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Computational study of Supercritical Forced Oscillations in a Mixed-Compression Air Inlet at Mach Number of 2

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Abstract

This study examines forced oscillations under supercritical conditions in a supersonic air inlet designed for a Mach number of 2. The preparation of inlet geometry, fluid flow simulations, and result post-processing were conducted using Ansys Fluent software and in-house Fortran and Matlab numerical codes. Turbulence modeling was performed using the k-ω SST model. Flow disturbances at the inlet's exit, originating from combustion chamber fluctuations, were simulated via a sinusoidal excitation function. The excitation function's amplitude and frequency were evaluated as key parameters. A significant finding is the identical frequency between the excitation and internal flow oscillations, despite the complex nature of the flow. Additionally, the impact of excitation parameters on upstream propagation of the fluctuations was investigated, alongside a comprehensive study of supersonic flow phenomena.

Keywords: Mixed-compression inlet; Axisymmetric inlet; Forced oscillation; Supercritical state; Excitation function; Numerical simulation; Supersonic flow; Shock wave interaction.

1. Introduction

The advancement of aerospace propulsion relies heavily on air-breathing engines. Supersonic inlets play a critical role in compressing airflow efficiently with minimal total pressure loss. Previous studies have focused on unsteady flow behavior within such inlets, but a comprehensive analysis of forced oscillations in supercritical operating conditions remains unexplored. This study aims to address this gap by investigating forced oscillations in a mixed-compression supersonic inlet under varying excitation conditions.

1.1. Performance Parameters of a Supersonic Inlet

Supersonic inlets utilize shock waves for air compression, which can lead to adverse effects such as increased drag, flow spillage, and total pressure loss. The following key parameters are used to evaluate inlet performance:

Total Pressure Recovery (TPR) represents the ratio of total pressure at the inlet exit to the free-stream total pressure, defined as:

$$TPR = \frac{P_{0e}}{P_{0\infty}} \tag{1}$$

Mass Flow Ratio (MFR) expresses the ratio of captured mass flow to the total available mass flow in the free stream:

$$MFR = \frac{\rho_\infty A_\infty V_\infty}{\rho_\infty A_C V_\infty} = \frac{A_\infty}{A_C} \tag{2}$$

It reflects the inlet's ability to capture and utilize airflow effectively.

Flow Distortion measures the uniformity of airflow at the inlet exit, affecting combustion stability. It is defined as:

$$FD = \frac{P_{t.\max} - P_{t.\min}}{P_{t.avg}} \tag{3}$$

Drag Coefficient (C_D) quantifies aerodynamic resistance, influencing propulsion efficiency:

$$C_D = \frac{D}{\frac{1}{2}\rho V_\infty{}^2 A} \tag{4}$$

These parameters provide a comprehensive assessment of supersonic inlet performance, guiding the optimization of aerodynamic design.

1.2. Operating Conditions of a Supersonic Inlet

Supersonic inlets function in three distinct regimes—subcritical, critical, and supercritical—depending on the position of the terminal normal shock wave relative to the throat. In the subcritical regime, the shock wave stands upstream of the throat, while in the supercritical regime, it moves downstream. The critical regime occurs when the shock wave is positioned exactly at the throat. The throat location varies by the inlet type. In external compression inlets, it is at the cowl lip, whereas in mixed compression inlets, it is located inside the inlet.

1.3. Stability in Supersonic Inlets

In supersonic inlets, oscillations in the flow and shock wave system, known as buzz, can reduce engine thrust, cause combustion chamber shutdown, and impose structural loads up to 10 times higher than steady conditions. These effects are particularly critical in supercritical states, where supersonic aircraft operate most frequently. Previous research has examined shock wave interactions, oscillation amplitudes, the relationship between shock position and back pressure, and the damping effects of high-frequency oscillations [7- 8-9-10-11-12]. Additionally, studies have explored the connection between combustion chamber pressure oscillations and forced flow oscillations, emphasizing their role in vortex formation within the engine [13,14]. This study aims to bridge the gap in understanding forced oscillations in supercritical conditions by analyzing oscillations across various excitation amplitudes and frequencies, assessing their impact on the upstream flow field to evaluate inlet stability and performance.

