

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

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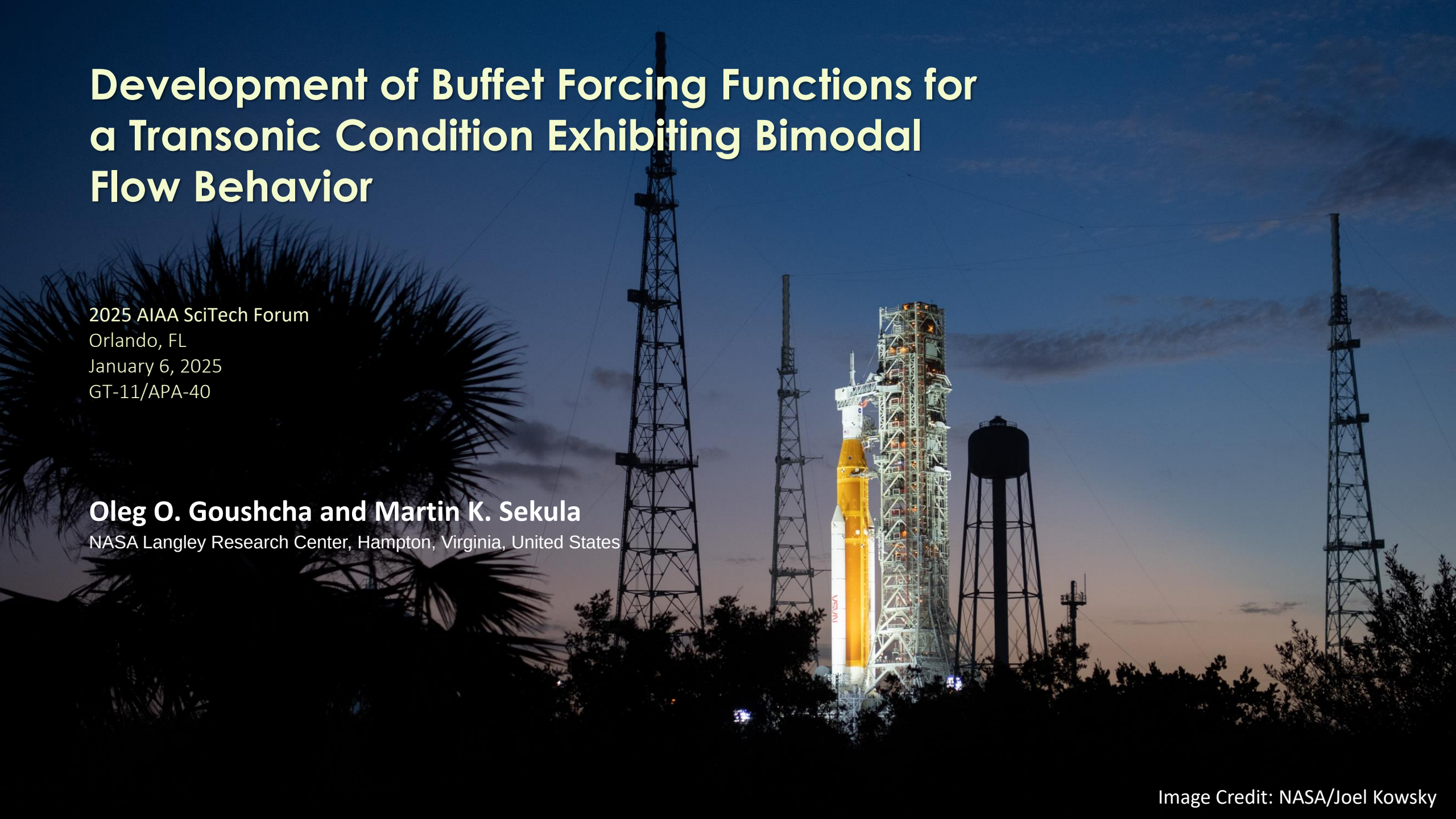


Image Credit: NASA/Joel Kowsky



Introduction

- A 2022 wind-tunnel test was conducted to characterize transonic buffet environment of a Block 1B Space Launch System (part of a broader SLS buffet test campaign)
- Bimodal behavior was observed in pressure signal under nominally-steady flow conditions
- Current methods for characterizing buffet environment, i.e. development for Buffet Forcing Function (BFF) are not appropriate for modelling this bimodal behavior
- Of interest is to develop a better approach to model the bimodal flow to more accurately predict the buffet environment in flight
- The approach should model bimodal behavior independent of the flow physics
- Current work is an initial step in this effort

Introduction: Buffet Environment Wind-Tunnel Test



- NASA Langley Transonic Dynamics Tunnel
- 3-percent Space Launch System Block 1B
- 466 unsteady pressure transducers were installed to capture surface pressure on the model
 - 42 longitudinal stations
 - At each station sensors were distributed axisymmetrically around the circumference
- Pressure measurements were integrated to produce orthogonal loads for each station

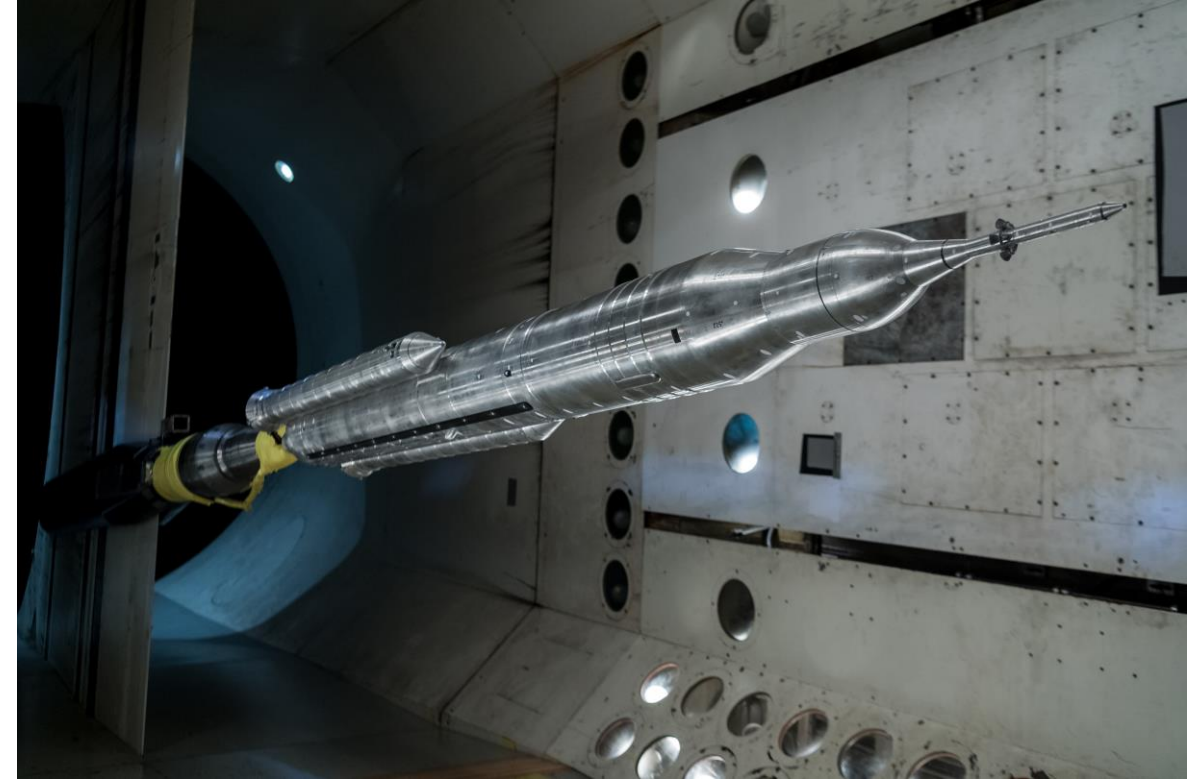
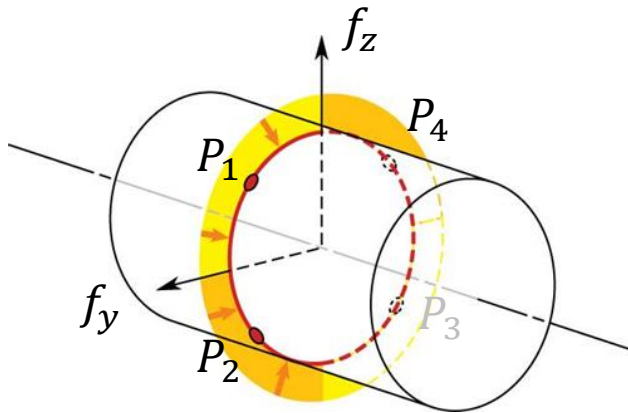
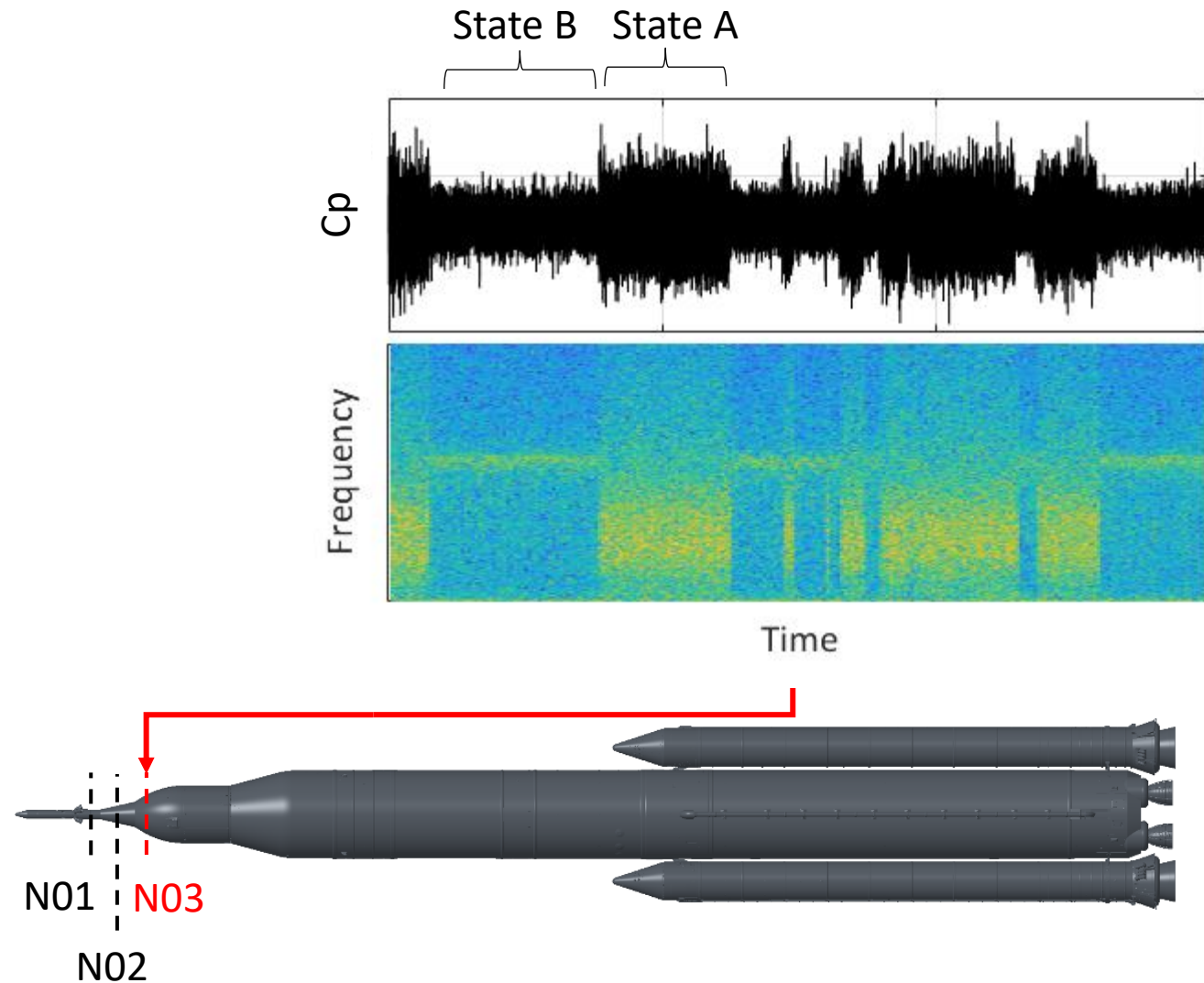


