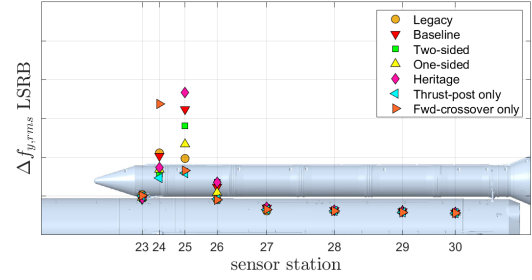


(b) $\alpha = 4^\circ, \beta = 0^\circ$.

Fig. 20 Comparison of BFASTST core $\Delta f_{yz,rms}$ between configurations, $M_\infty = 0.80$.



(a) $\alpha = \beta = 0^\circ$.



(b) $\alpha = 4^\circ, \beta = 0^\circ$.

Fig. 21 Comparison of BFASTST LSRB $\Delta f_{yz,rms}$ between configurations, $M_\infty = 0.80$.

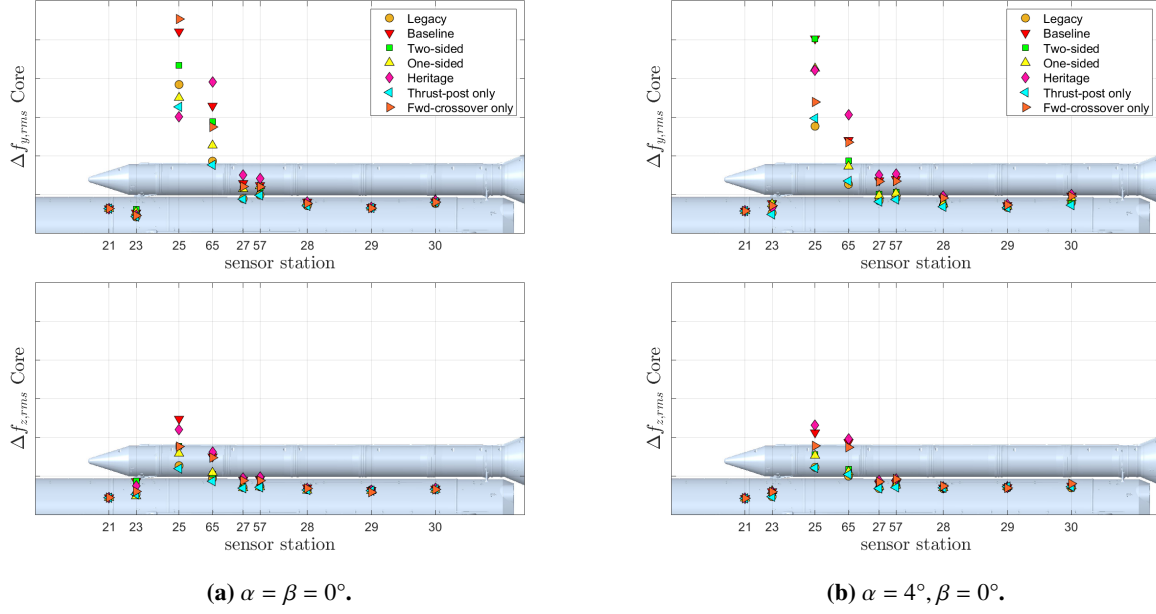


Fig. 22 Comparison of BFASTST core $\Delta f_{yz,rms}$ between configurations, $M_\infty = 0.92$.

