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Comparison of Wind-Tunnel and Flight Unsteady Pressure Stochastic Characteristics for the SLS Artemis I Flight

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Outline

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  - Repeatability ($C_{p,\text{rms}}$ and C_p' spectra)
- **Comparison of Flight and Wind Tunnel Data**
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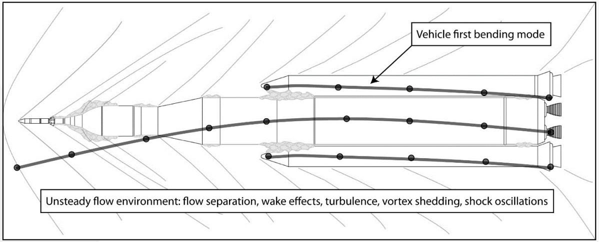
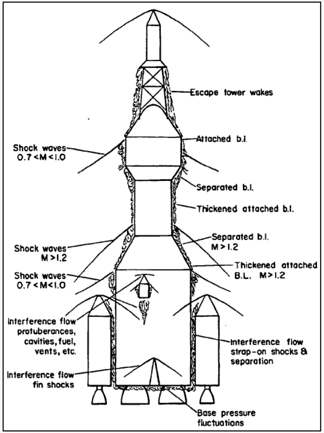
- **Questions**

Launch Vehicle Buffet
Background

- **Launch vehicle buffet: complex spatio-temporal pressure field may excite launch vehicle structural modes**
- **Contributing fluid structures**
  - Turbulent boundary layer flow
  - Separated flow
  - Oscillating shocks (shock-boundary layer interaction)
  - Intermittent flow attachment/detachment
  - Flow past protuberances (wakes and vortex shedding)





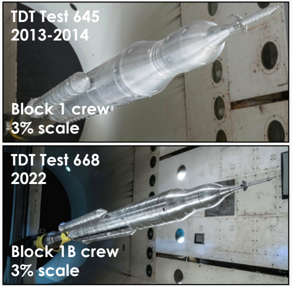
Fleming, E. R., "Transonic Buffeting Loads Experience at The Aerospace Corporation," Tech. Rep. TOR-95(5530)-6, Mar. 1995.

Launch Vehicle Buffet
Preflight Predictions – Wind Tunnel Testing

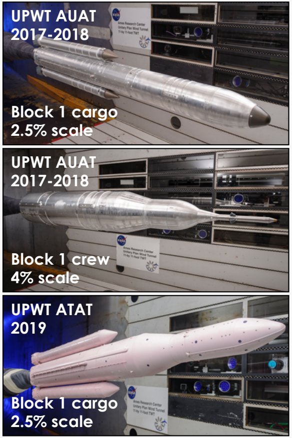
- **Importance of wind tunnel testing and time-accurate CFD**
  - Relatively difficult to obtain detailed analytical/empirical predictions without testing
  - Fluctuating pressure field has demonstrated high configuration and flight-condition dependency
    - Databases developed using experimental data, with CFD simulations to support interpretation of experimental data, to improve understanding of flow features, and for comparative analyses
- **Model-scale testing versus full-scale flight**
  - Impact of accelerating flight and transient flow conditions (steady versus accelerating conditions)
  - Geometric and trajectory scaling (to include extrapolation of experimental database to higher M_∞)

Data Description
Wind Tunnel Data

- **Several WT tests conducted at TDT and UPWT to characterize unsteady aerodynamics during ascent using rigid models densely instrumented with pressure transducers**
  – Test 645 data used to generate buffet database for the Artemis I flight – these data are baseline comparison in this study
- **Comparisons presented**
  – $C'_{p,rms}$ at several core stations
  – Peak frequencies at two core regions characterized by narrowband frequencies



