

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

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In this paper, high-spatial-resolution unsteady Pressure Sensitive Paint (uPSP) data are utilized to compare two methods for panel Buffet Forcing Function (BFF) estimation for the Space Launch System (SLS). Such methods are based on discrete pressure measurements within a panel but employ coherence factors to account for partially-correlated fluctuating pressures across the whole panel. In one method, coherence factors are derived based on the Corcos model, whereas the second method utilizes experimentally-derived coherence factors. To simulate discrete measurements using uPSP data, suitable subsets of the data are extracted. When full uPSP resolution is retained, uPSP data provide a benchmark to assess discrete-measurement-based methods. The analysis focuses on the peak SLS buffet environment located downstream of the Forward Attachment Hardware (FAH) between the core stage and solid rocket boosters. 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. Such sensitivity originates from deviation of the experimentally-based coherence function from an exponential decay assumption. On the other hand, 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 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.

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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.

Acronyms

ATAT	=	Ascent Transient Aerodynamics Test
BFF	=	Buffet Forcing Function
CLA	=	Coupled Loads Analysis
FAH	=	Forward Attachment Hardware
FRF	=	Frequency Response Function
LV	=	Launch Vehicle
LSRB, RSRB	=	Left Solid Rocket Booster, Right Solid Rocket Booster
OML	=	Outer Mold line
RBM	=	Rigid Buffet Model
SLS	=	Space Launch System
TBL	=	Turbulent Boundary Layer
uPSP	=	unsteady Pressure Sensitive Paint

Nomenclature

A_z	=	projected area of panel in the z -direction
C_p	=	pressure coefficient
D	=	core diameter
F_i	=	panel orthogonal buffet forcing function, acting in the i -direction
$\tilde{F}_i$	=	panel fully-coherent buffet forcing function
$\mathcal{F}$	=	Fourier transform
H	=	frequency response function
i	=	axis indices ($i : 1 = x, 2 = y, 3 = z$)
j, k	=	supernode indices
l_i	=	coherence length along the longitudinal ($i = 1$) or azimuthal ($i = 3$) directions

L	=	longitudinal width of panel
n	=	frequency index
p'	=	surface fluctuating pressure
Q	=	freestream dynamic pressure
x, y, z	=	longitudinal, lateral, and vertical axes of the vehicle
U_c	=	turbulence-convection velocity
α_1	=	streamwise decay constant
α	=	angle of attack
β	=	sideslip angle
Γ	=	cross-spectral density function
γ	=	coherence function
θ	=	body coordinate system azimuthal angle
ξ_1	=	streamwise distance from reference supernode
φ	=	phase angle
ϕ	=	autospectrum
Φ_i^F	=	power spectral density of the force F_i
ω	=	angular frequency
ω_{buffet}	=	upper frequency limit of typical buffet bandwidth for LV
ζ	=	coherence factor

I. Background and Methodology

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) [1]. To model these buffet loads, CLA employs suitable forcing functions, called buffet forcing functions (BFFs) [2] that consist of unsteady 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 wakes, etc.

Figure 1 illustrates different BFF computational methods for LV design. These methods can be divided into two main groups: discrete-measurements method (Branch-1) and direct integration (Branch-2). In the discrete-measurements method, which is the current state-of-the-art, surface fluctuating pressures, p' , are measured in a wind tunnel at discrete locations on the Outer Mold Line (OML) of an LV rigid buffet model (RBM). Because buffet-related p' are only partially correlated, the integration process involves coherence factors, ζ , to simulate the effect of this partial correlation. Coherence factors are either based on a mean coherence over the buffet spectrum (Branch-1a, Fig. 1), or they are

frequency dependent (Branch-1b, highlighted by a box in Fig. 1). Frequency-dependent coherence factors can be computed based on the Corcos model [3] or can be experimentally derived (Refs. [2, 4, 5]).

In recent efforts, Soranna et al. [6] presented a validation of Corcos-based coherence factors, and associated BFFs, based on high-spatial-resolution unsteady Pressure Sensitive Paint (uPSP) data from wind-tunnel tests of the SLS. While it was shown that Corcos-based ζ do a reasonable job at BFF estimation (except for non-TBL environments), a question remained about how well these modeled ζ compare to experimentally-derived ones. To address that question, in the present work, experimentally-derived ζ are computed from a set of discrete measurements extracted from full-resolution uPSP data (same data as in Ref. [6]). These discrete measurements simulate those typically obtained by pressure transducers. Then, by retaining full spatial resolution, direct integration of uPSP data (Branch-2 in Fig. 1) provides a benchmark for validation of experimentally-derived ζ and associated BFFs.

The analysis shown next focuses on the surface pressures measured on the SLS Block 1 Cargo core component that are produced by the forward attachment between the core stage and the solid rocket boosters, where multibody effects are responsible for peak p' environment (Fig. 2). As a reference, the body coordinate systems employed in this paper are shown in Fig. 3.

A. Test description

The data were collected during the SLS Ascent Transient Aerodynamics Test (ATAT) conducted in August and September 2019 at the NASA Ames Research Center (ARC) Unitary Plan Wind Tunnel (UPWT). While ATAT utilized both the 11-Foot Transonic Wind Tunnel (11-Foot TWT) and the 9- by 7-Foot Supersonic Wind Tunnel (9x7 SWT) at UPWT, uPSP data were only collected in the 11-Foot TWT. Using this experimental method, the buffet environments for two SLS configurations were examined: 1) the SLS Block 1 Cargo, on which the Europa Clipper Science Mission 1 (SM-1) was initially manifested, and 2) the SLS Block 1B Cargo with a low-fineness-ratio ogive payload fairing. The analysis presented in this paper is based on the first configuration, the 2.5-percent scale SLS Block 1 Cargo vehicle, shown in Fig. 2-a. Testing in the 11-Foot TWT was conducted at a unit Reynolds number of 3×10^6 per foot, the Mach number ranged between 0.70 and 1.40, and the angle-of-attack and sideslip angles ranged between ± 6 degrees. The uPSP measurement technique was utilized to acquire extremely high-spatial-density unsteady-pressure data at a sampling rate of 10 kHz. Details of this optical measurement method are documented in Ref. [7].

B. Methodology

The aforementioned uPSP data were analyzed using a panel method described in Ref. [8]. This method consists of defining contiguous panels on the model surface and spatially averaging the uPSP-measured unsteady pressures over hundreds of uPSP measurement locations within each panel. The panel method generates a coarse grid of “supernodes” whose centroids are shown in Fig. 4. In the rest of the paper, the term supernodes will be used. The reason for spatial

averaging is to reduce the electronic shot noise present in uPSP data (see Ref. [5] for details). A drawback of spatial averaging is a reduction of the spatial resolution.

The analysis presented focuses on the SLS Block 1 Cargo configuration and the buffet environment on the core stage downstream of the booster forward attachment structure as shown in Fig. 2. The ATAT model grid contains 954,894 uPSP nodes of which 479,079 uPSP nodes are located on the core stage. The nodes on the core stage were assembled into 10,800 panels defined by 180 uniformly-spaced longitudinal stations, divided into 60 evenly-spaced azimuthal sectors. The corresponding nondimensional longitudinal and azimuthal resolutions are $\Delta x/D = 5.7\%$ and $\Delta\theta/2\pi = 1.7\%$, where x is the longitudinal axis (Fig. 3), θ is the body coordinate system azimuthal angle, and D is the core stage diameter.

II. Results

The next sections present the following comparisons between Corcos-modeled and experimentally-derived quantities: 1) coherence lengths, 2) BFF coherence factors, and 3) BFF power spectral densities. For simplicity, the analysis that follows is based on streamwise coherence only. Modeling of crossflow coherence factors is discussed in Ref. [6].

A. Coherence lengths

Consider a buffet region defined by a panel on the core stage such as the one shown in Fig. 4 (yellow markers). This region is located in proximity of the forward attachment hardware (FAH) connecting the core and solid rocket boosters (a closeup view of the wind-tunnel representation of the FAH hardware is shown in Fig. 2-b). For this region, the analysis that follows compares experimentally-derived coherence lengths to those based on the Corcos model.

1. Experimentally-derived coherence length

Experimentally-derived longitudinal coherence lengths $l_1(\omega)$ (ω is the angular frequency) are obtained using arrays of uPSP supernodes that simulate discrete pressure transducers that are traditionally used to measure p' . The uPSP supernode approach enables an assessment of sensor density and distribution on the coherence lengths. Figure 4 illustrates this concept (see red markers). Figure 4-a presents a typical arrangement of pressure transducers for BFF estimation based on wind-tunnel tests. This configuration is referred to as low fidelity, in contrast with a high-fidelity configuration shown in Fig. 4-b that is used as a benchmark. The latter consists of 18 contiguous supernodes including the reference supernode.