Photo: NASA

Bimodal Flow Downstream of Launch Abort System Observed



- Bimodal flow phenomenon observed in pressure data at $M=1.10$, $\alpha=2^\circ$, $\beta=0^\circ$
- Pressure oscillated between two states:
 - State A: more broadband frequency content with lower mean frequency
 - State B: Tonal, single dominant frequency content
- Integrating the pressure to develop BFF will produce continuously oscillating loads, instead of single or limited number of events



Bimodal Flow Investigation Background: Classic Studies



- Chevalier and Robertson 1963-1964: observed bimodal flow around expansion corners of a generic cone-cylinder geometry. Phenomenon described as *continuous and random switching between separated subsonic flow and attached supersonic flow*
- Ericsson 1967: expanded the bimodal flow study to include pitch angle dependency
- Rainey 1965, Cockburn and Robertson 1974: observed bimodal flow on launch-vehicle wind-tunnel models:
 - Mercury-Atlas
 - Saturn-Apollo
 - Atlas-Agena
- In the above references, the bimodal behavior occurred at an expansion corner

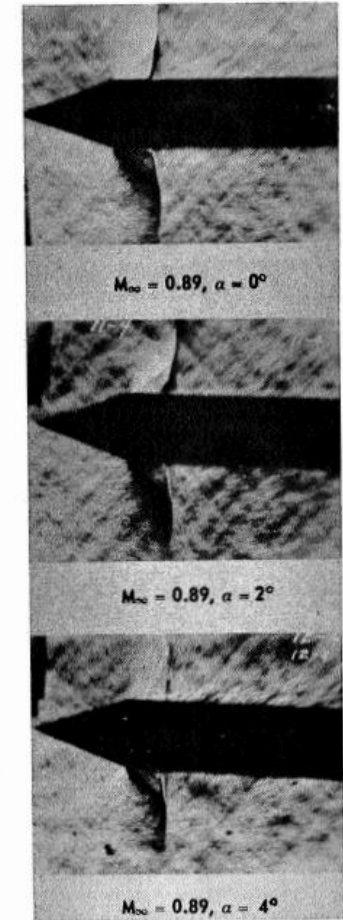


Fig. 2-1 Aerodynamic Characteristics at $M_{\infty} = 0.89$ of a 20° Cone-Cylinder Body With Separated Flow (Cont.)

Ericsson, L.E. "Steady and Unsteady Terminal Shock Aerodynamics on Cone-Cylinder Bodies." NASA Contractor Report (CR 61560).

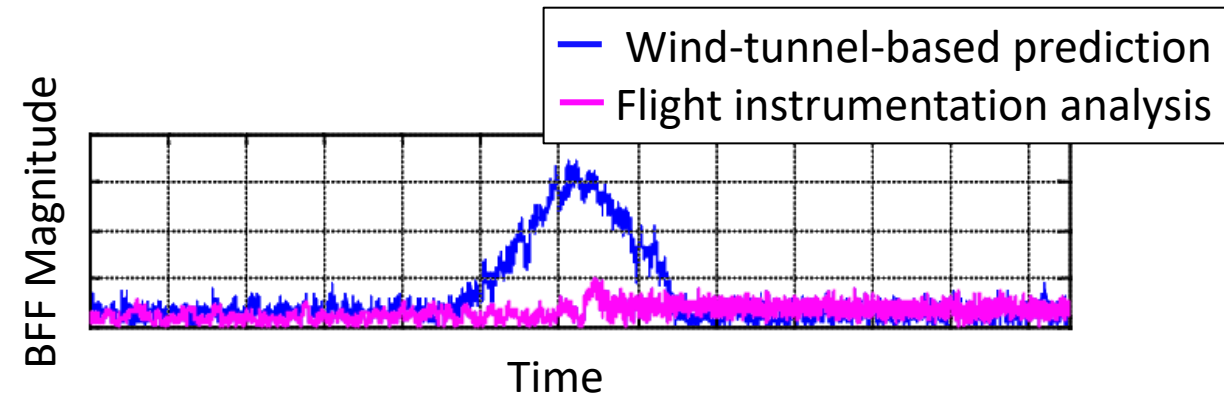
Bimodal Flow Investigation Background: Ares I-X

- Sekula, Piatak, Rausch 2010: observed bimodal flow in **buffet wind-tunnel test** on the upper stage simulator during the wind-tunnel test of the Ares I-X
- BFF was modelled
 - Identified a largest event by choosing a maximum RMS of a windowed time history
 - Window size chosen to excite the vehicle first bending mode
 - Hypothesized that in an accelerating flight vehicle spends short time in the critical Mach range where bimodal flow is possible and will allow for only single change in states
- Result was overly conservative BFF and did not accurately how bimodal flow manifest in flight

