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ON THE FORMATION OF WAKE INDUCED STRUCTURES IN A BASIC ANNULAR JET

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ABSTRACT The formation of the wake-induced structures in a basic annular jet under acoustic excitation has been studied with conditional sampling technique. Different triggering criteria were adopted on two simultaneous streamwise velocity fluctuations measured at the same axial and radial position on opposite azimuthal planes in order to detect the passage of the wakes in different azimuthal modes. Besides the shedding of the first mode wake or the zero mode wake, intermediate jet vortices in the outer mixing region are observed to coalesce together forming the wake-induced structure. Similar to their wake counterparts, the first mode wake-induced structures on the two opposite azimuthal planes are located in a staggered pattern while the mode zero wake-induced structures propagate downstream at the same front.

INTRODUCTION

In a basic annular jet with a blunt-ended centrebody, the flow structures in the outer region are excited by the wake structures shed periodically in the inner region, resulting in the formation of wake-induced structures which frequency is the same as the wake shedding frequency (Ko and Chan, 1979). The wake and wake-induced structures were both shown to contain a dominating first azimuthal mode constituent (Ko and Lam, 1985). While the wake structures possess a quasi-two-dimensional vortex-street character, successive wake-induced structures alternate on the two sides of a quasi-two-dimensional orderly plane (Lam et al., 1986). Besides the first mode constituent, the wake-induced structures were also found to be dominant in the mode zero constituent (Ko and Lam, 1985). In this paper, based on conditional sampling technique using two triggering wires, wake-induced structures formed under the excitation of the first or zero mode wake structures are investigated.

APPARATUS AND EXPERIMENTAL TECHNIQUE

The diameter of the outer nozzle and the centrebody of the annular air jet under study were respectively D of 6.6 cm and d of 3.0 cm. The jet exit velocity U_e was 50 m/s, giving a Reynolds number U_eD/ν of 2×10^5. Throughout the experiment, upstream acoustic excitation at the frequency of the intermediate jet vortex, which was formed from four successive initial jet vortices via two pairing processes in cascade, was applied in order to obtain better eduction results. The signals from two single hot wire probes placed inside the annular potential core near the inner mixing region at x/D = 0.5 and y/D = ± 0.275 were the triggering signals (Figure 1). A recovery cross-wire probe was used to measure the velocity fluctuations at different locations. The adopted triggering criteria assumed the passage of a zero mode wake when both triggering signals reached the relative maximum above a threshold level of 0.75 σ within ± 0.2 ms and the passage of a first mode wake when both signals reached the relative maximum above 0.75 σ within 1.2 $\pm$ 0.2 ms. Thus, coherent axial and lateral velocities (U_c and V_c) corresponding to flow structures of different modes were obtained.

RESULTS AND DISCUSSIONS

Figures 2a to 2d show the spatial distributions of coherent vorticities ($\Omega_c = \partial V_c/\partial x - \partial U_c/\partial y$) triggered by the first mode wake at τ = 0.45, 1.45, 2.95 and 3.45 ms respectively, where τ is the time relative to the triggering instant. At τ = 0.45 ms, a negative vorticity region, which is probably related to the triggering first mode wake structure, is observed with centre at x/D = 0.7 and y/D = 0.15 and is labelled by $W1_-$. This wake is shown to rotate clockwisely by the corresponding coherent velocity vector map (not presented here). In the outer mixing region, regions of positive coherent vorticity ($J2_+$ to $J4_+$) are observed at positive y positions and those of negative coherent vorticity ($J2_-$ to $J4_-$) at negative y positions. All these regions are those outwardly rotating intermediate jet vortices of frequency 1600 Hz and wavelength of 1/3 D. The intermediate jet vortex has been shown by spectral analysis to be formed from four successive initial jet vortices via two pairing processes in cascade (Lau, 1991).

At τ = 1.45 ms, $W1_-$ has convected to x/D = 1.3 and another first mode wake $W1_+$ rotating in anti-clockwise direction is observed at x/D = 0.6 and y/D = -0.15. The axial separation of $W1_-$ and $W1_+$ is 0.7 D and the wavelength of the first mode wake is estimated to be 1.4 D. Identities of the intermediate jet vortices $J4_+$ to $J6_+$ are clearly observed in the outer mixing region. The axial positions of $J4_+$ and $J6_+$ are the same as $W1_-$ and $W1_+$ respectively. The lateral position of $J5_+$, which is under the influence of the positive lateral velocity fluctuations induced by the trailing edge of $W1_-$ and the leading edge of $W1_+$, is further away from the jet central axis. As a result, its convection velocity is smaller than that of $J6_+$ and these two vortices $J5_+$ and $J6_+$ coalesce to form the paired jet vortex $J56_+$ near x/D = 1.05 at τ = 2.25 ms as shown in Figure 2c. When $J56_+$ is formed, its axial location is the same as that of $W1_+$. Further downstream, the intermediate jet vortex $J7_+$ following $J56_+$ is displaced inwardly by the lateral velocity fluctuations of the wake. Consequently, $J56_+$ and $J7_+$ coalesce to form the wake-induced structure $J567_+$ at x/D = 1.6 as shown in the coherent vorticity map at τ = 3.45 ms. Intermediate jet vortices $J7_-$ to $J9_-$ near y/d = -0.5 coalesce to form another first mode wake-induced structure near x/D = 1.8 at τ = 5.45 ms. This suggests that the first mode wake-induced structures on the two opposite azimuthal planes are located in a staggered pattern.