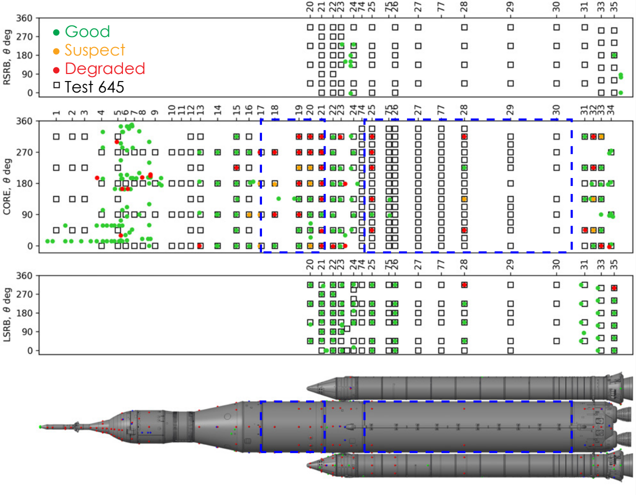
[Source: NASA]



[Source: NASA]

Data Description
Flight Data

- **Distribution of external unsteady pressure sensors (sampling rate ≥500 sps) shown to right**
- **Most degraded/suspect core sensors due to icing**

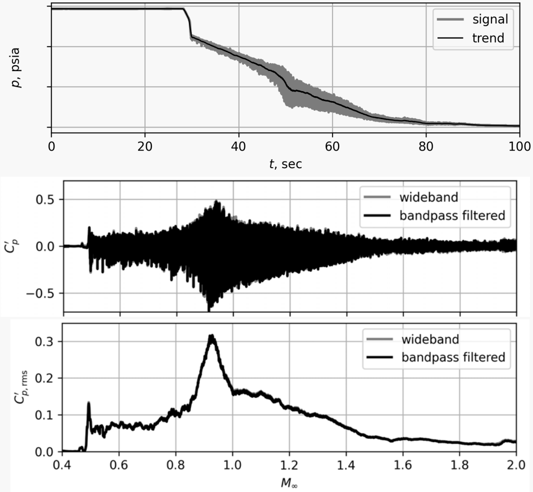


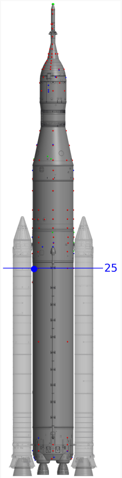
Flight Data
Signal Processing

(1) Estimate signal time history trend (Savitzky-Golay filter)

(2) Process fluctuating (detrended) signal
   a) Normalize fluctuating signal by best estimated trajectory q_∞ to calculate C_p'
   b) Bandpass filter C_p' to 0.5-100 Hz

(3) Compare flight and wind tunnel data
   a) Running $C'_{p,\mathrm{rms}}$ using fixed time or M_∞ windows
   b) C_p' spectra



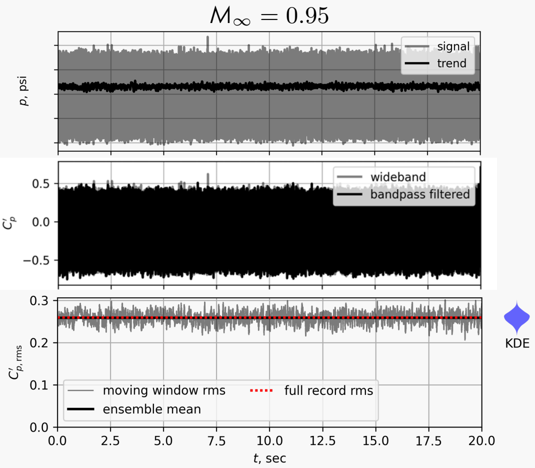


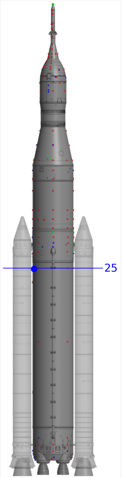
Wind Tunnel Data
Signal Processing

(1) Query WT test points for closest-attitude matches
   a) Determine flight-equivalent WT time window using geometry and velocity scaling