	Starting	Ending
Wind-tunnel	Subsonic	Subsonic
Flight	Subsonic	Supersonic



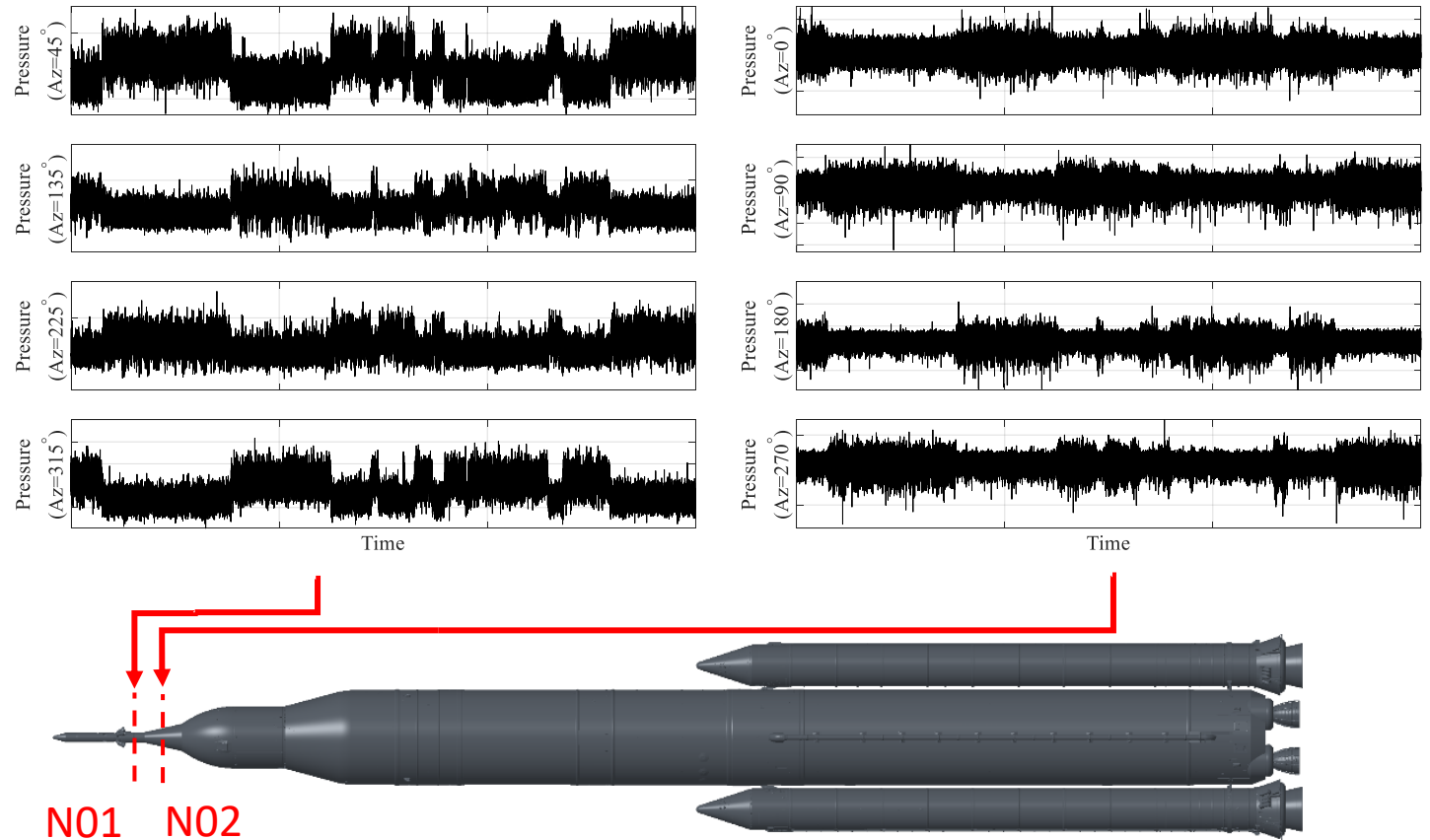
Photo Credit: NASA



Sekula, Piatak, Rausch 2010

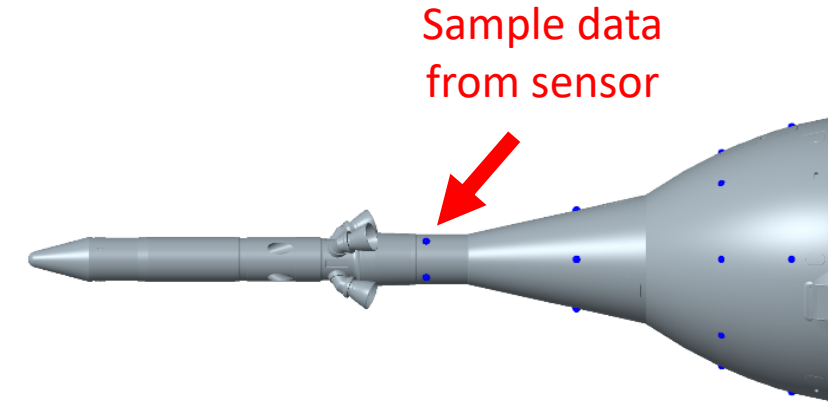
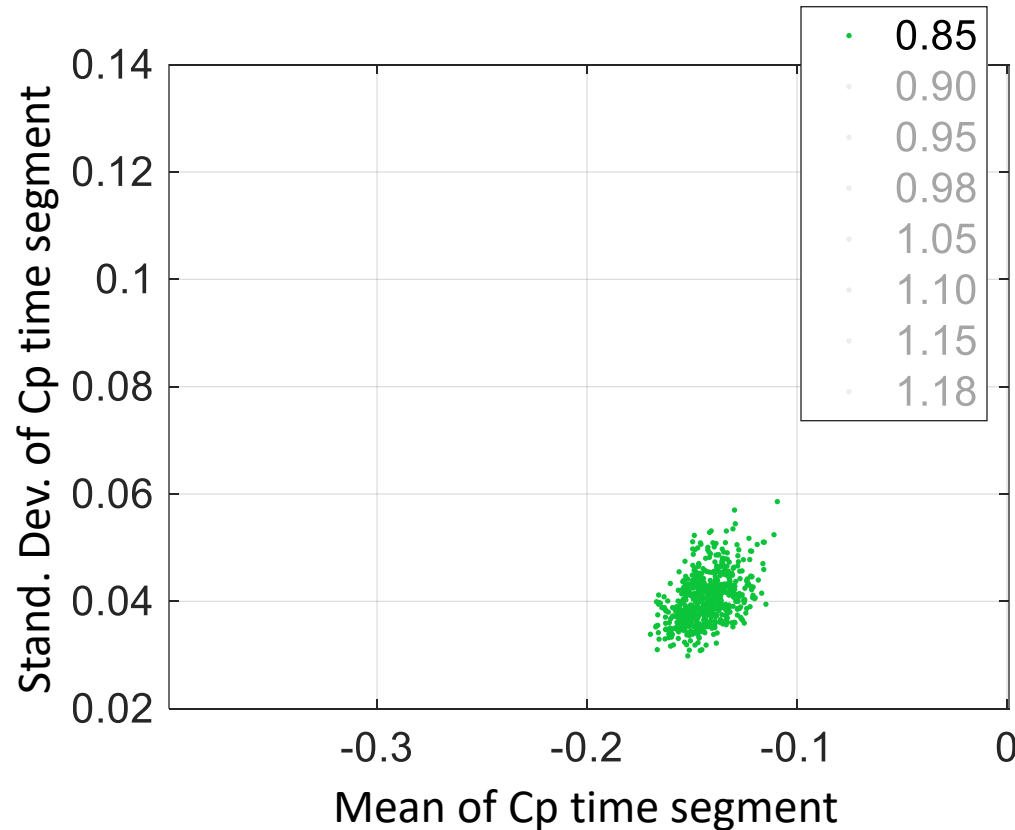
Automation of the State Characterization Process

- First, identify the presence of the bimodal flow
- Second, develop an approach to characterize the flow as two distinct states
- Observing pressure time histories at longitudinal stations N01 and N02:
 - At N01 the two states differ in mean value of the signal
 - At N02 the two states differ in amplitude of fluctuations
- It is natural to quantify the mean and standard deviation of windowed time histories



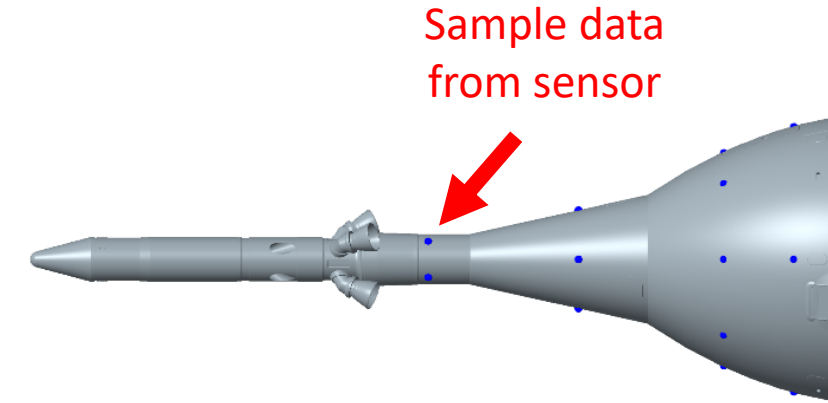
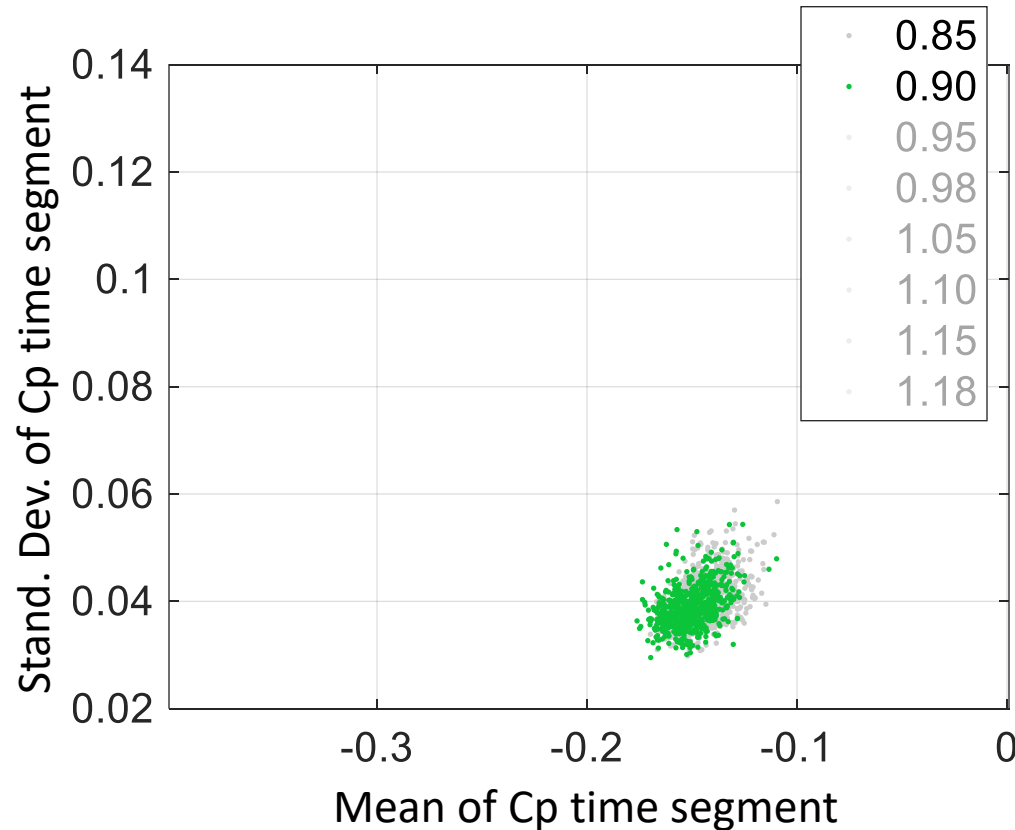
Mean – Standard Deviation Scatter Plot: Mach Variation

- The time history of pressure measured directly downstream of LAS at Azimuth 45°
- Time history is split into 600 time segments
- Mean and standard deviation of each window is computed
- Set of mean and std values is shown as a scatter plot (each dot represents a window)



