

Validation of Shadowgraph Spectral Analysis using an SLS Block 2 Wind-Tunnel Model

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A flow quantification method has previously been developed that uses high-speed shadowgraph images to extract frequency content of a transonic flow field around a wind-tunnel model. In this method, a classical spectral analysis is performed on shadowgraph video pixels to identify their intensity fluctuation frequencies. The spatial change of the image intensity is related to the second derivative of the density gradient. Examining the change of the density gradient as a function of time can be used to understand the flow-field pressure fluctuations. Time-varying pressure measurements collected during a Space Launch System (SLS) unsteady aerodynamic test of an advanced Block 2 booster design are used to calibrate the shadowgraph-based measurements. The test was performed at the NASA Ames Research Center Unitary Plan 11-by 11-Foot Transonic Wind Tunnel and investigated the aerodynamic environment downstream of candidate booster forward attachment hardware geometries of the SLS Block 2 Cargo configuration. Time-correlated shadowgraph video and model surface pressure measurements were acquired during the test and served as an ideal opportunity to calibrate and validate the shadowgraph image intensity method.

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Nomenclature

A	=	amplitude
Az	=	azimuth angle
C	=	constant
C_p	=	coefficient of pressure
f_x	=	spatial frequency
f, f_t	=	temporal frequency
I	=	pixel intensity
K	=	Gladstone-Dale constant
l	=	distance from region of interest to the video recording plane
L	=	length of integration region in z
M	=	Mach number
n	=	index of refraction

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P	=	point
p	=	pressure
s	=	path length
t	=	time
v_c	=	convective velocity
x, y, z	=	local coordinates
β	=	sideslip angle
ϵ_x, ϵ_y	=	light ray deflection angles
δ	=	variation
Δ	=	quantity change
ρ	=	density
ϕ	=	phase
ζ_1, ζ_2	=	limits of integration in z
∇	=	Laplace operator
$()_{ref}$	=	reference value
$()^*$	=	quantities of the disturbed light ray

Introduction

Shadowgraph photography is a well-established method to visualize flow features in a compressible fluid. It has been widely used to view the shock formation on various launch vehicle configurations during transonic/supersonic wind-tunnel test programs such as the Space Transport System (Space Shuttle) [1], Ares I-X [2], and more recently the Space Launch System (SLS) [3, 4]. The analysis is often qualitative and used to supplement direct measurements of the flow properties. For example, a shadowgraph image can be used to identify a shock location and confirm pressure trends observed in wind tunnel model surface pressure measurements [3]. In this paper, shadowgraph data are combined with pressure measurements to provide a more quantitative analysis technique. First, the shadowgraph data were calibrated using pressure measurements. After a successful calibration, pressure was estimated independently based on the shadowgraph images and verified using the pressure measurements.

Quantitative analysis using shadowgraph and schlieren methods have been implemented in the medical field to develop ultrasound techniques [5, 6]. Some attempts to quantify the flow from shadowgraph-like images were also conducted in fluid mechanics. Kolhe et al. [7] used rainbow schlieren deflectometry to predict distribution of density, pressure, and temperature of a supersonic free-jet. Mauger et al. [8] used quantitative flow visualization to predict the cavitation inside a fuel injection nozzle. In the presents work, the quantitative analysis of the shadowgraph is applied to a recent wind-tunnel study of an SLS model.

The current analysis utilizes data from the Booster Obsolescence Life Extension (BOLE) Forward Attachment Structure Trade Study Test (BFASTST) performed at the NASA Ames Research Center Unitary Plan 11- by 11-Foot Transonic Wind Tunnel (11-Ft TWT) [9]. A photograph of the installed wind-tunnel model can be seen in Figure 1a. The test article was a 2.5 percent model of the SLS Block 2 Cargo vehicle, which consisted of two solid rocket boosters (SRBs) attached to a core stage. The primary objective of the test was to investigate the aerodynamic environment downstream of various booster forward attachment hardware geometries. In total, seven configurations were tested via a test matrix of wind-tunnel conditions with varying Mach number and model attitude. Two geometries, named "Baseline" and "Legacy" will be discussed here. The 3-dimensional rendering of these geometries is shown in Figure 2b. The Mach number values ranged from 0.60 to 1.20 and vehicle attitude was varied in pitch and sideslip from -6° to 6° . At each test point, 189 unsteady pressure transducers (Kulites[®]) distributed over the model were simultaneously sampled to collect model surface pressure data together with a shadowgraph video. It has been shown that dominant aerodynamic forcing on the vehicle in the transonic portion of the flight occurs around and downstream of the forward attachment hardware [10]. Therefore, the focus of the analysis was to predict the pressure fluctuations that are driven by the forward attachment hardware in the booster-core gap. In the present analysis, a subset of the measured surface pressure data for "Baseline" forward attachment hardware geometry was used to calibrate the shadowgraph. The calibration was then verified by using shadowgraph data from the "Legacy" forward attachment hardware configuration to determine pressure fluctuations in the core-booster gap. These shadowgraph-based pressures were then compared to the pressure-transducer-measured values to assess the accuracy of the shadowgraph-intensity-based technique.

