

Fast Pressure-Sensitive Paint Imaging Of Three-Dimensional Non-Stationary Shock Oscillations In A Mach-5 Intake With Synchronised Schlieren Support

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ABSTRACT

Unique non-stationary shock oscillations in high-speed intakes are inherently unsteady and can exhibit three-dimensional features, even in nominally planar geometries. Conventional optical techniques, such as schlieren, provide valuable qualitative information but rely on line-of-sight integration, which limits their ability to resolve spanwise variations of shock motion. In the present study, a porous PtTFPP-based polymer-ceramic pressure-sensitive paint (PC-PSP), operated in a fast-PSP configuration, is applied to investigate non-stationary shock oscillations in a Mach 5 planar intake under throttled operating conditions (TR = 28%). The fast-PSP measurements, acquired at 20 kHz using a Photron FASTCAM SA-Z camera, provide time-resolved surface pressure information on the intake ramp, allowing the shock footprint to be tracked in both streamwise and spanwise directions. To support the interpretation of the fast-PSP data, synchronised high-speed schlieren imaging was performed at the same frame rate, enabling direct comparison between the flow-field shock structure and its corresponding surface-pressure footprint at selected instants in time. Quantitative analysis of the fast-PSP data includes power spectral density estimation, time-frequency spectrograms, Dynamic Mode Decomposition (DMD), and pixelwise Fast Fourier Transform (pixelwise FFT). PSD analysis recovers dominant oscillation frequencies near 290 Hz, consistent with previous schlieren-based measurements on the same intake. DMD extracts spatially coherent oscillatory modes that exhibit clear spanwise asymmetry, and pixelwise FFT maps reveal that different regions of the ramp respond preferentially to different oscillation frequencies. Together, these results demonstrate that fast-PSP is a powerful tool for resolving three-dimensional shock oscillation behaviour that cannot be captured using integrative optical methods alone, while also highlighting the practical challenges associated with illumination, coating durability, and image processing in high-speed applications.

1. Introduction

Supersonic intakes can experience unsteady shock oscillations, commonly referred to as buzz, which may lead to partial or full unstart and loss of performance. High-speed schlieren imaging has been extensively used to study such flows and has been effective in identifying shock

motion and dominant oscillation modes. However, schlieren provides an optically integrated, two-dimensional representation of density gradients in a three-dimensional field and does not give direct information on surface pressure or spanwise variations (Wagner et al., 2009; Chang et al., 2012; Berto et al., 2020).

Pressure-sensitive paint (PSP) provides full-field surface-pressure measurements and, with recent developments in fast porous and polymer/ceramic formulations, can achieve response rates suitable for unsteady high-speed flows (Peng & Liu, 2020; Gregory et al., 2014). Previous schlieren measurements on the present Mach-5 intake identified a bi-stable shock oscillation behaviour in which low-amplitude precursor oscillations alternate with large-amplitude buzz events; in the present work, the term non-stationary shock oscillation is adopted to emphasise the time-varying and aperiodic nature of these oscillations rather than implying only two discrete states (Gurbuz et al., 2025). Although that study employed centreline schlieren imaging, it is well established that nominally planar intakes with sidewalls sustain three-dimensional shock–boundary layer interactions that can deviate substantially from two-dimensional behaviour (Eagle et al., 2011; Sabnis & Babinsky, 2023); the fast-PSP measurements presented here provide the first direct evidence of this three-dimensionality in the surface pressure field of the present intake.

This study aims to explore the capability of fast pressure-sensitive paint to capture non-stationary shock oscillations in a Mach 5 intake, including spanwise variations, that are not accessible using optically integrated diagnostics. By synchronising fast-PSP with high-speed schlieren, the study also provides a direct comparison between an integrative optical method and a surface-based pressure diagnostic.

2. Experimental Setup

2.1. HSST facility, test model and schlieren setup

Experiments were conducted in the University of Manchester High SuperSonic Tunnel (HSST) under freestream conditions corresponding to Mach 5 (a full description of the facility is available in Ref. (Gurbuz et al., 2025)). Air stored in a 1700 kPa reservoir was delivered to the facility through a dome valve, which regulated the required upstream total pressure during the run. A heating system was used both to set the desired Reynolds number and to avoid condensation during expansion through the nozzle. The typical test condition for the present study was upstream total temperature of about 350 K and a total pressure of 685 kPa, giving a Mach number of 5 at the nozzle exit. Using Sutherland's law to estimate viscosity, the Reynolds number per unit length was calculated as $1.69 * 10^7 m^{-1}$.

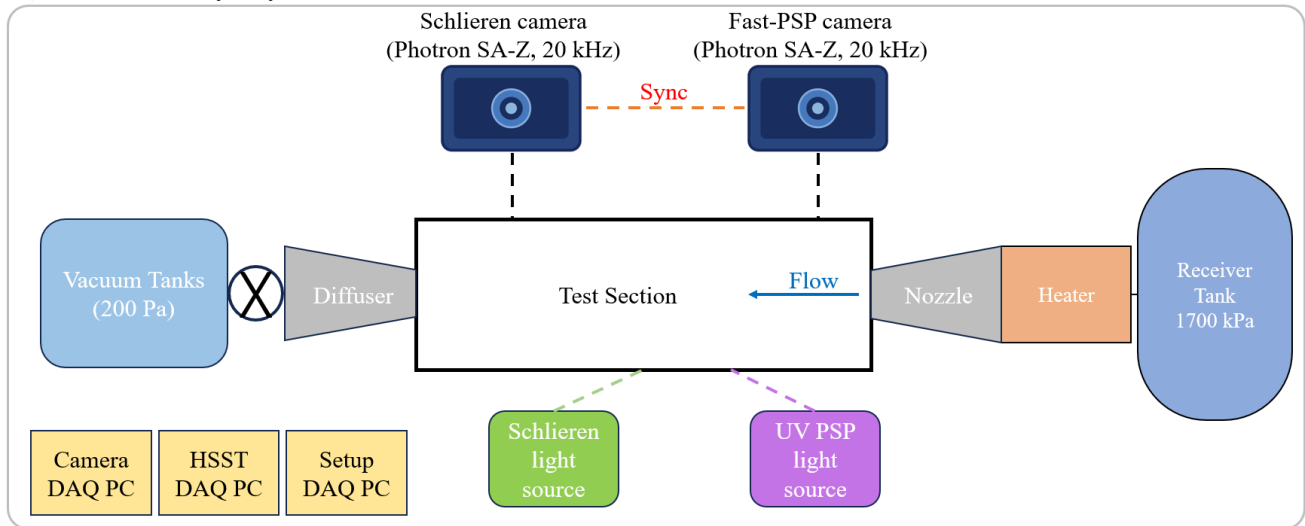
The test model is a two-dimensional planar intake with a 10° ramp and a 34×14 mm isolator cross-section, described in Ref. (Gurbuz et al., 2025). Exit blockage was adjusted using fixed orifice

plates to control the throttling ratio (TR). The throttling ratio is defined

$$TR = (A_{th.place} / A_{exit}) * 100\% \quad (1)$$

where $A_{th.place}$ is the blocked area by the orifice plate at the isolator exit, and A_{exit} is the cross-sectional area of the isolator exit. The schlieren system followed the same Z-type configuration used in the earlier study, with the addition of a slit placed upstream of the first parabolic mirror to improve light control and set sensitivity and range. Optical access to the test section was provided by a 170 mm circular quartz window installed in the roof of the test section, allowing simultaneous viewing of the intake ramp by the fast-PSP camera and illumination from an external UV light source. Besides, two parallel rectangular quartz windows (300 mm $\times$ 210 mm) mounted in the access doors provided side-view optical access for schlieren imaging. Both measurement techniques employed Photron FASTCAM SA-Z high-speed cameras operating at a frame rate of 20 kHz. The fast-PSP camera sensor was cropped to 512 $\times$ 1024 pixels to capture the ramp surface field of view, while the schlieren camera sensor was cropped to 1024 $\times$ 240 pixels to capture the side-view flow field. Further details of the fast-PSP camera and illumination arrangement are given in Section 2.2. A schematic overview of the experimental setup and the optical arrangements for both measurement techniques is shown in Figure 1.

a) Overall Facility Layout



b) Test Section Detail – Fast-PSP & Schlieren Arrangement

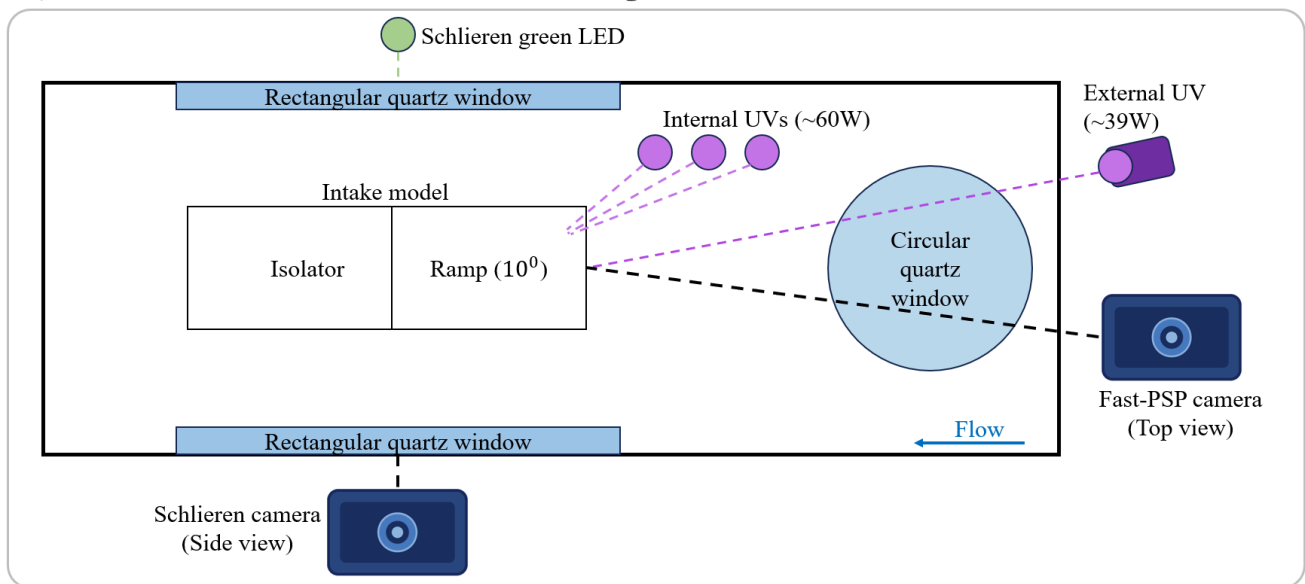


Figure 1. Experimental setup schematic for the Mach 5 intake experiment: *a)* overall facility and overall setup layout, *b)* closer test-section view indicating the intake model and illumination arrangements.

