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Experimental Studies on the Interaction of Jets with the Vortex Wake of Slender Bodies

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Abstract : An experimental study has been conducted to examine the low-speed aerodynamic characteristics of a pair of circular jets behaviour in the vortex-wake of a blunted cone cylinder-body combination with and without a 70^o leading edge sweep delta wing. The induced flow-field was examined via two-dimensional hot-wire anemometry surveys. Comparisons were made between the induced wake with and without the circular jets. The flow field over the models was visualized using smoke and oil flow visualization. The jet-pair was found to undergo severe distortion within a very short distance from the nozzle exits. The shape of the jets was shown to change considerably when placed in the vortex wake flow field of the models, which caused the jet-pair to spread and become entrained within the vortices and wake created by the models.

Keywords : Delta wing, Jet, Vortex, Wake, Slender bodies.

1. Introduction

There are environmental concerns about the possible entrainment of co-flowing jets in the vortex wake of an aircraft. Engine exhaust products entrained in the vortex wake would have different dispersion and mixing characteristics from those in simple co-flowing jets (Menon and Wu, 1998). If the exhaust does become entrained in the wake of an aerodynamic body, the jet is likely to become cooled. This cooling effect could change considerably the chemical characteristics of exhaust products and could stop a number of exhaust reactions from taking place. As a consequence, it may be possible to reduce the production of chemical pollutants (Garnier et al., 1997). Military technologists are also concerned with how the exhaust characteristics may influence the target acquisition effectiveness of optically based sensors due to distortion of wake signature (Wang et al., 2000). Vortex–plume interactions alter the acoustics and mixing characteristics of high-speed jets, a process that must be clearly understood to achieve accurate predictive capabilities (Seiner et al., 1997). However, in spite of the existing practical applications and progress made in the understanding of the turbulence mechanism in a wake vortex, an essential lack of information still exists, especially explaining the entrainment and mixing processes of the engine emissions in the vortex wake. The earliest experimental investigation on the subject is that of Werle and Fiant (1964), where flow visualization studies of jets issuing into the vortex wake of a Concorde-type plan form were conducted. El-Ramly and Rainbird (1977) examined the effect of engine exhaust on a wing tip vortex of a Boeing 747 configuration. Jacquin and Garnier (1996) investigated numerically the dynamics of a jet in aircraft vortex wakes. Brunet et al. (1999) presented experimental results of a hot jet behind a generic wing plan form. Wang et al. (2000) studied the interaction between the vortex-wake of a 75-degree leading-edge sweep delta wing and a circular jet issuing from a tube parallel to the centreline of the wing. It was shown that the wing vortices were only mildly affected in terms of their trajectory by the jet. In all cases the jet was compressed vertically but substantially elongated laterally. The horizontal spreading of the jet progressed non-linearly with angles of attack. Gago et al. (2002) performed a three dimensional temporal numerical simulation of the interaction between a jet and a vortex wake. The induced turbulence by the jet flow field interacted with the vortex, resulting in large-scale structures generated outside the vortex core, whereas the region very close to the core kept its laminar state. Wang and Zaman (2002) examined the low speed jet behaviour in the trailing vortex wake of a wing. The jet exhibited a far quicker maximum velocity decay compared to the baseline co-flowing jet of the same velocity ratio. The trajectories of the leading-edge vortices were shown to be slightly influenced by the jet. The peak vorticity and circulation of the leading edge vortices appeared to be substantially reduced, when the leading edge vortices began to ingest a jet possessing a high momentum. The present study aims: a. to examine the vortex wake and flow field characteristics of a delta wing slender body combination and cylindrical bunted cone body, b. to investigate the effects of co-flowing jet-pair in the near field on the vortex wake, c. to quantify the distortion of wake signature, and d. to contribute to the existing database of jet and vortex wake interaction, and jet spreading and entrainment.