Computation of $l_1(\omega)$ consists of the following steps:

- 1) the coherence function, γ , is computed between p' measured at the reference supernode, j , and any of the downstream supernodes k :

$$\gamma(\omega) = \frac{|\Gamma_{jk}(\omega)|}{\sqrt{\phi_j(\omega) \phi_k(\omega)}} \quad (1)$$

where Γ_{jk} and $\phi_{j,k}$ represent the cross-spectral density function and the autospectrum, respectively. Equation 1 is evaluated using the MSCOHRE function in MATLAB™ (since MSCOHRE computes the magnitude-squared-coherence, γ^2 ; here, the square root of the output is used), where the pressure time histories are windowed using a 512-sample Hamming window with 50% overlap between windows.

- 2) For each discrete frequency ω_n , a distribution $\gamma(\omega_n, \xi_1)$ is defined, where ξ_1 is the streamwise separation distance between the reference supernode and supernode k (ξ_1 is marked in Fig. 4-a).
- 3) $l_1(\omega_n)$ is computed by nonlinear least-square fitting of the exponential function $e^{-\xi_1 / l_1(\omega_n)}$ to the experimentally-derived values of $\gamma(\omega_n, \xi_1)$ (Refs. [5, 9]) to yield a discrete-measurement-based coherence length.

Figure 5 compares experimentally-derived coherence lengths to those based on the Corcos model (the latter are discussed in the next section). Brown circles show a distribution of l_1 as a function of frequency for the low-fidelity supernode configuration of Fig. 4-a. As a benchmark, the black curve represents l_1 estimated using the high-fidelity supernode array defined in Fig. 4-b. On the x -axis, frequencies are normalized using a reference value ω_{buffet} that is an upper limit of a typical LV buffet bandwidth. Highlighted peaks in Fig. 5 correspond to frequencies of vortex shedding off the FAH (hardware shown in Fig. 2-b) as well as tunnel tones associated with the ARC 11-Foot TWT empty tunnel background acoustics. Comparing low- and high-fidelity l_1 trends, there is a reasonable agreement up to $\omega/\omega_{\text{buffet}} \sim 0.3$. At $\omega > 0.3 \omega_{\text{buffet}}$, and apart from vortex shedding and tunnel slot tone frequencies, the low-fidelity l_1 estimate is overconservative relative to the benchmark.

To identify a source of overconservatism, Fig. 6 shows distributions of $\gamma(\xi_1)$ at sample frequencies marked by dashed lines in Fig. 5. On the x -axis, ξ_1 is normalized by the core stage diameter D . In both Fig. 6-a and Fig. 6-b plots, brown symbols correspond to the low-fidelity supernode array of Fig. 4-a, whereas black symbols are based on the high-fidelity array of Fig. 4-b. In Fig. 6, curve fitting of low- and high-fidelity data is shown by solid curves, following the same color scheme as the underlying discrete γ -distributions. Note that since the low-fidelity supernode array is a subset of supernodes of the high-fidelity array, the low-fidelity $\gamma(\xi_1)$ distribution is also a subset of its high-fidelity correspondent. At $\omega/\omega_{\text{buffet}} = 0.03$ (Fig. 6-a), exponential curves corresponding to low- and high-fidelity data-fit closely overlap and, accordingly, $l_1(\omega)$ values are nearly identical at this frequency (see dashed vertical lines in Fig. 6-a and corresponding l_1 values plotted in Fig. 5). At $\omega/\omega_{\text{buffet}} = 0.67$ (Fig. 6-b), distributions of $\gamma(\xi_1)$ deviate from an exponentially decaying trend, especially for high-fidelity data. As a result, curve fitting exponential functions through low- and high-fidelity data yields largely different answers, neither of which provides an accurate representation of the underlying distributions. Accordingly, at this frequency, the ratio of coherence lengths based on low- and high-fidelity supernode arrays is 2.99.

Identifying and modeling a clear mechanism for deviation of $\gamma(\xi_1)$ from an exponential decay at certain frequencies is a challenging task. It was observed [6] that, at Mach=0.79, scatter in $\gamma(\xi_1)$ shown in Fig. 6-b is captured by a form of the Corcos longitudinal coherence function that includes the phase term (see Ref. [6] for further details). The same is not true at higher Mach numbers where other phenomena, non-TBL related, could be responsible for deviations of $\gamma(\xi_1)$ from a decaying exponential. Such mechanisms are presently unknown. Nevertheless, improving sensor spatial resolution near the reference sensor is a way of minimizing overconservatism in estimated coherence lengths, albeit adding complexity and cost.

2. Corcos-based coherence length

Based on the Corcos model, the streamwise coherence length is [6]:

$$l_1(\omega) = \frac{U_c}{\alpha_1 \omega} \quad (2)$$

where values of the streamwise decay constant, α_1 , for the subject region on the SLS are tabulated in Ref. [6]. In Eq. 2, U_c is the turbulence-convection velocity that is assumed equal to half the freestream velocity [8]. Coherence lengths estimated based on the Corcos model are shown in Fig. 5 by blue lines. Corcos-based $l_1(\omega)$, that by definition follow an ω^{-1} trend (Eq. 2), provide a reasonable approximation of the benchmark (black curve). However, trends of experimentally-derived coherence lengths (brown circles and black curve) are nonmonotonic, due to the impact that FAH vortex shedding has on the coherence function as well as spurious tunnel-related phenomena (strut shedding, slot tone), such as those marked in Fig. 5.

B. Coherence factors

1. Methodology

The concept of coherence factors is explained in Ref. [6]. In the following, key points are summarized to support the analysis. For a buffet region such as the reference panel shown in Fig. 4, a coherence factor, ζ , is an approximation of the frequency response function (FRF), $H(\omega)$, between a fluctuating force F_i acting on that panel (referred to as Buffet Forcing Function, BFF) and its fully-coherent estimate, $\tilde{F}_i$. The latter assumes that fluctuating pressures acting on every point across the panel area share the same time history as p' acting on a reference point inside the panel. In the frequency domain, the relationship between F_i and $\tilde{F}_i$ is:

$$F_i(\omega) = H(\omega)\tilde{F}_i(\omega) = |H(\omega)| e^{i\varphi(\omega)} \tilde{F}_i(\omega) \quad (3)$$

where $\varphi(\omega)$ is the phase angle between F_i and $\widetilde{F}_i$. Assuming $\varphi = 0$ deg., and $\zeta(\omega) \sim |H(\omega)|$, Eq. 3 becomes:

$$F_i(\omega) \sim \zeta(\omega) \widetilde{F}_i(\omega). \quad (4)$$

It is customary to define ζ as a function of a coherence length, $l(\omega)$, for the turbulent flow over the subject panel and a characteristic panel dimension, L :

$$\zeta(\omega) = \zeta(l(\omega), L). \quad (5)$$

In this paper, Eq. 5 is applied to streamwise coherence lengths, i.e., $\zeta = \zeta_1$ but, as discussed in Ref. [6], Eq. 5 can be applied to crossflow coherence lengths as well. Regarding the functional form of $\zeta(\omega)$ (Eq. 5), the following formulation is chosen [6]:

$$\zeta_1(\omega) = \begin{cases} \sqrt{\frac{l_1(\omega)}{L}} & \text{if } l_1(\omega) < L \\ 1 & \text{if } l_1(\omega) \geq L \end{cases} \quad (6)$$

where $l_1(\omega)$ can be based on a model or experimentally derived. In Eq. 6, L is the longitudinal width of the panel.

2. Application

Figure 7 compares streamwise coherence factors (ζ_1) for the reference panel of Fig. 4 based on: 1) the Corcos model (blue lines) and 2) experimentally-derived ζ_1 for configurations shown in Fig. 4. The black line corresponds to the high-fidelity configuration of Fig. 4-b and the brown symbols represent its low-fidelity equivalent (Fig. 4-a). Shown in green is a benchmark uPSP-based FRF amplitude, $|H(\omega)|$, for the same panel (see Ref. [6] for details on H computation). The shaded area represents frequencies impacted by a tunnel slot tone. The data correspond to a test condition where the Mach number is 0.79 and the vehicle attitude is zero degrees.

Within a typical transonic buffet bandwidth, trends of Corcos-based coherence factors are consistent with $|H(\omega)|$. Experimentally-derived coherence factors are also in agreement with the benchmark. However, at $\omega/\omega_{\text{buffet}} > 0.3$ and apart from certain spectral features (FAH vortex shedding and tunnel slot tone), the low-fidelity ζ_1 distribution overestimates its high-fidelity counterpart, as expected, due to coherence length disparities discussed in Section II.A.1. Flow phenomena that are characterized by high p' -coherence cause deviations between Corcos-based and experimentally-derived coherence factors. For example, at $\omega/\omega_{\text{buffet}} \sim 0.55$, where FAH vortex shedding occurs, Fig. 7 shows $\zeta_1 \sim 0.8 - 1.0$ for experimentally-derived coherence factors, while the Corcos model predicts 30 – 50% lower levels.

