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DYE VISUALIZATION OF A YAWED SLENDER DELTA WING

İlyas KARASU
Gaziantep University
Faculty of Aeronautics and Aerospace
Aerospace Engineering
Gaziantep Turkey

***Beşir ŞAHİN**
Çukurova University
Faculty of Engineering and Architecture
Mechanical Engineering
Adana Turkey

Hüseyin AKILLI
Çukurova University
Faculty of Engineering and Architecture
Mechanical Engineering
Adana Turkey

Çetin ÇANPOLAT
Çukurova University
Faculty of Engineering and Architecture
Biomedical Engineering
Adana Turkey

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* *Corresponding author,B. Şahin, E-mail address: bsahin@cu.edu.tr*

ABSTRACT

In the present experimental study, effects of yaw angle, β on the flow structure at high angles of attack, α with 70° sweep angle, Λ were investigated using the dye visualization technique. In the case of zero yaw angle, β a pair of leading edge vortices take place on both sides of cords axis are more or less symmetrical over the delta wing. These symmetrical vortical flow structures start deteriorating when angle yaw, β is introduced. Onset of vortex breakdown location on the windward side occurs further upstream, on the other hand, the leading edge vortex on the leeward side breaks down further downstream. A perceivable interactions are consisted between structures of vortical flows developed from pair of leading edge vortices after onset of vortex breakdowns. It can be concluded that the magnitude of the leading-edge vortices, onset of vortex breakdowns, and formation of unsteady flow structures generated after vortex breakdowns are substantially affected by yaw angle, β. Angles, θ_1 and θ_2 between centerline of the delta wing and both central axes of spiral vortices vary as a function of yaw angle, β.

INTRODUCTION

Because of high maneuverability and superior aerodynamics performance, delta wings are primarly used in the design of combat aircrafts. Flow structures over delta wing consist of two counter-rotating leading edge vortices. Separated flow from the leading edge form a curved free-shear layer rolling up into a core [1]. Earnshaw [2] showed that leading edge vortices of a delta wing could be divided into three different regions; vortex core, viscous sub-core and outside of vortex core (free-shear layer).

Leading edge vortices induce a flow in the spanwise direction towards the upper surface and this the outward flow separates from the surface forming a smaller secondary vortices outboard and below primary vortex [3]. Leading edge vortices in a fully developed stable stage causes extra lift and increases maximum angle of attack, α and this improves maneuver capability of aircrafts [4]. As the angle of attack, α of delta wing increases, leading edge vortices expand suddenly leading to vortex breakdown or vortex bursting [5]. Vortex breakdown is decomposition of leading edge vortex. The size of this leading edge vortex expands or swirls and finally bursting of vortex takes place to develop and shed large scale vortices [6]. Lee et al. [7] performed an experimental study about delta wing for steady and unsteady flows. They showed that separated leading edge vortices controlled by inviscid shear layer for the Reynolds number of 23000 since viscosity does not play a role in delta wing aerodynamics. They compared the coefficient of lift (C_L) determined from their result with previously published experimental data obtained at the Reynolds number of Re=6x10^6 Both results have very close numerical values at the same angle of attacks, α moreover vortex breakdown location were also compared with other two different experimental studies. They showed that the location of breakdown points are not same and differences were not appreciable. Yayla et al. [8] performed an experimental investigation over a nonslender diamond wing which has40° sweep angle, Λ. They investigated the effect of yaw angle, β on the formation of vortex breakdown and vortical flow structures using the dye visualization technique. They concluded that up to 4° yaw angle, β, there are no clear changes in the location of vortex breakdown, but at higher yaw attack, β, for example, more than 4°, vortex breakdown location moved towards the leading edge on windward side while on the leeward side, the second vortex breakdown location occurs further downstream, namely, asymmetrical onset of vortex breakdowns are observed. Canpolat et al. [9] investigated the flow structures of nonslender delta wing having 40° sweep angle. It is concluded that when the delta wing is positioned with a certain yaw angle, β, with reference to the central axis of the wing the symmetrical flow structure disappears. Resulting in earlier occurrence of vortex breakdown on the windward side of the delta wing, as compared with the leeward side. The main vortices in cross flow planes take place in the inner side close to the central axis of the delta wing. Sohn and Chang [10] investigated the effect of centerbody on a yawed double delta wing by using off-surface flow visualization and wing-surface pressure measurements. It is concluded that up to 24° angle of attack, α the presence of the centerbody have a small influence on the suction pressure distribution over the upper wing surface, even at the large yaw angle of β=20°. They also revealed that at higher angle of attack, α between 28° and 32°, presence of centerbody causes to decrease the magnitude of pressure coefficient when compared with 0° yaw angle, β. Sohn et al. [11] performed an experimental study on the vortex flow visualization of a yawed delta wing with leading edge extension (LEX). Interaction between LEX and delta wing were investigated at some angle of attacks, α and yaw angles, β. Their results reveal that the wing vortex and the LEX vortex coiled around each other while maintaining comparable strength and identity when yaw angle, β is 0° an increase of angle of attack, α intensifies the coiling and shifts the cores of the wing and LEX vortices inboard and upward. Furthermore, the coiling, the merging and, the diffusion of the wing and LEX vortices increase on the windward side, whereas the same critical processes became delayed significantly on the leeward side when the wing is yawed. Dynamics of vortices on the windward and leeward sides of the wing changed significantly as a function of yaw angle, β. Nakamura and Yamada [12] investigated aerodynamic characteristics of spin over a delta wing. They concluded that when the wing is yawed, asymmetric pressure distribution over two halves of the wing took place and this pressure difference causes different lift forces on the two sides of the wing this could cause spin. At low angles of attack, α when the wing has a yaw angle, β the upper surface pressures on the windward wing-half become lower than those on the leeward wing-half but near the stall angle the upper surface pressures of the leeward wing-half become lower than those in the windward wing-half. Verhaagen [13] conducted an experimental survey in order to investigate the effect of sideslip (yaw) over a 65° delta wing having a constant angle of attack, α with 30° using different experimental techniques. He concluded that when β is 0°, the flow over the delta wing is dominated by two primary and secondary vortices and with yawing, the vortices are observed to move towards the leeward edge with increasing sideslip angle, β and hence vortex burst location on the windward side of wing moves towards the apex, the vortex burst on the other side moves in opposite direction. He also concluded that on the windward side of the wing reduction of the suction on upper surface is seen so the amplitude of the oscillation of the vortex burst along the spiral vortex axis increases with the yaw angle, β.