2. Problem Definition

This study investigates a mixed compression air inlet designed for a Mach number of 2. The flow at the inlet's exit is excited by an oscillatory function, which requires solving the governing equations in an unsteady state. The applied excitation function for static pressure P at the exit is given by:

$$P = K\,sin(2\pi f t) + J \qquad (5)$$

where K, f, and J are the amplitude, frequency, and mean value of the back pressure, respectively.

Figure 1,**Figure 1**shows the boundary conditions and computational grid, and **Error! Reference source not found.**presents the boundary condition data. These values are identical to the experimental values of the studied inlet in the supersonic wind tunnel [15].

Table 1. Boundary Condition Data

Boundary	Boundary Values or Conditions		
Far-field	$T = 167.7K$	$M = 2$	$P = 10555Pa$
outlet	$P = K\,sin(2\pi f t) + J$	$T_t =$ ٣٦٧ K	
Wall	No-slip condition		
Axis	Axisymmetric condition		

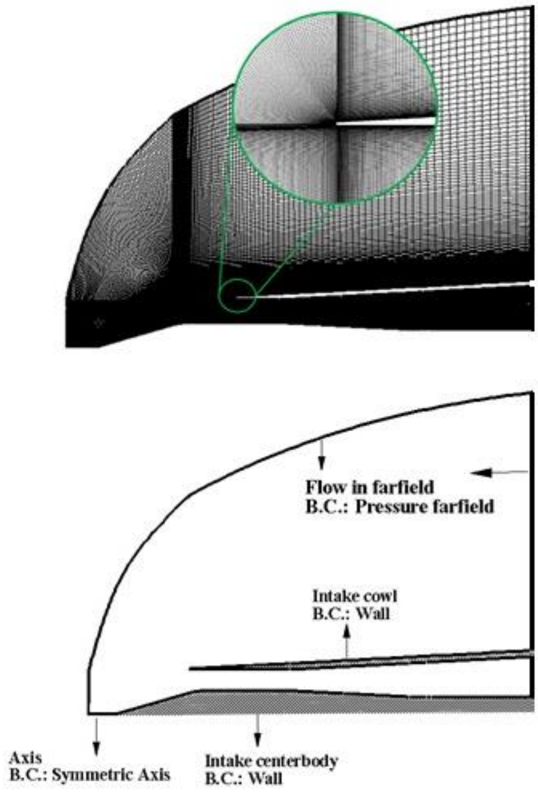

Figure 1. The computational grid and the boundary conditions

The values of P represent static pressure. For different values of K and J, four frequencies (10, 100, 500, and 1000 Hz) were analyzed. Numerical results indicated that for very small values of K and J, flow oscillations dampen quickly, while for very large values they shift the inlet operation from supercritical to subcritical.

Key assumptions include unsteady state analysis, axial symmetry, compressibility, and fully turbulent flow. The k-w SST turbulence model [16] was used for turbulence modeling, with a density-based approach for solving the governing equations. The Sutherland equation was used to calculate molecular viscosity, and the Roe method was employed for inviscid flux discretization. Convergence was determined by ensuring residuals below 10^{-5} and stable oscillatory pressure values at each cycle.

2.1. Numerical Sensors

Numerical sensors were placed at various locations within the inlet to analyze the flow characteristics. S sensors measure static pressure on the spike surface, T sensors measure total pressure, and R surfaces calculate and report the average value of the quantity being studied. As seen from Figure 2, the presence of a normal shock wave near sensor S8 indicates critical operating conditions, with subcritical conditions upstream and supercritical conditions downstream of this sensor.

2.2. Grid Independence Study

This study assesses the grid independence of the solution using three different computational grids with varying cell sizes. The results for pressure ratio variations along the spike length in steady-state conditions indicated that grid b with 79400 cells, provided a good balance between computational cost and accuracy, as pressure profiles for grids b and c (198500 cells) were nearly identical.