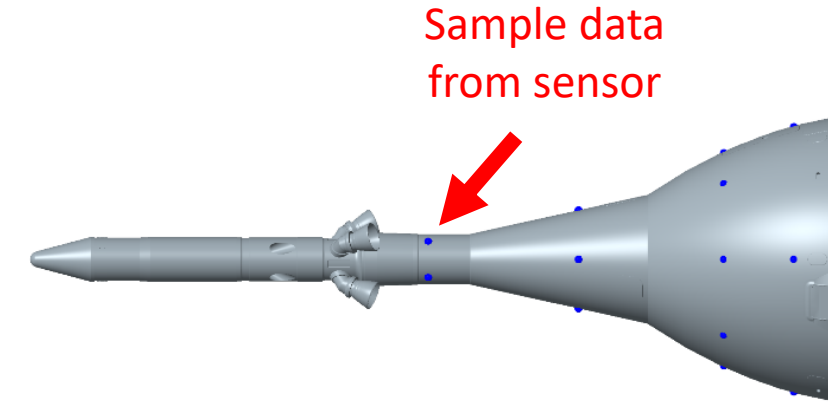
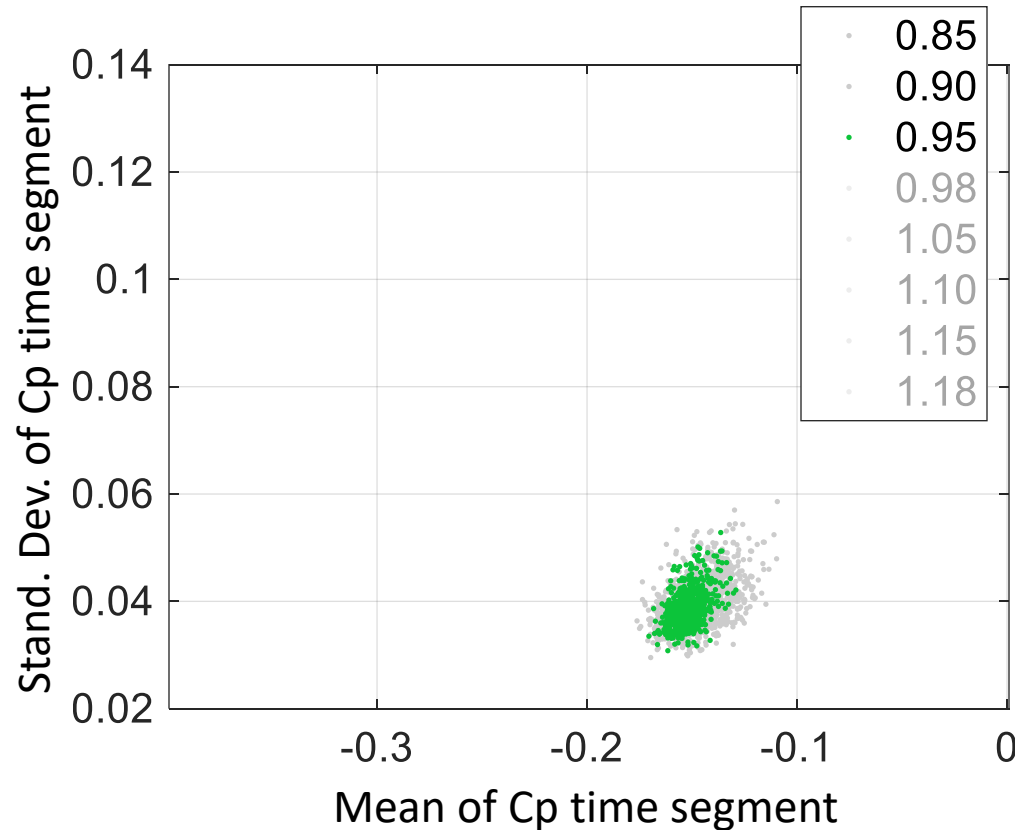
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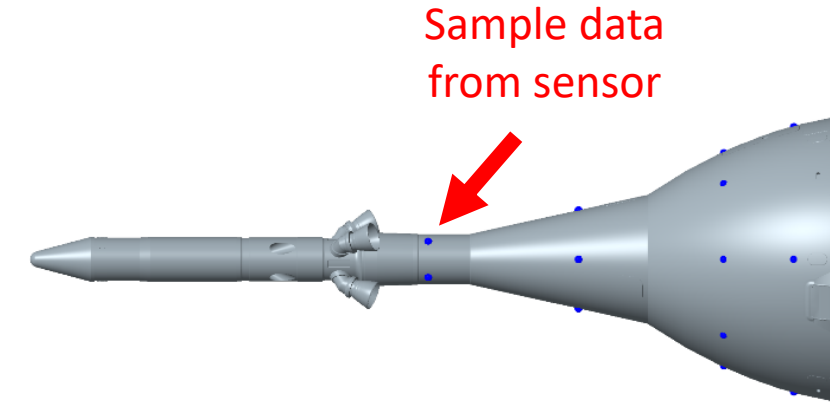
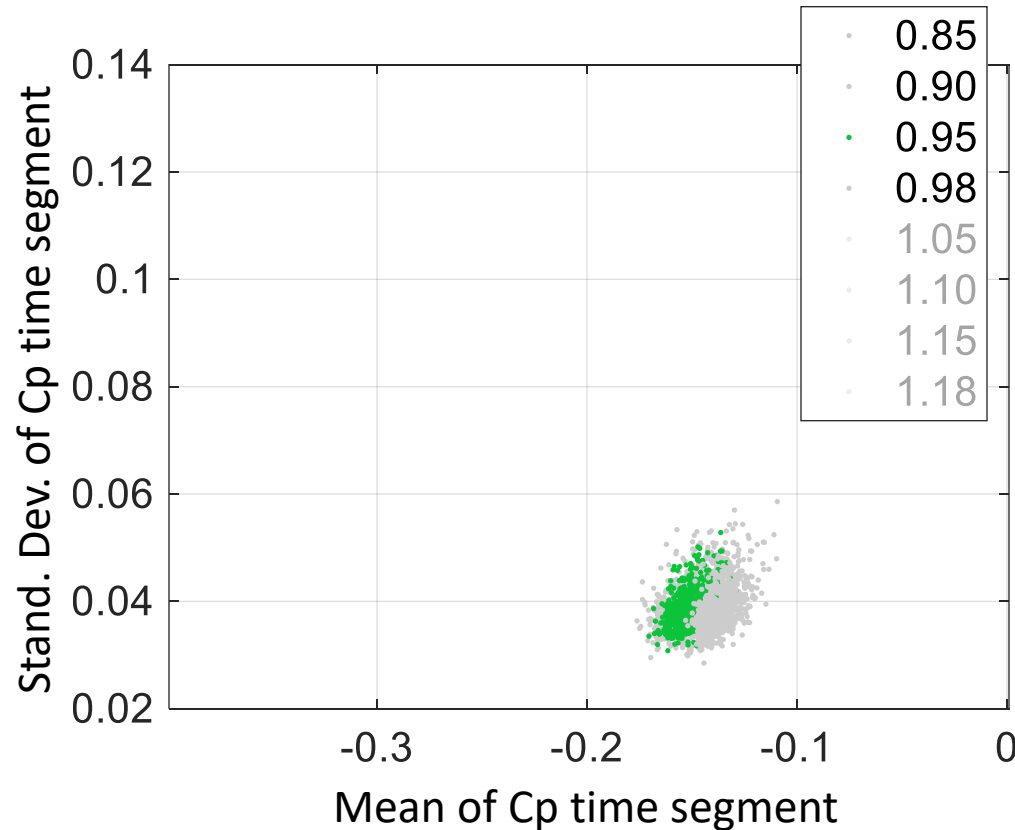
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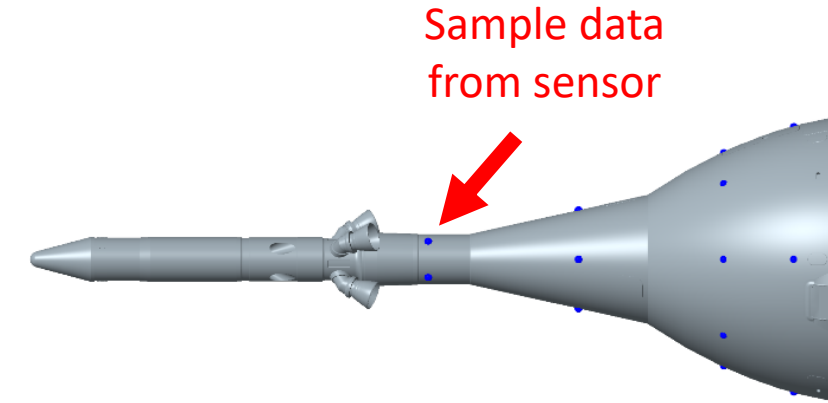
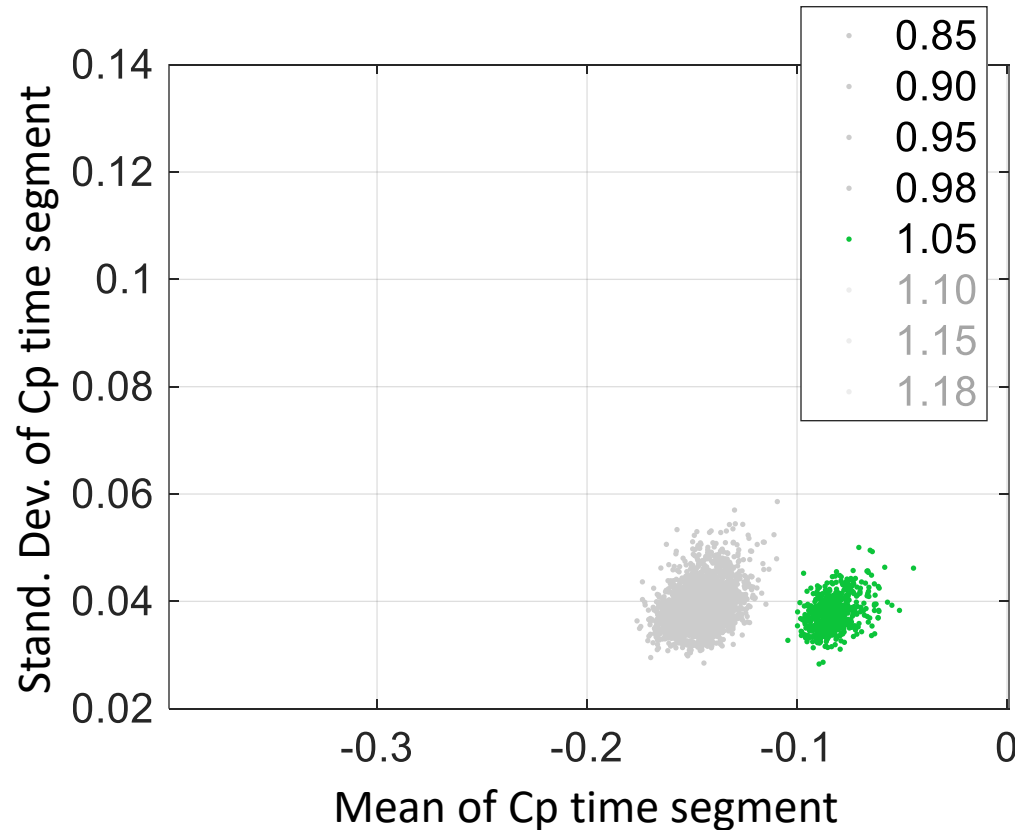
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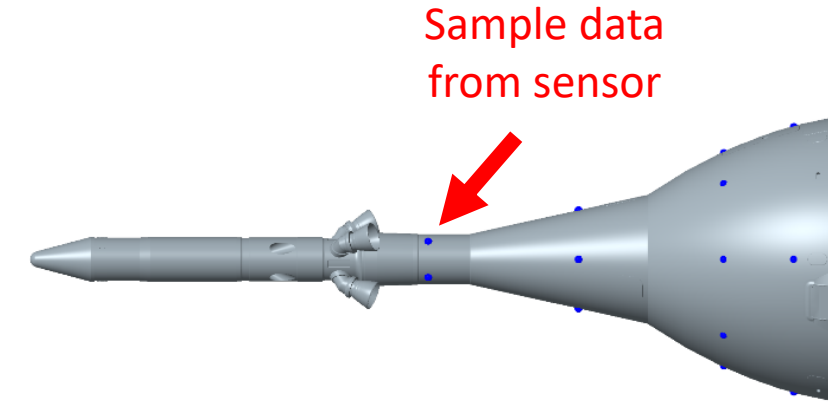
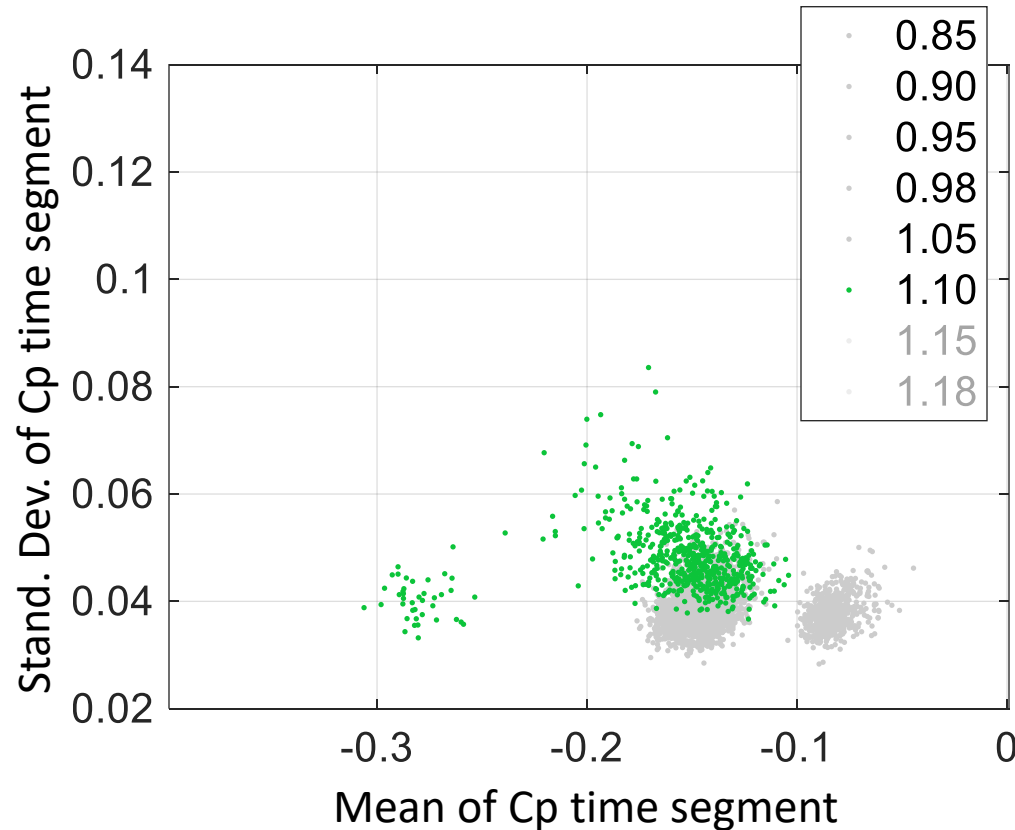