The objective of the present experimental study is to demonstrate effects of angles of attack, α within the range of $25^0 \geq \alpha \geq 35^0$ and yaw angles, β within the range of $0^0 \geq \beta \geq 20^0$ on the development of vortex breakdowns, and behavior of vortical flow structures in the region downstream of vortex breakdown locations using dye visualization.

EXPERIMENTAL SET-UP

Experiments were carried out in water channel in the Fluid Mechanics Laboratory at Çukurova University. Test section of the water channel is constructed of transparent Plexiglas. Dimensions of the test section are; 8000 mm length, 1000 mm width and 750 mm depth. To maintain turbulence intensity lower than 0.5 % in addition special design, honeycomb screen was located entrance of the contraction section. Figure 1represents schematic of experimental system.

Water depth was kept constant at 530 mm during the all experiments, frequency of the pump used to control of flow was kept at 20 Hz, and corresponding free-stream velocity was 80 mm /s. The delta wing with sweep angle, Λ=70° made of plexiglas has a chord of 25^0 mm, 6 mm thickness and leading edges were beveled 45°. Temperature water inside the channel was 20 C°, Reynolds number based on the delta wing chord was 20.000. Experiments were conducted in plan and side views. Laser sheet was passed from the center of leading edge vortex for side-view measurements; it was located parallel to surface of the delta wing for plan view, but, in the case of measurements in side view plane, laser sheet was located perpendicular to the surface of delta wing.

A Rhodamine type dye is used to visualize flow structures by releasing a specified amount of dye that shines under the laser light sheet passing through the defined flow field.

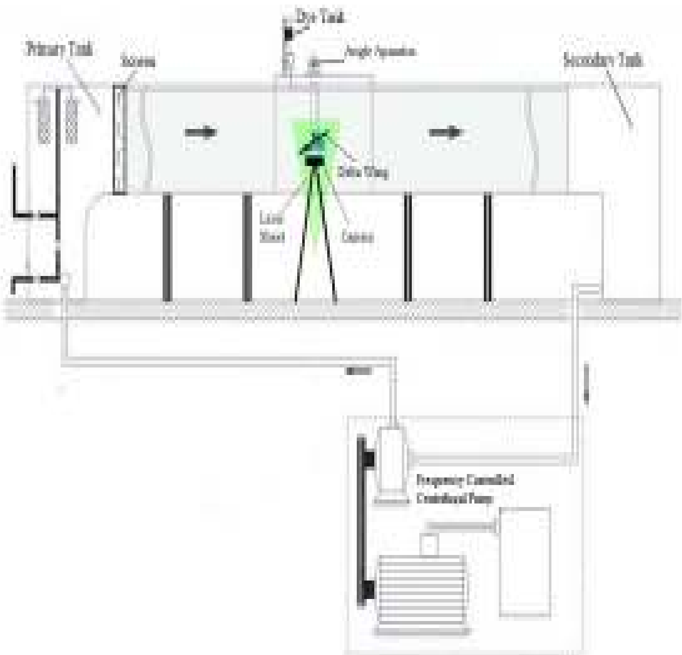

FIGURE 1 SCHEMATIC OF EXPERIMENTAL SYSTEM IN SIDE-VIEW PLANE

Dyes received from a small tank located almost 1 meter higher from the delta wing via plastic hoses and needles and amount of the dye to be released is set by means of apparatus on the hoses. The SONY HD-SR1 video camera was employed to record instantaneous video images of the vortex flow structures. There are 3 dye injection points on either side of the leading edges, namely, leeward or windward sides of the wing. Dye releasing points were located at 5%, 30% and 55% of the chord length, c. Angles of attack, α and yaw angles, β were given by means of a streamlined special apparatus which keeps the delta wing stationary. Magnitudes of velocity of dyes released from six different locations are almost same with the flow velocity.

RESULTS AND DISCUSSION

At a yaw angle of β=0° for all angles of attack, α symmetrical vortex pairs are observed, however onset of vortex breakdowns oscillate over a certain distance. While one of the leading edge vortices breaks down in closer location to the apex than the other one. For both spiral vortices, it is not possible to identify a constant breakdown location. Because vortex breakdown locations always change and these changes take places over a certain mean values which are shown in figure 3.

As shown figure 2, when dye is released from three different locations on each sides of the wing, a dye released from the location close to the apex moves along the central axis of the leading edge vortices, but dye released from other locations provide opportunity to observe secondary vortices and vortical flow structures in the periphery of the leading edge vortices.