(2) Estimate trend and process fluctuating signal in same way as flight data (using scaled window and frequency bandwidth)

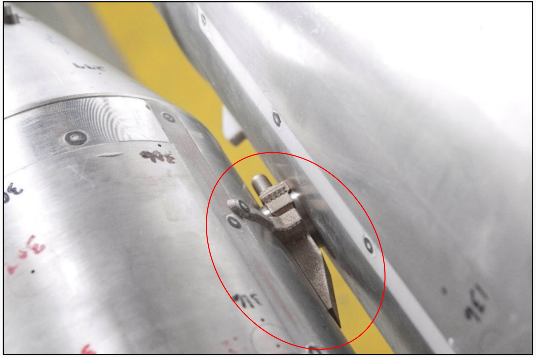
(3) WT test point contains many flight-equivalent windows ⇒ WT prediction distributions based on ensemble statistics
   a) $C'_{p,\text{rms}}$ KDEs
   b) Spectra percentile bounds





Wind Tunnel Data
Booster Forward Attachment Hardware (T645)

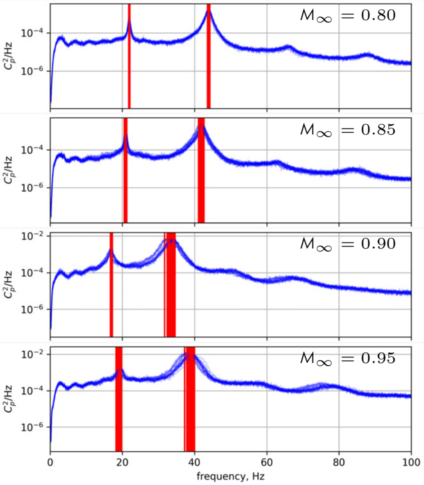
- **Fluctuating pressure magnitudes highest in multibody region downstream of booster-to-core forward attachment hardware**
  - Interaction between booster nose CCJ shock and FAH wake drives energetic unsteady pressure modes with narrowband frequency peaks
  - Environment sensitive to FAH geometry and vehicle attitude
  - Sensor spatial distribution relatively high for WT model, but still can be challenging flowfield to characterize

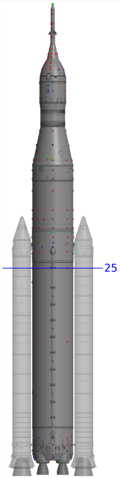


[Source: NASA]

Wind Tunnel Data
FAH Wake f_{peak} ID (T645)

- C'_p **spectra for repeat points at several** M_∞ **for the** $90°$ **sensor located at this station**
  - Red vertical lines correspond to peak narrowband frequencies (full scale)
- **As** M_∞ **increases**
  - Peaks broaden
  - Peak variability increases

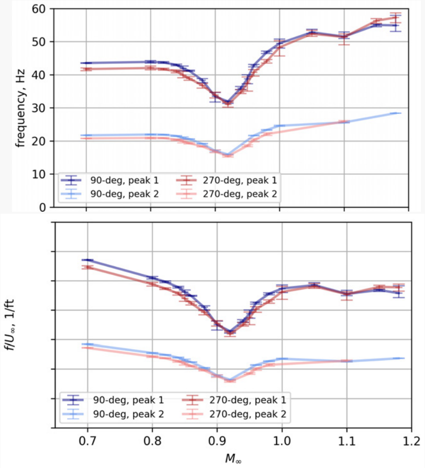


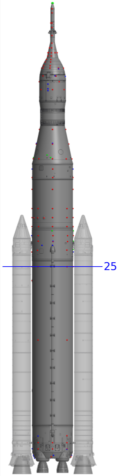


Wind Tunnel Data

FAH Wake f_{peak} (T645)

