

**ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES**

M.Sc. THESIS

Mehmet Oğuz TAŞCI

**EFFECTS OF YAW ANGLE ON VORTEX FORMATION
DOWNSTREAM OF A SLENDER DELTA WING**

DEPARTMENT OF MECHANICAL ENGINEERING

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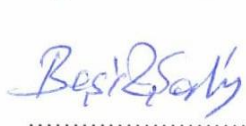
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We certify that the thesis titled above was reviewed and approved for the award of degree of the Master of Science by the board of jury on 16/01/2017.

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ABSTRACT

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In the present work, basic features of counter rotating pair of leading edge vortices and vorticity concentrations downstream of vortex breakdowns in end-view planes of the delta wing with 70° sweep angle, Λ were experimentally studied both qualitatively and quantitatively using Rhodamine dye and the particle image velocimetry (PIV) technique. Experiments were conducted by altering angles of attack within the range of $25^\circ \leq \alpha \leq 35^\circ$ and yaw angles, β within the range of $0^\circ \leq \beta \leq 20^\circ$. Present investigation focused on crossflow structures in sequentially-located at five different end-view planes along the cord axis, C at locations $x/C=0.2, 0.4, 0.6, 0.8$ and 1.0 . A trajectory of leading edge vortices, locations of vortex breakdown, and vorticity concentrations occurring downstream of vortex breakdowns and their interactions were observed using dye visualizations. Time-averaged velocity vectors $\langle V \rangle$, pattern of streamlines, $\langle \psi \rangle$ velocity components, u and v , contour of vorticity distributions, $\langle \omega \rangle$ and root mean square of streamwise velocity, $\langle u_{rms} \rangle/U$ and transverse velocity, $\langle v_{rms} \rangle/U$ components were determined by the PIV technique.

When the delta wing is yawed, macro scale symmetrical flow structures are altered considerably. The windward side vortex breakdown location moves towards the apex of delta wing. Trajectories of leading edge vortices slide sideways close to the central axis of the delta wing.

Key Words: Delta Wing, Stereo PIV, Vortex Breakdown, Yaw Angle

ÖZ

YÜKSEK LİSANS TEZİ

SÜPÜRME AÇISI YÜKSEK OLAN DELTA KANATLARDA SAPMA AÇISININ GİRDAP OLUŞUMUNA ETKİLERİ

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Bu çalışmada, 70 derecelik süpürme açısındaki, Λ delta kanadın arka görünüş düzlemindeki girdap çökmeleri, akış yönü çevrinti oluşumları ve birbiri tersi yönünde dönen kanat uç girdaplarının temel özellikleri; Rhodamine boya ve parçacık görüntülemeli hız ölçüm tekniği kullanılarak hem nicel hem de nitel olarak incelenmiştir. Deneyler, hücum açısı $25^\circ \leq \alpha \leq 35^\circ$ aralığında ve sapma açısı ise $0^\circ \leq \beta \leq 20^\circ$ aralığında değiştirilerek gerçekleştirilmiştir. Bu çalışma, arka görünüş düzleminin veter eksenine, C boyunca $x/C = 0.2, 0.4, 0.6, 0.8$ ve 1.0 olmak üzere, beş farklı noktadaki akış yapısı gözlemlenmiştir. Boya görselleştirmeleri kullanılarak, hücum kenarı girdapları, girdap çökmelerinin konumları ve akış boyunca meydana gelen girdap oluşumları ve bu akış yapılarının birbirleriyle olan ilişkileri gözlemlenmiştir. Zaman ortalama hız vektörleri $\langle V \rangle$, akım çizgilerinin dağılımı $\langle \psi \rangle$, hız bileşenleri u ve v , eşdeğer girdap eğrilerinin dağılımları $\langle \omega \rangle$, ve akış doğrultusundaki ve yanal yöndeki u ve v hız bileşenlerinin karelerinin karekök ortalamaları $\langle u_{rms} \rangle/U$ ve $\langle v_{rms} \rangle/U$ bileşenleri, PIV tekniği belirlenmiştir.

Delta kanada sapma açısı, β verildiği zaman simetrik makro ölçekli akış yapıları büyük ölçüde değişmektedir. Akışa maruz kalan yöndeki girdap çökme noktası, delta kanadın ucuna doğru hareket etmektedir. Rüzgâra maruz kalan delta kanat kenarı girdaplarının yörüngeleri, delta kanadın merkez eksenine doğru yaklaşarak kaymaktadır.

Anahtar Kelimeler: Delta kanat, Stereo PIV, Girdap çökmesi, Sapma açısı

EXPENDED ABSTRACT

There are several factors that influence delta wing aerodynamics, particularly formations of vortical flow over a delta wing. For example, primary factors are angle of attack α , yaw angle β , sweep angle Λ , roll angle, θ wing thickness, t , leading edge geometry and conditions of free-stream flow as well as the Reynolds Number, Re . More precisely the geometry of delta wing has close relations with the formations of leading edge vortices and their bursting incidences.

Vortex bursting phenomena is key source of striking delta wing which triggers large mechanical vibrations leading to heavy fatigue destruction and causes the loss of load-bearing ability of a material under periodic load application.

Delta wings are differed from the other type of wings because a couple of leading edge vortices, separations, vortex breakdowns and chaotic vortical flows are generally available on the suction sides of delta wings.

It is identified that aerodynamics of high angle of attack, α is one of the most important elements in aircraft design for the view of lift force F_L . A delta wing would also ensure high lift coefficient, C_L at a larger angle of attack, α comparing to the wing of passenger aircrafts. Leading edge vortices at high angles of attack, α create most portions of lift forces, F_L . But, vortex bursting close to the surface of delta wing deteriorates maneuverability of air vehicles and causes material fatigues due to unsteady wind loadings. Comprehension of these types of flows is very important for better aircraft maneuverability. A delta wing furnishes the Unmanned Combat Air Vehicles (UCAVs) with capability of sharp maneuvers and tactical advantages. Maneuverability of all these geometrical styles are restricted by the occurrence of vortex bursting and stall influencing both overall forces and moments of aircrafts.

Although substantial scientific and technological information was obtained about instantaneous and time-averaged flow structures of delta wings with relatively large sweep angles, Λ in recent years, but influences of yaw

angle, β were not studied. Recent demands on UCAVs have encouraged researchers to pay more attentions in characterizing flow structures of delta wings. Present investigation focuses on the unsteady flow structure which occurs downstream of onset of vortex breakdown serving as a source of buffeting and causing stall that reduces the lift force, F_L .

Crossflow studies in end-view planes of delta wings have not been conducted in detail in the literature for slender delta wings. There are only a few studies are available for non-slender delta wings. Because of that reason, present investigation focuses on an unsteady flow structures in crossflow planes along the central cord axis of the delta wing in sequential locations such as $x/C=0.2, 0.4, 0.6, 0.8$ and 1.0 , where consequences of vortex bursting and stall phenomena vary according to angles of attack, α over the range of $25^\circ \leq \alpha \leq 35^\circ$ and yaw angles, β over the range of $0^\circ \leq \beta \leq 20^\circ$. Basic features of counter rotating axial vortices and vorticity concentrations after onset of vortex breakdown in five different end-view planes of delta wing with 70° sweep angle, Λ are examined both qualitatively and quantitatively using Rhodamine dye and the PIV system.

In the light of present experiments, it is seen that with increasing yaw angle, β symmetrical flow structure is disrupted continuously. Dispersed wind-ward side leading edge vortices cover a large part of flow domain; on the other hand, lee-ward side leading edge vortices cover only a small portion of flow domain. Emphasizes in current investigation is given on crossflows in end-view planes between the leading and trailing edges of delta wings at five different stations, $x/C=0.2, 0.4, 0.6, 0.8$ and 1.0 where consequences of vortex bursting and stall phenomena vary according to angles of attack, α and yaw angle, β . In the past, a great deal of effort was spent on the studies of delta wing aerodynamics with a high sweep angle, Λ . It is possible to say that flow structures over this kind of wings are understood very well.

On the other hand, the effects of yaw angles, β on a delta wing aerodynamics have not been studied in detail yet. Particularly, there is a limited published work on the aerodynamics of slender delta wings as a function of yaw angle, β . For this reason, as a motivation of present work, further studies are required in order to understand flow structures and aerodynamics of slender delta wings in detail.

Delta wings, which are generic plan-forms of MAVs and UCAVs, have a serious control and instability problems due to not having conventional aerodynamic control surfaces. For these wings; coactions between the leading edge vortex and boundary layer, the leading edge vortex bursting, a localized surface flow separation, effects of these incidents on a wing surface vibration and buffeting due to wind loads are among fundamental research topics. It is possible to discover a method to control instability problems by making further investigations on these topics and to understand flow phenomena better. Locations of vortex bursting over delta wings are not stable and display fluctuation along the vortex axis.

The Reynolds number of the present experiments, Re was 20000 and the span of the delta wing was 180 mm. In end-view plane, symmetrical flow structures in macro scales are developed in the case of zero yaw angles, β for all case of angles of attack, α . In the light of present experiments it is seen that with increasing yaw angle, β symmetrical time-averaged flow structures are disrupted continuously.

Time-averaged streamline topology $\langle \Psi \rangle$ obtained from time-averaged velocity data shows that there are two saddle points, S_1 and S_2 , and foci, F_1 and F_2 . Saddle points, S_1 and S_2 , are clearly seen and located below the foci, F_1 and F_2 . Time-averaged streamline patterns, $\langle \Psi \rangle$ show a well-defined swirl pattern. The saddle points, S_1 and S_2 , and center of foci, F_1 and F_2 , gradually move downward and get closer to each other as angle of attack, α is increased because of stall flow regions expands in size as a function of both angle of attack, α and yaw angle, β . Patterns of streamlines, $\langle \Psi \rangle$ of counter rotating flow recirculation are dissimilar in

terms of size and magnitude. Differences between size and severity of vorticity concentrations are easily seen in PIV results that are quantitatively visualized in terms of streamlines, $\langle \Psi \rangle$ and velocity vectors, $\langle V \rangle$.

Time-averaged velocity vectors, $\langle V \rangle$ indicate a well-defined a pair of identical swirling flow cells for the case of zero yaw angle, β for all cases of angles of attack, α that are considered in the present work. But, a well-defined recirculating flow region on the windward side gradually attenuates and diminishes and finally a single flow circulating loop is only seen in the image of velocity vector distributions $\langle V \rangle$ on the leeward side in the case of higher yaw angle, $\beta \geq 12^\circ$. Increasing yaw angle, β from $\beta=0^\circ$ to $\beta=4^\circ$ flow structures are subjected to small changes. Symmetrical flow structures are dramatically altered at a yaw angle of $\beta=20^\circ$ compared with the case of yaw angles from $\beta=0^\circ$ to $\beta=4^\circ$. The distribution of time-averaged velocity vectors, $\langle V \rangle$ exhibits several small scales circulations presented by localized swirl patterns of streamlines.

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NOMENCLATURE

A	: Area (m ²)
c	: Chord (mm)
f	: Frequency (Hz)
H	: Height of the tunnel test section or water level (m)
max	: Maximum
min	: Minimum
x, y, z	: Streamwise, transverse and vertical coordinate directions
Re	: Reynolds number
s	: Span (m)
t	: Time (s)
u, v	: Streamwise and transverse components of velocity (m/s)
U	: Freestream velocity (m/s)
V	: Vector

Abbreviations

CCD	: Charge Coupled Device
DAQ	: Data Acquisition
FOV	: Field Of View
Nd:YAG	: Neodymium-doped Yttrium Aluminum Garnet
PIV	: Particle Image Velocimetry
RMS	: Root-Mean-Square
SPIV	: Stereoscopic PIV

Operators

<...>	: Time-averaged
[...]	: Magnitude

Greek symbols

α	: Angle of attack (°)
β	: Yaw angle (°)
γ	: Scheimflug angle (°)
Δ	: Difference in the value of a physical quantity
θ	: Roll angle (°)
λ	: Wavelength (m)
μ	: Viscosity of fluid (kg/m/s)
ρ	: Density of fluid (kg/m ³)
ν	: Kinematic viscosity of fluid (m ² /s)
ϕ	: Amplitude of wave (m)
ω	: Vorticity (1/s)

1. INTRODUCTION

Aircraft maneuverability is one of most important features in integrity aircrafts. Vortex behavior of a delta wing and influence of vortices on entire aircraft characteristics and maneuverability are key parameters. There are several factors that influence delta wing aerodynamics, particularly formation of vortical flow over a delta wing. For example, primary factors are angle of attack α , yaw angle β , sweep angle Λ , roll angle θ , the Reynolds Number Re , wing thickness t , leading edge geometry and conditions of free-stream.

As well as the Reynolds Number, Re more precisely the geometry of a delta wing has a close relation with the formation of leading edge vortices and vortex bursting incidences. One of the most important flow events is vortex bursting over a delta wing.

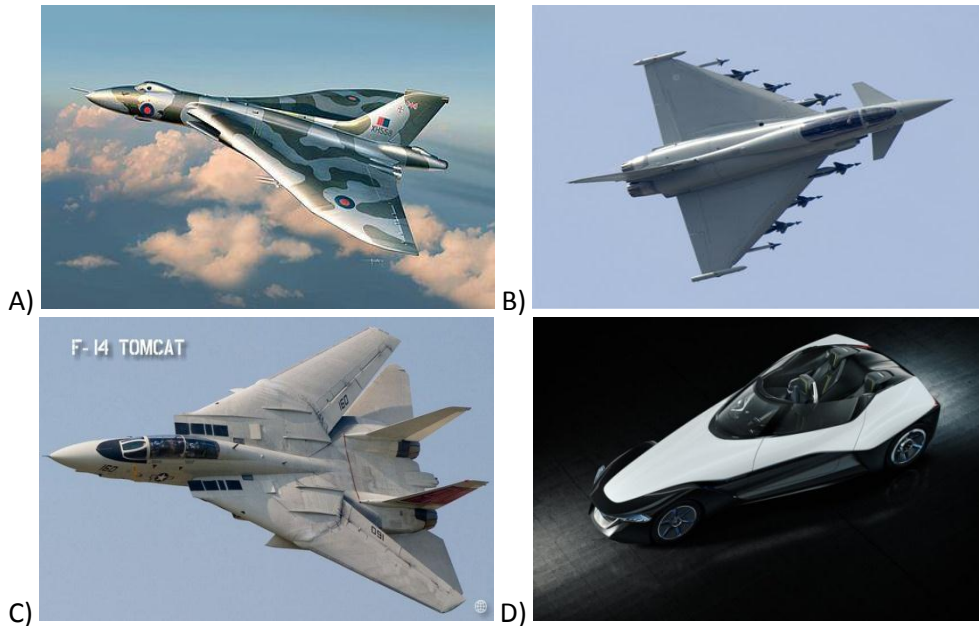
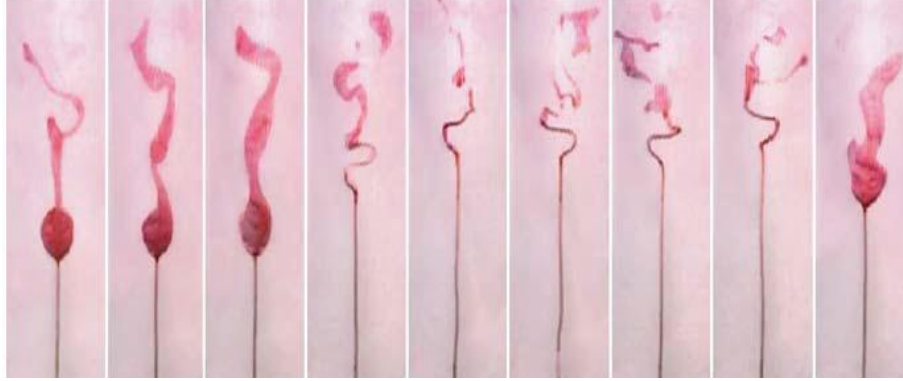
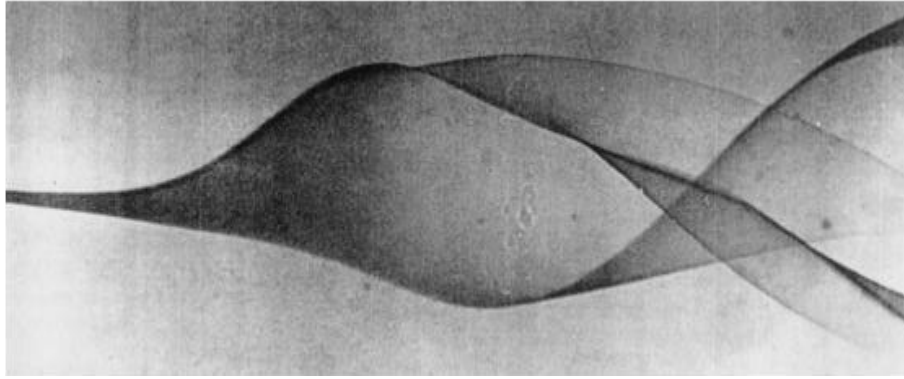


Fig.1.1.Examples of delta wing vehicles A)Avro Vulcan Bomber Jet,B)Eurofighter Jet, C)F-14 Tomcat, D)Nissan Blade Glider Electric Sports Car Concept



a) Bubble and Spiral type bursting (Kurosaka et al., 2003)



b) Double helix bursting (Sarpkaya, 1971)

Fig.1.2. Several types of vortex bursting in a tube

Vortex bursting phenomena is key source for striking the delta wing which triggers large mechanical vibrations leading to heavy fatigue destruction and causes the loss of load-bearing ability of a material under periodic load applications. Overall scene of vortex bursting close to the delta wing surface is presented in Figure 1.3.

Investigation of Lambourne and Bryer (1961) revealed that a couple of vortex bursting events have been monitored over a delta wing which are called spiral and bubble type vortex bursting, as shown in Figure 1.2. Previous research works reported that there are several types of vortex bursting some of them which are double helix bursting and combination of bubble and spiral type bursting.

It is identified that aerodynamics of high angle of attack, α is one of the most important elements in aircraft designs for the development of lift force, F_L .

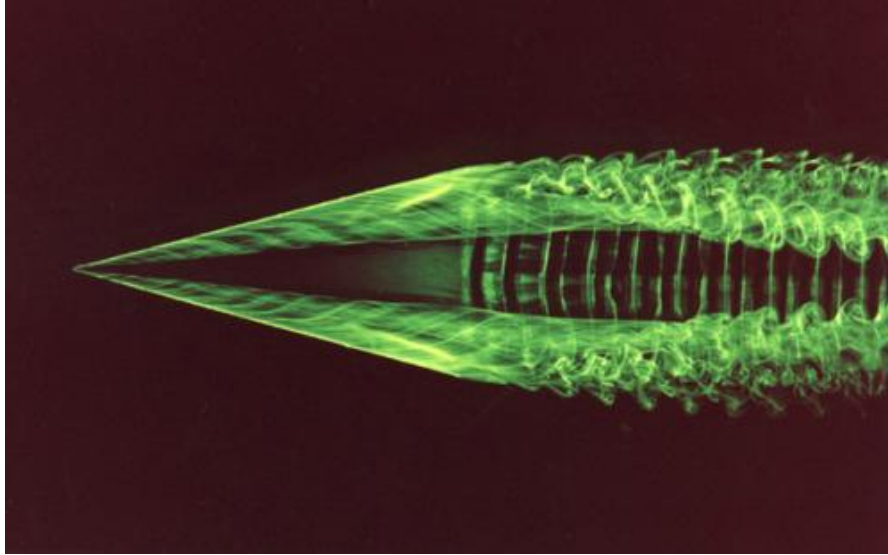


Fig.1.3. Representation of symmetrical vortex bursting over a high sweep angle delta wing

Many flows in nature have time-dependent, unsteady and free stream flow. For instance; flow around bridges, towers, automobiles, different regions of aircraft body and in compressors, turbines, pumps, heat exchangers. If concise overview is made for these types of flows, separation and vortex commanding flows can be seen commonly.

Delta wings act as a distinct element of air vehicles from the other type of wings because a couple of leading edge vortices, vortex bursting, separations and chaotic vertical flow are generally available. Basic advantages of delta wing are that steady flow would be held on a large range of attitudes and Mach numbers. A delta wing would also ensure high lift coefficient, C_L at large angle of attack α , comparing to the wing of passenger aircrafts. Leading edge vortices at high angles of attack, α creates the most portion of lift force, F_L . Leading edge vortices stay

stationary on airfoil because vorticity taking its source from leading edge is balanced by vorticity transported along the core of separation vortices.

It is well-known that in the case of basic delta wing, flow structures are formed by two well-defined counter-rotating leading edge vortices at a remarkable high angle of attack, α as shown in Figure 1.4. But, vortex bursting close to the surface of the delta wing deteriorates maneuverability of air vehicles and causes material fatigues. Comprehension of these types of flows is very important to be able to obtain good aircraft maneuverability. As shown in Figure 1.5, delta wing vortex formation, vortex bursting characteristics and main delta wing flow features are illustrated clearly.

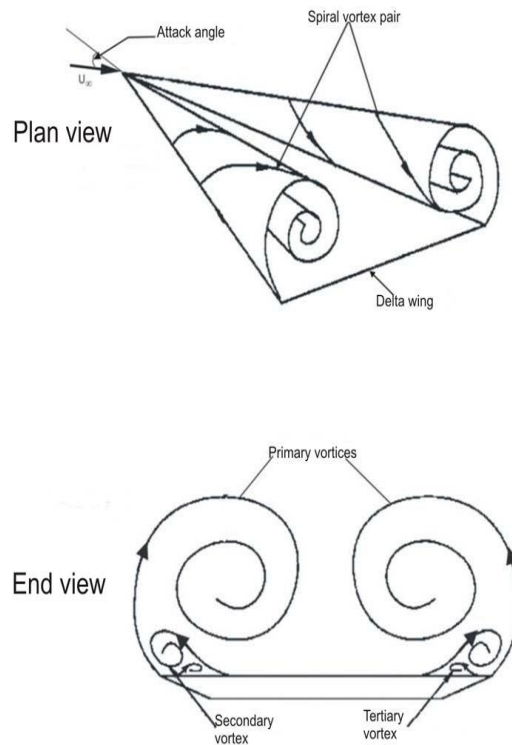


Fig.1.4. Sketch of vortical flow around a delta wing (Taylor and Gursul, 2004)

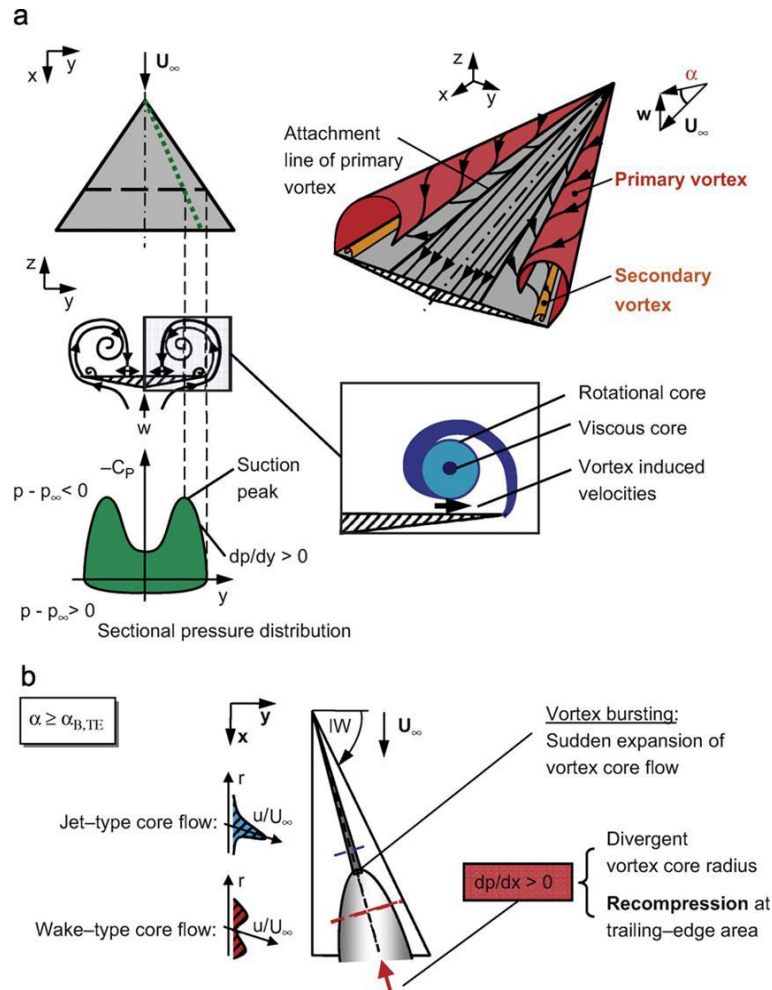


Fig.1.5. (a) Delta wing vortex formation and main delta wing flow features.
(b) Vortex bursting characteristics (Breitsamter, 2012)

Furnishing an Unmanned Combat Air Vehicles (UCAVs) with a capability of sharp maneuvers would provide tactical advantage. Future styles of UCAVs are shown in Figure 1.6. Maneuverability of all these geometrical styles are restricted by the occurrence of vortex bursting and stall phenomenon, which influence both overall forces and moments of aircrafts. Furthermore an important limitation of maneuverability under influence of onset of vibration caused by leading edge vortex bursting and potential failure of aerodynamic of UCAV.



Fig.1.6. Different types of UCAV plan-forms are shown (Wikipedia, 2016)

Cross-flow studies in end-view plane have not been conducted in great detail. A few studies are available. For example, Yaniktepe and Rockwell (2005) have performed experimental studies on diamond and lambda type wings about flow structures at trailing edge regions. In both wings vortical flow structures in cross-flow planes of trailing edge change rapidly with angles of attack, α .

Yavuz and Rockwell (2006) tried to control flow structures over delta wing surface by the trailing-edge blowing method. Their flow control methods were successful for curtain extends in controlling these vertical flow structures. That is to say, the trailing-edge blowing method is capable of varying topological flow patterns in close proximity to the delta wing surface significantly.

Unsteady flow structures occurring downstream of onset of vortex bursting serves as a source of buffeting and stall, that reduces the lift force, F_L . Flow structures of a delta wing with low sweep angle, Λ displays a well-defined flow characteristics, relative to the flow structures of slender delta wings which have been extensively investigated in the past. Emphasizes in current investigation is given on cross-flow in sequential end-view planes where vortex bursting and stall phenomena varies according to angle of attack, α and yaw angle, β . Extended research works have been conducted as a part of this thesis.

However researches in the field of low and moderate sweep angles of delta wings are quite limited compared to the case of delta wings with high sweep angle, Λ . It is worth to emphasize that the effects of yaw angles, β on a delta wing aerodynamics have not been studied in detail yet. Particularly, there is no published work on the aerodynamics of slender delta wings as a function of yaw angle β . For this reason, further studies are required in order to understand flow structures and aerodynamics of these wings in detail. Delta wings with low and moderate sweep angles which are generic plan-forms of MAVs and UCAVs have serious control and stability problems due to not having conventional aerodynamic control surfaces. For these wings; coactions between leading edge vortex and boundary layer, leading edge vortex bursting, localized surface flow separation, effects of these incidents on surface vibration and buffeting are among the fundamental research topics. It is possible to find a solution to control instability problems by conducting further investigations on these topics and to understand flow phenomena better.

For motivation of this study, a great deal of effort has been spent on the study of delta wing with a high sweep angle, Λ . Details of flow structures over these kind of wings were reported. It is expected that the main findings of this study can be useful for engineering applications and researches.

In the present work, flow structures on highly swept delta wing ($\Lambda=70^\circ$) were investigated in detail. Specifically, following points were studied: Analyzing and observing of the formation of leading edge vortices, effects of angles of attack, α and yaw angles, β on flow structures for the Reynolds number $Re=2 \times 10^4$ using the dye visualization technique and analyzing the measurements of instantaneous and mean velocities obtained by the PIV Technique.

2. PRELIMINARY WORK

2.1. Structure of Flow around Delta Wings

2.1.1. Vortex Bursting

Vortex bursting is a major vortical flow transformation on the surface of delta wing. There are plenty of investigations in the open literature, for comprehension of onset of bursting formation mechanism and controlling vortex bursting, both experimentally and theoretically.

During past forty years, major advances, both in academic and engineering inquiries, were carried out, for example, establishing of criteria and understanding of flow mechanisms of vortex bursting occurred over a delta wing with high sweep angle, Λ , and swirling flow in a tube and so on.

Location of vortex bursting over delta wings is not stable and displays random motion along the leading edge vortex axis. Menke (1999) performed experimental work on features and resource of sways of vortex bursting as a part of leading edge vortices. He conducted spectral analysis in order to prepare a survey on the unsteady behavior of vortex bursting location in terms of flow visualization. Vortex bursting sways cause quasi-periodic oscillations with a high-frequency and low amplitude displacements. That is to say, interactions between instantaneous vorticity concentrations cause quasi-periodic oscillations resulting in an anti-symmetric motion of bursting locations in between pair of leading edge vortices. Anderson (2001) stated that oscillations are larger and more coherent as time-averaged bursting locations approach each other as angle of attack or sweep angle are changed.

Flow structures close to the surface of non-slender diamond wing studied quantitatively and qualitatively by Yayla et al. (2009) using techniques such as dye visualization and the Stereo Particle Image Velocimetry technique. Flow compositions and transformations of vortex bursting were examined by altering yaw angle, β in the limit of $0^\circ \leq \beta \leq 15^\circ$ for angle of attack of $\alpha=7^\circ$ at $Re=10^5$. They

stated that when yaw angle, β increases, vortex bursting location on one side approaches to the wing apex, on the other side moves in the direction of free stream flow towards the trailing edge.

