

CHARACTERIZING UNIQUE BI-STABILITY PATTERN IN MACH 5 INLET BUZZ PHENOMENA

M.Tayyip Gurbuz^(*) Mark K. Quinn⁽²⁾ and Katharine L. Smith⁽³⁾

⁽¹⁾PhD candidate, School of Engineering, The University of Manchester, UK

⁽²⁾Senior Lecturer, School of Engineering, The University of Manchester, UK

⁽³⁾Reader, School of Engineering, The University of Manchester, UK

*muhammettayyip.gurbuz@manchester.ac.uk

ABSTRACT

Inlet buzz is an unsteady flow instability in high-speed intakes, affecting stability and engine performance. This study investigates buzz development in a 2D planar intake with a 10° ramp in Mach 5 flow, where exit blockage increases using fixed orifice plates. Schlieren imaging at 66 kHz is used to investigate the flow dynamics. At 28% blockage, big buzz appears with a dominant frequency of 290 Hz, modulating between 245–330 Hz over time. It is accompanied by precursor little buzz oscillations, creating a bi-stable flow pattern. As blockage increases, the oscillation shifts to a more stable big buzz mode, with frequencies rising to 491 Hz at 40% and 543 Hz at 50%. The amplitude of these oscillations initially grows, then stabilizes. Shock-boundary layer interaction and upstream shock motion drive these changes, shifting the separation bubble and forming an effective throat. The findings reveal a previously unreported bi-stability, where flow alternates between large-scale big buzz oscillations and intermittent little buzz-like structures, providing new insight into how blockage affects inlet stability.

1. INTRODUCTION

Buzz in supersonic intakes is generally categorized into two main types: "little buzz" and "big buzz" [1]. Little buzz, known as the Ferri Criterion [2], occurs in the supercritical regime and is characterized by high-frequency, low-amplitude oscillations driven by the instability of shear layers near the cowl lip. Big buzz, known as the Dailey Criterion [3], which is the precursor of inlet unstart, creates low-frequency, high-amplitude oscillations, resulting in total separation due to the interaction of the expelled normal shock with the oblique ramp shock in subcritical conditions. Certain studies identi-

fied unconventional types of buzz mechanisms, such as "added buzz" [4, 5], and "medium buzz" [6], though these phenomena are limited to low supersonic regimes (Mach 1.8–2.5).

Chang et al. [7] suggested a different flow pattern for hypersonic inlets (Mach 4.5–6.0), identifying a mixed oscillatory pattern (alternating strong and weak cycles) and a non-oscillatory violent pattern (nearly stationary shock system with slight fluctuations). These findings highlight the complexity of hypersonic inlet dynamics but focus on sequential, non-overlapping oscillatory modes. In contrast, this study reveals a unique bi-stability flow regime in a Mach 5 inlet, where little buzz oscillations act as precursors to big buzz oscillations within each cycle. Unlike Chang et al.'s mixed pattern, where strong and weak oscillations alternate one after the other, the oscillations in this study exhibit characteristics of both little and big buzz. Earlier studies [4, 5, 6, 7] have used relatively low data capture rates (up to 4 kHz); this work applies high-speed imaging at 66 kHz, a crucial advancement that enables the observation of previously unreported oscillatory dynamics in the flow.

2. EXPERIMENTAL SETUP

2.1 HSST Wind Tunnel

Experimental tests were carried out in the High Supersonic Tunnel (HSST) at the University of Manchester (see Fig. 1). Air, stored at 1700 kPa in the receiver tank, flows through a high-throughput dome valve to regulate total pressure. A heater allows the adjustment of the Reynolds number and prevents condensation during nozzle expansion to Mach 5. The test conditions included a plenum total temperature of 350 K, a freestream total pressure of 820 kPa, and a Mach num-

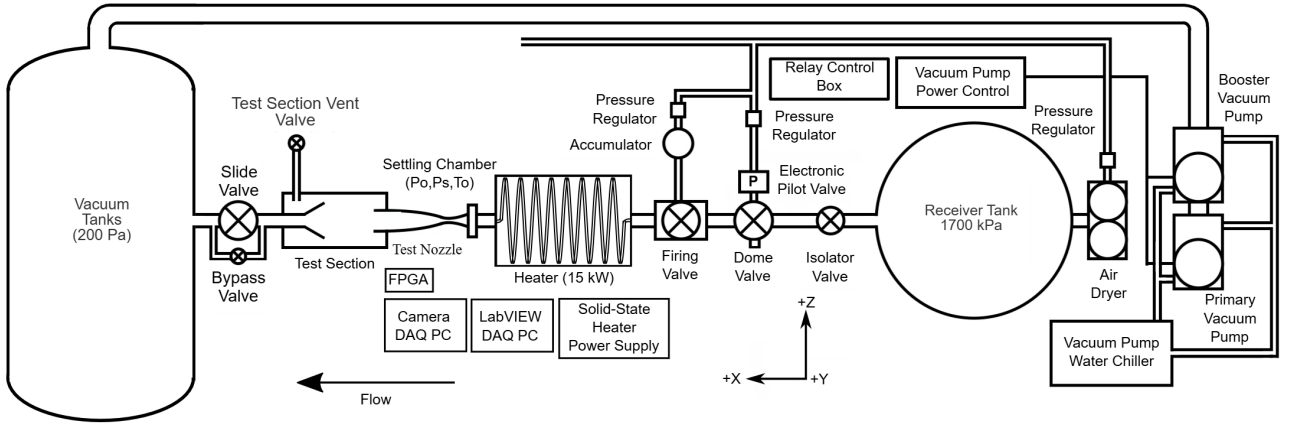


Figure 1: University of Manchester HSST [8]

ber of 5.0. The Reynolds number per unit length was $1.48 \times 10^7 m^{-1}$ by calculating the viscosity with Sutherland's two-coefficient law. Optical access for visual flow diagnostic methods was provided by two parallel rectangular quartz windows (300 mm by 210 mm) mounted in the access doors.

The designed intake model comprises a two-dimensional planar inlet featuring a single compression ramp surface, mounted on a two-legged floor mount system with a fixed orifice plate as a back-pressure mechanism, as illustrated in Fig. 2.

