AEROACOUSTIC NOISE GENERATION BY PLANAR JET PLATE IMPINGEMENT

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ABSTRACT

Noise generation by a high speed planar gas jet impinging on a flat surface has been studied as a function of impinging jet velocity and impingement distance. The impinging jet velocity is varied between 106 and 204m/s, but the jet slot width is kept constant at h=1.25 mm. Measurements are performed for impingement ratios ranging from z/h= 1 to 30, where z in the impingement distance. The frequencies of the dominant tones generated by the impingement are found to have an approximately constant Strouhal number based upon the impingement distance. A semi-empirical expression to predict the tone frequency is proposed. Phase measurements have been performed to determine the type of flow instability causing the acoustic tone generation. In addition, the susceptibility of acoustic tone generation to inclination of the impingement surface has been investigated.

1. INTRODUCTION

High speed gas jet flows impinging on various geometries are known to be susceptible to feedback excitation mechanisms and to produce strong acoustic tones. Instabilities arising in the shear layer of the jet are magnified as they travel downstream, eventually impinging on the solid boundary, causing distortion of the vorticity field. These disturbances are then fed upstream to the nozzle lip, causing new perturbations and thereby completing the feedback cycle. Of the research performed on impinging jets, the vast majority has focused on the flow acoustic feedback mechanism of *axisymmetric* jets impinging on a wall.

On the other hand, impinging planar jets have been the subject of far less research. Planar gas wiping jets are used in a wide variety of important industrial applications such as coating control applications, manufacturing of pulp and paper, photograph production and high performance heating and cooling applications. In many of these applications, planar gas jets impinge on a flat surface either normal or with some form of surface inclination. This paper investigates the noise characteristics of a planar jet impinging on a flat surface as a function of the impinging jet velocity as well as the impingement distance. Phase measurements have been performed to attempt to quantify the nature of the flow instability causing the acoustic tone generation. Finally, the susceptibility of surface inclination on the acoustic tone generation has been investigated.

2. EXPERIMENTAL APPARATUS

All experimental work was conducted using a planar air jet constructed out of Plexiglas® and Aluminum. A series of internal baffles located immediately upstream of the nozzle outlet were utilized to ensure a uniform exit velocity along the jet span, which was later validated by means of velocity measurements. The jet allows the adjustment of the slot thickness, h, to be varied within a range of $0 \leq h \leq 7.5$ mm. However, only one jet slot width of h = 1.25 mm was used for all present testing. Additionally, the span of the jet was L = 406 mm resulting in an aspect ratio of L/h = 280. Reynolds numbers based upon the jet slot width vary between $Re_h \approx 7{,}000$ and 14,000.

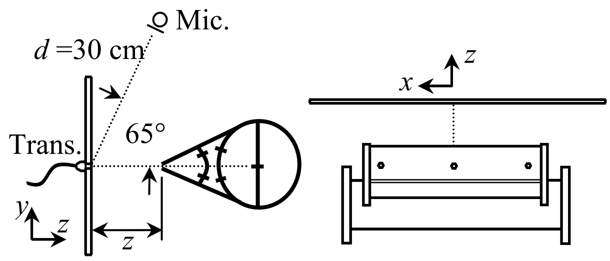

Figure 1: *Simplified schematic of experimental planar jet-plate impingement setup.*

The jet was pressurized by a 10 HP Sonic Air Systems 70 Series centrifugal blower connected to a piping system and plumbed to an air plenum feeding both ends of the jet, to ensure uniform flow distribution. Furthermore, the piping system employs several flow conditioning devices including screens and honeycomb sections to reduce the noise and turbulence levels exiting the blower. Plenum pressure was modulated from P = 0 to 0.315 Bar with a ball valve located well upstream of the flow conditioners. The isentropic flow velocity (V_i) of the jet, which is used in the current study for scaling purposes, was calculated using Equation (1) derived from compressible flow equations for a standard isentropic nozzle, where c is the speed of sound and P_∞ is standard atmospheric pressure.

$$V_i = C\sqrt{\frac{2\left[\left(\frac{P_\infty}{P+P_\infty}\right)^{-\left(\frac{\gamma-1}{\gamma}\right)}-1\right]}{\gamma-1}} \tag{1}$$