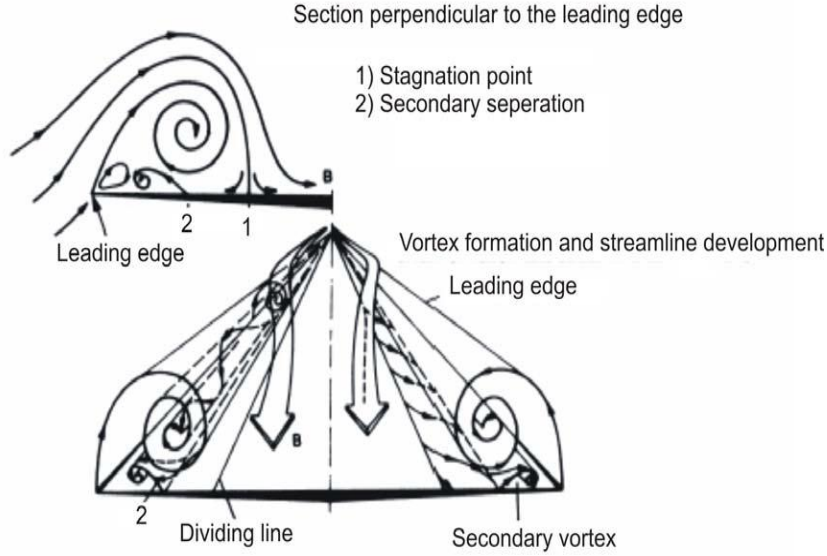


Fig.2.1. Representation of flow field transformations over a delta wing (Anderson, 2001)

Canpolat et al. (2009) monitored changes of flow structures on delta wing with respect to angle of attack α , and yaw angle β , for sweep angle of $\Lambda=40^\circ$. Variations of flow characteristics over a delta wing in plan-view plane under angles of attack of $\alpha=7^\circ, 10^\circ, 13^\circ$, and 17° , and varying yaw angles as $\beta=0^\circ, 6^\circ, 8^\circ$, and 15° . Dye visualization in crossflow plane were performed at locations of $X/C=0.6, 0.8$, and 1.0 along the central cord axis sequentially. Analyzing all dye visualization experiments at zero yaw angle β , it is seen that there are time-averaged symmetrical flow structures which take place over the delta wing. Additionally, there is a harmonious pair of leading-edge vortices starting from the apex of the delta wing. Structure of harmonious leading-edge vortices provides growing vortex bursting further downstream in free stream direction. Analyzing all

images in side-view plane reveals that a high-scale Kelvin-Helmholtz vortices take place at the bottom of unstable flow region, particularly for angles of attack of $\alpha=13^\circ$ and 17° . When yaw angle, β is taken as zero; symmetrical flow structure deteriorate and hence a vortex bursting takes place earlier on the windward side of delta wing as compared with leeward side.

Ozgoren et al. (2002) experimentally stated that there are three different vortex concentrations over flow structure delta wings with higher sweep angle, Λ at higher angle of attack, α . First of them is concentrations of azimuthal vorticity due to centrifugal instability of vortex having lower circulation and wave length value. Secondary concentration occurs due to vortex breakdown and has extremely higher circulation and wave length. Third circulation occurs because of instability of leading edge vortex and has higher wave length.

2.1.2. Highly Swept Delta Wings

There are vast varieties of technical and academic information for unsteady flow field around a slender delta wing. For instance, Erickson et al. (1989) has made some experiments with a cropped delta wing which has sweep angle of $\Lambda=65^\circ$ with and without LEX (Leading Edge Extension) at Mach numbers, $Ma=0.40$ and 1.60 based on free stream velocity, U . Obtained data and performed analysis boosted comprehension of vortical flow development, interactions, and vortex bursting behavior over a delta wing with the Leading Edge Extension. Ericsson (1995) reviewed actual data on the development of aerospace vehicles about improving maneuverability, having flight at a high angle of attack, α and vehicle motions of large amplitudes and high angular rates: His extensive revisal work divides available literatures, on topics of air vehicle aerodynamics predictions that have been commanded by effect of unstable separated flow, into four categories:

i) Reason and effect of asymmetric fore body flow separation with incorporated vortices.

ii) Reason of slender delta wing swing.

iii) Effect of motion of air vehicle on the dynamic of airfoil stall.

iv) Extrapolation from subordinate tests to full-scale free flight.

Ozgoren et al. (2002) recommended a criterion for beginning of vortex bursting and fluctuations of vorticity at high angle of attack, α using instantaneous vorticity results based on highly imaged density particle image velocimetry (PIV) data. Their delta wing model has been highly swept which had a sweep angle, $\Lambda=75^\circ$ and they monitored flow structures at angles of attack, such as $\alpha=24^\circ$, 30° , 32° and 35° . Co-existing distributions of azimuthal vorticity were classified using Particle Image Velocimetry (PIV) results as seen in Figures 2.2 and 2.3.

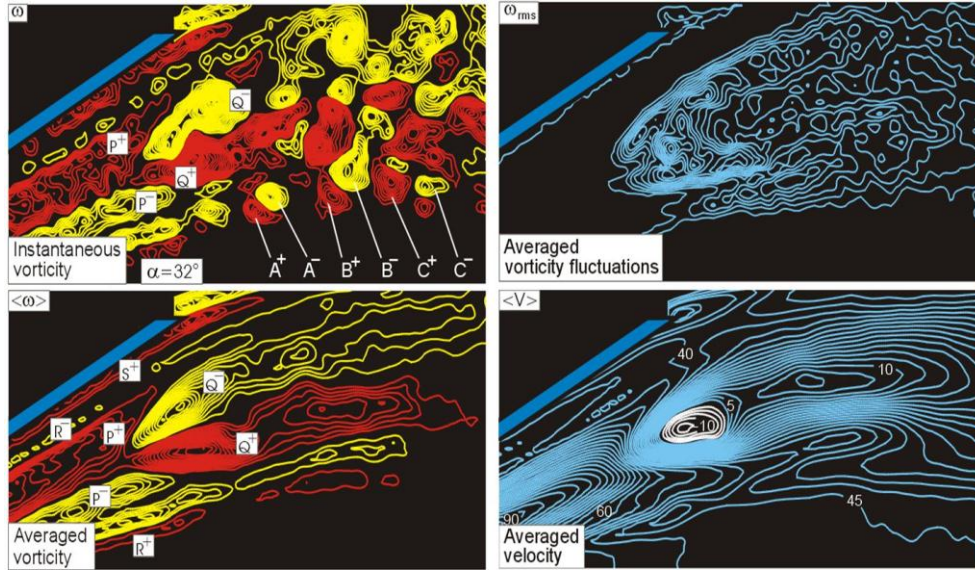


Fig.2.2. Patterns of instantaneous ω , $\langle\omega\rangle$, and ω_{rms} , in comparison with $\langle V \rangle$ at $\alpha=32^\circ$. Minimum and incremental values of instantaneous vorticity, ω are 1 and 0.75 s^{-1} , of $\langle\omega\rangle$ are 1 and 0.75 s^{-1} , and root mean square of ω_{rms} are 0.5 and 0.5 s^{-1} . For contours of $\langle V \rangle$, units of numerical values designated on contour lines are mm/s and incremental value between contours is 2.5 mm/s (Ozgoren et al. 2002)

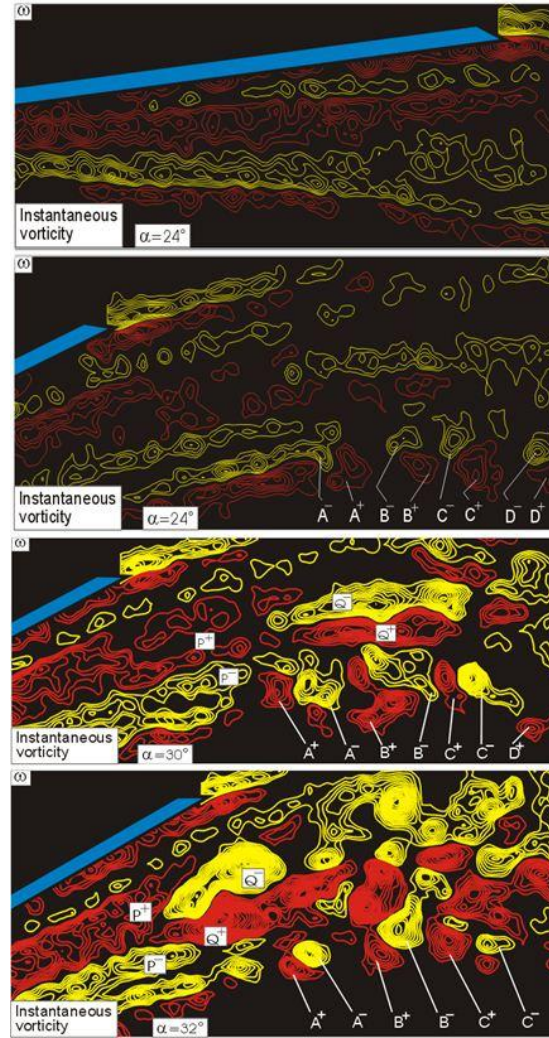


Fig.2.3.Effect of angle of attack, α on patterns of instantaneous vorticity, ω . Minimum and incremental values of ω for all cases are 1 and 0.75 s^{-1} (Ozgoren et al. 2002)

2.2. Parameters Affecting Vortex Bursting

Key parameters affecting location of vortex bursting over a delta wing are; sweep angle, Λ , the Reynolds number, Re , angle of attack, α , yaw angle β , roll angle, ϕ (Nelson and Pelletier, 2003).

2.2.1. Sweep angle, Λ

Payne and Nelson (1986) conducted an experimental examination on vortical flow over delta wings with different sweep angles, Λ . In this examination, LDA (Laser Doppler Anemometry) and smoke flow visualization were used to determine vortex bursting characteristics. They discovered that, when sweep angle, Λ increases, vortex bursting location moves towards the leading edge of the delta wing, and vortex core velocity can arrive up to 3 times of free-stream velocity. So, vortex bursting becomes wake-like flow under high angles of attack, α . Payne et al. (1988) implemented an experimental examination to investigate vortical flow over delta wings having 70° , 75° , 80° and 85° sweep angles, Λ . They defined that at constant angle, leading edge vortex bursting point is moving to the leading edge when sweep angle, Λ increases, especially with delta wings which have a high sweep angle, Λ . Vortex bursting location swings in between large scale, bubble type and spiral type of vortex bursting and vortical flow transformations occur between these two types of vortices. Moreover flow behaves like a jet-like in pre-bursting region but it behaved as a wake-like in post-bursting location.

Ogawa and Takeda (2015) conducted a numerical study on the clarification of the mechanism of generation and collapse of a longitudinal vortex system induced around the leading edge of a delta wing. It is found that rotational velocity and vorticity have their largest values at the tip of the vortex. The angle of the tip, θ which is between leeward side and windward side of the delta wing was taken 110° in their studies. Taking the angle of the tip, θ between 110° and 120° , the flow structure of the delta wing gets unstable. After 120° , the characteristics of the vortex are converted from the longitudinal vortex to the transverse one.

Yaniktepe and Rockwell (2004) performed the experiments of flow structure of stationary and perturbed delta wing which has a low sweep angle, $\Lambda=38.7^\circ$. The streamlines and vortices are obtained at different angles of attack, $\alpha=7^\circ$, 13° , 17° , 25° and different locations, x/C . The effects of perturbation on the delta wing are observed and compared with stationary position as shown in Fig 2.4.

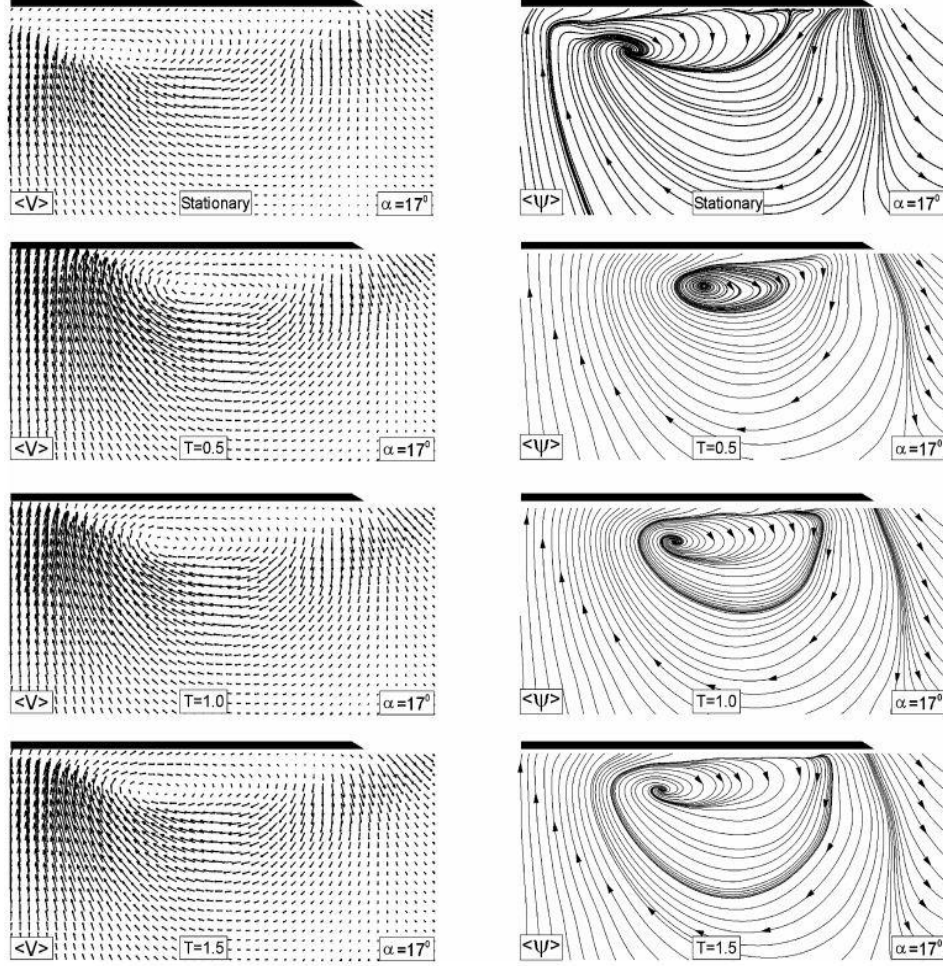


Fig.2.4. Effect of small perturbations of wing on time-averaged patterns of velocity $\langle V \rangle$ and streamlines $\langle \Psi \rangle$, relative to the case of the stationary wing. Perturbation amplitude is $\alpha_0 = 1^\circ$, and mean angle of attack is $\alpha = 17^\circ$. Perturbation is applied according to the equation of $\alpha(t) = \alpha + \alpha_0 \sin(2\pi t/T)$. The values of perturbation period are $T = 0.5, 1.0$ and 1.5 s. Spanwise extent of wing corresponds to $1.0 S$, in which S is the semispan of the delta wing at the location of the laser sheet, $x/C = 0.8$ (Yaniktepe and Rockwell, 2004)

2.2.2. Reynolds Number

Lee et al. (1989) implemented an experimental examination on aerodynamics of a delta wing having steady and unsteady flow response. They

represented that since separated leading edge vortices controlled by in-viscid shear layer dynamics; viscosity does not take an important role in delta wing aerodynamics. They compared the coefficient of lift (C_L) of this examination based on the Reynolds number, $Re = 2.3 \times 10^4$ with another experimental examination which was performed at the Reynolds number $Re = 6 \times 10^4$ and they found that experimental results for different Reynolds numbers, Re had very close values at the same angles of attack, α . Also, vortex bursting locations were compared and found that these locations were not the same but differences between locations were not significant for these two different experimental works of two different Reynolds numbers, Re .

Erickson (1981) conducted experiments in water tunnel for determining vortex core trajectory and core stability characteristics acquired on different delta wings which had sweep angles, Λ ranging from 60° to 80° . Experimental results represented that flow of at high angles of attack, α of slender delta wing having sharp leading edge, thin and flat structure was independent of the Reynolds number, because of that reason water channel experiments could be used to examine flow structures of a delta wing.

Coton et al. (2008) have studied the vertical flow structures over the delta wings with 65° sweep angle, Λ which has sharp and rounded leading edges at Reynolds numbers, $Re = 1 \times 10^6$ and 2×10^6 via flow visualization and force measurements. They finalized that when leading edge has been rounded, flow topology and forces have been dependent on the Reynolds number however at higher angles of attack, α dependency has been less, but the Reynolds number has important influence on pitching moment and tangential force.

2.2.3. Roll Angle

Cipolla and Rockwell (1998) performed an experimental work to search flow structures of a 65° sweep angle, Λ of the delta wing which has cylindrical central body. Flow structures in cross plane have been observed by means of the

PIV technique. Experiments showed vortex bursting location and flow topology that could change with self-excited excursions. Transformations could independently take place presented by pattern of streamlines or vorticity.

2.2.4. Yaw Angle

Johnson et al. (1980) conducted experimental examination about yaw angle effect, β on a delta wing which has 70° sweep angle, Λ . They defined that a fundamental difference is existed in the variation of the lift coefficient, C_L and the rolling-moment coefficient, C_M with yaw angle, β between low and high angles of attack α , and conditions. Also, at low angles of attack, α , the lift coefficient, C_L has a small decrease with increasing yaw angle, β while at a higher angle of attack α , this coefficient firstly decreases rapidly and then this decrease happens more gradually with altering yaw angle, β . They also finalized that the rolling moment coefficient C_M , presents a linear variation with increasing yaw angle, β at a low angle of attack, α but a strong nonlinear variation with yaw angle, β at a high attack angle, α takes place.

Karasu (2015) studied the structure of leading edge vortices in side view plane. He showed that yaw angle, β varying within the range $0^\circ \leq \beta \leq 20^\circ$ influences flow structure in side view plane. When yaw angle, β increased from 0° to 20° , Kelvin-Helmholtz (K-H) vortices were seen clearly.

Yayla et al. (2013) conducted an experimental work to view the structures of the leading edge vortex breakdowns at a cross-flow plane varying angles of attack within the range of $7^\circ \leq \alpha \leq 17^\circ$ and dimensionless locations, x/C of measuring planes along the delta wing central axis which has a low sweep angle, $\Lambda=40^\circ$ by using dye visualization and the PIV technique as shown in Fig. 2.5.

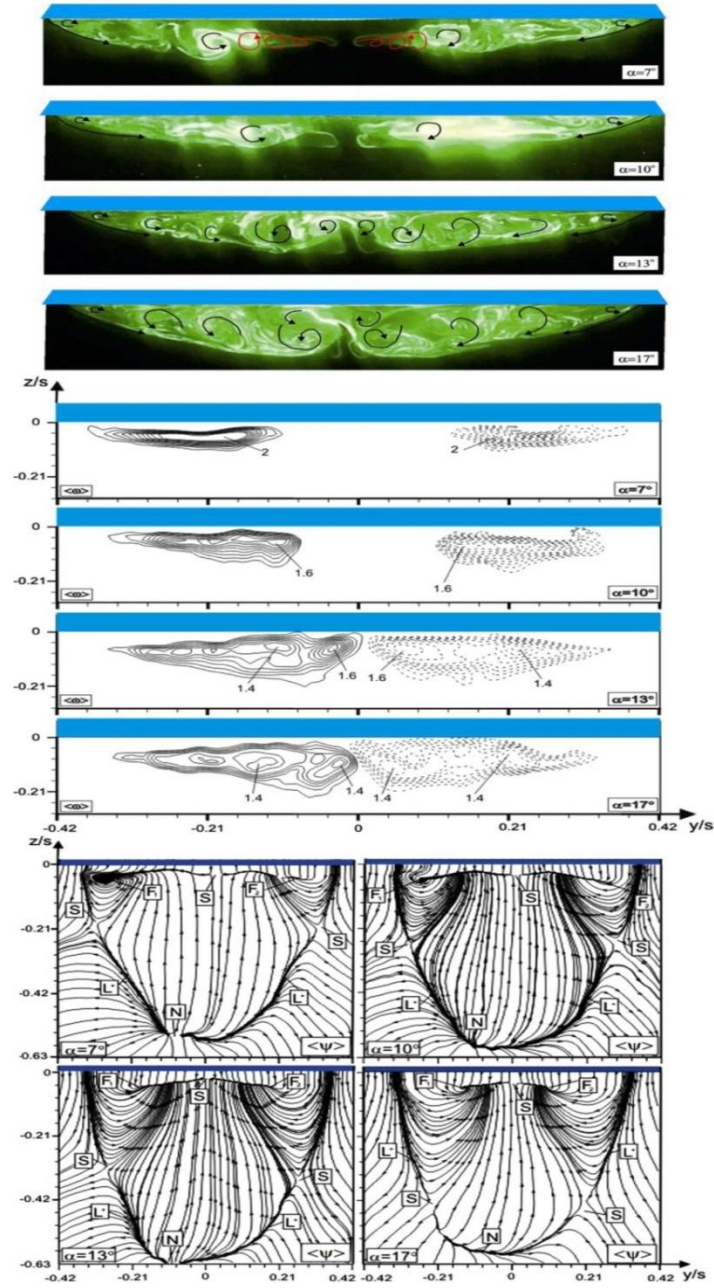


Fig.2.5. The formation and development of vorticity concentrations in cross-flow plane observed by dye visualization and the PIV technique (Yayla et al., 2013)

Canpolat (2008) performed experiments in his M.Sc. studies to observe location of the vortices of Kelvin-Helmholtz (K-H) vortices are changing clearly by varying the angle of attack, $7^\circ \leq \alpha \leq 17^\circ$ consistently as shown in Figure 2.6.

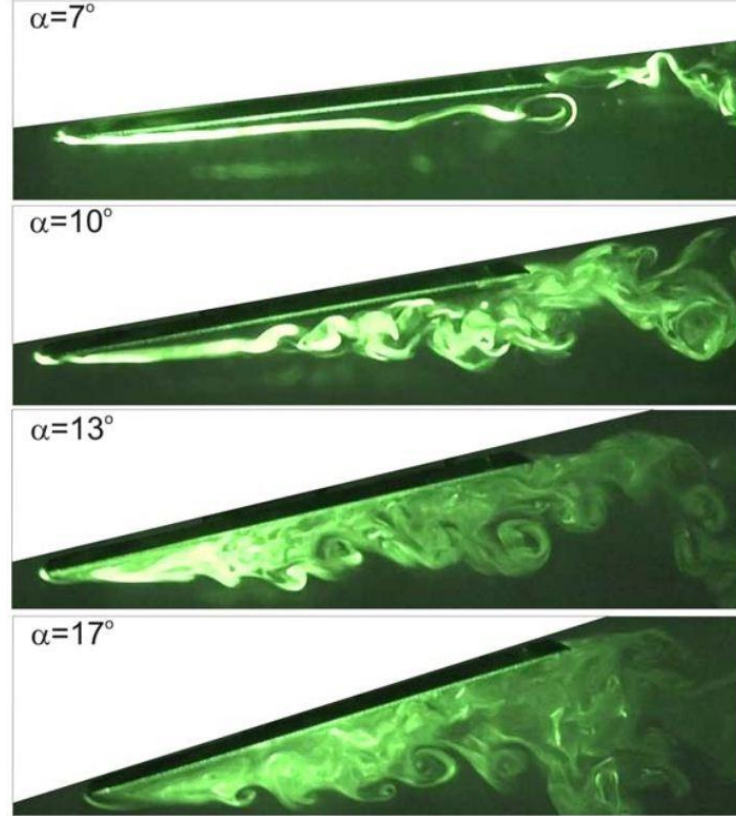


Fig.2.6. Representation of the locations of Kelvin-Helmholtz instabilities by varying angle of attack within the range of $7^\circ \leq \alpha \leq 17^\circ$ (Canpolat, 2008)

Sohn et al. (2004) performed an experimental study on a yawed delta wing connected with the LEX to visualize a vortical flow. Interactions between vortical flow of the LEX and the delta wing have been investigated at some angles of attack, α and yaw angles, β . They finalized that the wing leading edge vortex and the LEX vortex coated around each with comparable strength and identity when yaw angle, β was taken as 0° and increasing of attack angle, α condensed coating and shifted the location of leading edge vortices of the delta wing and the LEX

inboard and upward. It was also concluded that when the delta wing is yawed, coating, merging and diffusion of those leading edge vortices occur earlier in the windward side, whereas there was a delay in the occurrences of those flow structures

Canpolat et al. (2009) examined structures of flow on the surface of non-slender delta wing which has a 40° sweep angle, Λ . They concluded that when the delta wing has even a moderate yaw angle, β , a symmetrical flow structure vanishes. Vortex bursting occurs earlier on the windward side of the delta wing with respect to the leeward side.

Sohn and Chang (2010) searched the effect of central body on a yawed double delta wing using flow visualization and wing-surface pressure measurements. They concluded that up to 24° angle of attack, α availability of a central body had a small effectiveness on the pressure distribution of suction side of wing surface, even at the large yaw angle of $\beta=20^\circ$. They also defined that at higher angle of attack, α such as 28° - 32° , availability of a central body caused a decrease in the magnitude of pressure coefficient magnitude, C_p when compared with 0° yaw angle, β .

Yayla et al. (2010) performed experimental studies on the aerodynamics of a non-slender diamond delta wing which has 40° sweep angle, Λ . They searched an effect of yaw angle, β on vortex bursting by using the dye visualization technique. They concluded that up to 4° yaw angle, β there were no clear change in vortex bursting location, but at a higher yaw attack, β for example, after 4° , the point of vortex bursting moved towards the leading edge on the windward side, while this location came off further downstream on the leeward side, locations of asymmetrical vortex bursting have been seen over delta wing in plain-view plane as shown in Figure 2.7.

Canpolat (2015) observed the effect of perturbation in cross-flow plane on the delta wing which has sweep angle, $\Lambda=40^\circ$ at different angles of attack, $7^\circ \leq \alpha \leq 17^\circ$ and the development of control of leading edge vortex bursting at

different dimensionless location, x/C are indicated. Stationary wing and perturbed wing are compared by using dye visualization and the PIV technique. The results of angle of attack, $\alpha=13^\circ$ are shown in Fig. 2.8.

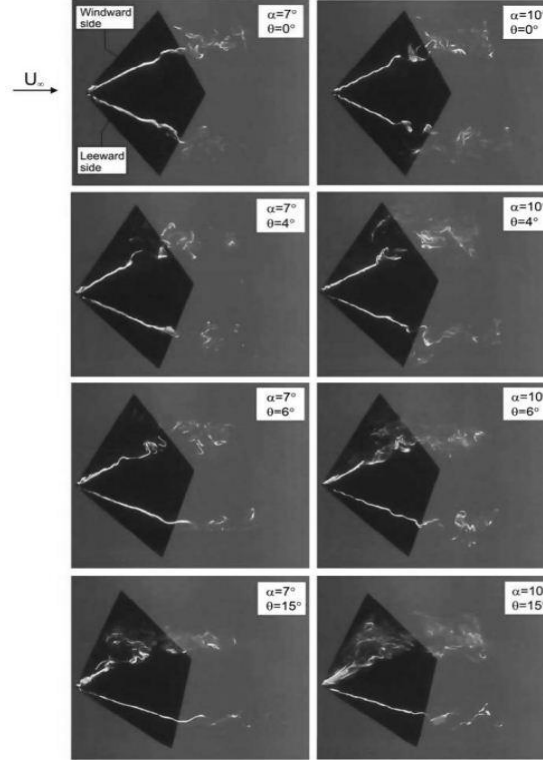


Fig.2.7. Formation and development of leading-edge vortices, vortex breakdowns, and separated flow regions as a function of angle of attack, α and yaw angle, β (Yayla et al., 2010).

Woodiga et.al.(2016) focused on the fields of the high-resolution skin friction in separated flows using quantitative global skin friction diagnostics based on luminescent oil visualizations over the delta wing which has sweep angle, $\beta=65^\circ$ and a $76^\circ/40^\circ$ double-delta wing with different junction fillet are obtained. The effects of the pitch, yaw, and roll angles on the skin friction topology are studied systematically. Also the topological features such as separation and attachment lines on these delta wings are identified.

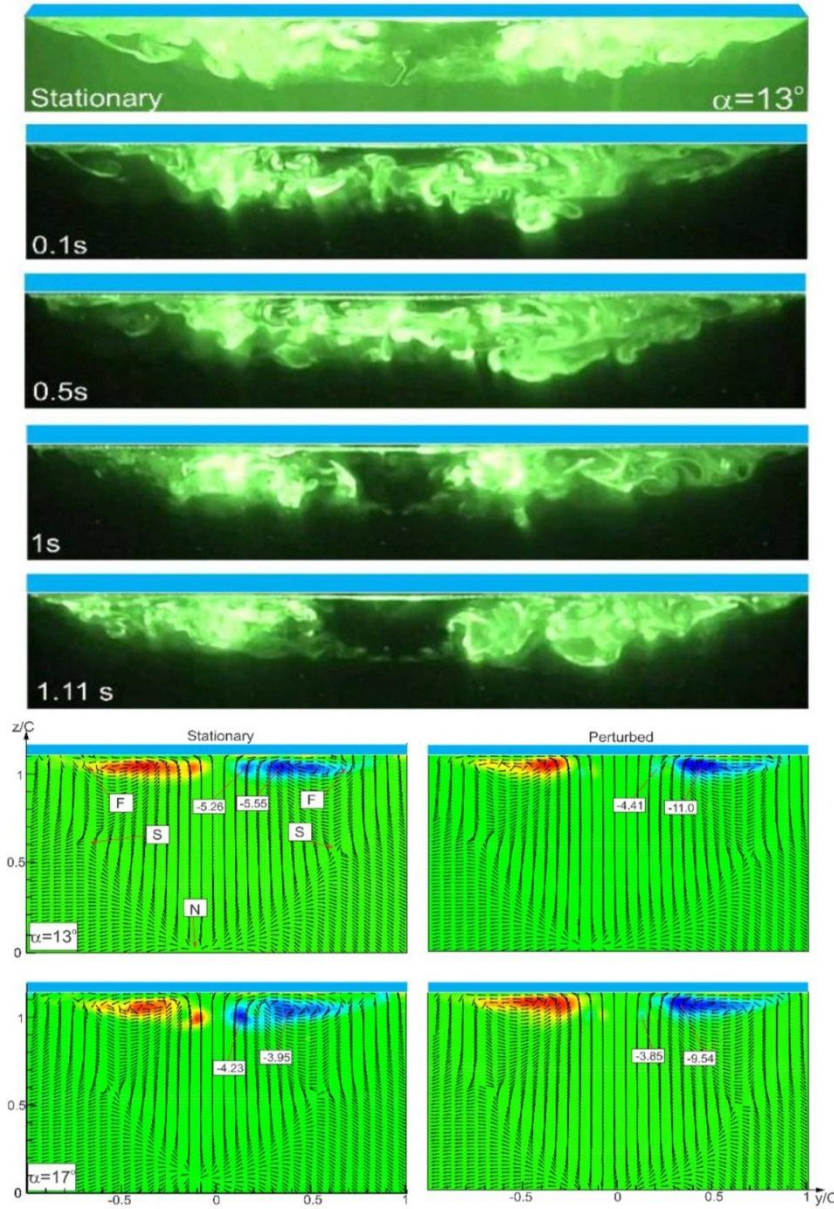


Fig.2.8. Development of the control of leading edge vortices of the delta wing at $\alpha=13^\circ$ from cross-flow plane of view. Patterns of the time-averaged vorticity contours, $\langle \omega \rangle$ overlapped with velocity vectors, $\langle V \rangle$ as a function of attack angle, α for the delta wing at $\alpha=13^\circ$ on cross-flow plane of view (Canpolat, 2015).

The effects of yaw angle, β on a slender delta wing aerodynamics have not been studied in detail yet. Particularly, there is not much published work on the aerodynamics of slender delta wings in cross-flow planes as a function of yaw angle, β . For this reason, as a motivation of present work, further studies are required in order to understand flow structures and aerodynamics of slender delta wings in detail.

