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Mitigation of impinging tones using central protrusion

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ABSTRACT

This article demonstrates that a simple modification such as installing a protrusion on an impingement plate can lead to reduction of jet impingement tones. This experimental work compares the acoustic variations in jets impinging on a flat plate, and plates with a central protrusion. The key strategy here is the modification of the stagnation flow region brought about by the introduction of the central protrusion. It is observed that the toneless acoustic power is almost the same for jet impinging on the plate with and without the central protrusion. It is also found that the protrusion is more effective in reducing tones in supersonic impinging jets than the tones in subsonic impinging jets. However, there is a slight increase in acoustic power when the jet impinges on a larger protrusion (greater than jet diameter) at high nozzle pressure ratios. Further, high speed flow visualization is carried out to relate the shock oscillations with the tonal frequencies. The noise source location is estimated by performing FFT on the flow visualization images. The acoustic and optical measurements are compared in terms of tonal frequency and found to be in agreement with each other.

1. Introduction

Jets are widely used in various industrial applications, such as cleaning, heating/cooling operations as well as thrust production in aircrafts and rockets. However, noise is a serious consequence in these applications. For example, the noise produced at rocket launching can cause malfunctioning of the electronic equipment present in the rockets. High speed jets induce structural and thermal load on the launching pad. In addition to this, jet impingement can cause lift reduction and thrust loss for V/STOL aircrafts. Various consequences of jet impingement during launching of rockets and details of the design of launching pad and jet deflectors is accounted in various NASA reports [1–4]. In case of V/STOL aircrafts with two nozzles, the impinging jets meet at a stagnation line and produce an upward-flowing fountain jet [5]. This fountain jet carries hot gases that enter the engine air intakes, thereby reducing the engine efficiency. The complex flow structure and the associated noise have intrigued the researchers. The present article demonstrates a passive noise control method for impinging noise - especially impinging tones. A brief outline of different noise sources involved in impinging jets and some noise control methods are presented in the next section.

The acoustic radiations from jets arise from multiple sources. The turbulent mixing noise is generated due to the mixing of jet flow with the surrounding fluid. This type of noise is dominant in the low frequency range and more directive towards the downstream. Turbulent mixing noise occurs in both subsonic and supersonic conditions. Supersonic jets also emit shock associated noise apart from turbulent mixing noise. Shock associated noise can be further classified into broadband shock associated noise (BBSAN) and screech. The BBSAN is centered around a high frequency and occurs due to the presence of shocks, whereas, distinct screech tones may occur in imperfectly expanded jets due to an acoustic feedback loop.

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In addition to the above mentioned noise sources, special tonal noise occurs when any obstacle is placed at a particular position in the jet path. These tones occur both in subsonic and supersonic impinging jets and they differ from the screech by their generation mechanism. In case of subsonic impinging jet, these tones occur due to the feedback loop as shown in Fig. 1(a). However, in the case of supersonic impinging jet, either feedback loop or random shock oscillation is responsible for impinging tones marked as A and B in Fig. 1 (b). Different noise sources present in the subsonic and supersonic impinging jets are shown in Fig. 1(a) and (b), respectively.

The interaction of the jet with ambient air at the jet boundary produces vortical instabilities in the shear layer. These instabilities are amplified as they move downstream. These instabilities impinges on the obstacle and produce strong pressure fluctuations, which propagate upstream as acoustic waves. These acoustic waves reach the nozzle exit and excite the shear-layer disturbances resulting in the shedding of new vortices. Thus, it completes the feedback loop responsible for impinging tones [6].

Powell [6] identified three origins of noise in impinging jets, (i) surface noise due to fluctuating surface pressure, (ii) layer noise produced from the boundary layer turbulence and (iii) wake noise from the turbulent wake. Marsh [7] found that the wall jet region of the impinging jet produces considerable increase in broadband noise, and observed a steady intense tone in some cases. The spectrum of noise is modified as nozzle-plate spacing increases; the amplitude and frequency of the dominant tone decrease, and the sharp peak transforms into a broadband-like hump. Experiments of Smith and Powell [8] showed that resonance effect enhances the sound intensity with plate size.