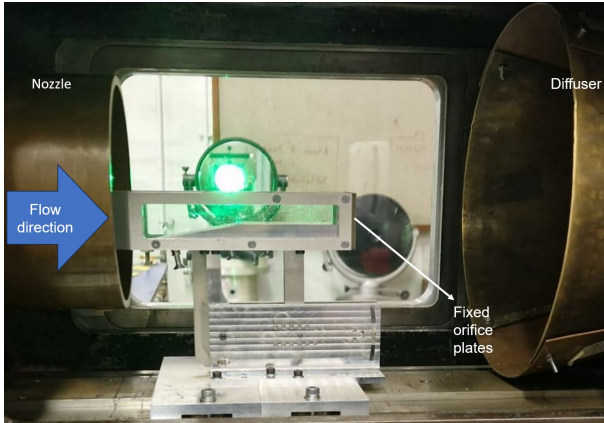


Figure 2: Mach 5 intake model in the HSST Test Section

2.2 Test Geometry

As the main objective of this study is to investigate inlet unstart rather than optimizing the inlet design, a simplistic design approach was employed, obtaining main dimensions through inviscid flow calculations and neglecting the boundary layer or related viscous effects. The test model geometry is given in Fig. 3. As seen, a single ramp has 10° inclination regarding the freestream direc-

tion. The isolator cross-section is 34 mm wide, 14 mm high, and it is 78 mm long.

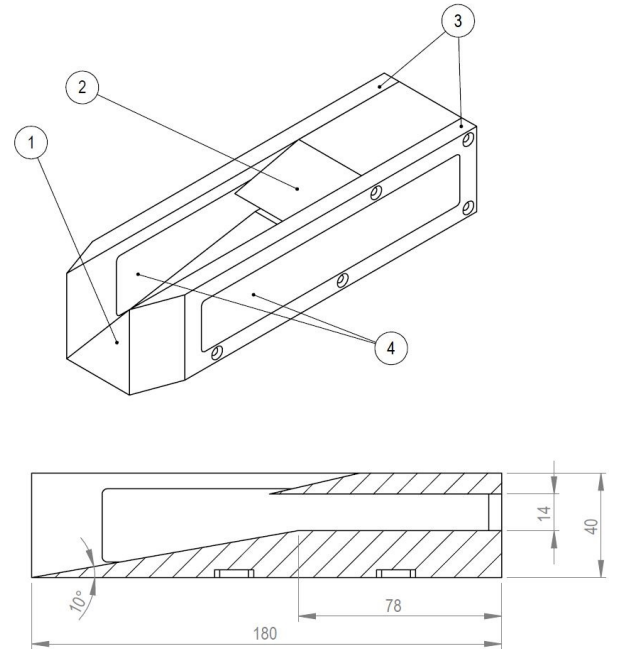


Figure 3: Fully assembled intake model: a) isometric view; the represented numbers are ramp (1) and cowl (2), sidewall metal frames (3) and sidewall acrylic windows (4) for optical access, b) lateral side section view. All dimensions in mm.

Fixed orifice plates were employed to regulate the throttling ratio, serving as a back-pressure increase mechanism. By changing these plates, the isolator exit height was adjusted between 0 mm and 7 mm, allowing for a range of test conditions. As mentioned previously, the isolator open exit is 14 mm in height without any additional blockage. The corresponding throttling ratios vary between 0 to 50%. The throttling ratio (TR) is identified

as

$$TR = (A_{th,plate}/A_{exit}) \times 100\% \quad (1)$$

where $A_{th,plate}$ is the blocked area by the orifice plate at the isolator exit, and A_{exit} is the cross-sectional area of the isolator exit.

For a self-started intake design, the theoretical Kantrowitz limit was adopted [9]. The limitation of the Kantrowitz line for the current intake design corresponds to $TR=0.25$. By increasing the throttling ratio further, the inlet can be easily unstalled.

2.3 Schlieren

The flow was imaged using a standard Z-type schlieren system (Fig. 4) comprising two 12" parabolic f/7.9 mirrors that provide an extensive and clear view of the whole test section. The light source used was Luminus Devices, CBT-90 Green. A static chip-on-board LED having a 9 mm^2 chip area provided the necessary amount of illumination for the ultra-high-speed camera (Phantom V1610) to capture the unsteady shock oscillations during inlet buzz. The sensor was cropped to 640×160 pixels to capture only the necessary information and the corresponding spatial resolution is 4.16 pixels/mm . With the reduced active sensor area, the flow was imaged at 66 kHz , enabling observation of the detailed buzz flow characteristics. The data was stored in the camera buffer before downloading to an external SSD. Prior studies on inlet buzz did not observe oscillations beyond 1 kHz and the current study observed oscillations up to around 523 Hz .

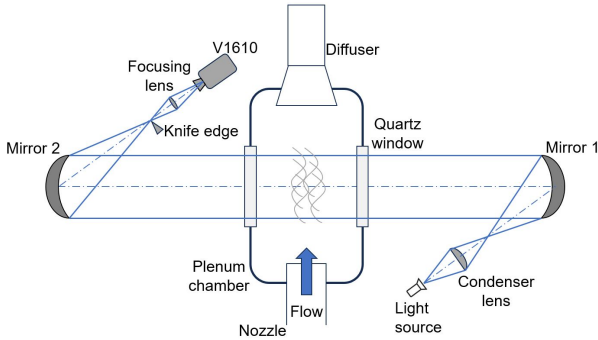


Figure 4: Top-down view of the schlieren system around the test section

Using the time-resolved schlieren images, the position, and therefore oscillatory motion of the shock, can be analyzed via suitable post-processing. The post-processing algorithm is presented in Fig. 5.