Overall scene of vortex bursting close to the slender delta wing surface is presented in Figure 3 (Karasu et al., 2015) in plan-view planes. As seen in the Figure 2.9, yaw angle, β influences onset of vortex location in dramatically.

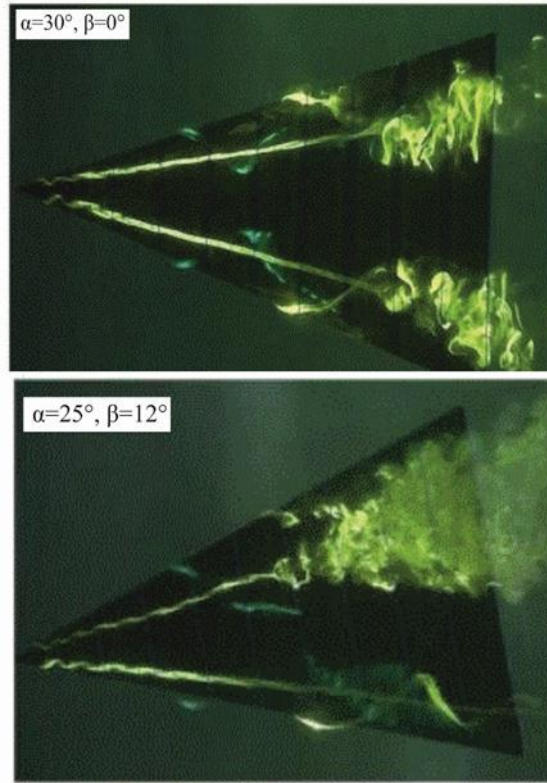


Fig.2.9.Representation of symmetrical vortex bursting over a high sweep angle of delta wing, Λ (Karasu et al., 2015)

2.3. Control Technique for Vortex Bursting

2.3.1. Passive Control

New unmanned combat air vehicle (UCAV) models which have been advanced require higher maneuverability. They are often associated with more moderate sweep angles, Λ (40° to 60°) and delta-type wing shapes. While extensive investigations were conducted on high sweep angled ($\Lambda > 60^\circ$) delta wings both experimentally and numerically, less research works were conducted for configurations of higher aspect ratio of delta wing. Nowadays, researchers put efforts to study aerodynamics of flexible delta wing. Further research works are necessary to gain detailed information of aero elastic response of a delta wing under variation of main parameters of wing as stated by Gordnier and Visbal, (2004).

In last decades, flexible wing aerodynamic was surveyed and it was shown that flexible wings influence vortical flow structures with a large scale (Gordon and Gursul, 2004). Kawazoe and Kato (2006) performed experimental investigations in a low-speed wind tunnel on aerodynamics forces and moments of flexible delta wing pitching motion. They have examined three types of flexible delta wing having 44%, 70% and 99% of delta wings as a flexible wing. Ratio of flexible wing body has different influence on aerodynamic characteristics of wing as seen in Figure 2.10.

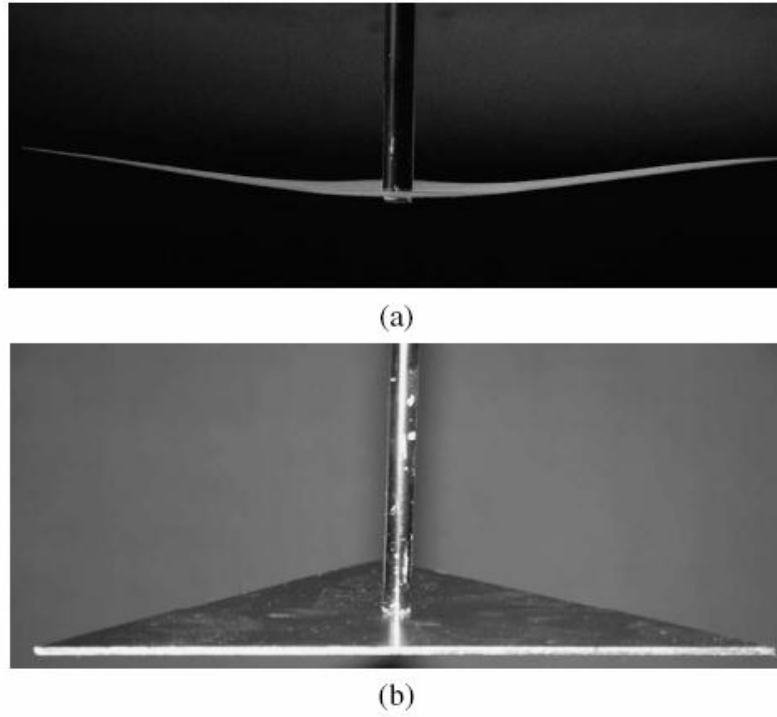


Fig.2.10. Deformation of C-type flexible delta wing compared with that of hard delta wing. a) C-type flexible delta wing b) Hard delta wing (Kawazoe and Kato, 2006)

3. MATERIAL AND METHOD

3.1. Water Channel

Water channel experiments were made in a close-loop water channel in Fluid Mechanics Laboratory at Çukurova University. Dimensions of water channel are set as 8000 mm length, 1000 mm width, 750 mm height and test section of water tunnel is made by Plexiglas transparent which has thickness of 15 mm.

Water Channel has two fiberglass tanks at inlet and outlet of channel and water was delivered from downstream tank to upstream tank. Just before reaching test section, water was pumped into a settling chamber and passed through a honeycomb section before 2:1 channel contraction. Arrangements such as tanks, chamber and honeycomb are located to ensure turbulence intensity lower 0.5 %. Also, 15kW electric driven pump which has a frequency controller to set flow speed is used to pump water.

3.2. Experimental Apertures

In this study, delta wing is kept static in water flow by a special mechanism which is designed to adjust angle of attack, α and yaw angle, β of delta wing manually. The delta wing is hold in a horizontal position by a slender support arm that stretched from mid-chord of the delta wing vertically. This arm has a 4 mm width and 35 mm stream-wise length. Assessment of arm setting involved comparison with complementary experiments involving a horizontal sting and comparison of location of vortex bursting for wings of different angles of attack, α and yaw angles, β . As a consequence, arm setting has no significant effect on the flow structures on the leeward side of the delta wing.

3.3. Experiments of Dye and 2D Particle Image Velocimetry (PIV)

3.3.1. Dye Visualization Experiments

Dye visualization is a technique to have an idea how flow pattern behaves in water channel while angle of attack, α and yaw angle, β are adjusted before 2D Particle Image Velocimetry measurements are taken seen in Figure 3.1. The dye visualization technique provides us no numerical information about flow structure of a delta wing but this technique shows a brief and rough idea about flow structure over a delta wing. A fluorescent dye which shines under a laser sheet was used to record color change to visualize flow characteristics over a delta wing during experiments. Dye is kept in a container which is located 1m above the free-surface of water channel. Dye is passed through a narrow slot located along the delta wing axis towards its apex and dye is injected by a thin plastic pipe. SONY HD-SR1 video camera is employed to capture instantaneous images of vortex flow structures over the delta wing. Images are taken by frame grabber software which is called Play Memories as seen in Figure 3.2. Same experimental setup is used for 2D PIV experimental setup as well as.

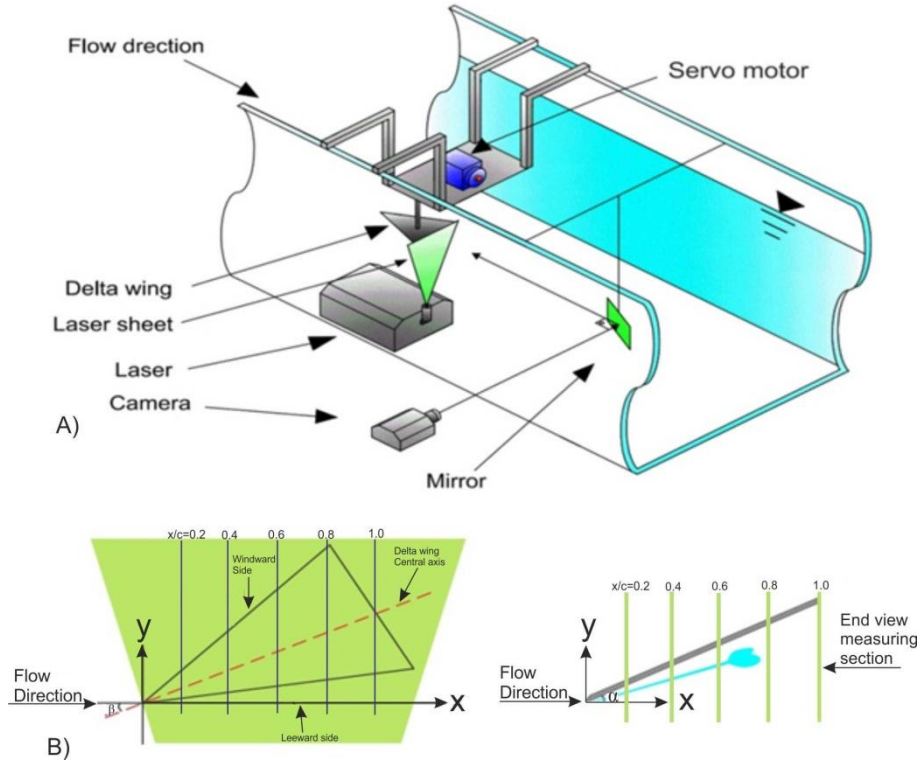


Fig.3.1.A) Schematic of the experimental set-up for dye visualization and Stereo PIV experiments for end-view plane at yaw angle, $\beta=0^\circ$, B) x/c ratios of dye visualization experiments at different yaw angles, β

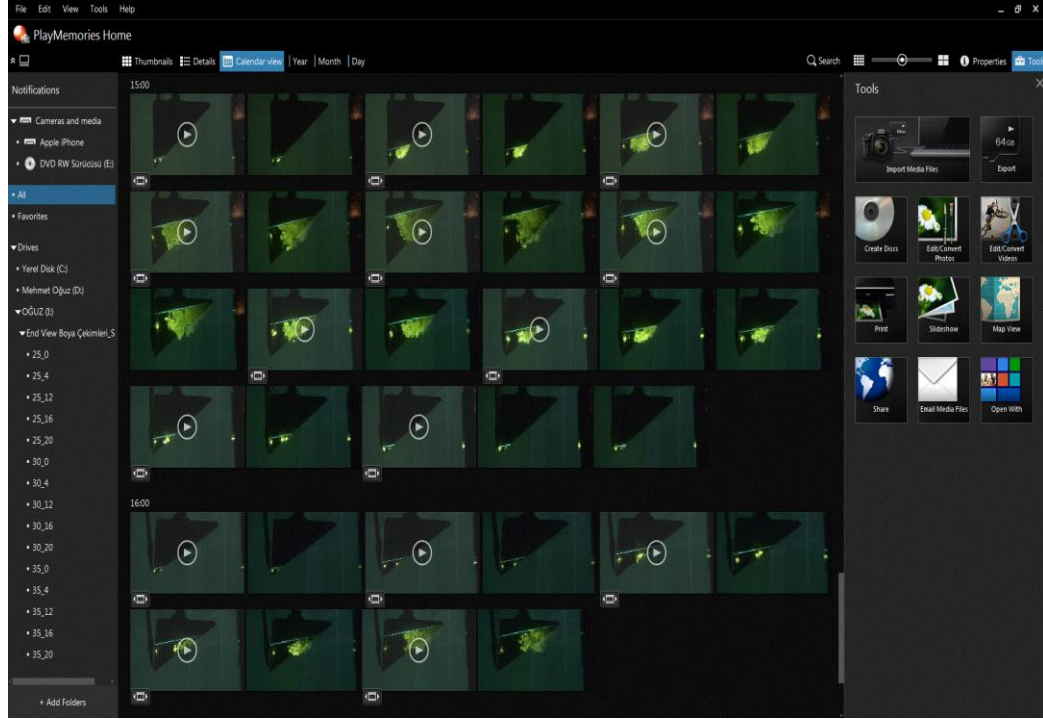


Fig.3.2. Play Memories, Image Capture Program

3.3.2. Experiments Performed by Particle Image Velocimetry Technique

3.3.2.1. Working Principle of PIV

Particle Image Velocimetry (PIV) is the velocity measurement technique which may be used to take time dependent field of velocity distributions for single and multi-phase flows. Two dimensional instantaneous velocity fields can be also taken with a high numbers as were done in the present work. Namely, the PIV technique ensures a general view of snap flow field. This feature lets user to examine an existence of small flow structures and their effect and obtain vorticity fields quantitatively. Particle Image Velocimetry (PIV) records distances that particles move in a certain period time between laser illuminations. In general, the user can obtain image acquisition, particle seeding locations and image processing with data analysis using a PIV system and related software program. Laser beams are generally employed as an illumination source in the PIV system. Particles are

illuminated by pulsed laser beam at a given time intervals to produce images that are recorded on a CCD camera. Ideal tracer particles are very small which follow flow field movement. Most common methods to define distance are particle tracking and correlation methods. Correlation field shows dominant distance between each particle and every other particle within interrogation spot. Maximum intensity spot, which shows each particle image correlation with itself, is located in a midpoint. A second peak, which is called positive displacement peak, that communicates to the dominant particle spacing. After displacement calculation of particles in a certain time, flow field velocity could have been found. Using instantaneous velocity vector field, vorticity, streamline topology and turbulent statistics can be determined. Average velocity field, vorticity contours, streamline topology and turbulent statistics are also calculated using instantaneous data.

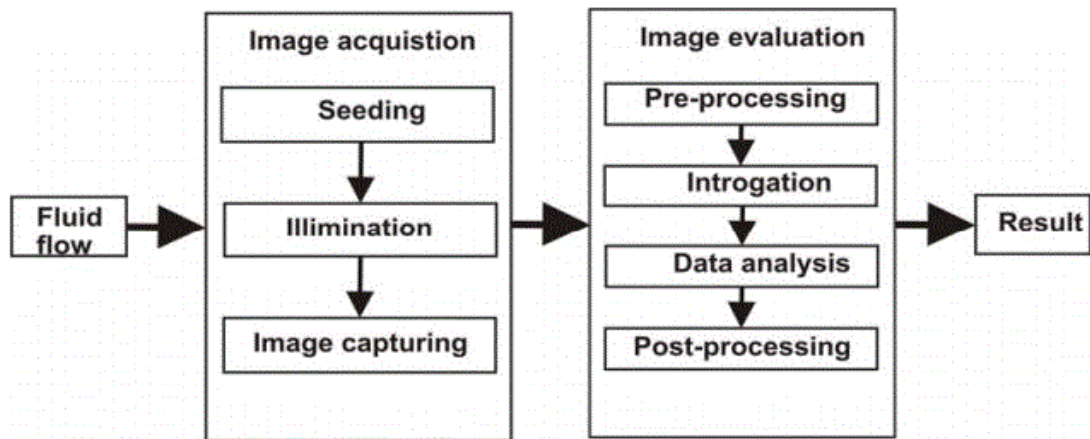


Fig.3.3. General PIV Process steps (Yayla, 2009)

3.3.2.2. PIV Illumination

Illumination is achieved by a laser beam. In general, laser light is chosen for this purpose to capture images precisely. In gas flow applications, a high light source should be available for well-built illumination. Sufficient laser light and tracer particles should be used to provide camera for having flow images

accurately. Large tracer particles are used for this purpose because of their high spreading efficiency. Characteristics of particles flowing with fluid are serious parameters. Smaller particles are very convenient for imitating flow behavior than larger tracer particles. Duration of light illumination pulse must be as short as possible in order to prevent image blurring. There is a time delay between two laser light pulses. This time interval must be adjusted according to the speed of particle which imitates fluid motion with great measures between a pair of images of tracer particles. During the experiments, locations and dimensions of measuring planes should be well defined.

3.3.2.3. The Adaptive Cross-Correlation Technique and Analysis

From the past to the present time, auto-correlation is one of most common methods because in the past it was not possible to separate initial and final particle positions on separated camera frames. Therefore, successive light-sheet pulses present image map for one camera. Naturally, this leads to vagueness in measurements, since it hasn't been possible to tell which of two recorded particle images initial and final locations. In recent years, development in camera technologies have let initial and final particle positions be recorded on separated camera frames, and thus cross-correlation and adaptive correlation has been used without auto-correlation directional vagueness (Dantec Dynamics Software Manual). Fundamental principle of Adaptive correlation is an iterative procedure: Images are received from CCD camera which has resolution of 1600×1200 pixels at a rate of 15 frames per second. Time delay between frames is $170 \mu\text{s}$ for the present experiment. To eliminate bad vectors, an approval is required. Approval is run by means of CLEANVEC software which is written by Meinhart and Soloff (1999). This software has four methods; RMS tolerance filter method, magnitude difference filter, absolute range filter and quality filter methods to remove bad vectors which are below defined doorstep value. To fill the place of deleted vectors bilinear interpolation with least squares fit is used. A total of 1050 images of

instantaneous velocity vectors are used for time-averaged flow data calculations. In order to define velocity field, a cross-correlation technique, with 32×32 -interrogation window, was used, with an overlap of % 50.

3.3.2.4. 2D PIV Experimental Setup

In this study, the 2D PIV technique is used to study effects of yaw angle, β on vortex formation over the slender delta wing. To investigate behaviors of trailing edge vortex bursting, experimental setup is used as shown in Figure 3.4. During the experiment, a laser beam is set normal to the flow direction. The mirror is positioned at a location which is 700 mm from the wake region of delta wing and the mirror is turned 45° taking the free-stream flow direction as a reference line to deliver vision of end-view of delta wing to the camera.

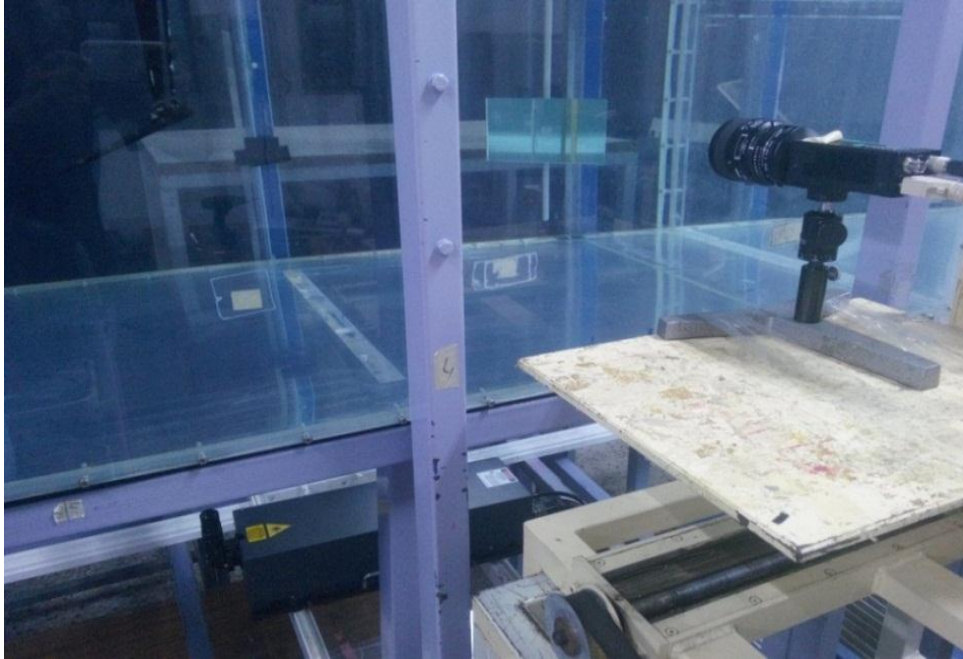


Fig.3.4. Photographic representation of experimental setup

Experimental Setup and calibration of 2D PIV is shown in Figure 3.5. Calibration is done via balanced ruler. One image is captured to use as a calibration measuring image. In the PIV computing program, “The Scale Factor for Measurement” is used to capture the real size of field of images. Lastly, images are taken by the balanced CCD camera.



Fig.3.5. Experimental Setup with CCD camera for Calibration

4. RESULT AND DISCUSSION

4.1. Flow Structure on a Highly Swept Delta Wing

4.1.1. Dye Visualization Results

Although substantial scientific and technological information was obtained about instantaneous and time-averaged flow structures of delta wings with relatively large sweep angles, Λ in recent years, but influences of yaw angle, β were not studied at all. Recent demands on UCAVs have encouraged researchers to pay more attentions in characterizing flow structures of delta wings. Present investigation focuses on the unsteady flow structure which occurs downstream of onset of vortex breakdown and services as a source of buffeting and stall that reduces the lift force, F_L .

The dye visualization technique is used over an end-view planes in five different stations such as $x/C = 0.2, 0.4, 0.6, 0.8$ and 1.0 in order to observe vortical flow structures further downstream of vortex bursting at a cross-flow plane. As soon as leading edge vortices break down, a complex flow structure is developed. Large scale vorticity concentrations take place in an inner side of leading edges which are close to the central axis of delta wing. Small size vorticity concentrations which are just next to the leading edge are also advanced close to main rotating vortices. They get smaller in size when they move close to the side edges of delta wing. Outer line of separated flow region moves away from surface of delta wing gradually as end-view cross-section is moved further downstream in the free-stream flow direction. Thus, the vortical flow structure diameter downstream of vortex bursting increases step by step as the flow moves further downstream in free-stream flow direction. Between vortical flow structure and surface of delta wing, there is a strong interaction. Intensity of this interaction gets weaker at the location of $x/C=1.0$ comparing to $x/C=0.2$. More or less, magnitude of non-steady flow structures caused by both leading edge vortices is the same. One side of delta wing, the leading edge vortex breakdown location which gets closer to the leading

edge side has a larger size vortex bursting than the other pair of leading edge vortex which appears in the other side of the delta wing moves towards the trailing edge of the delta wing. Because of this reason, magnitude of velocity in the region of the leading edge side vortex bursting is slower than the windward side and it means that we can easily see diameter difference of vortices between two sides which is visualized by dye and laser light. As shown in Figure 4.1-4.15, changes of vortex bursting location are illustrated clearly as a function of yaw angle, β .

When eye observation is made for all of dye visualization experiments, it is observed that double helix vortex starts from front end portion of delta wing initially and rotates in opposite direction to each other. These vortices are formed by three-dimensional shear layer separated from the wing surface.

At different angle of attack α , behavior of vortices is the same but locations of vortex bursting are different. For instance, at angle of attack, $\alpha=25^\circ$, and yaw angle $\beta=4^\circ$, vortex bursting at leeward side is located at around $x/C=0.8$ but in the case of angle of attack, $\alpha=35^\circ$ and yaw angle $\beta=4^\circ$, it is located at around $x/C=0.4$. When delta wing has no yaw angle β , time-averaged vortex bursting locations at both sides are symmetric. For magnitudes and locations of vortex bursting, we must apply the PIV technique to get exact velocity results.