At Mach=0.91 (Fig. 8-a), within $0.08 < \omega/\omega_{\text{buffet}} < 0.7$, Corcos-based coherence factors are greater than their counterpart at Mach=0.79. Note that at Mach=0.91, the Corcos model estimates $\zeta_1 = 1$ for most frequencies within $0.08 < \omega/\omega_{\text{buffet}} < 0.7$. Indeed, as discussed in Ref. [6], for this spectral range, Corcos decay constants at Mach=0.91 are 70-75% lower than those estimated at Mach=0.79, indicating that fluctuating pressures for this buffet region are

significantly more coherent at Mach=0.91 than at lower Mach number, thus resulting in larger coherence factors. Across the spectrum, distributions of experimentally-derived coherence factors at Mach=0.91 are consistent with the Corcos model, and hold a constant value equal to 1 within $0.08 < \omega/\omega_{\text{buffet}} < 0.7$. At higher frequencies, $\omega/\omega_{\text{buffet}} > 0.7$, for this higher Mach condition (Mach=0.91), low-fidelity ζ_1 overestimate high-fidelity ζ_1 levels.

Figure 8-b presents coherence factors for a Mach=0.95 condition with the vehicle at $\alpha = -4.0$ deg. angle of attack. At this vehicle attitude, where the reference panel is on the windward side of the core stage, trends of modeled and experimentally-derived coherence factors are in general agreement, and compare reasonably well to $|H(\omega)|$. Deficiencies in low-fidelity ζ_1 levels compared to high-fidelity estimates are observed throughout the entire spectrum.

C. Buffet Forcing Functions

In this section, modeled and experimentally-derived coherence factors are utilized to estimate panel BFFs that are then compared to BFFs based on direct integration of uPSP data. According to discrete-measurements methods (Fig. 1), an estimated panel BFF is computed as:

$$F_i(t) = \mathcal{F}^{-1}(\zeta(\omega)\tilde{F}_i(\omega)) \quad (7)$$

where $\mathcal{F}^{-1}$ represents an inverse Fourier transform and $\tilde{F}_i(\omega)$ is given by:

$$\tilde{F}_i(\omega) = C_p(\omega) Q A_i . \quad (8)$$

In the last equation, C_p is the pressure coefficient at a reference supernode inside the panel (Fig. 4), Q is the freestream dynamic pressure, and A_i is the projected area of the panel. A procedure for implementing Eq. 7 is provided in Ref. [6]. Corcos-based and experimentally-derived panel BFFs are obtained by substituting into Eq. 7 their respective coherence factors.

Figure 9 compares PSDs of F_z (the z -axis is shown in Fig. 3) for the reference panel of Fig. 4, Φ_z^F , estimated using the Corcos model (blue), experimentally-derived coherence factors (black curve and brown circles), and direct integration of uPSP data (green). Data are presented for Mach=0.79 and zero degrees vehicle attitude. Coherence factors shown in Figs. 7 are utilized to estimate BFFs based on the Corcos model and experimentally-derived BFFs. In Fig. 9, the black-dashed curve represents the PSD of a fully-coherent BFF, $\tilde{F}_z(\omega)$, which, as expected, is an overconservative estimate of the benchmark F_z , shown in green. Figure 9 prompts the following observations:

- comparing blue to black curves, the Corcos-based BFF closely tracks a BFF that is based on high-fidelity experimentally-derived ζ_1 (supernodes arrangement shown in Fig. 4-b). Exceptions are frequencies associated with highly-coherent flow phenomena (tunnel related phenomena and FAH vortex shedding, marked in Fig. 9), where experimentally-derived coherence factors are greater than 0.8 (Fig. 7), i.e., insufficient or no attenuation is applied. At these frequencies of high p' -coherence, Corcos-based coherence factors provide reasonable

attenuation.

- The low-fidelity, supernode-based BFF (brown circles) tracks its high-fidelity analog (black curve) up to $\omega/\omega_{\text{buffet}} < 0.3$, but this low-fidelity BFF is overconservative at $\omega/\omega_{\text{buffet}} > 0.3$, as expected.

Figure 10 extends comparisons of Fig. 9 to higher Mach numbers. At Mach=0.91 (Fig. 10-a), within $0.08 < \omega/\omega_{\text{buffet}} < 0.7$, all BFF estimation methods discussed in this paper (Corcos-based and experimentally-derived ζ_1) lead to an overestimation of the benchmark BFF (green curve). This overestimation is expected since $\zeta_1 \approx 1$ within this frequency range (Fig. 8-a). As explained in Ref. [6], at this Mach condition, vortex-shedding-induced fluctuating pressures, whose energy spreads across the subject spectral range, cause a breakdown of the assumption $\zeta(\omega) \sim |H(\omega)|$ (introduced in Section II.B.1). This breakdown is a result of a high p' -coherence, which leads to $\zeta_1 \approx 1$, while, simultaneously, a spatial nonuniformity of p' in both longitudinal and azimuthal directions lowers the FRF between $F_z(\omega)$ and $\tilde{F}_z(\omega)$.

At Mach=0.95, $\alpha = -4.0$ deg. (Fig. 10-b), the reference panel is located on the windward side of the core stage. In this environment, that is presumably dominated by turbulent boundary layer fluctuations, Φ_z^F distributions based on the Corcos-model (blue curve) and on high-fidelity experimentally-derived coherence factors are in good agreement with the benchmark (green curve). The brown symbols indicate that a low-fidelity BFF is mostly overconservative with respect to the benchmark, except at $\omega/\omega_{\text{buffet}} = 0.04$ where the low-fidelity BFF is underconservative. This underconservatism is observed also for the Corcos-based BFF, at slightly higher frequency, $\omega/\omega_{\text{buffet}} = 0.07$.

1. Buffet environments on other locations of the vehicle

In this section, Φ_z^F comparisons of Fig. 9 are extended to panels on the core stage located downstream of the FAH. The locations of these panels are illustrated in Fig. 11. Figures 12–15 present modeled and experimental Φ_z^F for the panels of Fig. 11 and for Mach=0.79, $\alpha = 0$ deg. and $\beta = 0$ deg. Figure 12 presents Φ_z^F for panels #1 through #4, Fig. 13 presents Φ_z^F for panels #5 through #8, and so on. Note that because panel #2 of Fig. 11 is the same as the reference panel of Fig. 4, Φ_z^F distributions of Fig. 12-b (panel #2) are the same as those shown in Fig. 9.

For all Φ_z^F data shown in Figs. 12–15, at $\omega/\omega_{\text{buffet}} > 0.3$, low-fidelity BFFs (brown circles) are overconservative relative to uPSP direct integration (benchmark shown in green). High-fidelity BFFs (black curves) follow the benchmark more closely than low-fidelity ones. Trends of Φ_z^F based on the Corcos model (blue curves) are in reasonable agreement with the benchmark. At panels #5 through #16 (Figs. 13–15), underconservatism is observed at the subharmonic of FAH vortex shedding, $\omega/\omega_{\text{buffet}} = 0.28$ (see for example panel #10 in Fig. 14-b). Examining panels on the 45 deg. azimuth (Fig. 11) revealed that at panels #6, #10, #14, for the frequency range containing the FAH subharmonic, Corcos-based coherence lengths are smaller compared to panel #2. For example, the ratio of Corcos-based l_1 between panel #10 and panel #2 is 0.41. Hence, at the FAH subharmonic, larger attenuation (i.e., smaller ζ_1 based on the Corcos model) is applied on panels located downstream of the FAH compared to, e.g., panel #2, resulting in underconservatism with

respect to the benchmark.

D. Conclusions

This paper compares results of different Buffet Forcing Function (BFF) estimation methods for the Space Launch System. The analysis focuses on a buffet region downstream of the Forward Attachment Hardware (FAH) between the core stage and solid rocket boosters where the vehicle experiences peak fluctuating environments due to multibody effects. High-spatial-resolution unsteady Pressure Sensitive Paint (uPSP) data are utilized to simulate discrete pressure measurements that are typically obtained using pressure transducers. This is accomplished by downselecting suitable subsets of full resolution uPSP data, referred to as uPSP supernodes. When full spatial resolution is retained, uPSP data also provide a benchmark to BFF estimation methods that are based on discrete, low-spatial resolution measurements.

A key quantity for BFF estimation is the coherence factor, ζ_1 , that approximates the frequency response function (FRF) between a fluctuating force on a region of the vehicle and a fully-coherent estimate of that force based on discrete measurements. Two ζ_1 estimation methods are employed, one is based on the Corcos model and the second is based on experimentally-derived coherence factors. Both methods yield ζ_1 distributions that are in reasonable agreement with a benchmark FRF based on direct integration of uPSP data. However, experimentally-derived coherence factors are sensitive to the number of supernodes utilized to compute coherence lengths. To characterize this sensitivity, high- and low-fidelity longitudinal supernode arrays are defined, spanning the same distance downstream of a reference supernode but containing 18 and 4 supernodes, respectively.

