

Development of Buffet Forcing Functions using Frequency-Dependent Coherence Factors

J. Micheal Ramey, Martin K. Sekula, Patrick S. Heaney, David Piatak, Francesco Soranna

Aeroelasticity Branch

NASA Langley Research Center

Hampton, VA 23831

Extended Abstract

Launch vehicle transonic buffet environments produce large fluctuating pressures on the surface of the vehicle. Transonic buffet occurs as a launch vehicle passes through the transonic regime, typically Mach 0.8 to 1.2, where phenomena such as flow separation and shock dynamics produce large fluctuating pressures. The unsteady aerodynamic forces produced by these phenomena can excite both global and local vehicle structural responses. The consequences of incorporating poorly characterized buffet forces into the design process can range from inefficient structures that can reduce the vehicle capabilities to undersized structures that, in the worst case scenario, may result in structural failure (Refs. 1, 2, 3). It is thus imperative to appropriately characterize the transonic buffet environment.

Modeling buffet-related aerodynamic forces can be accomplished by developing buffet forcing functions (BFFs) – a series of orthogonal force time histories acting at various longitudinal stations on the vehicle centerline, each representing the net forces caused by surface pressures acting on a longitudinal segment of the vehicle. Buffet forcing functions are traditionally developed using experimentally-measured pressure time histories that are acquired using sensors embedded in the skin of a rigid wind tunnel model of a launch vehicle. Each of these discrete measurements is used to approximate the fluctuating surface pressures acting on a large wetted surface area of the vehicle. Accurate extrapolation of pressure variation across these large areas is not possible, thus coherence-based factors are employed to reduce the effective surface area used in the pressure integration, thereby approximating the effects of temporal and spatial variation in surface pressure (Ref. 4).

The accuracy and validity of these coherence-based factors has long been a topic of research and discussion, but difficult to quantify. Recent advances in a measurement technique called unsteady pressure sensitive paint (uPSP) have changed that. In 2015, a wind tunnel test – called the Buffet Verification Test (BVT) – was conducted at the NASA Ames Research Center (ARC) Unitary Plan Wind Tunnel (UPWT) 11-Foot Transonic Wind Tunnel (11-FT TWT) (Ref. 5). The test involved a highly-instrumented model of a notional launch vehicle forebody (shown in Figure 1), including uPSP, to improve the understanding of the transonic buffet environment. Comparisons of BFFs produced using discrete pressure measurements extracted from uPSP to BFFs produced by continuous surface integration of uPSP helped validate and identify shortcomings of currently-accepted BFF methodology and develop methods to improve them (Refs. 6, 7).

One of the main findings from these comparisons is the need to employ frequency-dependent longitudinal coherence factors. Up to now, coherence factors were based on averaging the coherence over a user-specified frequency range (Ref. 4). This averaging results in an underprediction of coherence at some frequencies and an overprediction at others (see Figure 2). The factors developed from this averaged approach are then applied to the entire BFF spectra. The spectral content of the resulting forcing functions will tend to be overpredicted at frequencies associated with low coherence and underpredicted at frequencies of high coherence. Replacing the single-value coherence factor that is based on an average coherence value

with a coherence factor that is a function of frequency should produce a more accurate prediction of the BFF spectra.

Figure 3 presents a comparison of two coherence factors for a model segment downstream of the payload fairing aft-facing frustum. In blue is the coherence factor based on an average (or mean) coherence value and in red is the frequency-dependent coherence factor function. These factors were applied to forcing functions based on 8 discrete measurement locations distributed in an axisymmetric manner at a single model station. The power spectral density functions for the resultant BFFs are presented in Figure 4 along with the BFF developed by integrating the uPSP across the surface of the same segment of the model. This uPSP-based BFF is used as a benchmark since it is based on continuous pressure measurements across the model surface. The effect of the different coherence factor approaches is clearly seen in the autospectra in Figure 4. At low frequencies, the frequency-dependent coherence factors match the uPSP-integrated loads well, while at higher frequencies the average-based coherence factors result in a better comparison to the uPSP-integrated loads. For buffet-related phenomena, the lower-frequency range of the BFFs is of more interest, indicating that the frequency-based coherence factors may provide a more reasonable estimate of the buffet-related loads.

The introduction of frequency-dependent coherence factors necessitated a reexamination of how coherence factors are calculated and applied along the length of the vehicle. The current approach used to determine coherence factors requires the launch vehicle to be divided into segments for which a single aerodynamic phenomenon is considered the dominant flow feature. The location of these boundaries is guided by an analysis technique that indicates where on the vehicle the station-to-station coherence does not fit the exponential decay function typical of turbulent flows. These poor-fit locations are then used by the BFF developer to guide the selection of the boundaries between segments (Ref. 4). A sample result from this technique is provided in Figure 5, where a coefficient of determination (a measure of the quality of a curve fit) is plotted as a function of the longitudinal station. The vertical lines represent the developer-selected boundaries between different aerodynamic segments of the BVT model. These boundaries are generally selected to be downstream of identifiable drops in the coefficient of determination. This process of identifying boundaries between these segments is computationally intensive and the selection of these boundaries is ultimately based on engineering judgement.

