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Comparison of Corcos-Based and Experimentally-Derived Coherence Factors for Buffet Forcing Functions Estimation

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AIAA SciTech Forum, January 23-27, 2023

Acknowledgements

- The uPSP test team at the *NASA Ames Research Center*, to include **Nettie Roozeboom**, **Jennifer Baerny**, **Jie Li**, **David Murakami**, **Marc Shaw-Lecerf**, **Paul Stremel**, and **Lucy Tang** and also **Jessica Powell** at the *NASA Johnson Space Center* for their invaluable assistance in acquiring, processing, and analyzing the uPSP data analyzed in this paper.
- **Craig Streett**, *NASA Langley Research Center*, for his invaluable inputs on buffet research.

Outline

1. Introduction
2. Description of the wind-tunnel test and Unsteady Pressure Sensitive Paint (uPSP) data
3. Comparisons between Corcos-based and experimentally derived:
 - Coherence lengths
 - Coherence factors for Buffet forcing functions (BFFs)
 - BFFs power spectral density
4. Summary

Introduction

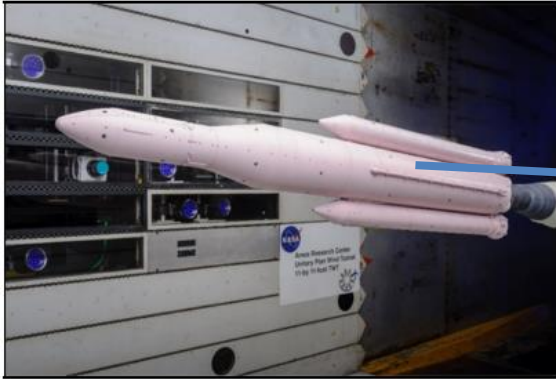
- In the design of launch vehicles (LVs), special attention is given to **transonic buffet loads**, often ranking among the highest dynamic loads predicted by coupled loads analyses (CLA).
- To model these buffet loads, CLA employs suitable **forcing functions**, called buffet forcing functions (**BFFs**) that consist of **fluctuating forces** in the time or frequency domain at many discrete locations on the LV.
- The BFFs model various aerodynamic environments associated with buffet, including: turbulent boundary layers (TBLs), shocks, flow separation, protuberance wake, etc.
- **Because buffet-related fluctuating pressures p' are only partially correlated, the BFF integration process involves coherence factors, ζ .**

Motivation of the present work

- Utilize high-spatial resolution uPSP data to compare experimentally-derived BFFs estimated using discrete pressure measurements to high-fidelity BFFs based on direct pressure integration.
- Compare BFFs based on the Corcos model to experimentally-derived BFFs.
- Insights from comparisons of Corcos-based BFFs and varying degree of fidelity uPSP-based BFF will lead to understanding of conservatism present in BFFs based on classical discrete sensor methods in which spatial resolution is low.

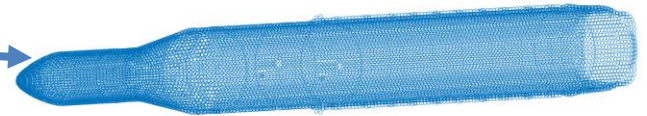
Data description

- The analysis is based on data from the Ascent Transient Aerodynamics Test (ATAT) that was conducted in 2019 at the NASA Ames Research Center 11-Foot Transonic Unitary Plan Wind Tunnel
- A photograph of the SLS Block 1 cargo 2.5-percent scale model for uPSP testing is shown below
- uPSP data: approaching 1M uPSP-nodes, sample rates up to 20 kHz
- Test conditions: $M_\infty = 0.70 - 1.40$, $\alpha, \beta = \pm 6$ deg
- A panel method is utilized to average the uPSP pressures over defined “supernodes”



SLS Block 1 cargo 2.5-percent scale model tested during ATAT (2019)