It is shown that fewer supernodes, i.e., larger spacing between pressure measurements, produce larger coherence lengths, hence larger coherence factors, compared to high-fidelity measurements that employ a larger number of supernodes. For example, at Mach=0.79 at a frequency corresponding to 67% of a typical buffet bandwidth, the ratio of coherence lengths based on low- and high-fidelity supernode arrays is 2.99 and, correspondingly, the ζ_1 ratio is 1.73. Such discrepancy in coherence length estimates originates from deviations of the underlying distribution of $\gamma(\xi_1)$ from an exponentially decaying trend. High-fidelity measurements result in a steeper exponential decay curve fit of γ near the origin, thus causing lower coherence lengths. Identifying and modeling clear mechanisms for deviation of $\gamma(\xi_1)$ from an exponential decay at certain frequencies is a challenging task. While at Mach=0.79, it was observed that deviations of $\gamma(\xi_1)$ from an exponential decay can be modeled by a modified form of the Corcos coherence function, the same is not true at higher Mach numbers where non-TBL-related phenomena, that are presently unknown, could be responsible for these deviations.

Coherence length sensitivity to the spacing between supernodes, i.e., pressure measurements, propagates to BFF estimation. The PSD of an estimated fluctuating force F_z based on a low-fidelity supernode array bounds its high-fidelity counterpart from above. BFFs based on a high-fidelity supernode array approximate more closely a benchmark F_z based on direct integration of uPSP data but are still conservative relative to such a benchmark.

For all methods presented in this paper, at near transonic conditions, BFF estimation for panels in close proximity of the FAH becomes more challenging. At Mach=0.91, fluctuating pressures p' associated with vortex shedding off the FAH are more coherent and nonuniform compared to a lower Mach number. While high p' coherence causes a saturation of coherence factors to a value of one, pressure nonuniformity within the panel makes BFF estimation more sensitive to the pressure measurement location within the panel. As a result of these factors, it is shown that both Corcos-based and experimentally-derived BFFs overestimate the benchmark at this condition.

An analysis of multiple panels downstream of the FAH reveals that the present implementation of the Corcos model produces underconservative BFF estimates of the benchmark at the subharmonic of FAH vortex shedding. This is a direct consequence of the Corcos-based coherence factors not being able to capture non-TBL environments. Experimentally-derived coherence factors do not suffer from this limitation as coherence lengths and coherence factors are obtained separately for each frequency. However, experimentally-derived coherence factors suffer from sensitivity to sensor spacing that the present implementation of the Corcos model does not.

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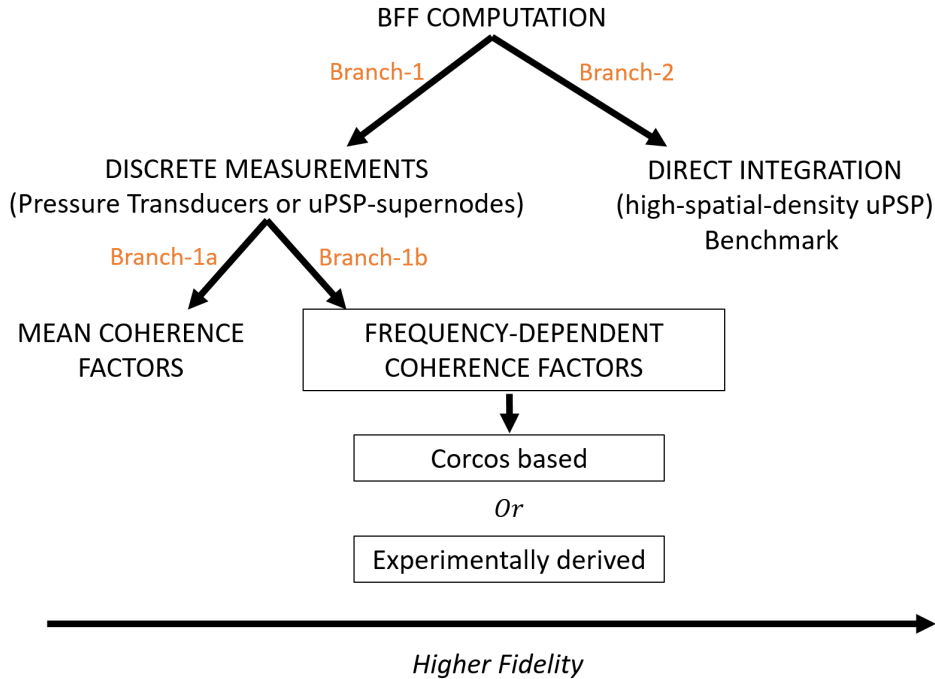
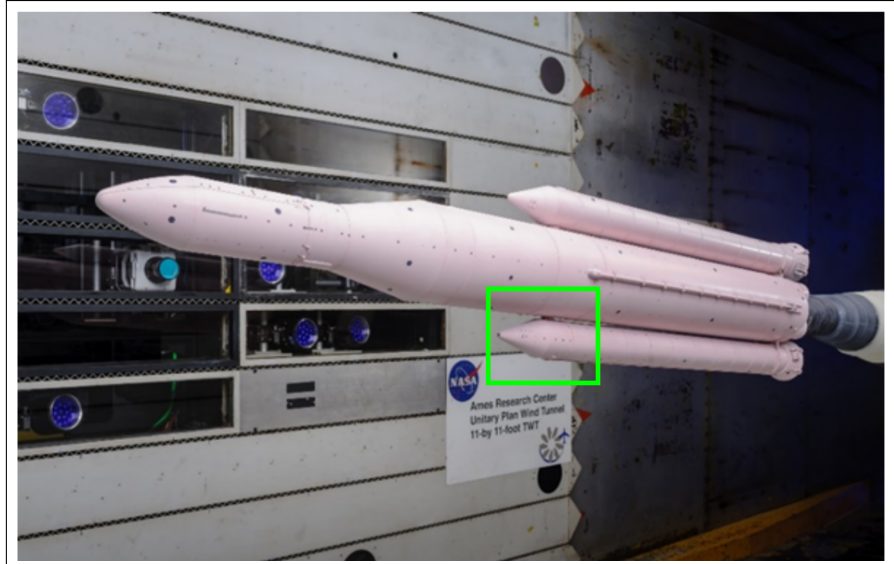


Fig. 1 Computation methods for BFFs. Highlighted within a box are frequency-dependent coherence factors (Corcos based or experimentally derived) that are subject of study in this paper.



(a) SLS Block 1 Cargo 2.5-percent scale model tested during ATAT. Highlighted in green: booster forward attachment hardware (see detailed view below).



(b) SLS Booster forward attachment hardware.

Fig. 2 SLS buffet environment subject of study in this paper [Photos: NASA].

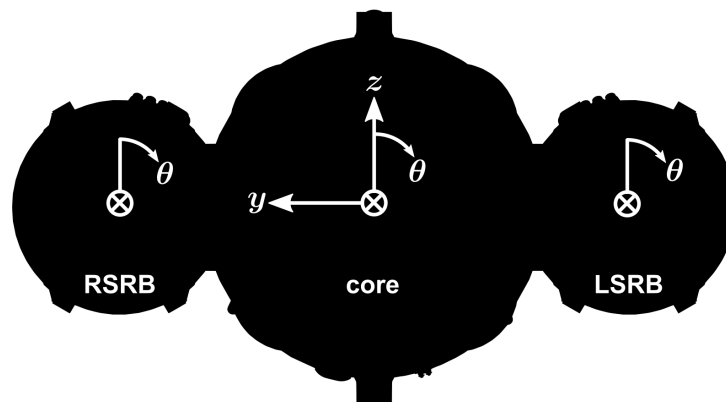


Fig. 3 Body coordinate systems on the core and on the left/right side solid rocket boosters, LSRB/RSRB. View in the aft-facing, $+x$, direction.