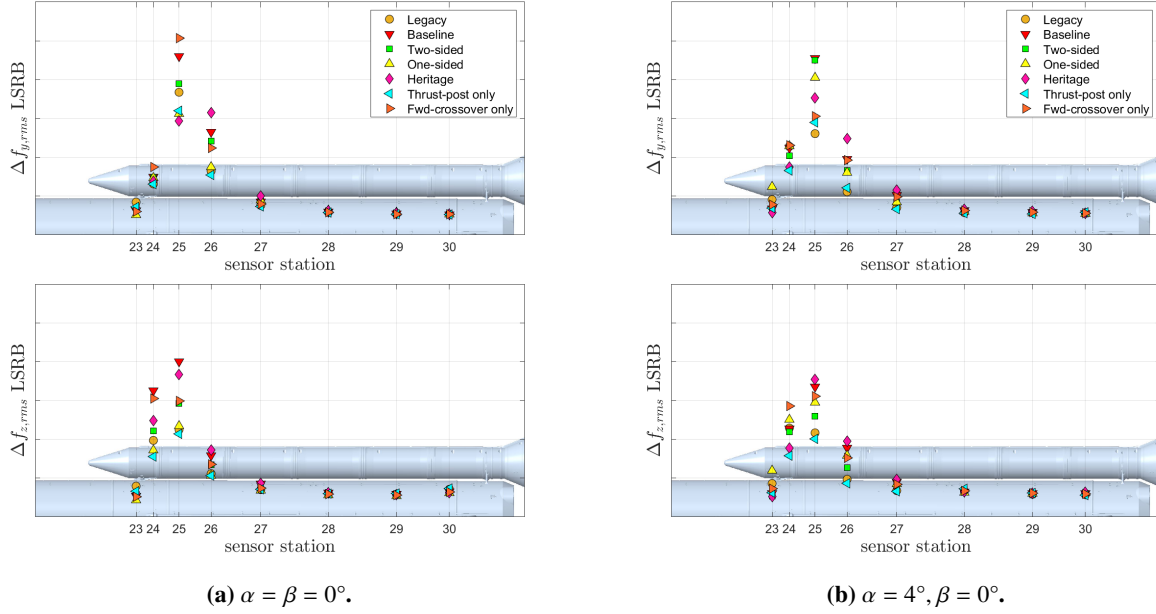


Fig. 23 Comparison of BFASTST LSRB $\Delta f_{yz,rms}$ between configurations, $M_\infty = 0.92$.

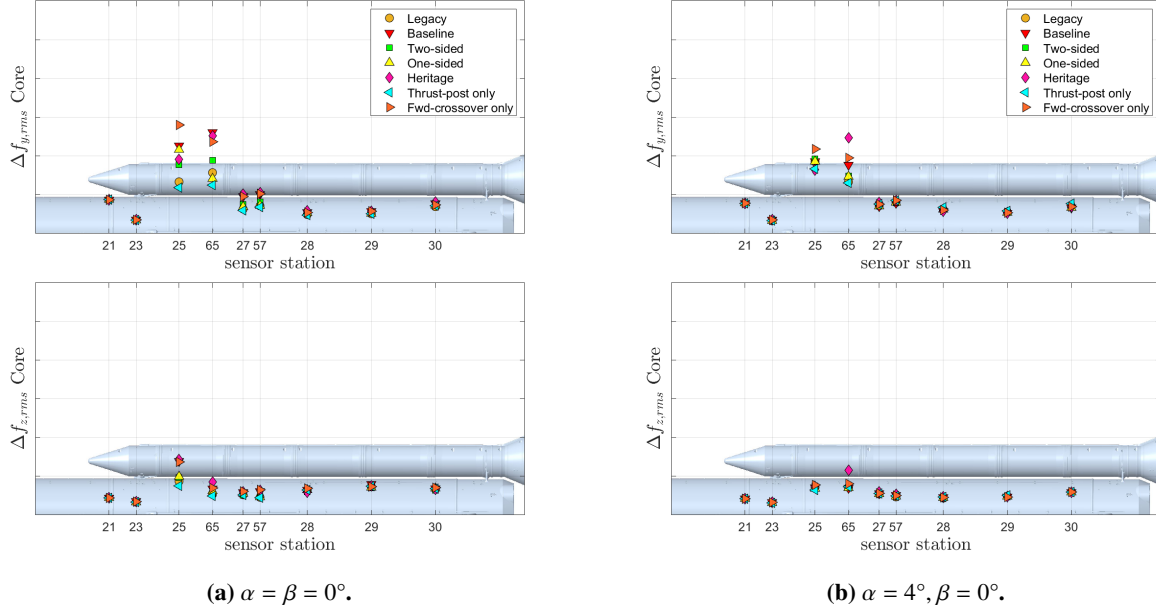


Fig. 24 Comparison of BFASTST core $\Delta f_{yz,rms}$ between configurations, $M_\infty = 1.05$.