Experimental Setup

The shadowgraph acquisition setup is a production-level system developed at the NASA Ames Research Center Unitary Plan Wind Tunnel, that is integrated with the facility data acquisition system [11, 12]. The system is capable of recording images at up to 51,000 frames per second, allowing for the ability to resolve high-frequency flow features. Figure 2a shows a time-averaged shadowgraph image of the SLS model at zero effective angle of attack under a $M = 0.92$ nominal flow condition. The shadow from the core of the model is seen in the middle of the image oriented horizontally. The model is positioned to allow optical access of the gap between the core and the two SRBs, seen below and above the core. Also seen in the image are the structural beams of the wind-tunnel. Unfortunately, the structural support of the experimental facility impaired the view of the flow directly downstream of the forward attachment hardware. This obstruction limited some of the capability to observe the flow in the region of interest.

Figure 2b shows the standard deviation of the pixel color intensity of the recorded shadowgraph video. The intensity-preserving color scheme [13] was used to represent these data with lighter colors indicating the higher-intensity fluctuations. A region of lighter, more orange hue is observed in the near-field region of the core, indicating a boundary layer of separated flow that originated further upstream on the model. The shock structure can be seen in Figure 2a at the beginning of the core-booster gap and this region is enlarged in the figure insert to more clearly show these shocks. This core-booster gap immediately downstream of the cone/cylinder junction in Figure 2b contains the brightest color intensity (standard deviation) consistent with expected high fluctuations in the fluid properties there. These high fluctuations propagate downstream into the gap and dissipate as they travel downstream. Based on the visible fluid domain not blocked by wind-tunnel wall structure in Figure 2b, the dominant pixel color intensity fluctuations, and hence the dominant flow property fluctuations originate at the beginning of the core-booster gap. The source of these fluctuations is the complex flow field created by the proximity of the core, SRB, and the forward attachment hardware and is dominated by the shock emanating off the booster nosecone, which is disturbed by pressure fluctuations from vortex shedding off the forward attachment hardware.

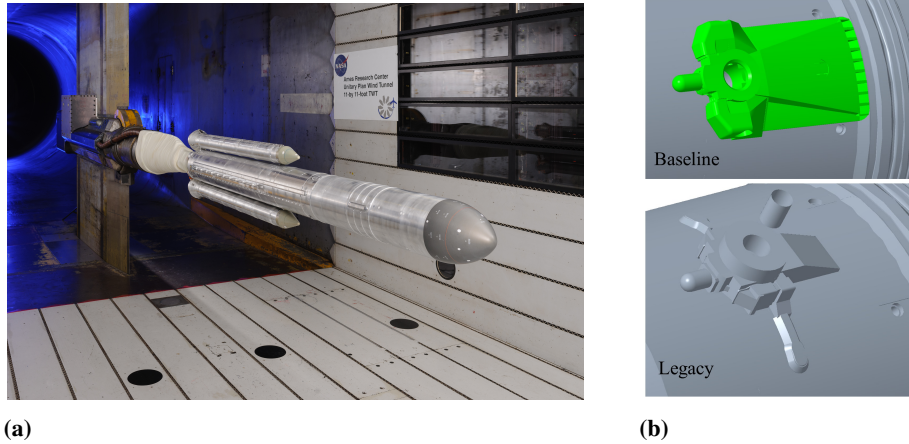


Fig. 1 (a) An SLS Block 2 Cargo model at NASA Ames Research Center Unitary Plan Wind Tunnel [Photo: NASA]. (b) 3-dimensional rendering of the "Baseline" and the "Legacy" booster forward attachment hardware.

An instantaneous shadowgraph image is presented in Figure 3a. It captures tunnel background flow phenomena and shocks that were not observed in the time-averaged shadowgraph, Figure 2a. Fine-scale flow phenomena that are seen in the near-field region of the core confirm the presence of the disturbed boundary layer, which is also evident in Figure 2b. Since the present analysis was focused on flow fluctuations produced by the forward attachment hardware, the discussion will be centered on a flow region downstream of it, a region roughly highlighted by a dashed rectangle in Figure 3a.

The analysis begins by extracting a time-series of the light intensity, I , from a shadowgraph video for each pixel in the camera frame. A classical discrete Fast Fourier Transform (FFT) analysis was performed on each time-series resulting in a distribution of the pixel intensity fluctuation amplitude at the associated frequency, f . For each frequency, the FFT amplitudes of all pixels in the frame were averaged to produce an ensemble FFT amplitude for the entire field. A plot of FFT amplitude versus frequency obtained from a video of the model at zero total angle of attack in Mach 0.92 flow is provided in Figure 4a. Three distinct amplitude peaks annotated as f_1 , f_2 , and f_3 can be observed. To identify the origin of pixel intensity fluctuation at f_1 , f_2 , and f_3 , the color map of the intensity was extracted for each frequency