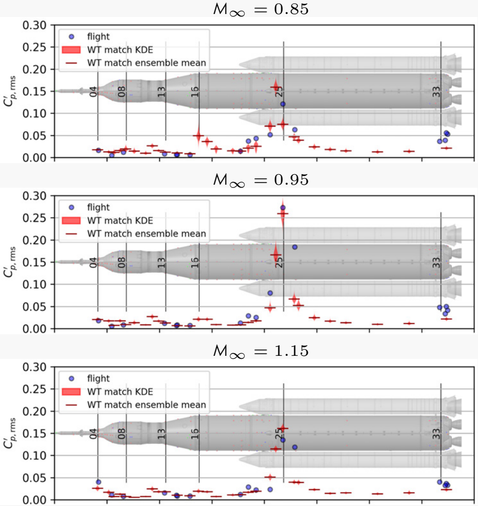
- **Comparison of peak frequencies identified at this station on the left and right side of the core**
  - Mean and max/min peak frequencies for all repeats
- **Observations**
  - Significant dip in peak frequencies between $M_\infty \in [0.85, 0.98]$
  - Relatively consistent offset between the left and right side of the core
- **Relatively flat curves for frequencies normalized by freestream velocity provides some evidence that velocity scaling lower supersonic data to higher M_∞ may be adequate**





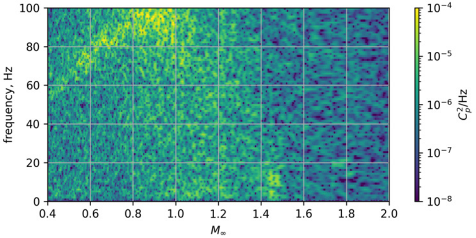
Flight and WT Data
$C'_{p,\mathrm{rms}}$ Longitudinal Distribution

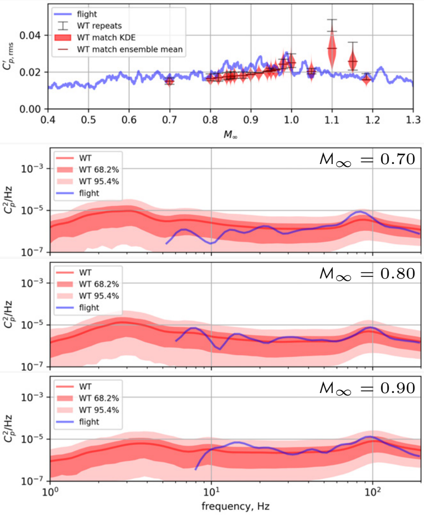
- **Longitudinal distribution of $C'_{p,\mathrm{rms}}$ for sensors located in the vicinity of $\theta = 90°$**
- **Observations**
  - Forward of the multibody region, flight and WT data match relatively well
  - Increased flight unsteadiness on the engine section
  - Increased flight unsteadiness in the FAH region, and comparison of spatial distribution challenging
    - Longitudinal extent of increased unsteadiness measured during flight potentially larger in the FAH region

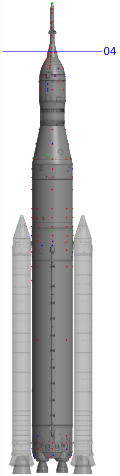


Flight and WT Data
LAS, Station 4

- **Spectral ridge associated with the LAS nozzles wake in spectrogram**
- $C'_{p,\mathrm{rms}}$ **trends compare generally well**
- M_∞**-windowed spectra appear to be relatively good matches**



