

Development of Buffet Forcing Functions for a Transonic Condition Exhibiting Bimodal Flow Behavior

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A wind-tunnel test campaign was used to derive Buffet Forcing Functions (BFFs) of the Space Launch System Block 1B vehicle configuration by measuring and integrating unsteady surface pressures on a 3-percent scale rigid buffet model (RBM) tested at the NASA Langley Transonic Dynamics Tunnel. The model was tested at predetermined and repeatable pitch and side-slip angles and flow Mach numbers encompassing a full range of possible flight conditions. Although each data point was collected at a steady wind-tunnel condition, a transient, bimodal flow behavior was observed in some Mach 1.10 measurements. The pressure time series was alternating between two states, which differed either in mean or fluctuation amplitude values, or both. As a consequence of this behavior, segments of the resultant BFFs can differ based on the duration that each measurement spends in a particular state. In this paper, a methodology is proposed, which envelopes the range of BFFs magnitudes resulting from this random bimodal phenomenon in pressure time histories of certain sensors.

Nomenclature

α	=	Model pitch angle
β	=	Model side-slip angle
C_p	=	Pressure coefficient
C_f	=	Force coefficient
i	=	Counter
r	=	Local outer mold line radius
R	=	Reference radius
θ	=	Azimuth coordinate

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.

Introduction

Transonic buffeting is one of the dominant aerodynamic environments experienced by a launch vehicle as it ascends through the atmosphere. This unsteady environment is quantified using Buffet Forcing Functions (BFFs). Often, these BFFs are a set of centerline loads computed for a range of flow and vehicle attitude conditions, which are then used in a coupled-loads analysis to predict the structural responses of the rocket. Forcing functions themselves can be derived from time-accurate computational fluid dynamics (CFD)[1] simulations and/or wind-tunnel testing [2–4]. Wind-tunnel-based BFFs are typically derived from discrete pressure measurements from sensors embedded in the

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model skin or, more recently, using an unsteady pressure-sensitive paint [5–7]. This work is focused on analyzing the sensor-based BFF calculations using data collected during a 2022 wind-tunnel test of a Space Launch System Block 1B crew model at the Langley Transonic Dynamics Tunnel. A 3-percent scale rigid buffet model (RBM) was instrumented with unsteady Kulite[®] pressure transducers distributed in a ring-like configuration at 42 longitudinal stations along the entire model. For each ring of sensors, the measured pressure time histories were azimuthally integrated to obtain orthogonal sectional forces at each station. This procedure was applied to pressure data collected at predetermined and repeatable model pitch and side-slip angles and flow Mach numbers to examine a full range of possible flight conditions.

A phenomenon was observed in the unsteady pressure data collected at a free-stream Mach number of 1.10. Although the wind-tunnel condition was set at a constant value, it appears that pressure measured using sensors located on the front of the model continuously exhibited a transition between two flow states. To illustrate this transition, the signal from eight sensors located in the vicinity of the Launch Abort System (LAS) motor nozzles is shown in Fig. 1. The left four plots show signals measured by sensors positioned at an azimuth (Az) angle of 45° , 135° , 225° , and 315° at a station just downstream of the LAS nozzles, which is labeled N01. The right four plots show the signal from two sensors at a further downstream sensor station, N02, which is located on the conical transition from the LAS to the spacecraft fairing, where the sensors are located at azimuth $Az = 0^\circ$, 90° , 180° , and 270° . Both sets of plots indicate that the local flow field is fluctuating between two states. For the sensors directly downstream of the LAS nozzles, station N01, the two flow states appear to be differentiated by an instantaneous change in the mean value of the pressure signal, while for the sensors at station N02, the two flow states appear to differ in the amplitude of fluctuations. The transition appears to occur at random times and nearly-simultaneously on the affected sensors in the nose region. The result of this flow state switching is that the spectral content of the BFF at this station varies based on the switching behavior of the pressure between the two states. It is of interest in the present work to develop a BFF dataset, which envelopes the possible loads based on all scenarios of the switching behavior. The current work will be further extended to develop a BFF dataset which is more representative of the behavior during accelerating flight, since this random, multiple switching phenomena is a product of the stationary nature of wind tunnel testing.

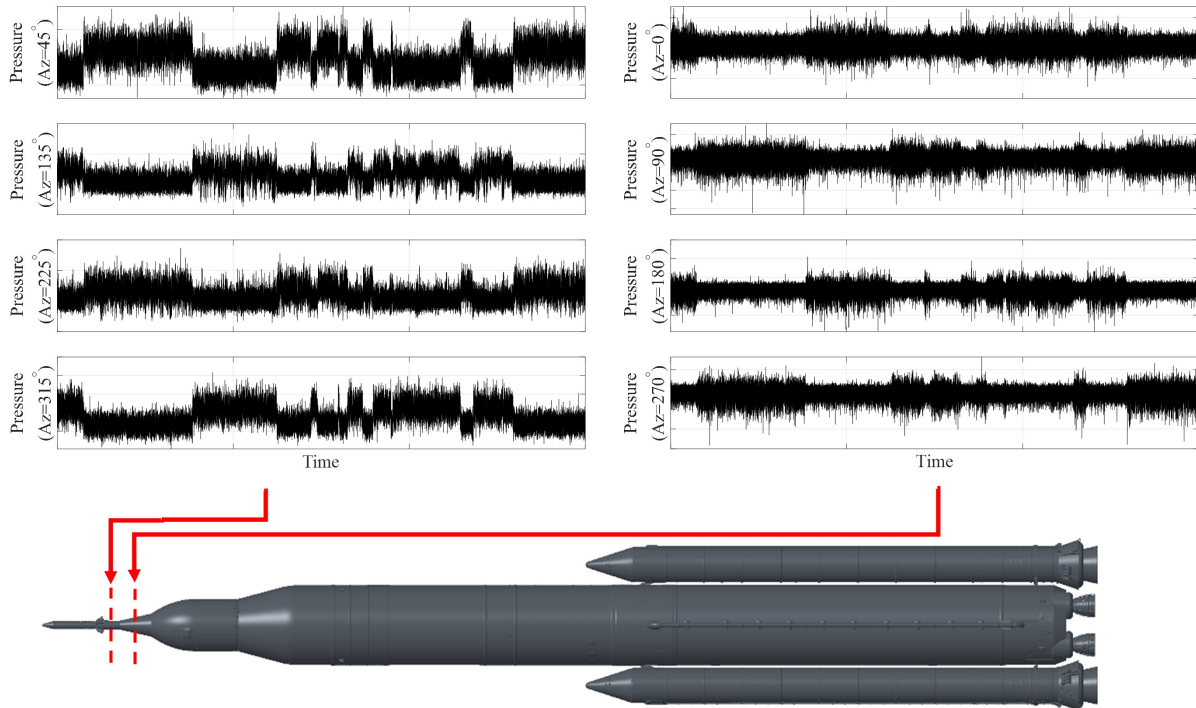


Fig. 1 Signal exhibiting flow state switching on sensors located around the nose of the rigid body wind-tunnel model, $M=1.10$, $\alpha = 2^\circ$, $\beta = 0^\circ$.