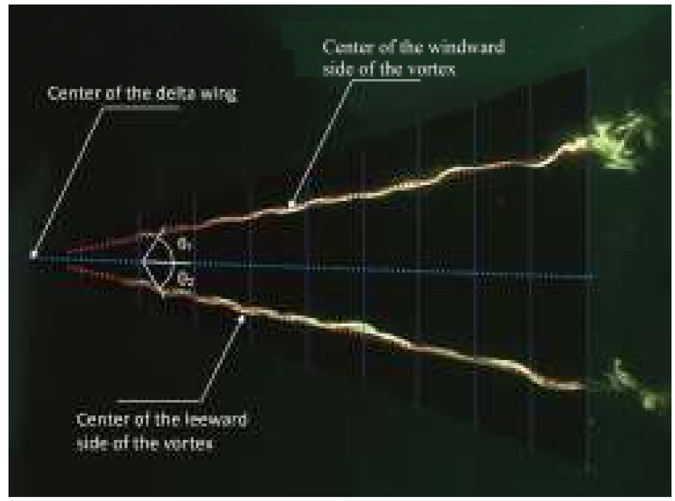

FIGURE 2 DYE VISUALIZATION OF LEADING EDGE VORTICES FOR A=25°, B=0°

Figure 3 shows the dimensionless vortex breakdown locations of windward side of the delta wing, since leeward side vortex breakdown locations moves further downstream out of image plane. As seen from figure 3, in the case of β=0° for α=25° vortex breakdown takes place at locations of x/c =1.1 and x/c=0.85, for α=30°, location of vortex breakdown occurs at x/c=0.9 and x/c=0.75 and finally increasing the angle of attack, α to a value of α=35° location of vortex breakdown occurs at a location close to the apex, for example, at x/c=0.65 and x/c=0.5. Finally, it can be concluded that vortex breakdown locations moves upstream and downstream randomly for the same angle of attack, α. Also both spiral and bubble types vortex breakdown were observed, moreover oscillations of the leading edge vortex breakdown locations can be seen in figure 4 for angle of attack α=30° and β=0°.Figures, 5,6,7 and 8present dye visualization in plan view plane, blue lines represents locations of x/c with x/c=0.1 interval. While figures 5,6 and 7 show mean vortex breakdown locations and figure 8 presents flow behaviours focusing interactions of the leading edge vortices. Figures 9, 10 and 11 demonstrate dye visualisation in side view plane which show mean vortex breakdown locations. As shown in figures 4, 5 and 6, when the delta wing is yawed, it is observed that symmetrical vortex structure deteriorates rapidly leading to the formation of asymmetrical vortices.

While windward vortex breakdown location moves towards the apex, leeward vortex breakdown location moves further

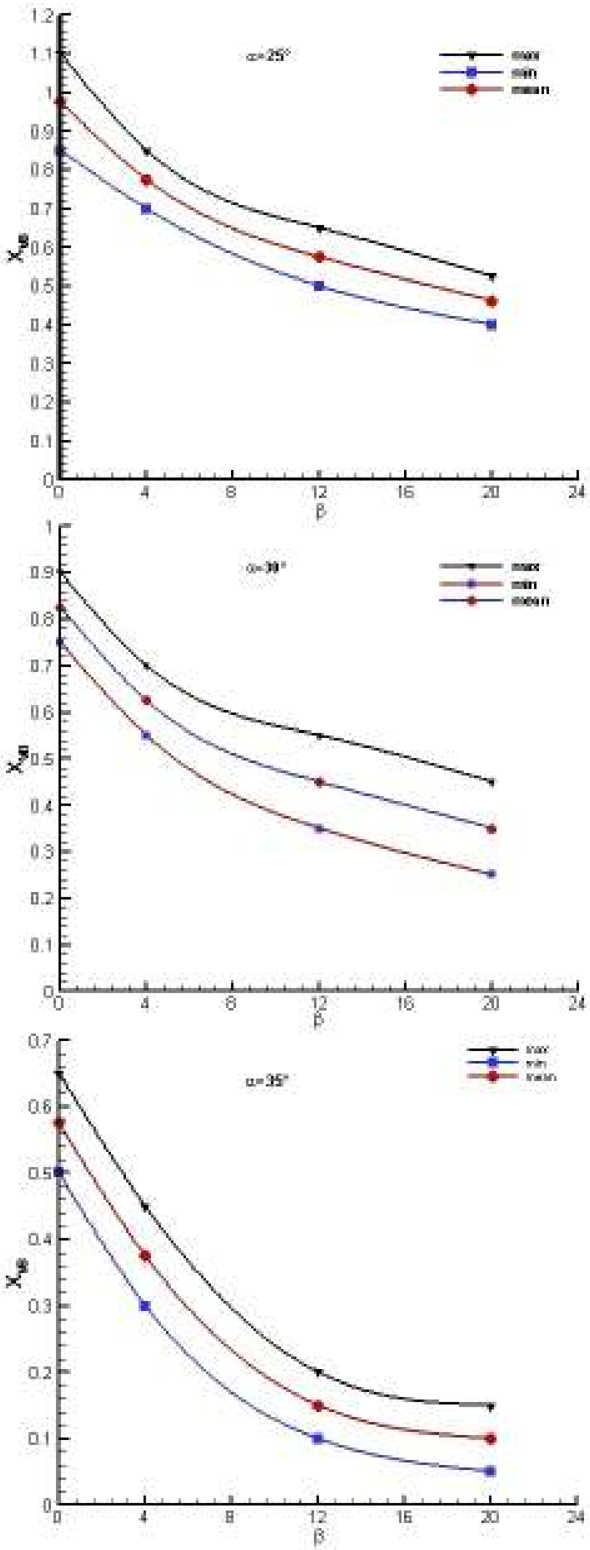

FIGURE 3 DIMENSIONLESS LOCATIONS OF VORTEX BREAKDOWN ON WINDWARD SIDE OF THE DELTA WING

downstream. At the highest yaw angle, β for example, β=20°, vortex breakdown locations observed from an instantaneous flow data moves forward and backward in an unsteady motion. In summary, onset of vortex breakdowns take places at x/c=0.55 and x/c=0.4, for α=25° similarly, at x/c=0.45 and x/c=0.25 for α=30°. But at α=35° vortex breakdown occurs close to the apex of the delta wing. At high yaw angles, β locations of vortex breakdown move downstream of the trailing edge of the delta wing as well as out of camera images.