The spatial distributions of coherent vorticities triggered by the zero mode wakes ($w1_-$ and $w1_+$) at τ = 0.45 and 3.95 ms are shown in Figures 3a and 3b respectively. $w1_-$ and $w1_+$ are shown to be associated with negative and positive coherent vorticities respectively (Figure 3a). Similar to the first mode pattern, successive intermediate jet vortices ($j4_+$, $j5_+$, $j4_-$ and $j5_-$), under the influence of the zero mode wakes, also coalesce to form the paired jet vortices, $j45_+$ and $j45_-$ (Figure 3b). These paired jet vortices subsequently coalesce with the following intermediate jet vortices to form the zero mode wake-induced structures further downstream. Hence, the zero mode wake-induced structures on the opposite azimuthal planes are convecting downstream at the same front.

CONCLUSION

The eduction results obtained by imposing triggering criteria on two streamwise velocity signals show not only the dominant first mode wake structures but also the zero mode wake structures. Successive intermediate jet vortices in the outer mixing region are observed to be displaced laterally and coalesce together under the influence of the wake structures, resulting in the formation of the wake-induced structures. While the first mode wake-induced structures on the two opposite azimuthal planes are located in a staggered pattern, the zero mode wake-induced structures propagate downstream at the same front.

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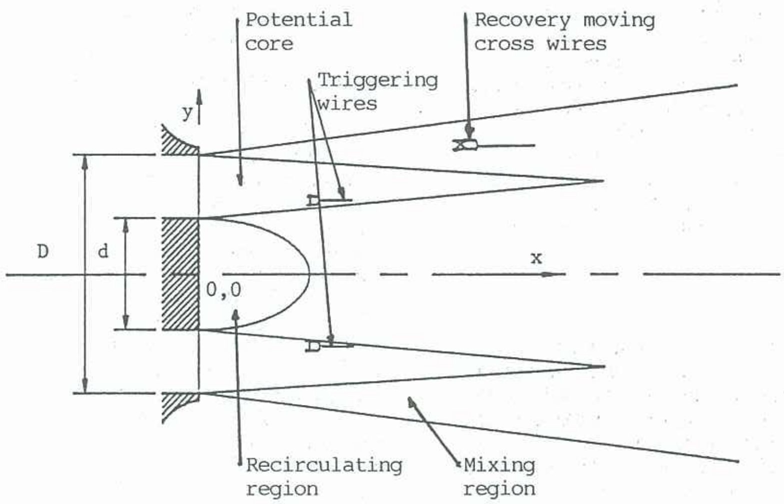

Figure 1: Schematic diagram of the annular jet.
(U_e = 50 m/s; Re_D = 2 x 10^5).

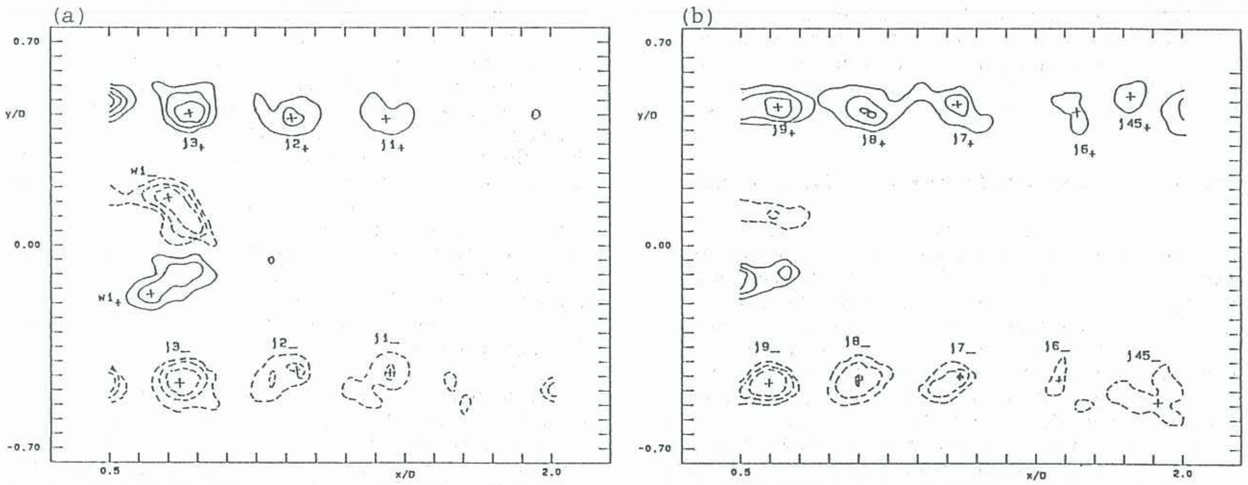

Figure 3: Spatial distributions of coherent vorticities Ω_c triggered by zero mode wakes.
(a) at τ = 0.45 ms and (b) at τ = 3.95 ms.
Normalised contour levels: ±0.5; ±0.75; ±1.0; ±1.5.

