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Effect of nozzle thickness on the self-excited impinging planar jet

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ABSTRACT

The self-excited oscillation of a large aspect ratio planar jet impinging on a flat plate is investigated experimentally at a single transonic jet velocity to clarify the effect of varying the jet thickness on pattern of jet oscillation and frequency of resulting acoustic tone. The study has been performed for a series of jet thicknesses, 1 mm to 4 mm, each of which is tested for the complete range of plate position, i.e. impingement distance, over which acoustic tones are generated. The results reveal that the jet oscillation is controlled by a fluid-dynamic mechanism for small impingement distances, where the hydrodynamic flow instability controls the jet oscillation without any coupling with local acoustic resonances. At larger impingement distances, a fluid-resonant mechanism becomes dominant, in which one of the various hydrodynamic modes of the jet couples with one of the resonant acoustic modes occurring between the jet nozzle and the impingement plate. Within the fluid-resonant regime, the acoustic tones are found to be controlled by the impingement *distance*, which is the length scale of the acoustic mode, with the jet thickness having only minor effects on the tone frequency. Flow visualization images of the jet oscillation pattern at a constant impingement distance show that the oscillation occurs at the same hydrodynamic mode of the jet despite a four-fold increase in its thickness. Finally, a feedback model has been developed to predict the frequency of acoustic tones, and has been found to yield reasonable predictions over the tested range of impingement distance and nozzle thickness.

1. Introduction

High-speed impinging planar jets are used in a wide variety of different industrial applications such as coating control applications (Arthurs and Ziada, 2012; Arthurs et al., 2012), thermal processing of stock material during metal forming (Ferrari et al., 2003), the production of plate glass, polymer films (Camci and Herr, 2002) and paper products (Viskanta, 1993; Chung and Luo, 2002). Although these flows produce very high rates of heat transfer and large shear stresses making them useful in many applications, they are also known to be liable to the generation of very intense acoustic tones due to interaction of the jet vortical structures with the impingement plate. As first suggested by Powell (1953), the generation of these tones is a part of a feedback mechanism between instabilities in the jet free shear layers, and acoustic disturbances produced by the impingement of coherent structures at the downstream impingement surface. The generation of these acoustic tones can lead to issues with noise levels, and potential vibration and fatigue concerns if the aeroacoustic tones of

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the jet are allowed to couple with mechanical modes of surrounding structures. Some research has indicated that these self-excited flows may have beneficial effects in heat transfer applications, with a more than 70% increase in heat transfer rates being observed for self-excited planar impinging jet flows at low Mach numbers (Camci and Herr, 2002). PIV measurements by Arthurs and Ziada (2012) have shown that the total fluctuation levels in the self-excited planar jet can reach as much as 60% of the initial jet velocity, which would undoubtedly increase heat transfer rates over an equivalent steady flow.

Of the geometries involving impinging jet flows examined in previous studies, geometries involving axisymmetric jets have received the bulk of attention in the literature, with Marsh (1961) first documenting an increase in overall sound pressure levels and discrete acoustic tones for the impinging axisymmetric jet, and the early works of Wagner (1971) and Neuwerth (1972) characterizing the range of impingement ratio and Mach number for which tones are generated, and the jet-staging phenomenon brought about by the excitation of tones by a series of different shear layer modes. Ho and Nossier (1981) and Nossier and Ho (1982) examined the noise generation and feedback mechanism in their two part study on the impinging axisymmetric jet, and attributed the generation of acoustic tones to a feedback mechanism between instabilities in the jet free shear layer which grow into large scale coherent structures, and pressure fluctuations generated by the impingement of these structures at the downstream surface. Later works by Tam and Ahuja (1990) and Panicker and Raman (2007) investigated the presence of helical instabilities at transonic Mach numbers. In addition, a number of authors such as Krothapalli et al. (1999), Elavarasan et al. (2000) and Henderson et al. (2005) have investigated axisymmetric impinging jets using supersonic flow, however the behavior of these systems often involves more complex dynamics of shocks which are not present in the subsonic case.

Investigations of high-speed planar jets impinging on a flat plate have been far less common in the literature, with some recent research by Arthurs (2012), Arthurs and Ziada (2012) and Arthurs et al. (2012) performed to characterize the aeroacoustic response and shear layer modes of the impinging planar jet, but only for a single nozzle thickness of $h=3$ mm. The impinging planar jet was found to generate acoustic tones over two specific regimes, a so-called linear regime occurring at moderate Mach numbers ($0.4 \leq M \leq 0.6$) where acoustic tones are associated with a feedback mechanism, first proposed by Powell (1953), consisting of flow instabilities convecting in the jet shear layers and acoustic pressure fluctuations produced by impingement of the flow structures on the plate, and a so-called fluid-resonant mechanism occurring at higher Mach numbers ($0.6 \leq M \leq 1.0$), where this traditional excitation mechanism couples with one of the *resonance acoustic modes* occurring between the nozzle and the impingement surface. These resonance modes, also called trapped modes (Hein et al., 2004), consist of various patterns of standing acoustic waves occurring in the air volume between the nozzle and the impingement surfaces. The tones were found to be excited over a large range of impingement ratio ($2.0 \leq x_o/h \leq 32.0$), where x_o is the distance between the nozzle and the plate and h is the thickness of the jet nozzle. Measurements of the flow field for a variety of conditions revealed that tones were generated by a series of five anti-symmetric hydrodynamic modes, along with a single symmetric mode occurring only for small impingement ratios. Other studies involving supersonic impinging planar jets have been performed by Krothapalli (1985), Norum (1991) and Tam and Norum (1992), each of which showed a qualitatively similar aeroacoustic response compared to the subsonic impinging planar jet.

There has been significant work performed on other related geometries utilizing impinging planar jets such as the jet-edge and jet-slot systems (e.g. Powell, 1961; Ziada, 1995; Lin and Rockwell, 2001; Ziada, 2001; Billon et al., 2005; Glesser et al., 2008), which share the same feedback mechanism, and thus show some common features in their self-excited response. However, these cases typically involve jets with very low Mach numbers in the incompressible flow regime, and attempts to model these systems generally neglect the upstream propagation time of acoustic disturbances, as they typically have only small effects on the self-excited frequencies, though some investigations of the jet-edge system have been

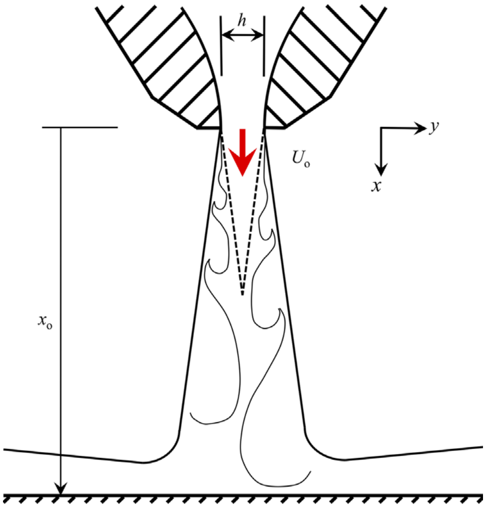

Fig. 1. Basic schematic of the impinging planar jet geometry, showing the impingement distance (x_o), the nozzle thickness (h).