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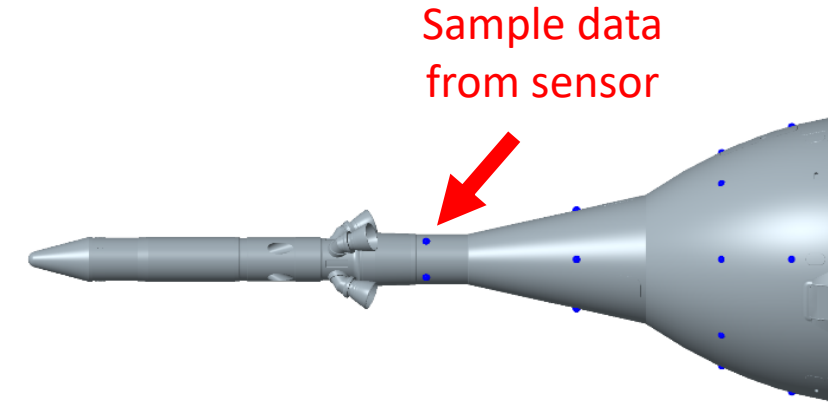
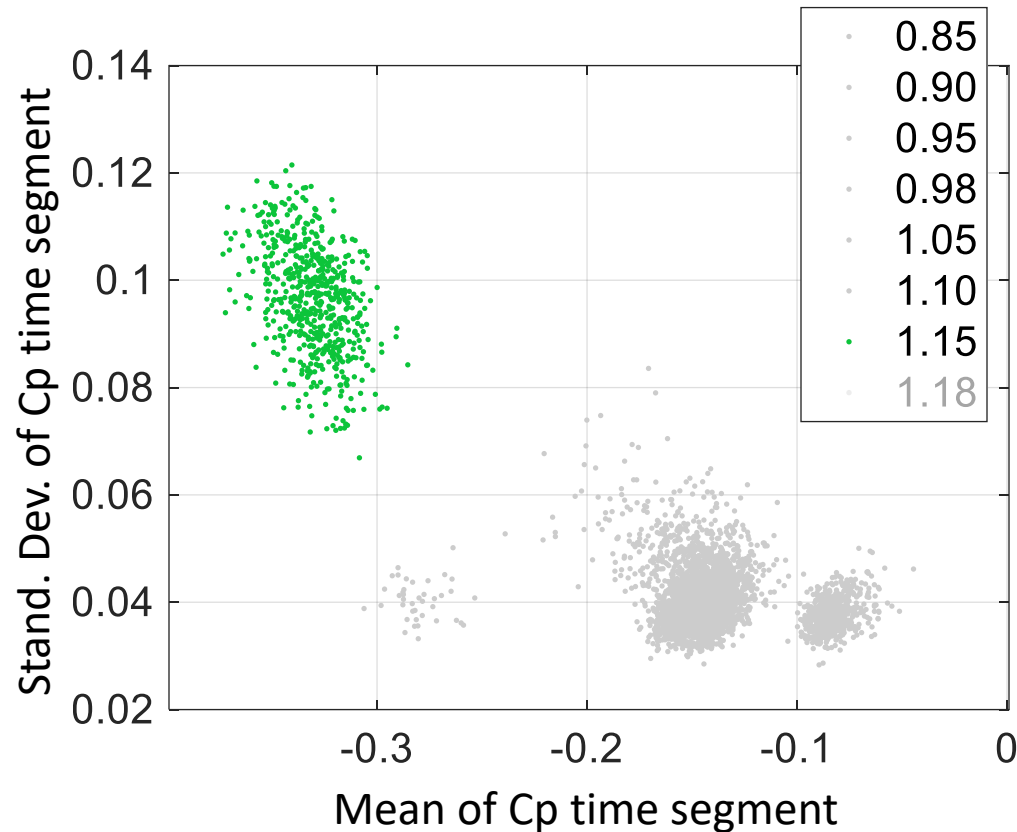
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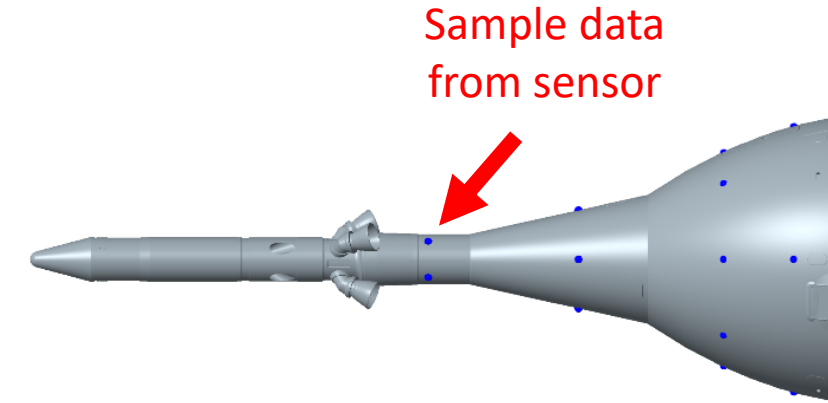
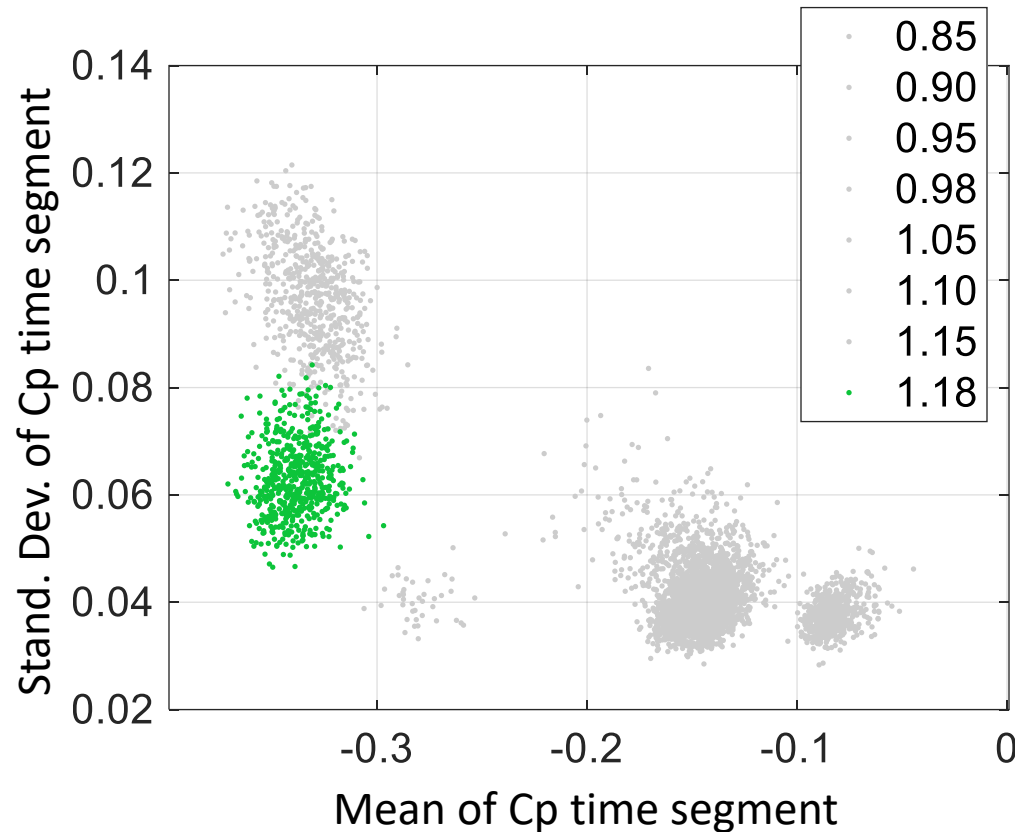
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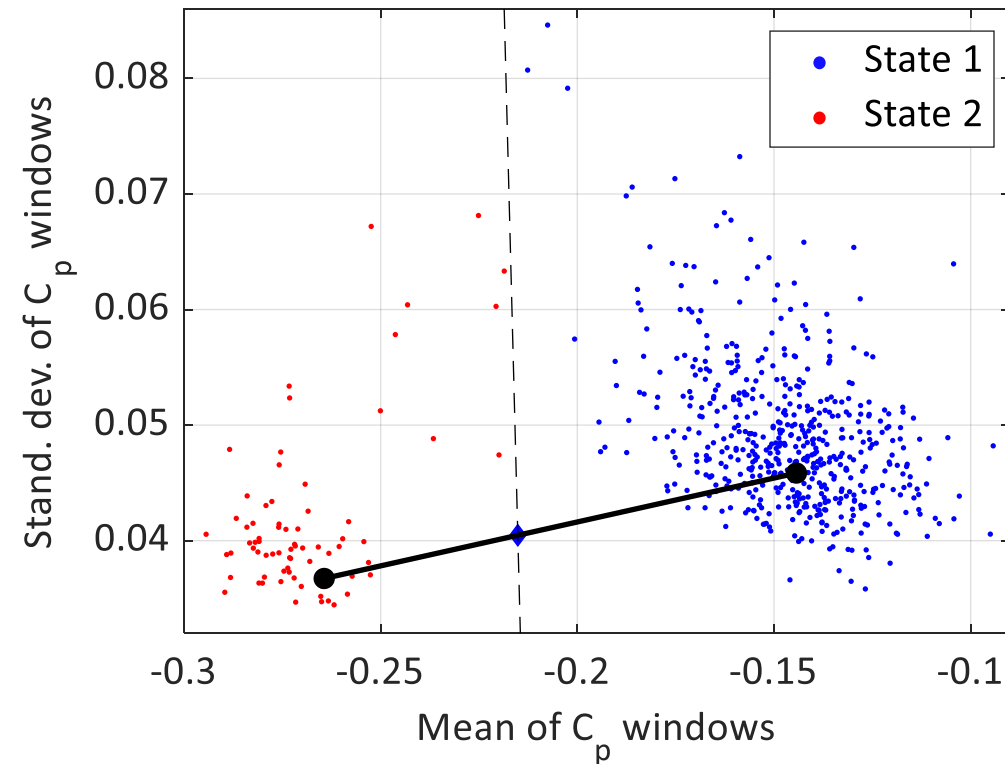
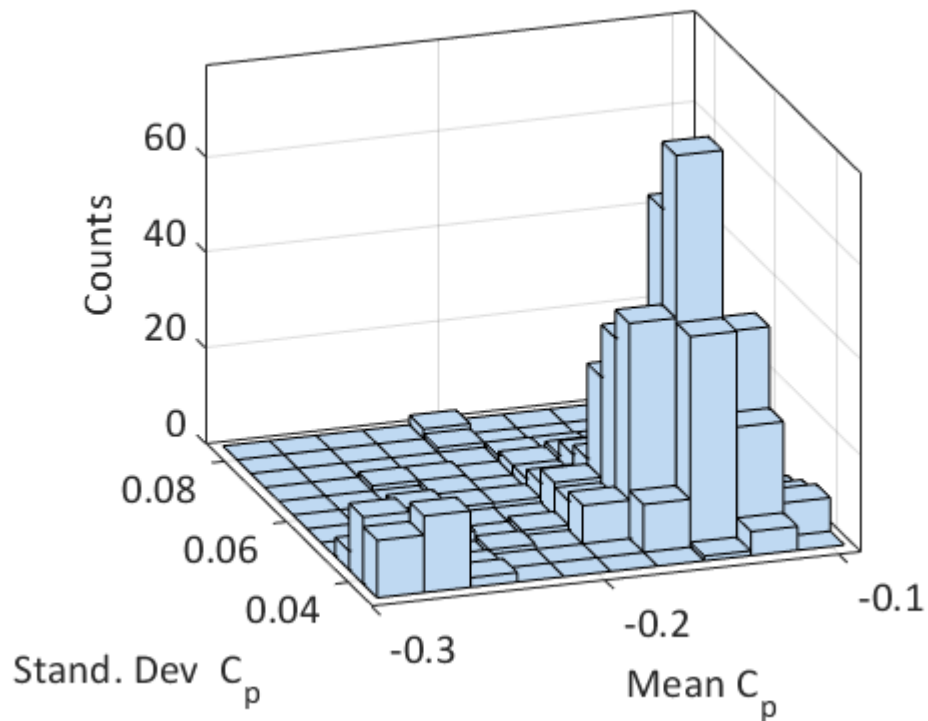
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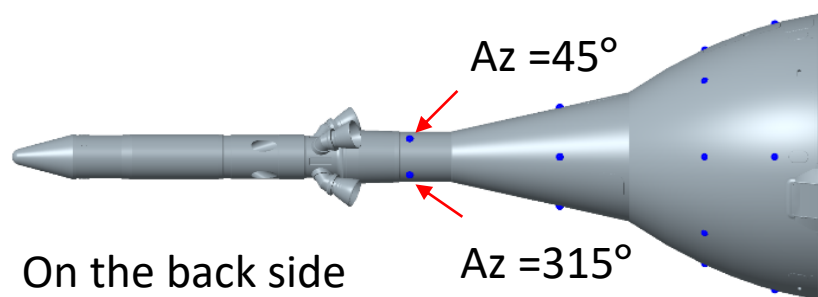
Algorithm to Characterize States within Time History