As illustrated in Fig. 5, the raw schlieren images were first normalized to a wind-off image to filter the visual noise. A one-dimensional line (yellow line in Fig. 6) along the isolator centerline was selected as the region of interest to track the separation-induced shock position

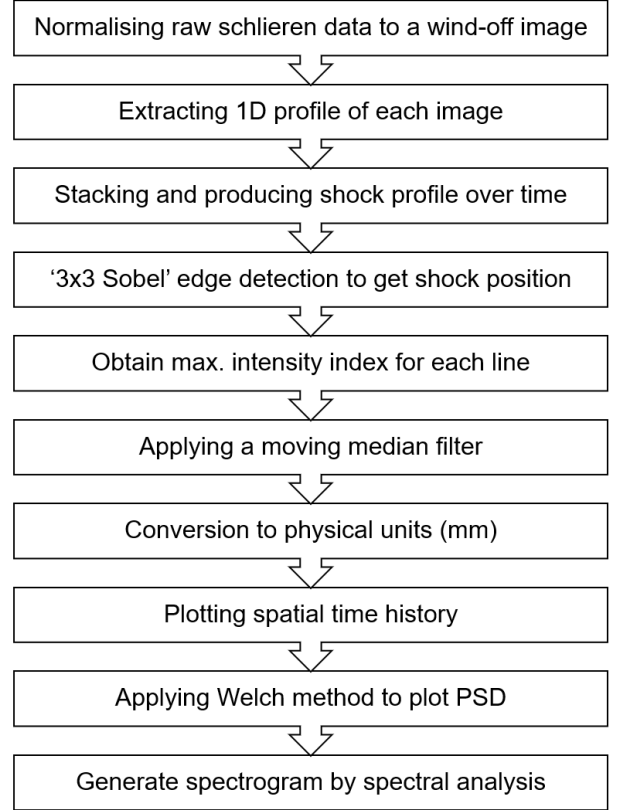


Figure 5: Image processing flow chart

denoted as A. The extracted shock position from each image was then compiled over time (one pixel per frame) to construct a time-history representation of shock motion. Fig. 6 demonstrates the initial image processing steps to obtain the shock position profile.

In Figure 6b and 6c, the oscillatory patterns belong to cases with $TR=28\%$ and $TR=40\%$, respectively. The straight horizontal thick line in both cases represents the fixed position of the ramp shock. During the buzz cycle, when flow spillage occurs, the separation-induced shock moves upstream, disrupting the ramp shock and causing the thick line to disappear from the stacked images (see 6b and 6c).

The extracted shock position profile was imported into MATLAB (R2022a) for further analysis. A two-dimensional Sobel edge detection filter was applied to detect profile edges, allowing precise identification of the shock position. The maximum intensity index for each line was then determined, followed by the application of a moving median filter to smooth the detected peak locations and mitigate potential noise artifacts. Since the extracted shock position was initially represented in pixel units, a conversion to physical units (millimeters) was performed to obtain the actual displacement amplitude. The resulting shock displacement-time history profile was analyzed using Welch's method to compute the

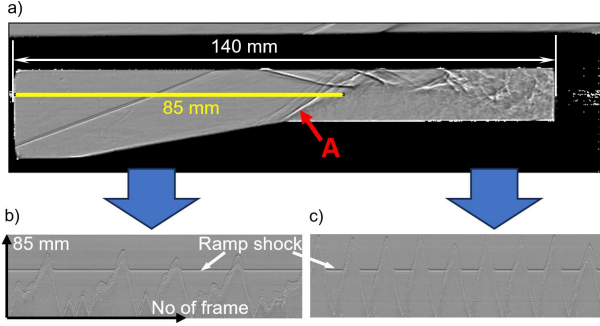


Figure 6: Initial image processing steps, a) The line of interest, b) buzz oscillation map at TR=28% with stacked images, c) buzz oscillation map at TR=40% with stacked images

Power Spectral Density (PSD) components, which provides insight into the dominant frequency of the oscillatory motion. Finally, a spectral analysis was conducted, integrating both time- and frequency-domain representations, concluding in the generation of a spectrogram that visually captures the temporal evolution of the shock oscillation characteristics.

3. RESULTS AND DISCUSSION

As a baseline, the TR = 0% case was evaluated, corresponding to a fully open isolator channel exit. The time-averaged and normalized schlieren image at fully opened condition is presented in Fig. 7. Since the cowl tip is not visible in the schlieren images, its approximate boundaries were outlined in a light yellow colour relative to the incoming flow. The cowl tip is flush with the outer edge of the observation window.

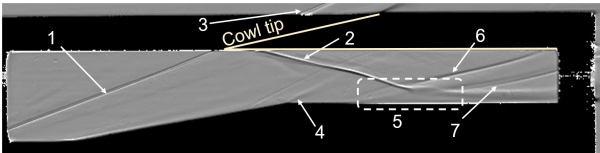


Figure 7: Flow pattern of the intake with the duct exit fully opened (TR = 0 %), Represented numbers are: 1) Ramp shock, 2) Reflected shock, 3) Cowl tip shock 4) Shoulder expansion 5) SBLI, 6) Separation-induced shock, 7) Reattachment shock

As shown in Fig. 7, the ramp shock impinges on the cowl tip, indicating the expected critical (design) condition based on theoretical inviscid flow predictions. It is important to note that the intake configuration employed in these tests follows an aggressive design, preventing operation in a supercritical regime. As discussed previously (Section 1), a supercritical condition would lead to the ingestion of ramp shock in the intake flow field.

The ramp shock (1) reflects off the cowl and creates a reflected shock formation (2). The shoulder expansion waves (4) interact with this reflected shock, slightly curving it. The impinged reflected shock then creates an adverse pressure gradient over the local boundary layer causing a local flow separation due to Shock-Boundary Layer Interaction (SBLI) (5) (see the dashed square zone). Because the high-pressure region behind the shock propagates upstream through the subsonic portion of the boundary layer, the separation point shifts upstream of the theoretical inviscid impingement location of the incident shock. The separated boundary layer results in a separation-induced shock (6) followed by downstream reattachment, generating a reattachment shock (7). This broad shock structure remains almost constant until the initiation of a buzz at TR of 28%.

With the flow structure of the fully open case established, the analysis now shifts to the TR=28% condition, where the onset of buzz was observed. Unlike the fully open case, in which the internal shock system remains stable, the introduction of partial blockage alters the nature of the oscillations, leading to a transitional flow regime. To investigate the effect of reduced blockage on shock dynamics, the oscillatory pattern for TR=28% was extracted from the schlieren images. The physical profile of the shock position, along with a magnified time segment highlighting key oscillatory features, is presented in Fig. 8.