2. Experimental Set-Up

The investigation was performed in a 0.45 x 0.45 m blown-type low-speed wind tunnel facility at UMIST. All experiments were conducted at a free stream velocity of 18 m/s. The nominal turbulence level in the test section was 0.05%. Figures 1a and 1b show the geometry of the blunted-cone cylinder-body with and without the delta wing and the coordinate system employed. The flat-top delta wing had a 10 deg chamfer angle normal to its leading edges, a 70-deg sweepback angle, a 0.078 m span at the trailing edge, a constant thickness equal to 0.003 m and an aspect ratio of 1.45 based on the delta wing plan form area (0.00627 m^2). Two circular pipes of 0.007 m inside diameter were introduced through the bottom floor of the tunnel. The straight sections were fitted with flow conditioning screens to produce an axisymmetric flow at the exit of the pipes. The jets were supplied by air via the Department's pressure delivery network and controlled using a regulator. The mass flow of the incompressible jets was monitored with an orifice meter, from which the average velocity was inferred via the continuity relation. The average velocity of the dual exhaust system was further checked using a single miniature straight hotwire anemometer system (TSI 1260A) made of tungsten with diameter of 4 μm. The single wire had a length of 0.0015 m with a flat frequency response up to 30 kHz. The velocity of the exhaust system was set to be the same as that of the wind tunnel. The jet-pair was placed on the upper surface of the models along the centreline of the cone-cylinder body for all cases tested. To isolate the influence of the vortex wake itself on the evolving plume, the orientation of the jet-pair was fixed parallel to the free stream direction instead of varying with the model's angle of attack.

Table. 1. Position of the models in the cross-stream (y, z) plane (unit: metres).

incidence	-10°	0°	10°
centre of blunted cone nose	0, 0.017	0, 0.02	0, 0.024
centre of cylinder body base	0, 0.024	0, 0.02	0, 0.017
port delta wing tip	-0.04, 0.024	-0.04, 0.02	-0.04, 0.017
starboard delta wing tip	0.04, 0.024	0.04, 0.02	0.04, 0.017
centre of dual jet exhaust system	0, 0.038	0, 0.038	0, 0.038

Note: All coordinates relative to the geometric longitudinal centreline of the test section.

The wake field and surface flow characteristics of all models tested were mapped at incremental incidences of 5° from –20° to 20°. Two-dimensional flow surveys were conducted using hotwire anemometry at a distance of 13 jet diameters from the rear of the models. The data were taken with the spacing, $\Delta y = \Delta z = 0.002$ m. A standard X-probe (TSI-1241) made of tungsten with diameter of 4 μm, mounted on a computer-driven traverse was employed for the diagnostics, measuring the direction as well as the magnitude of the u-v velocity components. At each measurement location, data acquisition was performed over 12 s at a sampling rate of 1000 Hz. Stability of all parameters considered was achieved after approximately 8 s. The v data were corrected for the error introduced by the mean shear and the finite separation of the sensors in the X-array based on the methodology described by Bell and Metha (1993). The oil flow technique was employed to map in detail the surface flow characteristics of the models tested. The smoke technique assisted the interpretation of the surface flow patterns mapped by the oil flow and provided useful information about the wake of the models. Table 1 shows the position of the models within the wind tunnel for the cases presented in the article.

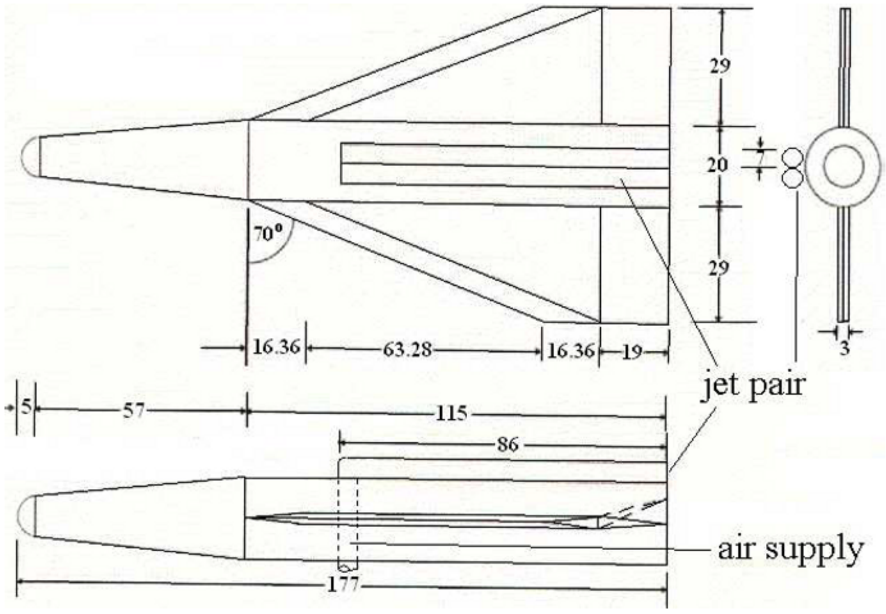


Fig. 1a. Geometry of the models (unit: mm).