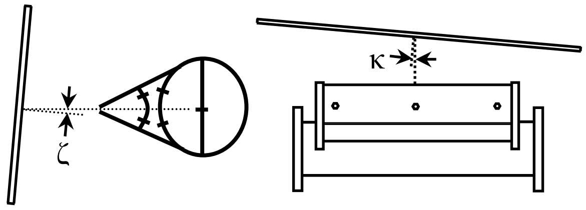

Figure 2: Simplified schematic of stream-wise (ζ) and span-wise (κ) jet-plate inclination angles.

The flat plate used for jet impingement was constructed of 7 mm thick aluminum plate and measured 205 mm × 490 mm. The plate was mounted on a 3-axis traverse which could be manipulated in the *x-y-z* directions to within ±0.025mm. In order to study the effects of plate inclination on noise generation, the plate could also be inclined up to κ = 5° in increments of 0.01° in the span-wise direction, and the jet inclined up to ζ = 45° in increments of 0.5° for testing of stream-wise inclination. Schematics of both stream-wise and span-wise inclination are shown in Figure 2.

Noise measurements were performed using a ¼” G.R.A.S. pressure microphone with one microphone being positioned in the acoustic near field using an electronically controlled 3-axis traverse at a distance of 300 mm from the impingement point of the jet at the center of the jet span, and at an angle of 65° from the jet plane. Furthermore, an Endevco 8510B pressure transducer was also mounted in the plate to measure both static impingement pressure as well as fluctuating pressure, and its position relative to the impingement point could be manipulated by the mechanical 3-axis traverse of the plate. A PC based data acquisition system utilizing LabView® was used to capture all data. Measurements were performed to ensure that all noise measurements were performed in the acoustic near field. In addition a series of acoustic baffles were positioned around the jet, plate, and measurement positions to further reduce the effects of sound reflection and reverberation within the room.

3. NORMAL JET-PLATE IMPINGEMENT

3.1 Overall Characteristics of Jet-Plate Noise

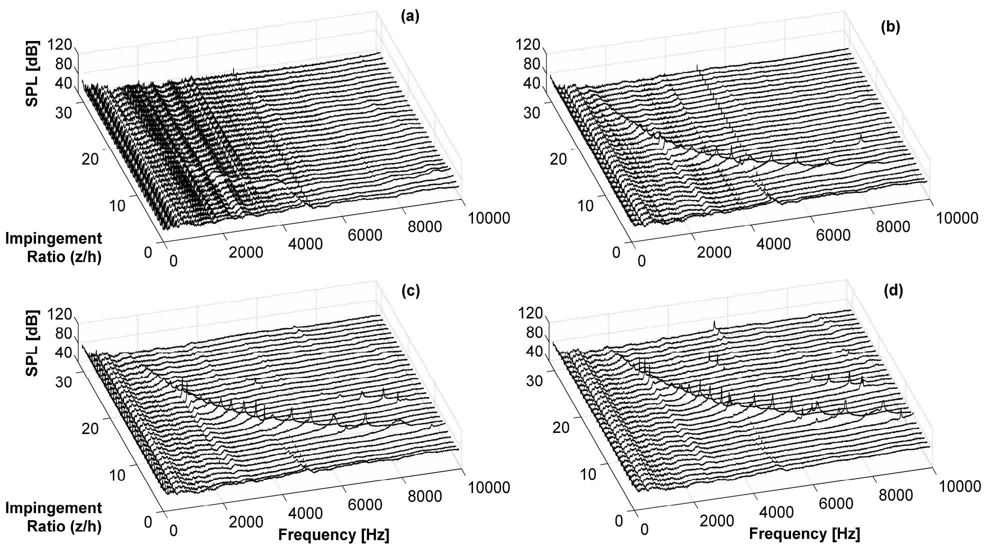

Figure 3: *Aeroacoustic response of planar jet-plate impingement as a function of impingement ratio (z/h) for isentropic jet velocities of* V_i *= 106 m/s (a), 148 m/s (b), 179 m/s (c) & 204 m/s (d).*