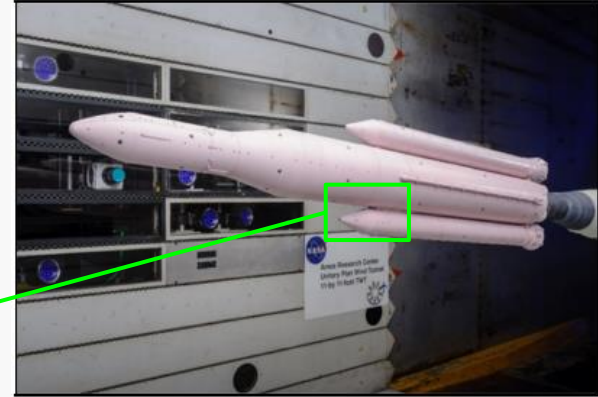
○ uPSP supernodes



core stage:
479,079 uPSP nodes → 10,800 supernodes

Buffet region of interest/peak buffet environment

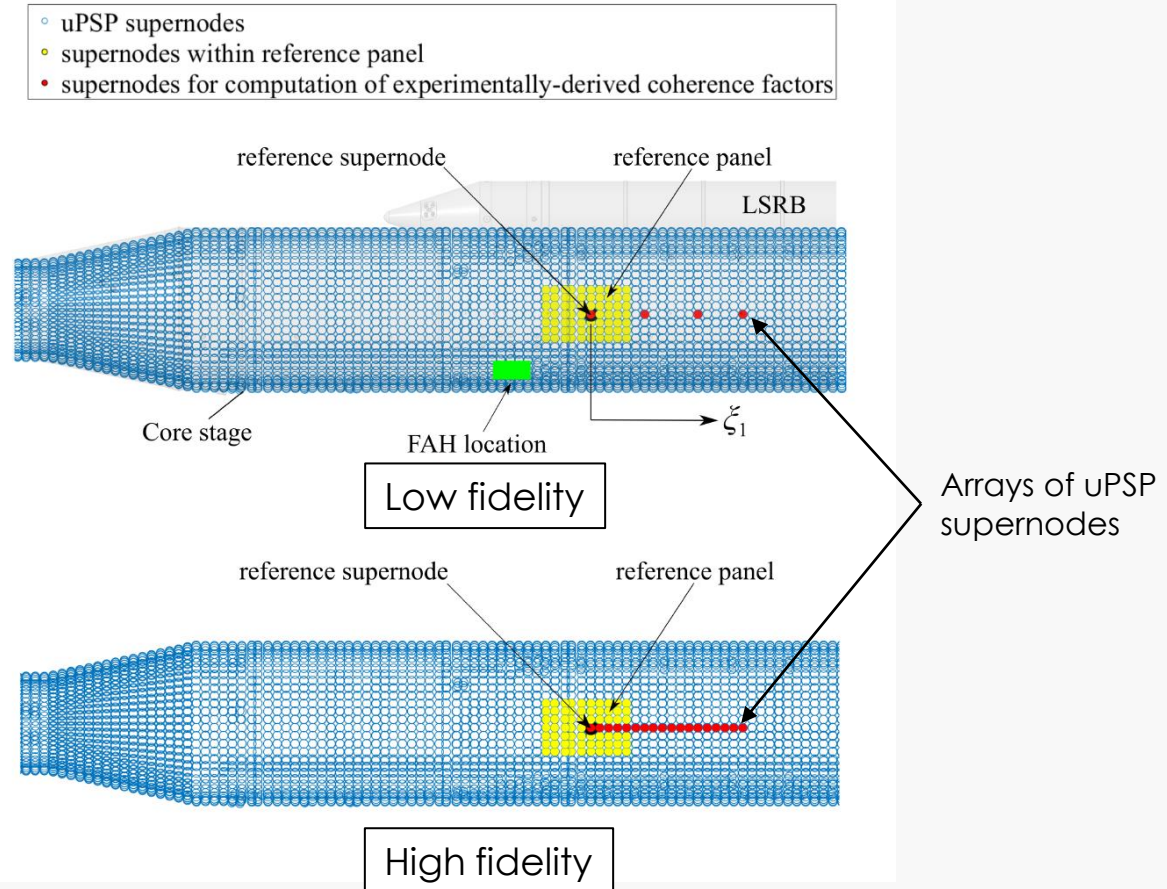
Booster forward attachment hardware



SLS Block 1 cargo 2.5-percent scale model tested during ATAT (2019)

Streamwise coherence length. Supernode arrays

- Consider a buffet region defined by a panel on the core stage such as the one shown on the right in yellow.
- This region is in proximity of the Booster forward attachment hardware (FAH).
- Arrays of uPSP supernodes simulate discrete pressure transducers that are traditionally used to measure p' .**
 - Top: Low fidelity array (4 sensors)
 - Bottom: High-fidelity array (18 sensors)
- The next slide describes how the coherence length is computed based on these supernodes arrays and based on the Corcos model.



Coherence length. Corcos model Vs. experimentally derived

Coherence length definition:

$$l_1(\omega) = \int_0^{\infty} \gamma(\omega, \xi_1) d\xi_1$$

γ = coherence function

ω = angular frequency

ξ_1 = streamwise distance from reference supernode

- **Based on the Corcos model:**

$$l_1 = \frac{U_c}{\alpha_1 \omega}$$

α_1 = Corcos streamwise decay constant (calibrated based on uPSP data)

U_c = turbulence-convection velocity

- **Based on supernode arrays:**

l_1 is computed by non-linear least-square fitting of the exponential function $e^{-\xi_1/l_1(\omega_n)}$ to values of $\gamma(\omega_n, \xi_1)$ experimentally derived from uPSP supernode arrays.

Coherence length. Corcos model Vs. experimentally derived

- **Blue: Corcos model.**

Coherence-lengths based on the Corcos model follow a negative slope, linear trend on a log-log scale.

- **Black: uPSP-based, high-fidelity l_1 .**

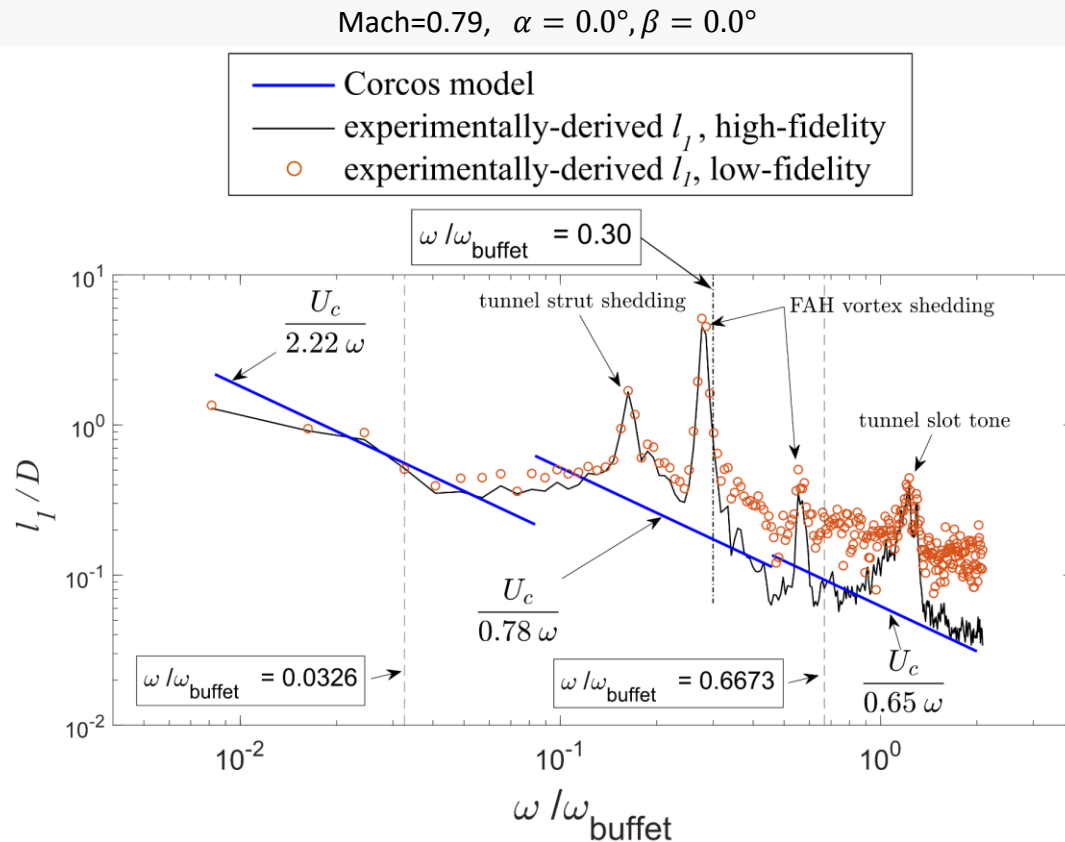
Good agreement with the Corcos model except for frequencies associated with:

- Vortex shedding off the forward attachment hardware.
- Spurious wind tunnel tones.