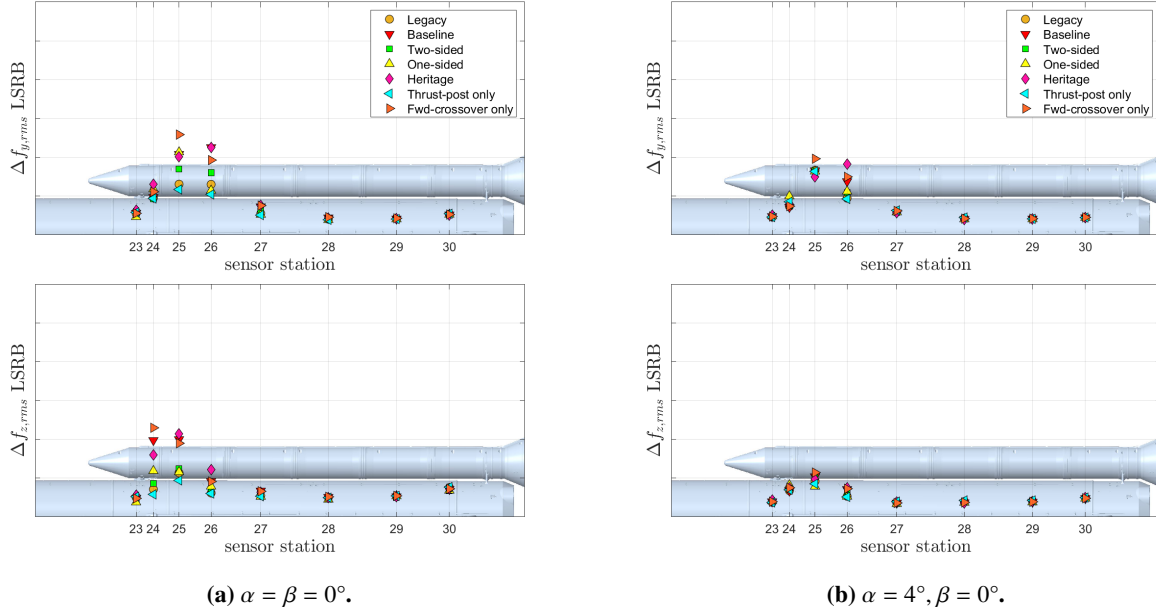
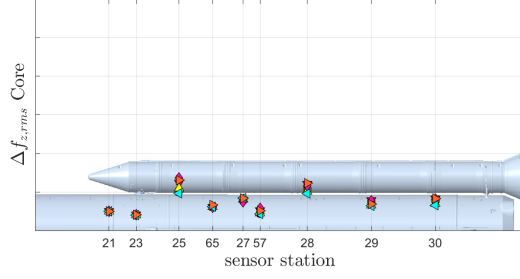
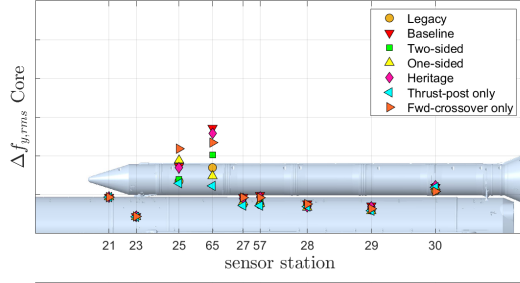
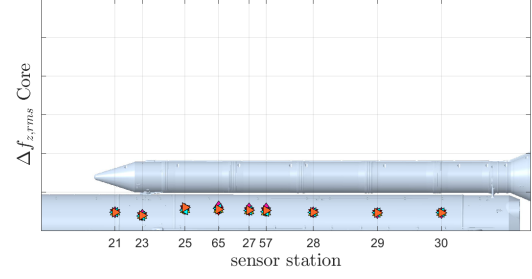
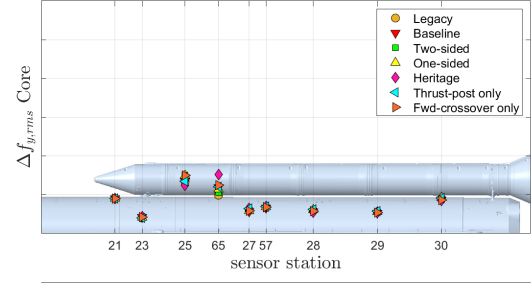


Fig. 25 Comparison of BFASTST LSRB $\Delta f_{yz,rms}$ between configurations, $M_\infty = 1.05$.

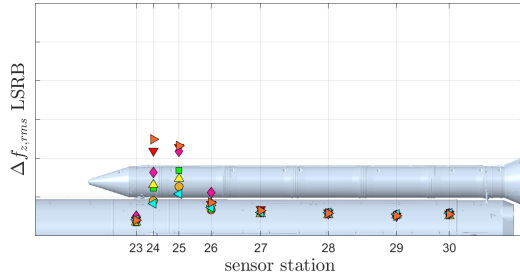
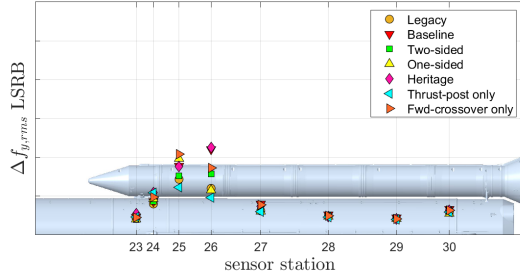


(a) $\alpha = \beta = 0^\circ$.