The state switching phenomenon has been documented in literature starting with examination of notional launch

vehicle and missile geometries in the 1960's and 70's. Chavalier and Robertson [8, 9] studied a cone-cylinder geometry and observed an alternating flow behavior downstream of the expansion corner on the model. Robertson describes the cause of this behavior as a recurring cycle of flow alternating continuously between a subsonic separated flow around an expansion corner formed by a cone-cylinder transition and the attached supersonic flow affecting downstream shocks and boundary layer separation. Similarly, Ericsson [10] performed an experimental study on the cone-cylinder models and observed a similar flow behavior. The alternating flow was also studied around the nose cone expansion corner on models of launch vehicles, such as a Mercury-Atlas and Saturn-Apollo by Rainey et al. [11] and on Atlas-Agena by Cockburn and Robertson [12].

More recently, the bimodal flow phenomenon was seen originating from the expansion corner formed by the spacecraft and the upper stage simulator during the wind-tunnel test of the Ares I-X [13–15]. The Computational Fluid Dynamics (CFD) simulations of the Ares I-X vehicle performed by Massey and Chwalowski [16] also modeled this flow phenomenon. The data from an Ares I-X test flight revealed a single event where flow switched from a separated subsonic flow to a supersonic attached flow around the expansion corner as the vehicle accelerated through the transonic regime, as opposed to a continuous flow state switching observed during constant-Mach number wind tunnel testing[2]. This single flow state change event was modeled prior to flight by developing sectional BFFs and then using a moving window to identify the largest fluctuating loads based on standard deviation. The window size was equivalent to the first bending mode of the vehicle, to assume the worst-case scenario. A comparison of this modeling approach to flight data noted several issues - a significant overprediction of the event amplitude, a trajectory dependence of the event, and an inconstancy in the model of the underlying flow physics which cause the event. The preflight model was based on pressure time histories that started off in a subsonic state, switched to the supersonic, and then returned to back to the original state, while the flight data started in a subsonic state and progressed until the entire circumference of the expansion corner was supersonic [13].

The importance of studying the bimodal flow is further highlighted by aerodynamic data collected from an Artemis I test flight, launched on November 16th, 2022, which measured flow state oscillation on one of the solid rocket boosters during the ascent. The time series of the pressure measurement shown in Fig. 2 exhibits a series of fluctuations. The signal indicates a significant presence of high frequency fluctuation associated with subsonic separated flow prior to a switch in flow state to an attached supersonic flow characterized by a significant change in the quasi-steady pressure and a large decrease in fluctuation. During the transition period between these two flow states, the pressure time history indicates that the flow switched states multiple times, similar to how bimodal flow manifests itself in a wind tunnel environment. These multiple changes in flow state are an indication of the time the vehicle spent at trajectory conditions (Mach number and vehicle attitude) where both flow states are possible. This paper is a first step in modeling the bimodal behavior and improve on the model proposed during the Ares I-X test flight, which was not based on flow physics and resulted in overconservative force estimates. A more detailed analysis of the Artemis I test flight data will be conducted as a part of the future work.

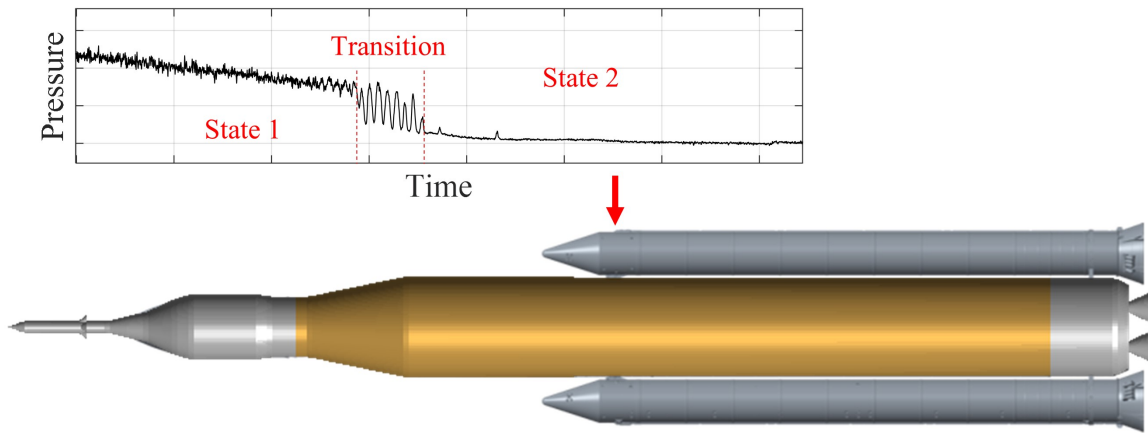


Fig. 2 Signal exhibiting flow state switching on a sensors located on the SLS solid rocket booster of Artemis I vehicle.

The observations listed above show the possibility of alternating flow behavior around the expansion corner. The current investigation, however, focuses on an alternating flow near the LAS region of the vehicle. This region does not contain an expansion corner, yet wind tunnel test data do show bimodal flow - the exact physics of this phenomenon is yet to be determined. More information about the nature of these two flow states can be gleaned by examining their time-varying spectral content of the pressure time histories. Due to placement constraints, sensors at stations N02 are located with a 45° clocking angle relative to station N01, therefore they may be measuring different flow environments. This supposition can be confirmed by examining the next ring of sensors at station N03, that consists of 8 sensors axisymmetrically spaced every 45° . The spectrograms from these three sensor stations are provided in Figure 3. These three stations indicate that the change between the two states is near-simultaneous around the LAS circumference. The two states are: 1) a “tonal” state, dominated by a single frequency, and 2) a “broadband” state, where there is broadband content that is biased towards lower frequencies. Station N03 also indicates an asymmetry in how these two flow states manifest themselves around the LAS. This asymmetry may be a result of the 60° clocking angle of the LAS nozzles, the presence of a LAS system tunnel at approximately 185° , and the 2° model angle of attack at which the data was acquired. Figure 4 shows a shadowgraph image constructed by averaging frames of a shadowgraph movie captured at $M = 1.10$. Red arrow points to a shock structure, which is present in the vicinity of LAS. The green arrow points to a shedding flow downstream of the LAS nozzles.