- **Brown: uPSP-based, low-fidelity l_1 .**

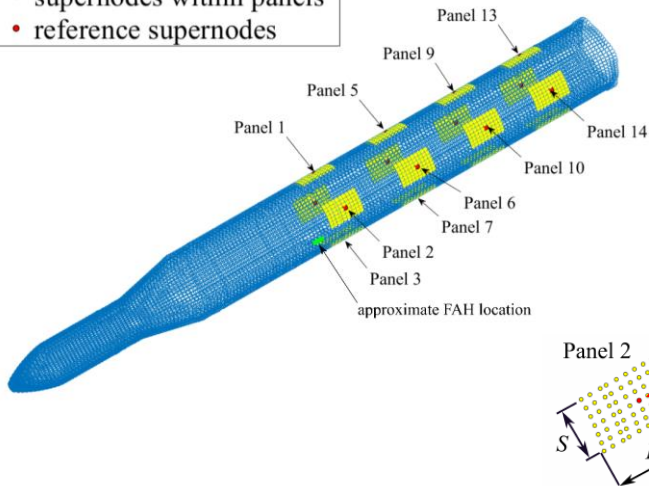
At $\omega > 0.3 \omega_{\text{buffet}}$, the low-fidelity l_1 estimate is overconservative relative to the high-fidelity estimate.

- Source of discrepancy: deviation of experimental $\gamma(\omega, \xi_1)$ distribution from an exponential decay assumption (details in the paper).



Panel buffet forcing function F_i estimation

- uPSP supernodes
- supernodes within panels
- reference supernodes



A panel BFF F_i acting on a panel in the i-direction, in the frequency domain is:

$$F_i(\omega) = |H(\omega)| e^{i\varphi(\omega)} \tilde{F}_i(\omega)$$

where:

ω = angular frequency

$|H(\omega)| e^{i\varphi(\omega)}$ = Frequency Response Function (FRF)

$\tilde{F}_i(\omega) = C_p(\omega) Q A_i$, Fully-coherent BFF

C_p = pressure coefficient measured at a **reference supernode**

Q = freestream dynamic pressure

A_i = projected area of the panel in the i-direction

Assuming: $\varphi = 0$ and $\zeta(\omega) \sim |H(\omega)|$, where $\zeta(\omega)$ = **coherence factor**, an **estimated panel BFF with coherence factor** is:

$$F_i(\omega) \sim \zeta(\omega) \tilde{F}_i(\omega)$$

The definition of coherence factor is provided in the next slide.

Coherence factors

Streamwise coherence factor:

$$\zeta_1(\omega) = \begin{cases} \sqrt{\frac{l_1(\omega)}{L}} & \text{if } l_1(\omega) < L \\ 1 & \text{if } l_1(\omega) \geq L \end{cases}$$

where:

L is the longitudinal width of the panel;

$l_1(\omega)$ is either based on the Corcos model or experimentally derived.

Coherence factors

Streamwise coherence factor:

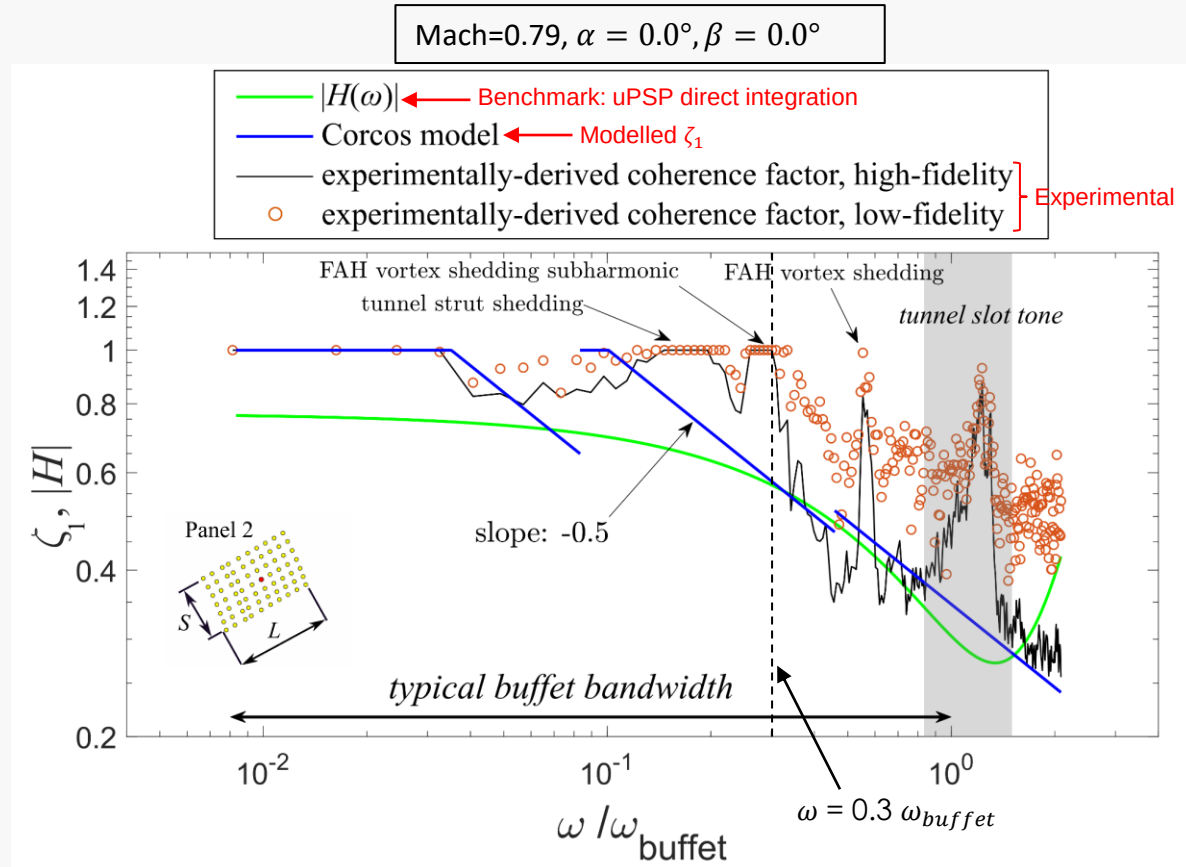
$$\zeta_1(\omega) = \begin{cases} \sqrt{\frac{l_1(\omega)}{L}} & \text{if } l_1(\omega) < L \\ 1 & \text{if } l_1(\omega) \geq L \end{cases}$$

where:

L is the longitudinal width of the panel;