Yayla et al. [8] stated that that up to 4° yaw angle, β there are no clear changes between locations of vortex breakdown occurring on both side of cord axis for nonslender delta wing with sweep angle, Λ of 40^0. In the present case, similarity of leading edge spiral vortices, onset of vortex breakdowns and vortical flow structures downstream of vortex breakdown are very sensitive to the yaw angle, β, even having yaw angle, β as 4^0 dissimilarity between two leading edge spiral vortices take places.

Figures 4, 5 and 6 present leading edge vortex breakdown locations with yaw angles, β. At low yaw angles, β dyes released from holes 2 and 3 form helix shape around leading edge vortices. Increasing yaw angle, β to a higher value, these holes ejects dye directly into the separation flow region after vortex breakdown in windward side. It is observed that Kelvin-Helmholtz instabilities increases with increasing yaw angle, β at a constant angle of attack, α, and also severity of vortex shedding increases.

At constant angle of attack, α wake region expand in size by stepping up yaw angle, β. Similarly, at constant β the size of wake region expends with increasing angle of attack, α. It can be concluded that the higher yaw angle, β the shorter distance takes place between onset of vortex breakdown and apex on the leeward side, but the case is opposite for windward side of the wing.

With Increasing yaw angle, β windward vortex core moves towards the chord axis and leeward spiral vortex core takes place along the leeward side of the delta wing. In additions, interactions between these windward and leeward vortices are observed clearly from dye visualization. A large scale vortices occurred after vortex breakdown on the windward side interact with spiral vortices moving along the edge of leeward side to oscillate this leading edge spiral vortex in lateral direction as shown figure 8.