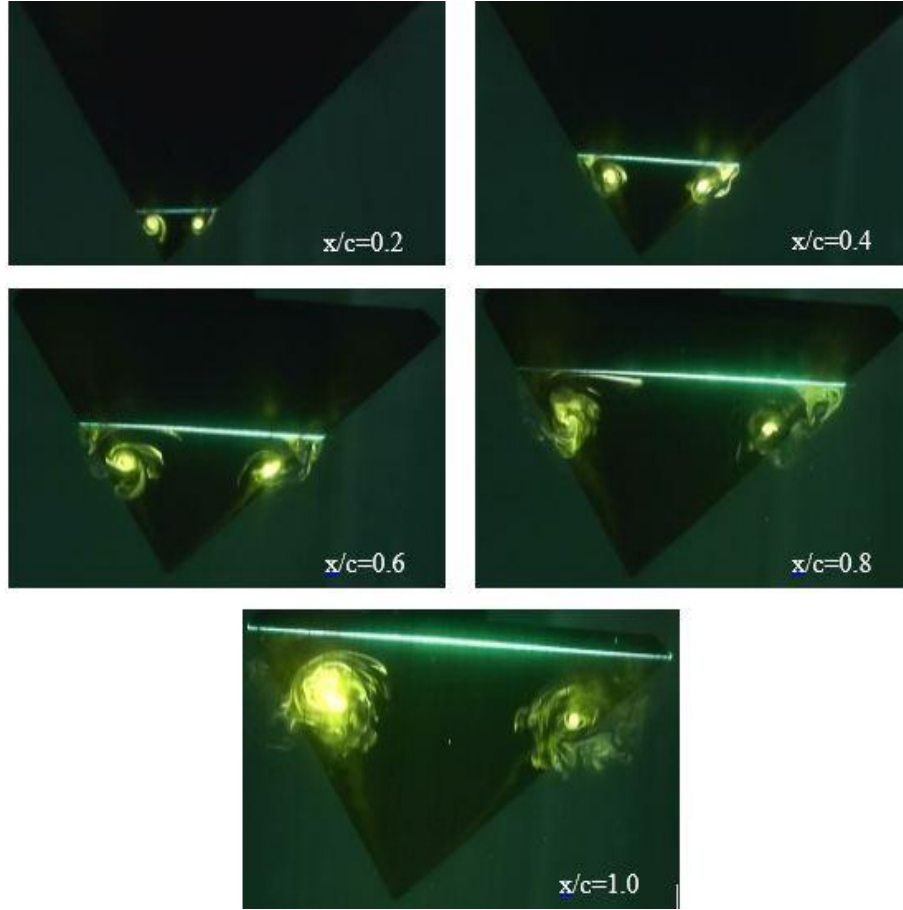


Fig.4.1. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=0^\circ$

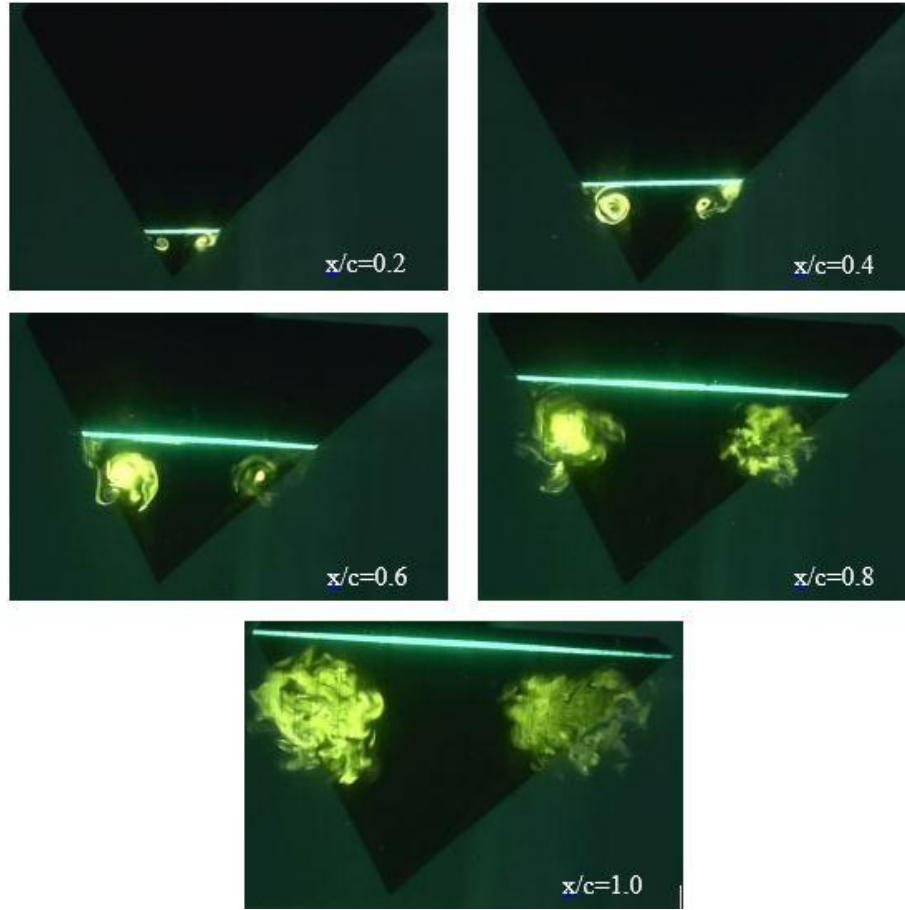


Fig.4.2. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=0^\circ$

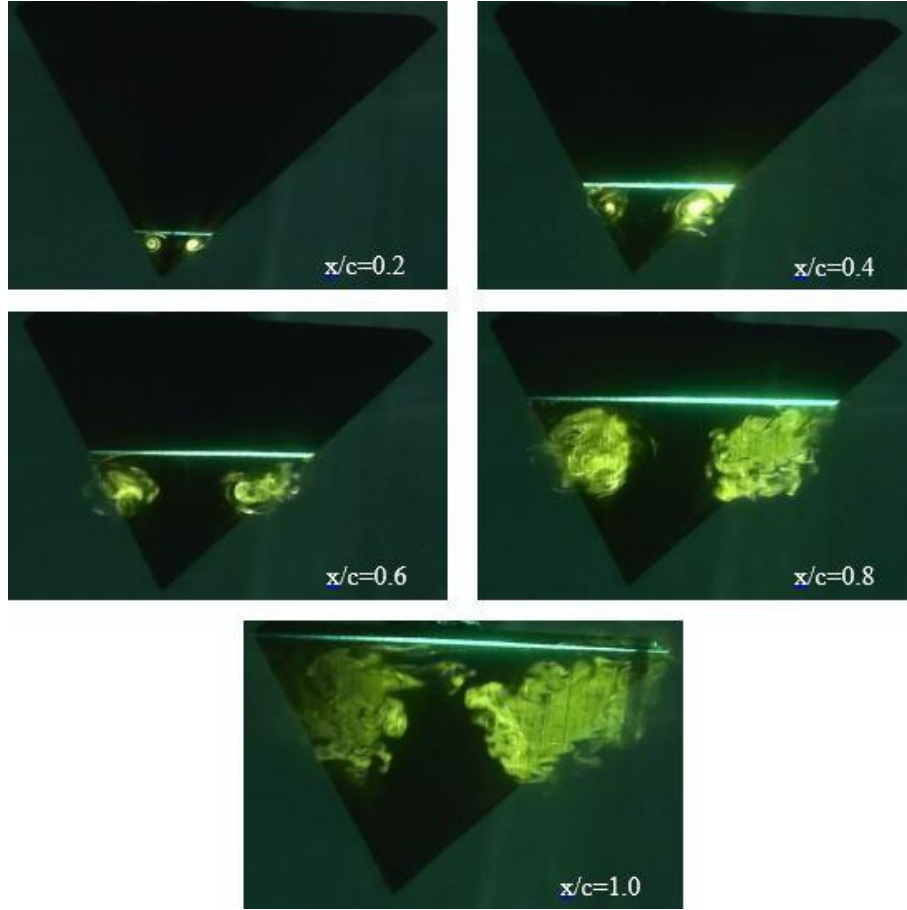


Fig.4.3. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=0^\circ$

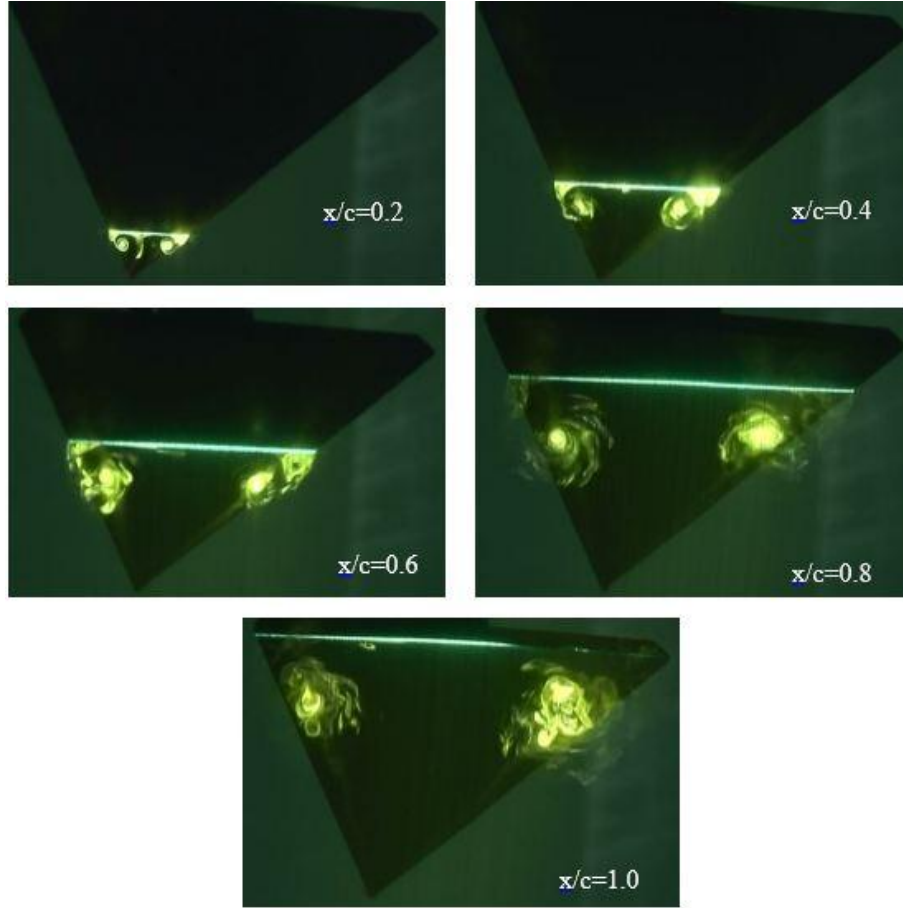


Fig.4.4. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=4^\circ$

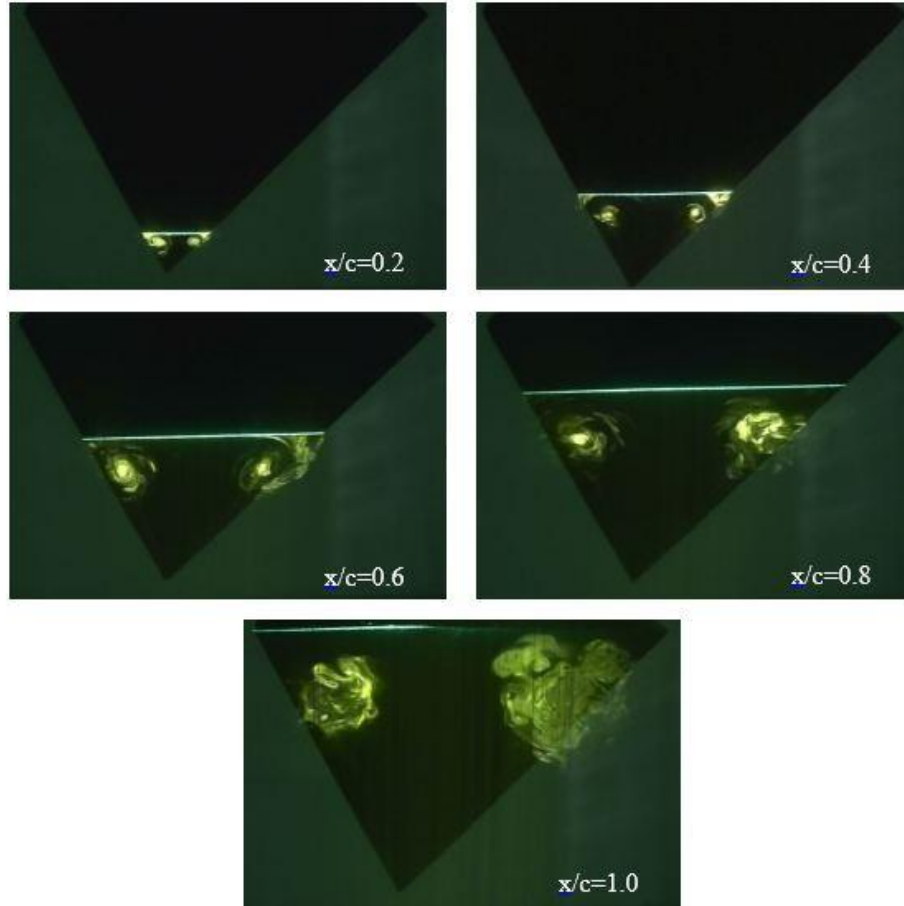


Fig.4.5. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=4^\circ$

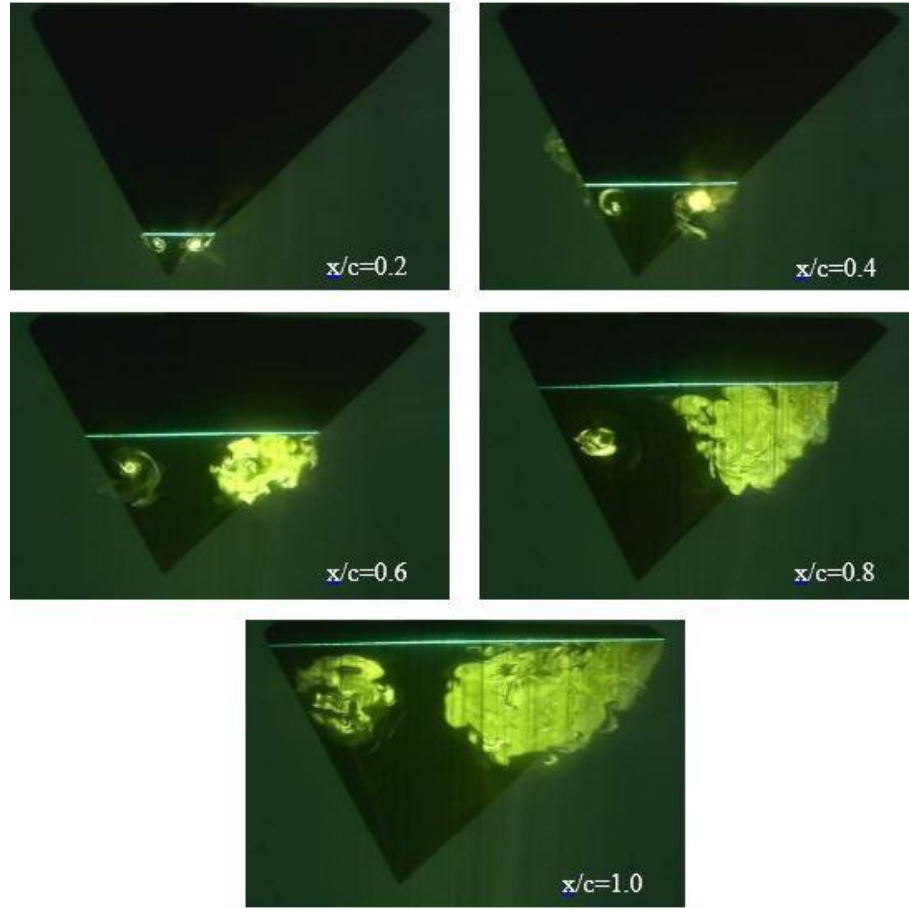


Fig.4.6. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=4^\circ$

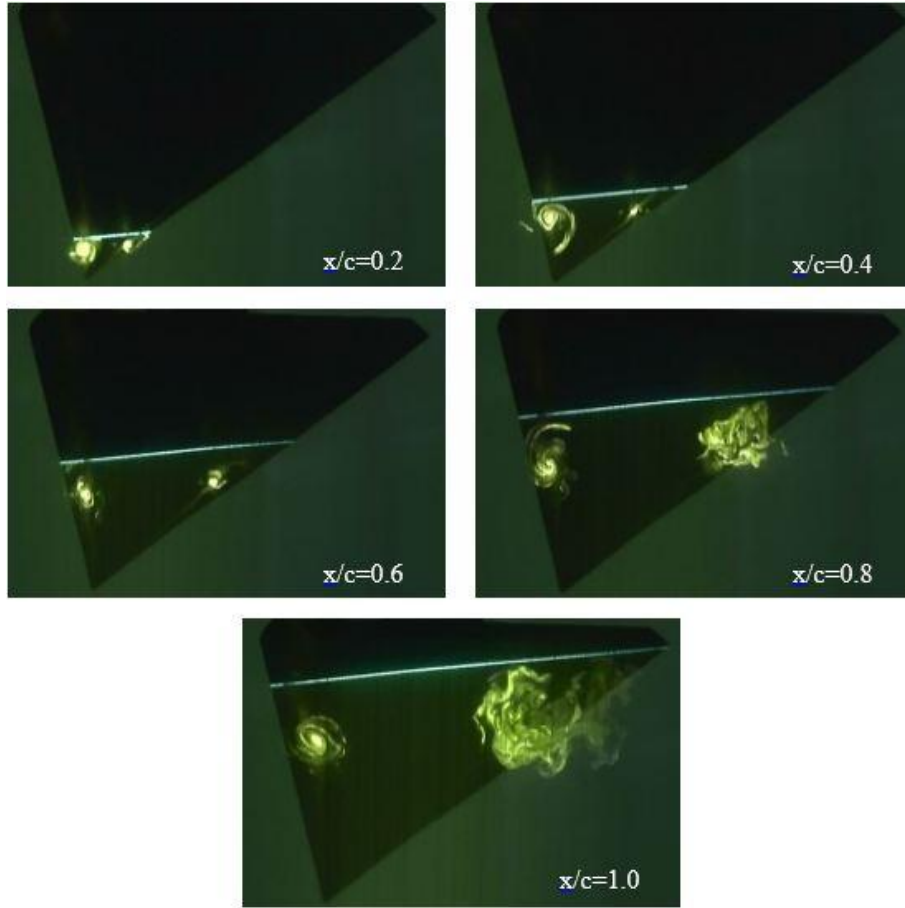


Fig.4.7. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=12^\circ$

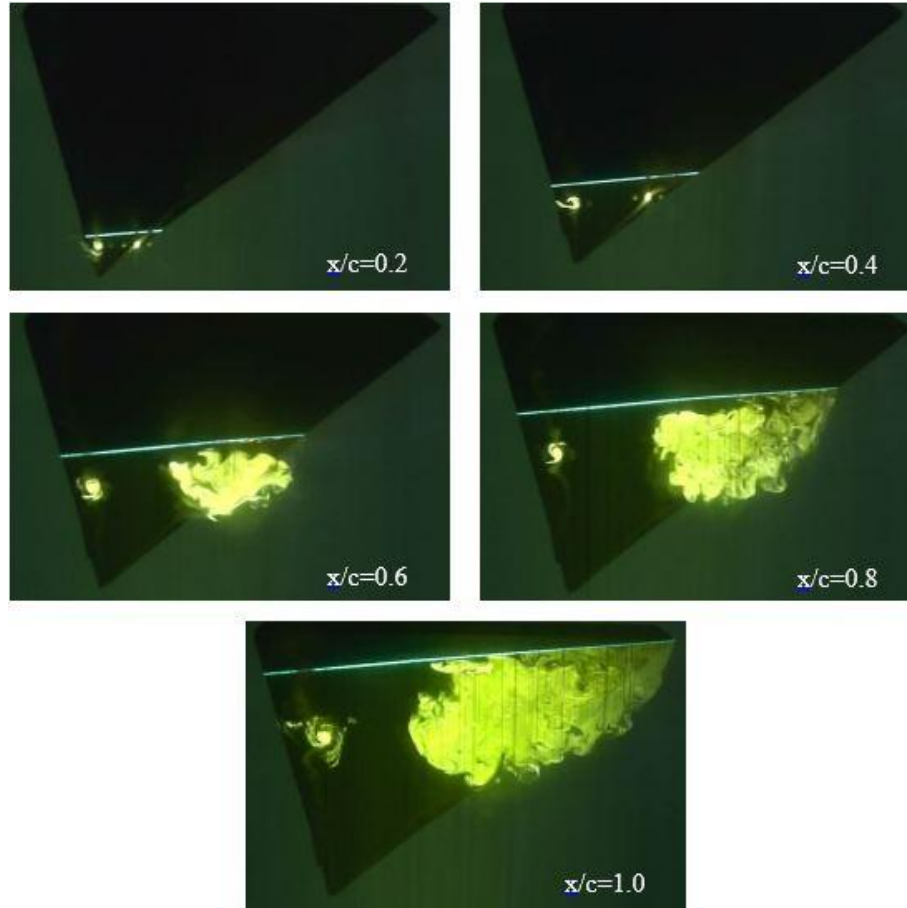


Fig.4.8. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=12^\circ$

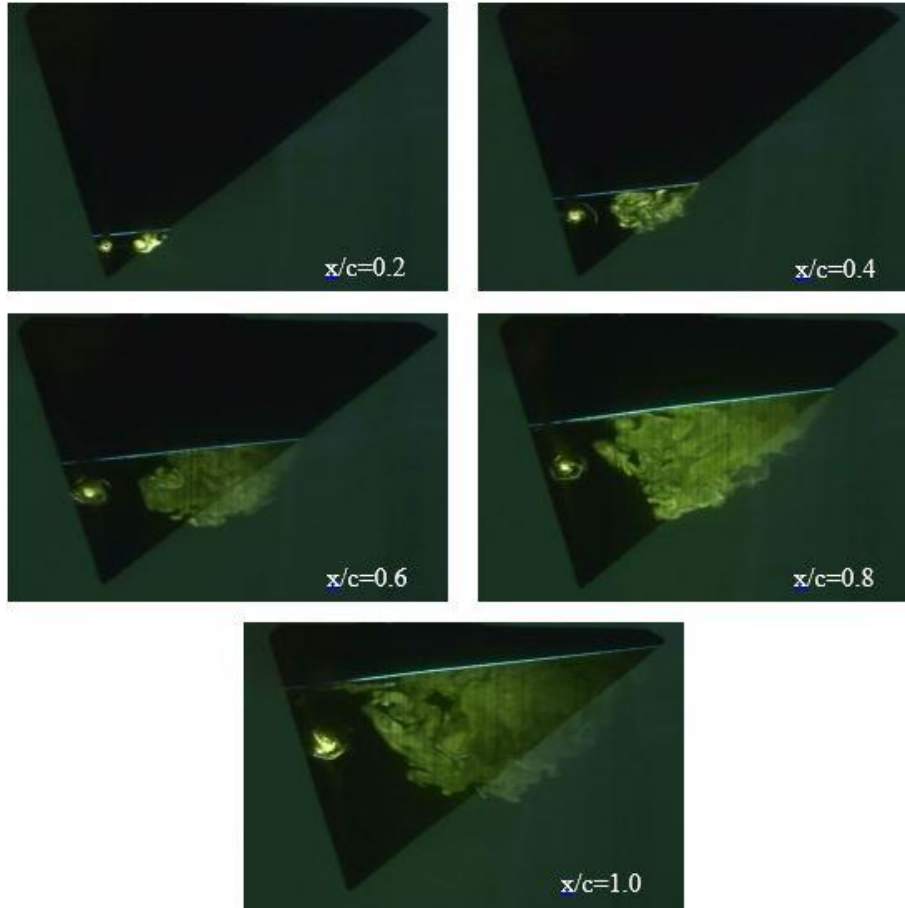


Fig.4.9. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=12^\circ$

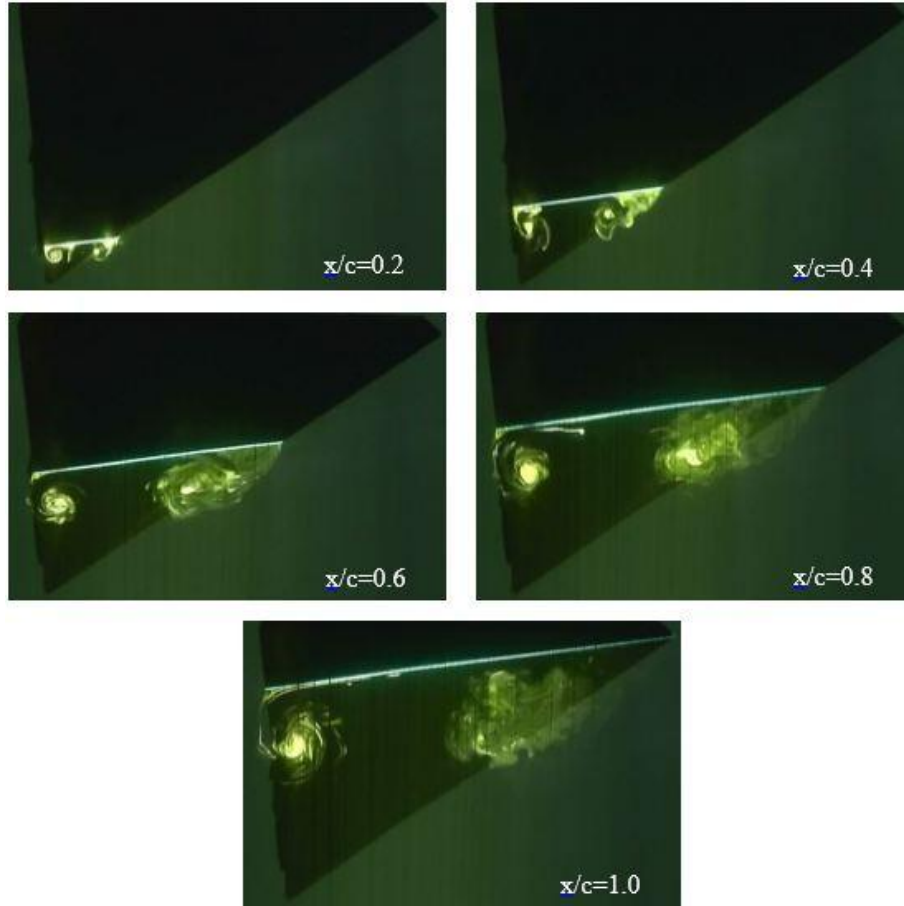


Fig.4.10. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=16^\circ$

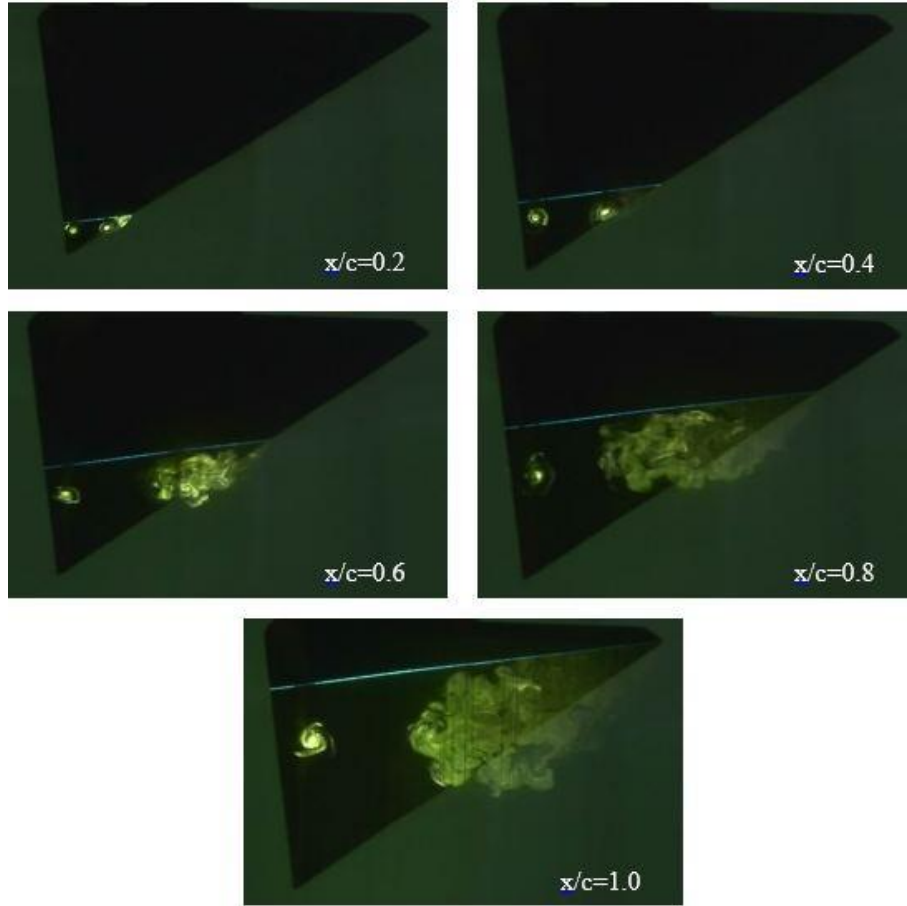


Fig.4.11. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=16^\circ$

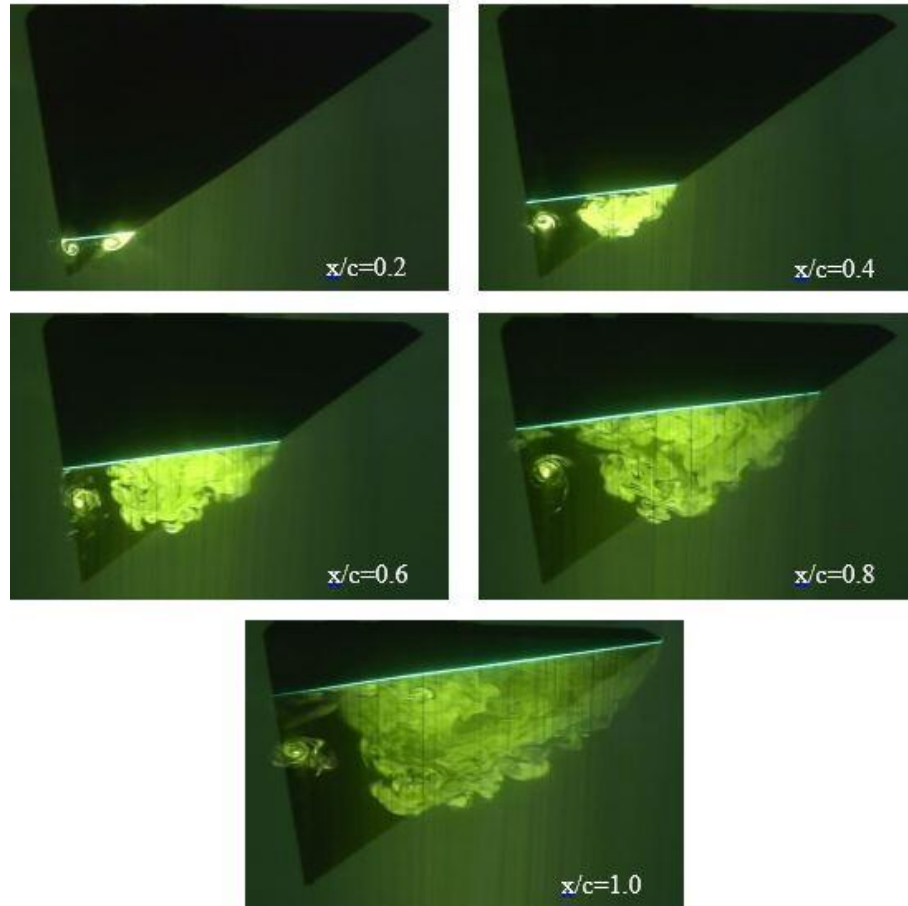


Fig.4.12. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=16^\circ$

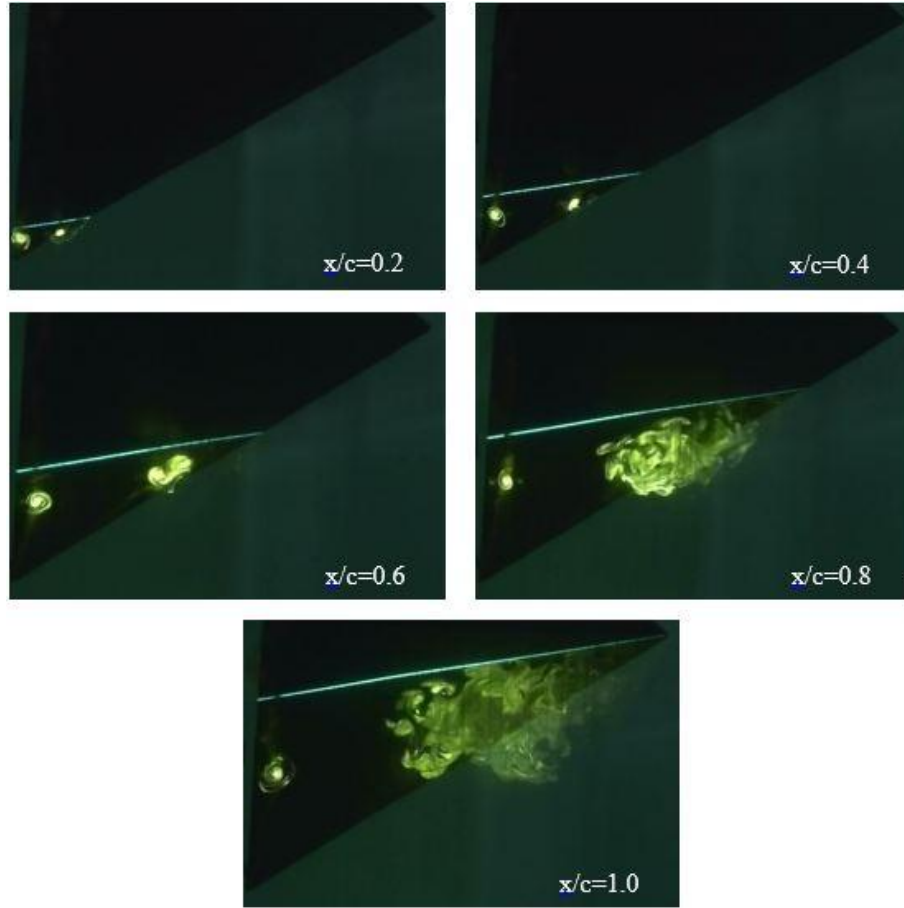


Fig.4.13. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=20^\circ$

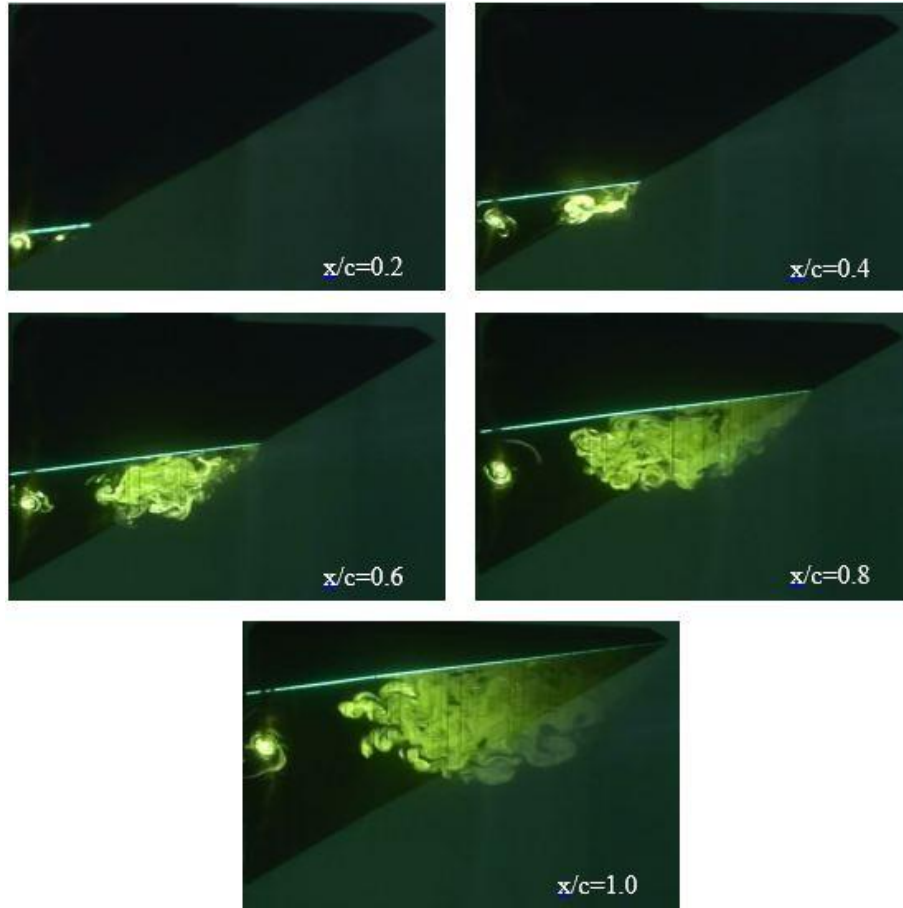


Fig.4.14. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=20^\circ$

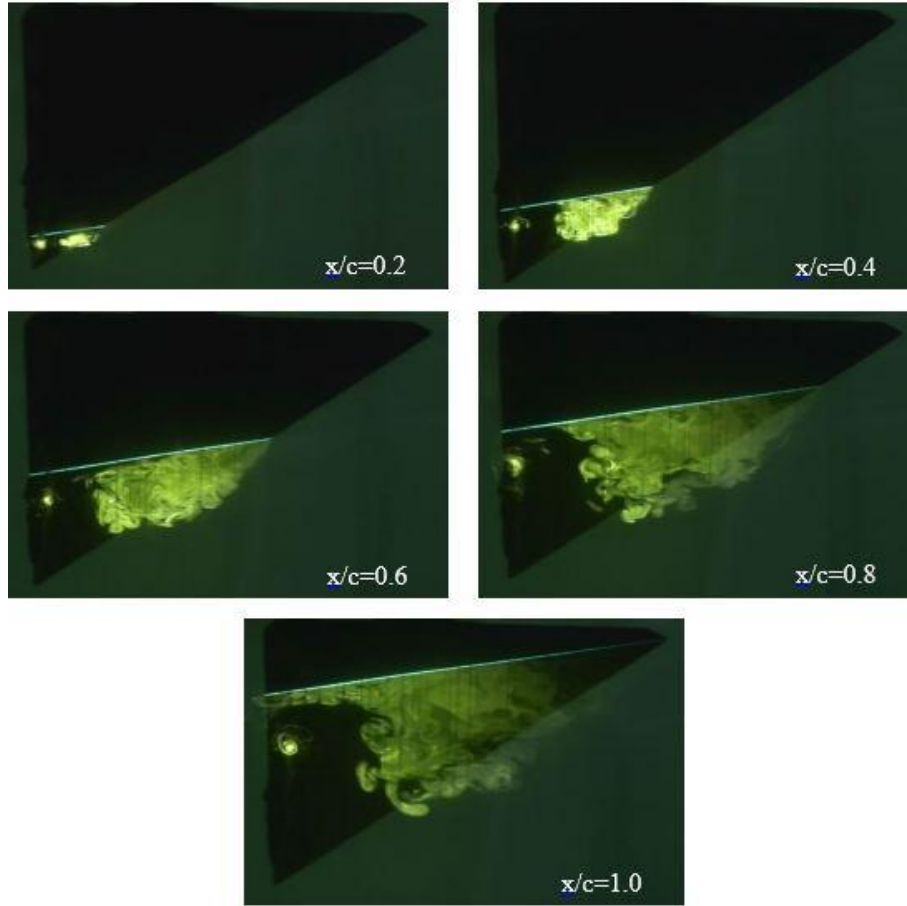


Fig.4.15. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view planes for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=20^\circ$

The dye visualization images taken in crossflow planes at $x/C=1.0$ are gathered in Fig. 4.16 in order to study vortical flow structures further downstream of the vortex bursting. As soon as the leading edge vortices break down, a complex flow structure is developed. A pair of main counter rotating vortices take place in end-view planes at $x/C=1.0$. Fig. 4.16 demonstrate that as soon as the location of vortex breakdown comes closer to the present measuring plane, $x/C=1.0$ the magnitude of interactions increases violently.