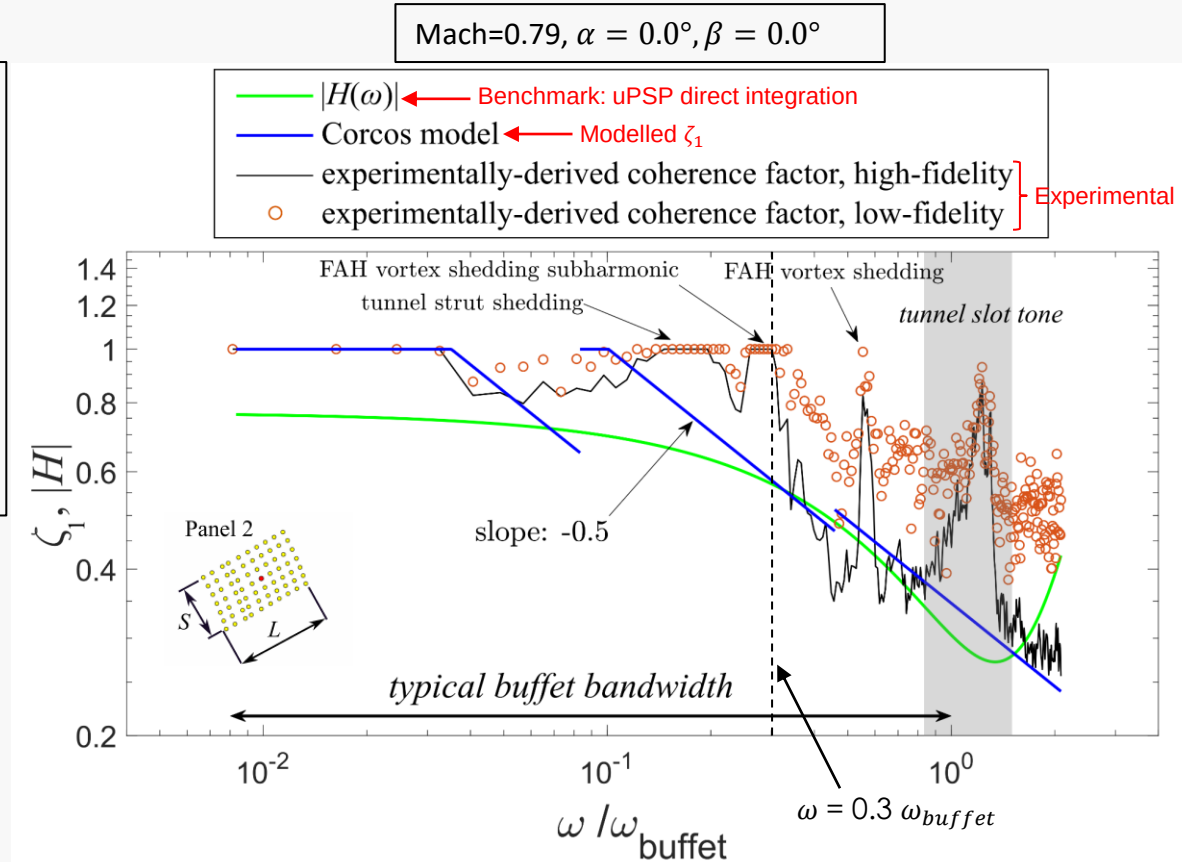
$l_1(\omega)$ is either based on the Corcos model or experimentally derived.

- Note: $|H(\omega)|$ is obtained by fitting a 2nd-order polynomial through the ratio $|F_z(\omega)/\tilde{F}_z(\omega)|$



Coherence factors

- Trends of **Corcos-based** and experimentally-derived coherence factors are consistent with $|H(\omega)|$.
- At $\omega > 0.3 \omega_{\text{buffer}}$, the **low-fidelity** ζ_1 distribution overestimates its **high-fidelity** counterpart, as expected, due to coherence length disparities.



PSDs of BFFs Φ_Z^F

Estimated BFF in the z-direction:

$$F_Z(\omega) = \zeta_1(\omega) \tilde{F}_Z(\omega)$$

where:

ζ_1 is the coherence factor.

$\tilde{F}_Z(\omega) = C_p(\omega) Q A_z$, Fully-coherent BFF

PSDs of BFFs Φ_Z^F

Estimated BFF in the z-direction:

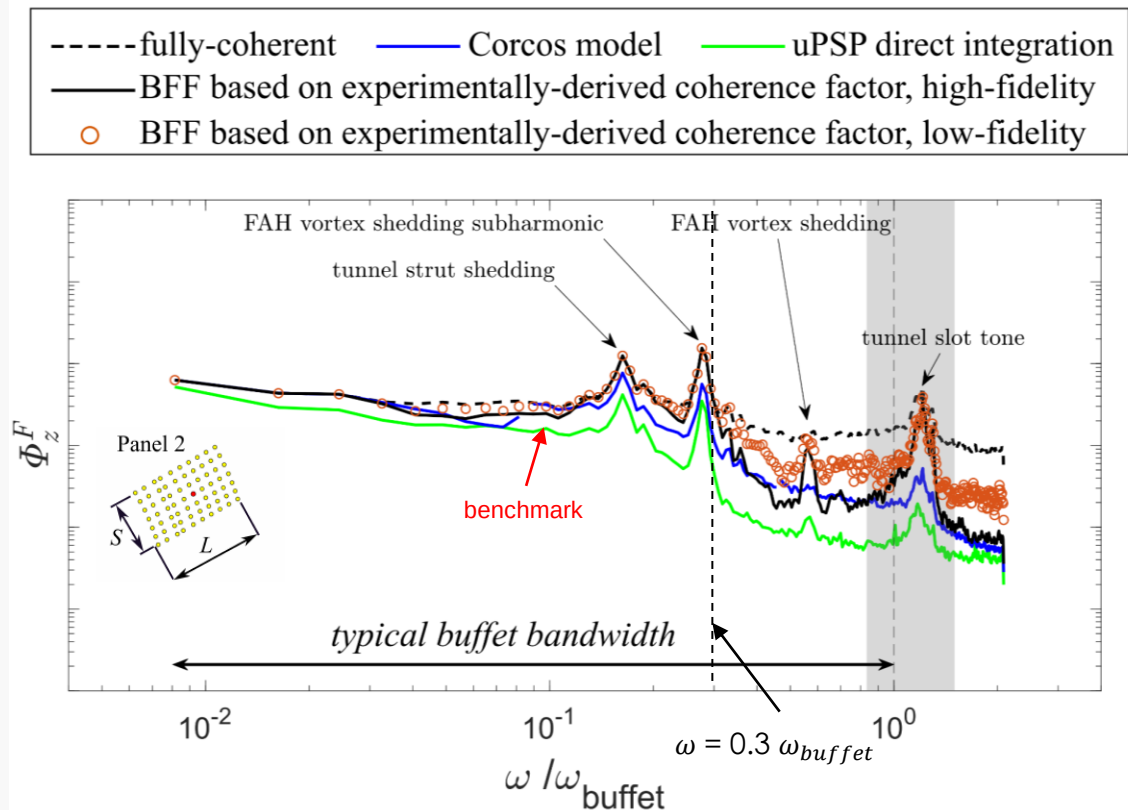
$$F_Z(\omega) = \zeta_1(\omega) \tilde{F}_Z(\omega)$$

where:

ζ_1 is the coherence factor.