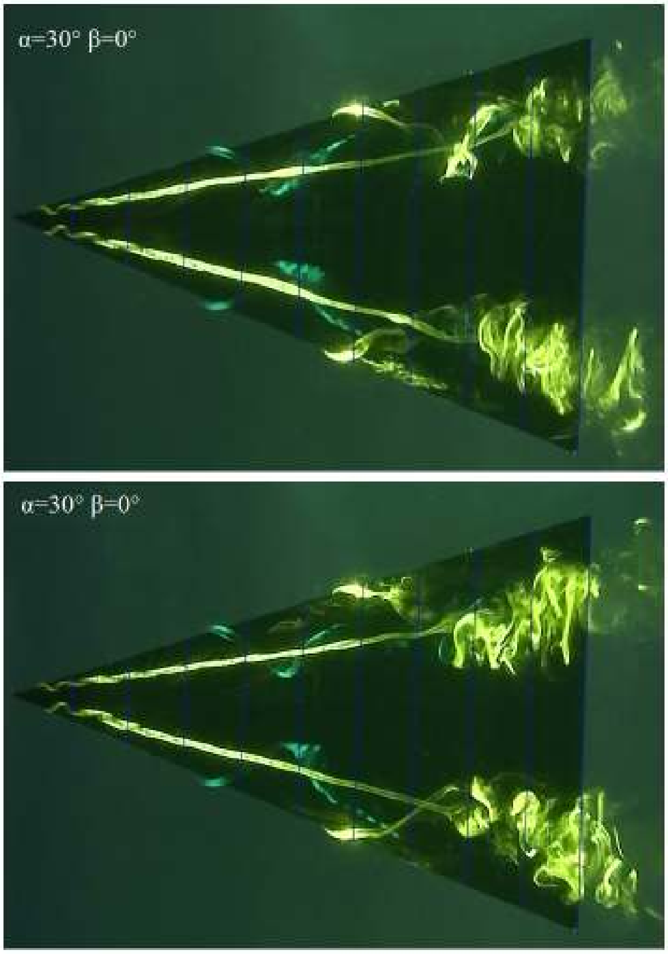

FIGURE 4 INSTANTANEOUS IMAGES REPRESENT MINIMUM AND MAXIMUM VORTEX BREAKDOWN LOCATION FOR A=30°, B=0°

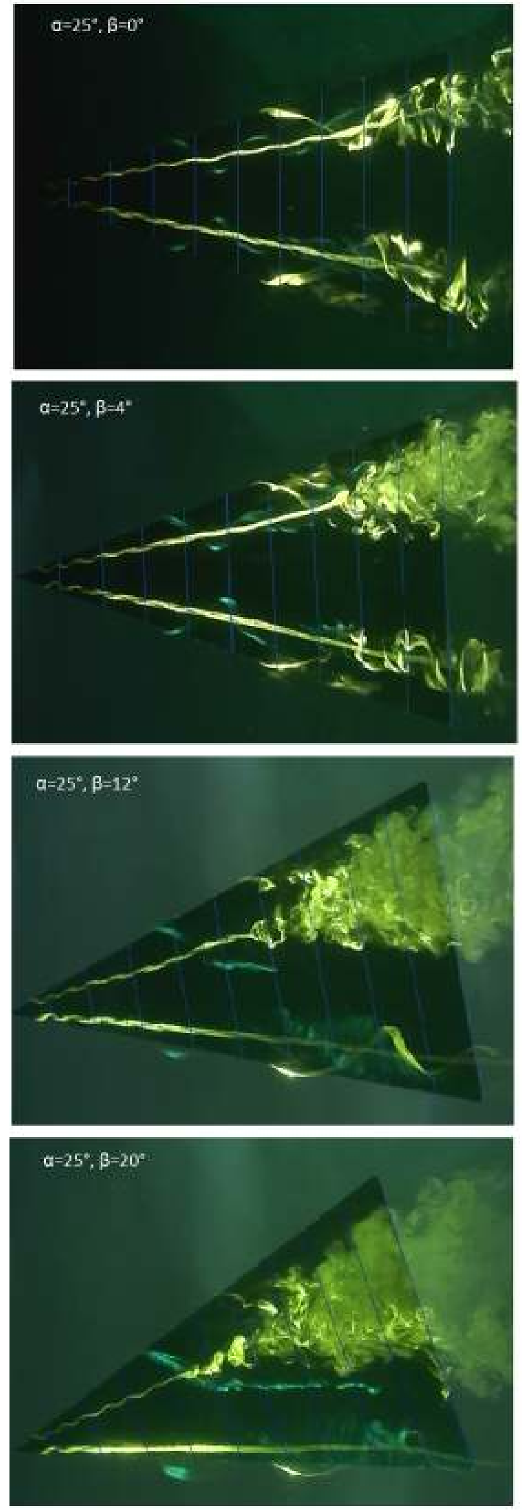

FIGURE 5 EFFECT OF YAW ANGLES, B ON WINDWARD LEADING EDGE VORTICES IN PLAN-VIEW PLANE FOR A=25°

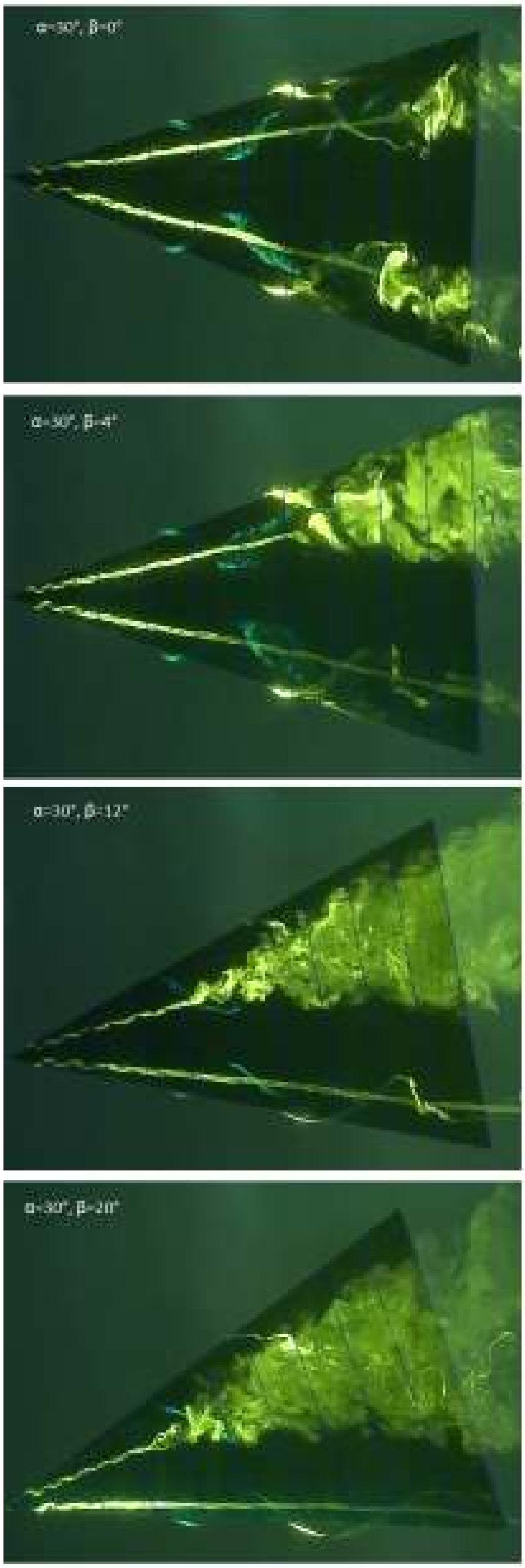