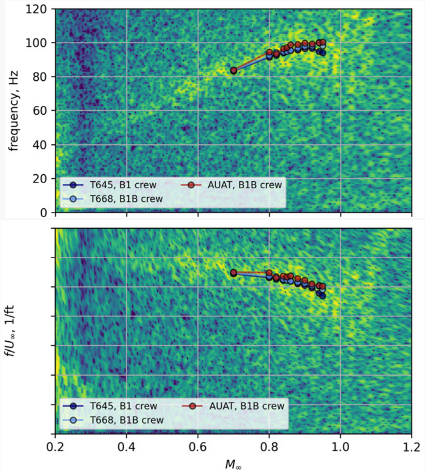


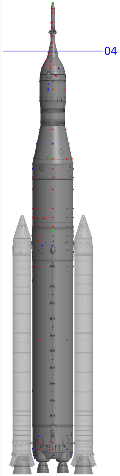


Flight and WT Data

LAS f_{peak}, Station 4

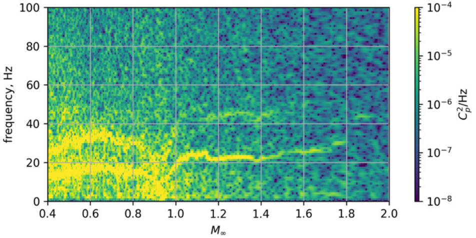
- **Peak frequencies (both trends and values) compare well**

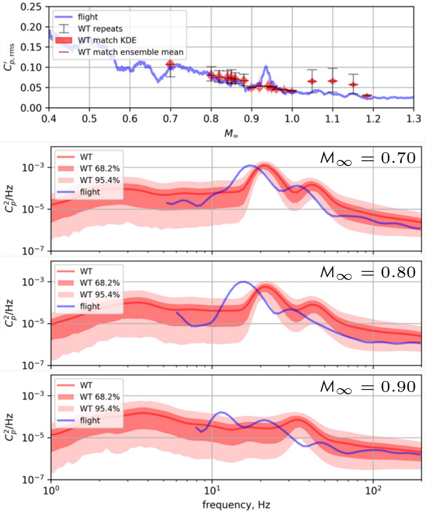


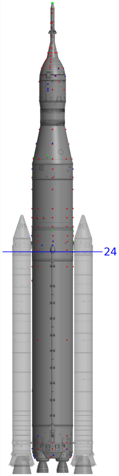


Flight and WT Data
Core, Station 24

- **Energy dominated by lower frequencies in narrowband peaks associated with FAH unsteady pressure modes**
- $C'_{p,\mathrm{rms}}$ **compare generally well**
- M_∞**-windowed spectra provide indication that peak frequencies do not match well**

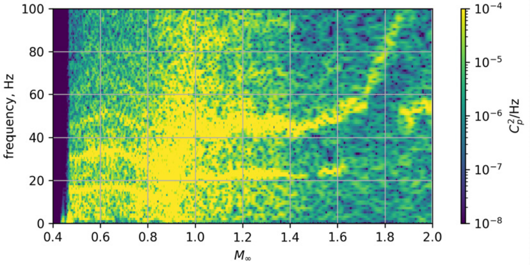


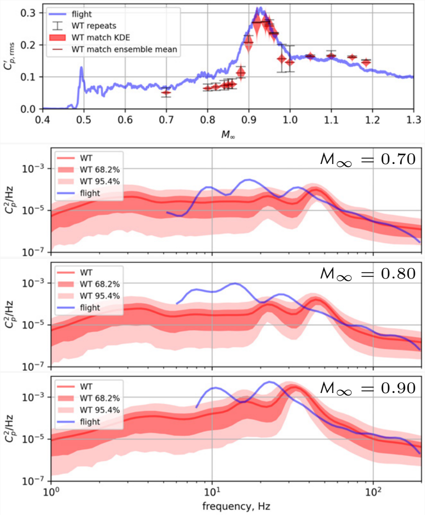


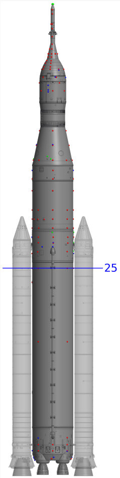


Flight and WT Data
Core, Station 25

- **In spectrogram, magnitudes for some modes remain high at higher M_∞**
- **Flight $C'_{p,\mathrm{rms}}$ envelopes WT prediction bounds for $M_\infty \leq 0.92$**
- **M_∞-windowed spectra also indicate that peak frequencies do not match well**