$\tilde{F}_Z(\omega) = C_p(\omega) Q A_z$, Fully-coherent BFF

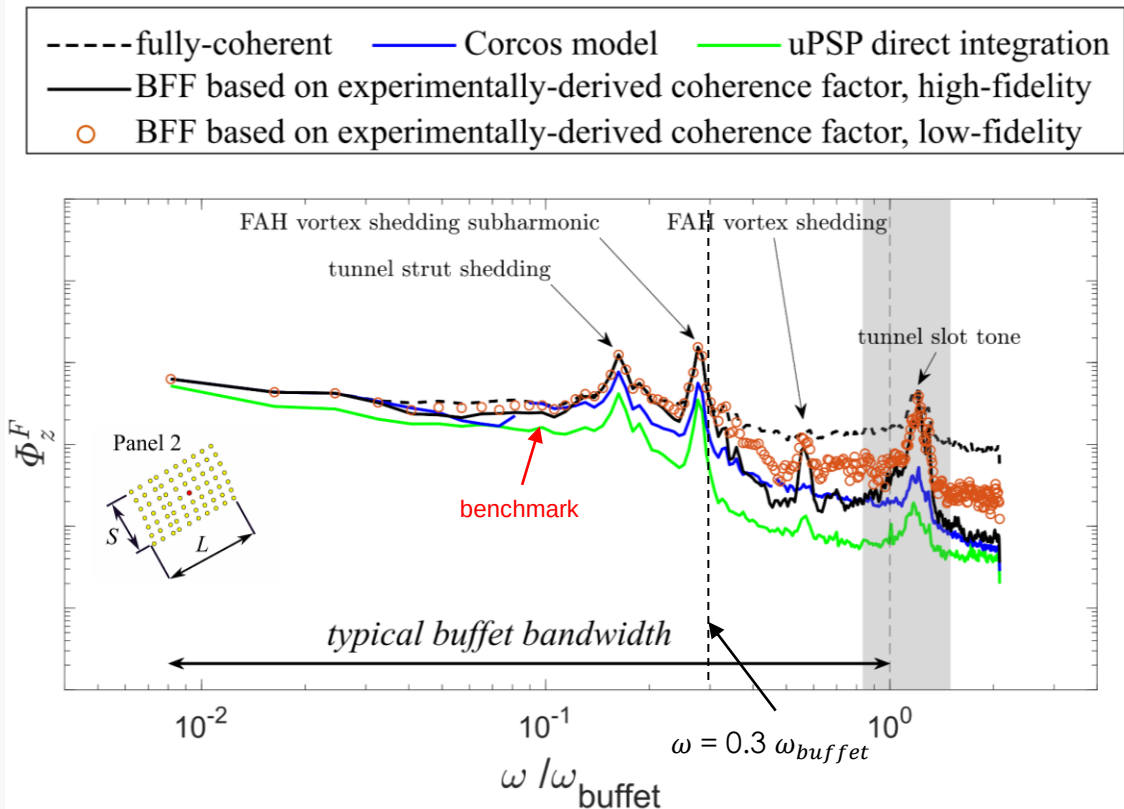
Mach=0.79, $\alpha = 0.0^\circ$, $\beta = 0.0^\circ$



PSDs of BFFs Φ_Z^F

- The fully-coherent BFF (dashed curve) is overconservative, as expected.
- The **Corcos-based BFF** closely tracks a BFF that is based on **high-fidelity** experimentally-derived ζ_1 .
- The **low-fidelity BFF** is overconservative at $\omega > 0.3 \omega_{buffet}$, as expected.

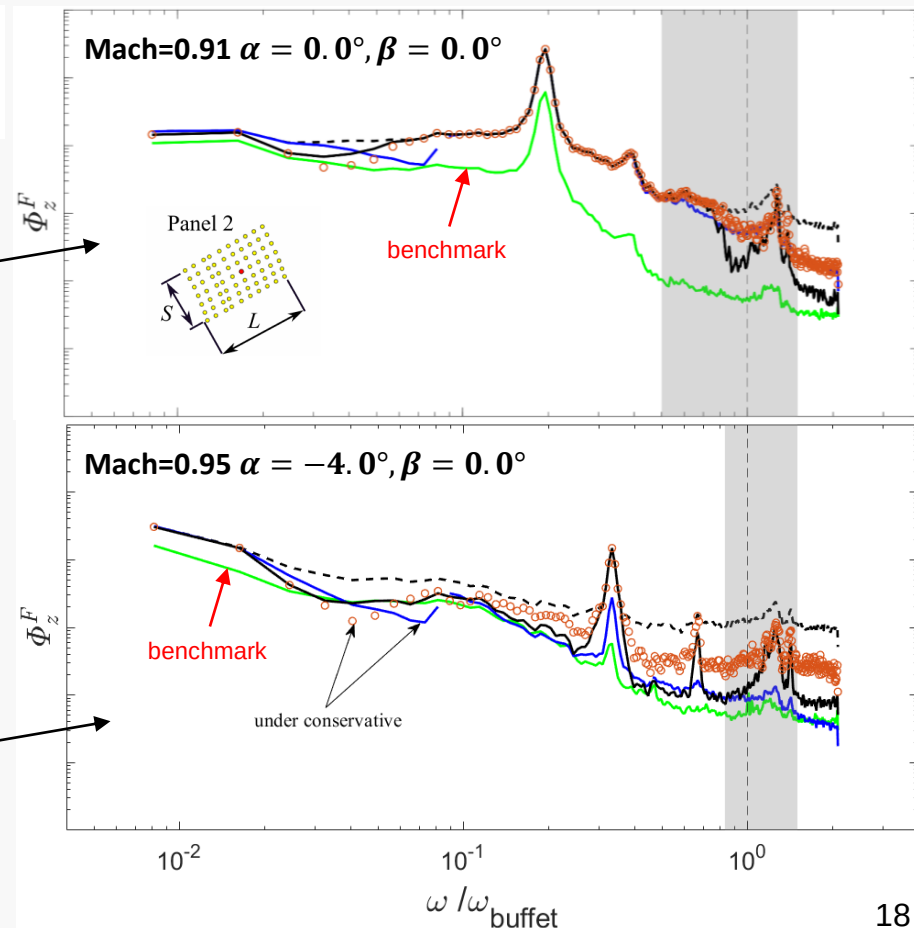
Mach=0.79, $\alpha = 0.0^\circ$, $\beta = 0.0^\circ$



PSDs of BFFs Φ_Z^F . Additional Mach/attitude Conditions.