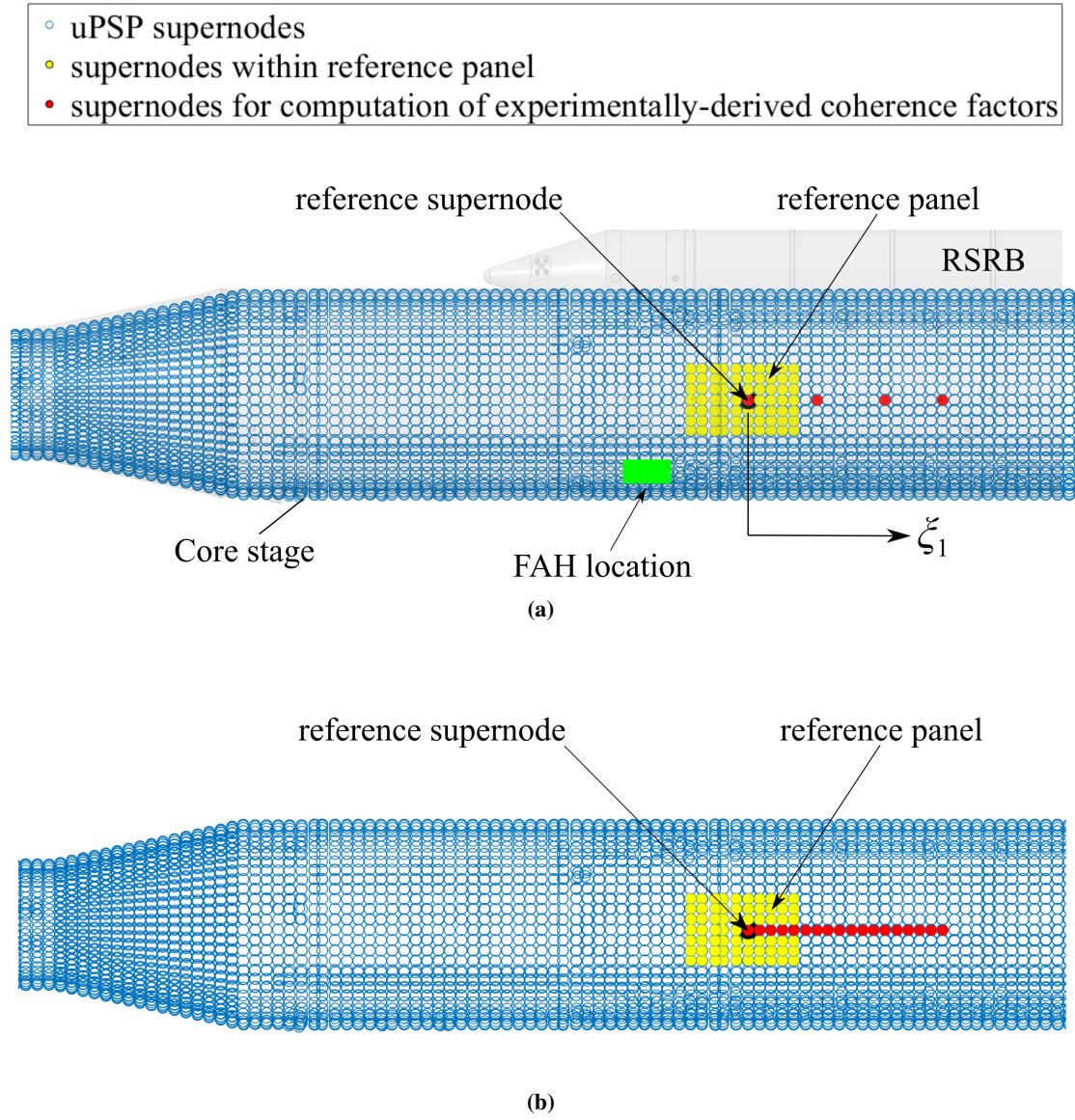


Fig. 4 uPSP supernodes for the SLS Block 1 Cargo core stage. Red markers: supernode configurations for computation of experimentally-derived coherence factors: (a) low fidelity, (b) high fidelity.

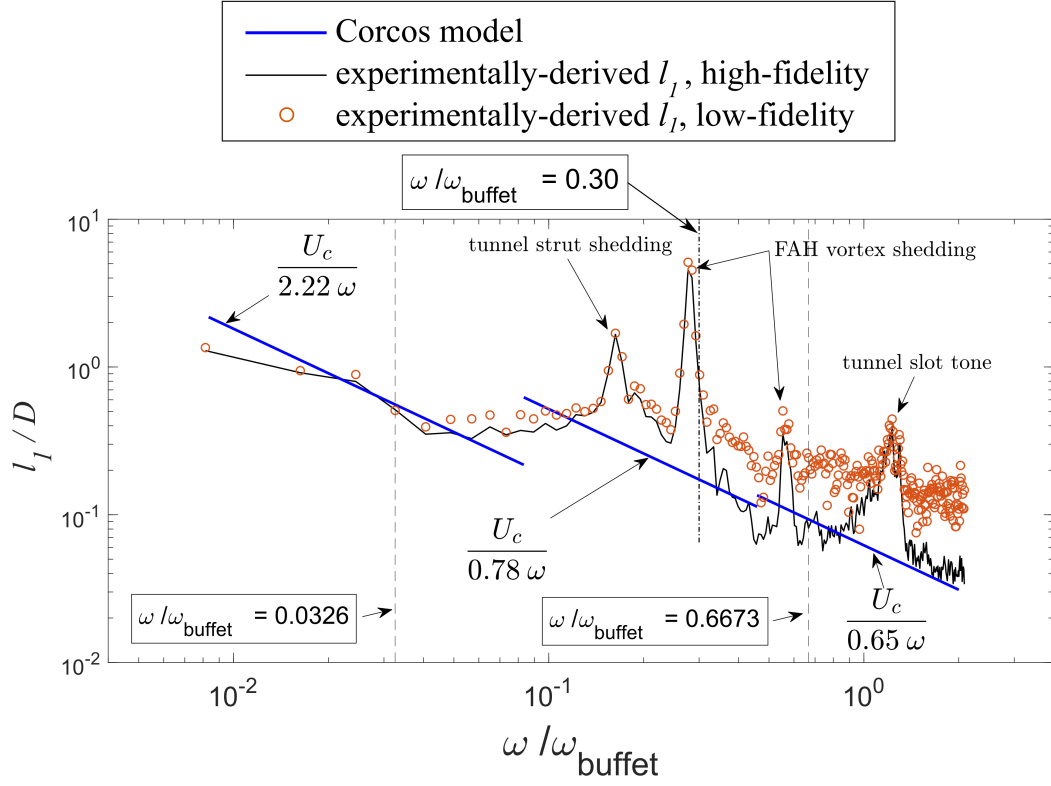
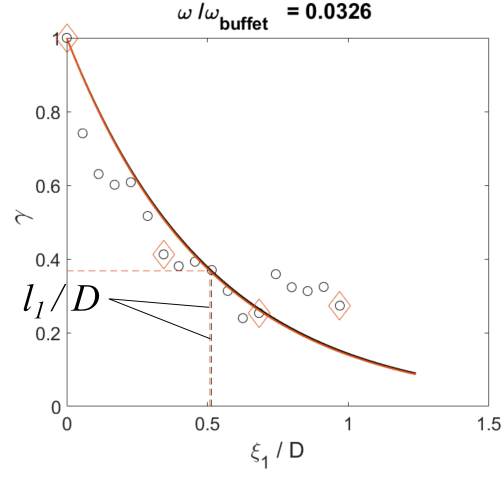
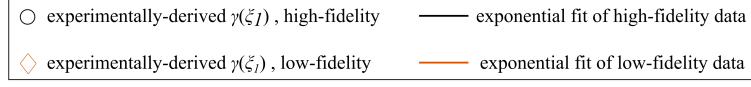
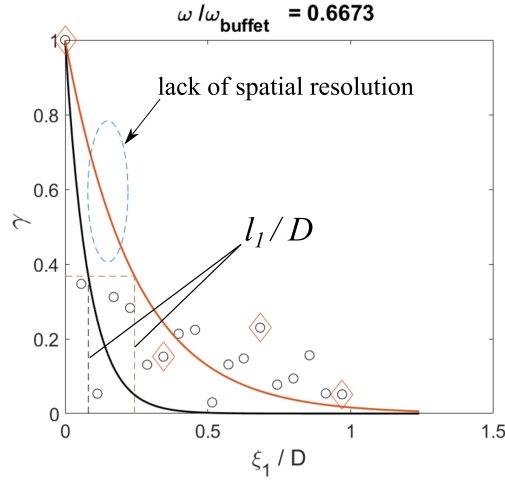


Fig. 5 Distributions of streamwise (l_1) coherence lengths as a function of frequency for the reference supernodes of Fig. 4. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.



(a) low frequency



(b) high frequency

Fig. 6 Distributions of $\gamma(\xi_1)$ for the reference supernodes of Fig. 4 and sample $\omega / \omega_{\text{buffet}}$ values marked in Fig. 5. **Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.**