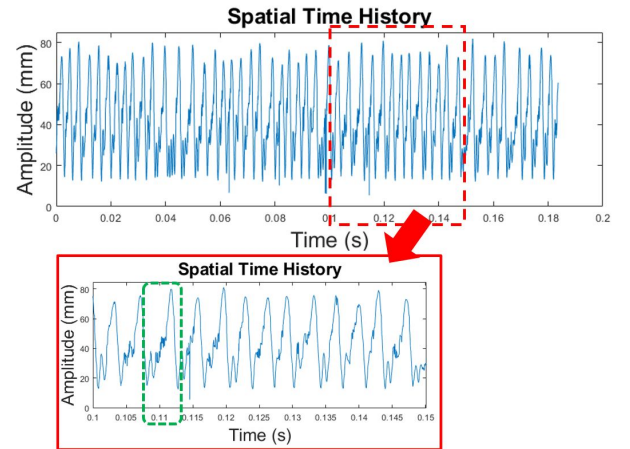


Figure 8: Spatial time history of the extracted shock profile position at TR=28%

In Fig. 8, the x-axis represents time in seconds, while the y-axis represents shock position in millimeters. The TR=28% case exhibits a transitional oscillatory pattern, characterized by alternating low- and high-amplitude shock movements. A magnified portion of the time history reveals how the shock motion evolves as the intake approaches buzz onset, highlighting the shift between low- and high-amplitude oscillations.

When the orifice plate with TR=28% is applied, the

flow cannot be steadily ingested due to the mismatch in mass flow between the inlet and exit sections. The resulting flow pattern indicates a transitional oscillatory pattern, marking the onset of buzz. While the oscillation pattern varies over time, it maintains repeating features across different cycles, as illustrated in Fig. 8. Most cycles consist of a few precursor low-amplitude oscillations before resulting in a high-amplitude big buzz process. In the selected representative cycle (highlighted by a green dashed square), two lower-amplitude oscillations (one full and one partial) precede the initiation of a dominant high-amplitude oscillation. Following each high-amplitude buzz peak, the mass flow is re-ingested into the intake as back pressure decreases, repeating the process.

To gain a deeper understanding of the underlying flow behavior, the selected cycle in Fig. 8 was analyzed in detail, and its complete expulsion and ingestion process is illustrated through the schlieren montage in Fig. 9.

As can be seen in Fig. 9, the separation-induced shock (Arrow A) struggles to resist the back-pressure changes due to its unsteady nature. At $t=0$ ms compared to the cases with lower TRs, there is an effective throat (dashed circle) in the isolator due to a large separation zone. The increased back pressure then pushes the internal shock structure upstream.

At $t=0.45$ ms, the shock structure at $t=0$ ms approaches the cowl tip (Arrow B). At this time, the back-pressure gradient at the last quarter of the duct creates a single λ shock (denoted as C), causing separation and downstream shear layer creation. (zone with red dashed square).

Once there is an internal pressure relief after $t=0.45$ ms, the incoming flow and the shock structure indicated with Arrow B at $t=0.45$ ms are ingested inside the duct (Arrow B') showing the flow pattern at $t=1.05$ ms. A shock train is formed in the upper part of the duct (indicated by D) with an effective throat area due to a large separation zone downstream of the ramp shoulder.

At $t=1.50$ ms, a normal shock train (Arrows E) [10] appears downstream of the duct and persists intermittently in different formations until around 2.48 ms, preceding the onset of the big buzz oscillation. During this period, low-amplitude, high-frequency oscillations momentarily cause a Mach reflection (Arrow F) to intermittently interact with the cowl tip normal shock (Mach stem), leading to localized pressure increases. As the oscillation progresses, the normal shock train labeled as G (characterized by a series of lambda shock patterns) occupies most of the isolator duct. Eventually, upstream movement of this unsteady shock system leads to the expulsion of the separation-induced shock from the duct.

At $t=3.15$ ms, the expelled shock (Arrow H) interacts with the ramp shock and forms a stronger separation shock above the ramp surface. At $t=3.62$ ms, a subsonic flow spillage occurs from the inside to the outside flow region at the cowl tip by further expelled separation shock.

At this moment, the internal flow field is fully subsonic.