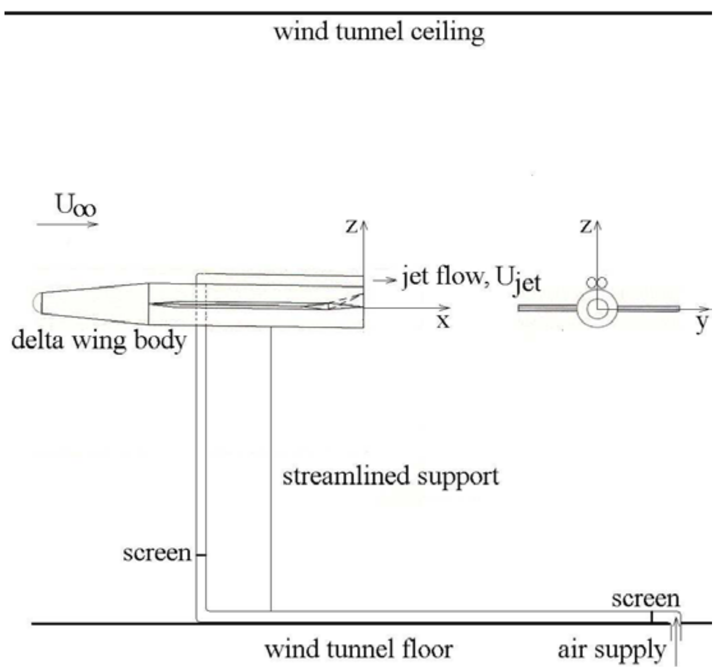


Fig. 1b. Experimental set-up and coordinate system (not in scale).

3. Results and Discussion

The Reynolds number of the cone-cylinder delta-wing model based on the total body length was $2.1x10^5$. For the pair of jets, the Reynolds number based on the orifice diameter of a single jet was $8.4x10^3$. In all cases, the wake maps present the velocity distribution, defined as $U=(u^2+v^2)^{0.5}$.

3.1 Co-Flowing Jet-Pair

The characteristics of the co-flowing jet-pair itself were investigated before the introduction of the models. The velocity of the exhaust system was set to be the same as that of the wind tunnel. Four survey stations, ranging from 1 to 13 jet diameters downstream were examined using spatial increments of 0.001 m. All remaining data acquisition tests were conducted with a spatial resolution of 0.002 m in both horizontal and vertical traverses. This resolution represented 2.7 % and 29 % of the span of the model and single jet diameter respectively. At one-jet diameter downstream location, the jet-system cross section was axisymmetric and the jet-pair axis was located at y= 0 m, z= 0.038 m in the cross-stream (y, z) plane relative to the geometric longitudinal centreline of the test section. Two velocity peaks were observed, which correspond to each jet. A typical measurement taken at 13 jet diameters downstream is shown in Fig. 2. The structure of the exhaust system remained stable and the location of the velocity peaks within the exhaust remained constant. The value of those velocity peaks is 17.8 m/s.

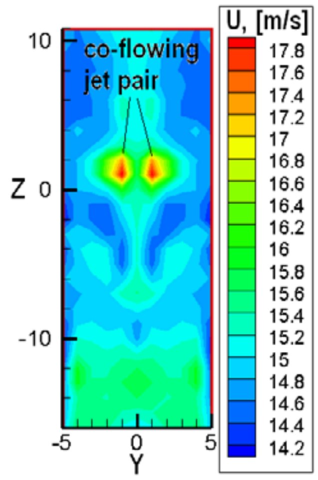


Fig. 2. Velocity distribution contours for the co-flowing jet pair at 13 jet diameters without model.

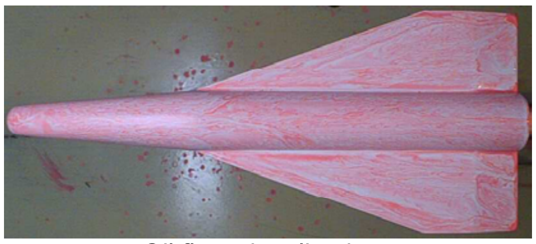
3.2 Delta Wing Body without Jets

The oil-flow and smoke visualization pictures show a pair of symmetric counter-rotating vortices to form on the leeward surface of the delta wing body with increasing incidence, Fig. 3. At incidence α= 3 deg, the leeward surface flow is attached except at the junction regions of the cone-cylinder delta wing body combination where a corner vortex is formed, Fig. 3(a). The oil-flow picture at incidence α= 15 deg, Fig. 3(b), depicts the complicated surface map which comprises of a series of alternating separation and attachment lines, due a system of clockwise and anticlockwise rotating vortices. Both the smoke and oil flow visualization methods show that the size and strength of the vortices increases and they become more rolled-up with increasing incidence, Fig. 3. Regions of separated flow are also evident in the trailing edge corner-tips of the delta wing. With increasing incidence, those separated regions extend slowly laterally and longitudinally towards the inner root and leading edge of the wing plan form, respectively.