For unsteady-state conditions, the Fast Fourier Transform (FFT) was applied to analyze pressure oscillations and extract the dominant frequency governing the flow. The FFT equation is given by:

$$X_k = \sum_{n=0}^{N-1} \binom{n}{k} x_n . e^{-i2\pi\, k\, n/N} \qquad (6)$$

where N is the number of samples, n is the sample index, x_n is the signal at sample n, k is the frequency (0 Hz to N−1Hz), and X_k is the Fourier transform result.

Results for Mach number 2 and an excitation frequency of 30 Hz confirmed that grid b was appropriate due to the consistency of dominant frequencies in grids b and c.

2.3. Time Step Independence Study

To evaluate the effect of time step on the results, grid b and the parameters from first row of **Error! Reference source not found.** were used at a frequency of 100 Hz. Four different time steps—10^{-2}, 10^{-3}, 10^{-4}, and 10^{-5} seconds—were considered. Time steps of 10^{-4} and 10^{-5} seconds exhibited very similar results, so to reduce computational cost, sec 10^{-4} was selected as the optimal time step.

3. Results and Discussion

3.1. Validation

The numerical results were validated against experimental data, demonstrating close agreement in pressure distribution along the inlet spike and frequency response characteristics. The Fourier transform analysis confirmed the accuracy of frequency predictions.

3.2. Pressure Variations Over Time

The amplitude of pressure fluctuations at different numerical sensors demonstrates a decreasing trend with increasing excitation frequency due to viscous dissipation. This damping effect reduces the fluctuation amplitude and eventually leads to their disappearance near sensor R3 shown in Figure 2.

Furthermore, the oscillation patterns indicate that certain sensors experience continuous fluctuations, while others are influenced by shock wave motion only during specific time intervals. This distinction is evident from the flattened pressure variations over time observed in some sensors.

3.3. Upstream Penetration of Excitation

The penetration of pressure fluctuations decreases as excitation frequency increases. At lower frequencies, fluctuations extend further upstream, while at higher frequencies, their propagation is significantly limited. This behavior is attributed to the reduced duration of pressure application at higher frequencies, which restricts the expansion of shock waves within the flow field.

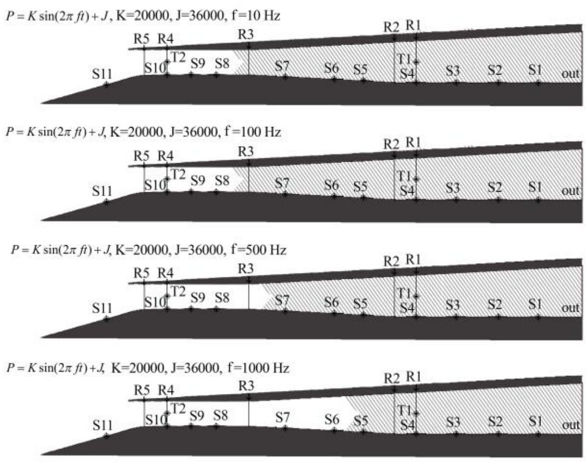

Figure 2. Upstream penetration of exit excitations at frequencies of 10, 100, 500, and 1000 Hz

3.4. FFT Analysis

The dominant frequency observed at different sensors closely matches the applied excitation frequency, with minimal deviation. This suggests that as long as the excitation function acts as a perturbation source in the flow field, the imposed frequency remains consistent with the measured fluctuations.

3.5. Flow Field Analysis

The oscillatory nature of the flow is analyzed over a single cycle, focusing on the latter half of the period. Results indicate that during each cycle, vortices form and evolve, with the vortex near the spike growing while the one near the cowl surface diminishes and eventually disappears as seen in Figure 3.