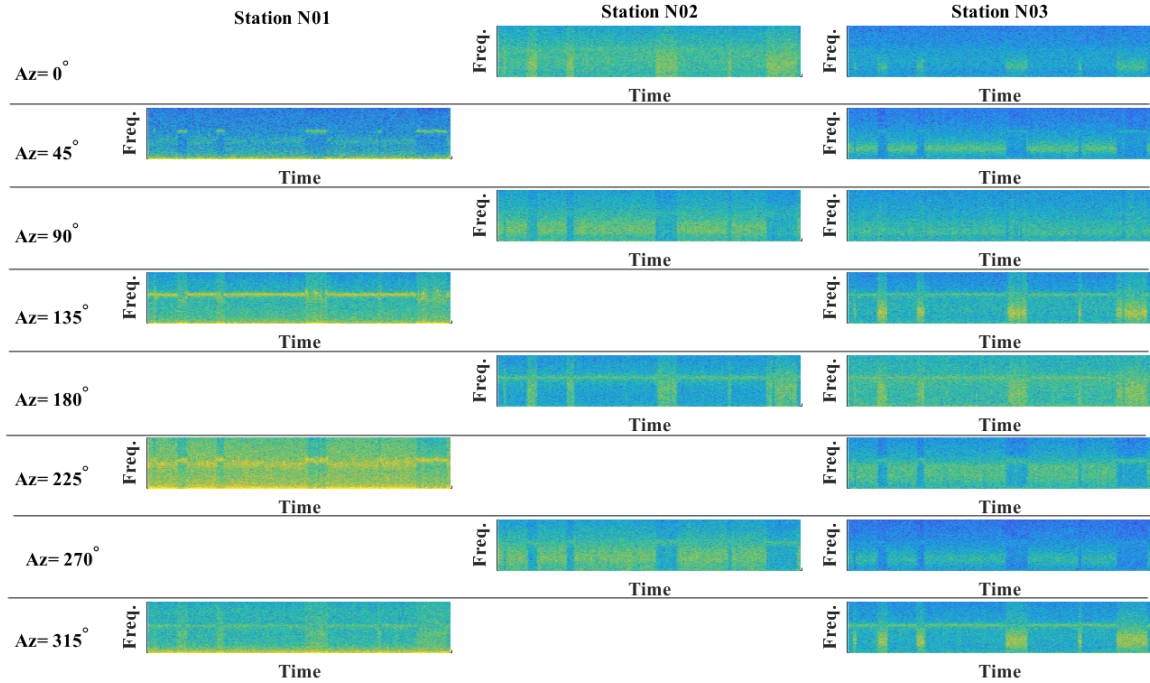


Fig. 3 Spectrograms of pressure time histories comparing Stations N01, N02, and N03. $M = 1.10$, $\alpha = 2^\circ$, $\beta = 0^\circ$.

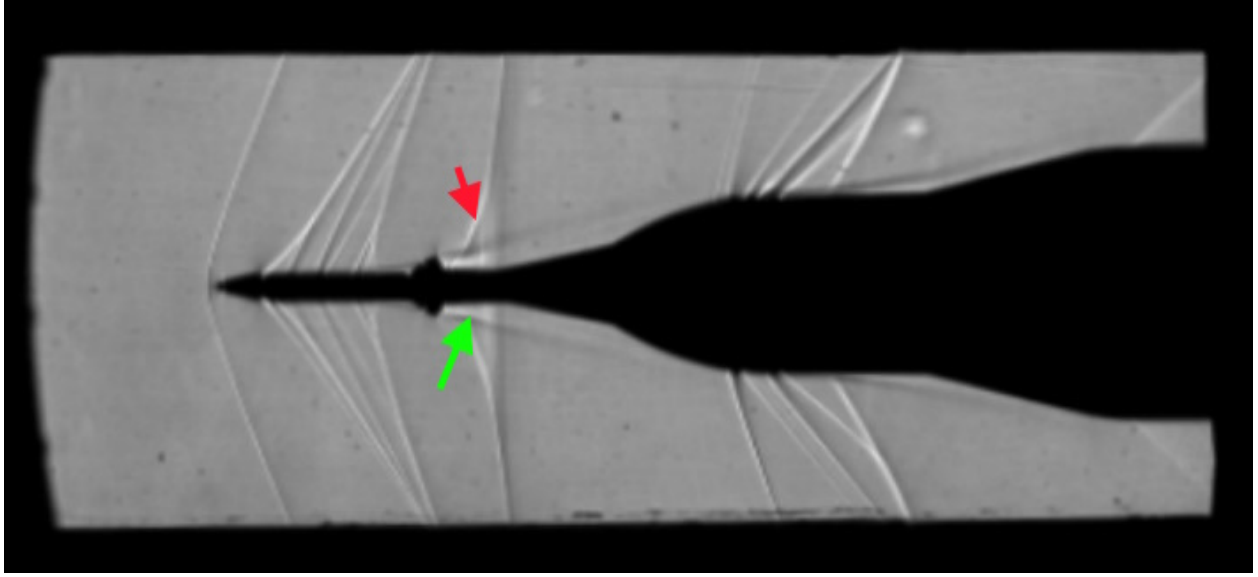


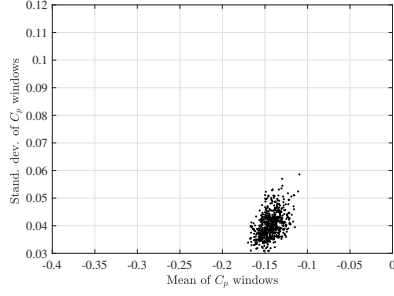
Fig. 4 Averaged shadowgraph image with red arrow pointing to a shock in vicinity of LAS and with green arrow pointing to shedding flow downstream of the LAS nozzles captures at $\alpha = 0^\circ$, $\beta = 0^\circ$, $M = 1.10$

It is of interest to develop the sectional BFF that would envelope the possible fluctuations due to flow state switching. The proposed methodology could then be applied to other regions where bimodal flow is identified.

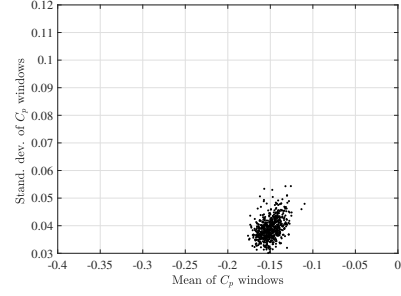
Analysis

As shown in Figure 1, pressure time-series measured by some sensors exhibited bimodal flow behavior, which appeared to alternate between two states. These flow states differed in either their mean value, or the fluctuation magnitude, or both. Therefore, variation of the mean and standard deviation values within pressure time-series for all sensors on the model can be utilized to identify bimodal flow. During the 2022 wind-tunnel test, unsteady pressure measurements for all model sensors were acquired in a time-correlated manner in 15 second data records at a 16,000Hz sampling rate using differential pressure sensors. Each pressure time history was first non-dimensionalized using the free-stream dynamic pressure. The coefficient of pressure was then windowed using a 0.025s time segments and statistics on each window were computed. For each sensor, the resulting set of mean values can be plotted versus the set of standard deviation values to create a scatter plot. For example, Figure 5a shows a scatter plot for N01 sensor located at azimuth location of 45° and free-stream Mach number of 0.85, and at 4° pitch angle of the model.

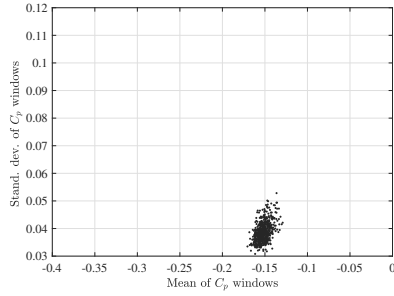
The influence of Mach number on this mean-standard deviation scatter plot was examined by performing the same analysis on a range of Mach number data. In this dataset, data were collected at predetermined free-stream Mach numbers between 0.85 to 1.18. The model attitude remained fixed at pitch angle of 4° . The resultant series of scatter plots is shown in Figure 5. For Mach Numbers 0.85 to 0.98, the scatter plot is centered around the same region with mean value roughly -0.15 and standard-deviation value of 0.04. At Mach number 1.05, the centroid of scatter plot increases to about -0.08 along the mean C_p axis. At Mach number 1.10, the scatter plot concentrates around two distinct regions. Each region is associated with data from one of the two bimodal states. Finally, for Mach values of 1.15 and 1.18 the mean component of the centroid of the scatter cloud decreases to roughly a value of -0.33. Simultaneously, the value of standard deviation for these data points is also increased.