----- fully-coherent — Corcos model — uPSP direct integration
 — BFF based on experimentally-derived coherence factor, high-fidelity
 ○ BFF based on experimentally-derived coherence factor, low-fidelity

- At Mach=0.91, within $0.08 < \omega / \omega_{buffet} < 0.7$, all BFF estimation methods discussed in this paper (Corcos-based and experimentally-derived ζ_1) lead to an overestimation of the benchmark BFF.
- This is due to highly coherent fluctuating pressures p' associated with vortex shedding, which cause $\zeta_1 = 1$.
- p' are also spatially nonuniform making BFF estimation more sensitive to the pressure measurement location within the panel [1].
- At Mach=0.95 $\alpha = -4.0^\circ$, where the reference panel is located on the windward side of the core stage, Corcos-based and high-fidelity experimentally-derived BFFs are in good agreement with the benchmark.



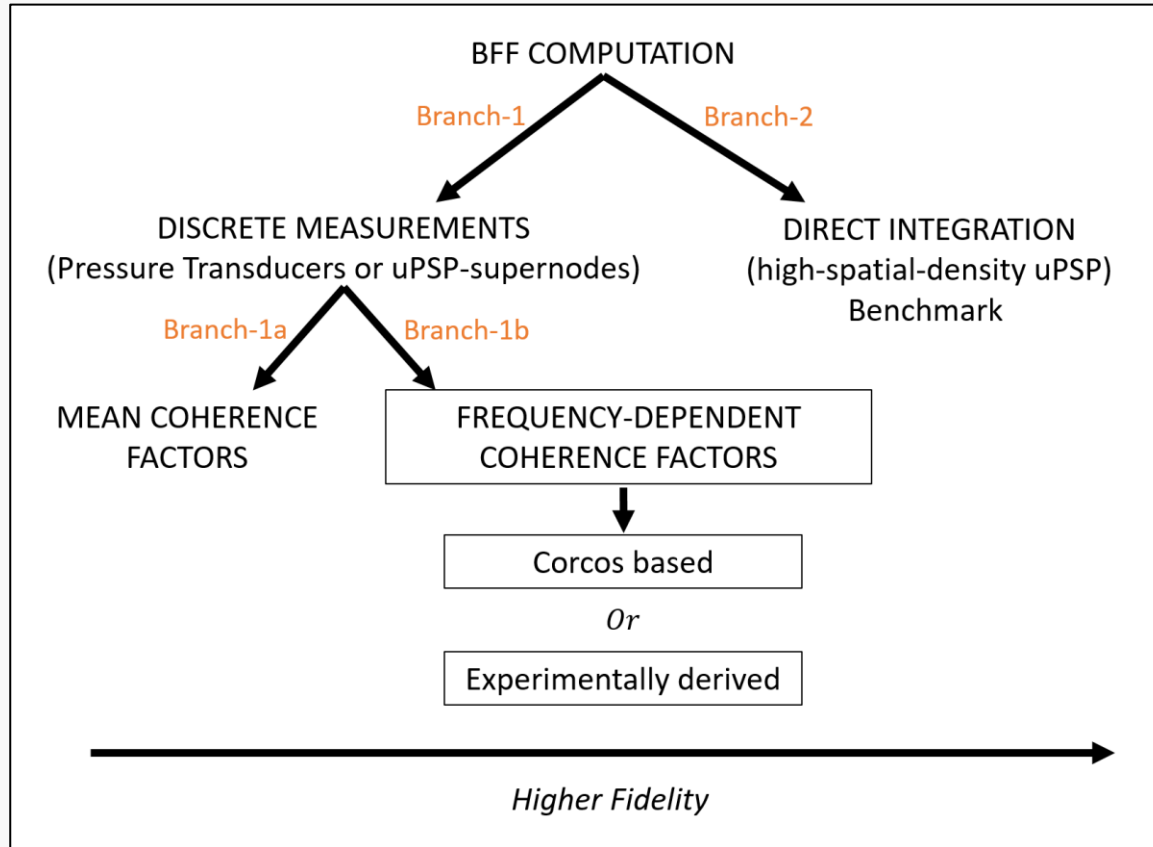
[1] Soranna et al., AIAA, Aviation 2022

Summary

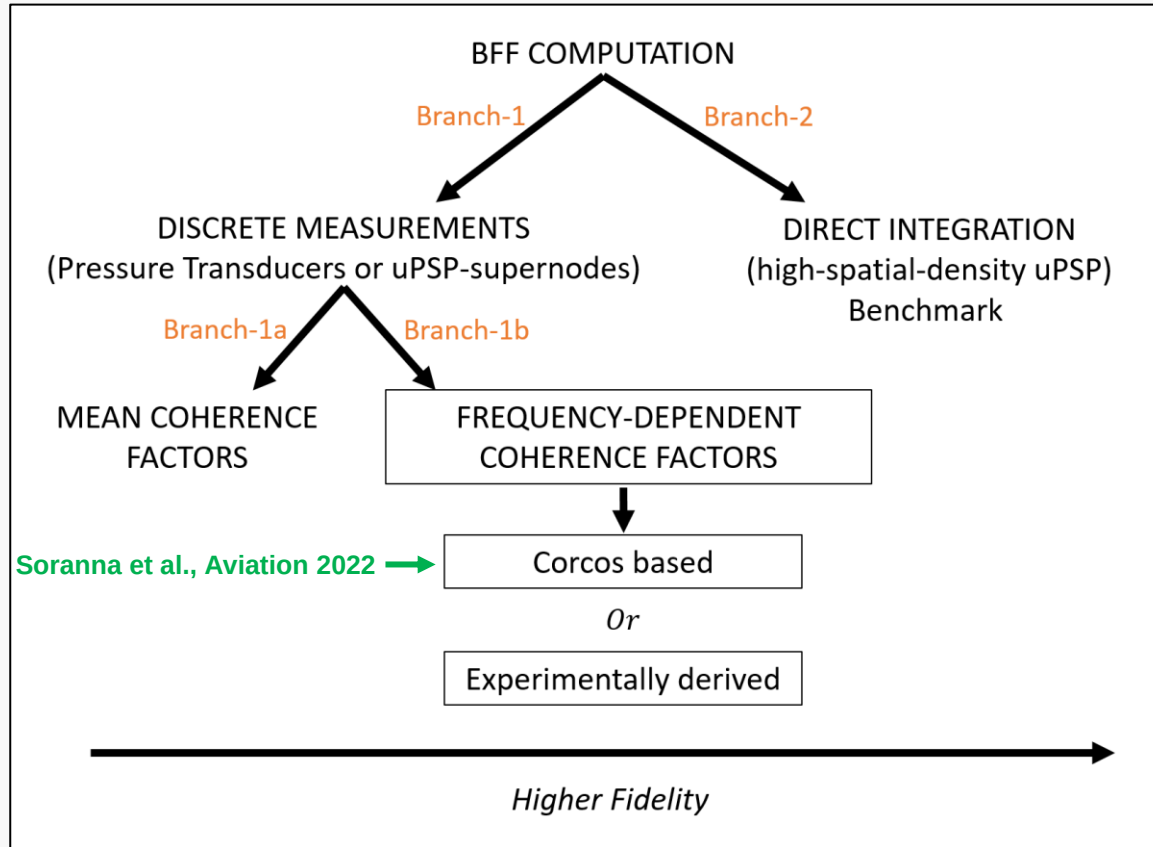
- In this work, a comparison between Corcos-based and experimentally-derived BFF data-products is presented, including coherence-length, coherence factors, and PSDs of BFFs.
- This study was made possible by a unique data set comprised of high-spatial-resolution uPSP measurements collected on a Space Launch System configuration.
- The analysis focuses on the core stage region located downstream of the booster forward attachment hardware (FAH). In this region, the vehicle experiences peak fluctuating forces due to vortex shedding off the attachment hardware.
- Trends of Corcos-based and experimentally-derived coherence factors are in reasonable agreement with the benchmark. However, at certain frequencies, experimentally-derived coherence factors are sensitive to the separation distance between pressure measurements utilized to compute coherence lengths.
- On the other hand, as discussed in the paper, the present implementation of the Corcos model fails to capture certain nonturbulent boundary layer related environments, such as a subharmonic of FAH vortex shedding.
- For all discrete-measurements-based methods presented in this paper, at near transonic conditions, increased pressure coherence and spatial nonuniformity lead to BFF overestimation and sensitivity to the pressure measurement location within the panel.