Figure 3 shows a series of waterfall plots of the jet-plate frequency response as a function of impingement ratio (*z*/*h*) for varying plenum pressures. A strong acoustic tone was excited for all jet-plate impingement cases with plenum pressures exceeding P = 0.14 Bar ($V_\mathrm{i} \approx$ 153 m/s). The acoustic tone strength increases with increasing plenum pressure and the tone is excited over increasingly larger ranges of impingement ratio as the plenum pressure increases. In all cases, peak acoustic excitation occurred at or near an impingement ratio of *z*/*h* = 12. The range of tone generation, also referred to as the *lock-in range*, of the planar jet case is quite different from what is typically encountered for the axisymmetric impinging jet case, which typically locks-in over a range of z/d from 1.5 to 6.

3.2 Frequency Analysis

The acoustic tones generated by the impinging planar jet displays a hyperbolic behavior with the frequency of the tone being proportional to the isentropic flow velocity (V_i) and inversely proportional to the impingement ratio (z/h). Figure 4 shows the frequency of the dominant acoustic tone as a function of the impingement ratio for a series of isentropic flow velocities. The Strouhal number (St_z) based upon the impingement distance z for all flow velocity cases tested is shown in Figure 5, where it should be noted that no appreciable tones were generated at flow velocities below V_i = 148 m/s. The Strouhal number is approximately constant, with a slight negative slope, and an average value of St_z = 0.324. Further work is currently ongoing to determine the root cause for this behavior. The frequency of the acoustic tone in most cases can be predicted to within 5% using the relationship given in Equation (2), which assumes a constant Strouhal number of St_z = 0.32. It should be noted that the tone frequency is expected to depend on the jet thickness (h) as well. However, h is not included in Equation (2) because only one jet thickness was used in the present tests. Additional work is planned to investigate the effect of h in some detail. For the jet-edge case utilizing planar jets, Ziada (1995) found the acoustic tones to be generated at a constant Strouhal number of $St_L \approx$ 0.4, which is slightly higher than that observed in the present experiments.

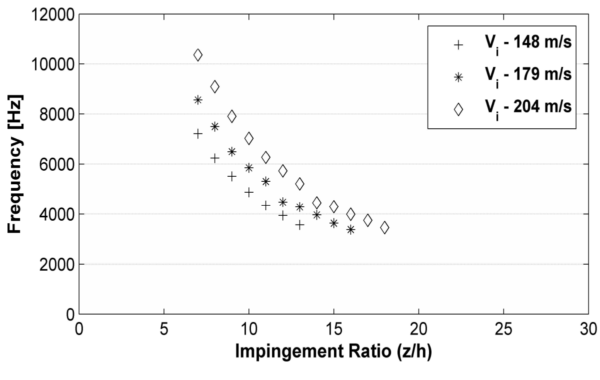

Figure 4: *Frequency of jet-plate acoustic tone as a function of impingement ratio (z/h) for varying jet velocities.*

Noticeably absent from the acoustic response of the impinging planar jet, is any form of mode switching or jet-tone staging. This phenomenon is a key feature of impinging axisymmetric jets, with the jet tone locking onto an approximately constant Strouhal number based upon jet diameter (St_d). In this case, the tone generated by the impinging planar jet varies through a very large range of Strouhal number (St_h), based upon the jet thickness, h, with no evidence of locking-in to any particular Strouhal number based on the jet thickness.

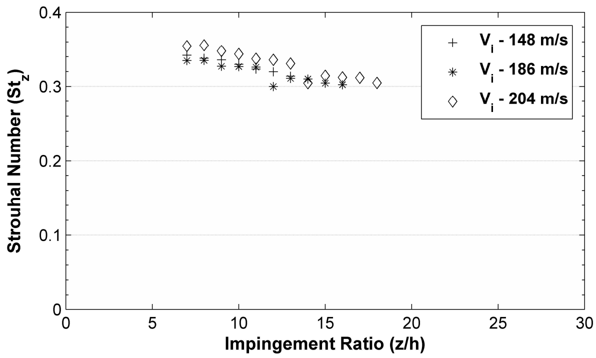

Figure 5: *Strouhal number based upon the impingement distance z (St_z).*

$$\frac{f \cdot z}{V_i} \approx 0.32 \;\rightarrow\; f \approx 0.32 \cdot \left(\frac{V_i}{z}\right) \qquad (2)$$