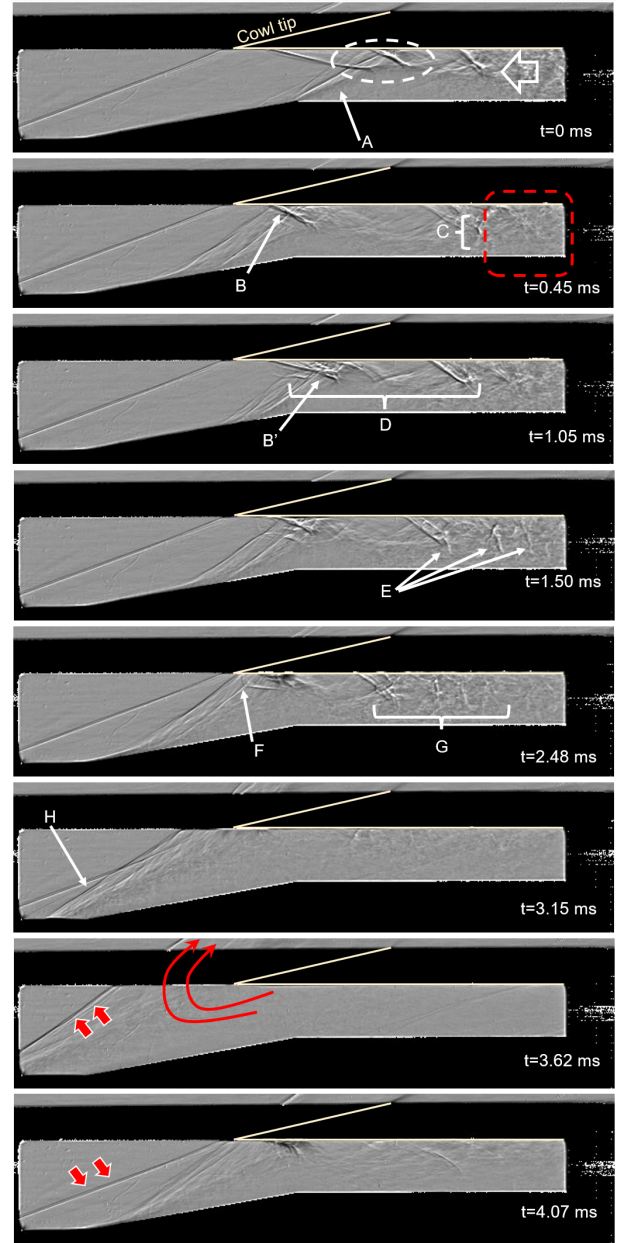


Figure 9: Flow pattern of the intake with the duct partially blocked - (TR = 28%)

Once the internal shock structure has been expelled, the internal pressure is reduced allowing the intake to partially begin restarting. Eventually, the internal supersonic flow again takes place. This whole procedure repeats itself as explained above.

The analysis of the TR=28% case has highlighted the transitional nature of the shock oscillations, where low- and high-amplitude fluctuations precede the onset of a large-scale buzz event. The extracted shock profile and schlieren visualizations revealed how the separation-induced shock struggles to maintain stability under back-

pressure variations, eventually leading to periodic expulsion and re-ingestion cycles.

As the total blockage increased to $TR=40\%$, the oscillatory behavior changed significantly. Unlike the transitional oscillations observed at $TR=28\%$, the $TR=40\%$ case exhibited a well-defined big buzz pattern characterized by high-amplitude, low-frequency oscillations. This distinction is evident in the spatial time history of the extracted shock profile, as shown in Fig. 10.

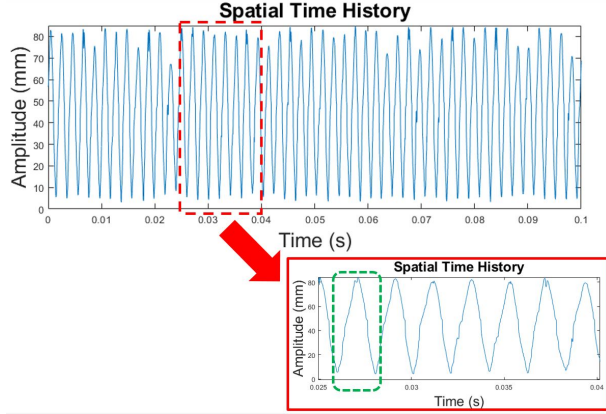


Figure 10: Spatial time history of the extracted shock profile position at $TR=40\%$

As seen in Fig. 10, the x-axis represents the time domain in seconds and the y-axis represents the displacement amplitude in mm units. The shock profile along the temporal domain demonstrates pure big buzz oscillatory characteristics. The specific shorter time period clearly shows this pattern. To further investigate the flow characteristics of this condition with the help of schlieren data, one representative cycle was chosen and indicated within the green dashed square line in the zoomed image.

At $TR=40\%$, the intake experienced high-amplitude, low-frequency oscillations. A single representative cycle from Fig. 10 is demonstrated in detail in Fig. 11 with the help of time-resolved schlieren images.

The characteristics of big buzz oscillations closely resemble a simple sinusoidal pattern, with the increased blockage leading to stronger terminal shock formations, which in some cases are referred to as normal shocks due to their formation in regions of high pressure gradients and their quasi-steady, oblique nature in certain flow conditions. As shown in Figure 11, when $t=0$ ms, a coalesced terminal shock structure (Arrow A) is close to interacting with the upstream flow field. This terminal shock then propagates upstream, interacting with the incoming supersonic flow. By $t=0.2$ ms, it induces a Mach reflection, generating a Mach stem near the cowl lip. Subsequently, the internal flow is expelled due to the detached ramp shock, leading to the formation of a strong separation shock. This separation shock travels upstream, nearly exiting the field of view by $t=0.95$ ms. As the duct internal

pressure decreases again, the ramp shock and the overall shock system are reingested into the intake around $t=1.51$ ms, restoring a flow configuration at $t=2.04$ ms that closely resembles the initial state at $t=0$ ms.

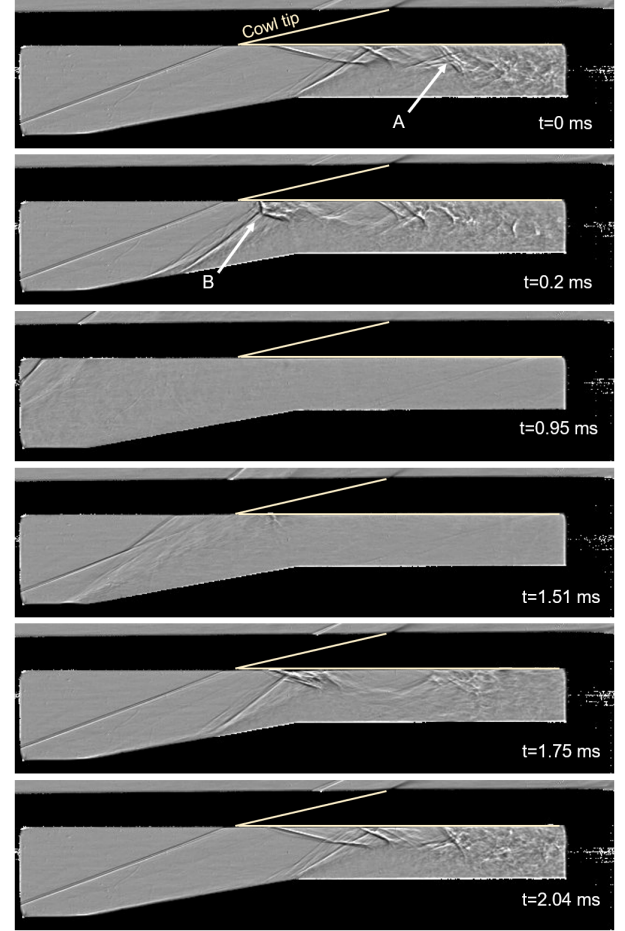


Figure 11: Flow pattern of the intake with the duct partially blocked - ($TR = 40\%$)

While the shock profile time history and schlieren data provided valuable insight into the temporal and spatial evolution of the shock system, they primarily captured the qualitative nature of the oscillations. More importantly, the shock profile presented non-stationary characteristics that cannot be investigated in the temporal domain. However, to gain a more quantitative understanding of the frequency content and dominant oscillatory modes, further spectral analysis is required.