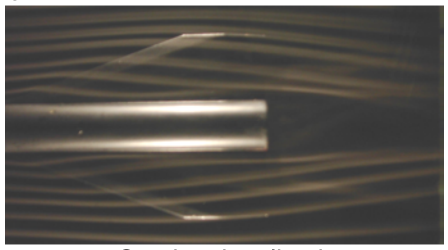
3.3 Effect of the Exhaust System

The presence of the wing plan form significantly deforms the jet-pair. At incidence α= 0 deg, the wake of the exhaust system is caught up with the wake of the cone cylinder delta wing body, which causes it to extend laterally and to be displaced slightly from its original position, Figs. 2 and 4(b). Two velocity peaks were measured, 20.1 m/s, Fig. 4(b). At incidence α= -10 deg, the wake of the exhaust is clearly visible and it can be distinguished from the wake of the trailing vortices of the delta wing body, Fig. 4(a). Both wake signatures are stretched sideways while compressed vertically and displaced upwards from their original positions due to their mutual interference effects and the dynamics of their neighbouring flow structures. Two velocity peaks were measured, 18.4 m/s, Fig. 4(a). It is conjectured that when the jet-pair becomes weaker, Fig. 4(a), the trailing vortices start tearing the jets. At incidence α= 10 deg, the mutual interference of the exhaust system and delta wing body wakes is more profound; the wake of the exhaust is significantly deformed and has become entrained in the wake of the body, Fig 4(c). The combined wake signature is displaced downwards relative to the original positions of the exhaust and body wakes alone, Figs. 2 and 4(c). Two velocity peaks were measured, 24 m/s. The comparison of Figs. 4(a), 4(b) and 4(c) indicates that the location of the velocity peaks can migrate laterally, causing the velocity along the axis of symmetry to be lower. It is conjectured that the increasing entrainment at higher incidences, causes acceleration of the jet-pair to higher velocities, whereas at lower incidences the opposite effect is occurring, Figs. 4(a), 4(b) and 4(c).

(a) incidence 3°



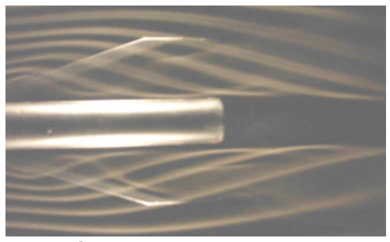
Oil flow visualization



Smoke visualization

(b) incidence 15°

Oil flow visualization



Smoke visualization

Fig. 3. Delta wing body without jets: flow field visualization.

Similar effects due to the presence of the jet-pair were observed for the cone-cylinder body, Figs. 5(a), 5(b) and 5(c). At incidence α= 0 deg, the wake of the exhaust system is more well defined and stronger due to the absence of the delta wing trailing vortical system, Figs. 5(b) and 4(b). Two velocity peaks were measured, 21.5 m/s, Fig. 5(b). At incidence α= -10 deg, the effect of the wake of the cone-cylinder body on the exhaust system is less pronounced, which causes a smaller upward displacement of the jet-pair wake in comparison to the delta wing body case, Figs. 5(a) and 4(a). Two velocity peaks were measured, 18.2 m/s, Fig. 5(a). At incidence α= 10 deg, the wake of the exhaust has become fully entrained in the wake of the body, Fig. 5(c), however, the downward displacement of the combined wake signature is smaller than that of the delta wing body case, which is due to the absence of the wing plan form, Fig. 4(c). Two velocity peaks were measured, 26 m/s. The comparison of Figs. 5(a), 5(b) and 5(c) indicates that the body wake is "pulling" the jet-pair wake inwards towards the axis of symmetry. The "pulling" effect of the cone cylinder body wake is more profound in the present case due to the absence of the competing effect from the delta wing vortices, which causes an increase in the entrainment of the jet-pair with higher velocity peaks.