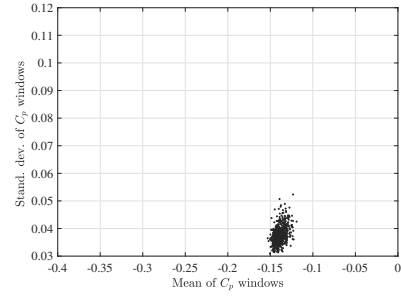
(a) $M=0.85$



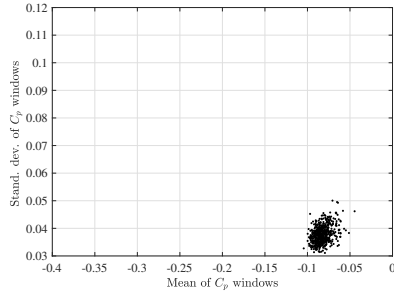
(b) $M=0.90$



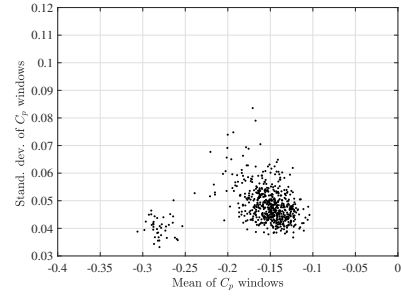
(c) $M=0.98$



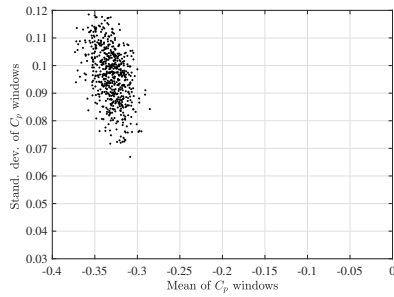
(d) $M=1.05$



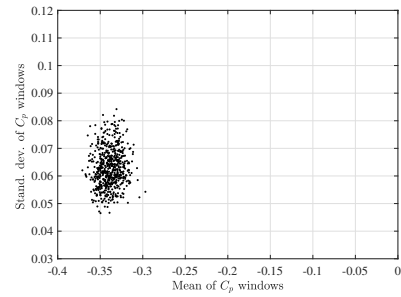
(e) $M=1.05$



(f) $M=1.10$



(g) $M=1.15$



(h) $M=1.18$

Fig. 5 The mean-standard deviation scatter plot of windowed C_p signal for (a) $M=0.85$ (b) $M=0.90$ (c) $M=0.95$ (d) $M=0.98$ (e) $M=1.05$ (f) $M=1.10$ (g) $M=1.15$ (h) $M=1.18$, $\alpha = 4^\circ$, $\beta = 0^\circ$, Station N01 and 45° azimuth angle.

A procedure was developed to identify and separate the bimodal cloud, such as the one in Figure 5(f), into two states. The analysis first computes a two-dimensional histogram from the mean-standard deviation data. The window size used to compute the histograms was chosen to provide enough fidelity to accurately identify the distinct peaks of

associated with two flow states. A sample histogram for data at $M = 1.10$ and pitch angle of 4° is shown in Figure 6(a). The locations of the two peaks in the histogram corresponds to the locations of centroids of the two states in the mean-standard deviation space. A line was calculated connecting the two centroids. Along that line, the histogram values were extracted and a location of minimum was identified. A perpendicular line passing through the location of that minimum is the threshold differentiating the two flow states. All points to the left of this line are labeled as State 2 and all points to the right are labeled State 1. This process is illustrated in Figure 6(b). The two centroids associated with each state are denoted by black circles. A solid black line connects the two centroids and the dashed line represents the threshold between the two states. For clarity, light red-colored data indicate State 2, while light blue-colored data indicate State 1.

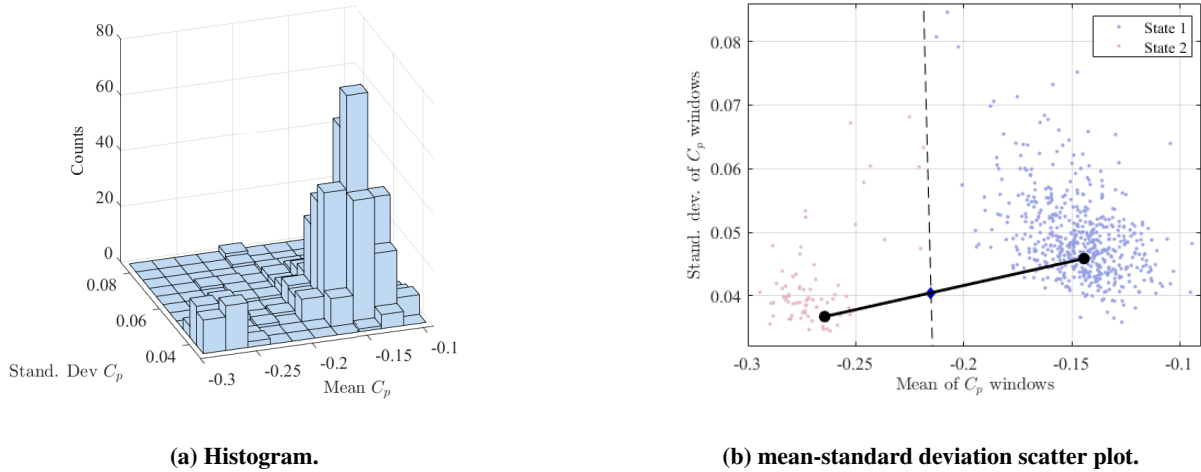


Fig. 6 (a) Histogram used in the state identification algorithm (b) characterized mean-standard deviation scatter plot, Mach 1.10 and $\alpha = 4^\circ$, $\beta = 0^\circ$, Station N01 and 45° . azimuth angle.

Pressure time histories that did not exhibit flow switching behavior remained entirely in either State 1 or 2. To characterize this flow, the location of associated scatter plot centroid was compared to a location of a scatter plot centroid associated with known State 1 and State 2 datapoints. If the location of the centroid was closer to the centroid location of time histories for a data point at zero model pitch angle and $M = 1.15$ condition, which was verified to be in State 2, then the flow in question was characterized as being in State 2. If the centroid location was closer to a verified State 1 flow, such as visually verified for model pitch angle 0° and $M = 0.70$ data point, then the flow was characterized as State 1.

A computer algorithm based on the above procedure can efficiently analyze all test data and identify test conditions and sensors which exhibit bimodal flow behavior. Cases where the algorithm does not find two distinct histogram peaks indicate that no flow state transition occurred. Cases where two peaks are identified, the pressure time history is separated and classified into States 1 and 2.

The algorithm described above is also able to quantify the percentage of time the signal represents either flow for each sensor. Four plots in Figure 7 show the percentage of time that State 2 occurs as a function of Mach number and model pitch for each of the pressure transducers at sensor station N01 located at azimuth angles 45° , 135° , 225° , and 315° . It can be seen that all data points collected at Mach numbers below a value of 1.10 remained in State 1 the entire duration of the data collection period. Conversely, data points collected at Mach number 1.15 remained the entire time in State 2. Mach 1.10 data, as shown in the time series above, did exhibit state switching. The percentage spent in State 2 initially appears random and no trend with pitch angle is evident. However, further examination does reveal certain notable features. For some angles of attack, the fluctuating pressures measured at azimuth angles 45° and 225° are often correlated as evident by noting that contour plot shows pressure in both sensors resided in State 2 majority of the time at $M = 1.10$ and pitch angles from -5° to 1° . Similarly, the pressure at azimuth 135° and 315° also seem to be correlated as evident both sensors residing mostly in State 1. It is also possible to observe a condition, such as sensor at azimuth 315° at $M = 1.10$ and pitch angle 4° , which resides predominantly in State 2 while the other three sensors exhibit pressure predominantly in State 1. This indicates that flow at some azimuthal angles exhibited transition from state to state completely independent of other azimuthal angles same station.