Spectral analysis enables the identification of the dominant frequencies of the shock oscillations and how they evolve across different blockage ratios. This is especially critical in distinguishing between stable and unstable flow regimes, especially in cases exhibiting bi-stability. To provide this, a three-dimensional waterfall plot (see Fig. 12) was introduced, providing an overall examination of spectral analysis by benefiting from PSD diagrams for

not only the cases of TR=28% and TR=40% but also the cases with TR=30% and TR=50%. This visualization allows for a direct comparison of frequency content and amplitude variations across different throttling ratios, revealing the relation between throttling ratio and shock oscillation frequency.

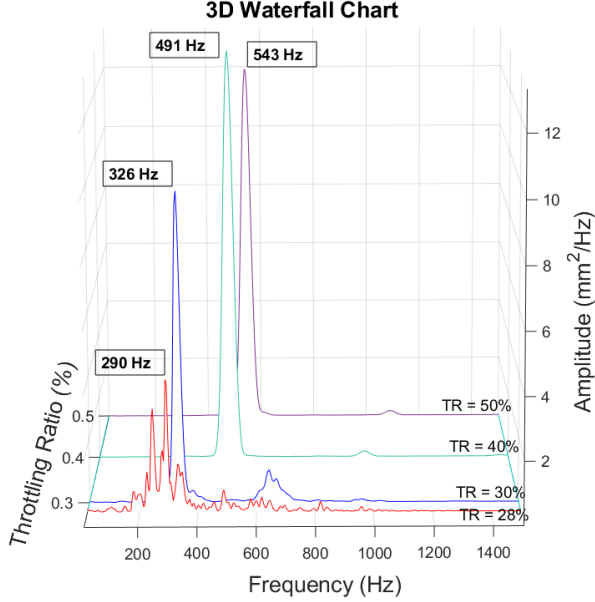


Figure 12: Waterfall plot of the PSD distribution for different blockage ratios (TR = 28%, 30%, 40%, and 50%)

In Fig. 12, the x-axis represents the frequency domain in Hertz, the y-axis represents the frequency amplitude, expressed in units of mm^2/Hz , representing the signal's strength in terms of physical displacement, and can be named the displacement amplitude, and the z-axis represents the blockage ratio in terms of TR.

As shown in Fig. 12, at the buzz initiation point of TR=28%, the flow exhibits bi-stable behavior, with a dominant frequency of 290 Hz (amplitude $4.16 \text{ mm}^2/\text{Hz}$). This flow oscillation is not a pure tone and there are secondary frequencies of lower amplitude close to the main peak. With a slight increase in the throttling ratio, the flow still exhibits bi-stability at TR=30%; however, big buzz oscillations become more dominant. The peak of the dominant frequency shifts to 326 Hz with a significantly higher amplitude of $9.80 \text{ mm}^2/\text{Hz}$, indicating that the shock system is transitioning toward a stronger, more periodic big buzz mode.

As mentioned previously, upon increasing the blockage ratio to TR=40%, the bi-stability disappears, and the flow settles into a stable pure big buzz oscillation (see Fig. 10 at 491 Hz, with an amplitude of $13.32 \text{ mm}^2/\text{Hz}$). The absence of secondary peaks suggests that the shock system has fully shifted into a high-amplitude, single-frequency oscillatory regime. The same characteristic is also present with a further increase in blockage ratio by

50%, resulting in an even higher dominant frequency of 543 Hz, with an amplitude of $11.93 \text{ mm}^2/\text{Hz}$.

Since the waterfall plot provided a broad spectral overview, a more detailed frequency-domain analysis is required to understand the evolving dynamics for cases where TR=28% and TR=40%. The reason for selecting these two cases was their relevance in representing the rest of the flow conditions. TR=28% case represents the region of transitional bi-stability (28%-30%) whilst the TR=40% case represents the pure big buzz oscillations.

As demonstrated in Fig. 12, the PSD diagram of 28% case was detailedly examined. PSD analysis was first used to observe the dominant frequencies present in the oscillatory behavior, offering a clearer picture of the energy distribution across different frequency bands. Following this, a time-frequency spectrogram was utilized to reveal how these frequencies evolve over time, providing a more comprehensive characterization of the unsteady flow dynamics. The analysis will begin with the TR=28% case before extending to the TR=40% case for comparative evaluation.

For the transitional bi-stable shock profile at TR = 28%, PSD diagram was generated by employing Welch's method (see Fig. 13), which is particularly effective for noisy or non-stationary signals due to its segment-averaging approach. A frequency range of 0-1500 Hz was shown to highlight the dominant features of the results.

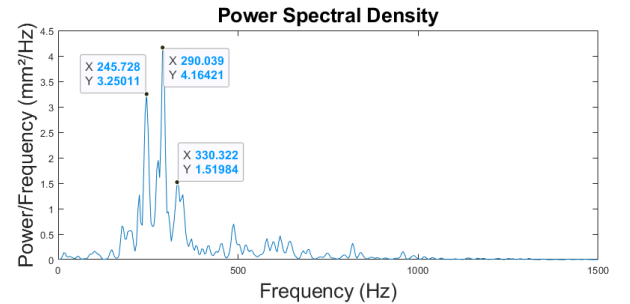


Figure 13: Power Spectral Density of the intake at TR=28%

In Fig. 13, the frequency amplitude is expressed in units of mm^2/Hz , representing the signal's strength in terms of physical displacement, and can be named the displacement amplitude (absolute spectral power). This metric highlights the oscillatory behavior of the shock system. To compute the spectral density, as mentioned, Welch's method was employed, which divides the time-domain signal into overlapping segments, applies a window function to each segment, and then averages the resulting frequency spectra to reduce noise and improve spectral estimation. In Fig. 13, a window size of 8192 samples with more than 95% overlap was used to ensure smooth spectral estimation while reducing noise.