The above technique for determining aerodynamic boundaries is based on averaged coherence (described in Figures 2 and 3) and assumes that even though the unsteadiness at different frequencies may be produced by different phenomena, the onset of these phenomena occur at the same stations. This assumption may not always be the case, particularly when using frequency dependent coherence factors. Therefore, aerodynamic boundaries need to be defined for different frequencies. Using the above approach to define these frequency-dependent boundaries is not practical since each frequency bin in the coherence analysis would need to be evaluated independently. Even a small window in the coherence calculation, such as $N = 2^8$, would require the entire boundary-determination process to be conducted 256 times, once for each frequency bin.

In this work, a new approach for calculating coherence factors is presented that eliminates the need to define aerodynamic boundaries. A graphical description of this approach is presented in Figure 6. The approach calculates the coherence length for a segment of the vehicle spanning three adjacent transducer stations. The process is started with the first three stations, then the second through the fourth stations, and so on until the end of the vehicle is reached. In Figure 6, each of these coherence length calculations is represented by a red horizontal line. Other than the first and last longitudinal station on the vehicle, each transducer station is used in the calculation of multiple coherence lengths. From these coherence lengths, the largest value is chosen as the coherence length associated with the station being evaluated. In Figure 6, this evaluation is represented by the green rectangle spanning the coherence length calculations associated with transducer station n . This

moving-segment approach can be applied to the averaged-coherence approach or the frequency-dependent coherence approach thereby eliminating the subjective nature of defining aerodynamic regions.

The differences in the frequency-dependent coherence factors determined using the user-defined boundary approach and the moving-segment approach are presented in Figure 7. The ordinate represents the longitudinal direction along the model while the abscissa represents frequency. The color intensity indicates the value of the coherence factor as a function of longitudinal station and frequency. Figure 7a presents the coherence factors for the user-defined aerodynamic regions. For reference, the locations of the boundaries between these regions are presented to the left of the waterfall plot. Figure 7b presents coherence factors developed using the moving-segment approach. There are three major areas of difference between the two methods. First, in the vicinity and downstream of the frustum (sta. 15-25 inches), the user-defined approach underpredicts the low frequency coherence in comparison to the moving-segment approach. The second difference occurs at the middle frequencies just upstream of the frustum, where the user-defined approach calculates higher coherence factors. Finally, at locations downstream of station 20 and at frequencies above 1200 Hz, the user-defined approach overpredicts the coherence factors. These differences in coherence factors are caused by defining the aerodynamic boundaries, which may for some frequencies inappropriately group transducer stations together, thereby affecting the resulting coherence factors. These coherence factors in turn change the spectral content of the final BFFs.

Full Paper

The full paper will provide a more detailed discussion of the coherence methods discussed above. Analysis and comparisons to uPSP data for the BVT model will be provided. The above techniques will be applied to develop new BFFs for the SLS B1 crew (SLS-1000X) vehicle, as a test case for an actual launch vehicle. BFFs developed using frequency-dependent coherence factors and the moving-segment approach will be compared to previously-developed BFFs using the average-coherence approach that were based on user-defined aerodynamic regions.

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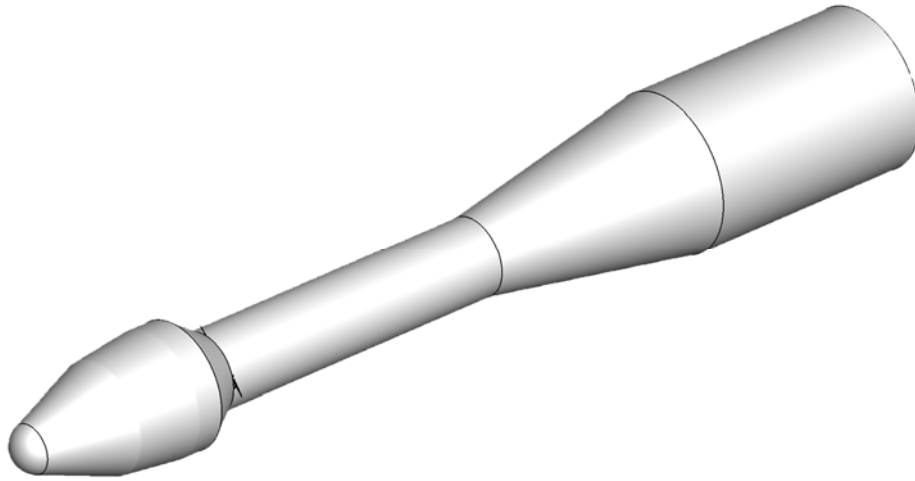


Figure 1. Graphical representation of the Buffet Verification Test model.