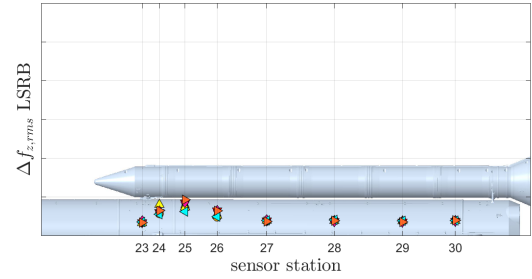
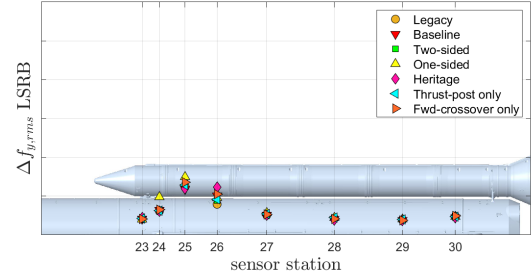


(b) $\alpha = 4^\circ, \beta = 0^\circ$.

Fig. 26 Comparison of BFASTST core $\Delta f_{yz,rms}$ between configurations, $M_\infty = 1.20$.



(a) $\alpha = \beta = 0^\circ$.



(b) $\alpha = 4^\circ, \beta = 0^\circ$.

Fig. 27 Comparison of BFASTST LSRB $\Delta f_{yz,rms}$ between configurations, $M_\infty = 1.20$.

VII. Conclusion

The transonic buffet environment of the Space Launch System (SLS) vehicle is an area of continued importance and study for the program. The Booster Obsolescence and Life Extension (BOLE) development program provides an opportunity to develop and test a new booster forward attachment structure that meets both functional and aerodynamic needs. The BOLE Forward Attachment Trade Study Test (BFASTST) was conducted to provide an early look into how various designs for the forward attachment hardware affect the aerodynamic buffet environment on the multibody region of the SLS vehicle.

The present work introduced seven configurations: four Candidate configurations (Baseline, Two-Sided, One-Sided, and Heritage), which were designs delivered by Northrop Grumman as potential geometries for the booster; two Research configurations (Fwd-Crossover-Only and Thrust-Post-Only), which allow for study of specific OML features; and a reference configuration (Legacy), which is based on the current SLS forward attachment geometry. The test campaigns of both BFASTST and the previous test, the Ascent Transient Aerodynamics Test (ATAT), were discussed, exploring the impact of model configuration and sensor distribution on the measured buffet environments.

The results from BFASTST and ATAT were examined using two parameters: fluctuating pressure environments and fluctuating sectional forces. The BFASTST Legacy configuration was compared to ATAT as a method to isolate booster changes between the two tests and to anchor the BFASTST measurements to previously measured environments most comparable. Then, the BFASTST configurations were compared to each other to assess the buffet environment of each.

The fluctuating pressures and sectional forces measured during the BFASTST test on the Legacy configuration were, in general, lower than ATAT. Geometry changes to the booster likely contribute to this trend, including a larger diameter and more pronounced field joints. In comparison, none of the BFASTST Candidate configurations convincingly produced lower environments than the reference Legacy configuration. The Baseline and Two-sided configurations produced consistently higher fluctuating pressure environments than the Legacy configuration, and the One-sided and Heritage configuration were only slightly lower than the Baseline and Two-sided.

A consistent theme throughout the analysis was sensor placement and spatial density. All configurations warrant further investigation since the data might be missing the peak environments, particularly the Heritage configuration. The sensor placement was designed for the Legacy configuration on the Block 1B vehicles, and other geometries will have different peak fluctuating pressure and peak BFF locations.

These results highlight the complexity of the interaction between the flowfield and the forward attachment hardware geometry. Only the fluctuating pressure and force magnitudes were examined during this report, while the frequency content could be just as important. Ultimately any design changes that are made to the forward attachment hardware will need to be assessed during future tests and subsequent CLA to address the impact that those design changes have on dynamic loads.

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