The power spectrum reveals that the dominant fre-

quency component corresponds to the large-amplitude oscillations of the bi-stable pattern, occurring at 290 Hz. Secondary dominant peaks at 245 Hz and 330 Hz are also observed, which may also be associated with the primary buzz cycle.

Given the complex nature of the bi-stable flow pattern and the non-stationary nature of the signals examined, traditional PSD analysis alone may not capture all the essential features of the dynamic behavior of the system. To address this limitation, a time-frequency analysis was employed using a spectrogram. The spectrogram for $TR = 28\%$ is presented in Figure 14, illustrating the frequency region of interest (0–1500 Hz) throughout the time history.

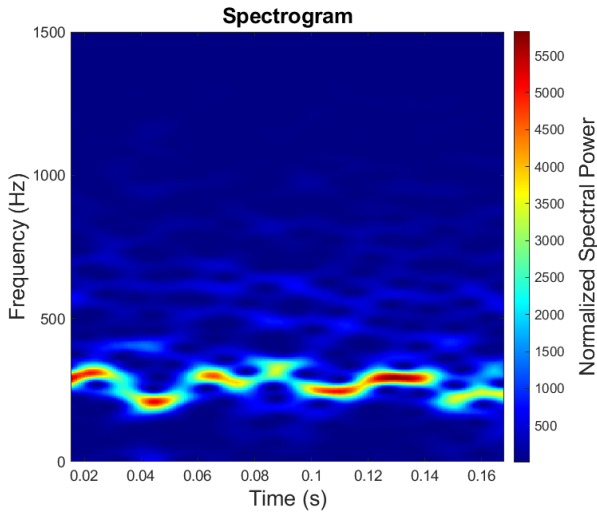


Figure 14: Spectrogram graph at $TR=28\%$

The y-axis represents the frequency domain throughout time history lying in the x-axis with the colormap representing the displacement amplitude in normalized spectral power. Unlike the PSD, which provides absolute spectral power (mm^2/Hz), the spectrogram shows the evolution of power over time in relative terms. The time and frequency resolution of the spectrogram are chosen carefully as 1.94 ms and 4.03 Hz, respectively, taking into account the trade-off between them.

The spectrogram in Fig. 14 reveals the time-varying frequency content of the shock oscillations, with the dominant energy concentrated approximately around the 245–330 Hz range. This band corresponds to the big buzz oscillations, with the 290 Hz peak representing the time-averaged dominant frequency. The modulation within this range reflects the unsteady nature of the shock system as it transitions between the expulsion and re-ingestion phases. Notably, similar studies on Mach 5 intakes have reported dominant big buzz frequencies of 110 Hz [7], 124 Hz [11], and 330 Hz [12], with the latter closely aligning with the upper bound of the observed frequency

range in this study. This variability was already captured in the PSD diagram (Fig. 13), where 290 Hz emerges as the primary mode, with 245 Hz and 330 Hz as secondary dominant frequency peaks. The frequency modulation suggests that the oscillatory behavior is governed by a bi-stable flow regime, where competing pressure gradients drive the shock system between stable and unstable states.

The spectrogram's color map (Fig. 14) further visualizes this unsteady behavior, showing a broad region of high intensity centered around the dominant frequency of 290 Hz. This spread suggests that multiple buzz cycles contribute to the oscillations. The most noticeable energy levels are observed between 0.12–0.14 ms, indicating the peak activity of the big buzz oscillations during this period.

The time history data (Fig. 8) revealed lower-amplitude oscillations, known as little buzz, which act as precursors to big buzz. However, these disturbances were not distinctly visible in the spectrogram or the PSD diagram. Their absence in the frequency domain analysis suggests that they do not contribute significantly to the dominant spectral content but instead reveal in the spatial time history plot, where they appear to initiate the transition toward high-amplitude big buzz cycles. This strengthens the role of little buzz oscillations as precursor disturbances that gradually destabilize the shock system, ultimately leading to the full-scale unstart behavior.

The case with a blockage ratio of 28% showed the complexity of the bistability pattern and its time-dependent characteristics, requiring a detailed spectral analysis to capture their transient nature. On the contrary, when the TR was increased to 40%, the flow exhibited a more stable periodic behavior dominated by pure big buzz oscillations, as observed in the time history analysis (see Fig. 10). Unlike the $TR=28\%$ case, where frequency modulation was obvious, the shock oscillations at $TR=40\%$ followed a regular cycle, suggesting a stationary flow regime.

Since the shock profile at $TR=40\%$ (Fig. 10) exhibited a nearly uniform periodic pattern, one can expect the PSD diagram to be concentrated around a single dominant frequency peak. Instead of relying on the spectral analysis with PSD diagram, a spectrogram was used to verify whether any frequency modulation occurred around the dominant frequency. The result, presented in Fig. 15, confirms the absence of this behaviour.

The spectrogram at $TR=40\%$ was generated using the same time and frequency resolution parameters as in the $TR=28\%$ case to maintain consistency. As demonstrated, the dominant frequency along the temporal domain remains nearly constant over time forming an uninterrupted horizontal colour band around 491 Hz. This stable frequency contrasts completely with the frequency modulation seen in the $TR=28\%$ case and confirms that the shock

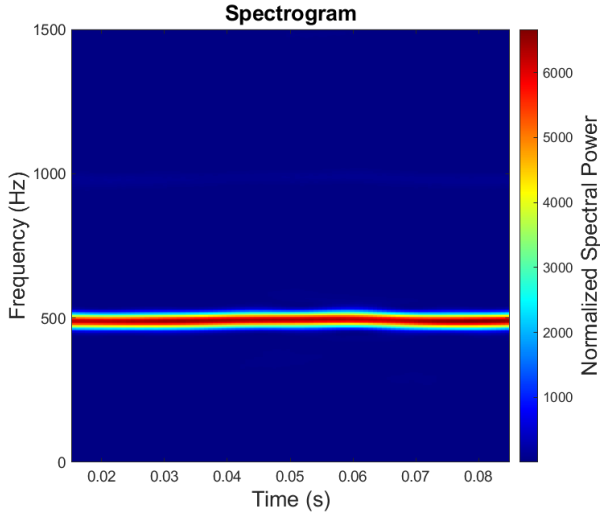


Figure 15: Spectrogram graph at TR=40%

system at TR=40% oscillates in a more periodic manner.