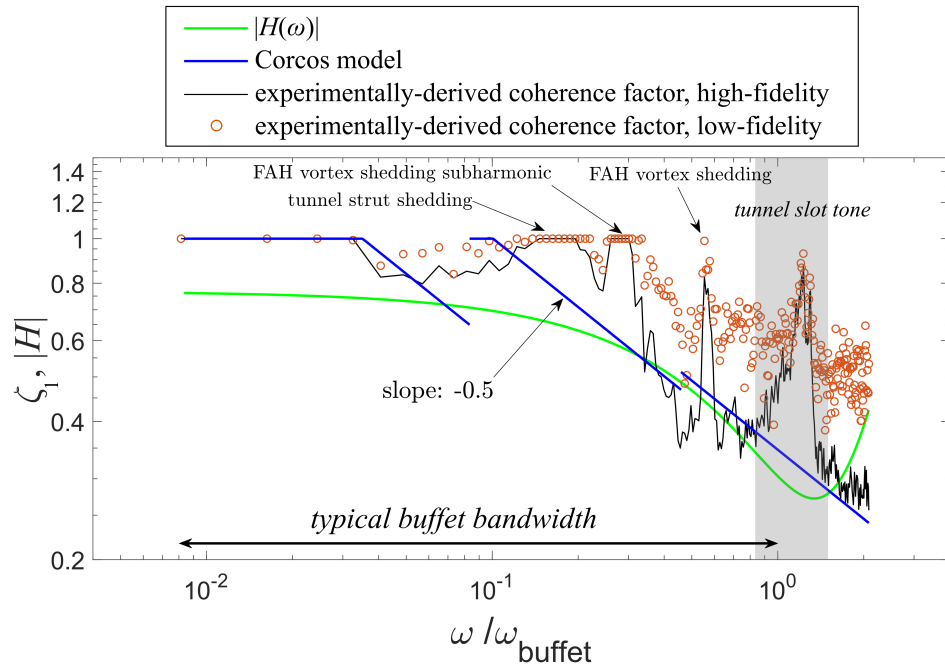
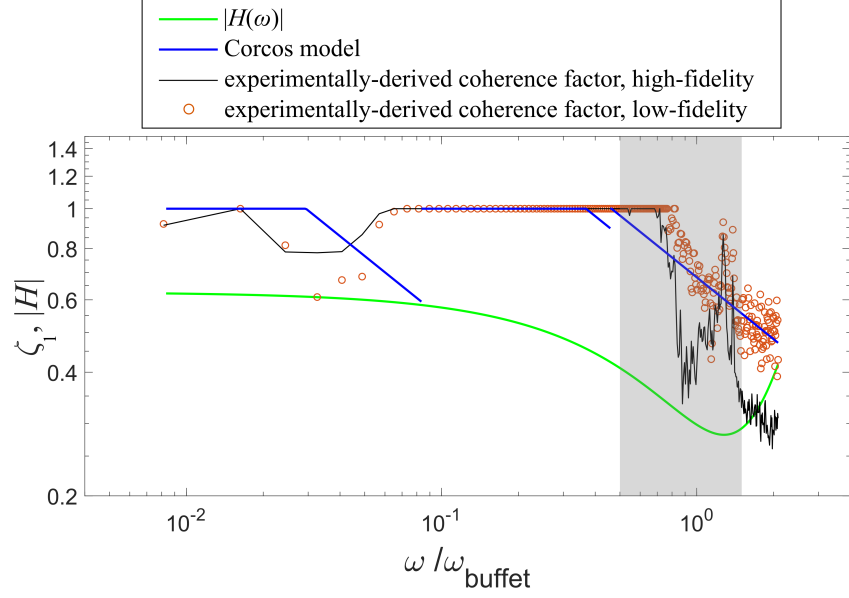
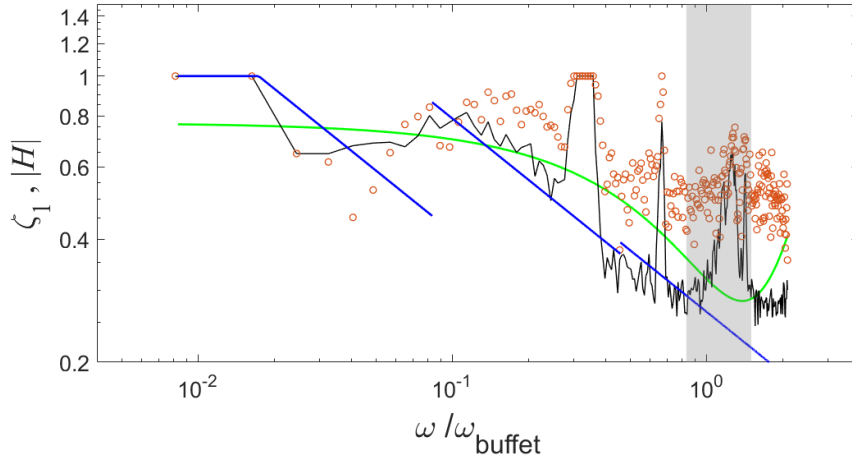


Fig. 7 Comparison between streamwise coherence factors (ζ_1) and uPSP-based $|H(\omega)|$ for the reference panel of Fig. 4. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.



(a) Mach = 0.91, $\alpha = 0$ deg., and $\beta = 0$ deg.



(b) Mach = 0.95, $\alpha = -4.0$ deg., and $\beta = 0$ deg.

Fig. 8 Comparison between streamwise coherence factors (ζ_1) and uPSP-based $|H(\omega)|$ for the reference panel of Fig. 4. Shaded: tunnel slot tone.

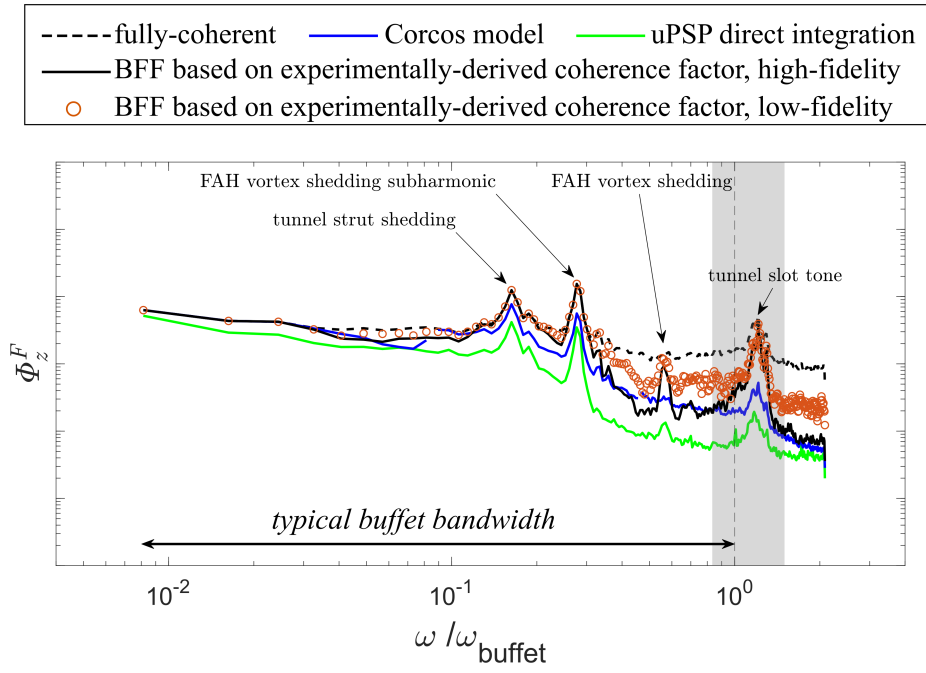
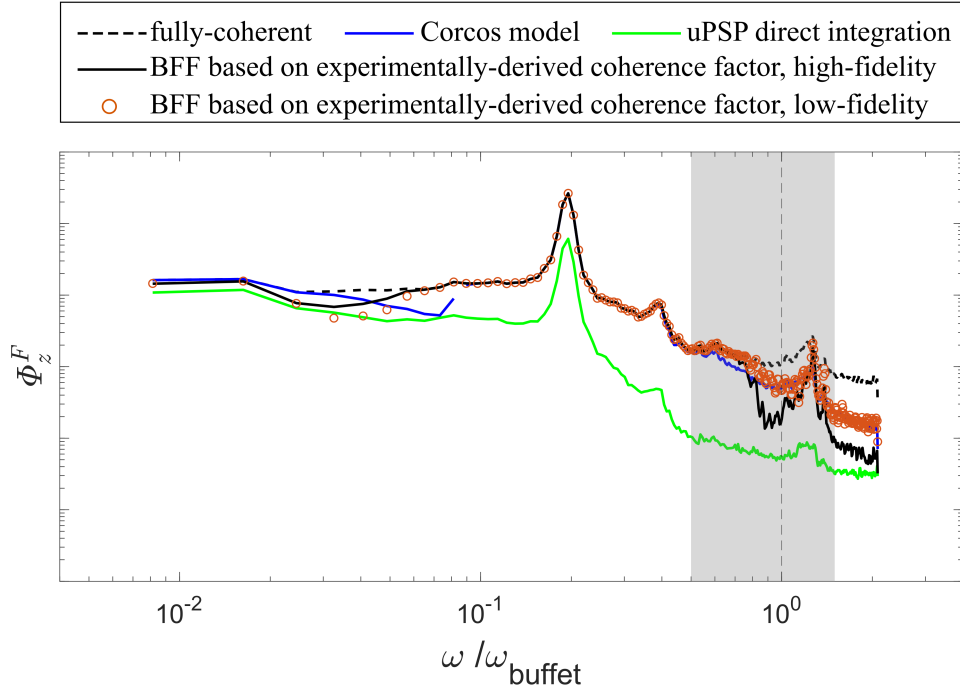
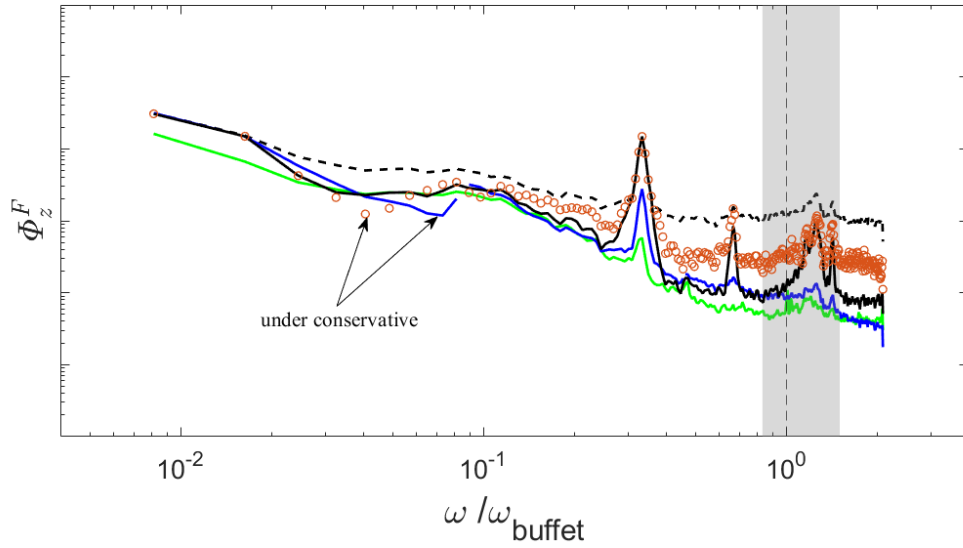


Fig. 9 Comparison of Φ_z^F for the reference panel shown in Fig. 4. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.