2.2. Fast-PSP setup

A porous PtTFPP-based polymer–ceramic pressure-sensitive paint (PC-PSP) was applied to the intake ramp surface following established procedures (Recipe: Ref. (Liu & Sullivan, 2005)). The painted region of interest (ROI) corresponds to the visible ramp surface between the ramp leading edge and near to the cowl lip, covering a physical area approximately 34 mm in width and 100 mm in length from the camera perspective.

Illumination for the painted area was provided by three high-power Luminus Devices UV LEDs mounted on an aluminium plate inside the top wall (internal 60 W) and an external in-house UV source (39 W), giving a combined UV power of 100 W. The ramp was viewed from above; the sensor was cropped during acquisition to focus on the ramp ROI. Cropped images were geometrically corrected in post-processing using a projective transform to map the camera view onto a rectified ramp plane (accounting for the 10° ramp angle and inclined camera geometry). A detailed view of the intake and illumination arrangement is shown in Figure 2. The fast-PSP camera was positioned above and slightly to the side of the external UV light source, viewing the ramp surface through the circular quartz window in the tunnel roof. The camera is not visible in the Figure as it is located above the field of view of this photograph; its position relative to the full experimental setup is schematically demonstrated in Figure 1.

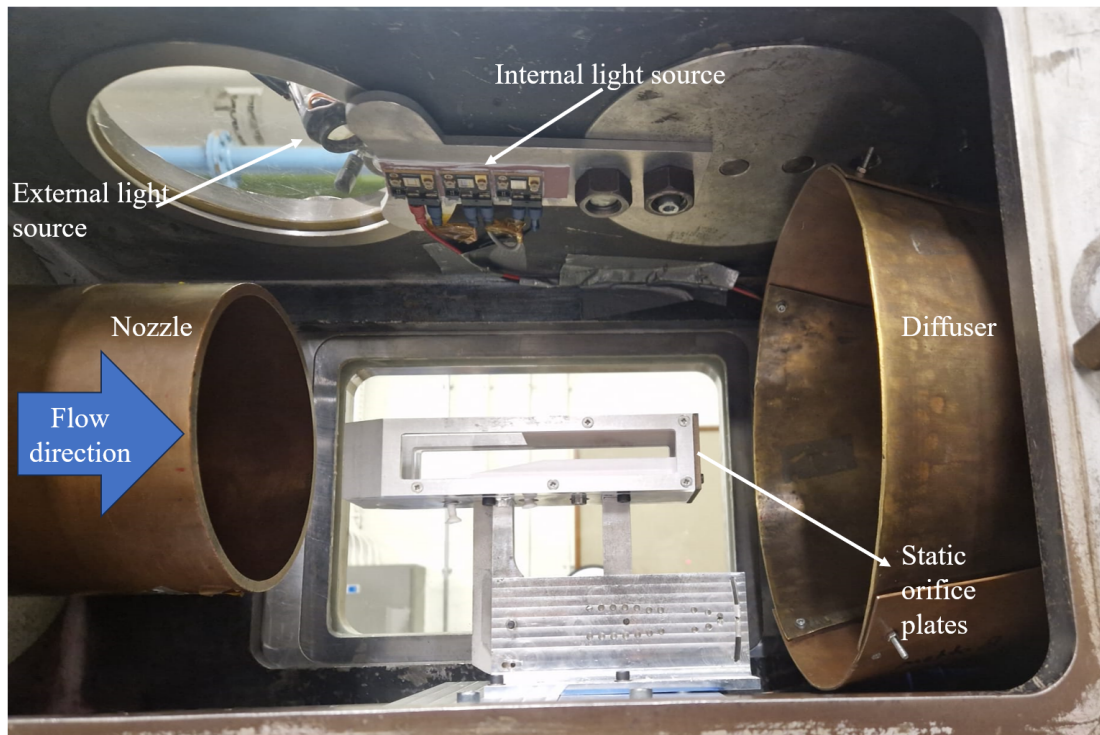


Figure 2. Mach 5 intake model installed in the HSST test section, showing the fast-PSP illumination arrangement

3. Methodology

3.1. Illumination, camera settings and practical notes

Illumination for the fast-PSP measurements was provided by three high-power Luminus Devices UV LEDs mounted on an aluminum plate inside the top wall (internal 60 W), and an external in-house UV source (39 W), giving a combined UV power of 100 W. The light sources were

arranged to maximise emission of the porous PC-PSP while keeping illumination shadows and reflections manageable. Fast PSP coatings typically provide strong luminescence; however, short exposure times required for kHz-rate acquisition with the Photron FASTCAM SA-Z significantly reduce the collected signal, resulting in lower signal-to-noise ratios. Owing to the inherently low luminance of fast porous PSP, a high total UV power of approximately 100 W was required to obtain a sufficiently strong signal and to resolve the non-stationary shock motion with adequate contrast. Without this level of illumination, the usable intensity range would become narrow and the shock pattern could not be reliably distinguished from background noise. The final acquisition settings were 20 μ s exposure time at 20 kHz frame rate.

The schlieren and fast-PSP cameras were operated in a master–slave configuration and synchronised at the frame level, enabling direct comparison of the two diagnostics at identical instants in time. During the synchronised measurements, the schlieren green LED introduced a small additional background contribution to the PSP signal. This effect was found to be approximately 1% of the PSP intensity level; however, as the schlieren LED was driven using a constant current drive circuit, the levels were extremely stable and therefore did not interfere with unsteady PSP measurements. Background and stray illumination effects are well recognized in PSP measurements and are commonly controlled or corrected using wind-off normalization and background subtraction techniques. The observed contribution level in the present study is small compared to the overall variation in PSP signal and is considered acceptable when reported and treated as a source of uncertainty, consistent with previous PSP studies conducted under unideal lighting conditions (Gregory et al., 2014; Matsuda et al., 2022).

Due to the porous nature of the PC-PSP, the coating exhibited lower durability and higher sensitivity to photodegradation than conventional steady PSP formulations. To minimise degradation, the painted model was prepared shortly before the experimental campaign and stored in a dark environment until use. The model was installed in the test section only during testing periods.

All experiments were conducted in a darkened laboratory environment to minimize background illumination. Preliminary tests indicated that ambient room lighting introduced a small but measurable variation in the recorded intensity (approximately 1.2% of the mean signal). Although the use of a post-run reference condition largely mitigates photo degradation effects in the intensity ratio calculation, reducing ambient illumination improves signal stability and reduces background noise in the high-speed PSP measurements.

Preliminary tests showed that thin PSP coatings produced insufficient emission intensity for reliable high-speed imaging. It was therefore found that a coating thickness of approximately 30–40 μ m was required to achieve a measurable signal with an acceptable signal-to-noise ratio at the short exposure times used for fast-PSP acquisition. Coatings thinner than this produced dark images with a low signal-to-noise ratio and were therefore unsuitable for the present measurements.

The final coating was applied using multiple spray layers to achieve the required thickness. When

local photodegradation reduced the signal level during extended testing, additional PSP layers were applied to restore the luminance, and the calibration procedure was repeated to maintain consistency between calibration and measurement data.

Reflections from the side windows and metallic frame elements were observed near the ramp side edges and were partially masked during post-processing. The model position relative to the internal LED array was adjusted iteratively to improve illumination uniformity and to reduce strong multi-shadow patterns, particularly near the cowl tip. These practical considerations were essential to achieve consistent fast-PSP image quality under the combined challenges of porous coatings, high-speed imaging, and unsteady supersonic flow.

3.2. PC-PSP calibration

An in-situ, a-priori calibration of the PC-PSP coating was conducted within the test section to ensure identical optical and illumination conditions to the main experiments. The chamber was initially evacuated to a baseline pressure of approximately 200 Pa. Following isolation, the static pressure was increased in controlled increments, with calibration images recorded at discrete levels from 5 kPa to 50 kPa in 5 kPa steps.

At each calibration point, mean intensity values were normalised as I_{ref}/I . The reference pressure (P_{ref}) was selected based on the wind-off averaged pressure recorded immediately following the tunnel run. This post-run reference was chosen because the pre-run static pressure exhibited high uncertainty (100–300 Pa), and the post-run condition more accurately represents the "thermal state" of the paint after exposure to the flow. Further details regarding the determination of P_{ref} and associated sensitivities are provided in subsection 4.4. A second-order polynomial fit was applied to the data:

$$\frac{P}{P_{ref}} = 0.3924 \left(\frac{I_{ref}}{I} \right)^2 + 1.956 \left(\frac{I_{ref}}{I} \right) - 1.356 \quad (2)$$

The calibration provided an excellent correlation with the measured data ($R^2 = 0.9999$), capturing the specific coating behaviour and viewing geometry. The calibration relationship was constructed using a reference pressure of 15 kPa, which was subsequently adopted in the final data reduction based on the sensitivity assessment described in Section 4.4. The resulting PC-PSP calibration curve is presented in Figure 3.