The spectrogram analysis further highlighted the key differences between the TR=28% and TR=40% cases. At TR=28%, the flow demonstrated clear bi-stability, with dominant oscillations fluctuating within the 245–330 Hz range. The presence of frequency modulation and the role of little buzz oscillations as precursors established the unsteady nature of this case, where the shock system continuously shifted between stable and unstable states. In contrast, the TR=40% case presented a more periodic flow, dominated by a single stable frequency at 491 Hz, confirming the absence of such modulation over time. This contrast emphasizes the unique complexity of the TR=28% regime, where the interplay between competing pressure gradients drives the system into a dynamic and unstable state.

4. CONCLUSION

The inlet buzz process was investigated in a floor-mounted intake model in a Mach 5 freestream flow. The model features a two-dimensional planar design with a 10° ramp angle and fixed orifice plates at the duct exit were used to increase back pressure.

Until a certain throttling ratio, the internal flow field remained steady, without presenting any significant unsteadiness. However, as the throttling ratio (TR) increased, the separated flow region thickened, affecting the internal shock system. Around TR = 28%, boundary layer separation caused a flow blockage, leading to unsteady shock expulsion from the intake capture area. The resulting flow characteristics exhibited a bi-stable flow pattern, in which low-amplitude precursor oscillations (little buzz-like structures) preceded high-amplitude big buzz oscillations. The dominant big buzz frequency

was 290 Hz; however, this was not stationary, fluctuating between 245–330 Hz due to possible hysteresis effects from changes in the effective throat area and back-pressure conditions.

Despite the absence of a shear layer (supercritical condition), certain blockage ratios that initiate big buzz still exhibited relatively high-frequency, low-amplitude oscillations within each cycle inside the isolator. These flow structures shares similarities with the Ferri criterion, where shock-boundary layer interactions sustain oscillations even in the presence of a dominant big buzz. The interplay between big buzz and these persistent small-amplitude oscillations define a bi-stability pattern, where the system transitions between large-scale oscillations and intermittent small-scale disturbances. The flow in this transitional regime does not exhibit stationary periodicity, with the dominant frequency of large-scale oscillations changing slightly through time.

As blockage increased further, the oscillation shifted towards a pure big buzz mode, with its dominant frequency increasing to 491 Hz at TR = 40% and 523 Hz at TR = 50%. The oscillation amplitudes initially grew with increasing blockage but then stabilized.

Three-dimensional flow structures from sidewall boundary disturbances may also affect the inlet buzz process. To better understand these effects, additional flow diagnostics like pressure-sensitive paint (PSP) or oil flow visualization should be used. Additionally, replacing fixed orifice plates with a dynamic back-pressure mechanism could help analyze the time-dependent evolution and hysteresis effects of inlet buzz more effectively.

ACKNOWLEDGMENT

The author gratefully appreciates financial support from the Ministry of Education of Turkey, under whose sponsorship this Ph.D. research is conducted. The authors also wish to thank the technical staff at the University of Manchester for their continued support. Thanks also to the Aircraft Research Association for the generous loan on the V1610 high-speed camera.

REFERENCES

- [1] SA Fisher, MC Neale, and AJ Brooks. On the sub-critical stability of variable ramp intakes at mach numbers around 2. 1970.
- [2] Antonio Ferri and Louis M Nucci. The origin of aerodynamic instability of supersonic inlets at sub-critical conditions. Technical report, 1951.
- [3] Charles Lee Dailey. Supersonic diffuser instability. *Journal of the Aeronautical Sciences*, 22(11):733–749, 1955.

- [4] MR Soltani and M Farahani. Experimental investigation of effects of mach number on the flow instability in a supersonic inlet. *Experimental Techniques*, 37:46–54, 2013.
- [5] Mohammad Reza Soltani and Javad Sepahi-Younsi. Buzz cycle description in an axisymmetric mixed-compression air intake. *AIAA Journal*, 54(3):1040–1053, 2016.
- [6] Hao Chen, Hui-Jun Tan, Qi-Fan Zhang, and Yue Zhang. Throttling process and buzz mechanism of a supersonic inlet at overspeed mode. *AIAA Journal*, 56(5):1953–1964, 2018.
- [7] Juntao Chang, Lei Wang, Wen Bao, Jiang Qin, Jun Niu, and Wei Xue. Novel oscillatory patterns of hypersonic inlet buzz. *Journal of Propulsion and Power*, 28(6):1214–1221, 2012.
- [8] Federico Berto, Ernesto Benini, Ciaras Wyatt, and Mark Kenneth Quinn. Time-accurate experimental investigation of hypersonic inlet buzz at mach 5. *AIAA Journal*, 58(5):2197–2205, 2020.
- [9] Arthur Kantrowitz and Coleman Dup Donaldson. *Preliminary investigation of supersonic diffusers*. National Advisory Committee for Aeronautics, 1945.
- [10] F Gnani, H Zare-Behtash, and K Kontis. Pseudo-shock waves and their interactions in high-speed intakes. *Progress in Aerospace Sciences*, 82:36–56, 2016.
- [11] J L Wagner, KB Yuceil, A Valdivia, NT Clemens, and DS Dolling. Experimental investigation of unstart in an inlet/isolator model in mach 5 flow. *AIAA journal*, 47(6):1528–1542, 2009.
- [12] Hui-jun Tan, Liu-gang Li, Yu-fen Wen, and Qi-fan Zhang. Experimental investigation of the unstart process of a generic hypersonic inlet. *AIAA journal*, 49(2):279–288, 2011.