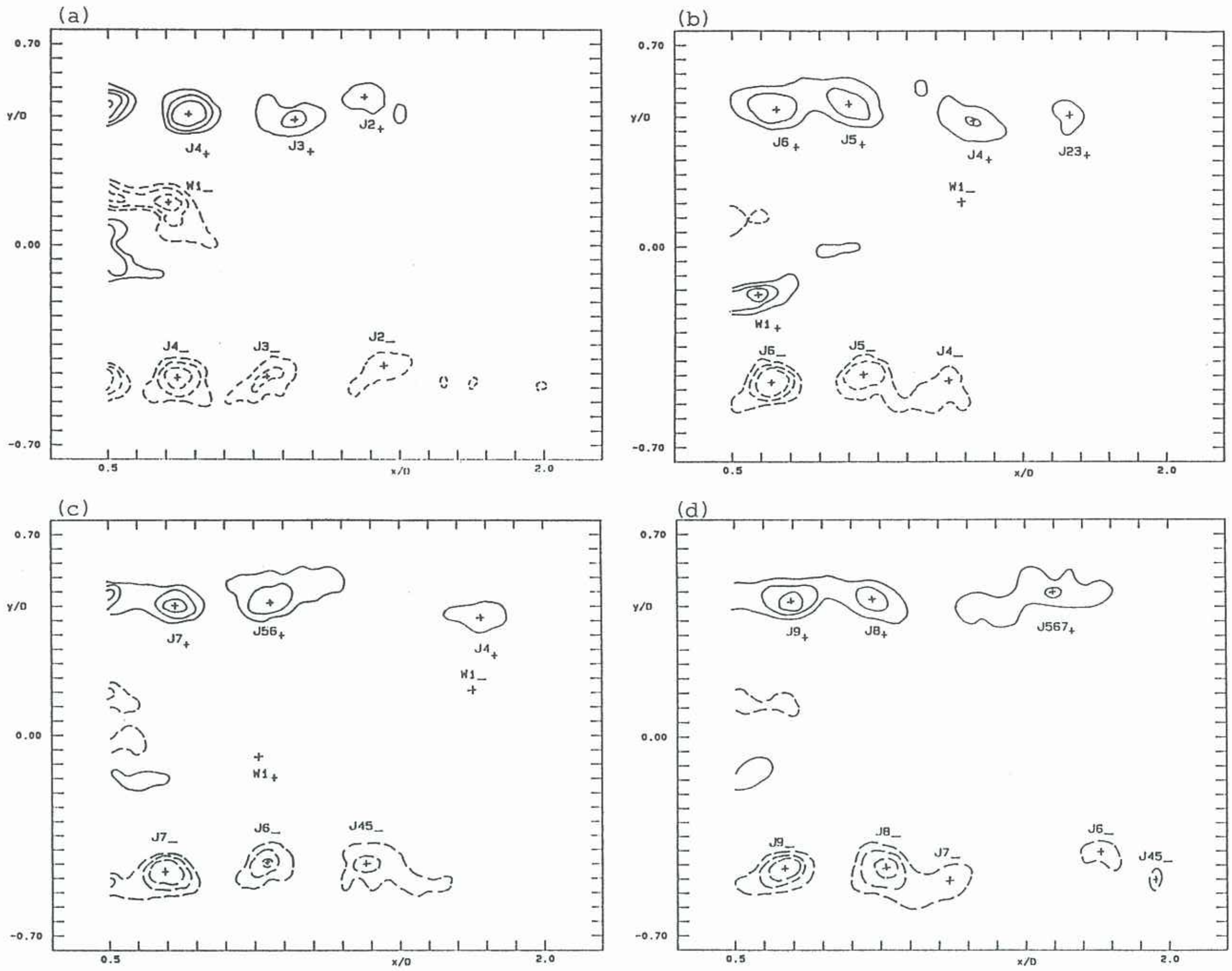

Figure 2: Spatial distributions of coherent vorticities Ω_c triggered by first mode wakes.
(a) at τ = 0.45 ms, (b) 1.45 ms, (c) 2.25 ms and (d) 3.45 ms.
Normalised contour levels: ±0.5; ±0.75; ±1.0; ±1.5.