Shock waves generated within the inlet adapt the flow pressure to the applied boundary conditions, leading to vortex formation along the spike and shell. As pressure penetration increases, the shock wave system extends further upstream, enlarging the flow separation region. The resulting wave patterns are asymmetric, influenced by the inlet geometry, directly impacting vortex size and number. Stronger shock waves near the shell cause localized separations, leading to additional vortex formation.

Over time, the vortex near the shell vanishes while the one near the spike strengthens and moves upstream. By the end of the cycle, the disturbance reaches its maximum penetration point, beyond which no further vortices develop. The process then reverses, restoring the initial state.

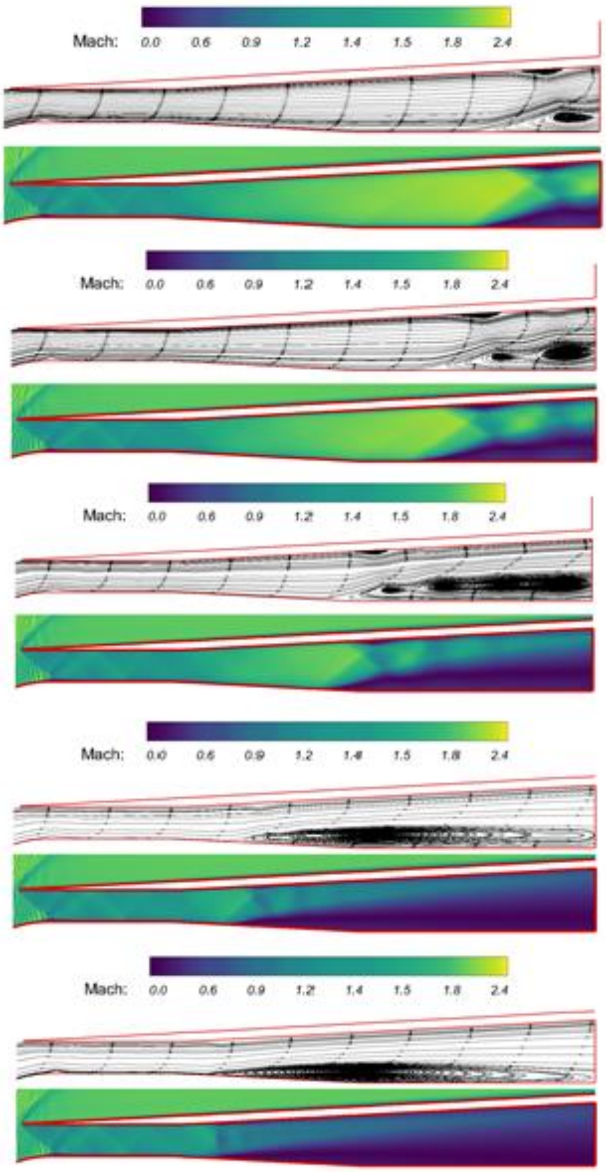

Figure 3. Streamlines and Mach number contours at different time instances for K=20000 and J=18000

This analysis demonstrates that flow oscillations generate varying vortex structures, significantly altering wave interactions and total pressure recovery. If these fluctuations occur with high amplitude or frequency, they can introduce flow instabilities, potentially disrupting propulsion system performance.

4. Conclusions

This study investigates the forced flow fluctuations in a supersonic air inlet under supercritical conditions by applying an excitation function at the inlet's end, simulating combustion chamber oscillations. The free-stream conditions included a Mach number of 2 and a static pressure of 10555 Pascal, matching the experimental setup. Four excitation frequencies (10, 100, 500, and 1000 Hz) were studied through 16 unsteady simulations. Results showed that higher excitation amplitudes and mean pressures increased disturbance penetration and delayed decay, while higher frequencies caused disturbances to decay faster. Pressure amplitude decreased from downstream to upstream, and the flow oscillation frequency closely matched the excitation frequency. The analysis revealed that flow field oscillations within the inlet were associated with significant vortex size variations, leading to flow distortion and total pressure recovery issues, which could be highly detrimental if uncontrolled. These findings highlight the importance of managing flow fluctuations in supersonic inlets to prevent performance degradation.

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