An investigation of vortex ring formation in strongly forced jet flows by high speed particle image velocimetry

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The periodic formation of vortex rings in the development region of a round jet subjected to high levels of acoustic forcing is investigated with High Speed Particle Image Velocimetry (HSPIV). The HSPIV measurements provided a time-resolved history of vortex ring evolution so that the roll-up time, pinch-off location and circulation of the vortex rings could be evaluated. The circulation of the vortex rings increased linearly with A with many cases exhibiting a trailing jet indicative of an optimal vortex ring as defined by Gharib et al. (1998) and Linden and Turner (2001). The location where the vortex ring started to roll-up moved progressively upstream towards the nozzle exit. It is shown that a universal formation time-scale exists based on the forcing period, T, determines the amount of vorticity periodically discharged from the nozzle exit that is rolled-up into the vortex ring occurs at t/T ≈ 0.3. Overall, the effect of high amplitude forcing is marked by a transition from amplification of shear flow instability to the periodic break-up of the jet into large-scale vortex rings sharing many of the features of starting jets.

1. Introduction and Experimental Method

Previous studies provide information about the vortex ring formation at starting jets, but mainly concentrate on the single vortex ring generation. However, no studies have investigated whether or not the existence of such a limiting process exists in forced jets.

The focus of this paper is to study the response of strongly forced jet flows and to characterize the resulting properties and timescales of the vortex rings. There are several issues of interest, for example, when does a forced steady jet become an unsteady jet? What is the amplitude and frequency dependence on vortex ring properties? Does a limiting process exist for forced jets? For this purpose, an experimental investigation has been performed using 2D High Speed Particle Image Velocimetry (HSPIV) for the quantitative examination of the flow field. HSPIV enabled velocity vectors and the derived quantities to be obtained with a high temporal resolution. Time-resolved iso-vorticity contours were used to identify the boundary of the vortex rings and track their evolution from the initial roll-up stage through to pinch-off.

2. Conclusion

In this study, investigation of periodic formation of vortex rings in the development region of a round jet subjected to high levels of acoustic forcing has been performed for a wide range of experimental conditions. Harmonic velocity oscillations of 20 to 130% of the mean flow at the jet exit were achieved for several forcing frequencies determined by the acoustic response of the system. High Speed Particle Image Velocimetry (HSPIV) was shown to be capable of providing required data which was used to characterize the flow field and the vortex ring structures. Time-resolved history of vortex ring evolution enabled the evaluation of circulation, roll-up time and pinch-off location of the vortex rings.

During a period of forcing it was observed that a single vortex ring forms and a trailing jet region followed indicating the presence of an optimal ring. This behaviour is similar to what was reported by Gharib et al. (1998) for the formation of a single ring in starting jets with large L/D’s. Although vortex ring size linearly increases with A, a limitation was observed with respect to the total circulation. This limitation is specific to the periodic nature of the exit velocity and regardless of A. The intersections of the vortex ring circulation lines with their corresponding total circulation curves occur at t/T = 0.30. The universal characteristics of this time step in the range of experimental conditions investigated leads to a universal formation number for the vortex ring formation in forced jets.

Comparison of the flow fields at different forcing amplitudes with unforced jet flow shows how the jet shear layer is periodically broken down into controlled large-scale coherent structures. As A was increased, the location where the vortex ring started to roll-up moved progressively upstream towards the nozzle exit.

Finally, the length- and timescales of the formation process based on the completion and pinch off of the vortex ring were shown. Pinch-off distances and times were determined for each experimental condition. Increasing A results in decrease in the pinch off time while pinch off occurs later at larger frequencies. Pinch-off distance is almost constant with A, except the A values smaller than 0.50. Non-dimensional pinch-off time collapses all the data showing that the x_p and T have a linear relationship where the slope, which can also be considered as the non-dimensional average vortex ring velocity until the pinch off incidence, is approximately 0.50.