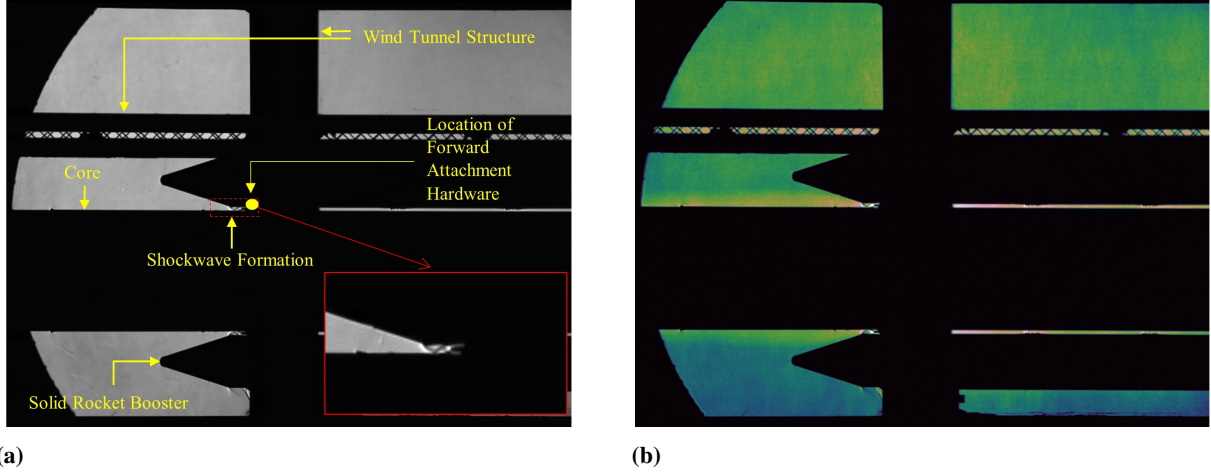


Fig. 2 (a) Time-averaged composite shadowgraph image showing the model core and boosters, and wind tunnel structural supports. (b) Image of pixel color intensity fluctuation standard deviation indicating dominant fluctuations originating in the region around forward attachment hardware [Photos: NASA].

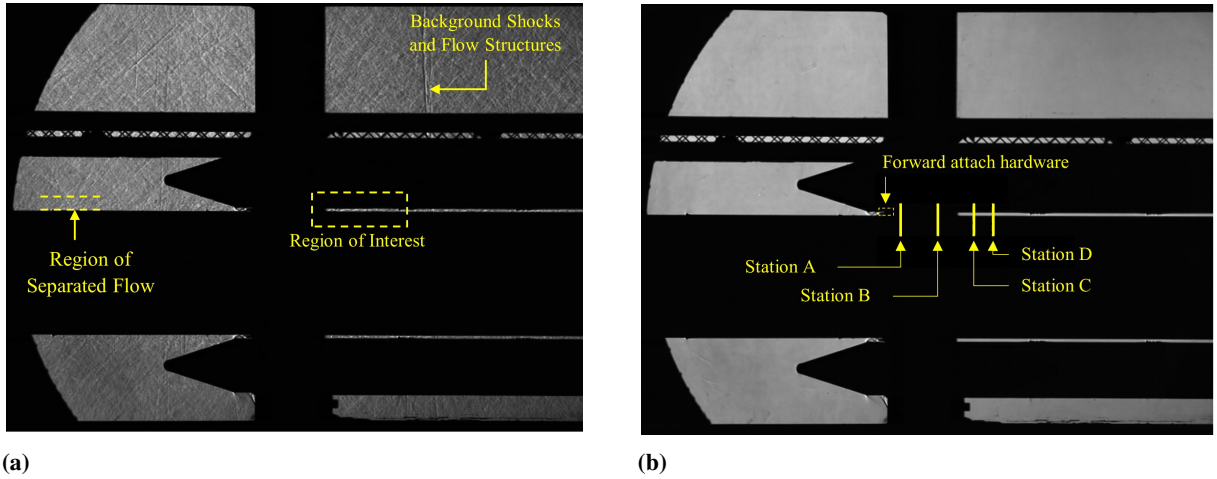


Fig. 3 (a) Instantaneous shadowgraph image showing tunnel background flow structures. (b) Approximate location of the pressure transducer longitudinal stations. [Photos: NASA]

and is shown in Figures 4b, c, and d. The scale of the colormap values is based on the maximum value corresponding to the saturation value of the camera sensor. In Figure 4b, the pixels, which exhibit the highest intensity, are concentrated around the model contours and the wind tunnel structure, indicating that f_1 is most likely a vibration frequency of the camera, the optical setup, or the tunnel structure. Figures 4b and c show the color map of the intensities at f_2 and f_3 , whose peak values are concentrated in the core-booster gap, indicating that the fluctuations are due to the flow phenomena downstream of the forward attachment hardware. It is interesting to observe that f_2 is a subharmonic of f_3 . The origin of this subharmonic will be discussed later. It will be shown that f_3 is a frequency of interest for this study. Therefore, f_3 was used as a reference frequency f_{ref} for all normalization.