- Build a two-dimensional histogram from mean-standard deviation scatter plot
- If two peaks are identified, separate groups of points and characterize each time window based on its proximity to one of the two peaks



Characterized Time History

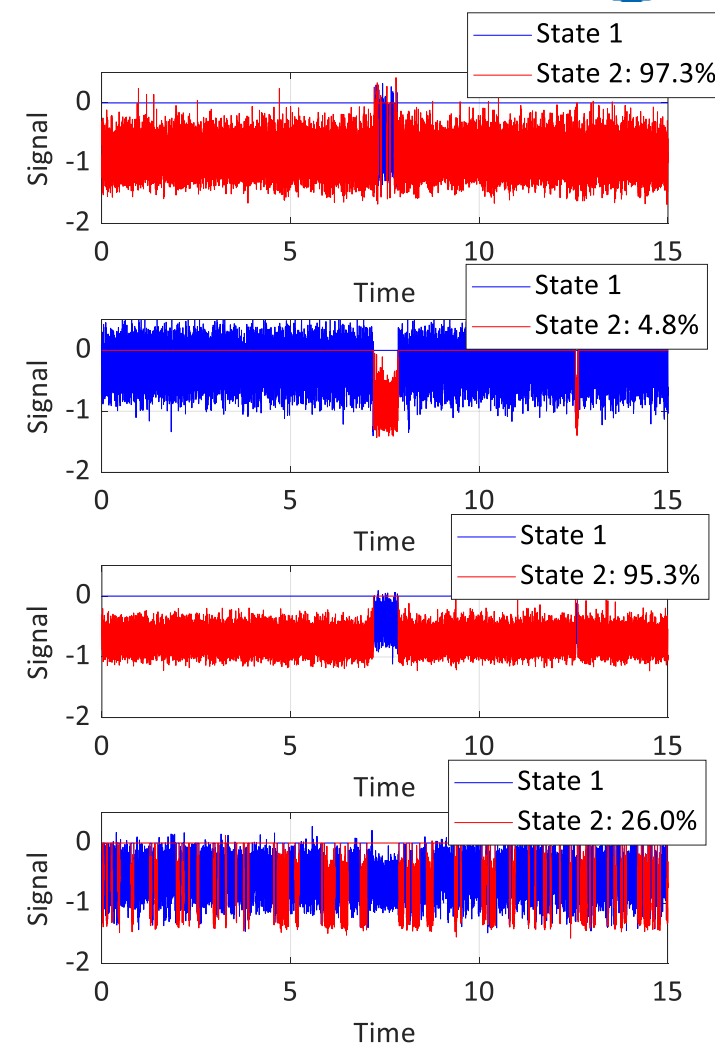
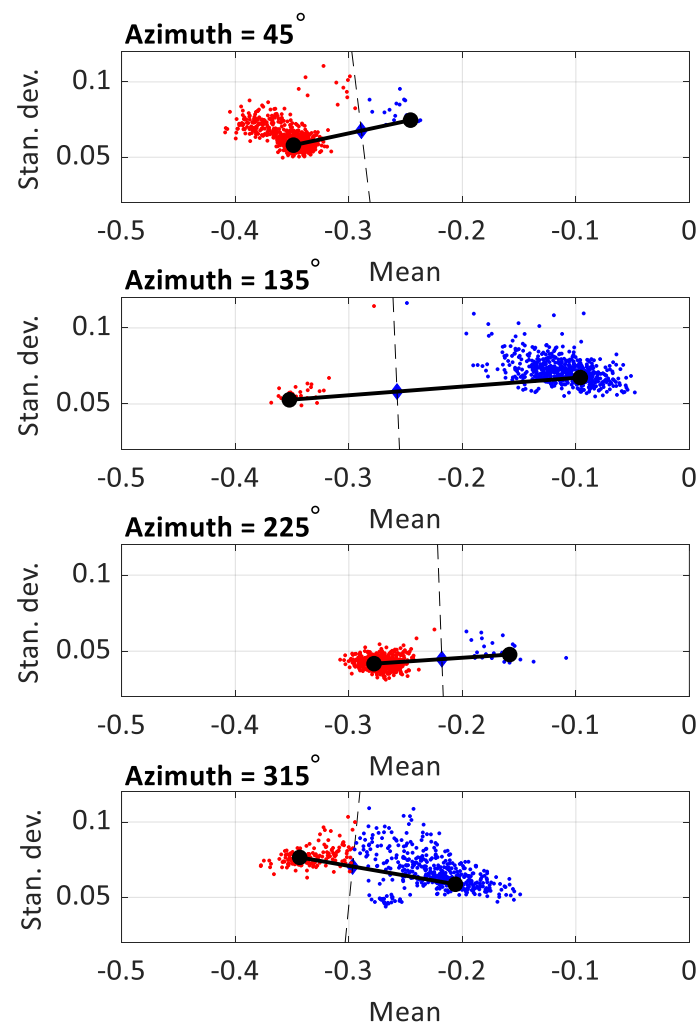
- Conditions: $M=1.10$, $\alpha=-4^\circ$, $\beta=0^\circ$
- Coupling is visible in the first three sensors, switching occurs nearly simultaneously
- Sensor at $Az=315^\circ$ appears to switch states independently of other sensors at the same station



On the back side

$Az = 135^\circ$

$Az = 225^\circ$

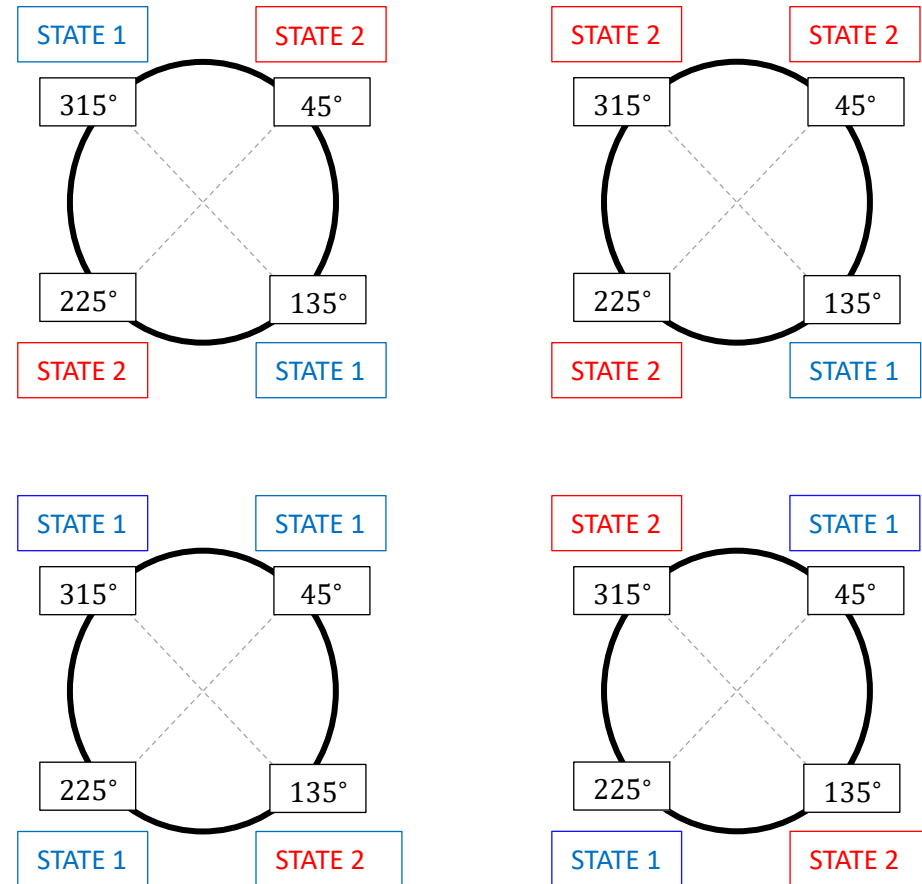


BFF Multi-mode Behavior

- The fact that state on sensors located at the same station do not strictly switch state at the same time allows for multiple states in the BFF
- The BFF is calculated by integrating pressure azimuthally

$$C_{fy} = \sum_i C_{p_i} \frac{r}{R} (\cos \theta_{i+1} - \cos \theta_i)$$

- If pressure on N sensors switch between two states, then there are 2^N states possible for BFF
 - For this case N=4, so 16 possible BFF states
- Some of the possible combinations shown on the right



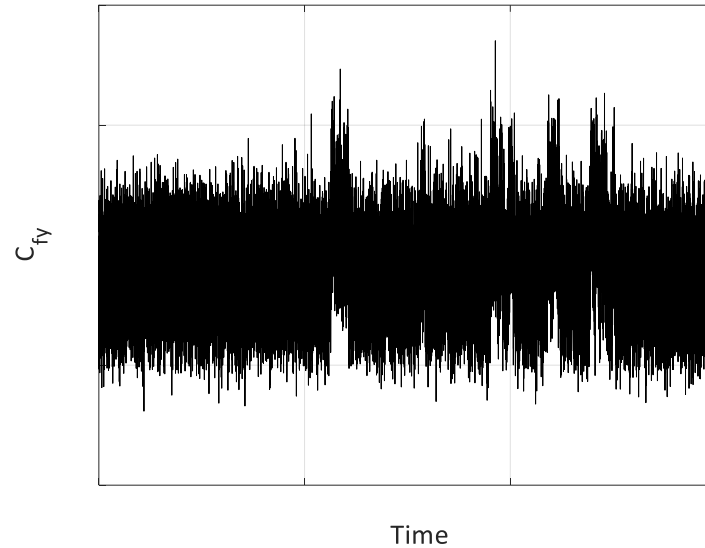
Other BFF states are possible ...