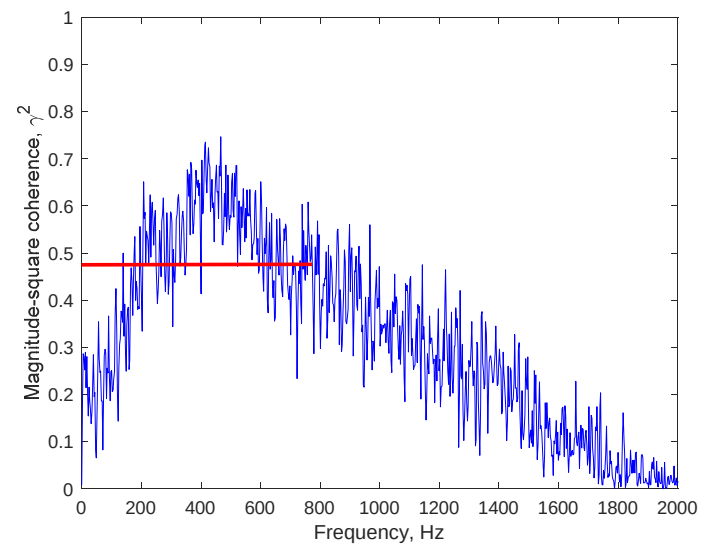


Figure 2. Sample coherence function and mean coherence for frequency range 3 to 800 Hz.

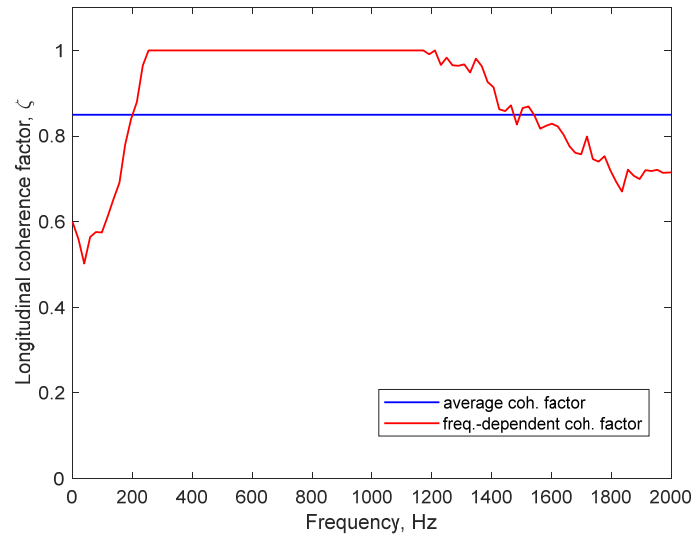


Figure 3. Mean and frequency-dependent coherence factors for model segment spanning station 31.0 to 34.6 inches, $M = 0.92$, $\alpha=4$ deg.

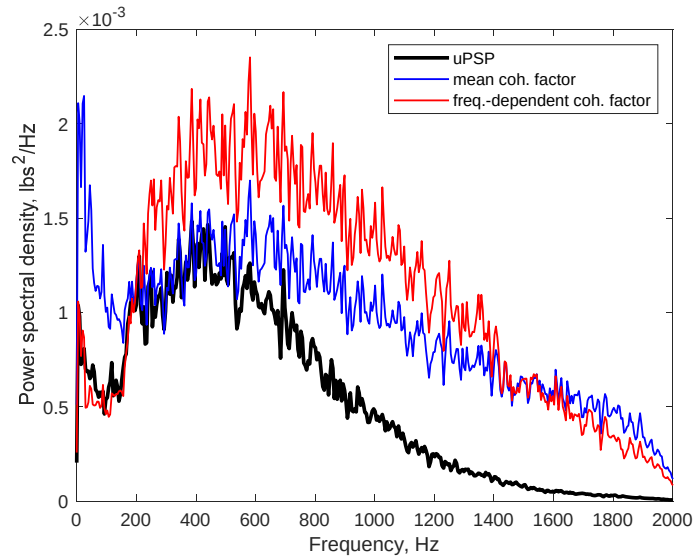


Figure 4. Comparison of BFF power spectral density function for BFFs with mean and frequency-dependent coherence factors and surface-integrated uPSP-based BFF for a model segment spanning station 31.0 to 34.6 inches, $M = 0.92$, $\alpha=4$ deg.