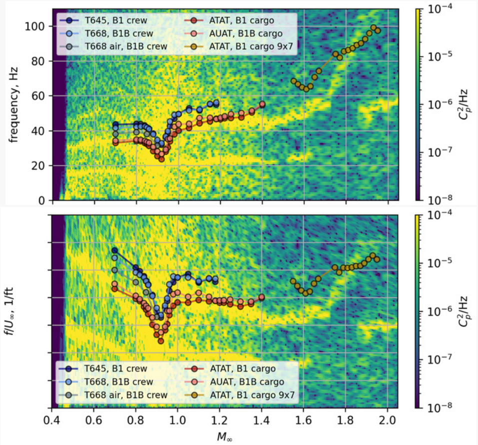


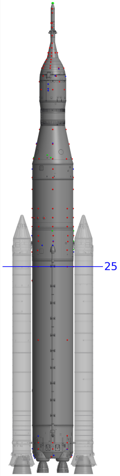


Flight and WT Data

Core f_{peak}, Station 25

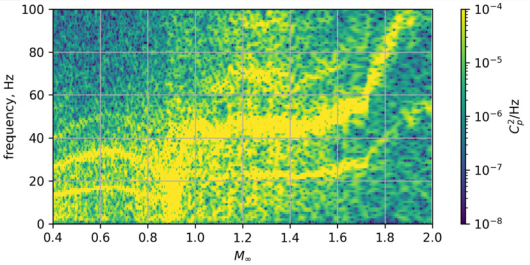
- **WT frequency peaks associated with the dominant unsteady pressure mode plotted in comparison to flight**
- **Trends for $M_\infty \leq 1.3$ compare well for all WT and flight data**
  - For higher M_∞, the flight trend appears to differ from the supersonic WT presented
- **Peak frequencies identified in TDT WT data are higher than flight and do not match as well as the data acquired during UPWT tests**
  - Differs from the peak frequency comparison downstream of the LAS nozzles

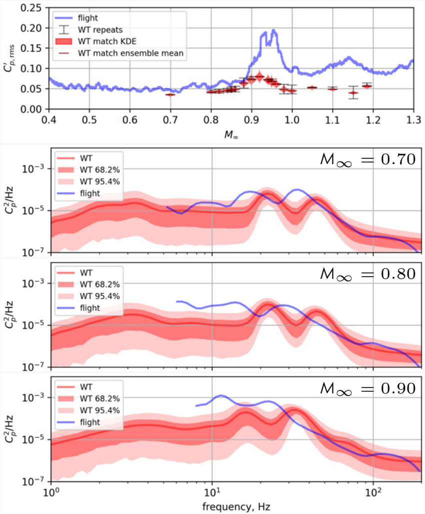


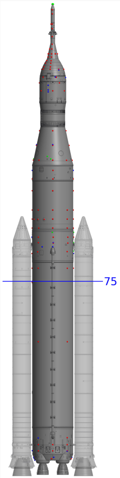


Flight and WT Data
Core, Station 75

- **Flight $C'_{p,\text{rms}}$ envelopes WT prediction bounds for all M_∞**
  - Spatial extent of increased unsteadiness in this region appears different between WT and flight
  - Challenge of characterizing due to sensor spatial resolution