As shown in Figure 3, both linear and second-order polynomial fits are presented for comparison. While the calibration data exhibit an almost linear response over the investigated pressure range, the second-order polynomial fit was adopted for the final calibration to account for any weak non-linear behaviour of the PC-PSP response. The inclusion of both fits demonstrates that the

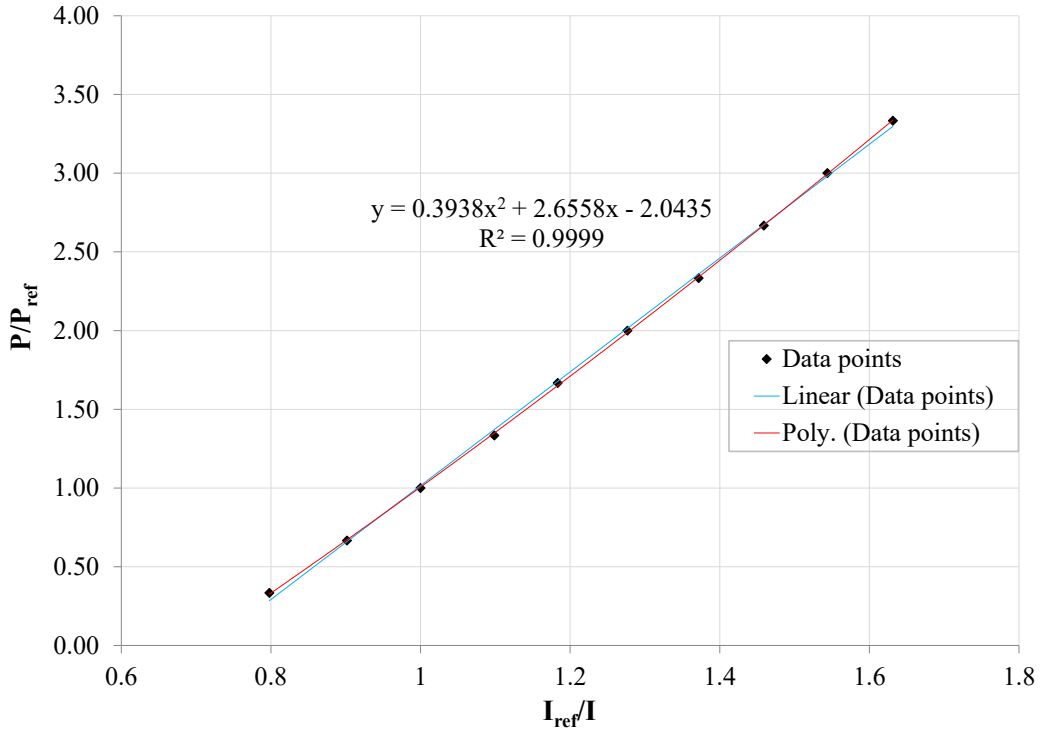


Figure 3. The calibration curve of PC-PSP with linear and polynomial fit.

calibration remains highly linear within the experimental pressure range and that the selected polynomial formulation does not introduce significant deviation from a linear representation.

To assess the robustness of the calibration relationship, two additional calibration points at 55 and 60 kPa were incorporated. The resulting second-order polynomial fit remained virtually unchanged and continued to provide an excellent correlation with the measured data ($R^2 = 0.9999$). This observation indicates that the calibration response remains approximately linear over the extended pressure range and supports the validity of the adopted calibration model.

Error bars are not shown in Figure 3. During calibration, the measured chamber pressure exhibited only small fluctuations around the target pressure levels, typically remaining within a few tens of pascals of the nominal value. These variations are significantly smaller than both the pressure range investigated and the marker size used in the figure. Consequently, the associated uncertainty is visually negligible and does not affect the observed calibration trend.

4. Results and Discussion

The following section presents synchronised fast-PSP and schlieren observations of the non-stationary shock dynamics at $TR = 28\%$, followed by quantitative analysis of the surface pressure

distributions extracted from the fast-PSP measurements. Spectral analysis is then applied to characterise the dominant oscillation frequencies, and Dynamic Mode Decomposition (DMD) is used to identify spatially coherent structures in the unsteady pressure field. Finally, a pixelwise FFT (pixelwise Fast Fourier Transform) analysis is presented to map the spatial distribution of spectral energy across the ramp surface, demonstrating the capability of fast-PSP to resolve three-dimensional frequency content inaccessible to line-of-sight diagnostics.

The throttling ratio of $TR = 28\%$ was selected as the primary test condition because it corresponds to the onset of buzz, characterised by non-stationary shock oscillations exhibiting a transitional bi-stable character, as established in the authors' previous schlieren study (Gurbuz et al., 2025). At lower throttling ratios, the internal shock system remains quasi-steady, while at higher values, the oscillation transitions to a more periodic, single-frequency big buzz mode. The $TR = 28\%$ condition therefore, represents the most dynamically rich regime and provides the most demanding test case for evaluating the fast-PSP diagnostic capability.

4.1. Synchronised Fast-PSP and Schlieren Overlay: Three-Dimensional Shock Structure

Figure 4 presents a synchronised overlay of the fast-PSP surface pressure field and the corresponding schlieren image at $t = 16.5$ ms, where $t = 0$ corresponds to the trigger time of the high-speed camera acquisition. The camera was triggered 2 s after the tunnel trigger, once the flow had established and reached a quasi-steady operating condition. The schlieren image is projected onto the rectified ramp plane, enabling a direct spatial comparison between the shock structure in the flow field and its corresponding surface-pressure footprint on the ramp.

In Figure 4, the fast-PSP pressure distribution is normalised by the freestream static pressure, $P_\infty = 1.29$ kPa, derived from the tunnel upstream total pressure of 683 kPa at Mach 5 using isentropic flow relations. The wind-off image acquired after each tunnel run serves as the intensity reference in the PSP data reduction, and the associated sensitivity considerations are discussed in subsection 4.4.

The schlieren image does not exhibit a single, sharply defined shock foot at the ramp surface. Instead, the shock appears axially extended and diffuse in the streamwise direction. This apparent smearing is consistent with line-of-sight integration inherent to schlieren imaging, where spanwise variations in shock position are superimposed in the optical projection. In contrast, the fast-PSP measurement provides a spatially resolved surface pressure field, revealing the instantaneous pressure rise associated with the shock footprint on the ramp surface.

At this instant, the fast-PSP data show that the pressure rise occurs over a finite streamwise region rather than at a single fixed location, with spatial variations in both the position and magnitude of the pressure increase across the ramp surface. These features indicate that the shock-surface interaction is inherently three-dimensional, even though the intake geometry is nominally two-

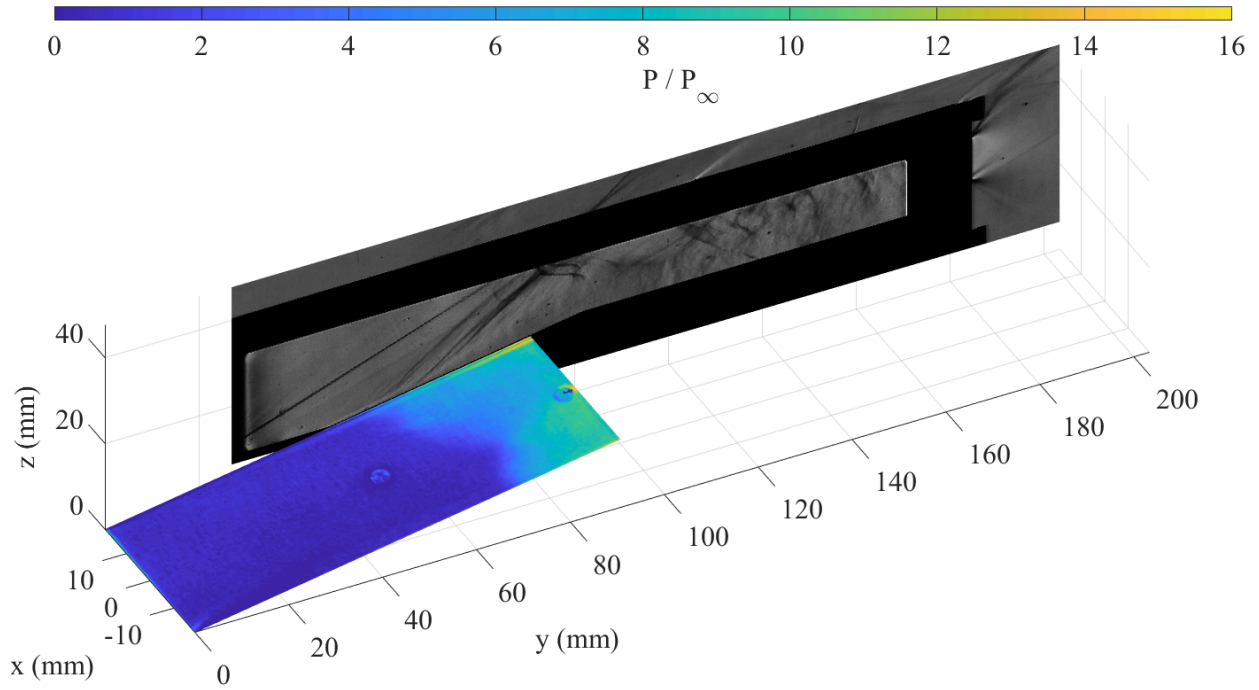


Figure 4. Synchronised fast-PSP surface pressure and schlieren image overlaid on the rectified ramp plane at $t = 16.5$ ms for $TR = 28\%$. Surface pressure is normalised by freestream static pressure P_∞ . The schlieren image is projected onto the same spatial grid to indicate the instantaneous shock location.

dimensional. Such spatial complexity cannot be unambiguously inferred from schlieren images alone due to their line-of-sight nature.