FIGURE 6 EFFECT OF YAW ANGLES, Β ON WINDWARD LEADING EDGE VORTICES IN PLAN-VIEW PLANE FOR Α=30°

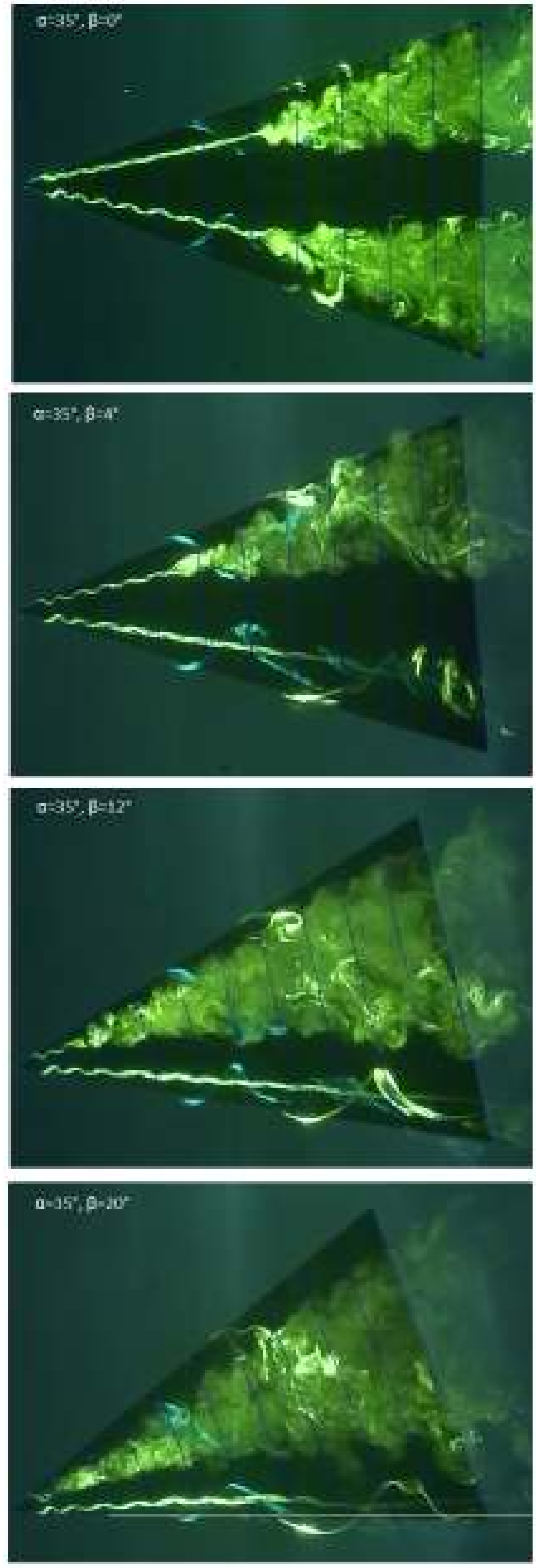

FIGURE 7 EFFECT OF YAW ANGLES, Β ON WINDWARD LEADING EDGE VORTICES IN PLAN-VIEW PLANE FOR Α=35°

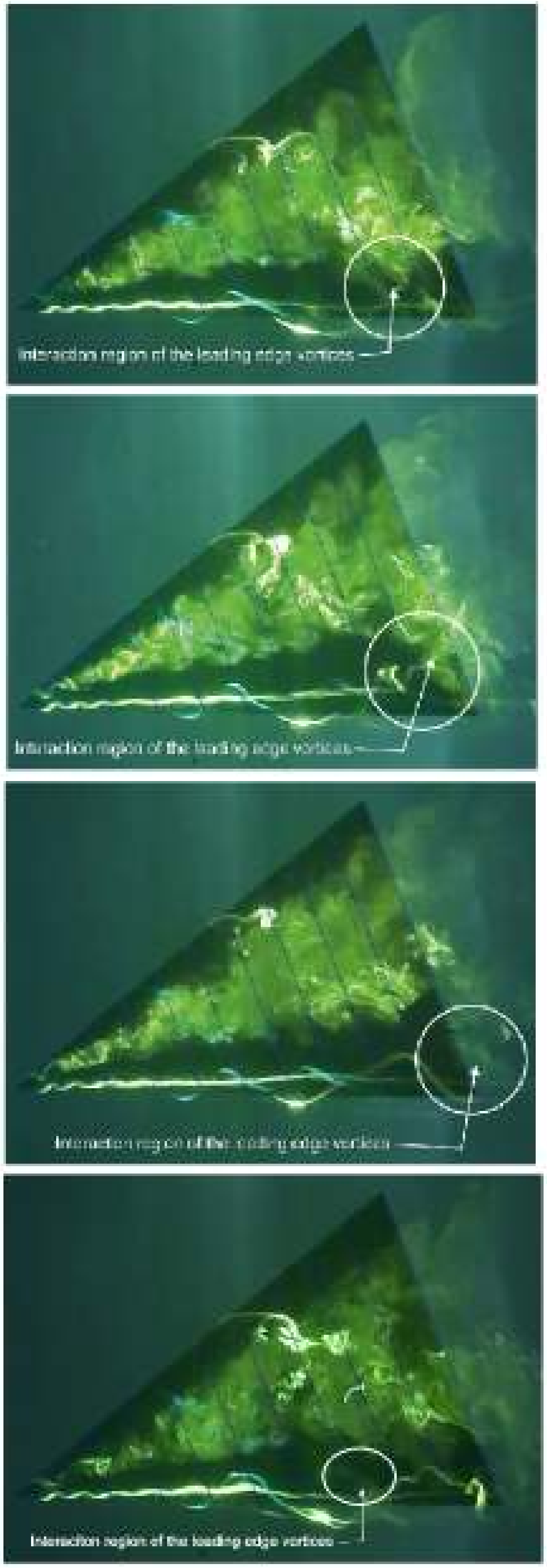

FIGURE 8 INSTANTANEOUS IMAGES REPRESENT VORTEX BREAKDOWN LOCATIONS AND INTERACTIONS OF LEADING EDGE VORTICES FOR A=35°, B=20°