Several pressure transducers were located in the identified region of highly fluctuating pressures. Their approximate locations are provided in Figure 3b. Station A is located directly downstream of the attachment hardware followed by stations B, C, and D. Note that stations A and B are optically blocked by the wind-tunnel structure. At each longitudinal station, several pressure transducers were azimuthally distributed on the core and the boosters to provide discrete pressure measurements around the circumference of each component. The booster, which appears at the bottom in Figures 2 and 3 was more densely instrumented. However, the visual access of the top booster was better, especially at nonzero angles of attack. Therefore, at zero degrees angle of attack, a condition with flow symmetry about the

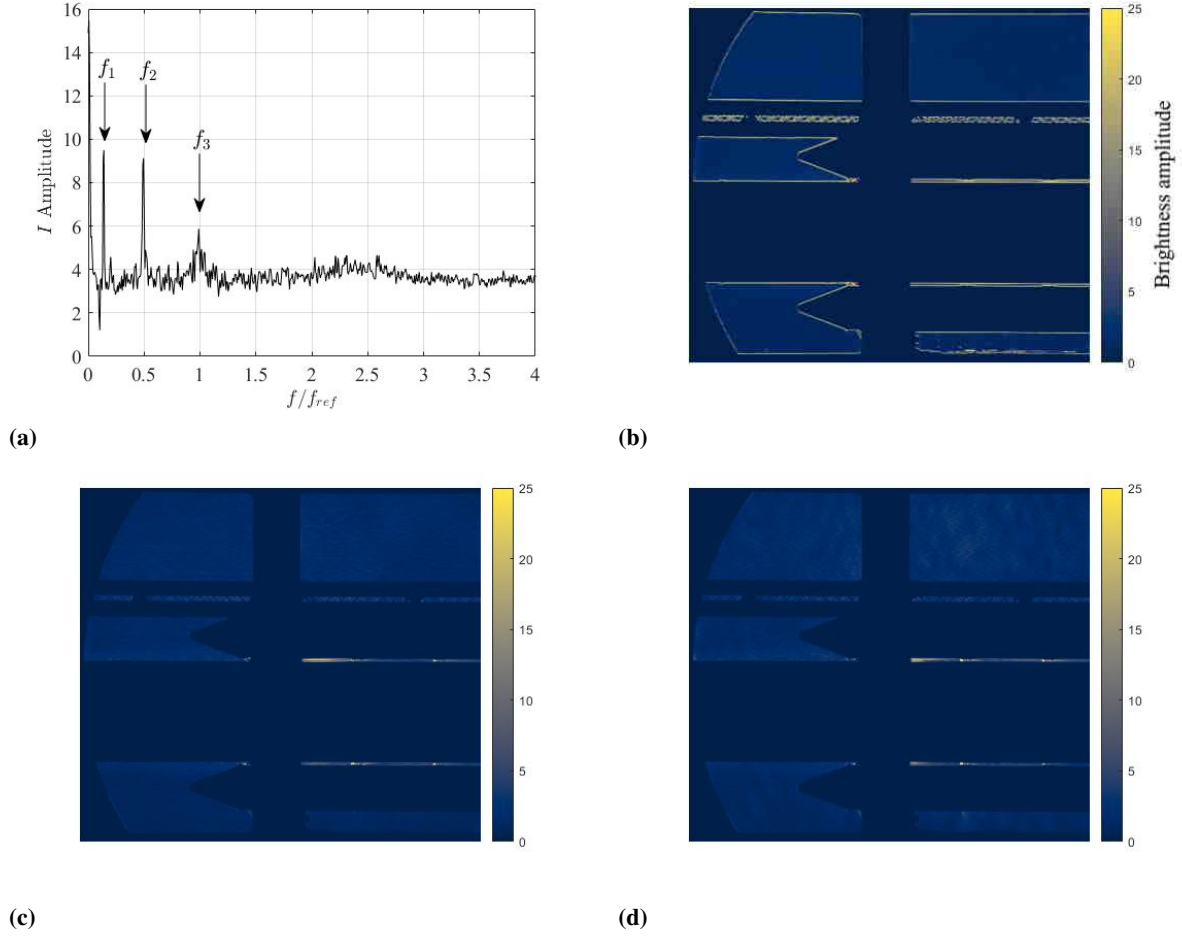


Fig. 4 (a) FFT amplitude of the pixel intensity for $M = 0.92$ and $\beta = 0^\circ$ (b) pixel intensity colormap at f_1 (c) pixel intensity colormap at f_2 (d) pixel intensity colormap at f_3

horizontal plane, measurements from the bottom booster were used to supplement measurements on the top booster. Pressures transducers were sampled using two rates. The "slow" record was sampled at $10,000 \text{ Hz}$ for a 15 s , whereas the "fast" record was sampled at $200,000 \text{ Hz}$ for a more-limited 2 s . Figure 5a shows a short segment of a time-series of the pressure signals recorded at station A using two selected sensors, one positioned on the core at $Az = 270^\circ$ and the second positioned on the booster at $Az = 90^\circ$. Effectively, the two sensors are facing each other across the core-booster gap. This measurement was performed at zero total angle of attack at 0.92 Mach number. A periodic signal seen in these time-series supports the expectation of cyclic vortex-shedding flow behavior downstream of the forward attachment hardware. Figure 5b shows the FFT amplitude of the two time-series. The booster sensor and the core both measure the dominant fluctuation at the same frequency, f_{ref} , and of nearly the same amplitude. Same fluctuations are observed in the shadowgraph data, Figure 4, indicating that both the shadowgraph and the pressure measurements sense flow features produced by the forward attachment hardware. It is of interest here to relate the amplitudes of the pixel intensity fluctuations to the amplitude of the pressure measurement, thereby calibrating the shadowgraph data.