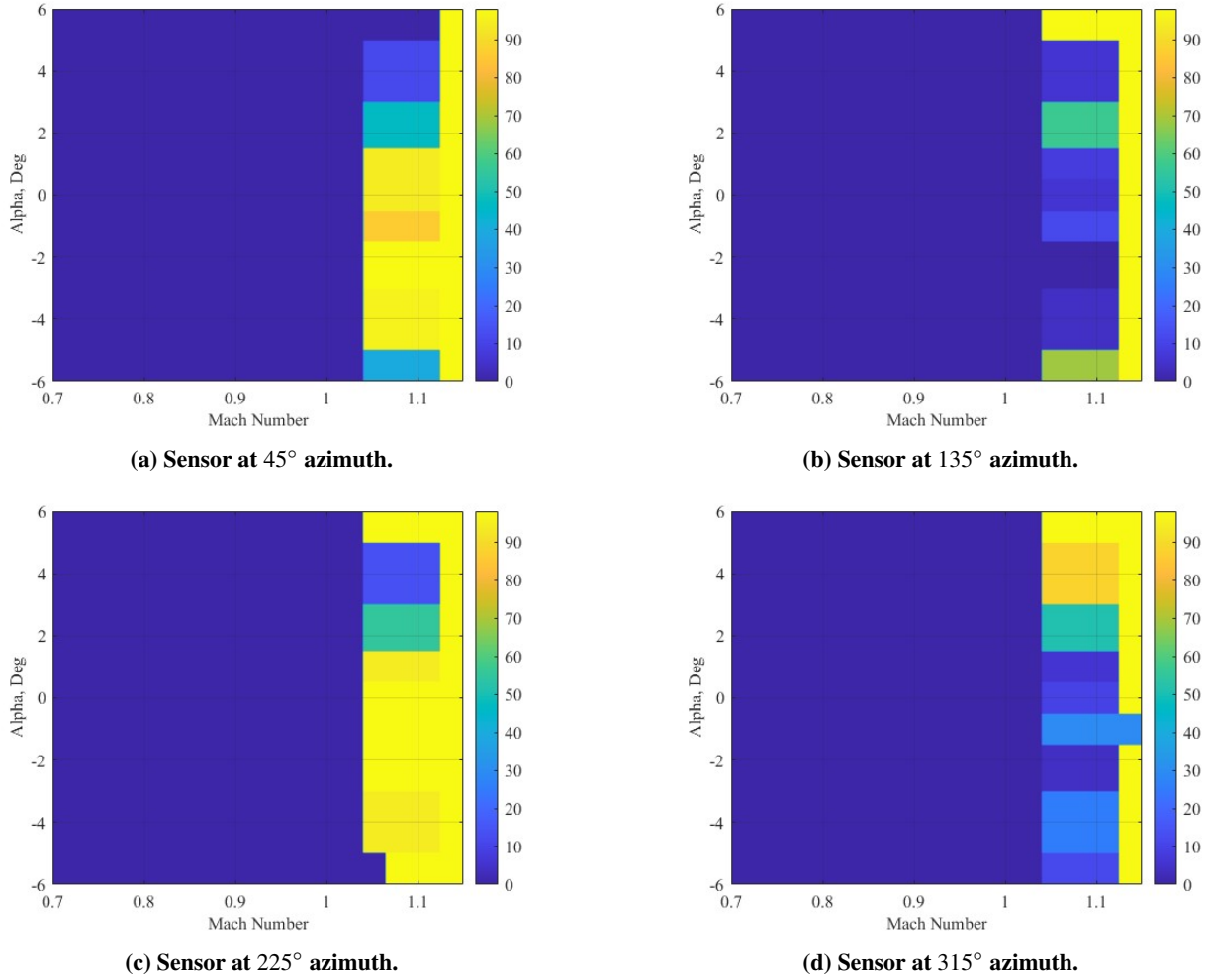


Fig. 7 Percent time signal is spent in State 2 for Mach sweep at model α angles from -6° to 6° .

The synchronization in state switching around the circumference at a model station, or lack thereof, can be better visualized with the processed mean-standard deviation scatter plot and the associated time-series shown in Figure 8, where the signal was color coded to identify the two states. In the Figure 8(a), processed data for all four sensors at longitudinal station N01 at a pitch angle 4° is shown. The classified mean-standard deviation scattered plot is shown in the left columns. The right column of plots shows the time series for the associated sensors where segments of the time history are color-coded based on whether the algorithm classified each time segment as State 1 or State 2. Overall, switching occurs in sync among all sensors. This synchronization is evident in the transition from one state to another at about 5.68s. However, it should be noted that pressure at 45° , 135° , and 225° transition from State 1 to State 2, while pressure at 315° from State 2 to State 1. This observation indicates that multiple azimuthally-localized flow state regions can exist at a single vehicle station, but the choice of flow states within each region is coupled to the other regions flow states.

This coupled behavior between azimuthal flow state regions is not the only mode of bimodal flow state switching. Figure 9 presents classified scatter plots and pressure time histories measured at station N01 at a Mach of 1.10 and a -4° angle of attack. The measured pressure time history at azimuth 315° shows a nearly-independent flow state switching compared to azimuthally-adjacent measurements at 45° and 225° , while measurements at 45° , 135° , and 225° show a clear coupling of the local flow states. Based on the frequent nature of the state switching at 315° azimuth, this particular flight condition (Mach and attitude) makes the local flow field more sensitive to potential events that can trigger a flow state change.

The pressure measurements presented in Figs. 8 and 9 indicate that this bimodal behavior can change depending