A small size vorticity concentrations occurred in counter rotating main vorticities are also well-defined. Under high angles of attach, α , the vortex break down occurs at an earlier stage of x/C . In this case, magnitude of large and small scales of vortices attenuated at $x/C=1.0$. As reported in the review work of the present study, Yaw angle, β is very effective parameter in deteriorating the symmetrical flow structures leading to asymmetrical flow characteristics. Namely, on the leeward side (Left hand side) of the delta wind, the locations of vortex break down moves further downstream while the oppositely oriented leading edge vortices breakdowns earlier. Either the leeward side or the windward side (Right hand side) leading edge vortex which ever breakdowns close to end-view plane of the delta wing, the magnitude of newly forming vortices become stronger. Here, free-stream flow direction is taken as a reference line for yaw angle, β and locations of end-view plane or crossflow measuring plane, $x/C=1.0$ is fixed according to zero yaw angle, β .

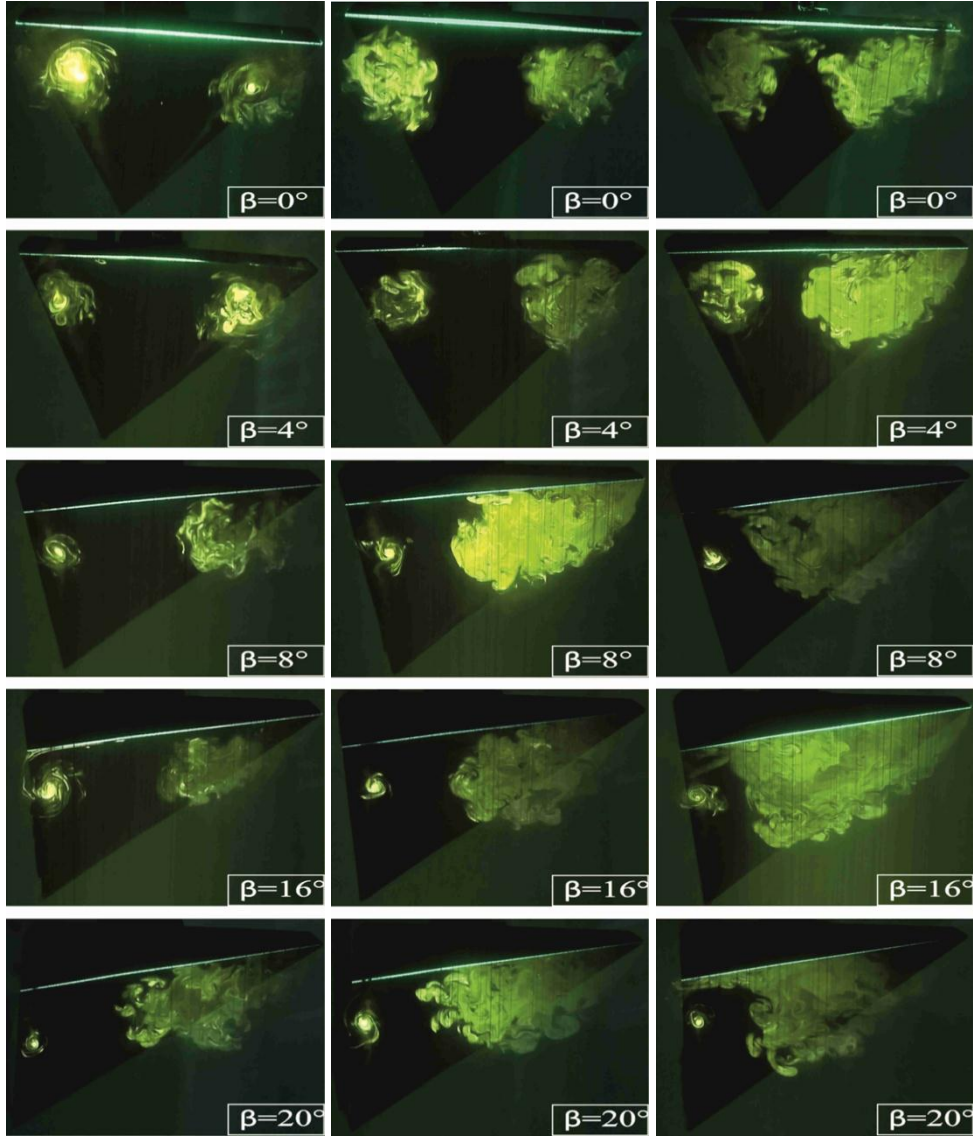


Fig.4.16. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view plane as a function of yaw angle, β at angle of attack, $\alpha=25^\circ$, 30° and 35° . The laser sheet is located at $x/C=1.0$

It is also reported in the review of this text, for example, taking the dimensionless cord length as $x/C=1.0$ and varying angles of attack, α 25° to 35° at yaw angle, $\beta=0^\circ$, both crossflow domains have similar size. The central points of

these reversed flow domains move downward as a function of angle of attack, α . Both crossflow planes contain numbers of vorticity concentrations having different magnitudes and rotational directions as seen in Figure 4.17.

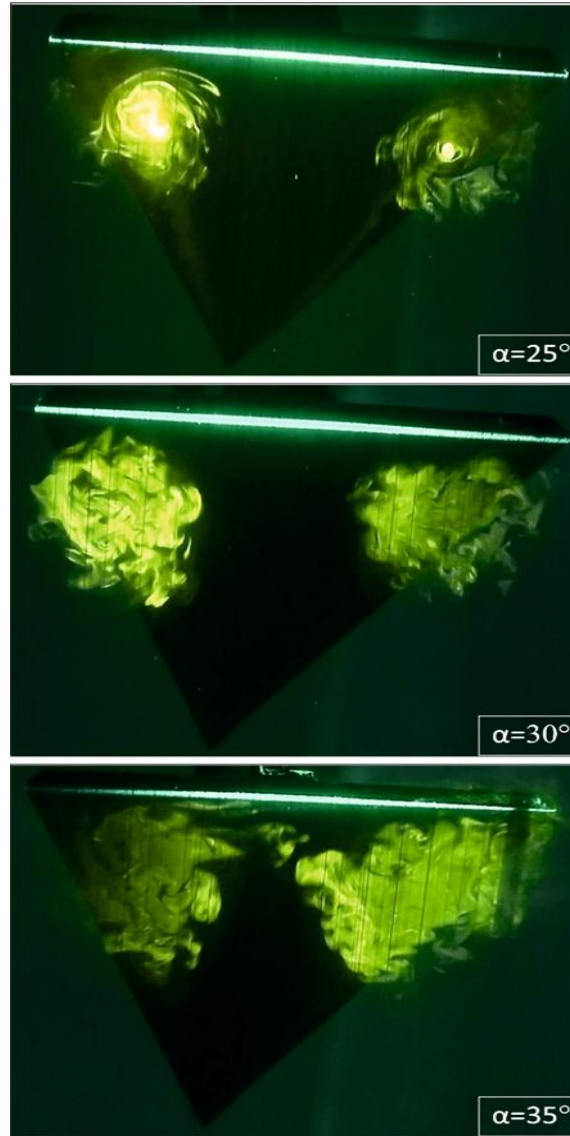


Fig.4.17. Formation of leading edge vortices and structures of vorticity after vortex breakdown in end-view plane as a function of yaw angle, β at angle of attack, $\alpha=25^\circ$, 30° and 35° . The laser sheet is located at $x/C=1.0$

4.1.2. Particle Image Velocimetry (PIV) Results**4.1.2.1. Patterns of Time-Averaged Vorticity, Streamline and Velocity Vectors Topology**

Time-averaged velocity vectors distribution $\langle V \rangle$, vorticity $\langle \omega \rangle$, streamline $\langle \Psi \rangle$ were calculated using instantaneous velocity obtained by the PIV system for angles of attack, $\alpha = 25^\circ, 30^\circ$ and 35° and five different yaw angles such as $\beta = 0^\circ, 4^\circ, 12^\circ, 16^\circ$ and 20° are illustrated in Figures 4.18 - 4.35. Laser light beam is located at $X/C = 0.2, 0.4, 0.6, 0.8$ and 1.0 sequentially since dye visualization is conducted on the same measuring-sections.

As shown in Figures 4.16 - 4.18, in the case of zero yaw angle, β flow structures in end-view plane such as $X/C=0.2, 0.4, 0.6, 0.8$ and 1.0 stations are symmetrical in macro scale over delta wing as seen in dye visualization presented in those figures. Solid and dashed lines indicate the rotational direction of vorticity concentrations in either positive or negative for instantaneous and time-averaged flow data.

Minimum and gradually increasing values of patterns of time-averaged vorticity are taken with the same scale at the same angle of attack, α and yaw angle, β value over end-view planes to make a comparison between experimental results, clearly.

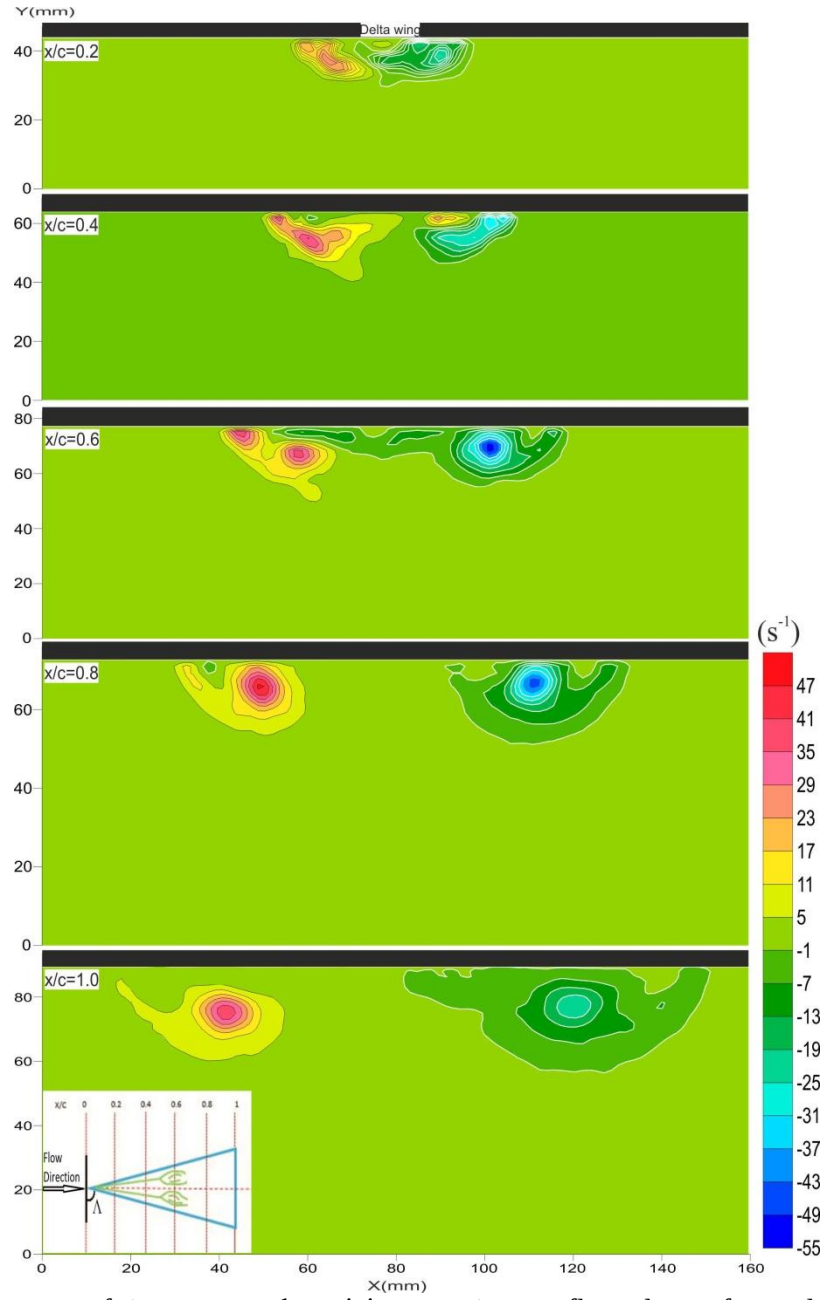


Fig.4.18. Patterns of time-averaged vorticity, $\langle \omega \rangle$ in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -55 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 6 \text{ s}^{-1}$

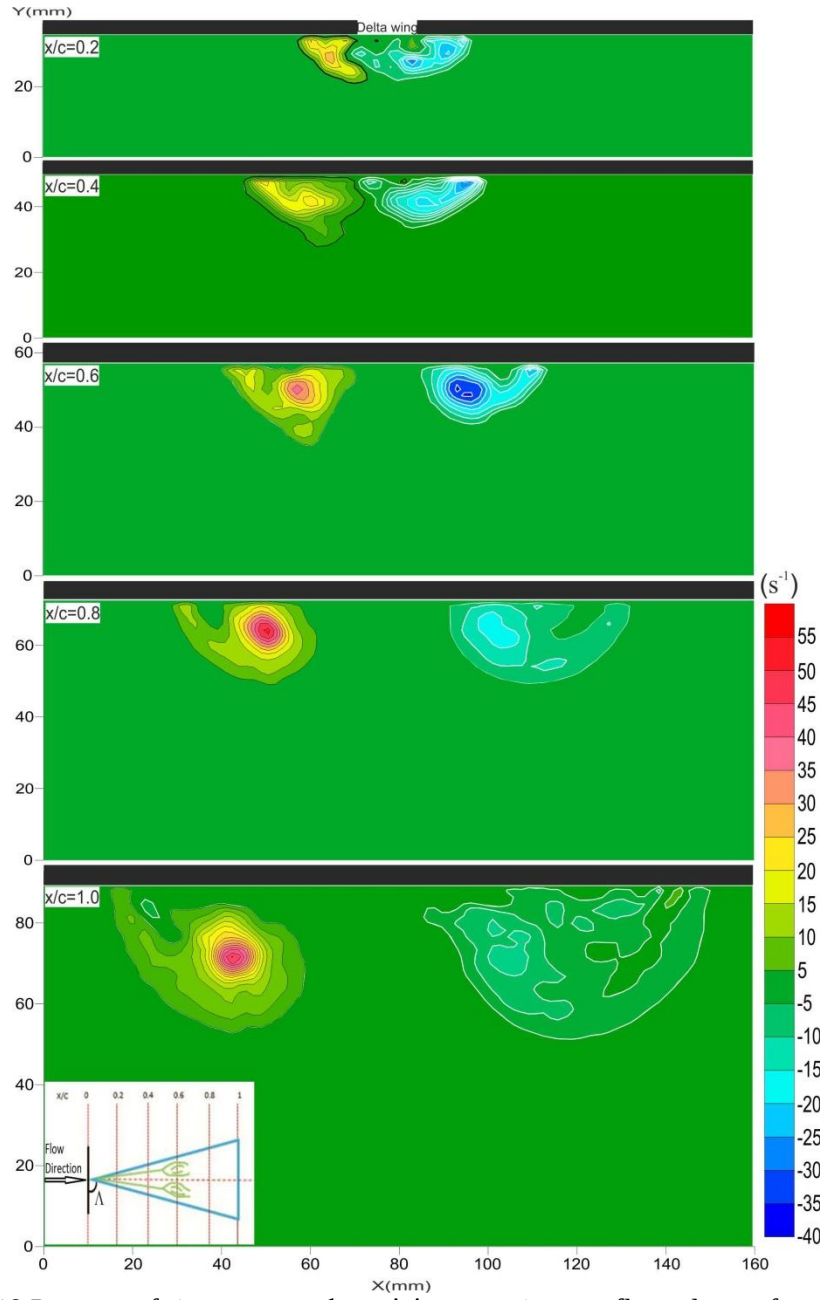


Fig.4.19. Patterns of time-averaged vorticity, $\langle \omega \rangle$ in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -40 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 5 \text{ s}^{-1}$

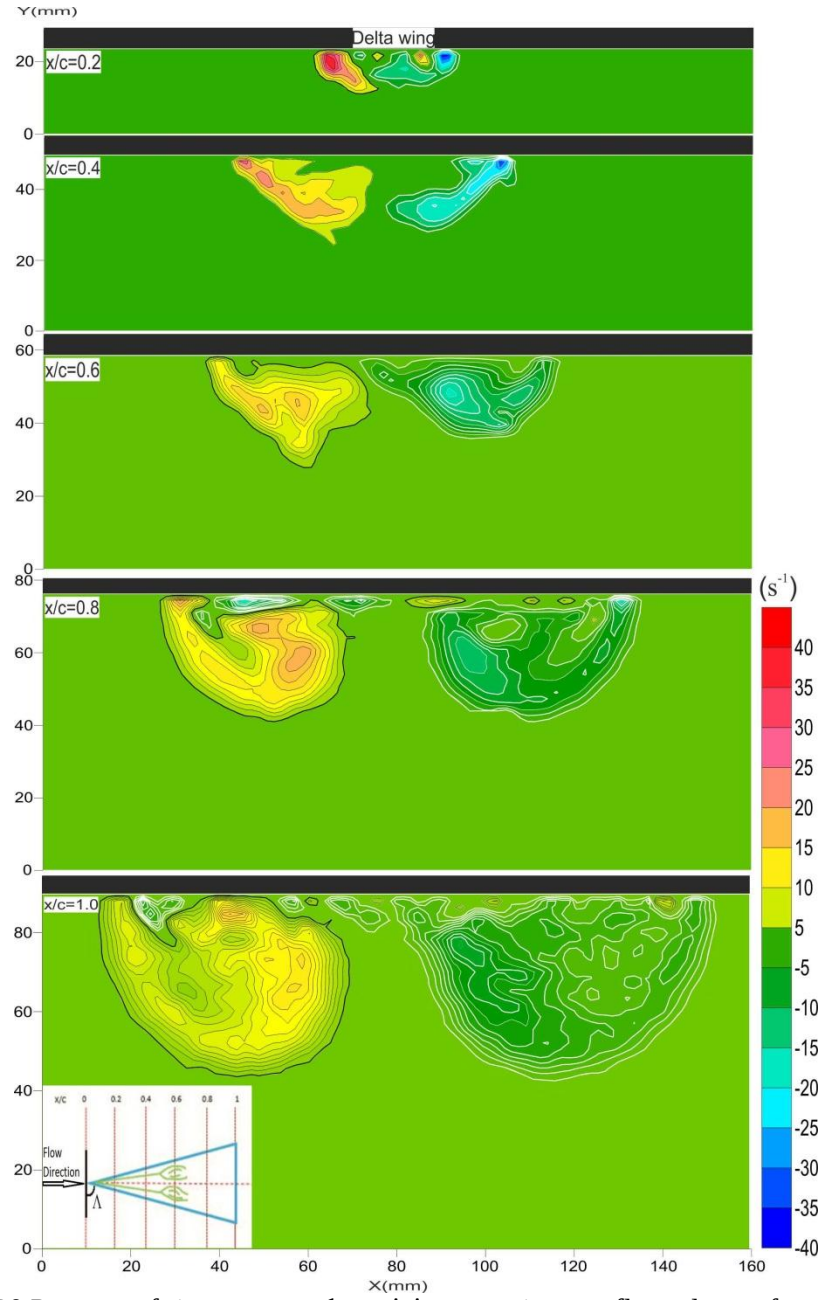


Fig.4.20. Patterns of time-averaged vorticity, $\langle \omega \rangle$ in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -40 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 5 \text{ s}^{-1}$

The inspection of images as seen in Figures 4.21 - 4.23 reveals the locations of foci, F_1 and F_2 , saddle points, S_1 and S_2 clearly. Central points of main vortices move towards the left hand side of wing as yaw angle, β is increased from $\beta=0^\circ$ to $\beta=20^\circ$. Actually, saddle points S_1 and S_2 take place on the boundary. This boundary identifies borderline between weak flow region and free-stream flow region. It is seen that structures of flow are extremely susceptible about alteration with respect to angle of attack, α under yaw angle, β effects. As angles of attack α , increases from $\alpha=25^\circ$ to 35° , topological characteristics of vortical flow are obviously distinguishable as seen in figures. Time-averaged patterns of vorticity $\langle\omega\rangle$, have an elongated shape and move slightly downward from the surface of delta wing comparing to the case of angle of attack, $\alpha=25^\circ$. Well-defined foci, F_1 and F_2 , are detectible in terms of streamlines, $\langle\Psi\rangle$. Below foci, F_1 and F_2 , two saddle points, S_1 and S_2 take place. Patterns of velocity vectors, $\langle V \rangle$ clearly show locations of swirling which is coincident with foci, F_1 and F_2 presented by streamline patterns, $\langle\Psi\rangle$. As seen from figures, velocity vector distributions, $\langle V \rangle$ show us that as yaw angle, β increases, leeward side leading edge vortex moves towards the left hand side of delta wing and the other leading edge vortex moves also towards left side close to the central line of delta wing.

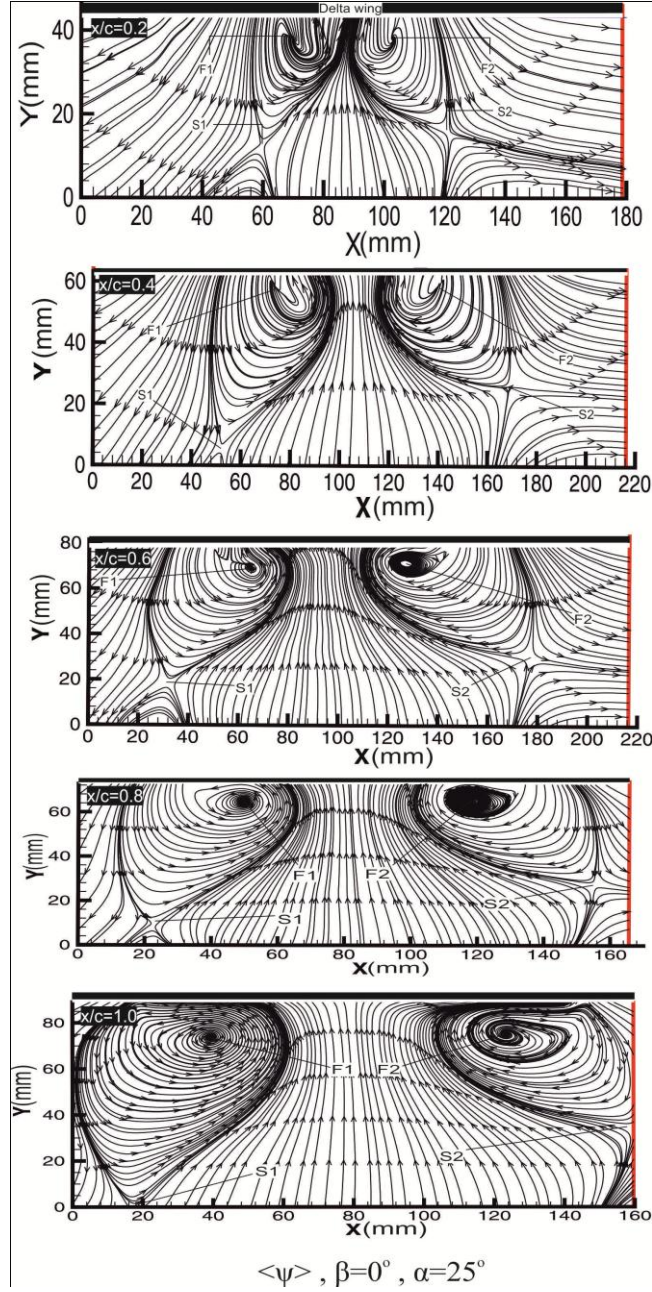


Fig.4.21. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

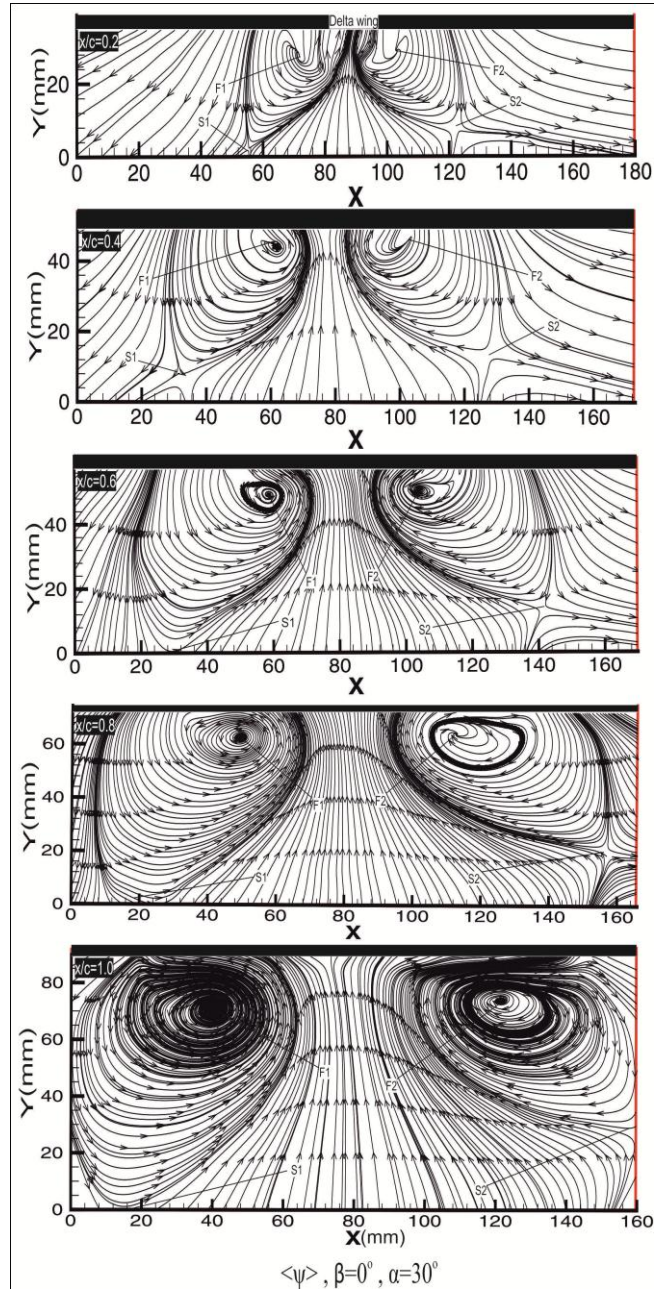


Fig.4.22. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

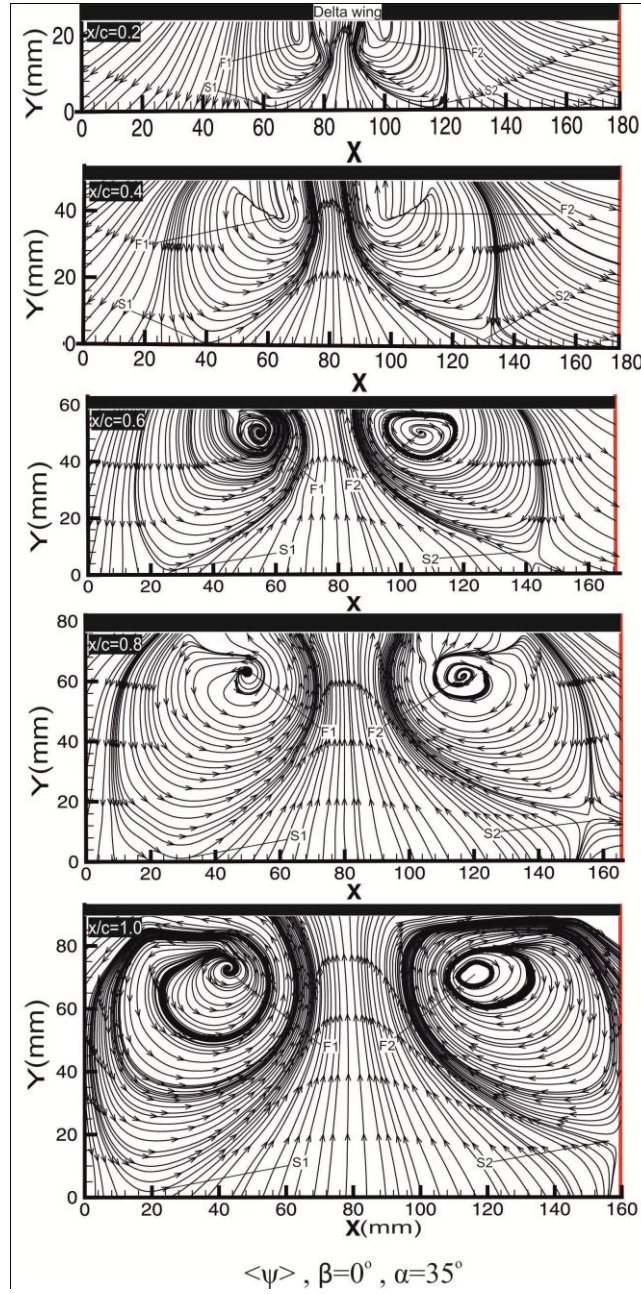


Fig.4.23. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

Images of Figures 4.24–4.26 indicate time average velocity vectors $\langle V \rangle$ as functions of angles of attack, α , yaw angle, β and x/C locations. If images of velocity vectors are taken before vortex breakdown, magnitude of velocity vectors is higher in narrow zones around the central points of swirling flows. But, this magnitude of velocity vectors increases and covers a larger area. Setting angle of attack, at $\alpha=25^\circ$ and having zero yaw angle, β as seen in Figure 4.24 demonstrates that the central point of swirling flows area closer to the surface of delta wing triggering a high magnitude of interactions between the surface of delta wing and reversing flows. In the case of zero yaw angle, β and keeping angle of attack as $\alpha=25^\circ$ both reversed flows caused by leading edge vortices either before or after the location of vortex breakdown are symmetrical. In summary, keeping yaw angle, β at zero degree and upgrading angles of attack, α to 30° and 35° , the central point of reversing flows shifts down causing interactions between reversed flows and the surface of delta wing around the central axis of delta wing. That is to say, by increasing angle of attack, α , the domain of velocity vector fields grows in size on both sides of wing central axis. Stall flows occupy zones of near side edges of delta wing for highest angle of attack such as $\alpha=35^\circ$ after onset of vortex breakdown as seen in Figure 4.26. The central points of these reversing flow presented by velocity vectors, $\langle V \rangle$ overlap with the results of streamline patterns.