(a) Mach = 0.91, $\alpha = 0$ deg., and $\beta = 0$ deg.



(b) Mach = 0.95, $\alpha = -4.0$ deg., and $\beta = 0$ deg.

Fig. 10 Comparison of Φ_z^F for the reference panel shown in Fig. 4. Shaded: tunnel slot tone. Dashed vertical line: upper limit of typical buffet bandwidth.

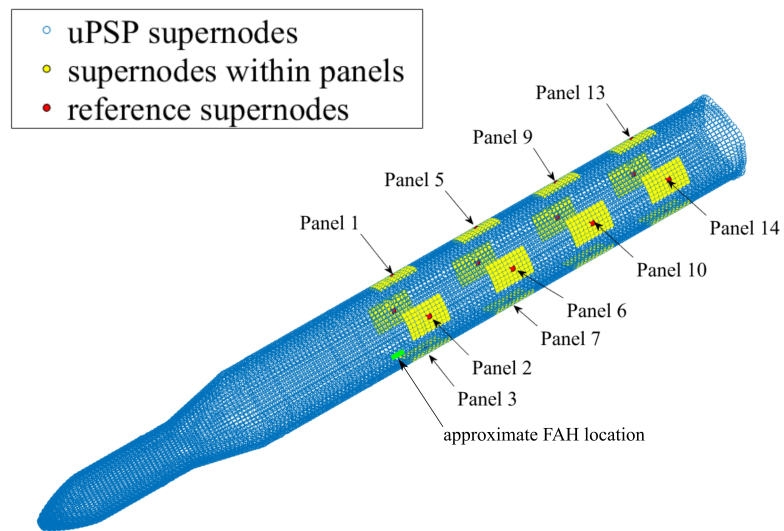


Fig. 11 Sample panels on the core stage for BFF analysis (regions marked in yellow). Note that panel #2 is the same as the reference panel of Fig. 4.

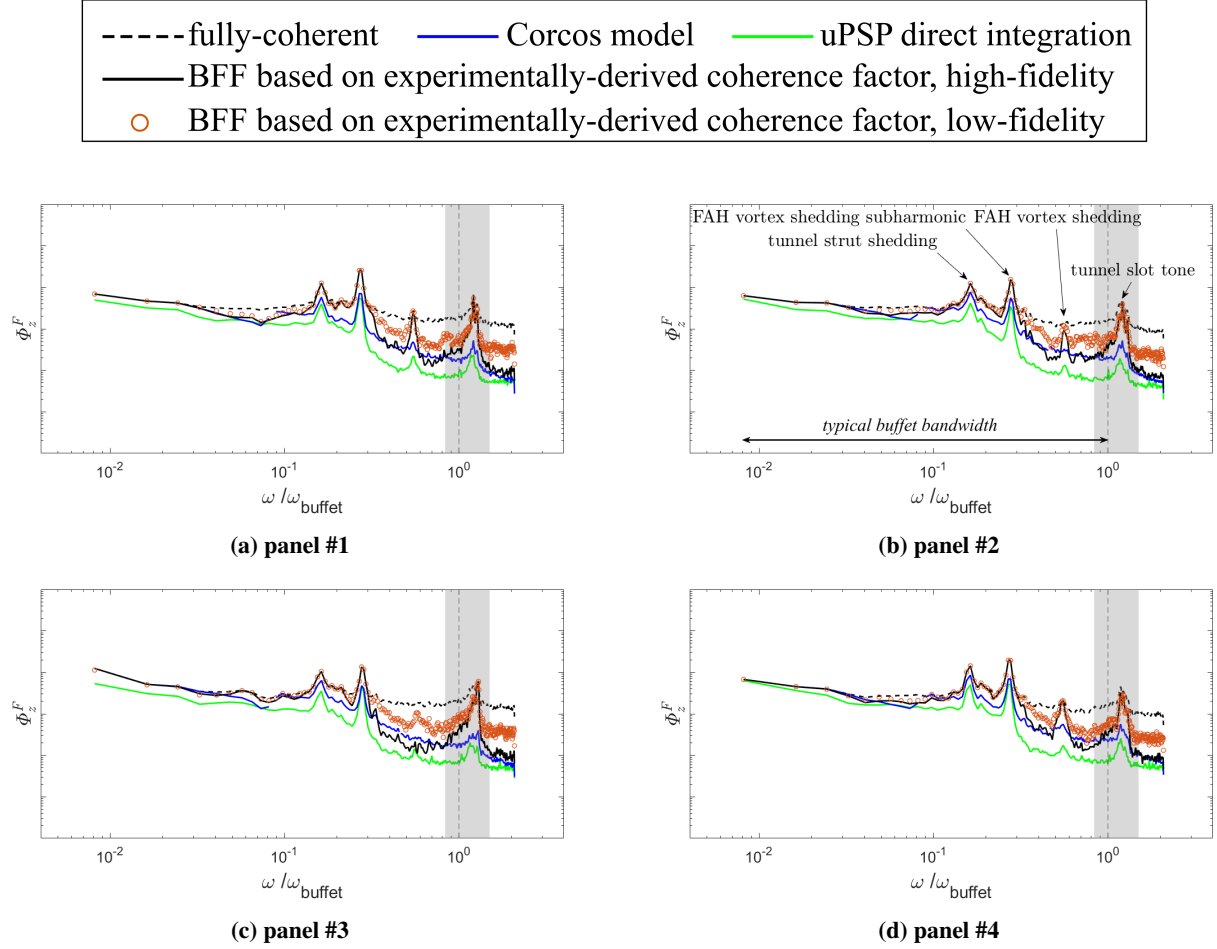


Fig. 12 Comparison of Φ_z^F for panels #1 through #4 shown in Fig. 11. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.

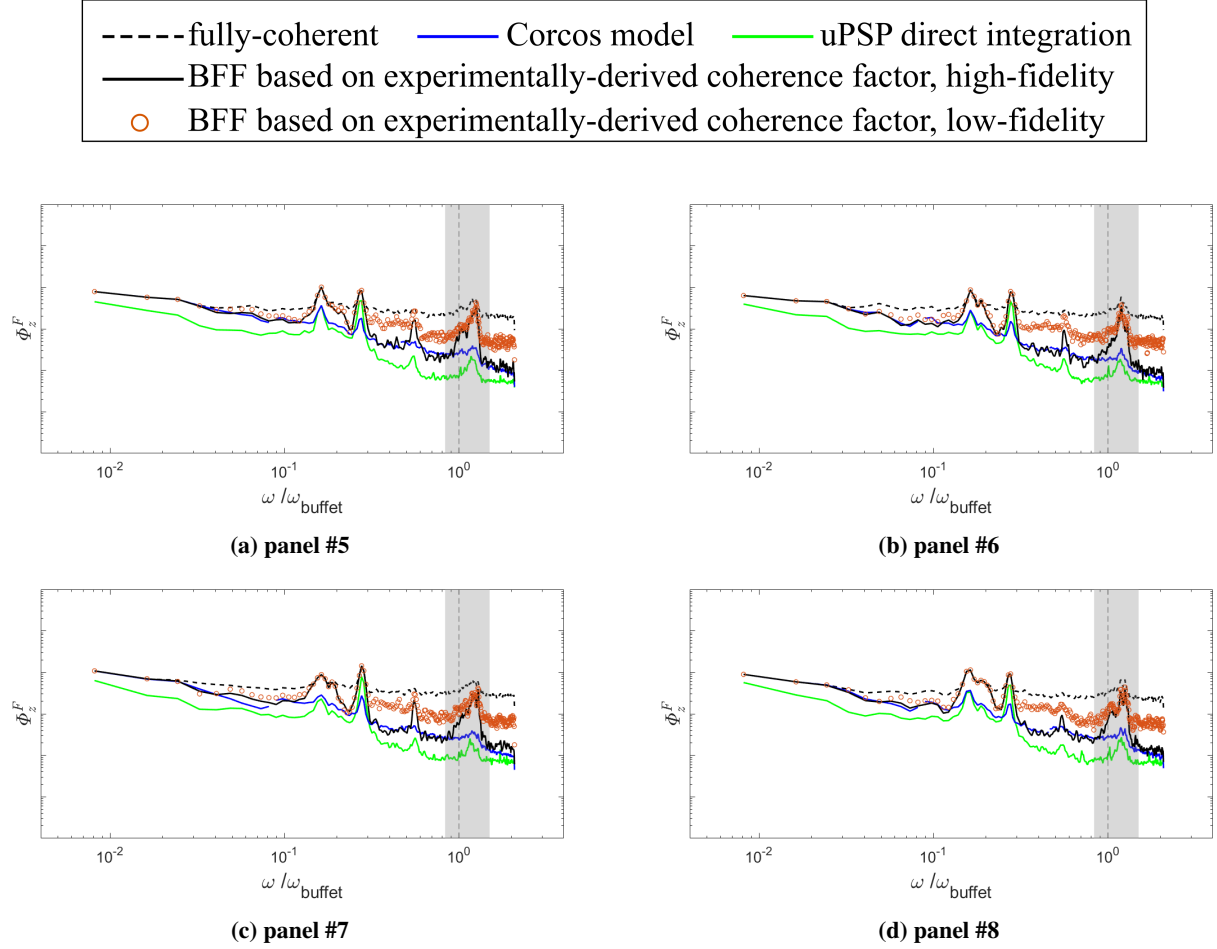


Fig. 13 Comparison of Φ_z^F for panels #5 through #8 shown in Fig. 11. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.