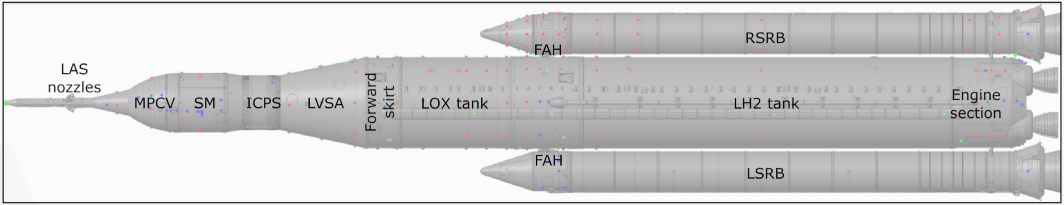


Summary

- **Wind Tunnel Data**
  - In general, point-to-point mean $C'_{p,\mathrm{rms}}$ compare well
    - Matched test points should yield good comparisons to flight data if subscale test articles and methods are accurate representations of full scale flight
  - Test-to-test $C'_{p,\mathrm{rms}}$ variability can be significant for tests conducted at different facilities
    - In multibody region small geometric differences can lead to significant differences in the unsteady pressure field
    - Peak frequencies consistently different between tests conducted at the two facilities
- **Comparison of Flight and Wind Tunnel Data**
  - $C'_{p,\mathrm{rms}}$ and C'_p spectra generally compare well for many stations on the vehicle
  - Significant differences present in the multibody region of the vehicle:
    - Peak frequencies of the booster forward attachment hardware wake
    - Spatial extent of high fluctuating environments associated with unsteady pressure modes
- **Current computational studies and future experimental work are ongoing to better understand differences between tunnels and between flight and tunnel**

Questions?

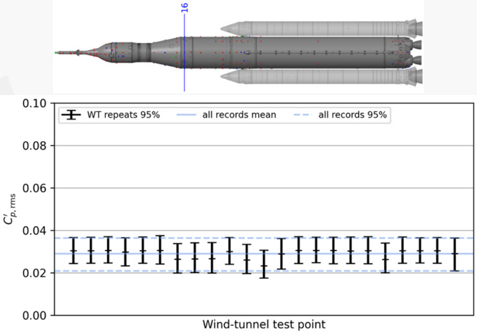
Extra
SLS Block 1 Crew Launch Vehicle

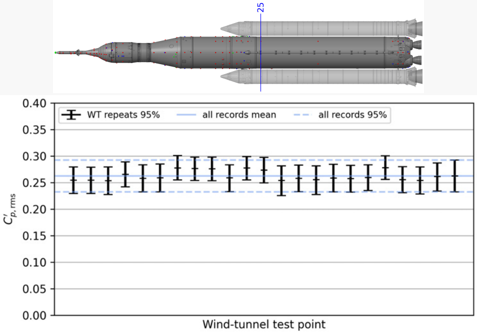


Extra

Point-to-Point, $C'_{p,\mathrm{rms}}$ (T645)

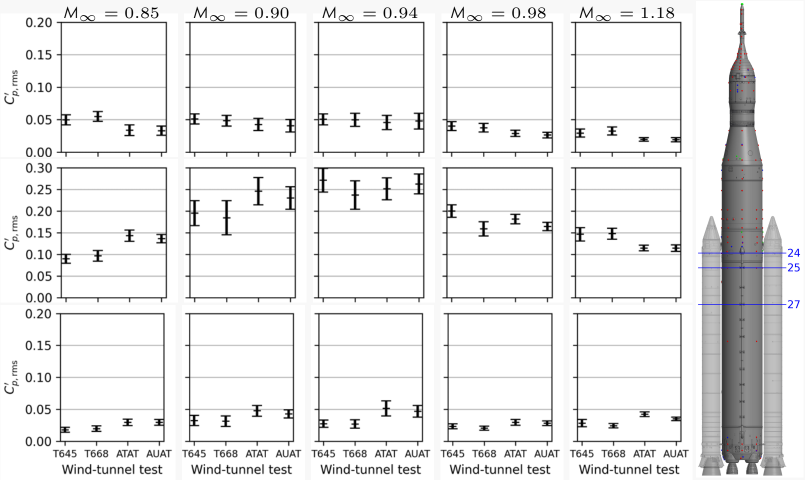
- **Many repeat data points acquired during Test 645 at $\alpha = \beta = 0^\circ$ for multiple M_∞**
  - For each point, flight-representative windows used to calculate $C'_{p,\mathrm{rms}}$ ensemble mean and 95% bounds
- **Point-to-point repeatability relatively consistent (shown here for $M_\infty = 0.95$)**
  - Model roll angle for each point is a significant source of variability