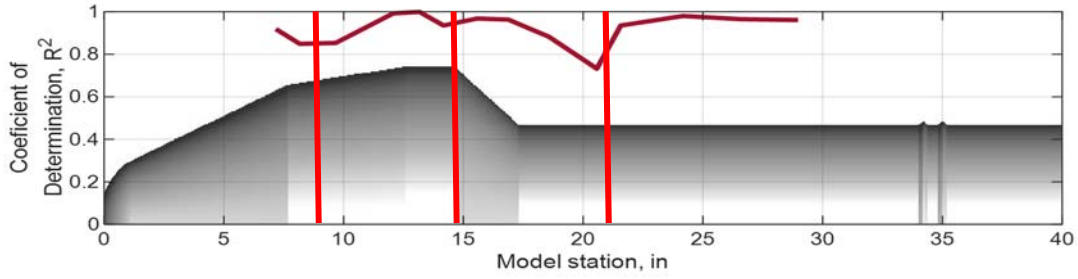


Figure 5. User-defined aerodynamic region boundaries based on coefficient of determination analysis.

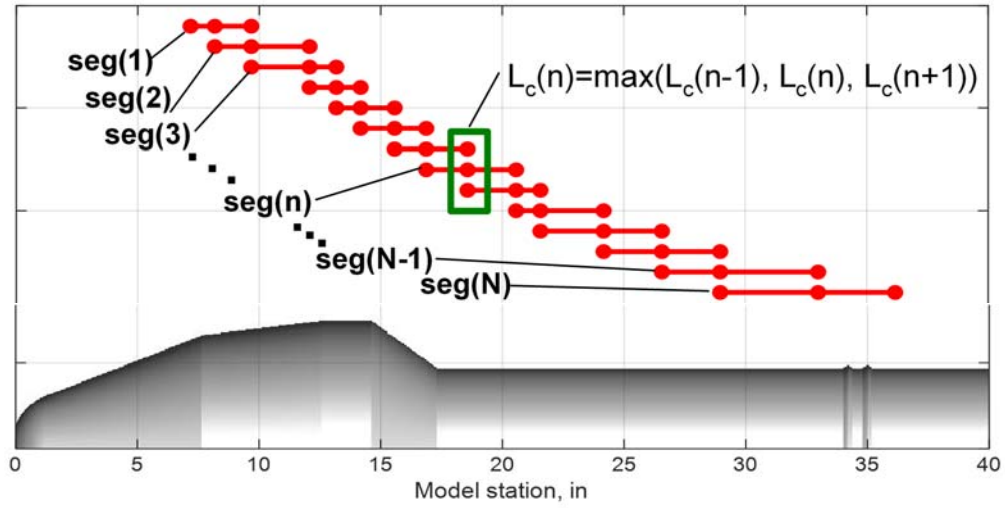


Figure 6. Visualization of moving-segment process for determining coherence lengths.

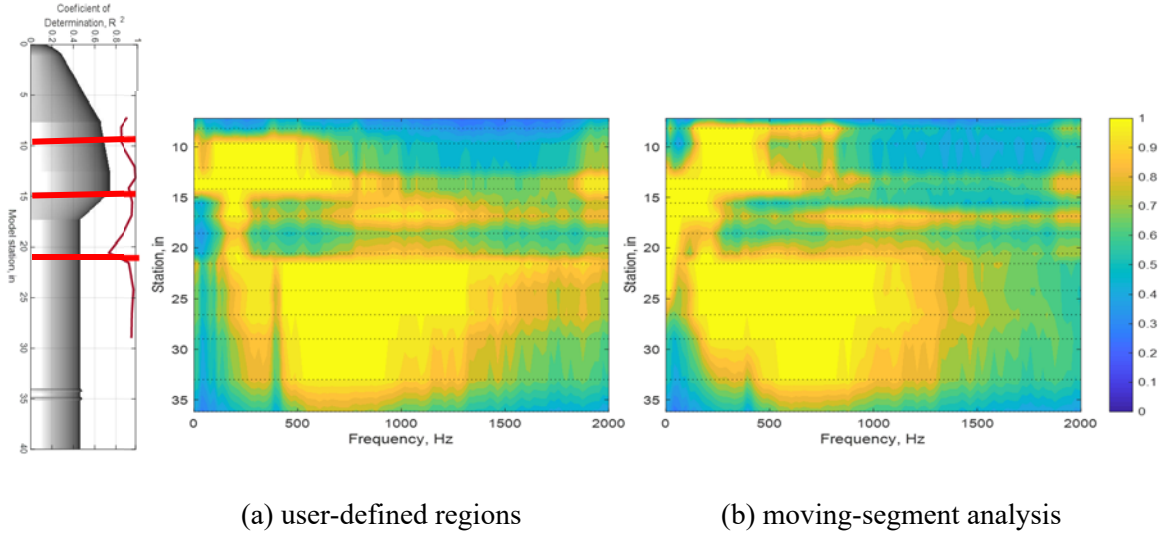


Figure 7. Effect of user-defined aerodynamic regions and moving-segment analysis on frequency-dependent coherence factors.