As seen in Figures 4.27 – 4.29, for angle of attack of $\alpha=30^\circ$ and yaw angle $\beta=20^\circ$ dimensionless value of x/C are indicated in figures from end-view plane. Symmetrical structures flow are changed at yaw angle $\beta=20^\circ$ clearly compared to the results of yaw angles of $\beta=0^\circ$ and $\beta=12^\circ$.

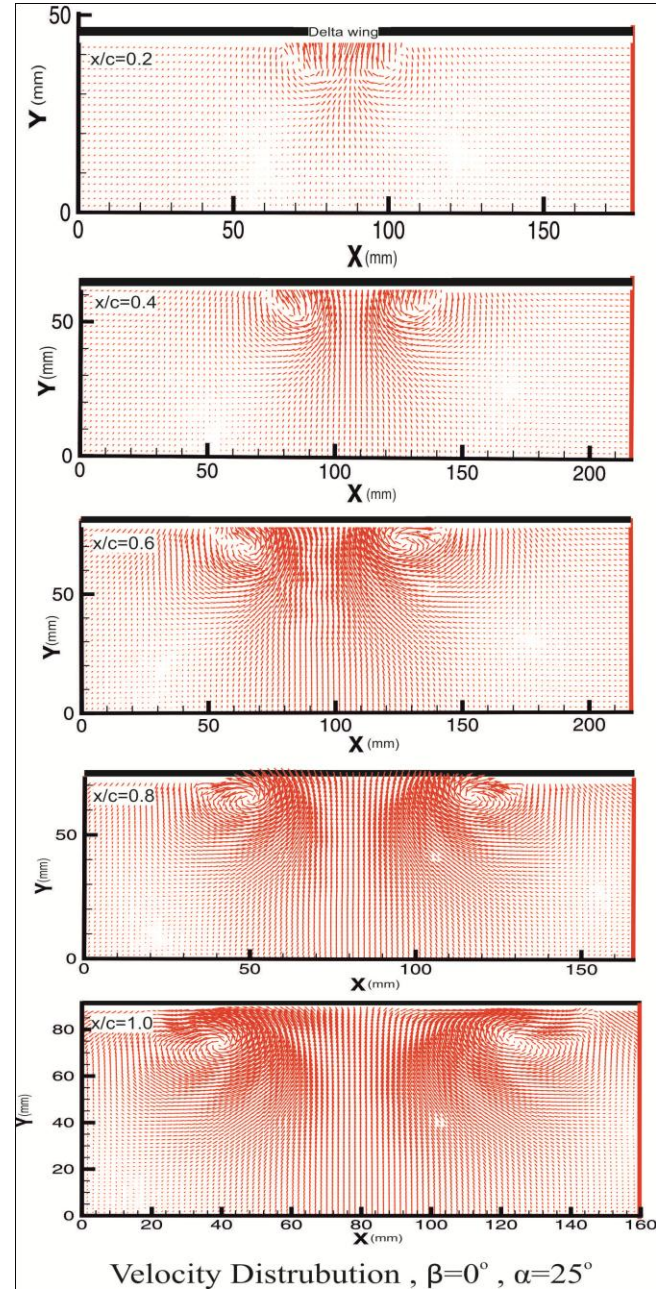


Fig.4.24. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

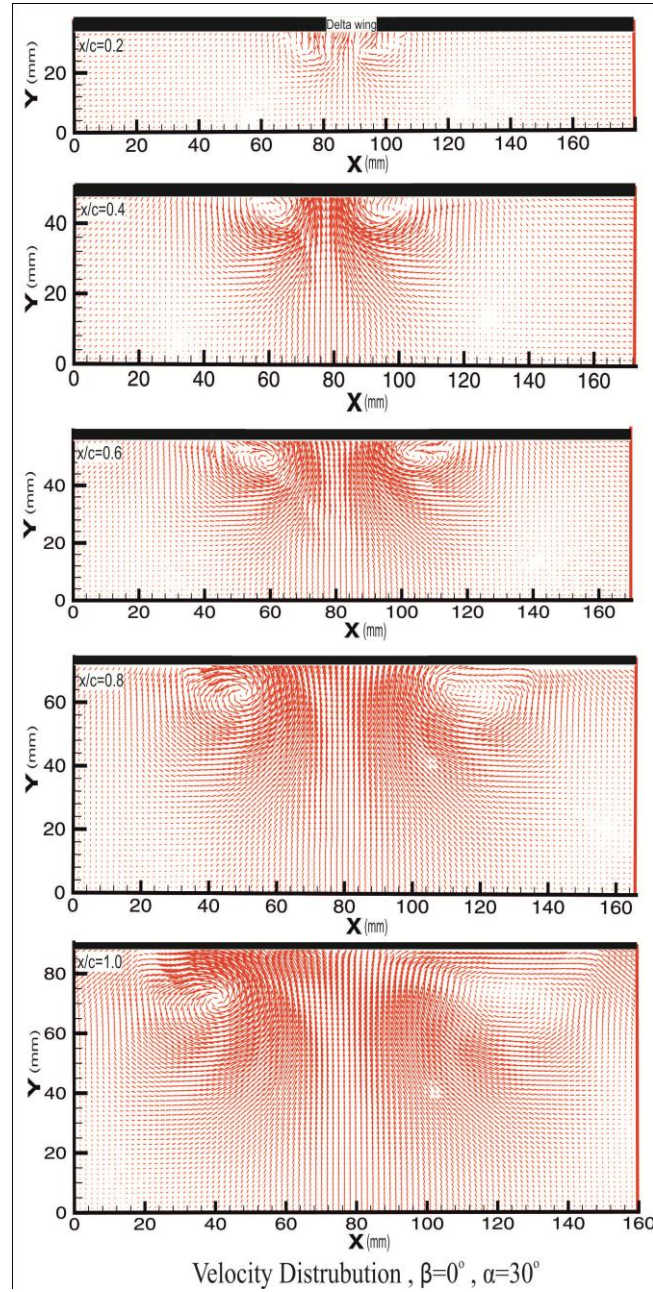


Fig.4.25. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

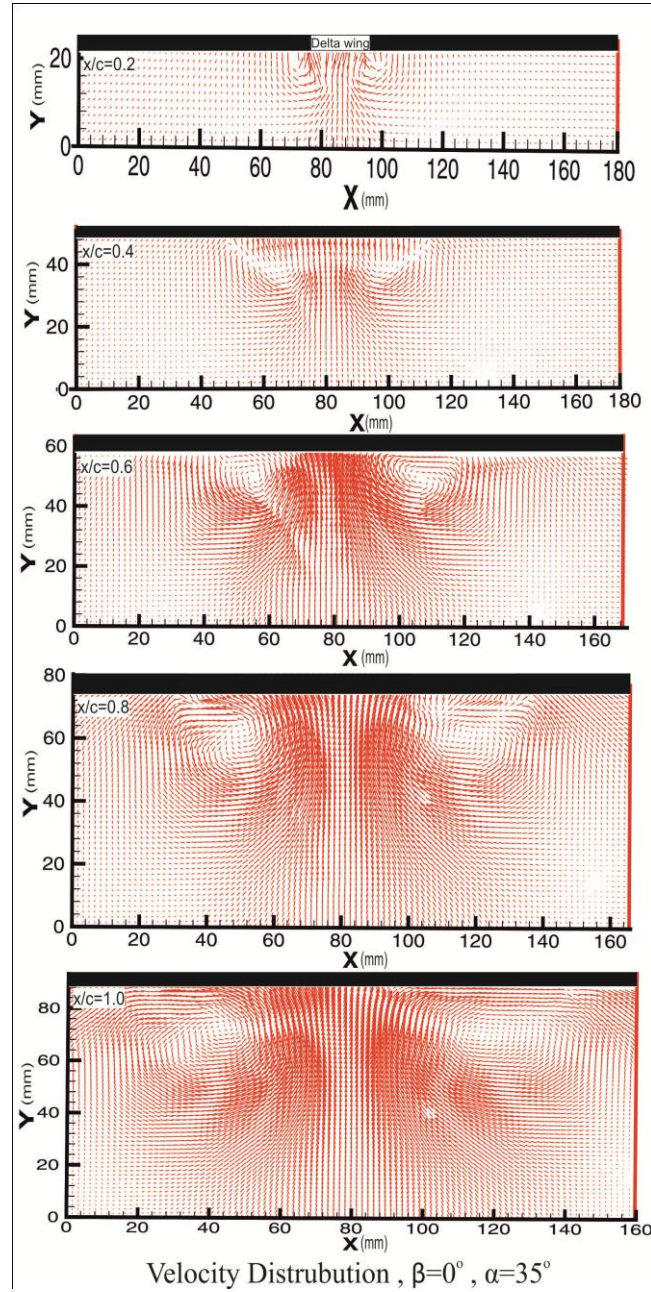


Fig.4.26. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=0^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

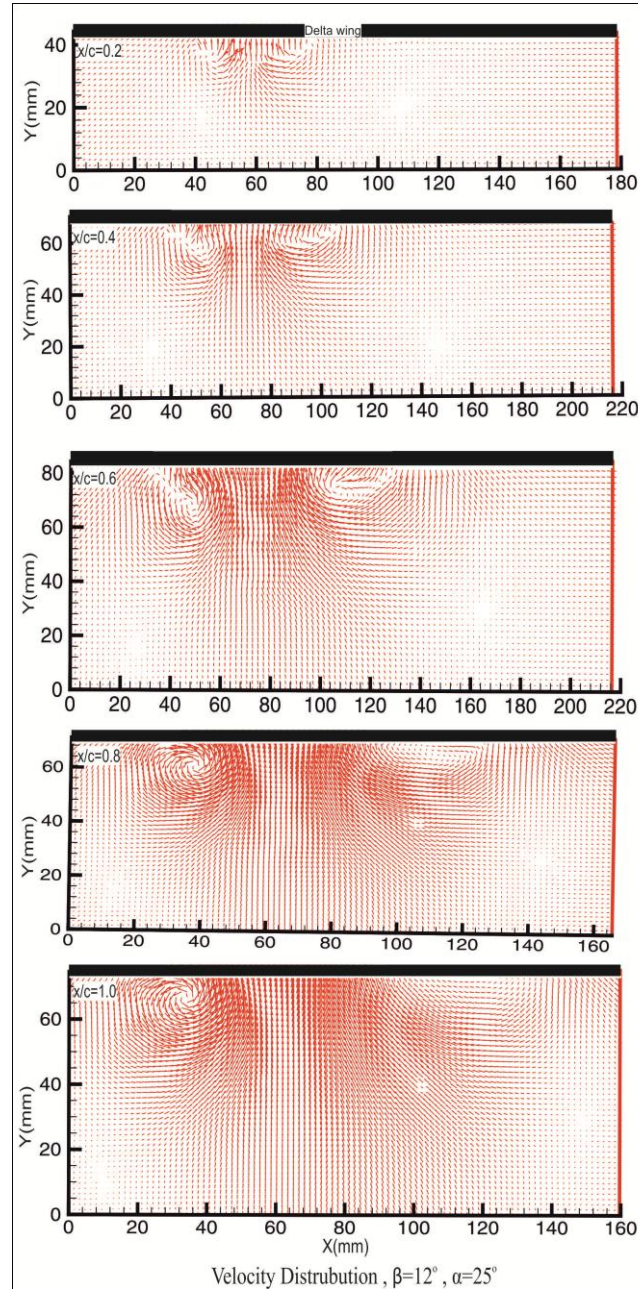


Fig.4.27. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=12^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

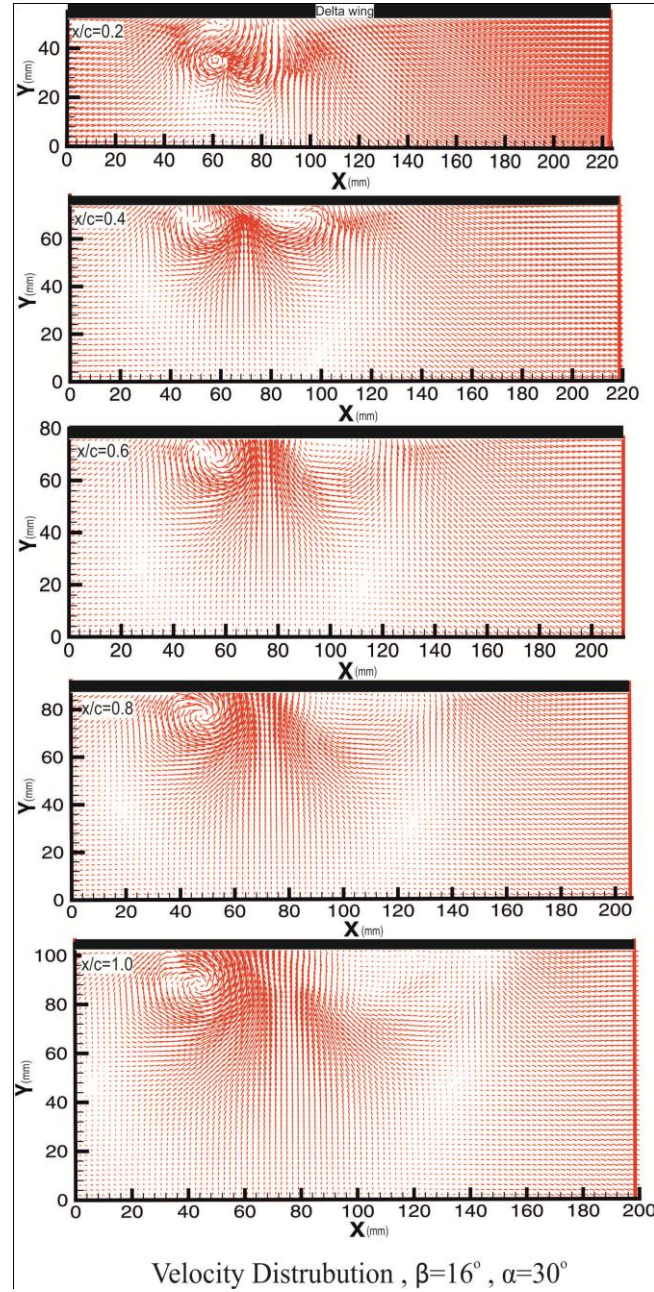


Fig.4.28. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=16^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

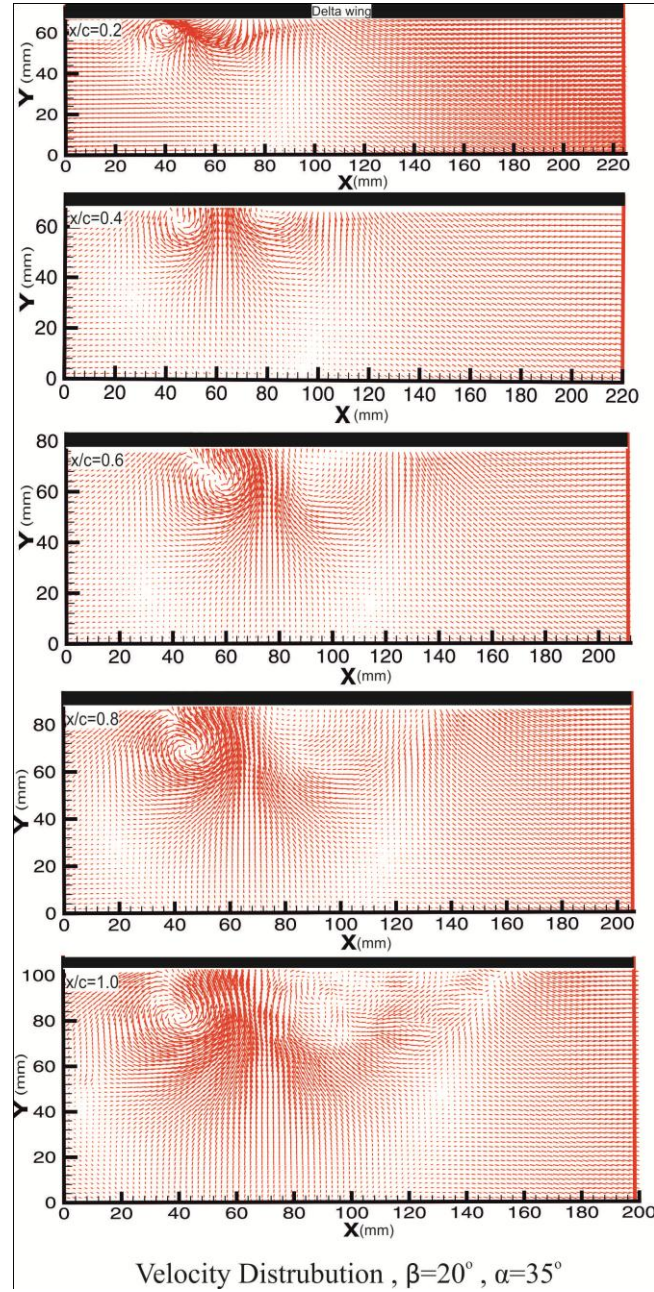


Fig.4.29. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$, in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=20^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

Flow structures of delta wing in end-view plane and equivalent vorticity values for angle of attack of $\alpha=25^\circ$ and yaw angles of $\beta=12^\circ, 16^\circ$ and 20° , and non-dimensional x/C values are shown. It is worth to mention that the results of turbulence statistics determined from instantaneous velocity readings of PIV under the effects of yaw angles of $\beta=0^\circ, 4^\circ$ and 8° were not included in text of thesis. Because all qualitative observations of flow structure under influence of yaw angle were provided at the beginning of this section. Secondly, flow structures of delta wing under yaw angles of $\beta=0^\circ, 4^\circ$ and 8° are altered with a low level. For these reasons, only selected test results of PIV were included in the text of thesis.

As seen in the dye visualization experiment, when yaw angle is set at $\beta=0^\circ$, there are symmetrical flow structures on both sides of axis of delta wing in macro scale. But, instantaneous flow data do not reveal these results after onset of vortex breakdown. Since flow structures are extremely unsteady and have random motions as demonstrated by the dye visualization as well as animations of instantaneous turbulent statistics derived from instantaneous velocity readings of the PIV system. Time-averaged patterns of vorticity concentrations, $\langle\omega\rangle$, rotating clockwise and counter clockwise do not have exact similarity between them under the influence of yaw angle, β . Difference between size, magnitude and severity of vorticity is easily seen in the PIV results that are quantitatively visualized by the coloring scale method. In Figures 4.30 – 4.32, vorticity concentrations rotated counterclockwise (in positive direction) are presented with solid black line and vorticity concentrations rotated clockwise (In negative direction) are presented with white solid line throughout the text. Under any case of angle of attack, α and yaw angle, β the size of flow domain and magnitude of vorticity concentrations of on the leeward and windward sides are more or less similar. But, these vorticity concentrations after onset of vortex breakdown have dissimilarity in terms of size of reversed flow domain and magnitude as well as settling places based on the reference line of central cord axis of delta wing. Dissimilarity of vortical flow

structures is amplified as a function of angle of attack, α , yaw angle, β , and cord length ratio, x/C .

For example, Patterns of time-averaged dimensionless vorticity, $\langle\omega\rangle$, having angle of attack, $\alpha=35^\circ$ and setting yaw angle as $\beta=20^\circ$ at $x/C=1.0$ indicates a well define vorticity concentrations on the leeward side (Left hand side) before onset of vortex breakdown. But, on the windward side (Right hand side) there are several small scale vorticity concentrations which take place after onset of vortex breakdown. As reported in the section of discussions given on distributions of velocity vectors, setting the delta wing with 35° angle of attack, α and having yaw angle, α of 20° causes a high rate of flow separation from the surface the delta wing with several positive and negative vorticity concentrations. The separated flow region occupies most part of the delta wing surface. In general, the magnitude of vorticity concentrations on leeward side is higher than magnitude of vorticity concentrations on the windward side in end-view plane of the delta wing. The structures of flows on both sides are influenced by yawing delta wing. Also, it is revealed by most presentations of flow properties that central point of vorticity concentrations or swirling flows move in the lateral directions towards the leeward side particularly, at $x/C=1.0$.

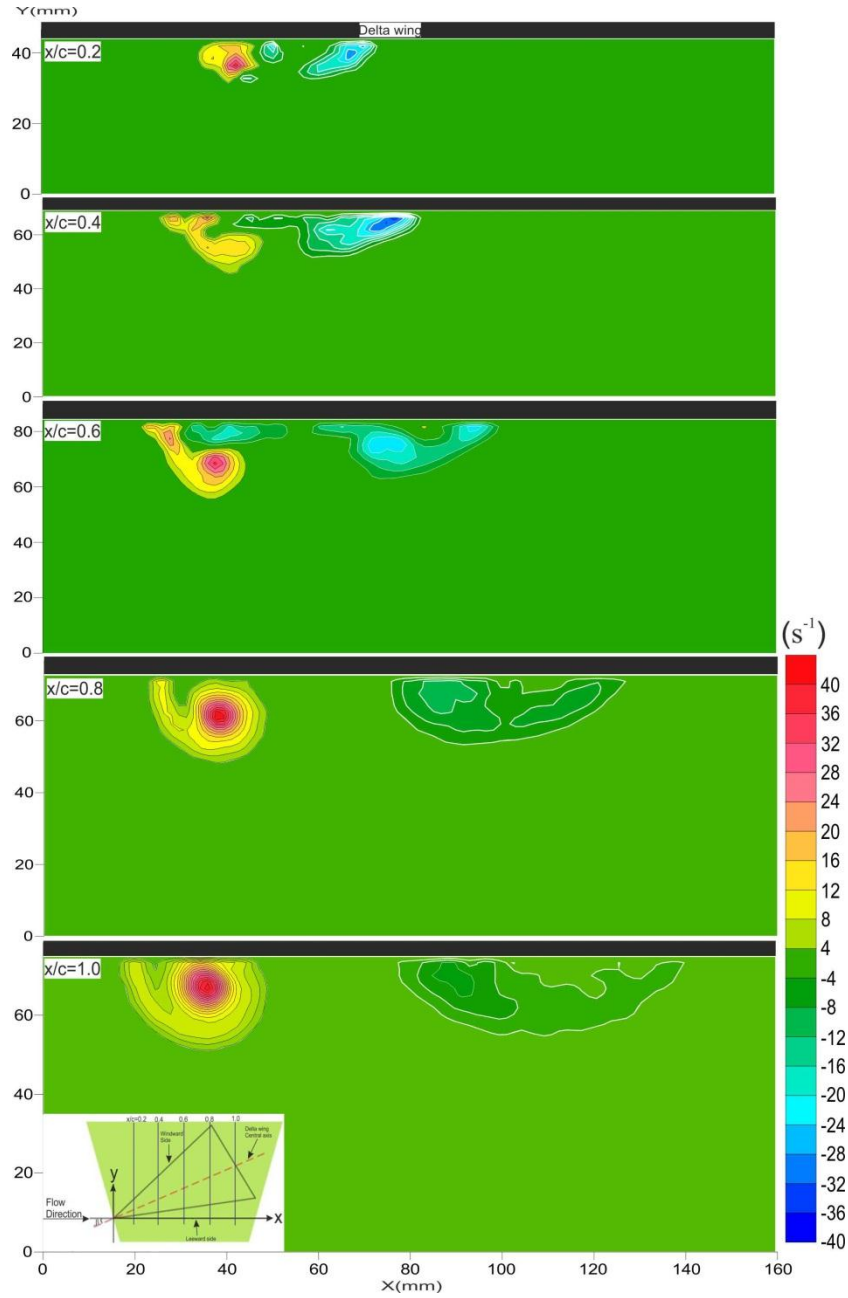


Fig.4.30. Patterns of time-averaged vorticity, $\langle \omega \rangle$, in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=12^\circ$. Laser light beam is located at $x/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -40 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 5 \text{ s}^{-1}$

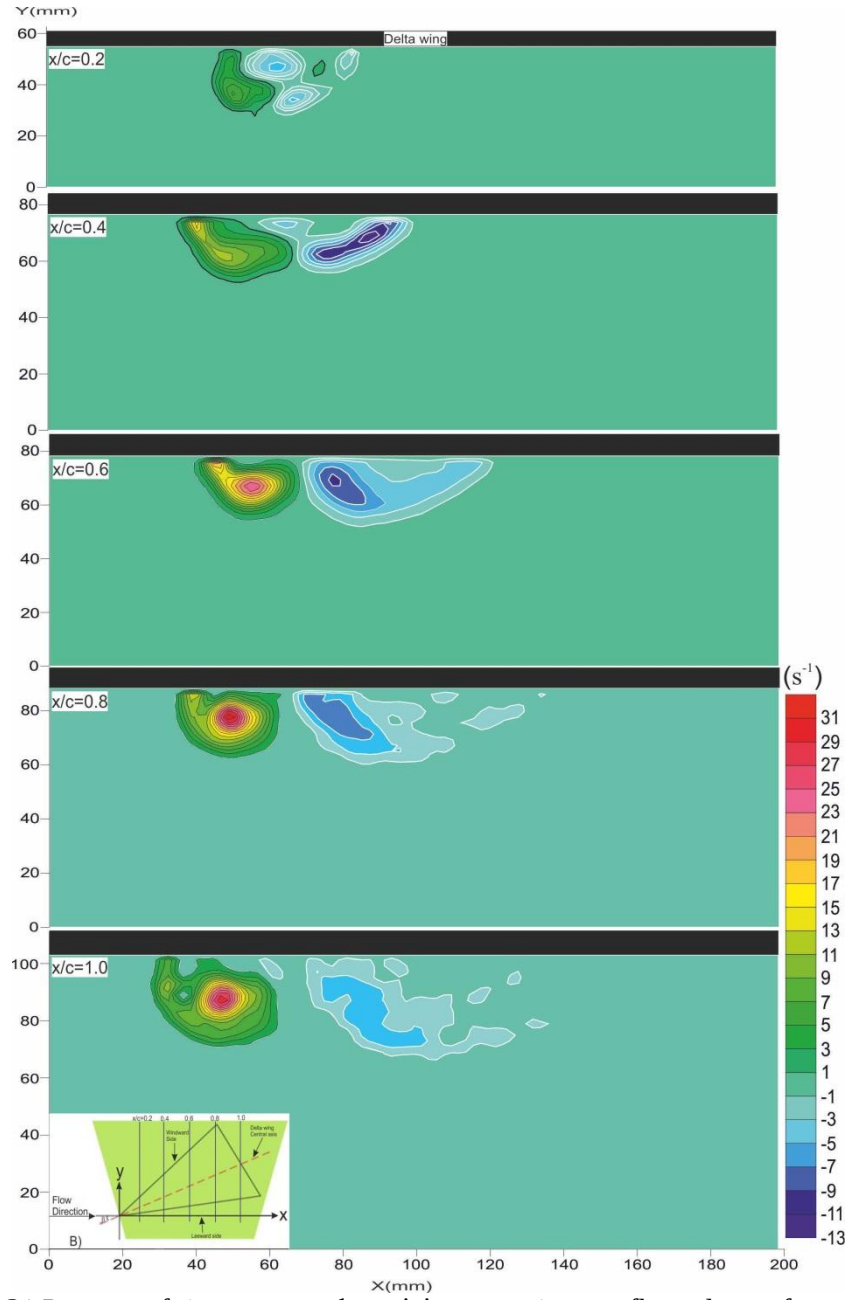


Fig.4.31. Patterns of time-averaged vorticity, $\langle \omega \rangle$, in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=16^\circ$. Laser light beam is located at $x/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -13 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 2 \text{ s}^{-1}$

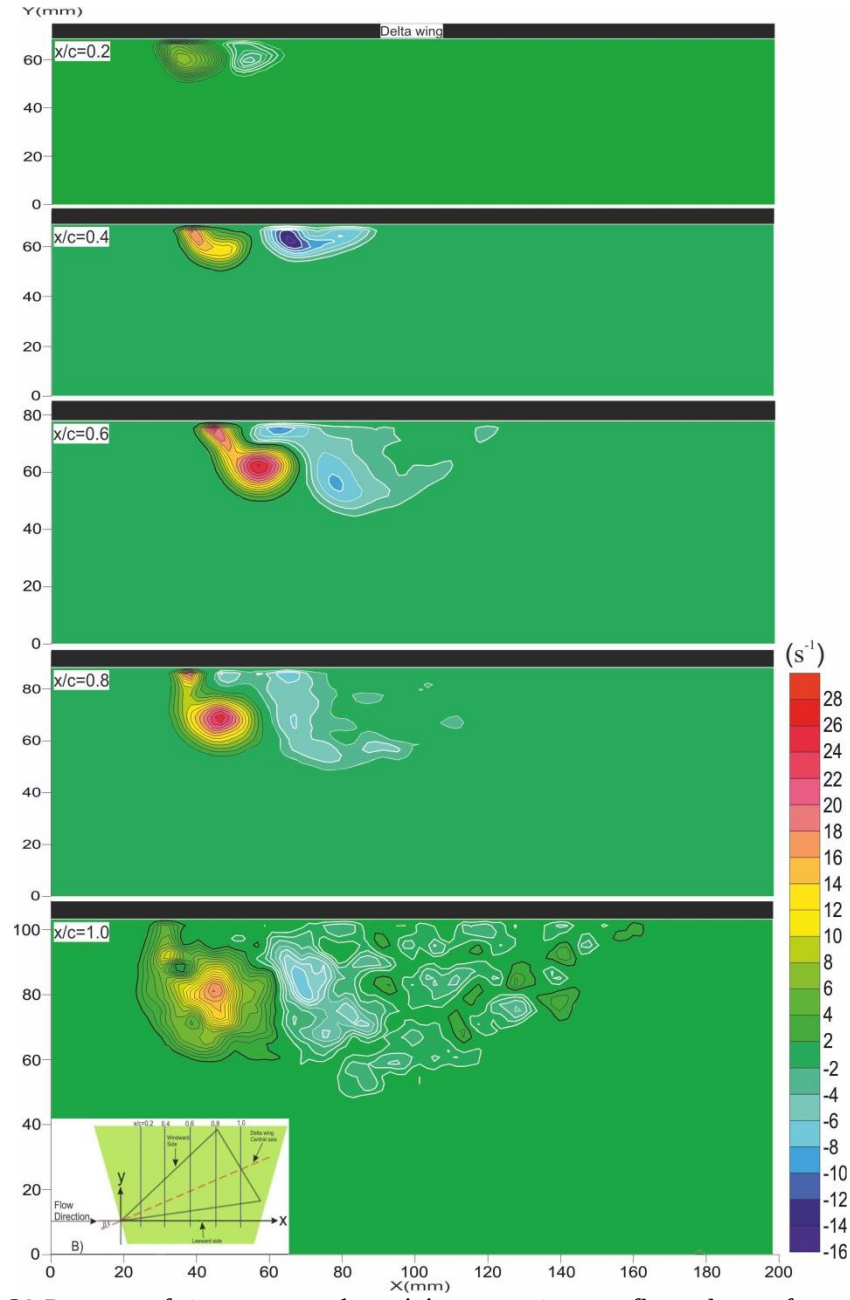


Fig.4.32. Patterns of time-averaged vorticity, $\langle \omega \rangle$, in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=20^\circ$. Laser light beam is located at $x/C=0.2, 0.4, 0.6, 0.8, 1.0$. For contours of time-averaged vorticity, minimum and incremental values are $[\langle \omega \rangle]_{\min} = -16 \text{ s}^{-1}$ and $\Delta [\langle \omega \rangle] = 2 \text{ s}^{-1}$

Patterns of time-averaged streamline, $\langle\Psi\rangle$, for angles of attack of $\alpha=25^\circ$, 30° and 35° and varying yaw angles, β over the range of $0^\circ\leq\beta\leq20^\circ$ are present in Figures 4.33-35. The laser sheet is sequentially located at dimensionless cord lengths such as $x/C=0.2, 0.4, 0.6, 0.8$ and 1.0 . Inspection of these images in figures shows that center of well-formed foci, F_1 and F_2 , saddle points; S_1 and S_2 distinctly designate symmetrical flow structures and the domain of main rotating vorticity concentrations. Central points of swirl patterns of streamlines, F_1 and F_2 move to the left hand side of wing because of rising yaw angle, β from 0° to 20° gradually moving the measuring cross-section of end-view plane along the free-stream velocity direction.