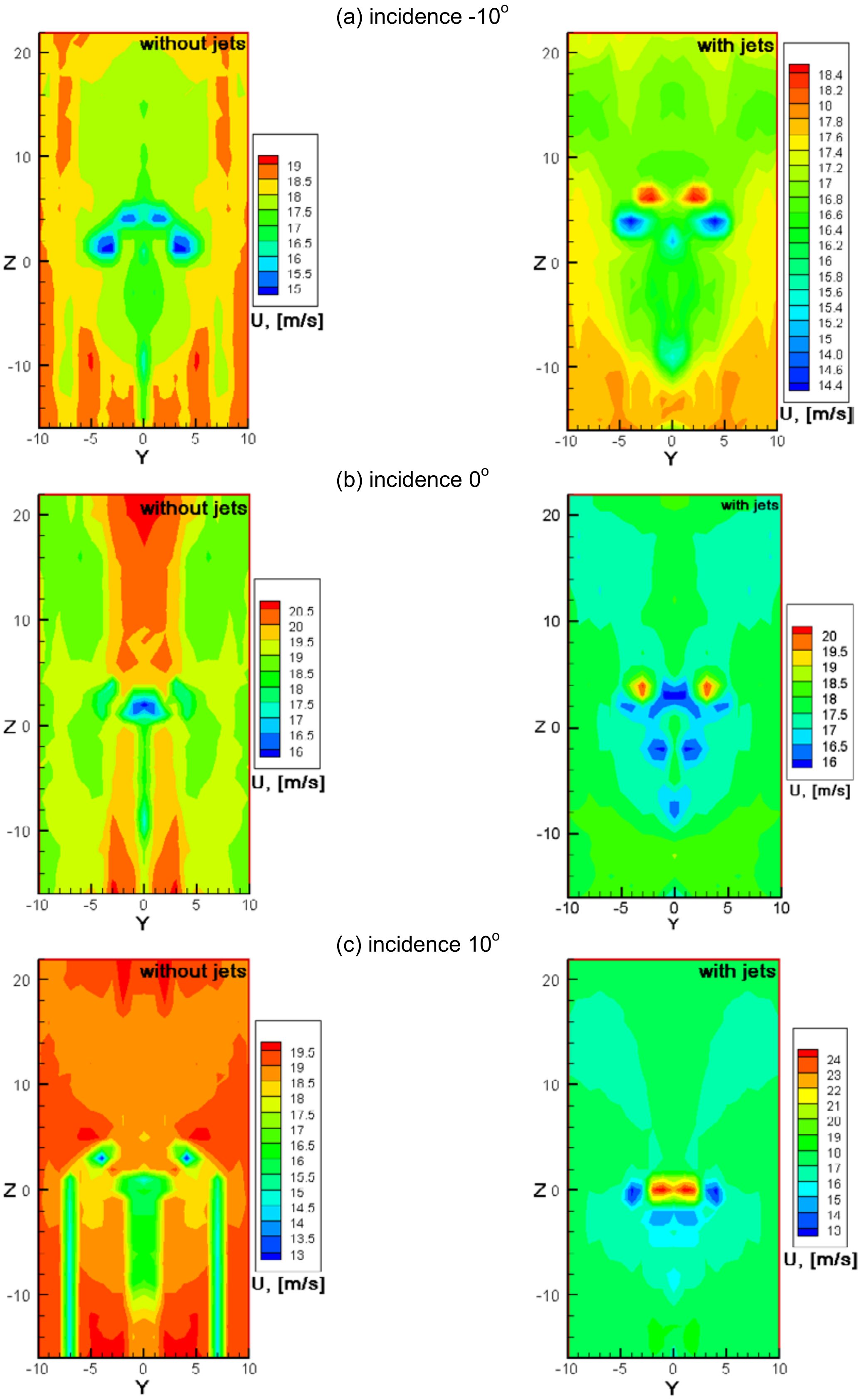


Fig. 4. Wake signature of the delta wing body with and without jets.