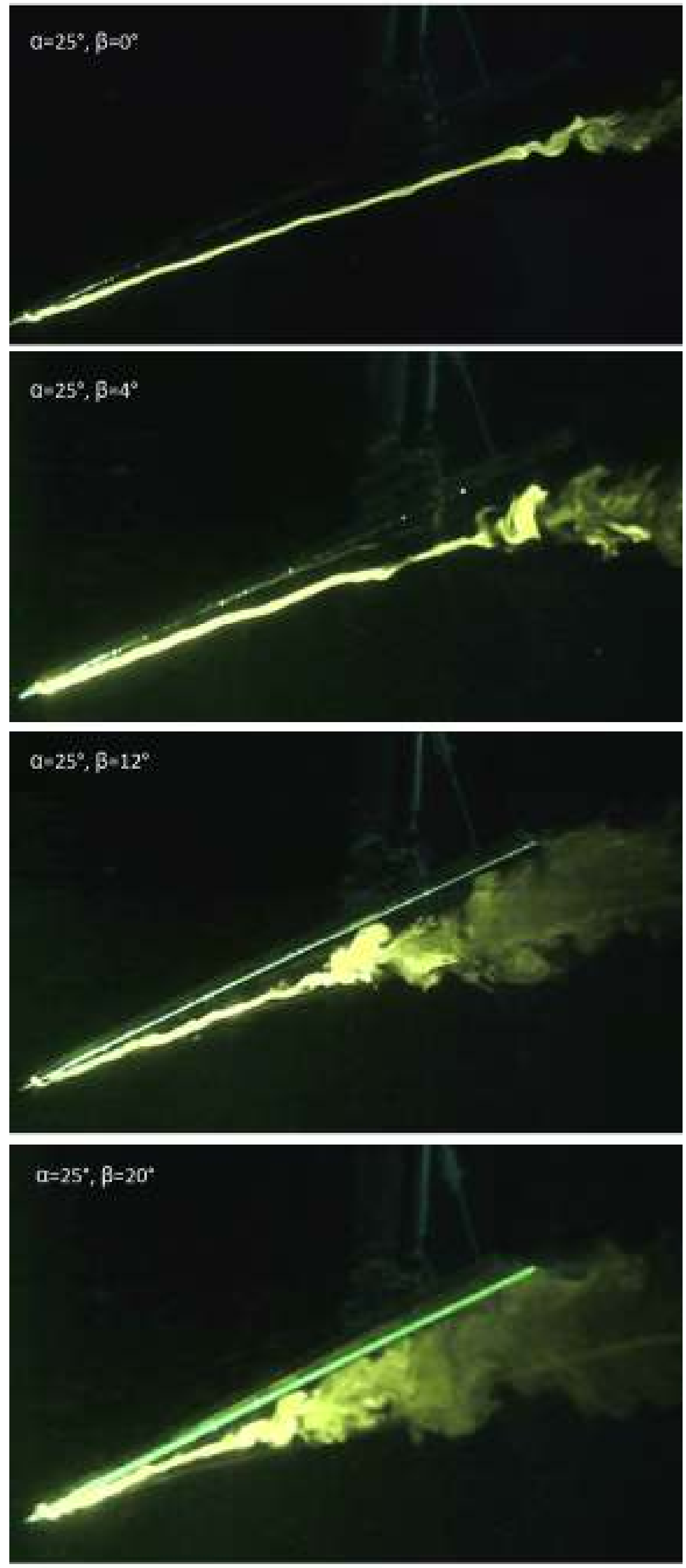

FIGURE 9 EFFECT OF YAW ANGLES, B ON WINDWARD LEADING EDGE VORTICES IN SIDE-VIEW PLANE FOR A=25°

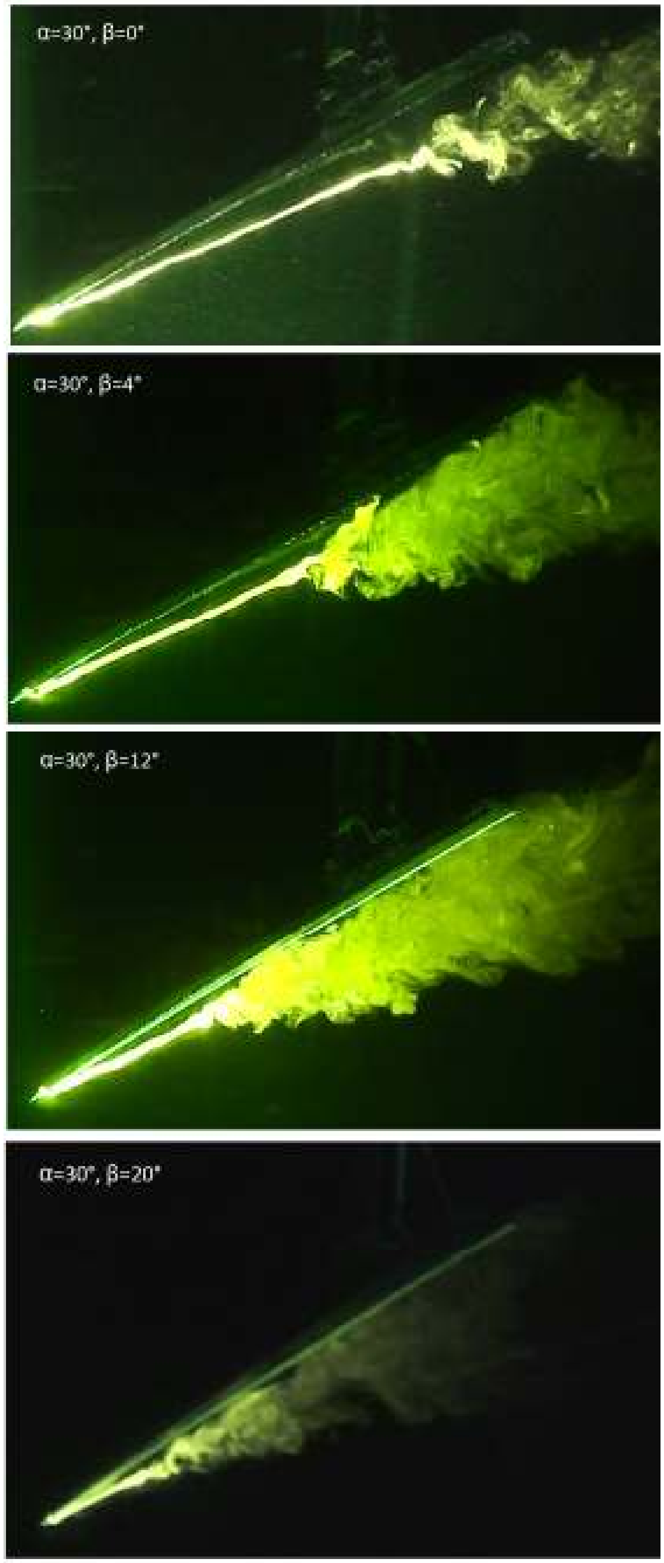

FIGURE 10 EFFECT OF YAW ANGLES, Β ON WINDWARD LEADING EDGE VORTICES IN SIDE-VIEW PLANE FOR Α=30°

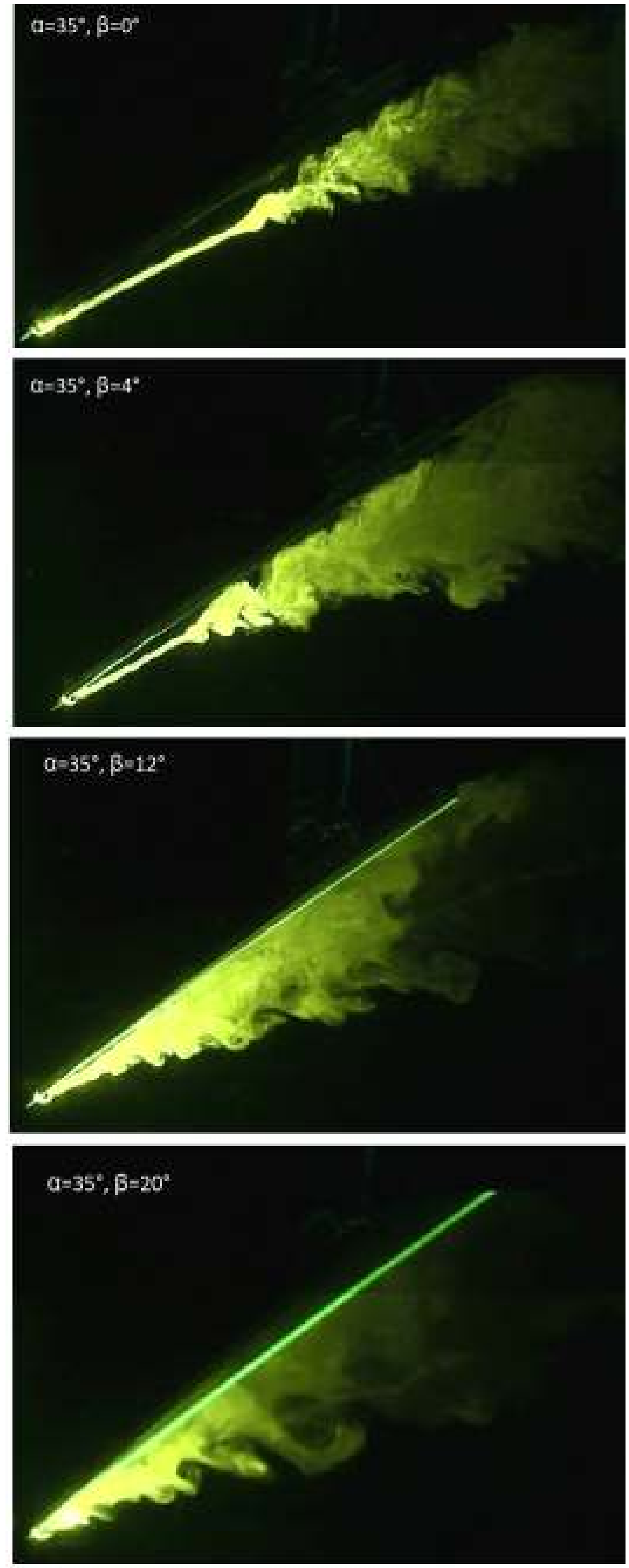

FIGURE 11 EFFECT OF YAW ANGLES, Β ON WINDWARD LEADING EDGE VORTICES IN SIDE-VIEW PLANE FOR Α=35°

CONCLUSIONS

Present experimental research focuses on the development of leading edge vortices over delta wing with sweep angle of Λ=70° under effect of yaw angle, β at three different arrangement of high angles of attacks, α using the dye visualization technique. It was observed that when the delta wing was yawed symmetrical flow structures are deteriorated. Vortex breakdown location of windward side moves towards to the apex while leeward side vortex breakdown moves further downstream. In additions changes of onset of vortex breakdown locations are function of yaw angles, β. Whole topology of flow structures in both windward side and leeward side is very sensitive with the variation of yaw angle, β. For example, leeward side leading edge spiral vortex moves close to the leeward side of the wing which is almost parallel to this side edge line, on the other hand, windward side leading edge vortex moves close to the centre of the delta wing and also becomes almost parallel to this central axis of the delta wing. Interactions between both leading edge vortices were also observed and this interaction causes leeward leading edge vortices to oscillate randomly in lateral direction.

Hence stalled flow is dominant at the surface of the delta wing at high yaw angles, β in the case of high angles of attack, α which cause adverse effects on the aerodynamics performance and asymmetrical development of vortices can lead adverse effects to deteriorate stability of the delta wing.

ACKNOWLEDGMENTS

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NOMENCLATURE

Λ sweep angle
α angle of attack.
β yaw angle.
θ angle between vortex core center and delta wing center.
X_{VB} dimensionless vortex breakdown location

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