Analysis

Some mathematical insight is needed to accurately perform the calibration of the shadowgraph data using the pressure measurements. The analytical description of the shadowgraph method is well documented in classical flow measurement texts [14–16]. A short description following Panigrahi [17] will be provided here with the help of a schematic in Figure 6. A light ray traveling in direction z across the test section will be deflected by angles ϵ_x , and ϵ_y in the presence of gradients in gas index of refraction, n . Instead of an undisturbed light ray impacting a point P in the

be ignored resulting in Equation 3.

$$\begin{aligned}\frac{d^2x}{dz^2} &= \frac{1}{n} \left(\frac{\partial n}{\partial x} \right) \\ \frac{d^2y}{dz^2} &= \frac{1}{n} \left(\frac{\partial n}{\partial y} \right)\end{aligned}\tag{3}$$

The derivative order in Equation 3 can be reduced by integrating this equation along z from ζ_1 to ζ_2 :

$$\begin{aligned}\frac{dx}{dz} &= \int_{\zeta_1}^{\zeta_2} \left(\frac{\partial \ln n}{\partial x} \right) dz \\ \frac{dy}{dz} &= \int_{\zeta_1}^{\zeta_2} \left(\frac{\partial \ln n}{\partial y} \right) dz\end{aligned}\tag{4}$$

These gradients can be used in the Jacobian transformation. This transforms an undisturbed light intensity field I into a disturbed on I^* with a summation to account for the fact that a single point in I^* can be influenced by a summation of disturbances from all I :

$$I^*(x^*, y^*) = \sum_{(x,y)} \frac{I(x, y)}{\left| \frac{\partial(x^*, y^*)}{\partial(x, y)} \right|}\tag{5}$$

The Jacobian determinant can be evaluated and simplified again assuming small light deflections, resulting in:

$$\left| \frac{\partial(x^*, y^*)}{\partial(x, y)} \right| \approx 1 + \frac{\partial \Delta x}{\partial x} + \frac{\partial \Delta y}{\partial y}\tag{6}$$

where $\Delta x = l dx/dz$ and $\Delta y = l dy/dz$ and dx/dz and dy/dz are provided by Equation 4. Solving Equation 5 for $(I^* - I)/I$ gives us the governing equation for the shadowgraph analysis:

$$\frac{\Delta I}{I} = l \int_{\zeta_1}^{\zeta_2} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) (\ln n) dz\tag{7}$$

The equation above can be simplified by linearizing $\ln n$ as $n - 1$ and applying Gladstone-Dale formula, $n - 1 = K\rho$, where K is a Gladstone-Dale constant and ρ is fluid density. However, Equation 7 requires further simplification to be utilized for shadowgraph calibration. The first simplification is based on an observation in Figure 4, which showed that the dominant fluctuations in the flow field occur in the core-booster gap. It is assumed that the density variation is negligible everywhere along each path, s , except for the booster region between ζ_1 and ζ_2 , or width L . Within this line segment, L , the density is assumed constant along the z -axis, defined in Figure 6. Thus, the integral in Equation 7 can be eliminated.

$$\frac{\Delta I}{I} = l L K \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) \rho\tag{8}$$

The density can be related to the pressure using the ideal gas law, but the formulation requires an assumption of constant temperature. The validity of this assumption was examined during a more recent wind tunnel test where an SLS model was also instrumented with surface thermocouples to be used in unsteady pressure sensitive paint analysis. The thermocouple data showed a variation of less than 0.5 deg F during an angle-of-attack sweep. This near-constant temperature measurement justifies the constant-temperature assumption, simplifying Equation 9 to

$$\frac{\Delta I}{I} = C_0 \nabla^2 P\tag{9}$$

In principle, Equation 9 can be solved numerically for the pressure distribution knowing the image pixel intensity distribution $\Delta I/I$, a constant C_0 , which contains optical and thermodynamic gas property information, and the pressure at the boundaries of the solution domain. The latter information is unknown since surface pressures measurements were limited to several discrete locations on the model. Therefore, a different approach is needed to relate the pixel intensity to the pressure.

Figure 5 shows the pressure measurements on the core and on the booster in the core-booster gap. It is evident that the pressure signal is periodic and nearly the same amplitude and phase on the core and the booster surfaces. This observation indicates that the dominant gradients of the pressure are in the x direction (direction of free stream velocity), and therefore, if the y -direction gradients are assumed to be negligible, Equation 9 simplifies to:

$$\frac{\Delta I}{I} = C_0 \frac{d^2 P}{dx^2} \quad (10)$$

The periodicity of the signal can be represented by a sinusoidal function, which varies in time t and x with frequencies f_t and f_x :

$$\begin{aligned} P(x, t) &= A_1 \sin(2\pi f_{x_1} x + 2\pi f_1 t + \phi) \\ \frac{\Delta I(x, t)}{I} &= A_2 \sin(2\pi f_{x_2} x + 2\pi f_2 t + \phi) \end{aligned} \quad (11)$$

subscripts 1 and 2 in Equation 11 indicate the properties for the pressure and pixel intensity, respectively. Note that since the shadowgraph directly senses the changes in density and hence pressure without any phase lag or frequency difference, the two periodic functions are the same and only their amplitudes differ. Substituting Equations 11 into 10, an expression for amplitude ratio is obtained:

$$\frac{A_2}{A_1} = C_1 f_{x_1}^2 \quad (12)$$

The amplitude ratio and f_{x_1} are easily obtained from the experimental data and Equation 12 can be solved for C_1 .