BACK-UP

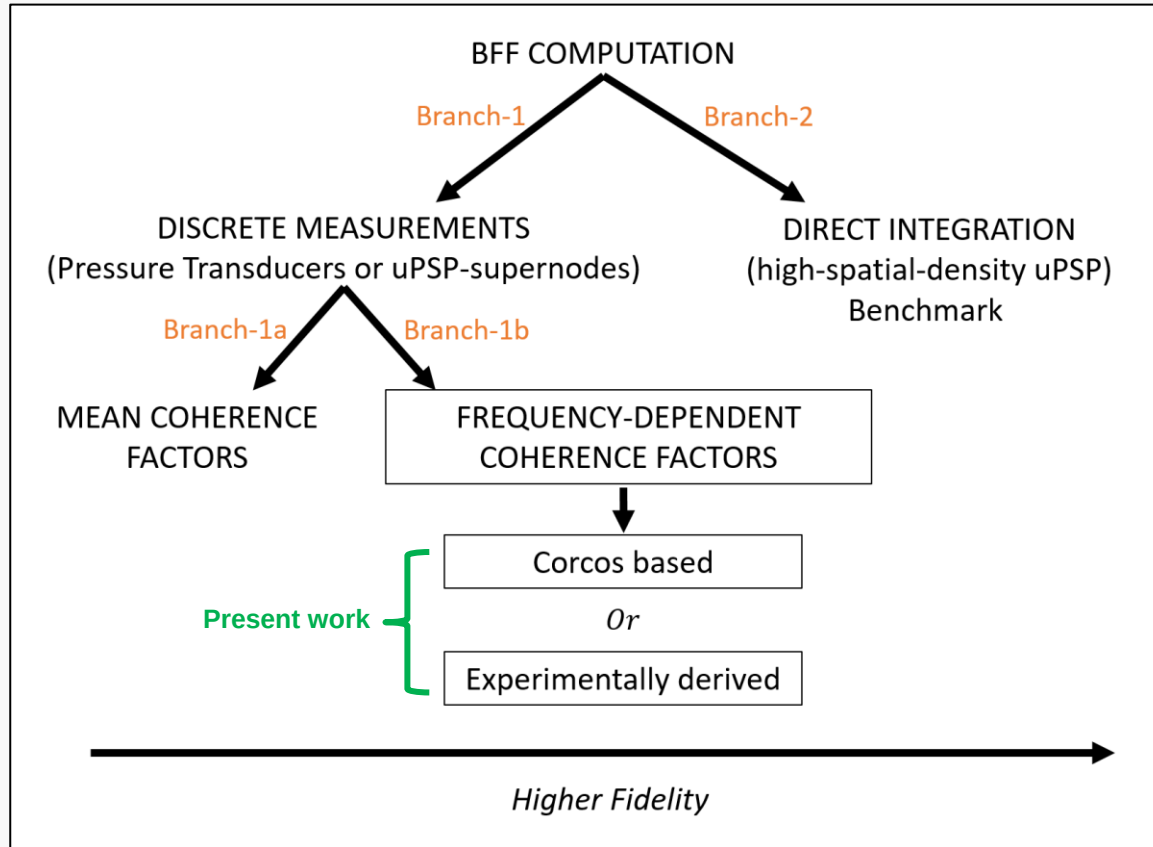
Introduction



Introduction



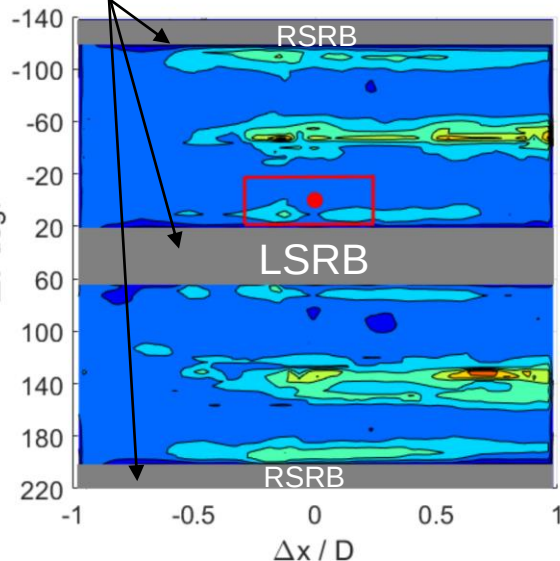
Introduction



Unwrapped distributions of $\Delta C_{p,rms}$ based on uPSP data

Mach=0.79 $\alpha = 0.0^\circ, \beta = 0.0^\circ$

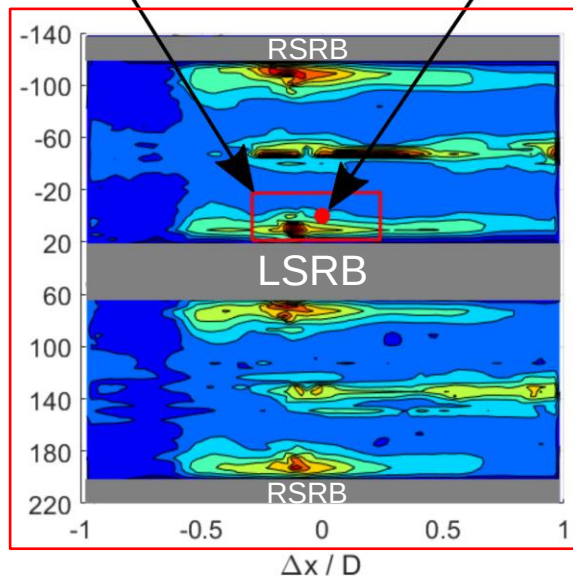
Lack of uPSP data due to SRB's blockage



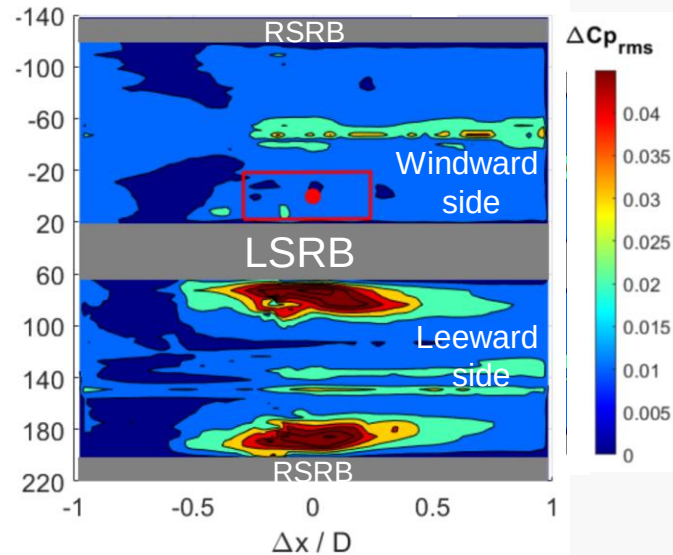
Mach=0.91 $\alpha = 0.0^\circ, \beta = 0.0^\circ$

panel #2 boundaries

reference supernode



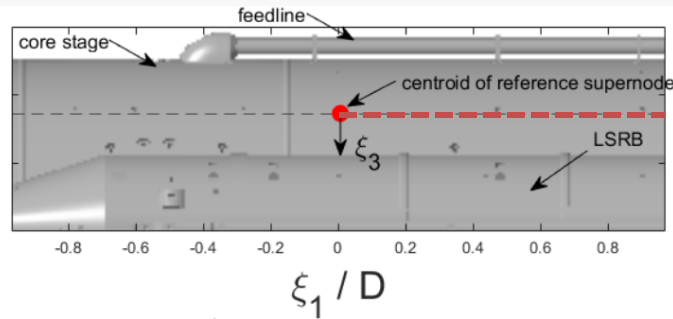
Mach=0.95 $\alpha = -4.0^\circ, \beta = 0.0^\circ$



- At Mach=0.91, pressure fluctuations within panel #2 boundaries are spatially nonuniform because of vortex shedding.
- Vortex shedding also contributes to elevated coherence levels compared to lower Mach number conditions or conditions where panel #2 is located off the trajectory of shed vortices (e.g., $\alpha = -4$ deg. case shown on the right).