Calculation of BFF: raw Cp

- Calculating force coefficient using raw pressures, multiple BFF states are not evident

$$C_{fy} = \sum_i C_{p_i} \frac{r}{R} (\cos \theta_{i+1} - \cos \theta_i)$$

Raw Cp data



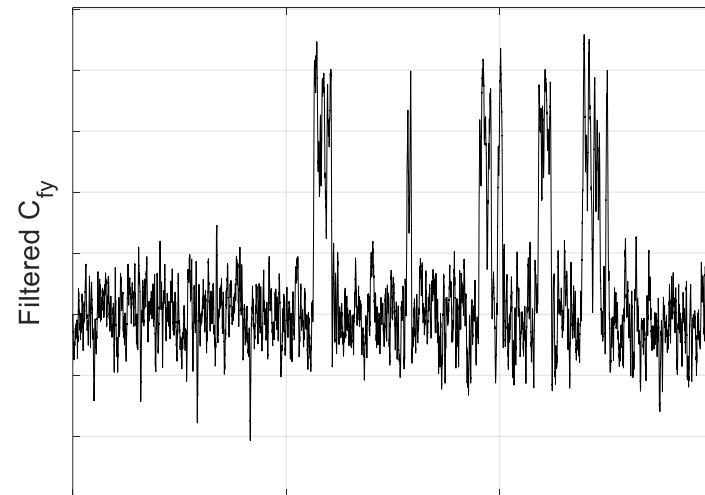
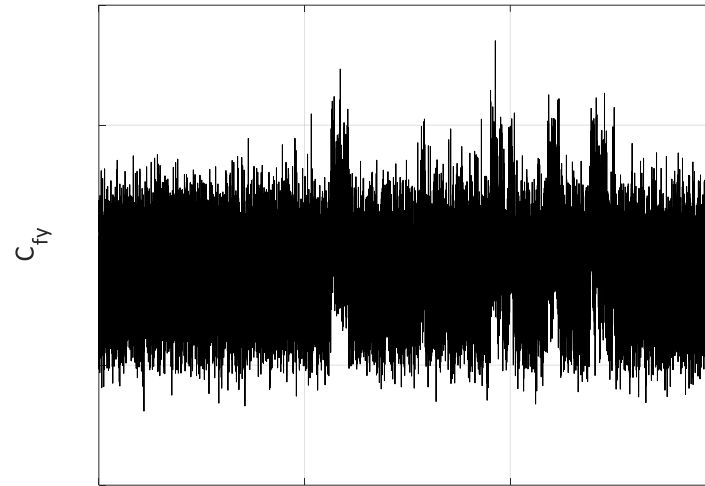
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Raw Cp data

- Let's filter the BFF



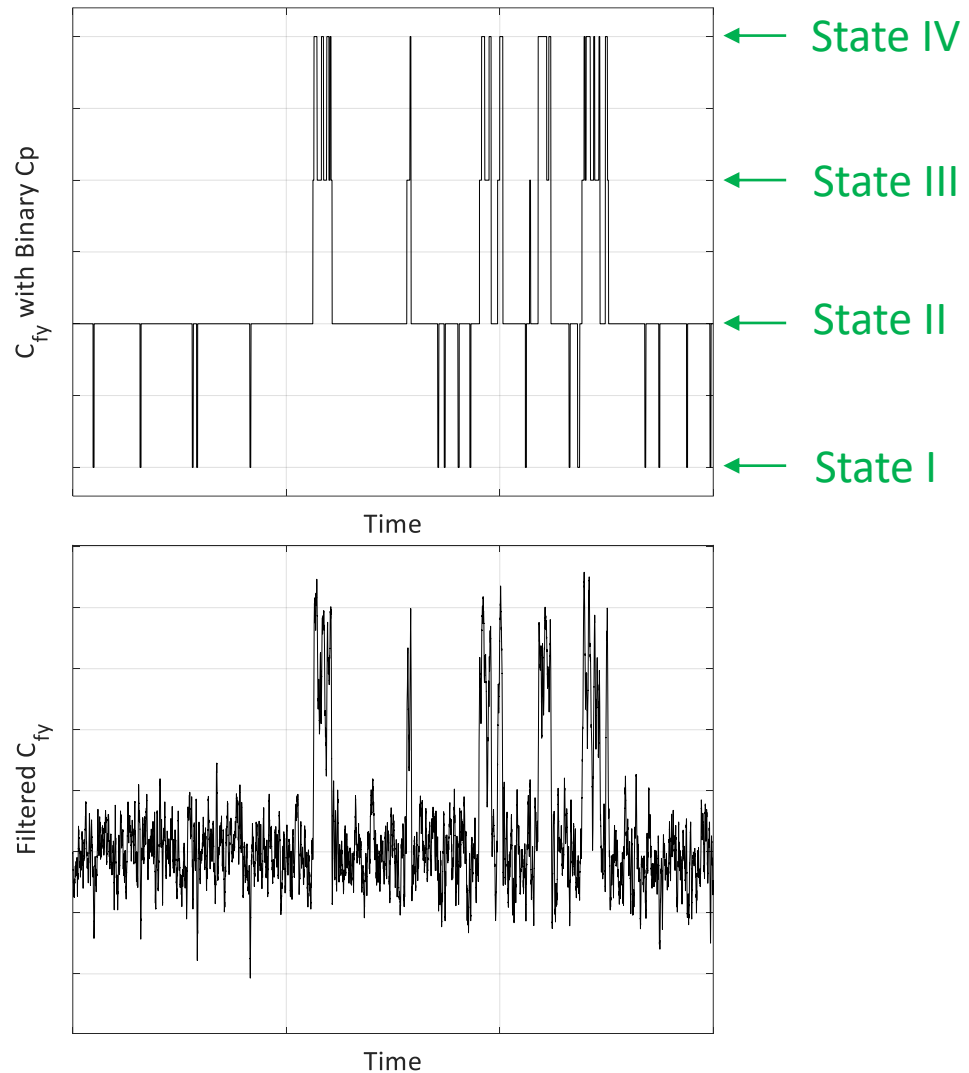
Calculation of BFF: Binary Cp Values

- Replace the pressure signal with artificially defined binary values assigned to each state

$$C_{fy} = \sum_i C_{p_i} \frac{r}{R} (\cos \theta_{i+1} - \cos \theta_i)$$

↓
A binary value
-1 for State 1
-2 for State 2

- At least four different states are easily identified
- The amplitude of the C_{fy} computed using artificial binary values for C_p is not representative of the actual force value
- Including C_{fz} will define the net impulsive force direction



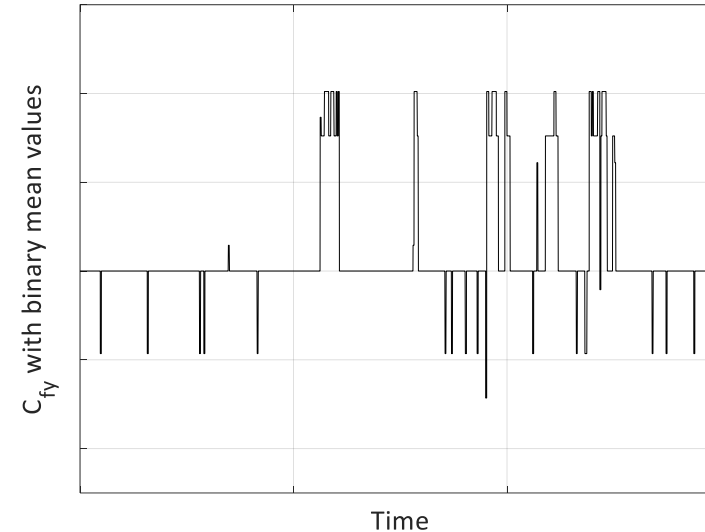
Calculation of BFF: Mean Cp Values

- Replace the pressure signal with mean of pressure associated with each state

$$C_{fy} = \sum_i C_{p_i} \frac{r}{R} (\cos \theta_{i+1} - \cos \theta_i)$$



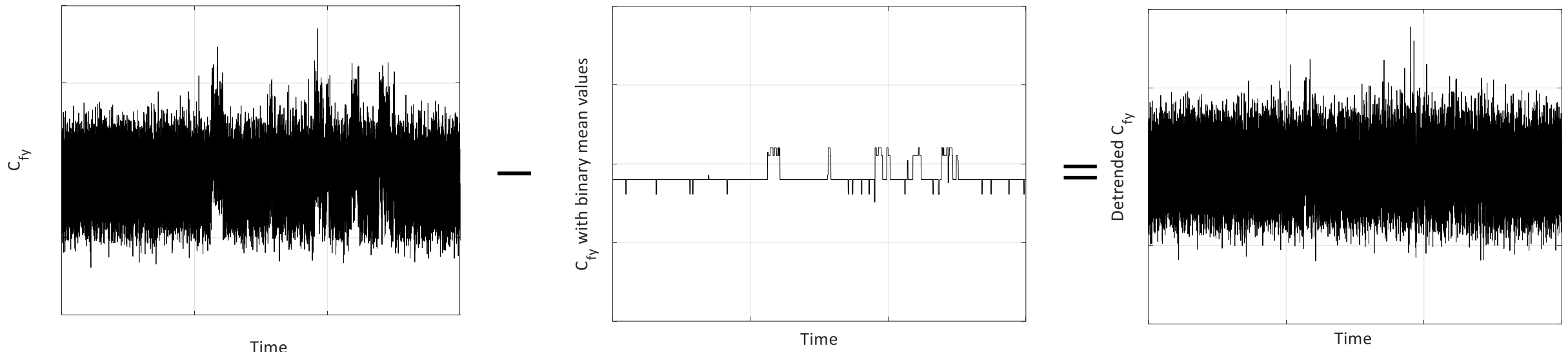
A unique mean value of each state
 mean(State 1) for State 1
 mean(State 2) for State 2



- At least 8 BFF states are identifiable
- These states were not visible in purely binary plot because identical values on two sensors will cancel the net effect
- The amplitude C_{fy} computed using means is accurate representation of the force magnitude