To quantify the pressure variations associated with the shock footprint observed in Figure 4, the following subsection describes the image processing approach and the regions of interest used to extract spatially resolved pressure information from the fast-PSP data.

4.2. Image Processing and ROI Definition

The fast-PSP image sequences were first rectified onto the ramp plane to correct for the perspective distortion introduced by the inclined camera viewing geometry and the 10° ramp inclination relative to the tunnel floor. During acquisition, the camera sensor was cropped to focus on the ramp region of interest. In post-processing, the cropped images were geometrically corrected using a projective transformation to map the camera view onto a rectified ramp plane, for both the camera tilt angle and the ramp surface inclination.

Dark-frame subtraction and wind-off normalisation were applied to remove fixed-pattern noise and illumination variations.

The image processing approach follows the methodology established in the earlier schlieren-based study on the same intake configuration (Gurbuz et al., 2025), with adaptations for fast-PSP data.

Two one-dimensional Regions of Interest (ROIs) - demonstrated with red lines - were defined on the rectified ramp surface, as illustrated in Figure 5.

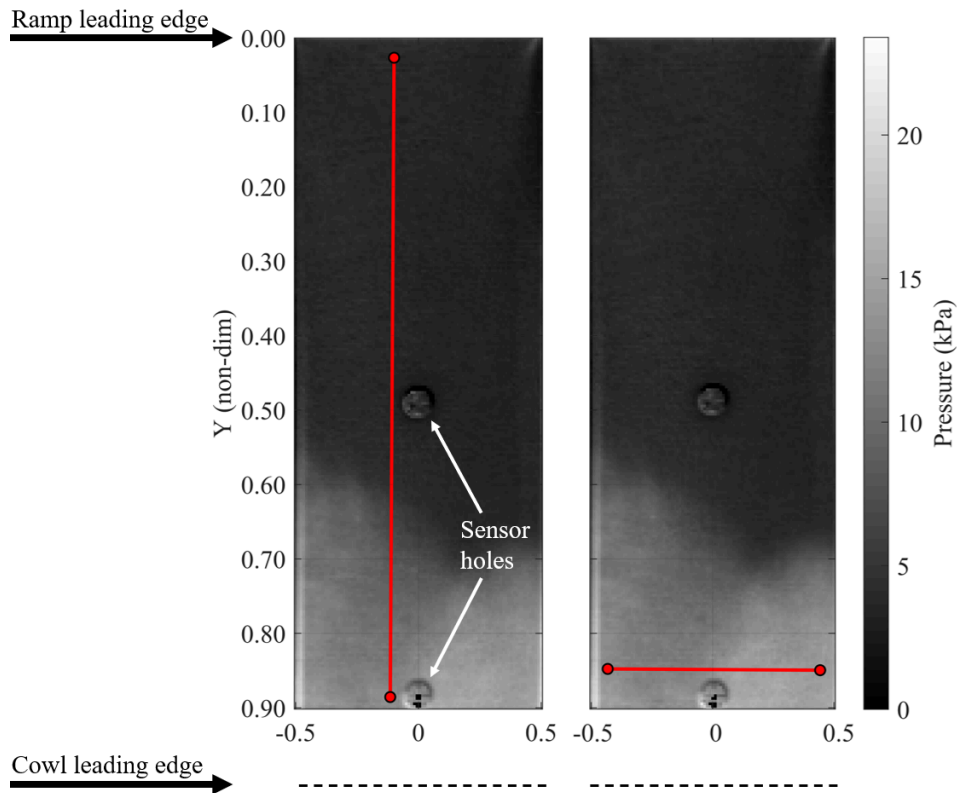


Figure 5. Rectified ramp-plane ROIs used for fast-PSP analysis: spanwise ROI (left) and streamwise ROI (right)

As shown in Figure 5, the ramp leading edge and the cowl leading edge are indicated for reference. Because the cowl leading edge lies outside the rectified ramp image, its location is represented schematically using a dashed line. The spatial coordinates are non-dimensionalised such that the streamwise coordinate extends from $x/L = 0$ at the ramp leading edge to $x/L = 1$ at the cowl leading-edge location, while the spanwise coordinate is referenced to the ramp centreline.

A streamwise region of interest (ROI), shown on the left side of Figure 5, was defined near the geometric centreline of the ramp surface. The ROI extends from the ramp leading edge to the downstream end of the second pressure-tapping location and was used to extract instantaneous surface pressure distributions along the ramp. This same streamwise ROI is referenced in subsection 4.4 to illustrate the influence of reference-pressure selection on the inferred pressure distribution. The ROI was positioned slightly off the centreline to avoid the plugged centreline pressure-tap holes, which would otherwise introduce local measurement artefacts.

A second ROI was defined in the spanwise direction across the ramp. For this spanwise ROI, pixel intensities were spatially averaged and stacked over successive frames to form time-resolved intensity maps, analogous to image stacking methodology used in the earlier schlieren-based anal-

ysis (Gurbuz et al., 2025). This approach enables the temporal tracking of shock motion and the identification of non-stationary oscillatory behaviour associated with the intake buzz dynamics.

The selected ROIs were chosen to provide information on both the instantaneous pressure distribution and the temporal evolution of the shock motion. As with any line-based extraction approach, the measured response depends on the spatial relationship between the ROI location and the instantaneous shock position. The streamwise ROI is subsequently used to examine the instantaneous shock-foot location through successive pressure profiles, while the spanwise ROI provides a time-resolved representation of the overall shock oscillation behaviour.

4.3. ROI-Based Fast-PSP Observations of Shock Oscillation

Fast-PSP measurements were analysed using the two previously defined one-dimensional regions of interest (ROIs) to examine instantaneous and time-resolved surface-pressure behaviour on the ramp. Only a short segment of the recorded time history is presented here to illustrate the non-stationary shock oscillation pattern. Figure 6 presents a sequence of instantaneous pressure distributions extracted from the streamwise ROI over a 0.4 ms interval during a representative buzz cycle. The sequence of pressure profiles demonstrates that the fast-PSP measurement captures the upstream propagation of the shock footprint with sufficient temporal resolution to track its motion frame-by-frame across the ramp surface — a measurement not possible with conventional steady PSP or with schlieren alone due to its line-of-sight limitation.

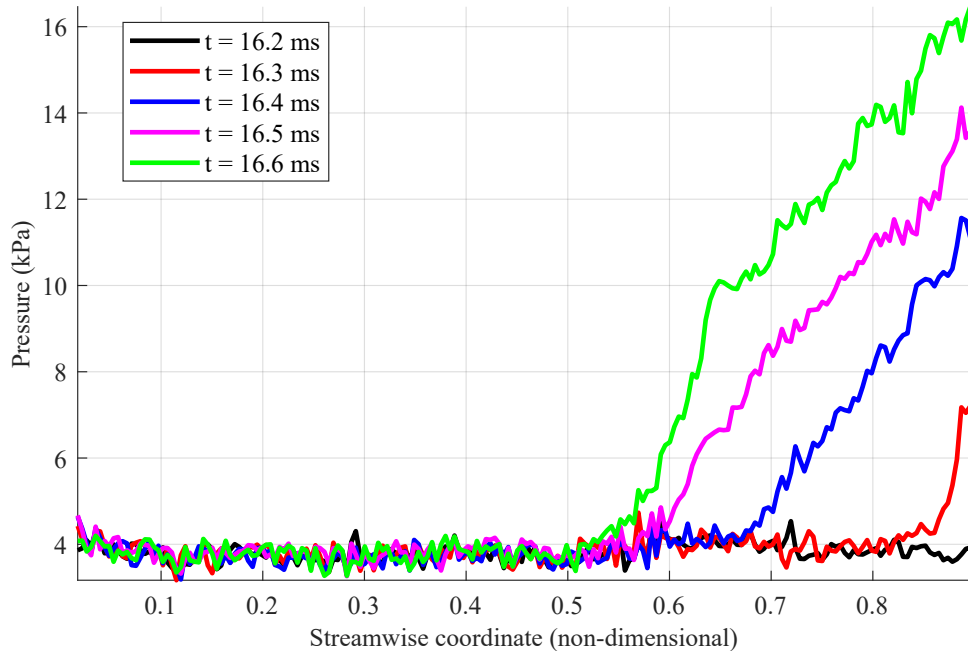


Figure 6. Instantaneous streamwise pressure distributions showing the upstream propagation of the shock footprint along the ramp.

The spanwise ROI is processed by averaging pixel intensity values along the horizontal ROI line and stacking them over time to construct a pressure-time history and is shown in Figure 7. This time history exhibits the non-stationary, bi-stable nature of the shock motion, characterised by alternating low-amplitude (little-buzz-like structures) and high-amplitude (big-buzz) oscillatory regimes, consistent with observations reported in the authors' previous schlieren-based study (Gurbuz et al., 2025). While the overall oscillation pattern differs in appearance from the corresponding schlieren-derived shock traces, this behaviour is expected because the fast-PSP measurements are derived from spatially averaged pressure information, whereas schlieren images rely on density-gradient-based edge detection. Nevertheless, both techniques identify the same underlying shock-motion behaviour, and the fast-PSP measurements demonstrate that both oscillatory regimes can be captured within a single time-resolved pressure record.