Results

Figure 7a shows the FFT amplitude of the pressure coefficient, C_p , measured with physical sensors for a "Baseline" model forward attachment configuration at sideslip angles $\beta \in [-6^\circ, 6^\circ]$. The frequency of the dominant FFT peak at $\beta = 0^\circ$, highlighted in red, is equal to f_{ref} , as expected based on the definition of f_{ref} in the Experimental Setup section. Figure 8a indicates that the frequency of this peak appears to be a function of the slideslip angle, β . The amplitude is also sideslip angle dependent, with largest amplitude occurring at $\beta = -6^\circ$, and coinciding with the lowest frequency of the dominant peak. and occurs at a lower frequency than f_{ref} . As β was increased, the peak amplitude decreases and the associated frequency increases. This monotonic behavior is ideal to perform the calibration of the shadowgraph intensity amplitude.

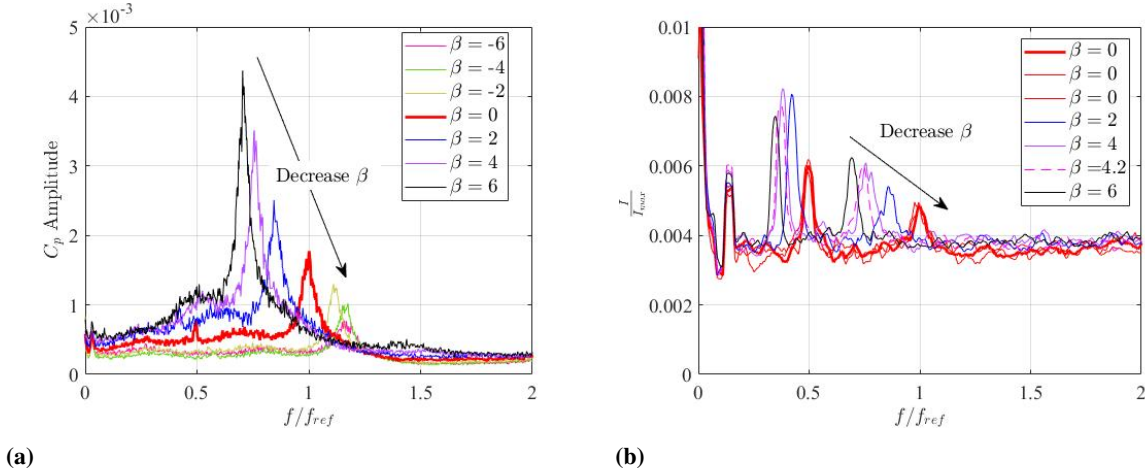


Fig. 7 (a) Station C C_p FFT amplitude variation for a β sweep. (b) Ensemble average of the shadowgraph intensity FFT amplitude variation for the same β sweep.

A series of shadowgraph intensity FFT amplitude plots are shown in Figure 7b. These were recorded at similar β angles and at the same Mach number as Figure 7a. The shadowgraph amplitude FFT values were obtained by averaging

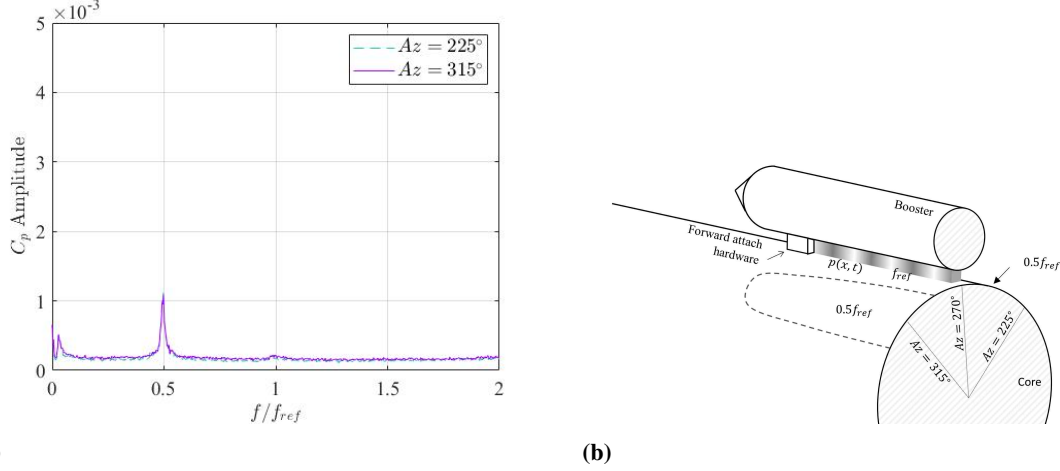


Fig. 8 (a) C_p FFT amplitude measures by sensors at $Az = 315^\circ$ and $Az = 225^\circ$ (b) Schematic showing the approximate region where flow exhibits subharmonic fluctuations.