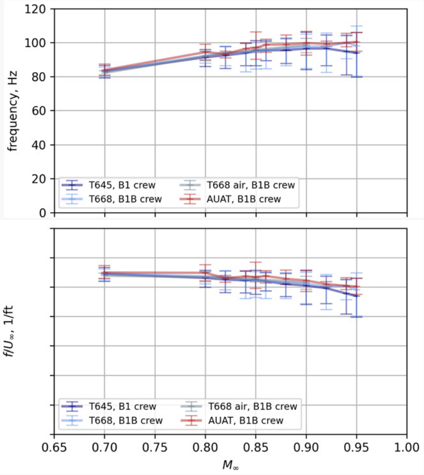
Extra
Test-to-Test, $C'_{p,\mathrm{rms}}$

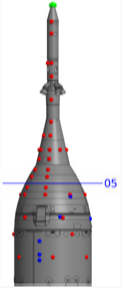
- **Repeat data mean and 95% bounds from several WT tests compared for $\theta = 90°$ sensor**
- $C'_{p,\mathrm{rms}}$ **generally compare well in the same facility, but often quite different between facilities**
  - Spatial extent of peak unsteadiness downstream of FAH may differ



Extra
Test-to-Test, LAS Nozzles Wake f_{peak}

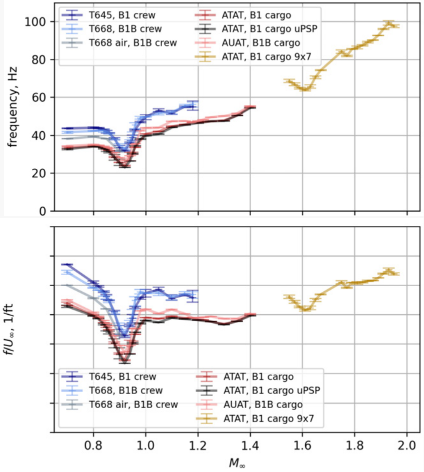
- **Comparison of peak frequencies identified at this station**
  - Mean and max/min peak frequencies for all repeats
- **Observations**
  - High variability due to broad nature of peaks measured at each sensor
  - Relatively good comparison between facilities indicates that test medium and model scale may not drive the LAS nozzle wake frequencies

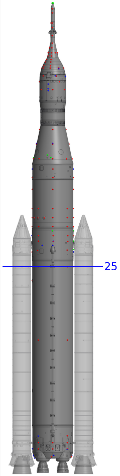




Extra
Test-to-Test, FAH Wake f_{peak}

- **Observations**
  - Trends match well between all tests, with peak frequency offset for tests conducted in the TDT
    - Air runs during Test 668 have lower frequencies, but still higher than those from UPWT
  - TDT data match fairly well in R134a, while there appears to be constant shift up in peak frequency for the AUAT data
  - Supersonic data during ATAT may suggest that velocity scaling lower supersonic data to higher M_∞ may not lead to proper frequency matching

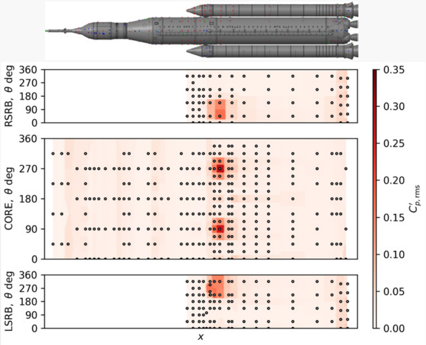




Flight and WT Data
$C'_{p,\mathrm{rms}}$ Unwrapped Distribution

- **Unwrapped distributions of $C'_{p,\mathrm{rms}}$ at $M_\infty = 0.95$ provide indication of regions of peak unsteadiness and spatial localization of these features with available sensors**

Wind Tunnel



Flight