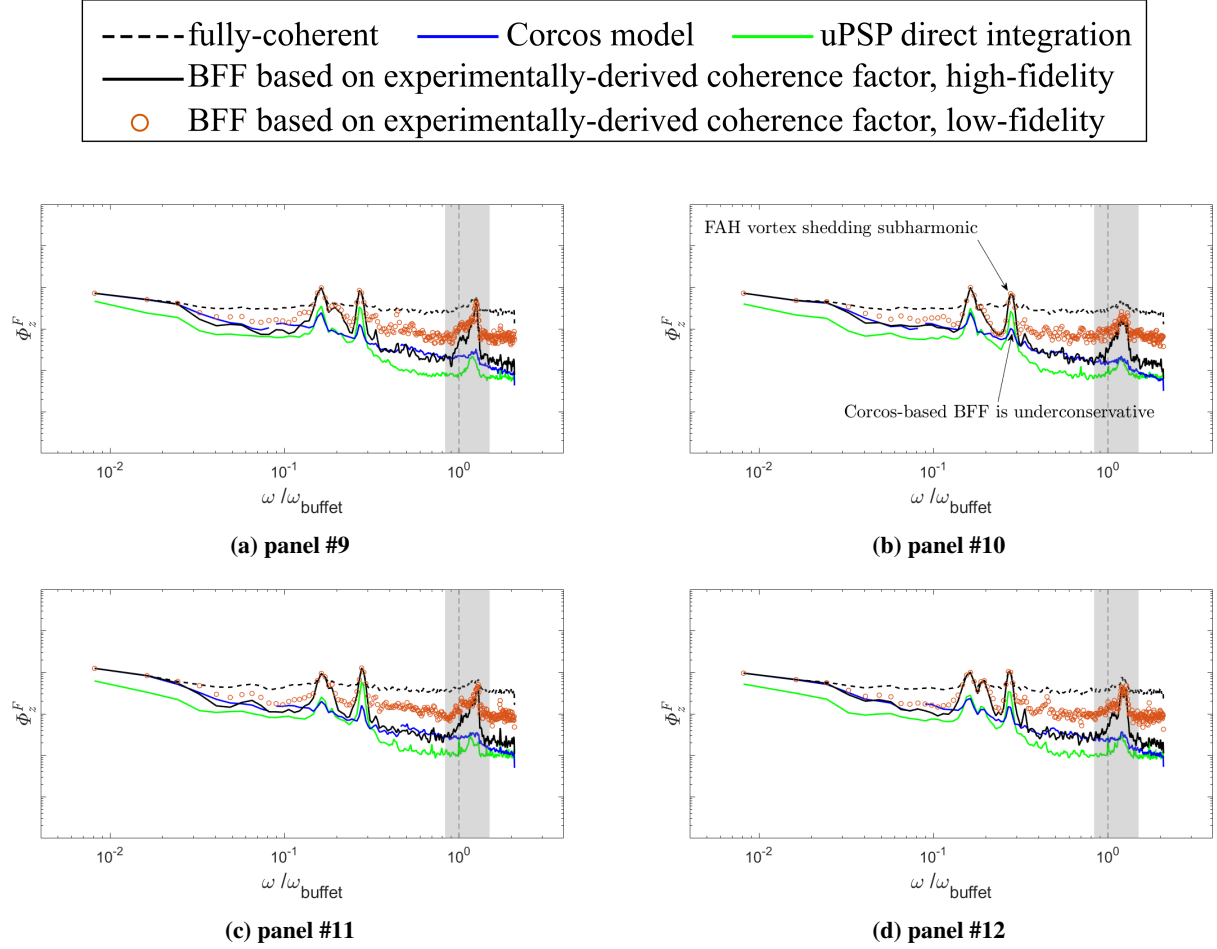


Fig. 14 Comparison of Φ_z^F for panels #9 through #12 shown in Fig. 11. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.

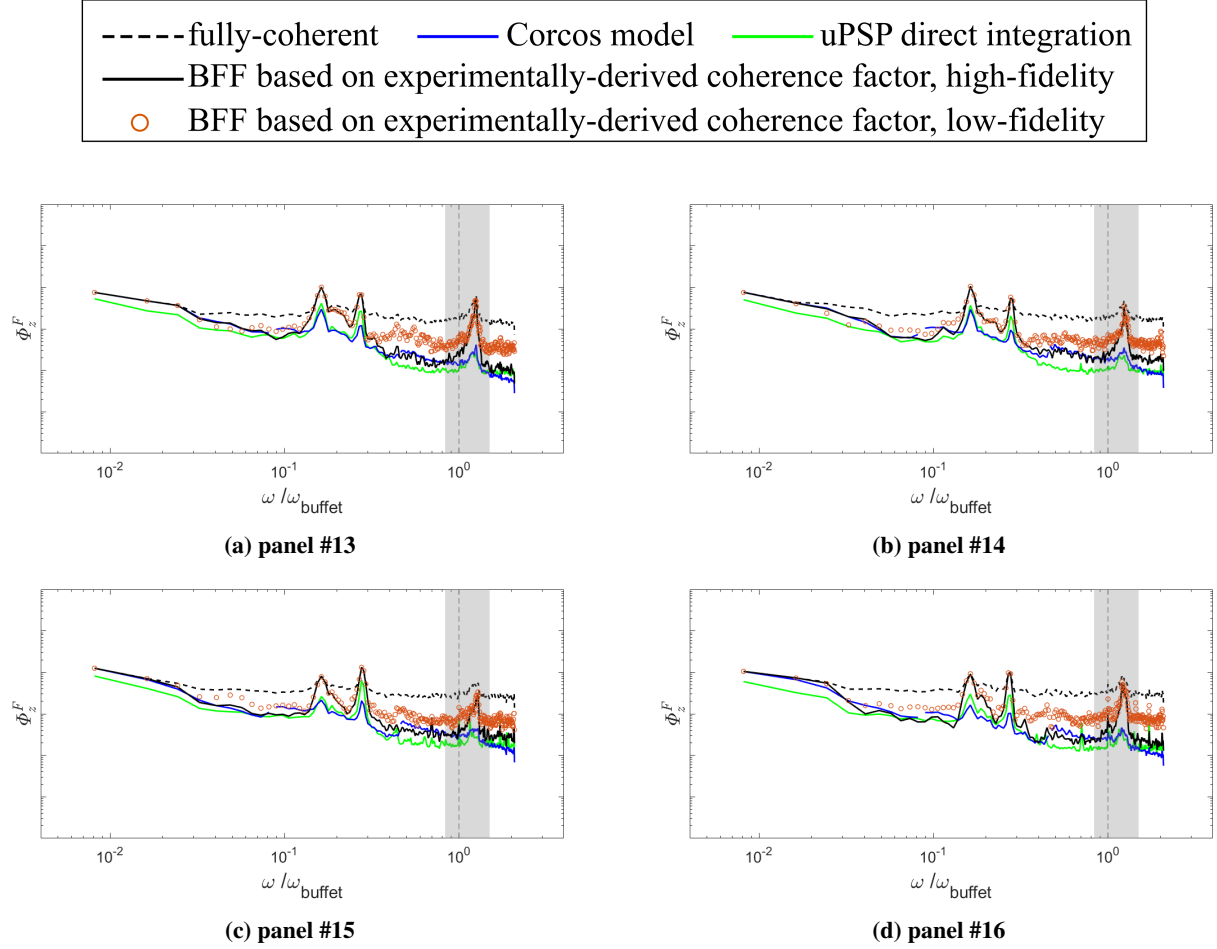


Fig. 15 Comparison of Φ_z^F for panels #13 through #16 shown in Fig. 11. Mach = 0.79, $\alpha = 0$ deg., and $\beta = 0$ deg.