Gubanova et al. [9] found that a central breakaway zone forms when the maximum value of the pressure is located along the axis of symmetry and at a certain distance from the obstacle. Wagner [10] argued that a feedback mechanism exists, in which the sound produced by the impingement of the vortices on the plate travels upstream through the jet core, which causes disturbances in the shear layer. Neuwerth [11] found 8 phases of feedback loops and concluded that jets can produce both symmetric and asymmetric modes. Semiletenko et al. [12] observed ceasing of shock oscillations when there is enough nozzle-plate spacing to accommodate a second compression shock ahead of the plate. Ginzburg et al. [13] found strong instability, when the pressures at the centre of the plate and peripheral regions of plate are equal. Gutmark et al. [14] showed a stretching of vortices near the wall, causing anisotropy in this region and also indicated that jet symmetry is unaffected by the presence of the plate over 3/4 of the nozzle-plate spacing.

Ho and Nossier [15] found convincing evidence of an acoustic feedback to the orifice, leading to discrete tone generation. The acoustic radiation caused due to the impact of the coherent structures on the obstacle passes through the ambient atmosphere to the nozzle. The frequency decreases with an increase in nozzle-obstacle spacing, this steady progression being interrupted by upward jumps in frequency which restores it to near its original higher values, corresponding to jet disturbances of shorter wavelength and of a greater degree of instability. Tam and Ahuja [16] suggested that the instability waves in the jet shear layers provide energy for the feedback loop.

Glaznev and Popov [17] found that oscillations ceased when Mach disk size is larger than the impinging plate size. Henderson and Powell [18] found that the impingement of an axisymmetric supersonic jet on a flat plate produces three classes of tones with different frequency characteristics. Two classes of tones are associated with small plates, and one class of tone is associated with large plates. For small plates, Hartmann type of instability occurs which is associated with the unstable shock-wave in the pressure recovery regions of the jet. This instability has much in common with the high harmonic oscillations of Hartmann whistle. In case of very highly under-expanded jets two modes of oscillations were observed. In case of large plates, acoustic feedback to the orifice involving instability occurs. The third type of instability is a random one, noted for large plates when located close to the nozzle similar to unsteady small-plate phenomenon. Lamont and Hunt [19] performed detail flow visualization study of the supersonic jet impinging on flat plates. They found that in the near field, these wave interactions tend to be the controlling factors but at larger distances from the nozzle, mixing effects become increasingly important. Similarly, they performed supersonic jet impingement on wedges [20] with different apex angle and found various flow pattern.

Krothapalli et al. [21] and Elavarasan et al. [22] measured forces generated on the plate due to jet impingement and found that when impinging plate was very close to the nozzle exit, suck-down forces were almost 60% of the jet thrust. The instantaneous velocity field data revealed that large scale structures stimulate an increase in entrainment. This results in an increase in suck-down forces responsible for lift loss.

Recently, Henderson et al. [23] observed that the impinging tones produced by jets at moderate and high under-expansion ratios originate from flow oscillations in the near-wall jet. Changes in the near-wall region of the jet are associated with the collapse of the stand-off shock wave during the oscillation cycle. Tones are produced when a Mach disk occurs in the flow and cease when the first or second shock wave assumes a conical shape. The impingement tonal frequency can be found using the phase-lock principle. The phase-lock principle states that the sum of the time taken for the instability waves to propagate from the jet exit to the obstacle and the time taken for the feedback acoustic waves to propagate from the obstacle upstream to the jet exit must be equal to an integer multiple of the oscillation period and can be given in terms of Strouhal number (S_t) as [24],

$$S_t = \frac{df_N}{U_j} = \frac{N\left(\frac{U_c}{U_j}\right)}{\frac{h}{d}\left(1 + \left(\frac{U_c}{U_j}\right)M_j\right)} \quad (N = 1, 2, 3, ...) \tag{1}$$

where, d is the jet exit diameter, h is the nozzle-plate spacing, f_N is the frequency, U_j is the jet mean velocity, U_c is the convection velocity of the downstream-travelling large structures and M_j is jet exit Mach number. N is an arbitrary integer. The