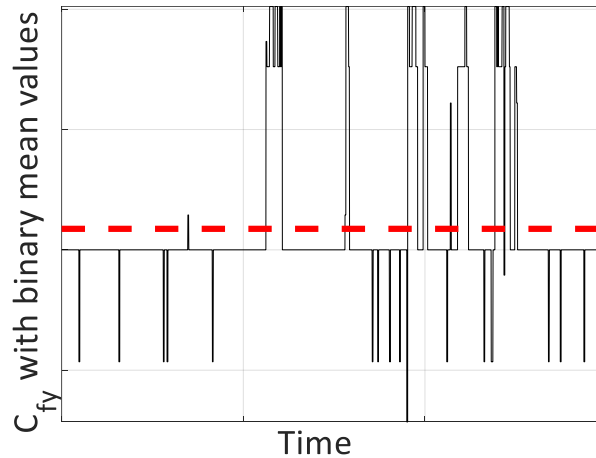
Calculation of BFF: Detrended Component

- Subtract the forces computed using means of each state from the raw signal resulting in a detrended signal
- Scales adjusted for uniformity

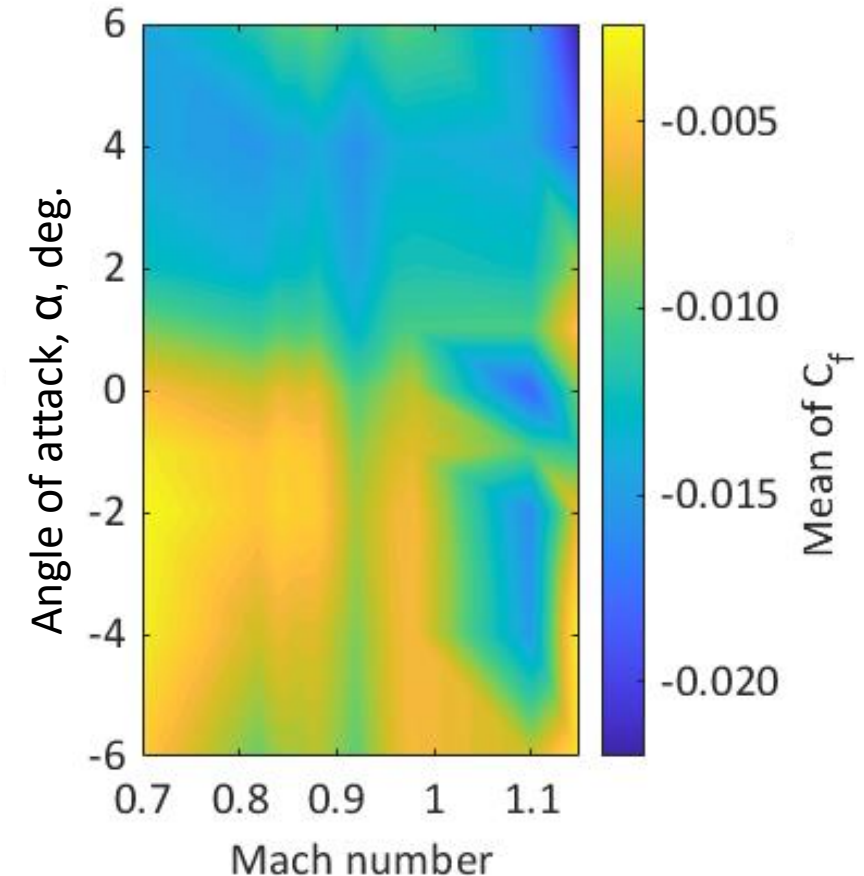


Calculation of BFF for α -M Space: Time-averaged

- The analysis can be expanded to cover a range of Mach and pitch model angle values
- Mean of the C_{fy} can be computed for each α -M combination

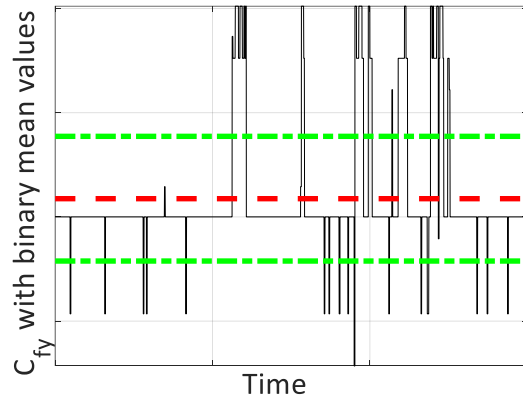


- Consistent behavior is observed for Mach 0.7 to 1.0. Mean load is correlated with the model pitch angles
- This behavior breaks down at $M=1.1$

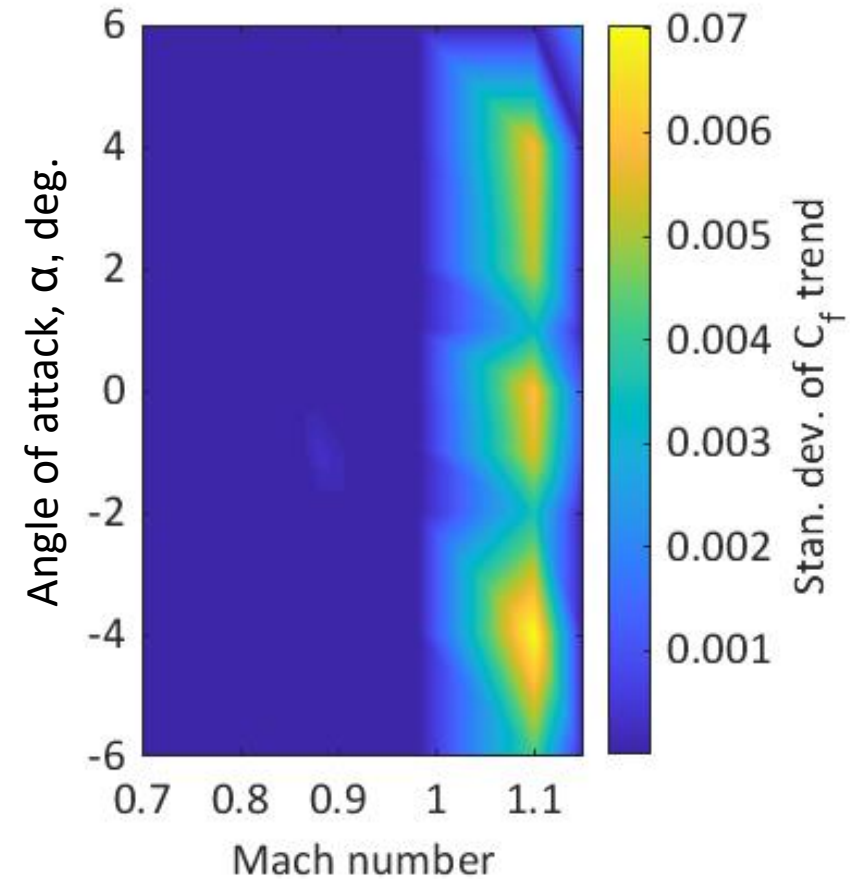


Calculation of BFF for α -M Space: Variation in Trend

- Stand. Dev. of the trend can be computed for each α -M combination

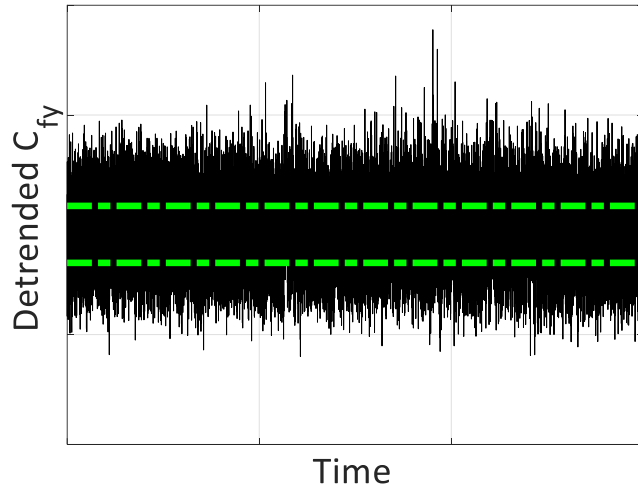


- Stand. Dev. of the trend of the trend has a non-zero value only in the presence of bimodal flow
- As expected, non-zero values are seen at $M=1.10$
- The fluctuation of the trend due to bimodal flow is responsible for breaking the force correlation to model pitch angle observed in previous slide

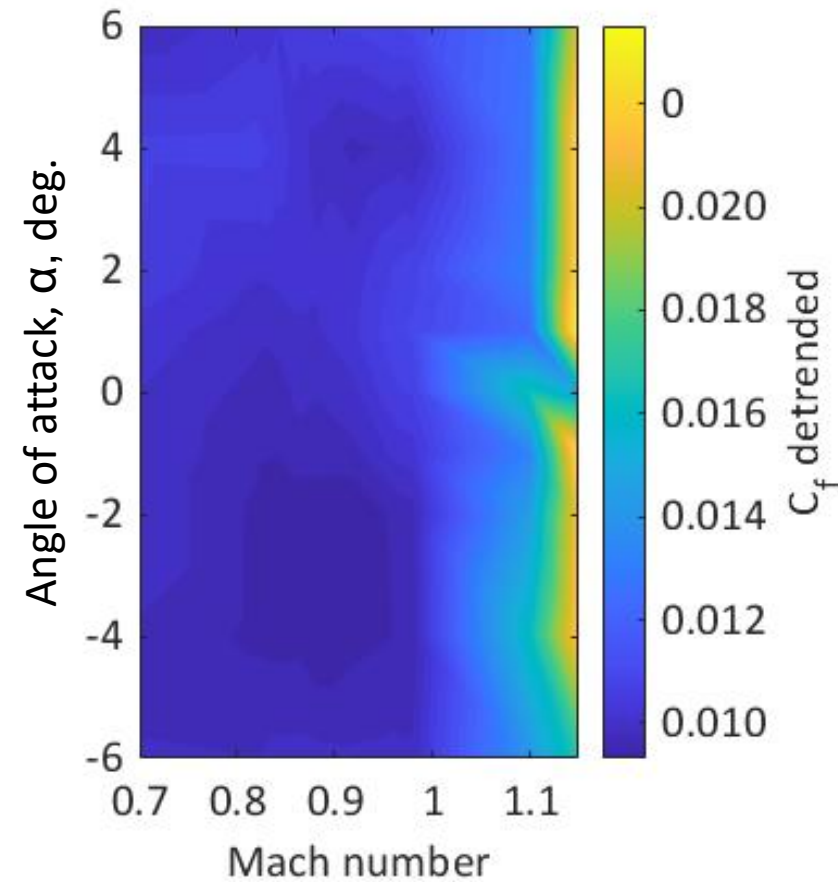


Calculation of BFF for α -M Space: Time-averaged

- Stand. Dev. of the fluctuating component can be computed for each α -M combination



- The Stan. Dev. of the fluctuating component is not affected by the bimodal flow, as expected





Conclusions

- 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
- This bimodal phenomenon differed from well known transonic bimodal flow occurring at large-angle expansion corners
- Bimodal phenomena can result in large, impulsive loads that act on a launch vehicle
- Present work outlined a method of characterizing the impact of the bimodal flow on buffet forcing functions
- 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

Questions?

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