- At Mach=0.91, direct integration of pressure fluctuations within panel #2 tends to smooth-out spatial gradients while integration based on a single supernode is more sensitive to the precise location of the reference supernode.**

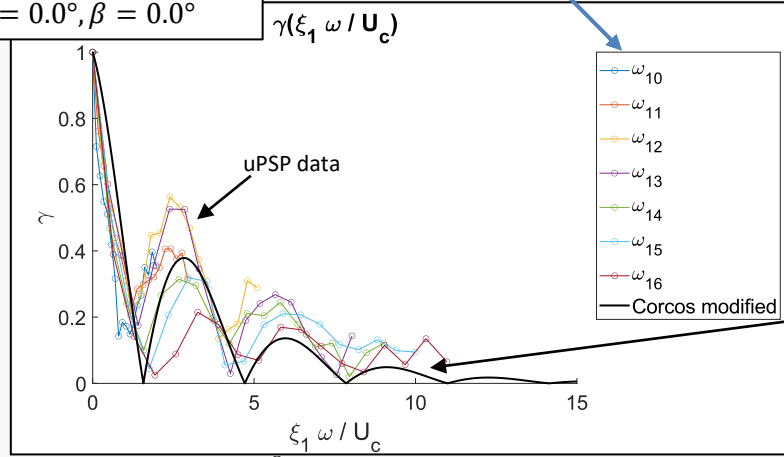
Similarity hypothesis, midfrequency

uPSP-based γ is computed along a longitudinal line in proximity of the booster forward attachment:



Midfrequency range (from ~8% to ~45% of a typical buffet bandwidth)

Mach=0.79 $\alpha = 0.0^\circ, \beta = 0.0^\circ$



- γ is characterized by a pronounced oscillatory behavior.
- This behavior is captured by the modified Corcos model where $\alpha_1=0.33$ (Vs. $\alpha_1=0.78$ for the unmodified Corcos model).
- The modified model could be used to improve legacy methods for estimation of coherence factors

Corcos-modified model:

$$A = e^{-\alpha_1 |\omega \xi_1 / U_c|} |\cos(|\omega \xi_1 / U_c|)|$$