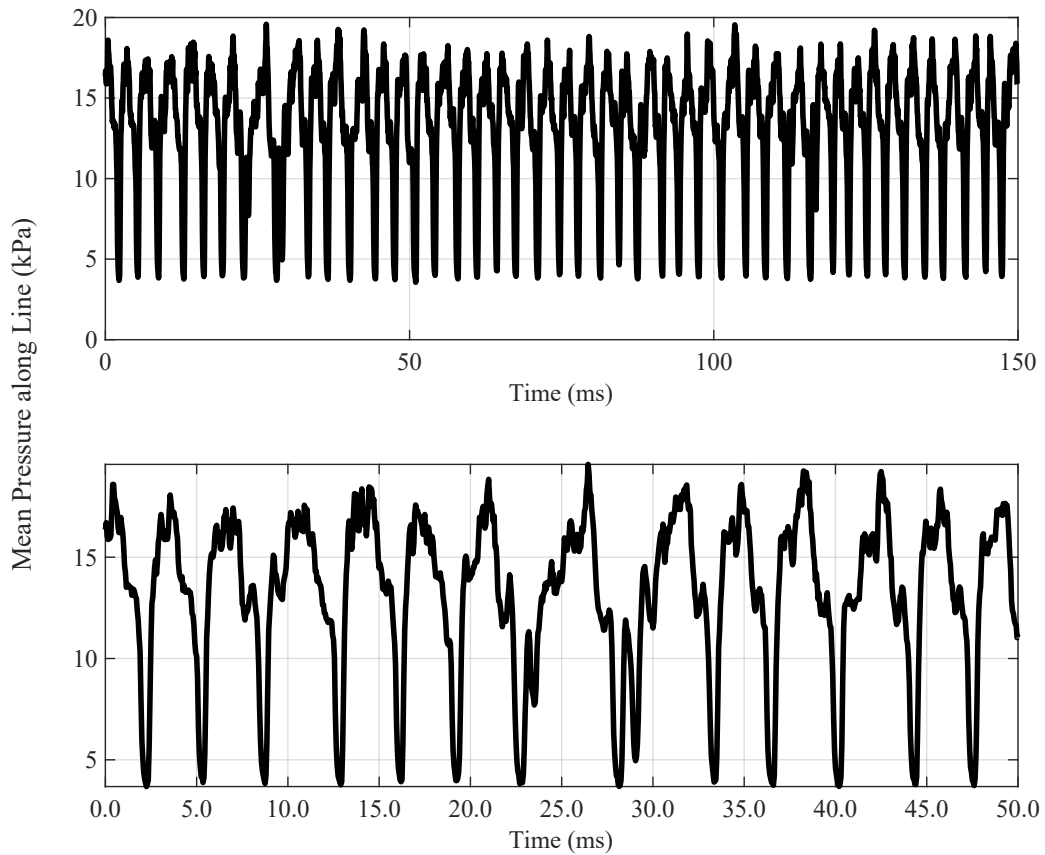


Figure 7. Time-resolved shock profile evolution along the spanwise ROI, including the partial acquisition history (top) and a zoomed view of the selected time interval (bottom).

Before proceeding to spectral analysis, the sensitivity of the calibrated pressure field to the choice of wind-off reference pressure is briefly examined, as this directly affects the quantitative reliability of all subsequent measurements.

4.4. Calibration Sensitivity and Reference Pressure Effects

To assess the reliability of the absolute measurements to the choice of reference pressure—an important issue in low-pressure hypersonic PSP measurements—the fast-PSP data were reprocessed using several plausible normalisation values. These included wind-off pressures measured immediately after tunnel shutdown (14.0–15.5 kPa) as well as a higher reference pressure corresponding to the midpoint of the calibration range (25 kPa). The resulting comparison showed that the inferred ramp theoretical surface pressure varied by approximately ± 1.3 kPa depending on the selected reference pressure. This demonstrates that the choice of reference condition has a measurable influence on the estimated pressure field and motivates the selection of a physically representative wind-off reference state for the final calibration.

For the final data reduction, a reference pressure of $P_{ref} = 15$ kPa was selected. This value lies within the range of measured post-run wind-off pressures (approximately 14.0–15.5 kPa) and produced the closest agreement with the theoretical ramp surface pressure in the steady-flow region upstream of the buzz shock interaction. The selected reference pressure was therefore adopted for both calibration and final pressure reconstruction, ensuring internal consistency between the calibration polynomial and the data reduction procedure.

Figure 8 shows the resulting streamwise surface pressure distribution in kPa along the intake ramp at a representative instant in time, with a blue solid line. The shaded grey band represents the ± 1.3 kPa uncertainty associated with the reference-pressure sensitivity. Also shown with a dashed line is the theoretical post-ramp-shock pressure level for a Mach 5 flow over a 10° ramp.

As can be seen in Figure 8, the x-axis represents the non-dimensional streamwise position x/L along the line, and the y-axis represents the calibrated surface pressure data in kPa. Upstream of the buzz shock interaction region (between 0–0.5 in x-axis), the measured ramp pressure is nominally constant along the streamwise direction and corresponds to the theoretical pressure downstream of the fixed ramp shock at the given conditions. In this region, the mean fast-PSP pressure level closely matches the theoretical value of 3.97 kPa. This agreement indicates that the calibration approach and reference-pressure selection provide a physically consistent estimate of the steady-state ramp surface pressure at Mach 5.

The present analysis focuses specifically on the sensitivity of the calibrated pressure field to the selected reference pressure. Other factors that may influence the measurement accuracy include illumination non-uniformity, image registration and rectification errors, coating photodegradation, and the spatial and temporal resolution limits of the imaging system. These effects were minimised through the experimental procedures described in Sections 2.2, 3.1 and 4.2 but were not quantified individually in the present work. As the primary objective of this study is to demonstrate the capability of synchronised fast-PSP measurements in a hypersonic intake environment, a comprehensive uncertainty propagation analysis is reserved for future investigations.

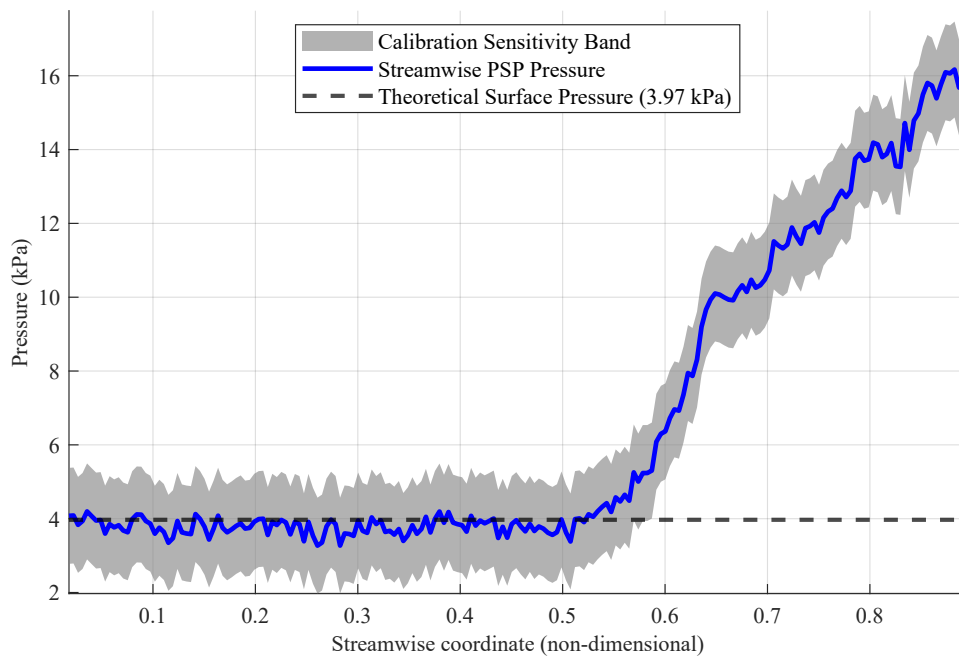


Figure 8. Streamwise surface pressure distribution along the ramp measured using fast PC-PSP. The shaded grey band represents the pressure variation associated with the reference-pressure sensitivity study (± 1.3 kPa). The dashed line indicates the theoretical post-ramp-shock pressure level.

In addition to the reference-pressure sensitivity, several practical constraints of the fast-PSP technique in this experimental environment are worth noting before interpreting the spectral results.

4.5. Limitations of the Fast-PSP Measurements

The present study is subject to several practical constraints associated with the fast-PSP technique and experimental setup. The porous PC-PSP formulation has inherently low luminance and degrades more rapidly than steady PSP, limiting the number of runs that can be performed before signal quality declines. To address this, additional PSP layers were applied over the existing coating once signal degradation became apparent. This overspraying approach restored the luminance without the time cost of full stripping and reapplication, and the calibration procedure was repeated following each additional coat to maintain measurement consistency. Reflections from the test-section windows and metal frames further reduce the usable area near the ramp edges, requiring careful masking during processing.

Additional limitations arise from the physical characteristics of the PSP. In very low-pressure regions, the emitted luminescence signal becomes weaker, reducing the signal-to-noise ratio and increasing susceptibility to measurement noise. This effect is most relevant in the low-pressure ramp region. Furthermore, the porous ceramic binder and high temporal acquisition rates introduce high-frequency spatial noise in instantaneous pressure fields. Background illumination,

including a small contribution from the green LED (1%), may introduce a minor intensity bias, though this is considered within acceptable limits. Despite these constraints, the technique remains robust for capturing the essential features of the non-stationary, bi-stable shock behaviour in this Mach 5 intake.

With the measurement uncertainties and practical limitations identified, the analysis now turns to spectral characterisation of the shock oscillations using the time-resolved fast-PSP data.