Table 1 Normalized computed and measured quantities during the calibration calculation and their uncertainties.

$\beta(^{\circ})$	$v_c(ft/s)$	$f_2(Hz)$	$f_{x2}(1/ft)$	A_2/A_1	C_1
0	$V_{c\beta=0} \pm 1.02\%$	$f_{ref} \pm 5 \times 10^{-5}\%$	$f_{x2_{ref}} \pm 0.96\%$	$A_{ref} \pm 8.77\%$	$C_{ref} \pm 9.19\%$
$\beta(^{\circ})$	v_c/v_{∞}	f_2/f_{ref}	$f_{x2}/f_{x2_{ref}}$	$(A_2/A_1)/A_{ref}$	C_1/C_{ref}
0	0.552	1	1	1	1
2	0.544	0.855	0.870	0.790	1.05
4	0.530	0.773	0.808	0.724	1.12
4.2	0.527	0.764	0.803	0.560	0.89
6	0.519	0.712	0.760	0.586	1.02

the FFT of the pixels in the core-booster gap region. Unfortunately, shadowgraph data were limited to only zero and negative β angles. Again, an expected peak is observed around f_{ref} . This peak exhibited same behavior as the directly measured pressure, decreasing in amplitude and increasing in frequency with increasing β .

The FFTs provided in Figure 7b indicate the presence of a signal that occurs at a subharmonic frequency of $0.5 \times f_{ref}$. This subharmonic signal, prominent in the shadowgraph FFT, is nearly absent in the measured pressure FFT at $Az = 270^\circ$, but is the prominent signal in the data for azimuthally adjacent sensors located at $Az = 315^\circ$ and $Az = 225^\circ$, shown in Figure 8a. The dominant peak in the flow environment outside the core-booster gap is located at $f = 0.5f_{ref}$, while the f_{ref} peak is relatively small. This indicates that the subharmonic flow fluctuations occur on the sides of the booster as shown in Figure 8b with a smaller amplitude at $Az = 270^\circ$ sensors. The light in the shadowgraph analysis passes through all disturbances that occur along a line of sight. Examining the core-booster gap, it should be noted the two dominant peaks in the frequency spectrum of the shadowgraph are caused by the combination of the disturbances measured by the sensors at $Az = 315^\circ$, 270° and $Az = 225^\circ$. This 2-dimensional projection of 3-dimensional flow features does not affect the present analysis, since the amplitude change in the f_{ref} is generally limited to the core-booster gap, and therefore, the peak can be measured independently.

According to the Equation 12, determining the calibration constant C_1 requires information about the amplitude ratio and the associated spatial frequency f_x . This frequency can be computed by dividing the temporal frequency by the local convective speed of the flow, v_c . The convective velocity was computed by dividing the sensor separation distance between stations A and D by the cross-correlation time lag in the signals measured at these stations. Table 1 shows the measured and calculated quantities that were used to compute the calibration constant, including their uncertainties, that

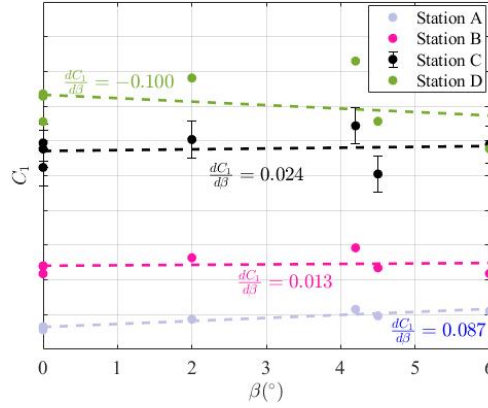


Fig. 9 Computed calibration constant C_1 for β sweep computed at four downstream pressure sensor stations.

are provided at the top of the table. The error associated with the local convective velocity was computed based on the uncertainty of the time lag in the cross correlation for the $\beta = 0^\circ$ test point. Convective velocity was normalized by the wind-tunnel free-stream velocity, v_∞ , measured by the facility. The normalized frequency associated with the peak is shown in the second column. The uncertainty of the frequency was calculated based on the FFT frequency resolution. The spatial frequency was then calculated by dividing the temporal frequency by the convective flow velocity and the associated uncertainty was propagated. The amplitude ratio at each sideslip angle was normalized by the amplitude ratio computed at $\beta = 0^\circ$. The uncertainty of the amplitudes was calculated using a standard error approach by measuring amplitude of the dominant peak of several repeat data points at $\beta = 0^\circ$. This repeatability analysis indicated that the scatter in the amplitudes is the primary driver of the error in this analysis. Finally, C_1 was calculated according to Equation 12.