4. NATURE OF FLOW INSTABILITIES

Measurements were performed to attempt to determine the nature of the flow instability causing the acoustic tone generation. An Endevco 8510B pressure transducer was mounted in the plate at the center of the jet span, and its position relative to the impinging jet flow was manipulated moving the plate relative to the jet using the mechanical 3-axis traverse. The phase difference between the near field microphone and the pressure transducer was recorded while performing measurements with the pressure transducer at various y positions relative to the impinging jet. The position of the reference microphone located in the acoustic near field was fixed at all times at a distance of 300 mm from the impingement point and an angle of 65 degrees relative to the horizontal. Amplitude spectra from the microphone and pressure transducer for a transducer position of y = +2mm are shown in Figure 6. The relative intensity of the acoustic tone and the dynamic pressure oscillations measured on the surface of the plate are readily apparent from the inspection of each spectrum.

From initial frequency analysis of the acoustic tones, which showed the Strouhal number based upon z to be approximately St_z = 0.32, the instability causing the generation of the tone was anticipated to be a conventional jet instability, either of a symmetric or antisymmetric mode. The amplitude of the dynamic pressure oscillations at the acoustic tone frequency as a function of the y position relative to the impinging jet was examined in an attempt to capture and quantify the relative magnitude of the impinging coherent structures thought to be generating the acoustic tone. The downstream position of the plate relative to the jet (z) was fixed and the plate was traversed through the flow in the y direction in increments of 0.3mm moving the plate mounted pressure transducer through the impinging jet flow, recording the static impinging pressure as well as the fluctuating pressure. It should be noted that all dimensions of the plate are large with respect to the scales of the flow, so that as the plate is moved, the impinging flow remains unchanged.

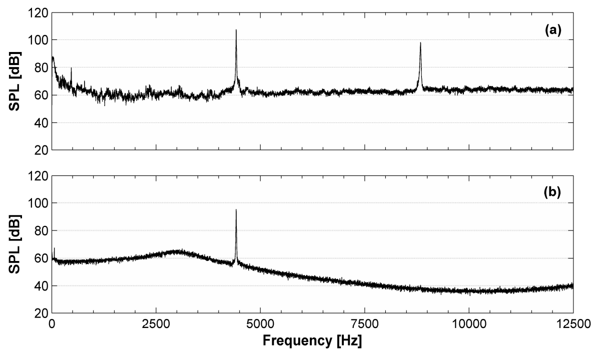

Figure 6: *Amplitude spectra of the (a) near field microphone and (b) plate mounted pressure transducer for a transducer location of y =+2mm, V = 174m/s and z/h = 12.*

Figure 7 shows the static impinging pressure of the jet on the plate and the fluctuating pressure component, captured at the acoustic tone frequency. Measurements performed with the plate positioned at other impingement ratios of z/h = 10 and 15 showed peak fluctuating pressure at very similar positions relative to the static impingement profile. It is interesting to note that the distributions of the mean and fluctuating pressures depicted in Figure 7 display a strong similarity to the distributions of mean and fluctuating velocities for a planar free jet excited by externally applied sound waves (Sato and Sakao, 1964).

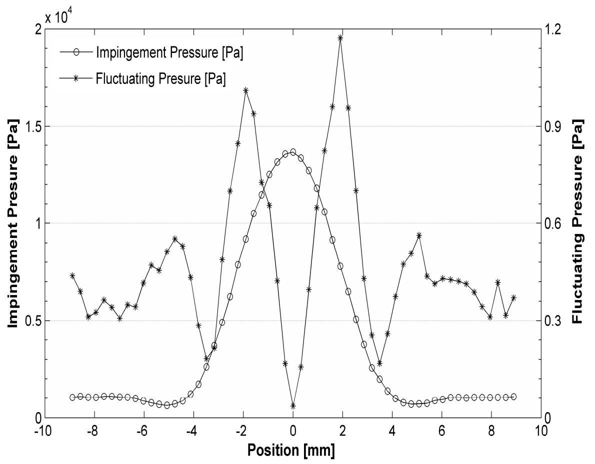

Figure 7: *Static impingement pressure and peak fluctuating pressure as a function of position on the impinging jet profile for V = 174m/s and z/h = 12.*