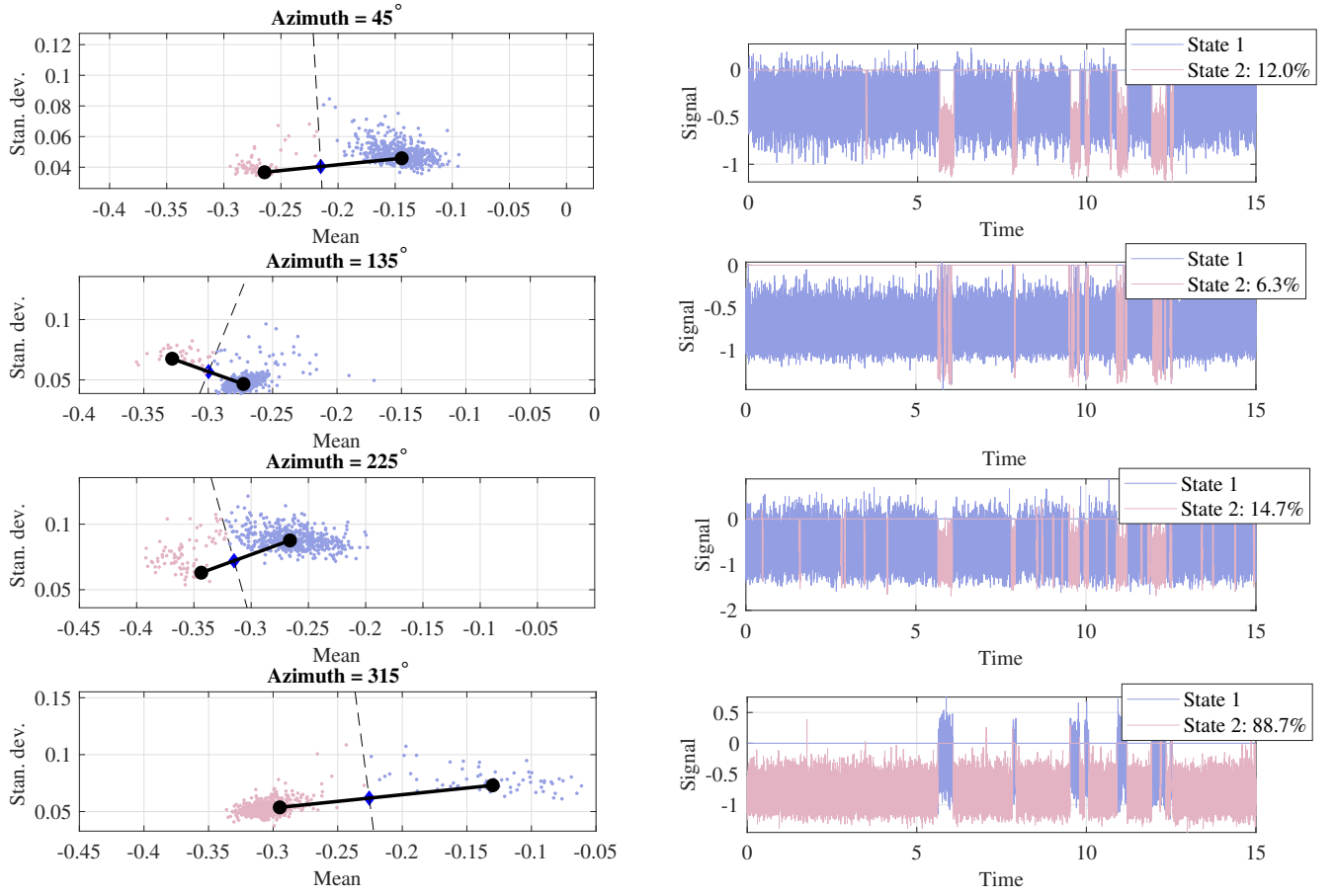


Fig. 8 Classification of flow states (a) mean-standard deviation scatter plot and (b) time-series, $M = 1.10$, model $\alpha = 4^\circ$, $\beta = 0^\circ$, Station N01.

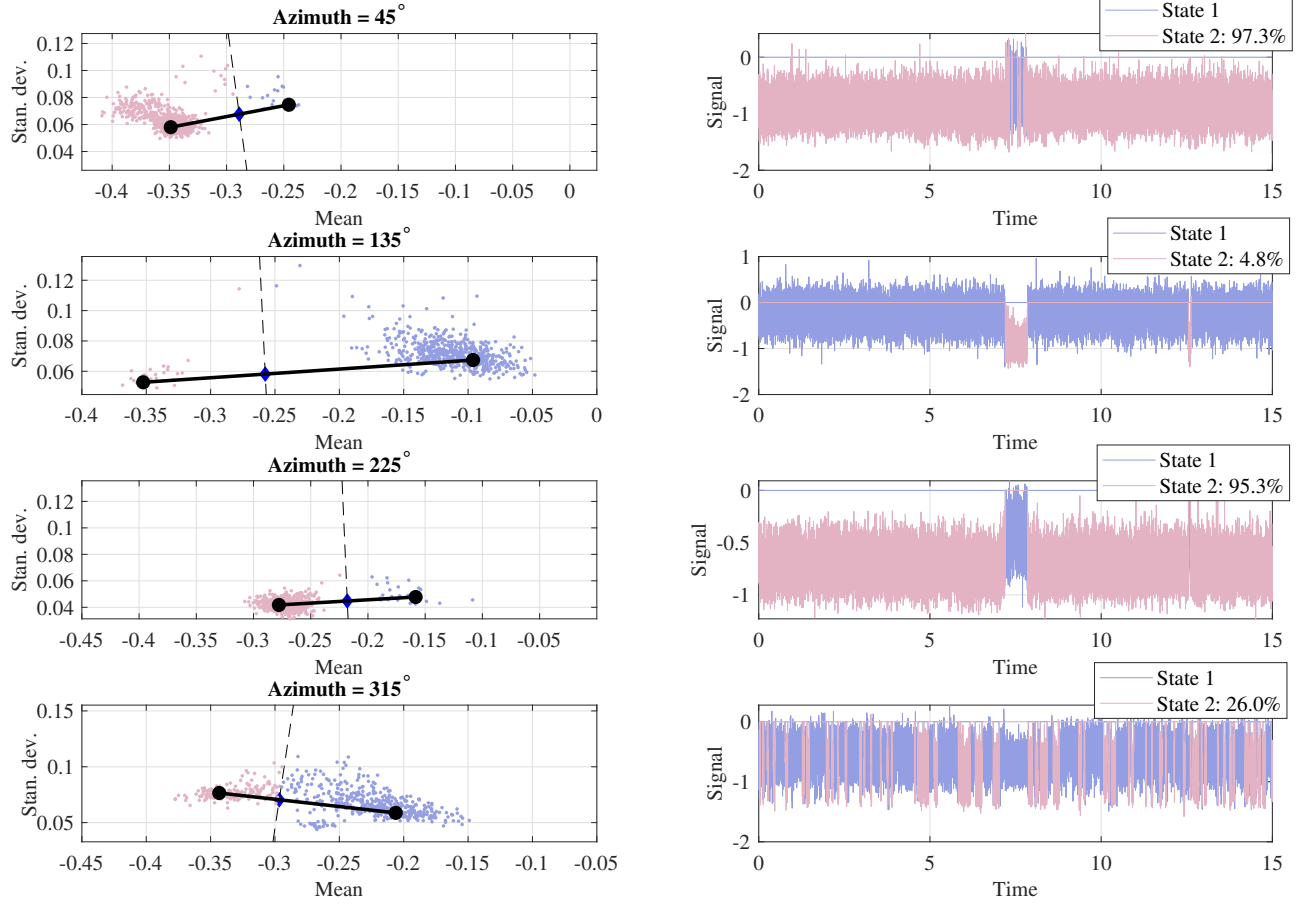


Fig. 9 Classification of flow states (a) mean-standard deviation scatter plot and (b) time-series, $M = 1.10$, model $\alpha = -4^\circ$, $\beta = 0^\circ$, Station N01.

on the vehicle attitude. Therefore, how it manifests itself during flight will be trajectory dependent. Since there is a possibility of each local flow field switching states independently of the others, there is a number of possible combinations of local flow states that can exist at a given longitudinal station.

After characterizing the state switching behavior, it is now of interest to assess how different combination of states affect the resulting Buffet Forcing Function. The initial step in BFF development is to integrate the pressures into sectional (force/length) loads as shown in Equation 1, where r is a local radius of the outer mold line, R is the reference radius, C_P is the non-dimensionalized pressure for the i -th sensor, and θ_i and θ_{i+1} are the azimuthal angles bounding the sensor circumferential integration. For sensors located at azimuth angles 45° , 135° , 225° , and 315° , bounding the pressure integration angles were 0° , 90° , 180° , and 270° .

$$C_{fy} = \sum_i C_{P_i} r / R [(\cos \theta_{i+1} - \cos \theta_i)] \quad (1)$$

To better observe the switching behavior in C_{fy} , the pressure time-series were smoothed using a moving average approach and the sectional non-dimensionalized force was then computed. The result of this calculation is shown in Figure 10(a) for a free-stream Mach number 1.10 and model pitch angle of 4° . As expected, in the presence of the bimodal behavior in the pressure time histories, the sectional force also exhibited a multi-modal behavior. The most prominent switching of flow states occurs at the times identified by green arrows in Figure 10(a). However, since local flow states can switch independently of the others, bimodal behavior can manifest itself in multiple ways or modes. From Figure 10(a) it is, however, difficult to identify other modes. Therefore, instead of using a raw non-dimensional pressure in Equation 1, a binary values were assigned to each pressure state. For State 1, a constant pressure of value -1 was assigned. Similarly, for State 2, a constant value of -2 was assigned to pressure. Summing these binary representation of the local flow states simplifies the identification of what bimodal flow field state is occurring by accentuating the various combinations of local flow states, as shown in Figure 10(b). In the example provided in Figure 10(b), four separate states are identified. Some of these states, highlighted with purple arrows, become more evident when Figure 10(a) is reexamined.