Actually, although this measuring section crosses the free-stream flow normally, but, all measuring section (end-view planes) crosses dimensionless cord axis at locations such as $x/C=0.2, 0.4, 0.6, 0.8$, and 1.0 . It is observed that the swirling patterns of streamlines, $\langle\Psi\rangle$ indicating flow circulations regions are not symmetrical.

Actually, saddle points S_1 and S_2 take place on a boundary. This borderline identifies the border between weak flow region and free-stream flow region. Flow structures is extremely susceptible about alteration of yaw angle, β and angles of attack, α . Well-defined foci, F_1 and F_2 , are presented by contour of streamlines, $\langle\Psi\rangle$. Below foci, F_1 and F_2 , two saddle points, S_1 and S_2 are developed. Taking the cord axis as a reference line on the left hand side or leeward side, well-defined swirl patterns of streamlines, F_1 keeps its structures without deforming under all yaw angles, β . As mentioned before, leading edge vortex on the leeward side does not break down over the delta wing or in the image that was taken by the camera during the experiments.

On the other hand, on the windward side, onset of vortex breakdown moves in the forward direction towards the leading edge of delta wing. Images as shown in end-view planes particularly for $x/C \geq 0.4$ present complicated flow structures that occurred after onset of vortex breakdown. Localized swirling flow features deteriorate while the flow moves downward in the free-stream flow direction for a high yaw angles. It is interesting to note that saddle points S_1 and S_2 never disappear for cases of the delta wing settings and x/C locations.

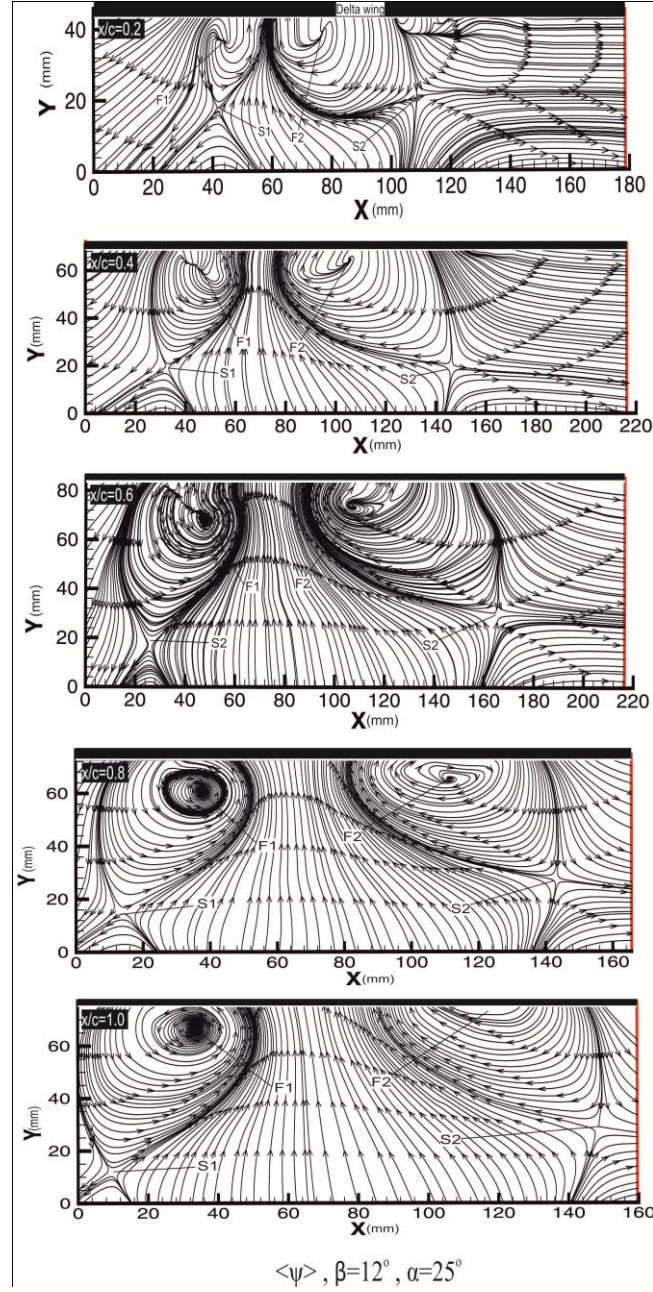


Fig.4.33. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=25^\circ$ and yaw angle $\beta=12^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

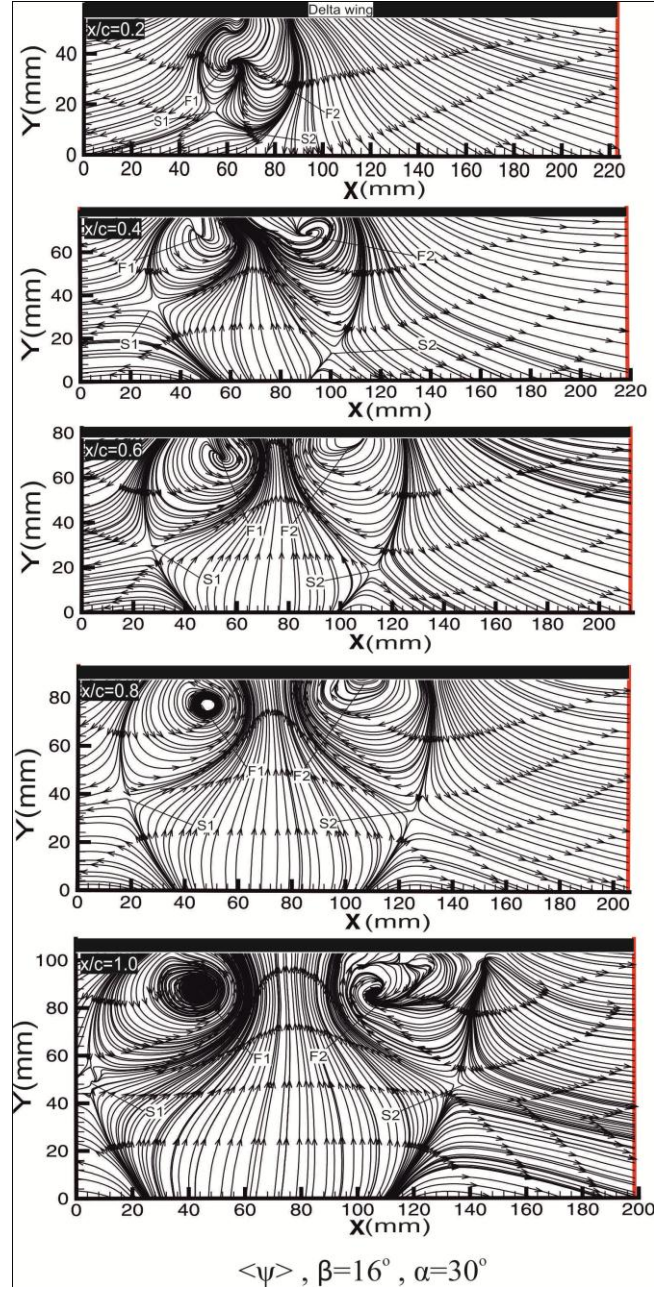


Fig.4.34. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=30^\circ$ and yaw angle $\beta=16^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

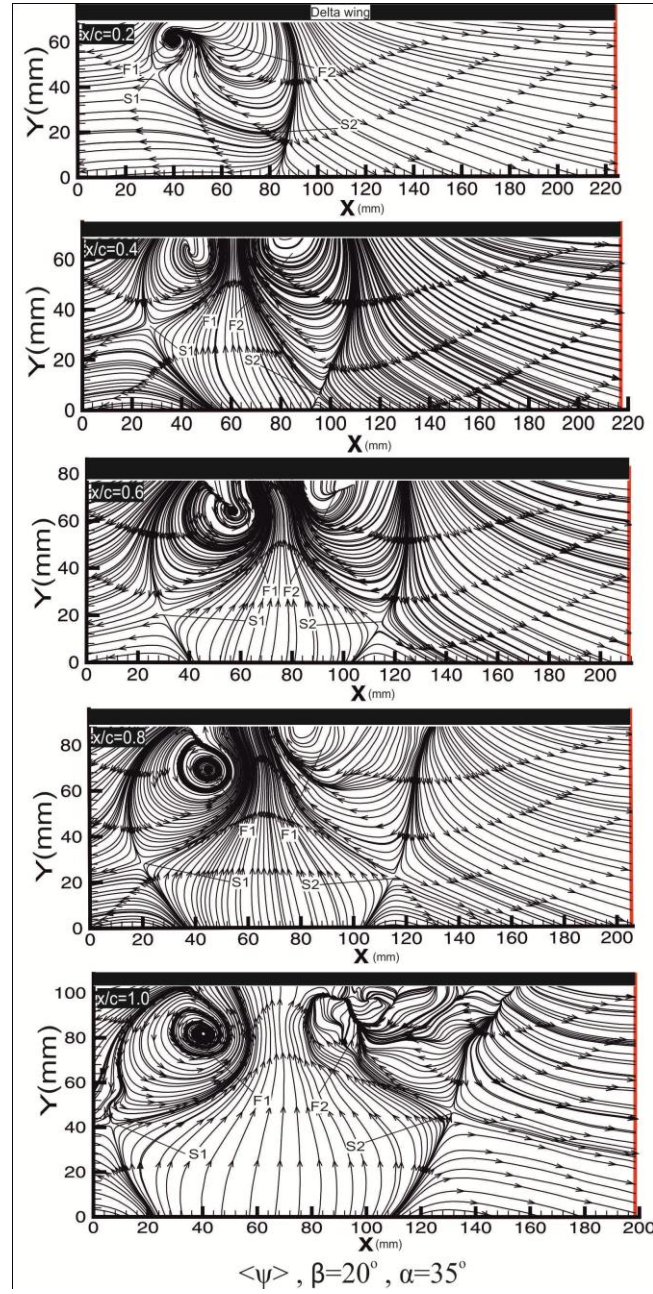


Fig.4.35. Patterns of time-averaged streamline, $\langle \Psi \rangle$, in crossflow planes, for angle of attack $\alpha=35^\circ$ and yaw angle $\beta=20^\circ$. Laser light beam is located at $X/C=0.2, 0.4, 0.6, 0.8, 1.0$

4.1.2.2. Velocity Fluctuations

Root mean squares (rms) of streamwise and transverse velocities, $\langle u_{rms} \rangle / U$, $\langle v_{rms} \rangle / U$ normalized by free-stream velocity, U are presented in figures shown below. As shown in figures when delta wing is yawed, the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ increase gradually on the leeward side while on the windward sides' decrease gradually as seen all in Figure 36-47.

At an angle of attack $\alpha=25^\circ$, the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ is 0.85 for yaw angle $\beta=0^\circ$. On the other hand, having yaw angle as $\beta=12^\circ$ the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ on the windward side is 0.24, but, on the leeward side is 0,5. Increasing angle of attack, α to a value of 30° , for yaw angle $\beta=0^\circ$ the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ is equal to 0,9, but setting this yaw angle as $\beta=16^\circ$ the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ becomes equal to 0.41 on the windward side and this magnitude of $[\langle u_{rms} \rangle / U]_{max}$ promotes to a value of 0.64 in the region of leeward side. When the angle of attack is set to value of $\alpha=35^\circ$ and keeping yaw angle as $\beta=0^\circ$, the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ is around 1.1, but, rising yaw angle to the value of $\beta=20^\circ$, the magnitude of $[\langle u_{rms} \rangle / U]_{max}$ corresponds to 0.7 on the windward side and 1.2 on the leeward side of the delta wing.

Magnitudes of $\langle v_{rms} \rangle / U$ increase for a certain degree then decrease gradually; moreover, maximum values of $\langle v_{rms} \rangle / U$ are seen on the windward side. At an angle of attack $\alpha=25^\circ$, dimensionless transverse velocity, $[\langle v_{rms} \rangle / U]_{max}$ has a value of 0.48 for a yaw angle of $\beta=0^\circ$. Setting this yaw angle, β to a value of 12° , dimensionless transverse velocity component, $[\langle v_{rms} \rangle / U]_{max}$ falls to the lower values such as 0.46. At an angle of attack, α for example, $\alpha=30^\circ$, for yaw angle $\beta=0^\circ$ maximum value of $[\langle v_{rms} \rangle / U]_{max}$ is 0.44, Increasing the yaw angle, β beyond 16° , the maximum value of $[\langle v_{rms} \rangle / U]_{max}$ increases around 0.63. At an angle of attack $\alpha=35^\circ$, dimensionless transverse velocity, $[\langle v_{rms} \rangle / U]_{max}$ has a value of 0.45 for yaw angle $\beta=0^\circ$, keeping the yaw angle, β at 20° dimensionless $[\langle v_{rms} \rangle / U]_{max}$ takes maximum value such as 1.05.

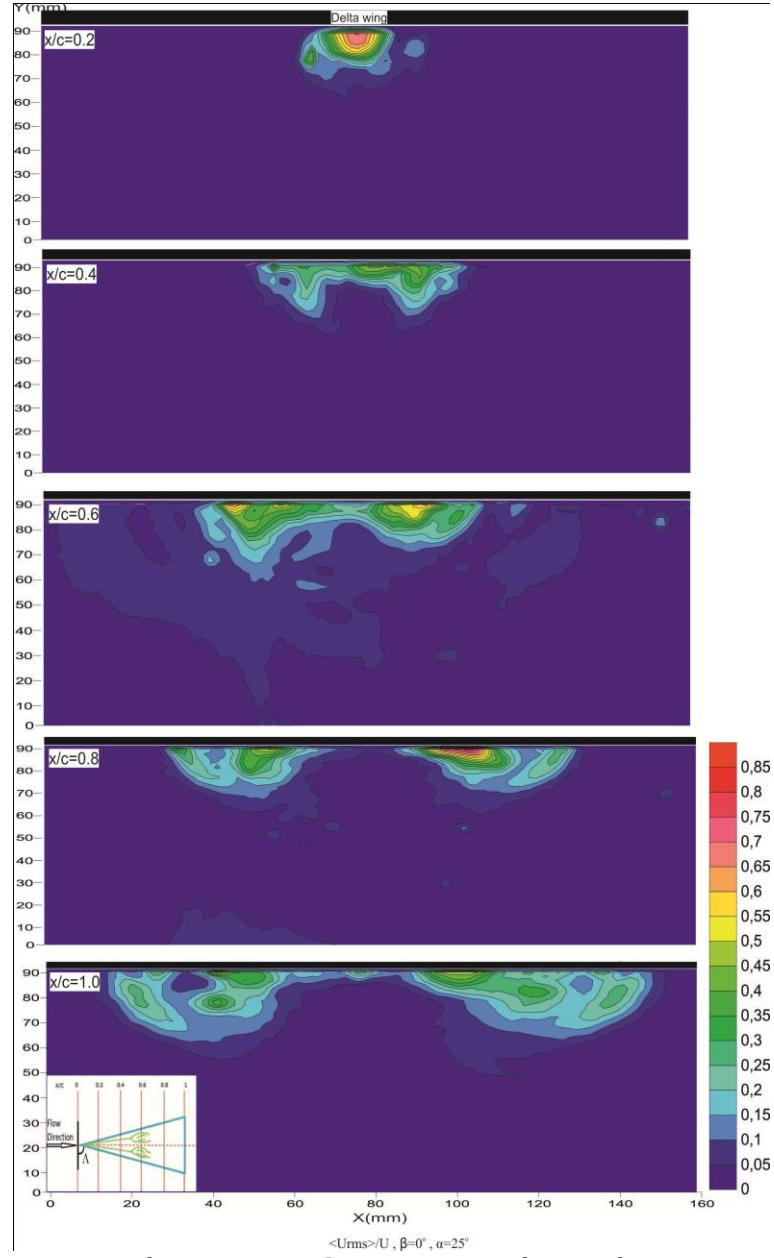


Fig.4.36. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 25^\circ$ and yaw angle, $\beta = 0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min} = 0.05$, and $\Delta[\langle u_{rms} \rangle / U] = 0.05$ respectively

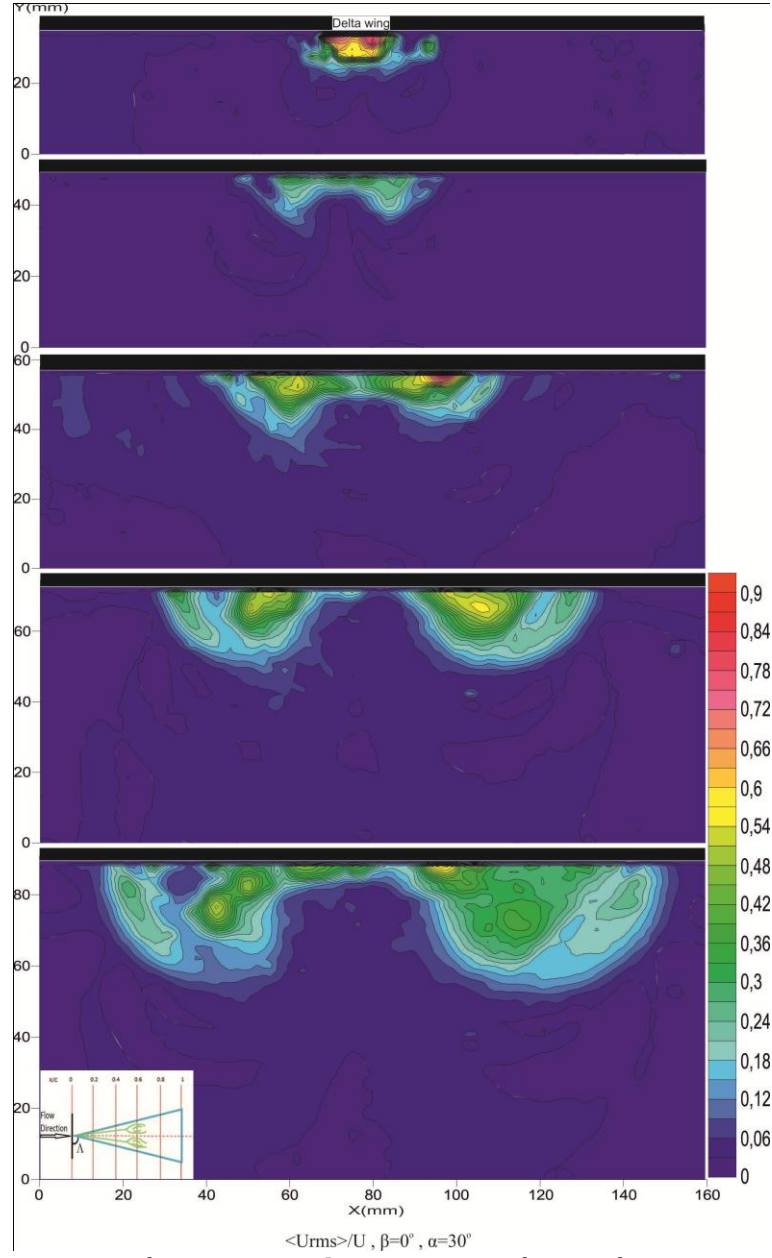


Fig.4.37. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha=30^\circ$ and yaw angle, $\beta=0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min}=0.06$, and $\Delta[\langle u_{rms} \rangle / U]=0.06$ respectively

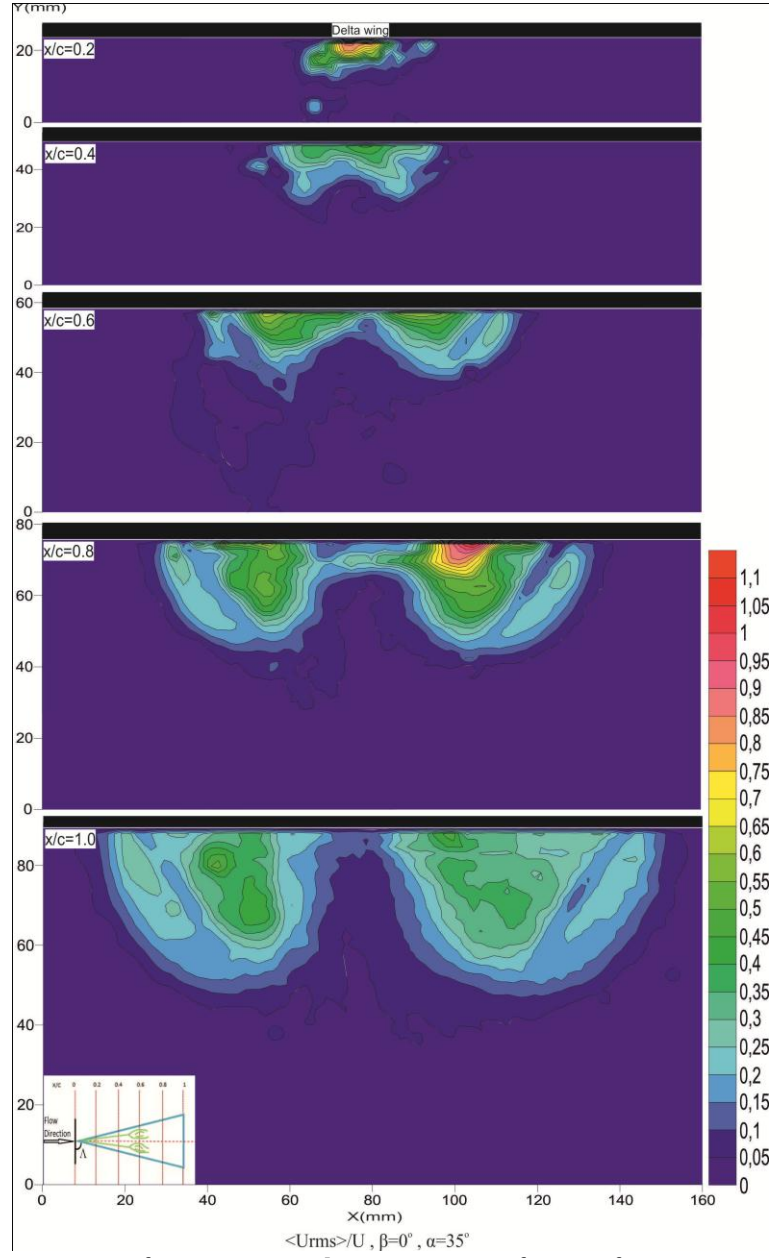


Fig.4.38. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 35^\circ$ and yaw angle, $\beta = 0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min} = 0.05$, and $\Delta[\langle u_{rms} \rangle / U] = 0.05$ respectively

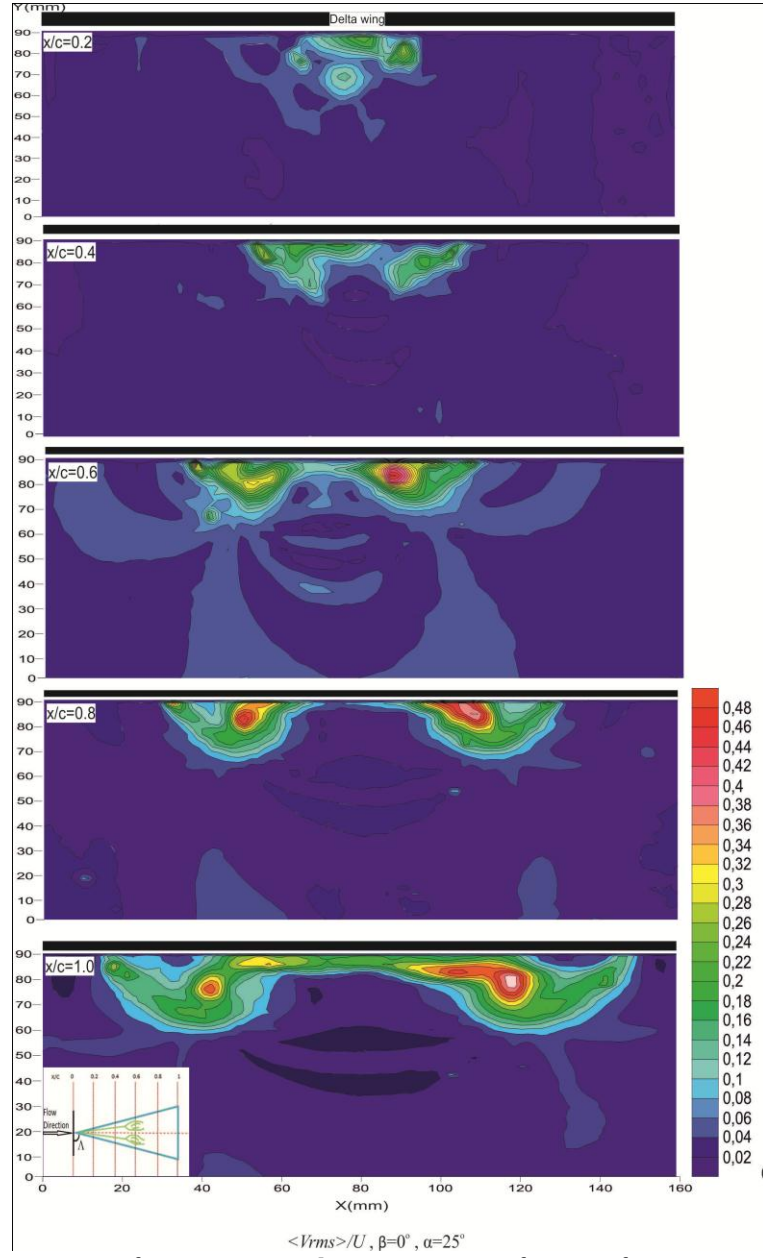


Fig.4.39. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha=25^\circ$ and yaw angle, $\beta=0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min}=0.02$, and $\Delta[\langle v_{rms} \rangle / U]=0.02$ respectively

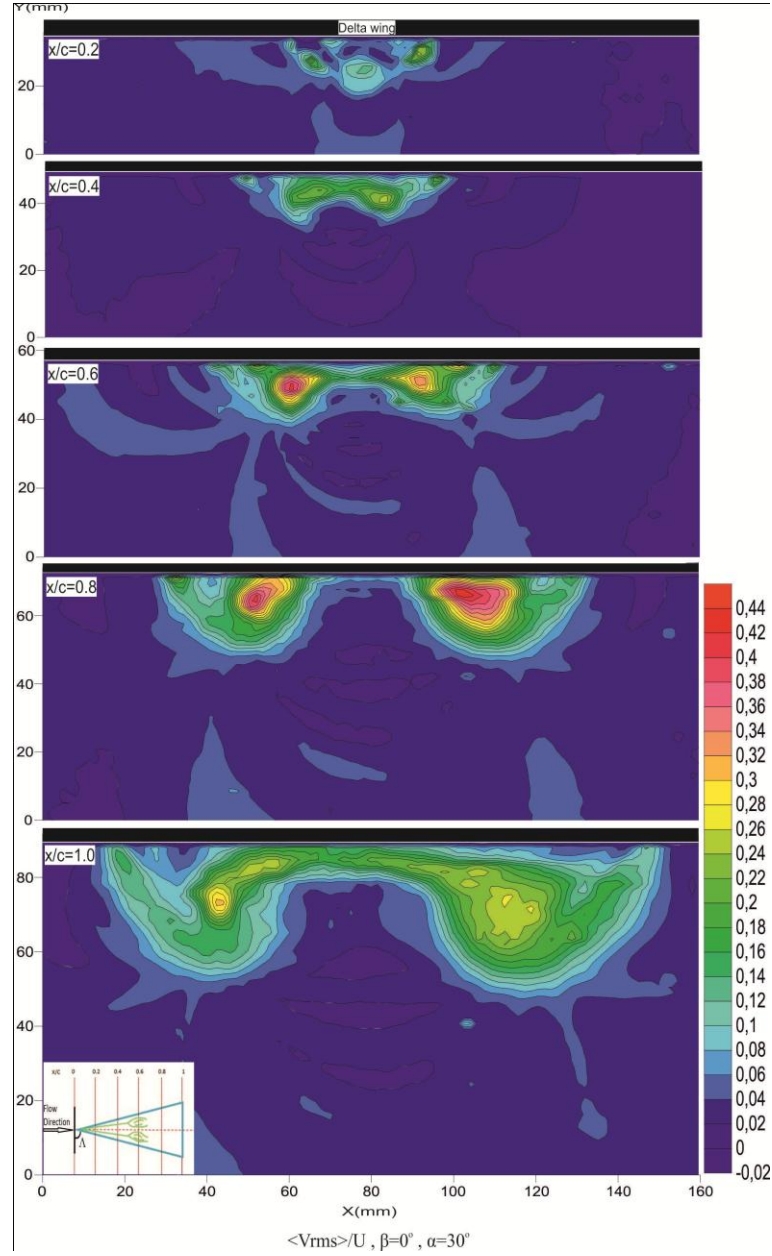


Fig.4.40. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 30^\circ$ and yaw angle, $\beta = 0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min} = -0.02$, and $\Delta[\langle v_{rms} \rangle / U] = 0.02$ respectively