The phase between the near field microphone and the pressure transducer was examined for a single impinging jet case of V = 174 m/s and z/h = 12. As noted earlier, the position of the reference microphone was fixed relative to the impinging jet flow and the plate mounted transducer was traversed through the impinging jet profile. Figure 8 shows the relative phase difference between the near field microphone and the plate mounted pressure transducer as a function of the transducer position relative to the impinging jet profile. An abrupt phase change of approximately 200 degrees is encountered as the pressure transducer is swept across the centerline of the jet, indicating that the jet instability producing the acoustic tone is likely antisymmetric. In addition to the abrupt phase change occurring at the jet centerline, there are significant phase variations as the pressure transducer enters areas of the jet flow where the pressure fluctuations are significant. These large phase variations are similar to those occurring across oscillating free shear layers. Despite these large variations, the phase distribution across one side of the jet centerline depicts the mirror image of that measured across the other side, with approximately 180 degrees phase difference between the two sides. These phase characteristics are further delineated in Figure 9, which shows the relative phase difference between symmetric points on either side of the jet centerline. At the location of peak fluctuating pressure (y = +/- 2mm) the relative phase difference is ~167 degrees. Measurements performed for the same jet velocity, but different plate to nozzle distances, showed similar results, with an abrupt phase change at the jet centerline and relative phase differences near 180 degrees.

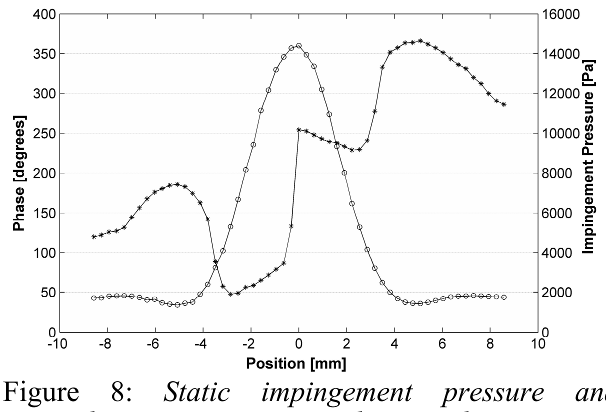

Figure 8: *Static impingement pressure and microphone-pressure transducer phase as a function of position on the impinging jet profile for V = 174m/s and z/h = 12.*

The results of the aeroacoustic response and phase measurements do not show any evidence of jet staging or mode switching, a commonly observed characteristic of impinging axisymmetric jet flows (Paniker & Raman, 2007).

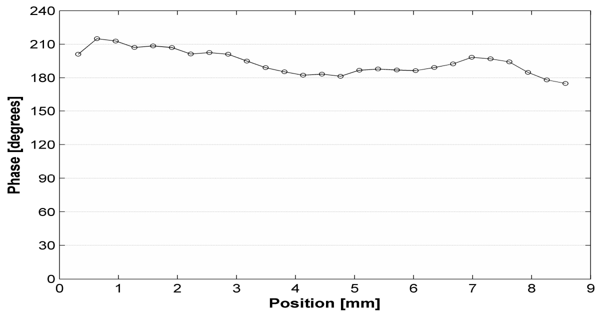

Figure 9: *Total phase difference between symmetric positions on either side of the jet for V = 174m/s and z/h = 12.*

5. EFFECT OF JET INCLINATION

All measurements examined to this point have been performed with the jet impinging normally on the plate. The effect of, and sensitivity to, surface inclination, both in the stream-wise and span-wise directions, were investigated, in order to gain further insight into the nature of the flow instabilities, and to investigate methods to reduce or eliminate the generation of acoustic tones. Figure 2 shows a basic schematic of span-wise and stream-wise plate inclination.