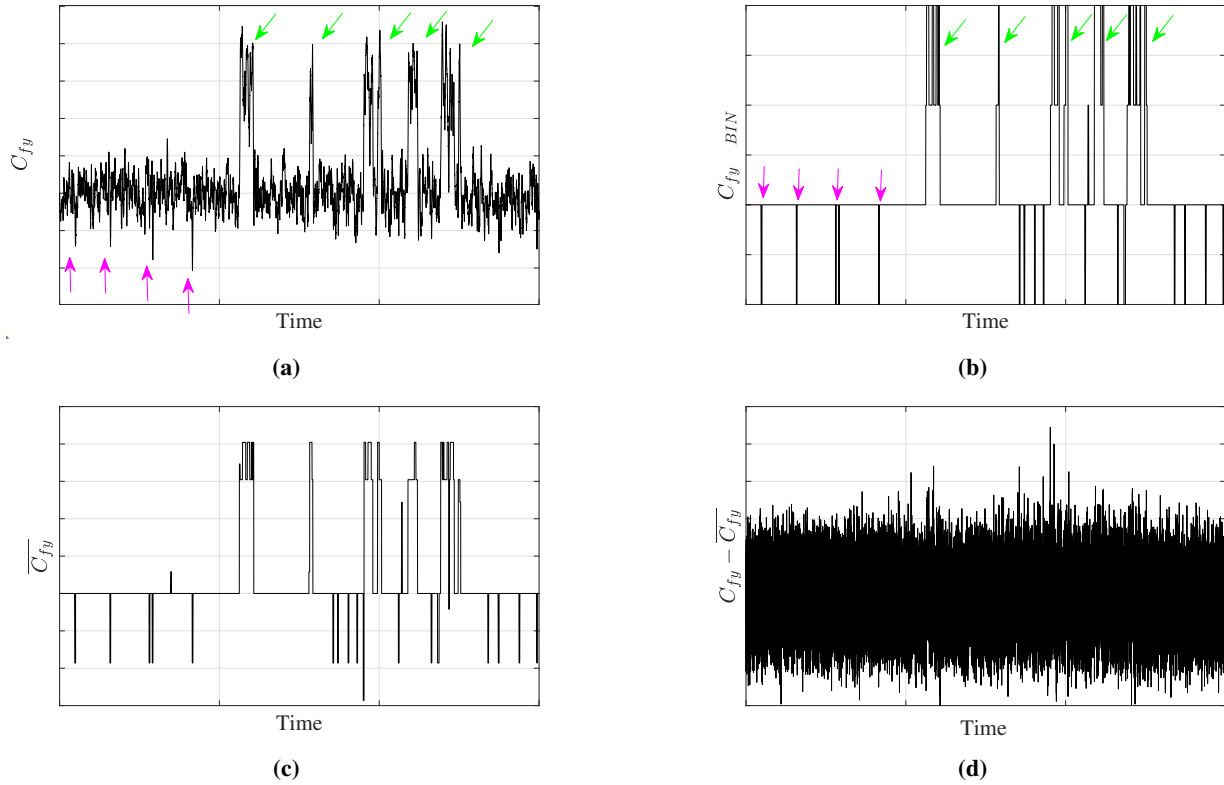


Fig. 10 Non-dimensional force (a) low-pass filtered time series, (b) computed using a binary values assigned to pressure value at each state, (c) computed using a constant mean pressure value assigned as pressure at each state, (d) detrended time series, at sensor station N01, Mach number 1.10, and $\alpha = 4^\circ$, $\beta = 0^\circ$.

The next step in this analysis is to determine the range of net force values due the changes in the quasi-steady mean pressures measured by each sensor. For each pressure time history, the binary values used to identify the two flow states, -1 or -2 , are replaced by the mean pressure corresponding to each flow state. Figure 10(c) presents the net quasi-steady force as a function of time, once the mean pressure components are integrated around the model circumference. Similarly for Figure 10(b), the distinguishable states are clearly seen in the sectional force time history, thereby bounding the range of impulsive loading produced by the abrupt change in the mean pressures due to a change in the local flow field. This mean-pressure-based net force can be subtracted from the integrated sectional force to isolate the fluctuating component of the sectional force as shown in Figure 10(d). The quasi-steady mean sectional force shown in Figure 10(c) can be more simply developed by integrating the pressure time histories and calculating a moving mean of the resulting forces, but the additional steps outlined above provide insight into the flow state switching process that can be leveraged to develop BFFs that are more representative of the flow state change as it occurs in the nonstationary environment present during flight.

The above procedure was extended to the dataset consisting of data points collected at a range of Mach numbers and model pitch angles. To assess the overall trends of bimodal flow behavior, a more general quantification of how the flow state switching affects the quasi-steady mean and fluctuating components of the sectional force is conducted. In particular, the mean and standard deviation of the quasi-steady mean forces (sample presented in Fig. 10(c)) and the standard deviation of the sectional force fluctuating component (sample is provided in Figure 10(d)) are determined for each test condition and the results are shown in Figure 11. The overall mean of the sectional force is shown in Figure 11(a) and, in subsonic regime, exhibits positive force for the negative pitch angles and negative force for the positive pitch angles. This trend is consistent with one side of the model being exposed to the flow on a leewards side when the model is at a non-zero pitch angle, creating a mean force. This trend breaks down around Mach 1.10 as the mean force is no longer solely dependent on the model pitch but also on the bimodal flow state switching. The fluctuation of the quasi-steady mean sectional force trend due to the state switching is shown in Figure 11(b). As expected, all values are nearly zero value except for around Mach number value 1.10. Lastly, the fluctuation of the detrended sectional force is seen in Figure 11(c). The most realistic modeling of the sectional force would involve a combination of the force trend fluctuation and the force fluctuating component. The duration in time where the forcing function will be influenced by the variation in the trend depends on the acceleration of the vehicle.

