Self-excited oscillations in low-density round and rectangular jets

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by

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Abstract

It is well known that low-density jets develop self-sustained oscillations when the jet-to-ambient density ratio falls below a critical value. Experimental studies on low-density jets have shown that the primary parameters controlling self-excited oscillations are the jet Reynolds number *Re*, the non-dimensional momentum thickness of the nozzle exit velocity profile D/θ_0, the ratio of jet to ambient density S. Much information is available on the dependence of self-excited oscillations on S, *Re*, and high values of D/θ_0. There is however a lack of experimental data on the effect of low values of D/θ_0 on self-excited oscillations, especially at the limiting value of 15 when the flow is fully developed with a parabolic profile, which is the condition in most practical situations. In addition, the information on oscillation characteristics of turbulent low-density jets is also minimal.

Non-circular jets have been the topic of extensive research because these jets have been identified as an efficient technique of passive flow control, and having increased flow mixing and combustion efficiency. There are only few experimental studies available in the literature regarding self-excited oscillations in low-density jets with rectangular geometry. The available literature explored the self-excited oscillations in low-density two-dimensional jets, also known as low-density planar jets. There is no available literature on the behavior of rectangular low-density jets. Rectangular jets have a finite aspect ratio, and they develop in two directions. The momentum thicknesses can be defined along the major and minor dimensions. Planar jets only consider the momentum thickness along the minor dimension, H/θ. The effect of the momentum thickness along the major dimension, W/θ, or the aspect ratio, is not available.

The present study focuses on experimental techniques to understand and fill the gap in the low-density round and rectangular jets regarding the self-excited oscillation characteristics, and study the effects of the various parameters such as Reynolds number, momentum thickness, density ratio, aspect ratio, etc. on self-excited oscillation. Experiments were conducted on two geometries: round nozzles of length-to-diameter (L/D) ratio of 175, 36 and 8, and rectangular nozzles of L/D ratio 8 and 175, with aspect ratio (AR) of 3, 6, 12 and 15. Variation of L/D ratio is used to achieve flows with different velocity profiles at the nozzle exit and hence control the momentum thickness. Schlieren flow visualization

and hot-wire anemometry is used study the jet dynamics. Data processing techniques like FFT and SPOD are used to analyze the data and extract the global oscillation frequency and modes. A calibrated hot-wire anemometer was used to obtain velocity profile information.

Two global modes are seen to exist in low-density round jets. The first mode, called G1 mode, is characterized by a sharp peak in the frequency spectrum, and is observed in laminar low-density jets. SPOD analysis reveals that the self-excited oscillations of G1 mode in jets with parabolic velocity profile is axisymmetric. The Strouhal number of G1 mode is seen to attain a lower limit of 0.275 ± 0.003. Strouhal number for the G1 mode in fully developed flow is seen to be independent of Reynolds number, indicating no effect of Reynolds number in fully developed flow. The second mode, called G2 mode, is characterized by a distinct but broader peak as compared to G1 mode, as is observed in turbulent low-density jets. The results confirms that turbulent jets can exhibit self-excited oscillations for $S \leq 0.53$. The jet is seen to transition from laminar to turbulent between $2200 \leq Re_a \leq 2700$ ($Re_a = \rho U_a D / \mu$, where U_a is the average jet velocity) through the occurrence of puff structures, during which the oscillating mode transitions from G1 to G2. Strouhal number for the G2 mode increases slowly with increase in Reynolds number, indicating a weak dependence. SPOD analysis reveals that the G2 modes is axisymmetric.

Low-density round jets have been reported to transition to a self-excited state through subcritical as well as supercritical Hopf bifurcations in the experimental study by Zhu et al. (2017). In the cases where subcritical Hopf bifurcation were observed, the width of the bistable region was found to be very small: (Re_H - Re_{SN})/Re_H $\approx$ 2% - 5%, where the subscripts H and SN denote the Hopf and saddle-node points respectively (Zhu et al., 2017). In the present experiments, the increment in Re is higher than the value reported by Zhu et al. (2017). Therefore, no comment can be made on the the nature of Hopf bifurcation of low-density round jets in the present experiments, which is also not an objective that is investigated in the present study.

Studies on rectangular low-density jet reveal that the jet transitions from a stable to a self excited state through subcritical and supercritical Hopf bifurcation. Only supercritical bifurcations are observed during transition when aspect ratio (AR) is greater than 12. For lower aspect ratios, the type of Hopf bifurcation is dependent on the density ratio. The jet transitions through a subcritical Hopf bifurcation within a range of density ratio, outside which it transitions through the supercritical Hopf bifurcation. SPOD analysis of low AR rectangular jets ($AR \leq 6$) show that the spatial structure of the oscillation is a symmetric mode. SPOD analysis reveals that the spatial structure of the oscillation in high AR rectangular jets ($AR \geq 12$) consists of three modes: a symmetric mode, a flapping mode in the major dimension and a complex mode similar to the ce_2 mode in elliptic jets. Previous studies call the ce_2 mode the 'pinched' mode due to the reduction or pinching of the jet along the axis. Strouhal numbers for low-density rectangular jets with parabolic profile along the minor dimension are seen to increase with increase in Re, which show that the major dimension has an influence on the oscillation frequency when $AR \leq 6$. Side jets, which are radial ejection of fluid from the main jet, are present in low-density rectangular jets, and in conjunction with low-density round jets of $D/\theta_0 = 15$, can be used to test the hypothesis for the existence/non-existence of the side jets.