4.6. Global Spectral Analysis of Shock Oscillation

Prior to spectral analysis, the pressure signal was extracted from the spanwise ROI by spatially averaging pixel-level pressure values for the ROI line at each time step, yielding a scalar pressure time series of $N = 10,240$ samples at $F_s = 20$ kHz (512 ms total).

Figure 9 presents the Power Spectral Density (PSD) distribution for spanwise ROI at $TR = 28\%$. The PSD was computed using Welch's method — a segment-averaging approach that divides the signal into overlapping windowed segments, computes the Fast Fourier Transform (FFT) of each segment, and averages the resulting power spectra. This reduces spectral variance and is well-suited to non-stationary signals such as the present buzz oscillation, where the instantaneous frequency drifts over time. An adaptive window of $N/6 \approx 1,700$ samples with 95% overlap was applied (Hamming window; $N_{FFT} = 8,192$), giving a frequency resolution of approximately 2.4 Hz. The PSD is normalised by its peak value and displayed on a logarithmic frequency axis. Normalising by the peak value sets the dominant mode to unity, allowing the relative strength of secondary peaks to be assessed independently of signal amplitude.

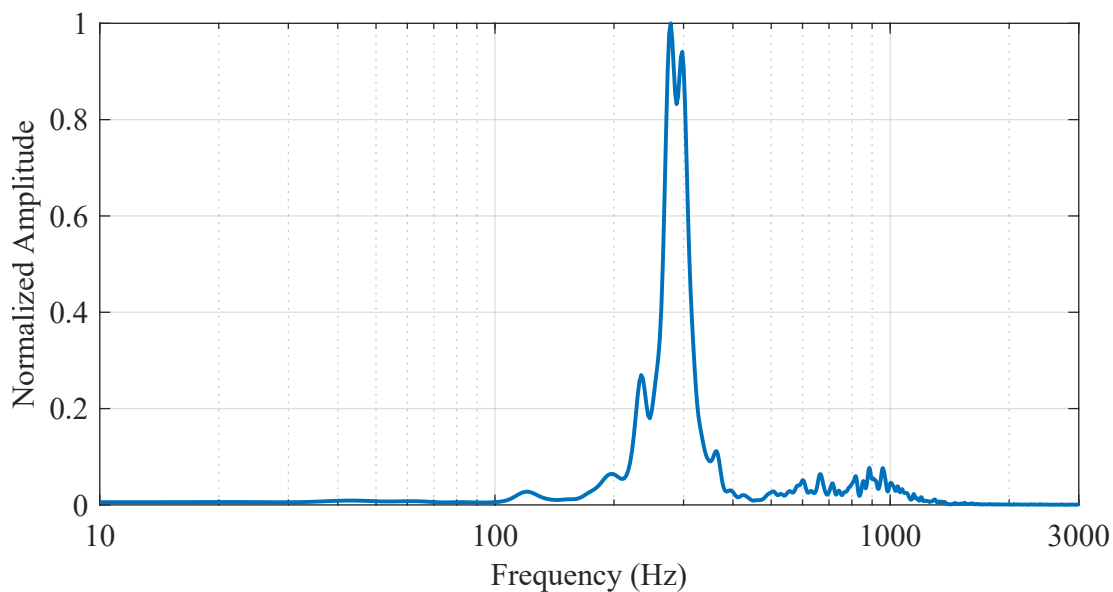


Figure 9. Power Spectral Density of the spanwise ROI pressure signal at $TR=28\%$.

As can be seen in Figure 9, the dominant peaks occur at 278 Hz and 297 Hz within the analysed limited frequency range of 10-3000 Hz. These values are consistent with the 290 Hz dominant frequency identified from schlieren-based analysis of the same intake at TR = 28% (Gurbuz et al., 2025). The small offset between runs is expected, given the non-stationary nature of the flow. Although the main spectral characteristics remain unchanged, previous observations have shown that individual runs may produce slightly different dominant frequencies, reflecting the inherently non-stationary behaviour of the buzz process. Additionally, minor variations in the identified peak frequencies can arise from the numerical parameters used in the Welch spectral estimation. The fast-PSP measurements therefore recover the correct spectral content from a surface-pressure signal, providing independent validation of the dominant oscillation frequencies obtained from schlieren measurements.

Figure 10 presents a time-frequency spectrogram computed from the same signal in the frequency range of 0-3000 Hz. The spectrogram was computed from the same signal using a short-time Fourier transform (Hamming window of 400 samples, 90% overlap; NFFT = 2,048). The choice of window length involves a direct trade-off: a shorter window improves time resolution (here ~ 20 ms per frame) at the cost of frequency resolution (~ 50 Hz), while a longer window would sharpen frequency peaks but obscure temporal variations. The 400-sample window was selected to resolve the modulating buzz dynamics while retaining sufficient frequency discrimination to separate buzz-band content from broadband noise. The colourmap represents spectral magnitude in dB ($20 \cdot \log_{10} |S|$), with warmer colours indicating higher energy.

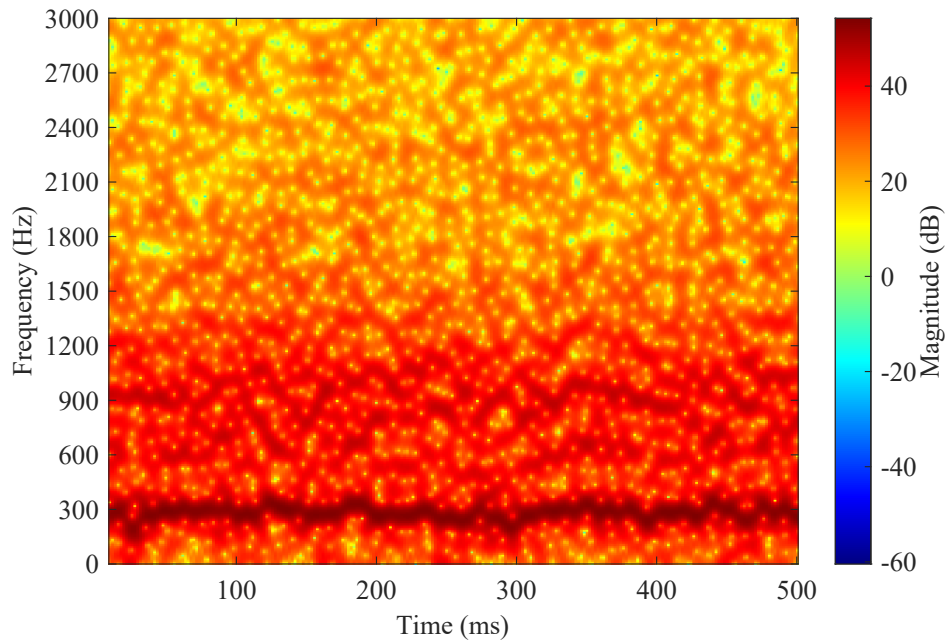


Figure 10. Spectrogram of the spanwise ROI pressure signal at TR=28%.

A persistent energy concentration approximately around the 230–330 Hz band is evident through-

out the acquisition, with visible temporal modulation consistent with the bi-stable oscillation characteristics. Broadband energy above approximately 1500 Hz is attributed to spatial noise in the porous PC-PSP formulation rather than physical flow content. Together, the PSD and spectrogram confirm that the fast-PSP system is capable of resolving both the dominant frequency and its temporal non-stationarity from a surface-based diagnostic.

While the spectral analysis characterises the frequency content of the shock oscillation along the spanwise ROI, it does not reveal how this frequency content is distributed spatially across the ramp surface. Dynamic Mode Decomposition is therefore applied to extract spatially coherent structures from the full pressure-field sequence.

4.7. Dynamic Mode Decomposition of the Fast-PSP Data

Dynamic Mode Decomposition (DMD) is a data-driven method that extracts spatially coherent structures — called modes — from a time-resolved dataset, each associated with a single oscillation frequency. A DMD mode represents a spatial pressure pattern that oscillates at its associated frequency; the collection of modes provides a decomposition of the unsteady pressure field into its dominant coherent components.

The calibrated pressure fields were mean-subtracted — that is, the time-averaged pressure at each pixel was removed so that DMD operates on pressure fluctuations only — and arranged into two time-shifted snapshot matrices separated by one sampling interval ($\Delta t = 50\mu s$). An economy Singular Value Decomposition (SVD) was performed on the first matrix, and the resulting reduced-order system was eigendecomposed to obtain the DMD eigenvalues, mode shapes, and modal amplitudes. Modes with frequencies outside the physically relevant range of 50–10,000 Hz were discarded. The remaining modes were ranked by their modal amplitude $|b_k|$, which quantifies the contribution of each mode to the fluctuating pressure field, and the three highest-ranked modes are presented. It should be noted that DMD applied to PSP data is sensitive to the manual ROI corner selection: small changes of order 1–2 pixels in corner placement can alter the ranking of individual modes. However, provided the eigenvalues remain distributed closely on the unit circle — as observed here — the decomposition is considered numerically stable and the dominant spatial structures are physically meaningful.

Figure 11 shows the DMD eigenvalue spectrum on the complex plane. Each point represents one mode; its angular position encodes oscillation frequency and its radial distance from the unit circle encodes stability — modes on the circle are neutrally stable, modes inside decay. The colour-bar indicates relative modal amplitude $|b_k|$; warmer colours identify modes that contribute most strongly to the pressure fluctuation field. The majority of eigenvalues lie closely on the unit circle, consistent with the sustained nature of the intake buzz, with a small number falling slightly inside, reflecting the non-stationary character of the flow over the finite record.