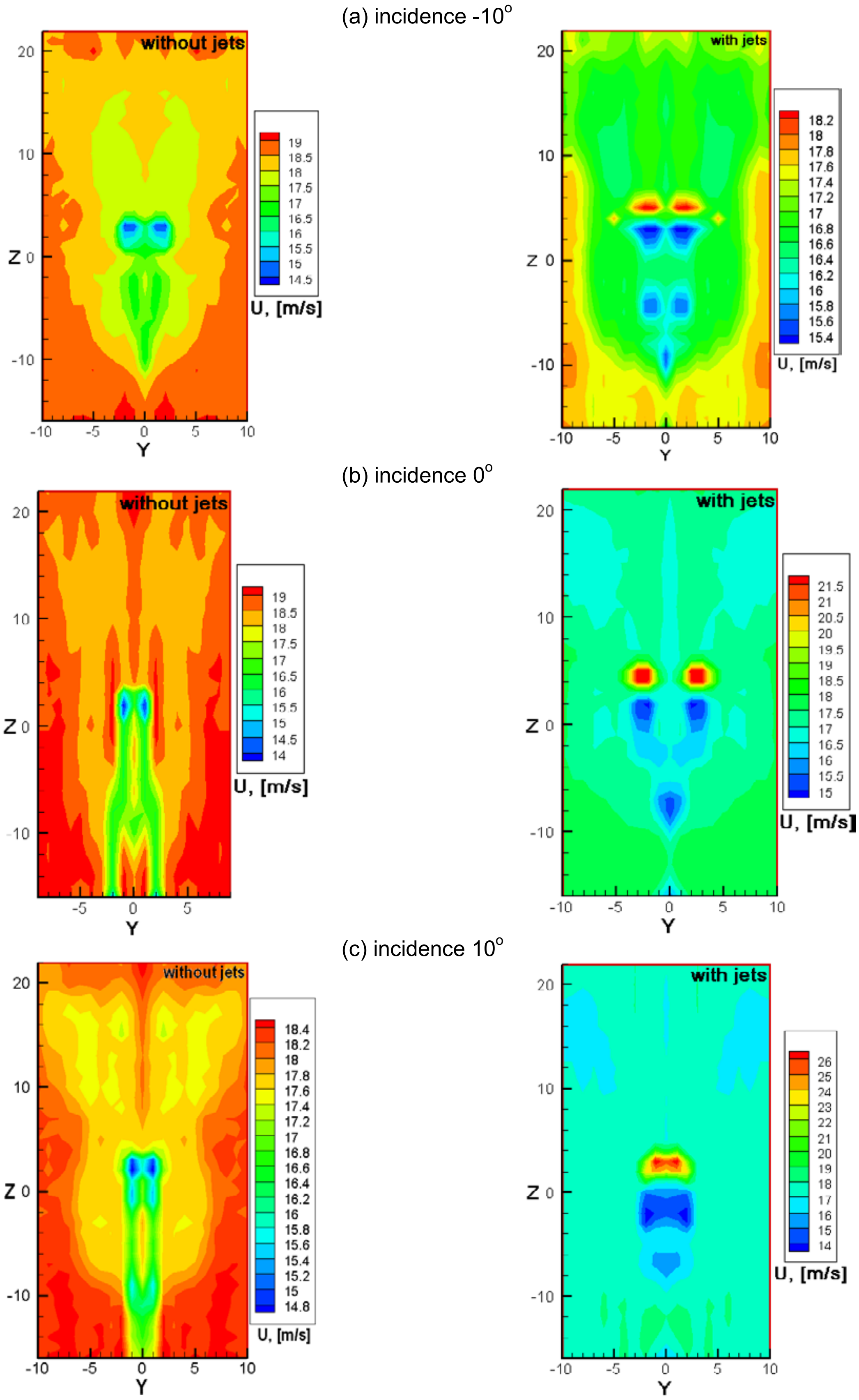


Fig. 5. Wake signature of the cone cylinder body with and without jets.

4. Conclusions

The present investigation shows the critical influence of a jet pair on the shape of the flow field of slender bodies with and without delta wings. The behaviour of an isolated co-flowing jet-pair could be quite different, when vortices shed from components such as those from flaps, wing-fuselage junctions, wing tips, etc., during cruising, landing and take off, pass by the vicinity of the jet system. For all cases tested, the entrainment and interference effects of the exhaust and body wakes were increasing with incidence and the development of the jet system was heavily influenced by the dynamics of both leading-edge vortices from the delta wing and body wake. The increasing entrainment at higher incidences caused acceleration of the jet-pair to higher velocities, whereas at lower incidences the opposite effect was observed. The “pulling effect” of the cone cylinder body wake alone was more pronounced due to the absence of the competing effect from the delta wing vortices, which caused an increase in the entrainment of the jet-pair with higher velocity peaks. Within a few diameters downstream from the exit of the jet pair, the structure of the exhaust system would deform into a shape predominantly governed by the properties of the flow field that surround it.

Acknowledgments

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