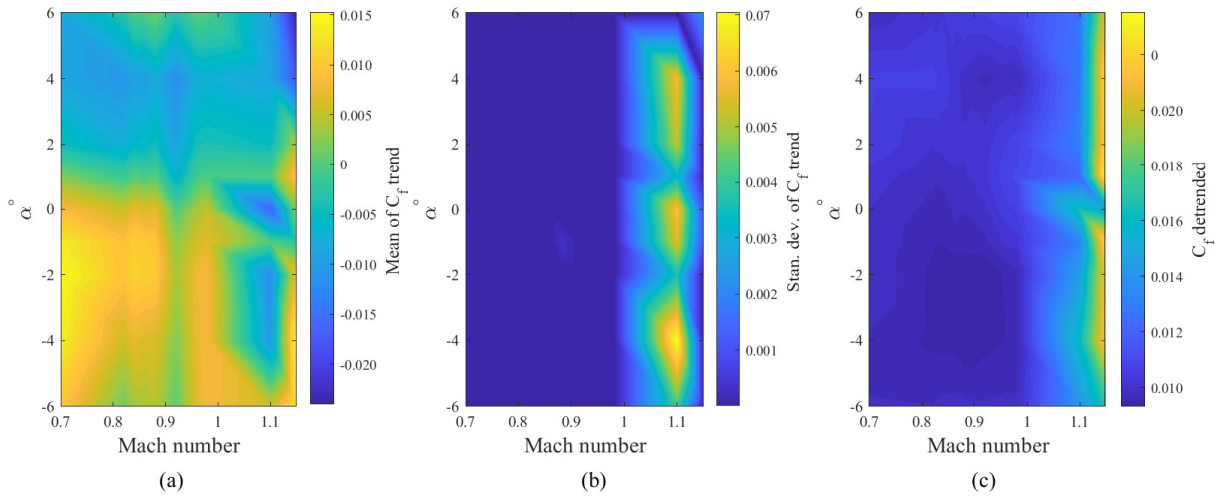


Fig. 11 Non-dimensionalized force (a) the mean of the trend, (b) standard deviation of the trend, and (c) the detrended fluctuating component, computed at sensor station N01.

Conclusion

A recent wind-tunnel test revealed a bimodal flow phenomenon associated with the Launch Abort System (LAS) nozzles of the Space Launch System model that occurred at Mach 1.10. The pressure time histories measured downstream of the LAS nozzles fluctuated between two distinct flow states even as the free-stream flow conditions were

nominally steady. The switching between flow states occurred near-simultaneously in all the measurements acquired around the vehicle circumference at a single station, although there were instances when the flow state change was more localized, visible in only a single measurement. This bimodal phenomenon differed from well known transonic bimodal flow occurring at large-angle expansion corners where the flow oscillates between separated subsonic flow and attached supersonic flow. Both of these bimodal phenomena can result in large, impulsive loads that act on a launch vehicle, which are not often considered as a loading case.

The present work proposed a method to identify the presence of bimodal flow that is agnostic to the bimodal flow physics. Furthermore, the work outlined a method of characterizing the impact of the bimodal flow on buffet forcing functions by identifying the range of changes in the quasi-steady mean and fluctuating components of the integrated line loads and how they are affected by model attitude and free stream Mach number.

Future efforts will focus on utilizing the analytical tools presented in this work to develop trajectory-dependent buffet forcing functions that appropriately model the bimodal flow behavior in an accelerating flow field experienced by a launch vehicle.

References

- [1] Voegele, A. P., and Sirignano, M., "Simulating Buffet Aerodynamics of a Hammerhead Model Using Hybrid RANS-LES CFD Modeling," *AIAA SCITECH 2023 Forum*, 2023. <https://doi.org/10.2514/6.2023-0430>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2023-0430>.
- [2] Piatak, D., Sekula, M., and Rausch, R., "Comparison of Ares I-X Wind-Tunnel Derived Buffet Environment with Flight Data," *29th AIAA Applied Aerodynamics Conference*, 2011. <https://doi.org/10.2514/6.2011-3013>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2011-3013>.
- [3] Ramey, J. M., Sekula, M. K., Piatak, D. J., Heaney, P. S., and Soranna, F., "Development of Buffet Forcing Functions using Frequency-Dependent Coherence Factors," *AIAA SciTech 2021 Forum*, 2021.
- [4] Piatak, D. J., Sekula, M. K., and Rausch, R., *Sensitivity of Space Launch System Buffet Forcing Functions to Buffet Mitigation Options*, 2016. <https://doi.org/10.2514/6.2016-0544>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2016-0544>.
- [5] Sekula, M. K., Piatak, D. J., Rausch, R. D., Ross, J. C., and Sellers, M. E., "Assessment of Buffet Forcing Function Development Process Using Unsteady Pressure Sensitive Paint," *AIAA Aviation 2019 Forum*, 2019. <https://doi.org/10.2514/6.2019-3503>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2019-3503>.
- [6] Soranna, F., Heaney, P. S., Sekula, M. K., Piatak, D. J., Ramey, J. M., Roozeboom, N. H., Murakami, D. D., Baerny, J. K., Stremel, P. M., Jessica, J. L., and Powell, M., "Analysis of Buffet Forcing Functions Estimated from Unsteady Pressure Sensitive Paint," *AIAA Aviation 2020 Forum*, 2020.
- [7] Heaney, P. S., Soranna, F., Sekula, M. K., Piatak, D. J., and Ramey, J. M., "Analysis of Transonic Unsteady Aerodynamic Environments using Unsteady Pressure Sensitive Paint for the Space Launch System Block 1 Cargo Launch Vehicle," *AIAA SciTech 2021 Forum*, 2021.
- [8] Robertson, J., "Unsteady pressure phenomena for basic missile shapes at transonic speeds," *Aerospace Sciences Meeting*, 1964. <https://doi.org/10.2514/6.1964-3>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.1964-3>.
- [9] Chavalier, H., and Robertson, J., "Pressure Fluctuations Resulting from an Alternating Flow Separation and Attachment at Transonic Speeds," *Arnold Engineering Development Center Rept. TDR-63-204*, 1964.
- [10] Ericsson, L., "Steady and Unsteady Terminal-Shock Aerodynamics on Cone-cylinder bodies," *Lockheed Missiles and Space Company Report L-87-67-2*, 1967.
- [11] Rainey, A. G., "Progress on the launch-vehicle buffeting problem," 1965, pp. 289–299. <https://doi.org/10.2514/3.28174>, URL <https://doi.org/10.2514/3.28174>.
- [12] Cockburn, J., and Robertson, J., "Vibration response of spacecraft shrouds to in-flight fluctuating pressures," 1974, pp. 399–425. [https://doi.org/https://doi.org/10.1016/S0022-460X\(74\)80226-9](https://doi.org/https://doi.org/10.1016/S0022-460X(74)80226-9), URL <https://www.sciencedirect.com/science/article/pii/S0022460X74802269>.
- [13] Sekula, M., Piatak, D., and Rausch, R., "Analysis of a Transonic Alternating Flow Phenomenon Observed During Ares Wind Tunnel Tests," *28th AIAA Applied Aerodynamics Conference*, 2010. <https://doi.org/10.2514/6.2010-4370>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2010-4370>.

- [14] Piatak, D., Sekula, M., and Rausch, R., "Ares Launch Vehicle Transonic Buffet Testing and Analysis Techniques," *28th AIAA Applied Aerodynamics Conference*, 2010. <https://doi.org/10.2514/6.2010-4369>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2010-4369>.
- [15] Piatak, D. J., Sekula, M. K., and Rausch, R. D., "Ares Launch Vehicle Transonic Buffet Testing and Analysis Techniques," *Journal of Spacecraft and Rockets*, Vol. 49, No. 5, 2012, pp. 798–807. <https://doi.org/10.2514/1.A32175>, URL <https://doi.org/10.2514/1.A32175>.
- [16] Massey, S., and Chwalowski, P., "Computational Aeroelastic Analysis of Ares Crew Launch Vehicle Bi-Modal Loading," *28th AIAA Applied Aerodynamics Conference*, 2010. <https://doi.org/10.2514/6.2010-4373>, URL <https://arc.aiaa.org/doi/abs/10.2514/6.2010-4373>.