5.1 Effect of Span-wise Plate Inclination (κ)

In all three of the flow velocity cases tested, the frequency of the dominant acoustic tone was shown to be approximately inversely proportional to the impingement distance, *z*, with substantially different values of tone frequency for relatively small changes in impingement length. Because of the relatively large amplitudes of the tones produced, it is currently thought that the tones are generated as a result of a feedback mechanism, whereby the coherent structure produced in the shear layers of the jet impinge on the plate, and the resulting pressure pulsation further excites shear layer instabilities at the jet exit. Inclining the plate along the span of the jet has the effect of continuously varying the impingement distance, and thus, the frequency of the tone being generated. It was thought that by inclining the plate relative to the jet span that the feedback mechanism could be interrupted and the oscillations could be suppressed. Tests were carried out to determine the sensitivity of span-wise plate inclination on the generation of acoustic tones.

Figure 10 shows the results of a series of tests performed at a constant jet velocity (V = 174 m/s) and a constant impingement ratio (z/h = 12) while varying the span-wise inclination from κ = -1.15° to κ = +1.15°. Because the plate is being inclined relative to the span of the jet exit, the impingement ratio becomes somewhat undefined, as it is varying continuously along the jet span. In all cases reported in this work, the impingement ratio stated is given at the center of the jet span. The acoustic tone shows strongest excitation for a span-wise inclination of κ = 0°, and for angles in both the positive and negative direction, a gradual reduction in tone intensity is observed. For inclination angles greater than κ = +/- 0.5°, there is no appreciable excitation of the acoustic tone, indicating that planar jet-plate excited tones are extremely sensitive to span-wise surface inclination.

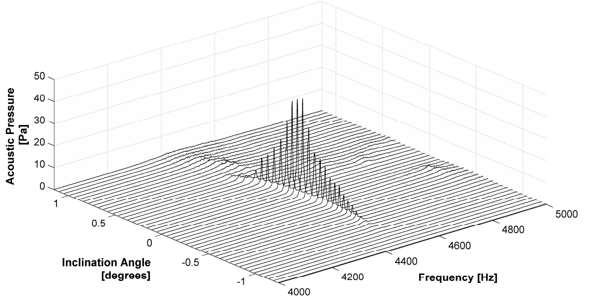

Figure 10: *Effect of plate inclination on the intensity of the dominant acoustic tone (V = 174 m/s, z/h = 12, f ≈ 4450 Hz).*

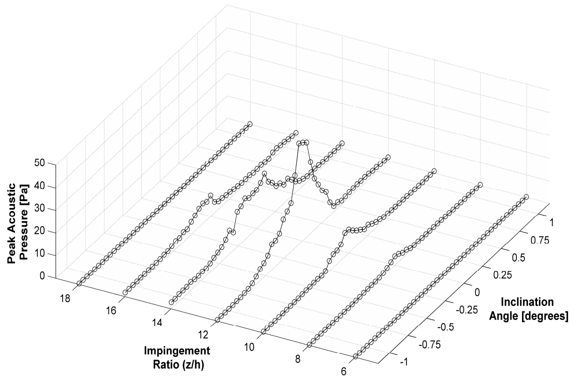

Figure 11: *Effect of plate inclination on the tone intensity of the dominant acoustic tone as a function of impingement ratio for V = 174 m/s.*

Figure 11 shows an extension of this analysis to additional impingement ratios. The peak acoustic pressure for a series of experiments with varying inclination angle at impingement ratios between z/h = 6 and 18 are shown. The results are consistent with the earlier observation that the majority of the acoustic tone excitation occurs between the angles of κ = +/- 0.5°, and larger inclination angles result in a near complete suppression of the tone.

As discussed earlier in this paper, the amplitude of the acoustic tone generated by planar jet-plate impingement for a constant flow velocity, varies considerably as a function of impingement ratio, with maximum acoustic excitation occurring at approximately z/h = 12 for most cases. Because the difference in amplitude between the different impingement ratio cases makes visual inspection of the data of Figure 11 somewhat difficult, the data has also been presented in a dimensionless form in Figure 12. In this figure, the peak acoustic pressure of each point has been non-dimensionalized by the maximum peak acoustic pressure for the tested impingement ratio. The reduction of peak acoustic pressure as a function of the inclination angle shows strong similarity between each of the different cases.