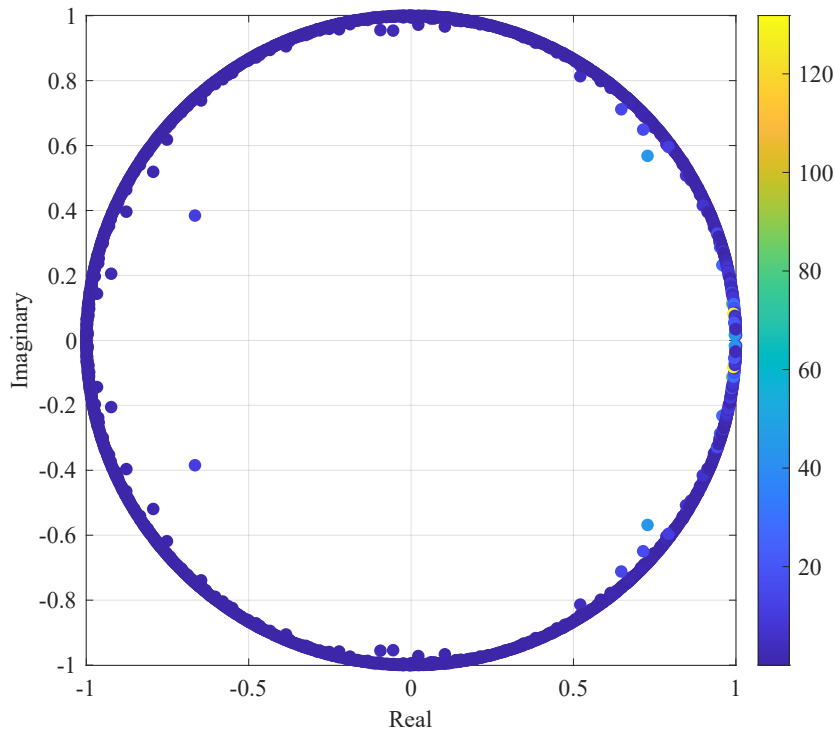


Figure 11. DMD eigenvalue spectrum of the fast-PSP pressure field. modes with warmer colours carry a greater dynamic contribution to the measured pressure field.

Figure 12 presents the real part of the three dominant DMD mode shapes on the rectified ramp plane. The colourmap represents the relative spatial amplitude of the pressure oscillation — warm colours indicate regions oscillating with high amplitude in one phase, cool colours the opposing phase; the scale is relative and does not correspond to absolute pressure. The frequencies of the three selected modes (294.5, 251.6, and 474.0 Hz) fall within or adjacent to the dominant spectral band identified by the PSD (278–297 Hz), confirming that DMD captures the same physical oscillation from a spatial perspective. All three modes display noticeable spanwise asymmetry, providing direct spatial evidence of three-dimensional shock behaviour that is inaccessible to line-of-sight schlieren imaging.

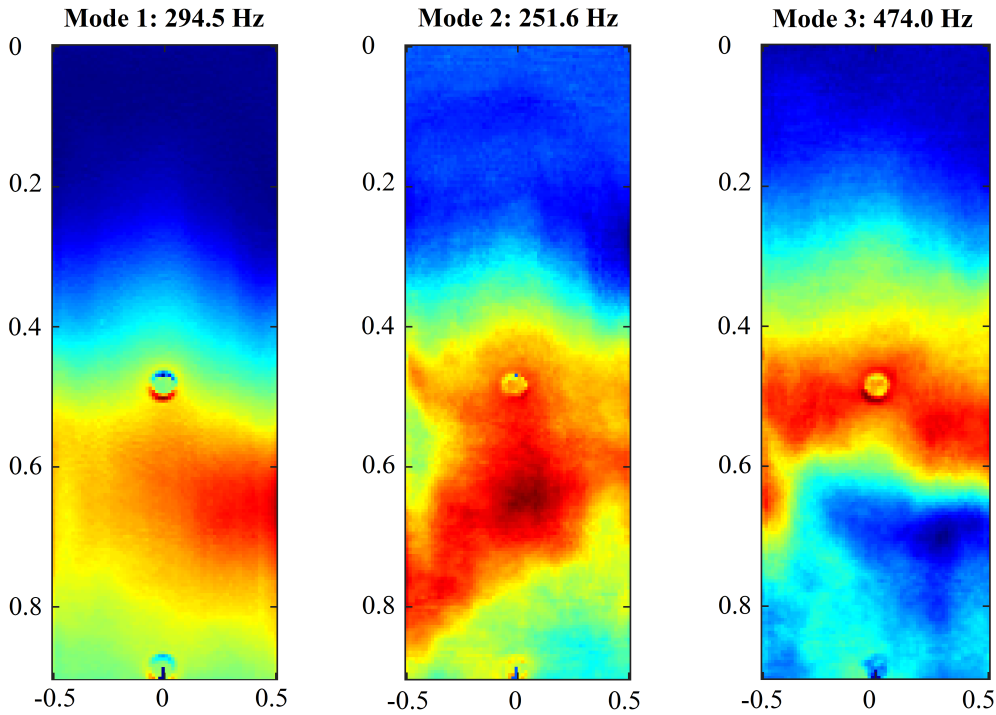


Figure 12. Dominant DMD mode shapes extracted from the fast-PSP pressure field. Warm colours (red/yellow) indicate positive pressure perturbation and cool colours (blue) indicate negative perturbation.

4.8. Pixelwise FFT of Fast-PSP Data

While DMD provides a global modal decomposition of the pressure field, the interpretation of individual mode shapes can be challenging when the flow exhibits non-stationary behaviour with multiple competing frequencies, as observed here. As a complementary and more directly interpretable approach, a pixelwise FFT analysis was performed. Rather than seeking global spatial modes, this method treats each pixel independently as a local pressure sensor: the time-mean is removed at each pixel, and Welch's method is applied independently to obtain a local power spectral density. This allows the dominant oscillation frequencies to be mapped spatially across the full ramp surface without any modal assumptions, and is directly analogous to the 1D ROI PSD presented in Section 4.6 — extended to every pixel simultaneously.

As an intermediate step, the individual pixel spectra were spatially averaged over all ROI pixels to produce the mean PSD shown in Figure 13. The y-axis is expressed in decibels $10 \log_{10} P$, where P is the mean spectral power density in kPa^2/Hz ; the dB scale compresses the wide dynamic range of the spectrum and makes it easier to identify physically meaningful peaks against the noise floor. The mean PSD confirms dominant spectral energy within the 130–700 Hz band, consistent with the 278–297 Hz peaks identified from the spanwise ROI PSD. The agreement between these two independent spectral estimates — one from a manually placed 1D line, the other from a spatial average

of all 9,006 ramp pixels — confirms that the dominant oscillatory behaviour is representative of the entire ramp surface.

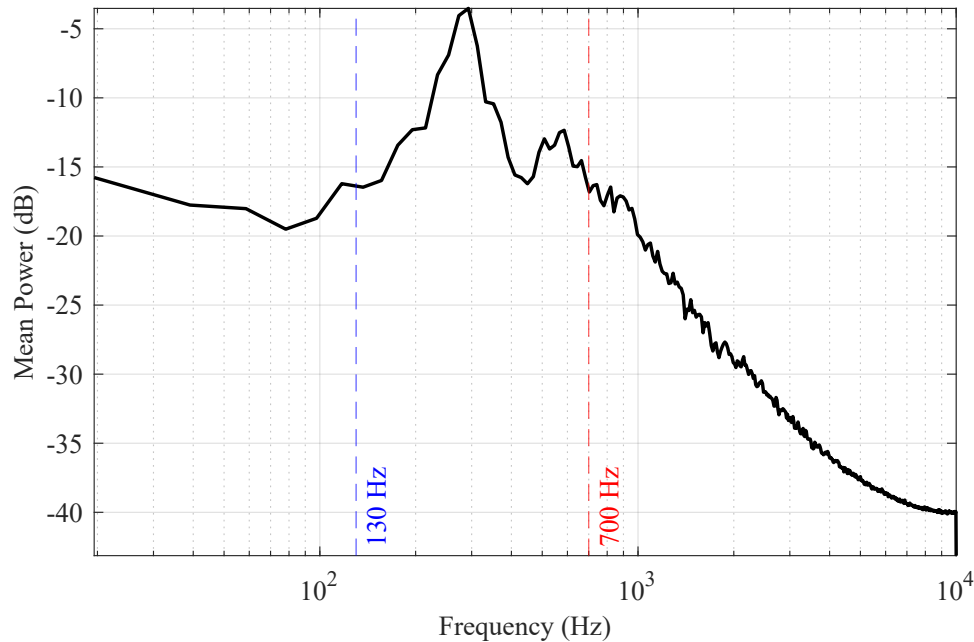


Figure 13. Spatially averaged pixelwise power spectral density over the ramp surface.

Figure 14 presents the dominant frequency at each pixel within two selected bands: 130–330 Hz and 330–700 Hz. At each pixel, the frequency bin carrying the maximum PSD within the band is identified and plotted, indicating which frequency locally dominates the pressure fluctuation.

In the 130–330 Hz band, the dominant frequency is distributed broadly and relatively uniformly across the ramp surface, with values concentrated near 250–300 Hz. This broad spatial coverage indicates that the primary buzz oscillation drives pressure fluctuations across the full ramp extent rather than being localised to a particular region. DMD Modes 1 and 2 (294.5 and 251.6 Hz) are associated with frequencies that fall within this same band, and their mode shapes reflect activity distributed across large portions of the ramp — the two approaches are therefore consistent in indicating that the low-frequency buzz content is not confined to a single spatial region but is a ramp-wide phenomenon.