In the above analysis, the amplitude ratio was computed by comparing the shadowgraph FFT to the pressure data FFT at station C. This calculation was repeated three more times using shadowgraph FFT data from station C and measured pressure data at stations A, B, and D. Figure 9 shows the computed values of C_1 at various β for all four calculations. A line was fit to each C_1 set and its slope is shown in the figure to illustrate the sensitivity of C_1 to changes in β . Coefficients computed using pressure data at station A have a slope of 0.087. This variation is likely evidence that one of the simplifying assumptions in the development of the calibration equation is not valid. Considering that station A is the closest one to the forward attachment hardware, the assumption of one-dimensional pressure variation (varying only in x and t) is most likely inappropriate in this region as flow did not have enough time to develop. Furthermore, the coefficients computed using pressure data at stations A and B seem to be of lower value when compared to the others. This difference can be explained considering that the pressure fluctuations are likely to be much higher closer to the forward attachment hardware. Meanwhile, the shadowgraph amplitudes computed in the region covering stations C and D, and do not reflect the increase in fluctuating pressure with proximity to the forward attachment hardware. Therefore, comparing the pressures at stations A and B with the intensity amplitude results in the lower C_1 value for these stations. The coefficient computed at station C shows the smallest slope magnitude, indicating an insensitivity to changes in sideslip, β . Whereas the coefficient trend at station D shows a -0.100 slope, again possibly indicating a breakdown of the one-dimensional flow assumption. Based on the above discussion, the coefficient calculated at station C is a reasonable candidate for the verification analysis.

The calibration process above was validated using the data set for the "Legacy" forward attachment hardware configuration, depicted in Figure 1b. The validation process required rearranging Equation 12 to solve for the amplitude of the pressure fluctuations.

$$A_1 = \frac{A_2}{C_1 f_{x_1}^2} \quad (13)$$

In Equation 13, C_1 is the constant computed in the calibration, A_2 is the amplitude of the pixel fluctuation measured in the core-booster gap region using the shadowgraph FFT, and f_{x_1} is the spatial frequency, which was recalculated for this new data set by dividing the temporal frequency of the shadowgraph FFT peak by the local convective velocity v_c . Evaluating Equation 13, the shadowgraph-based pressure fluctuation amplitude at frequency f_{ref} is obtained.

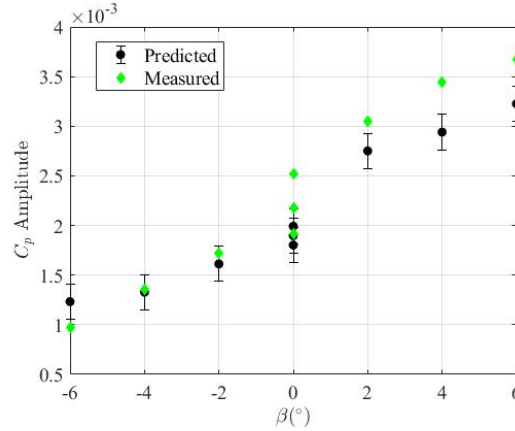


Fig. 10 C_p fluctuation amplitudes at station C based on the quantitative shadowgraph analysis compared to directly measured surface values at $M = 0.92$ test condition for "Legacy" forward attachment hardware.

These results are shown in Figure 10 together with the propagated uncertainty as indicated by the error bars. The shadowgraph-based values are compared to the pressure fluctuation amplitudes measured using the pressure transducers at station C. For negative values of β , the fluctuating pressure amplitude is predicted within the uncertainty. It appears that there is an offset in measured pressure amplitude values for the positive β values. This offset is not observed in the predicted values and remains unexplained.

Conclusion

A quantitative flow visualization analysis using high-speed shadowgraph test data was developed to measure pressure fluctuations downstream of a forward attachment hardware of the Space Launch System Block 2 wind-tunnel model. This optical measurement technique, based on shadowgraph video was calibrated using surface pressure measurements. The calibration process required the derivation and simplification of the analytical expression governing the shadowgraph image intensity distribution. The simplifications included the assumption of a constant-temperature and one-dimensional flow in the gap between the core and booster such that density varied only in time and downstream direction. It was shown that these simplifications were reasonable in a core-booster gap in the near-field region of the forward attachment hardware being studied in this work. Upon calculating the appropriate calibration constant, the method was verified by measuring the pressure fluctuation downstream of another forward attachment hardware configuration. The shadowgraph-based fluctuating pressure values were compared to the fluctuation amplitudes measured using pressure transducers. The two measurement approaches matched within the calculated uncertainty for negative vehicle sideslip angles. An offset was observed in measured pressure for the positive model sideslip angles, while the shadowgraph-based values did not estimate this offset. The cause of this difference is currently being evaluated.

The analysis indicates that the proposed calibration process can be used to predict near-body surface pressure fluctuations and potentially off-body pressure fluctuation amplitudes from shadowgraph images under similar test conditions, assuming that the temperature and optical setup are unchanged from the calibration runs. The long-term goal of this technique is to provide an additional technique to measure unsteady pressure trends in the core-booster gap after conducting a calibration at a single tunnel condition. Future work for using this technique is to apply it to the other five forward attachment hardware configurations that were tested during Booster Obsolescence Life Extension Forward Attachment Structure Trade Study Test.

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