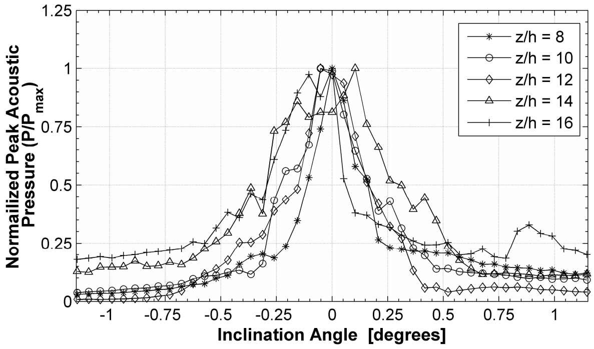

Figure 12: *Effect of span-wise inclination showing the normalized peak RMS acoustic pressure (P_{RMS}/P_{max}) versus Inclination angle for a series of impingement ratios.*

5.2 Effect of Stream-wise Plate Inclination (ζ)

Based on the earlier observation that the acoustic tones are likely driven by an upstream feedback excitation mechanism, it was anticipated that inclining the jet in the stream-wise direction would eventually interrupt or interfere with the pattern of flow impingement and also affect the pattern and strength of upstream feedback. The self-excited oscillations may therefore diminish. Tests were carried out to determine the sensitivity of the acoustic tones to stream-wise plate inclination. Due in part to lengthy setup time of the experimental apparatus, it was not possible to test small increments of stream-wise inclination, as was in the case for span-wise inclination. Tests were performed for stream-wise inclination angles of ζ = 0°, 5°, 10° and 15° for impingement ratio varying between *z*/*h* = 1 and 25.

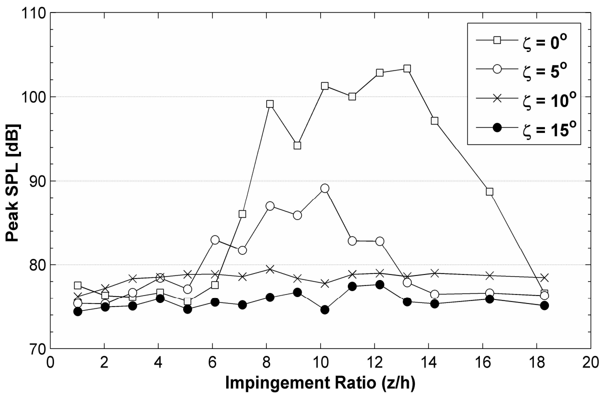

Figure 13: *Effect of stream-wise inclination angle on the peak SPL of the acoustic tone for a jet velocity of V = 174 m/s.*

Figure 13 shows the effect of varying stream-wise inclination angle on the acoustic tone strength over a range of impingement ratios. It is evident from the significant excitation for the case of ζ = 5° that the formation of acoustic tones is more than an order of magnitude less sensitive to stream-wise inclination than that of span-wise inclination. The addition of small amounts of stream-wise inclination seems to have the effect of decreasing the acoustic tone strength for a given impingement ratio, and also decreasing the lock-in range to a smaller range of impingement ratio. Some minor excitation is still evident in the amplitude spectra for stream-wise inclination of ζ = 10°, and a complete suppression is achieved with an inclination of ζ = 15°.

6. CONCLUSIONS

The acoustic excitation of a planar jet impinging on an infinite plate was investigated. The frequency of the dominant tone was shown to be proportional to the flow velocity of the jet and the inverse of the dimensionless impingement length as given by Equation (2). Phase measurements across the profile of the jet revealed that the acoustic tones are likely generated by an antisymmetric jet instability with a constant Strouhal number of $St_z \approx 0.32$. Jet-plate inclination was shown to be an effective method to suppress acoustic excitation, with the pulsations being more than an order of magnitude more sensitive to changes in span-wise inclination compared to stream-wise inclination.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the generous contributions of ILZRO, NSERC and the EDSVS (European Doctorate on Sound and Vibration Studies) Marie Curie Fellowship.

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