In the 330–700 Hz band, the high dominant frequencies (~ 500 –600 Hz) are concentrated in the upstream portion of the ramp, with an asymmetric curved boundary separating the two frequency-dominant regions. DMD Mode 3 at 474.0 Hz, which shows a concentrated warm-coloured structure in the upper-to-mid ramp with a similar curved, off-centre shape, is associated with a frequency in this same band — the spatial location of its high-amplitude region broadly corresponds to where the pixelwise FFT map identifies elevated higher-frequency content. While a one-to-one correspondence between a single DMD mode and a pixelwise frequency map is not expected, given the different mathematical foundations of the two methods, the spatial consistency between

them provides a degree of mutual support for both results.

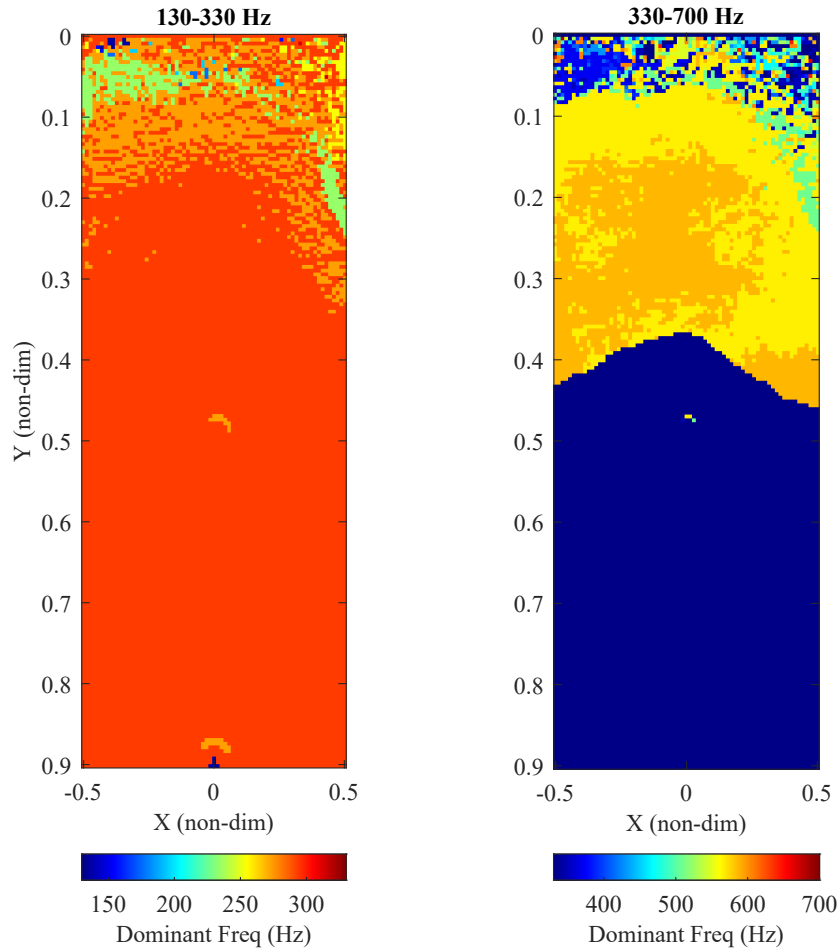


Figure 14. Pixelwise dominant-frequency maps for the selected frequency bands.

The dominant-frequency maps reveal spatially organised frequency distributions that vary across the ramp surface and exhibit clear spanwise asymmetry. These features are consistent with the three-dimensional shock footprint observed in the synchronised PSP-schlieren measurements and with the asymmetry identified in the DMD mode shapes. The pixelwise FFT therefore provides independent confirmation that the shock oscillation is organised in a three-dimensional manner rather than behaving as a purely two-dimensional flow structure.

The ability to simultaneously recover both the dominant frequencies and their spatial distribution across the ramp surface highlights a key advantage of fast-PSP over line-of-sight diagnostics such as schlieren. A detailed physical interpretation of the observed three-dimensional frequency distributions, including their relationship to the shock–boundary layer interaction, will be addressed in a forthcoming journal study that extends the present dataset to the full acquisition record and additional throttling conditions.

5. Conclusion

Fast pressure-sensitive paint measurements were successfully applied to a Mach 5 planar intake operating at the onset of buzz ($TR = 28\%$) to investigate non-stationary shock oscillations. The fast-PSP system, employing a porous PtTFPP polymer–ceramic formulation at 20 kHz with synchronised schlieren support, demonstrated the following capabilities:

Instantaneous surface pressure maps revealed a spatially distributed, asymmetric shock footprint on the ramp, confirming that the shock–surface interaction is inherently three-dimensional despite the nominally two-dimensional intake geometry — a result inaccessible to schlieren imaging. Overlapping streamwise pressure traces captured the frame-by-frame upstream propagation of the shock footprint, and the spanwise ROI time-trace reproduced the bi-stable oscillation character previously identified by schlieren ((Gurbuz et al., 2025)).

PSD analysis using Welch’s method identified dominant peaks at 278 Hz and 297 Hz, in close agreement with the 290 Hz schlieren result, accounting for the known run-to-run variability of this non-stationary flow. The time–frequency spectrogram confirmed the temporal modulation of the oscillation energy within the 230–330 Hz band, consistent with the bi-stable character of the flow at this throttling condition.

DMD extracted spatially coherent oscillatory modes from the mean-subtracted fast-PSP sequence, with eigenvalues distributed very close to the unit circle, confirming near-neutrally stable buzz dynamics. The dominant modes at 294.5, 251.6 and 474.0 Hz — falling within or adjacent to the spectral band identified by the PSD — exhibit spanwise asymmetry in their spatial structures, providing direct evidence of three-dimensional pressure organisation that is inaccessible to line-of-sight diagnostics.

Pixelwise FFT maps independently indicated a spatially organised frequency distribution across the ramp surface: the primary buzz band (130–330 Hz) drives broad ramp-wide fluctuations, while higher-frequency content (330–700 Hz) is concentrated in the upstream ramp region. The spatial boundaries between these frequency-dominant regions are broadly consistent with the structures identified in the DMD modes at corresponding frequencies, lending mutual support to both sets of results from two independent analysis methods.

In summary, these results establish fast-PSP as an effective diagnostic for resolving both the spatial and temporal complexity of non-stationary shock oscillations in high-speed intake flows. Ongoing work will extend the analysis to a full flow-physics investigation, including quantitative characterisation of the three-dimensional shock–boundary layer interaction and its relation to the observed spectral content.

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Nomenclature

Symbols

A_{exit}	Cross-sectional area of isolator exit [m ²]
$A_{th,plate}$	Blocked area by orifice plate at isolator exit [m ²]
f	Frequency [Hz]
f_s	Sampling Frequency [Hz]
N	Number of data samples [counts]
I	Wind-on PSP emission intensity [counts]
I_{ref}	Wind-off reference PSP emission intensity [counts]
P_{ref}	Reference pressure (wind-off) [kPa]
P	Static pressure [kPa]
P_∞	Freestream static pressure [kPa]
R^2	Coefficient of determination [-]
x/L	Non-dimensional streamwise coordinate [-]
Δ_t	Sampling Interval [μs]
b_k	Initial amplitude of DMD mode k [kPa]

Abbreviations

PSP	Pressure-Sensitive Paint
PC-PSP	Polymer-Ceramic Pressure-Sensitive Paint
HSST	High SuperSonic Tunnel
TR	Throttling Ratio
ROI	Region of Interest
PSD	Power Spectral Density
SVD	Singular Value Decomposition
FFT	Fast Fourier Transform

NFFT Number of Fast Fourier Transform Points
DMD Dynamic Mode Decomposition

References

- Berto, F., Benini, E., Wyatt, C., & Quinn, M. K. (2020). Time-accurate experimental investigation of hypersonic inlet buzz at mach 5. *AIAA Journal*, 58(5), 2197–2205.
- Chang, J., Wang, L., Bao, W., Qin, J., Niu, J., & Xue, W. (2012). Novel oscillatory patterns of hypersonic inlet buzz. *Journal of Propulsion and Power*, 28(6), 1214–1221.
- Eagle, W., Driscoll, J., & Benek, J. (2011). Experimental investigation of corner flows in rectangular supersonic inlets with 3d shock-boundary layer effects. In *49th aiaa aerospace sciences meeting including the new horizons forum and aerospace exposition* (p. 857).
- Gregory, J. W., Sakaue, H., Liu, T., & Sullivan, J. P. (2014). Fast pressure-sensitive paint for flow and acoustic diagnostics. *Annual Review of Fluid Mechanics*, 46(1), 303–330.
- Gurbuz, M. T., Quinn, M., & Smith, K. (2025). Characterizing unique bi-stability pattern in mach 5 inlet buzz phenomena. In *59th 3af international conference on applied aerodynamics* <https://www.3af-aerodynamics.com/>.
- Liu, T., & Sullivan, J. P. (2005). *Pressure and temperature sensitive paints*. Springer.
- Matsuda, Y., Katayama, S., Ikami, T., Egami, Y., & Nagai, H. (2022). Structured light illumination for pressure-sensitive paint measurement under ambient light. *Review of Scientific Instruments*, 93(5).
- Peng, D., & Liu, Y. (2020). Fast pressure-sensitive paint for understanding complex flows: from regular to harsh environments. *Experiments in Fluids*, 61(1), 8.
- Sabnis, K., & Babinsky, H. (2023). A review of three-dimensional shock wave–boundary-layer interactions. *Progress in Aerospace Sciences*, 143, 100953.
- Wagner, J. L., Yuceil, K., Valdivia, A., Clemens, N., & Dolling, D. (2009). Experimental investigation of unstart in an inlet/isolator model in mach 5 flow. *AIAA journal*, 47(6), 1528–1542.