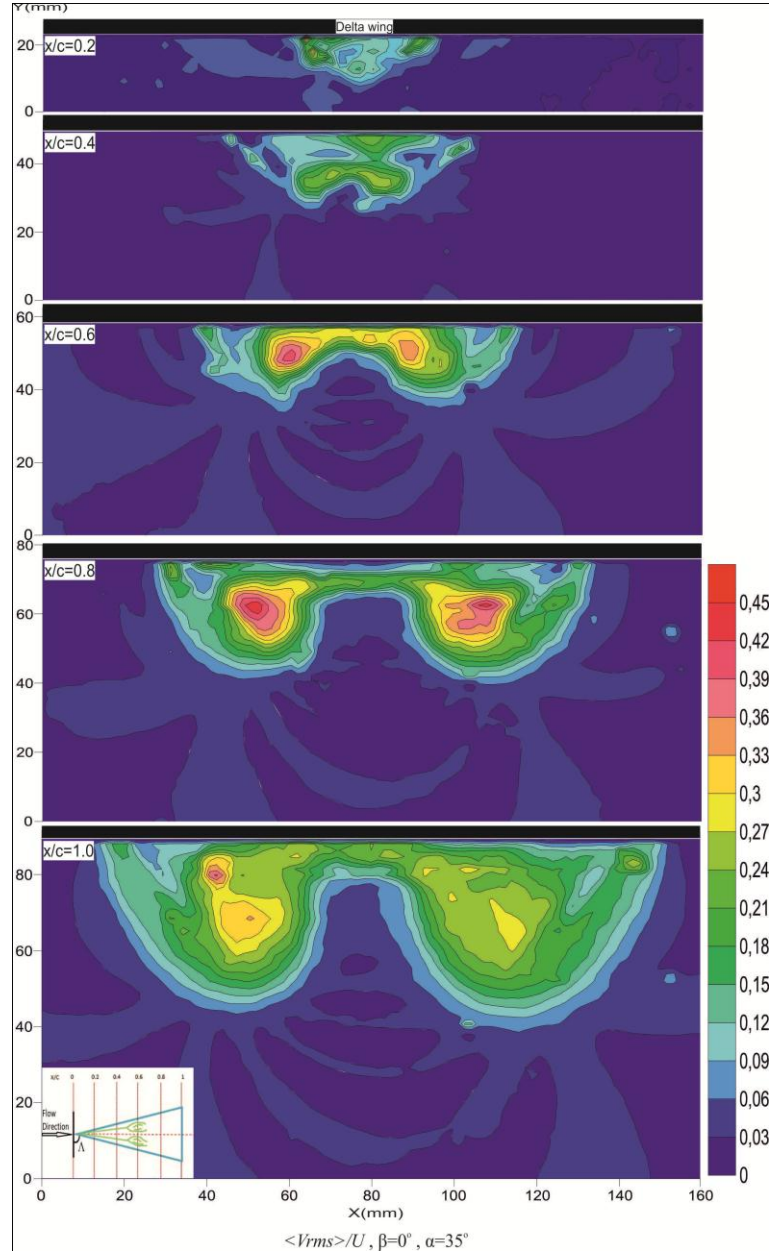


Fig.4.41. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 35^\circ$ and yaw angle, $\beta = 0^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min} = 0.03$, and $\Delta[\langle v_{rms} \rangle / U] = 0.03$ respectively

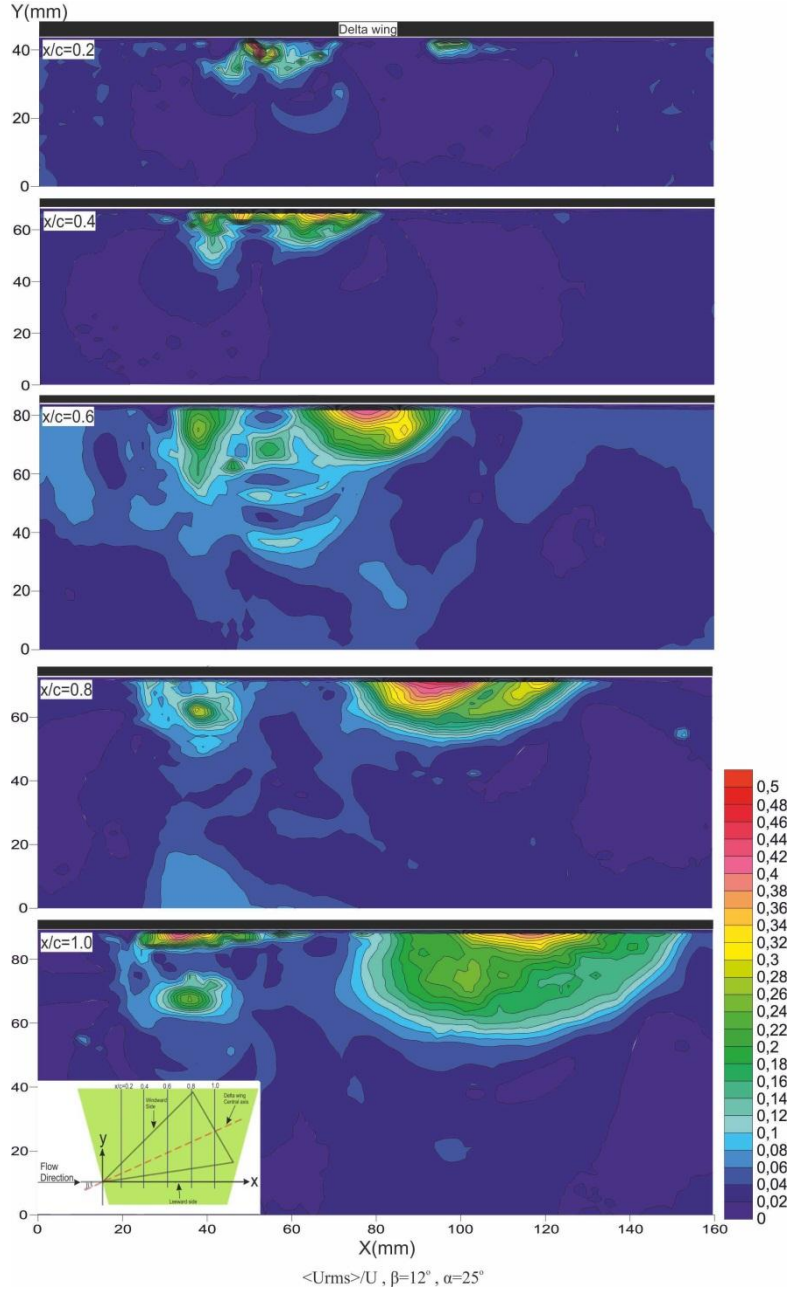


Fig.4.42. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 25^\circ$ and yaw angle, $\beta = 12^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min} = 0.02$, and $\Delta[\langle u_{rms} \rangle / U] = 0.02$ respectively

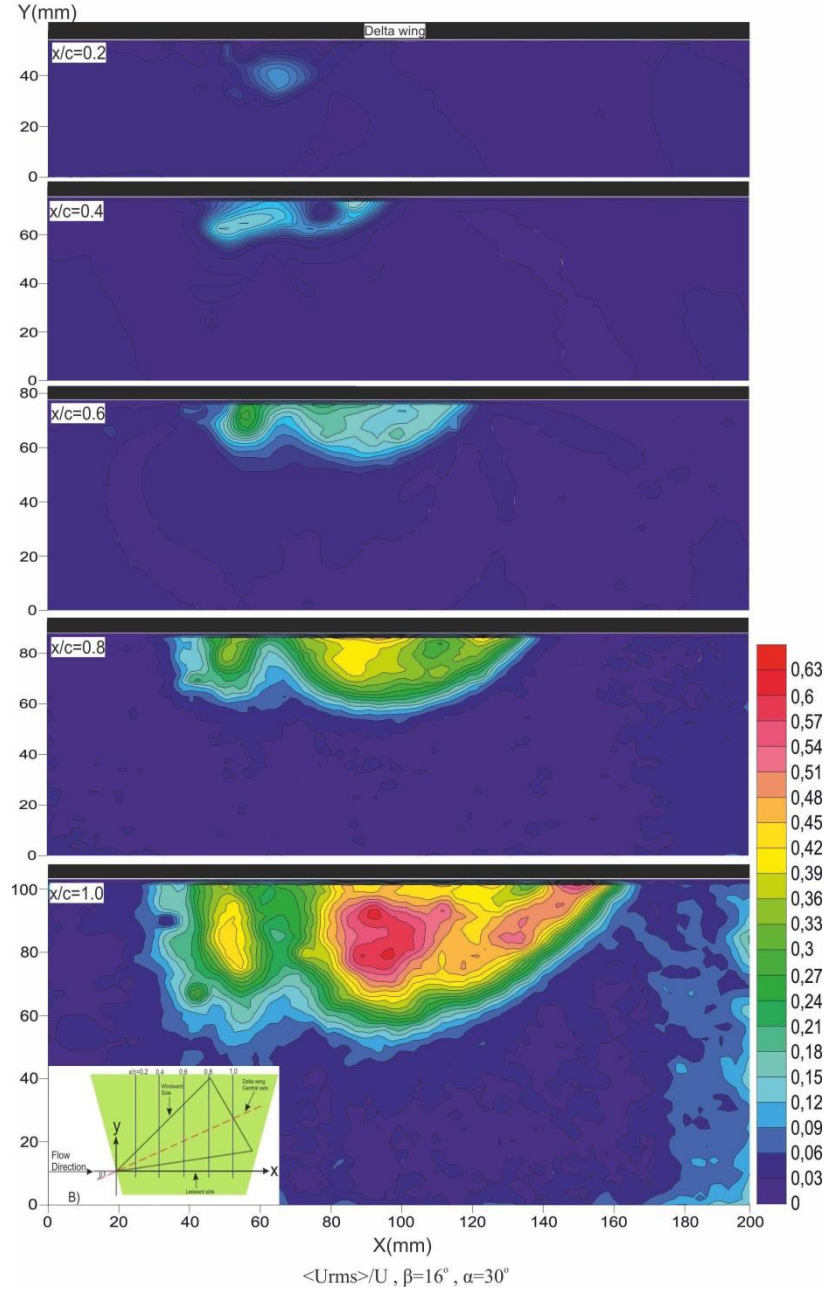


Fig.4.43. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 30^\circ$ and yaw angle, $\beta = 16^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min} = 0.03$, and $\Delta[\langle u_{rms} \rangle / U] = 0.03$ respectively

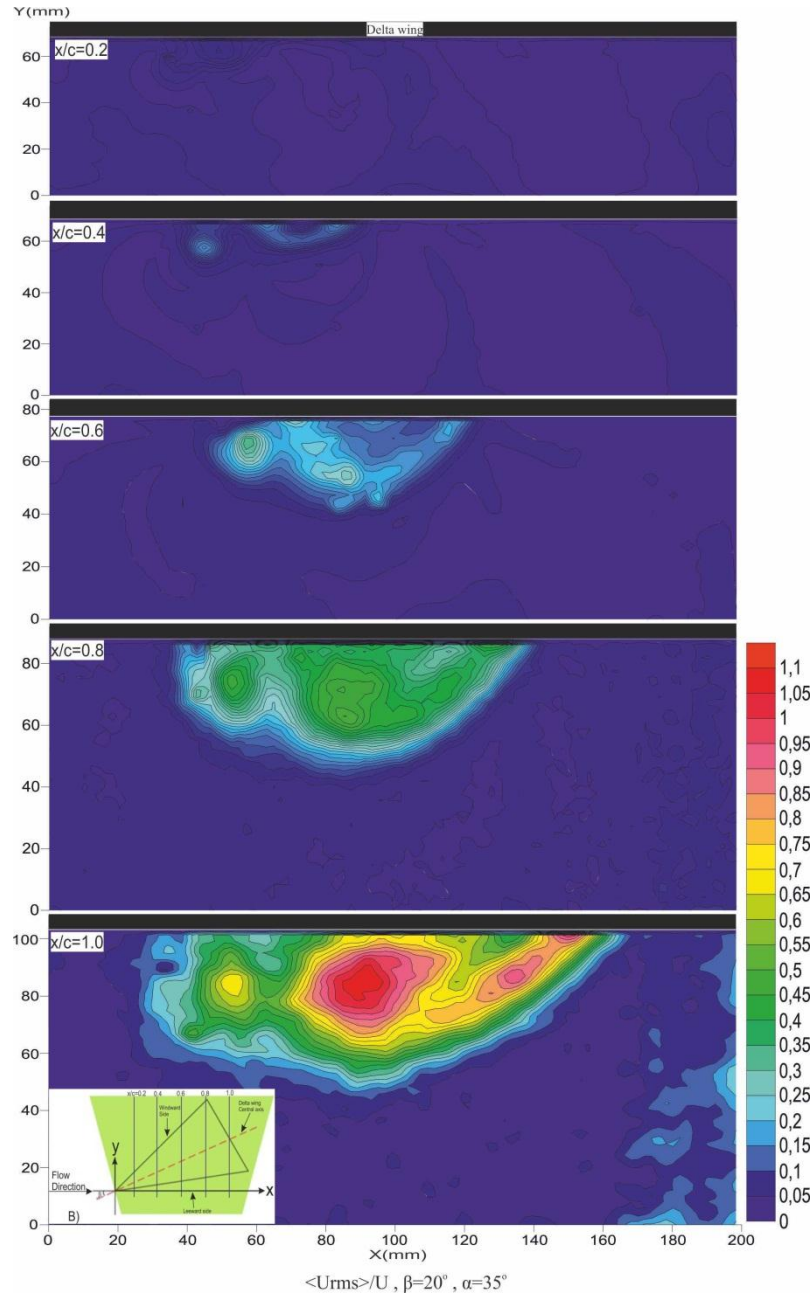


Fig.4.44. Contours of time-averaged components of rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 35^\circ$ and yaw angle, $\beta = 20^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle u_{rms} \rangle / U]_{min} = 0.05$, and $\Delta[\langle u_{rms} \rangle / U] = 0.05$ respectively

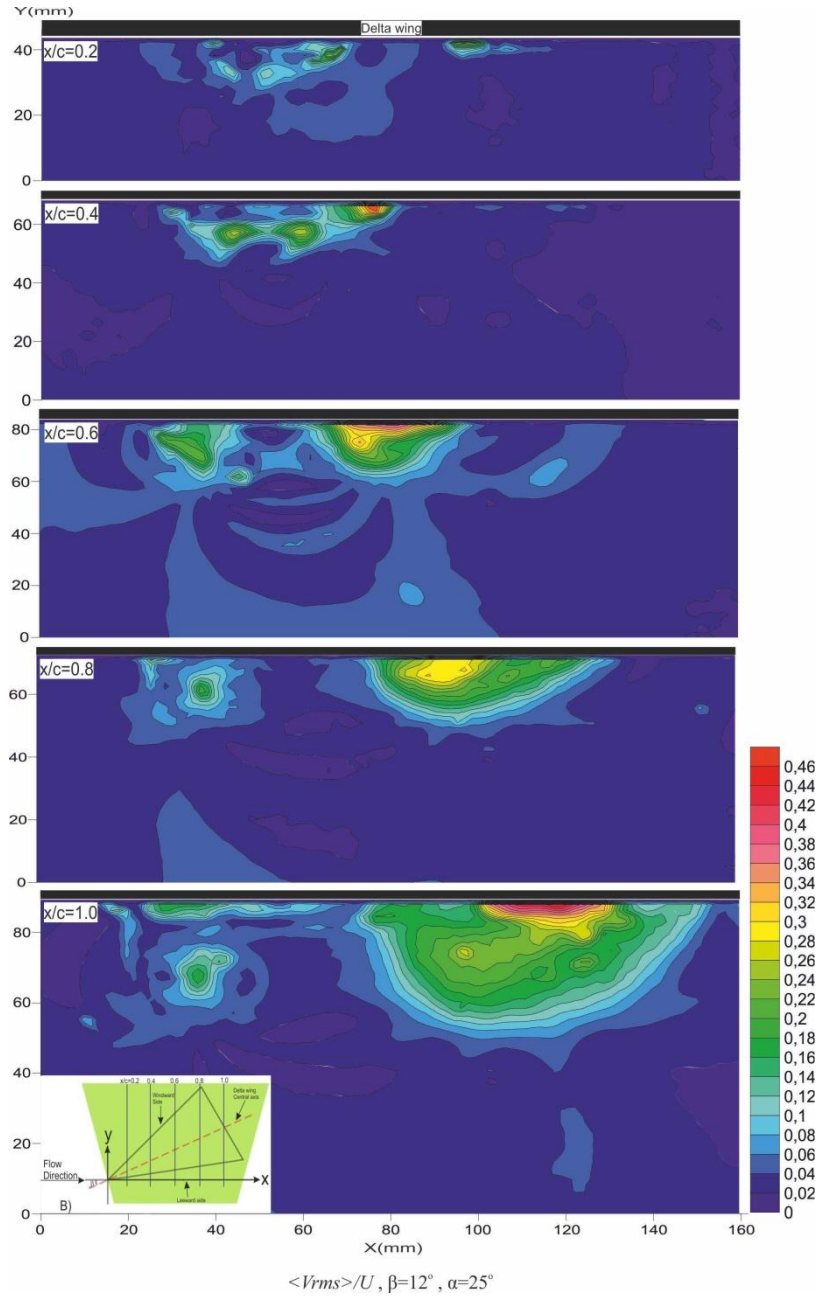


Fig.4.45. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 25^\circ$ and yaw angle, $\beta = 12^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min} = 0.02$, and $\Delta[\langle v_{rms} \rangle / U] = 0.02$ respectively

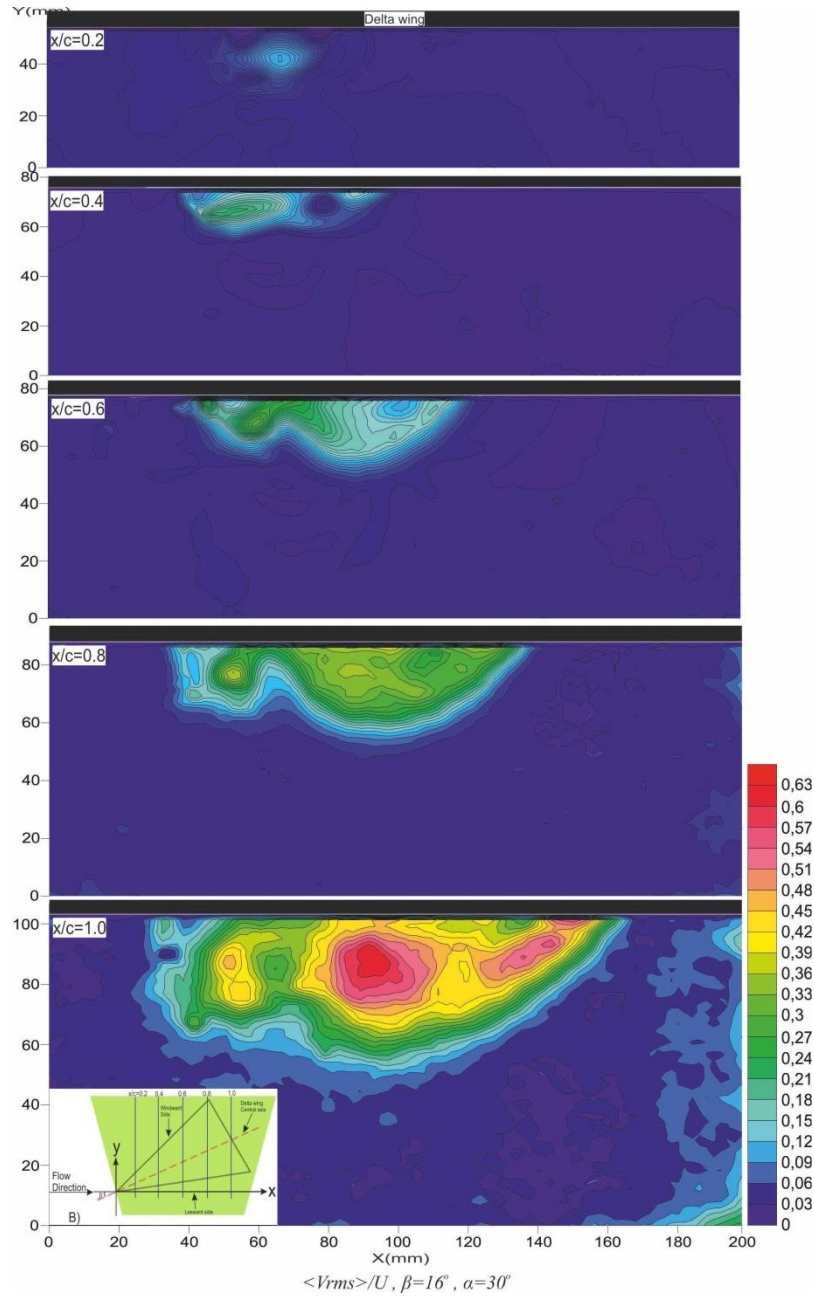


Fig.4.46. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 30^\circ$ and yaw angle, $\beta = 16^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min} = 0.03$, and $\Delta[\langle v_{rms} \rangle / U] = 0.03$ respectively

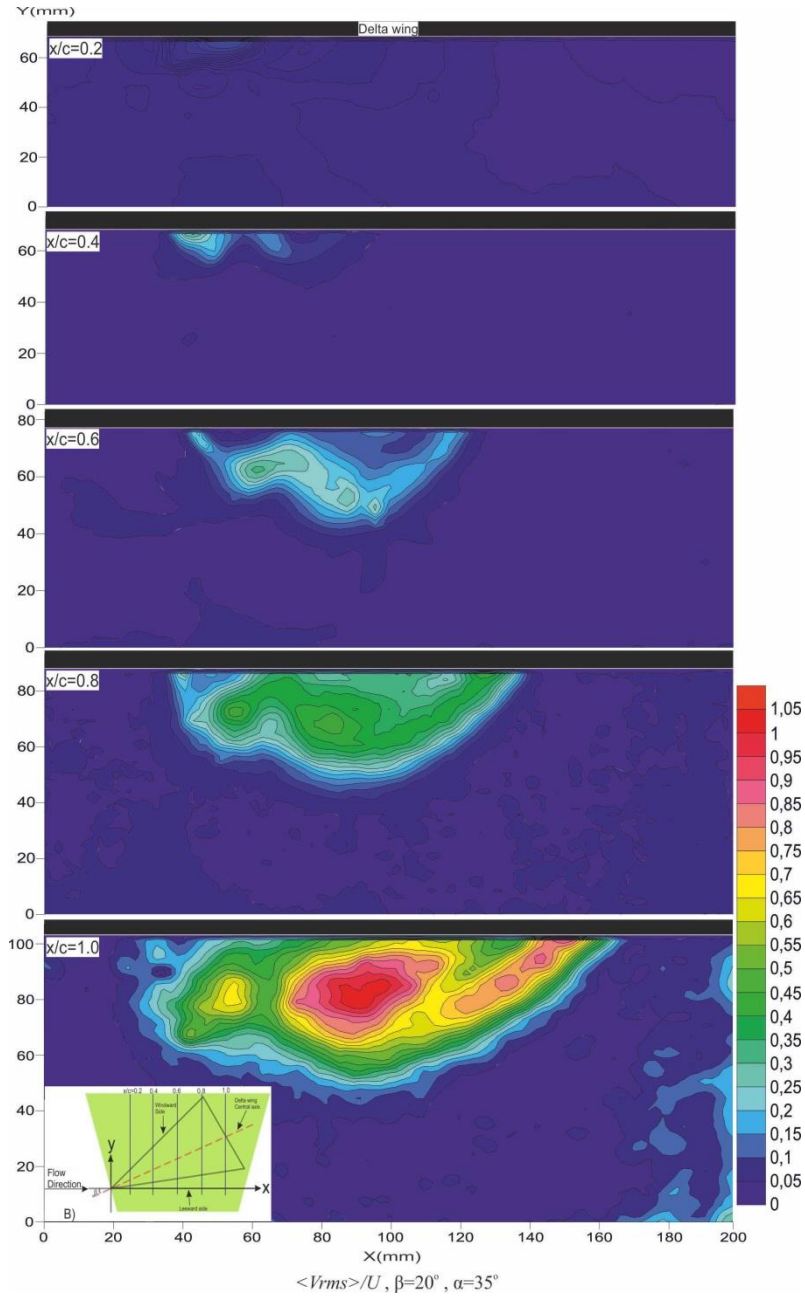


Fig.4.47. Patterns of time-averaged components of rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ in end-view plane for the angle of attack $\alpha = 35^\circ$ and yaw angle, $\beta = 20^\circ$, x/C ratio within the range of 0.2, 0.4, 0.6, 0.8 and 1.0. Minimum and incremental values are $[\langle v_{rms} \rangle / U]_{min} = 0.05$, and $\Delta[\langle v_{rms} \rangle / U] = 0.05$ respectively

A quantitative visualization of vortical flow provides detailed physics of flow structures. In order to see the effect of yaw angle, β on the flow structures in end-view plane of the delta wing, time-averaged velocity vectors, $\langle V \rangle$, streamline $\langle \Psi \rangle$ and vorticity, $\langle \omega \rangle$ are defined using instantaneous velocity data. As seen in figures laser sheet is passed through the cross-section at $x/C=1.0$ because dye visualization tests were conducted on the same cross-section. Patterns of time-averaged streamline, $\langle \Psi \rangle$, for angles of attack of $\alpha=25^\circ$ 30° and 35° and varying yaw angles, β over the range of $0^\circ \leq \beta \leq 20^\circ$ are present. The laser sheet is located at a location of $x/C=1.0$. Inspection of these images in figures shows that center of well-formed foci, F_1 and F_2 , saddle points; S_1 and S_2 distinctly designate symmetrical flow structures and the domain of main rotating vorticity concentrations. Central points of swirl patterns of streamlines, F_1 and F_2 move to the left hand side of wing because of rising yaw angle, β from 0° to 20° as seen in Figure 4.48. It is observed that the swirling patterns of streamlines, $\langle \Psi \rangle$ indicating flow circulations regions are not symmetrical.

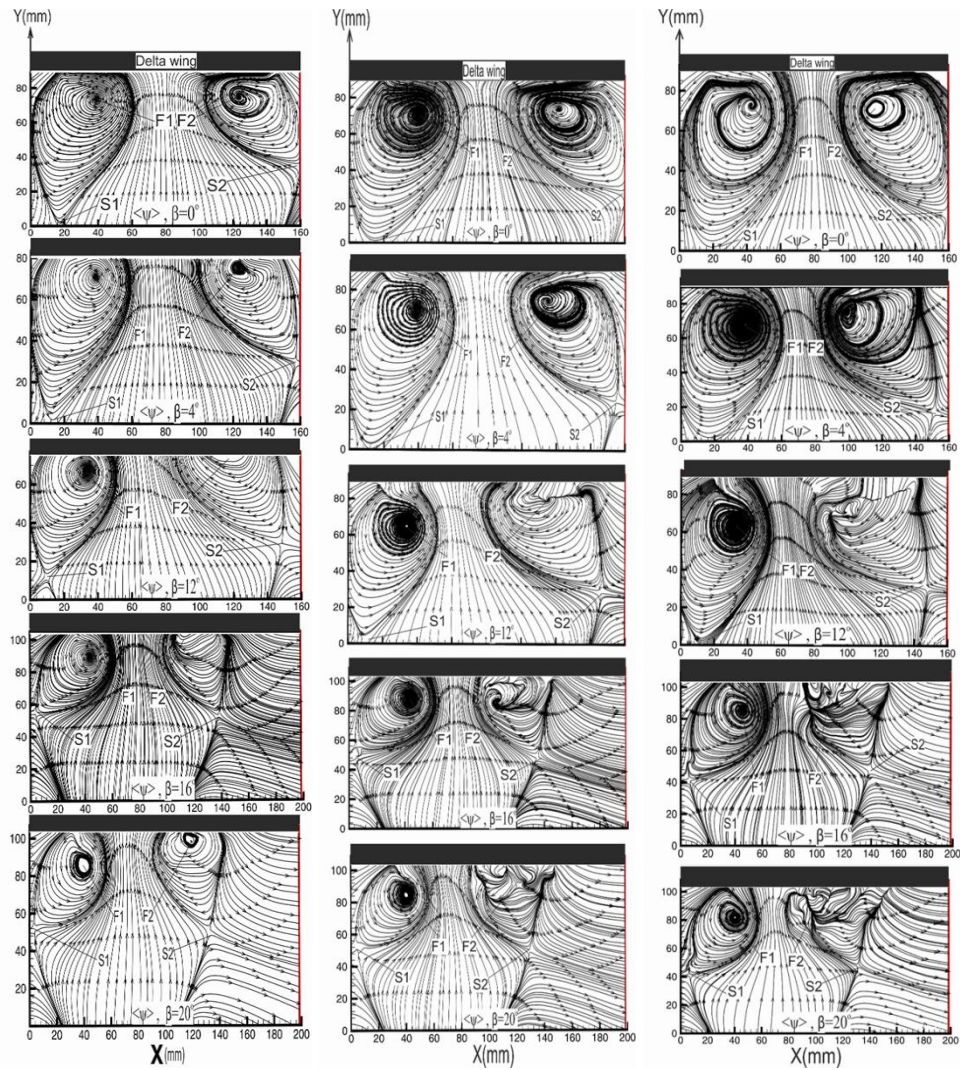


Fig.4.48. Patterns of time-averaged streamline, $\langle \Psi \rangle$, with variation of yaw angle, β for angle of attack $\alpha=25^\circ, 30^\circ$ and 35° . The laser sheet is located at $x/C=1.0$

Patterns of velocity vectors, $\langle V \rangle$ clearly show locations of swirling of flow which are coincident with the foci of streamline patterns, F_1 and F_2 . As seen in Figure 4.49, distribution of velocity vectors, $\langle V \rangle$ reveals that as the yaw angle β , increases, one of the leading edge vortices moves to the left hand side of delta wing and the other leading edge vortex also moves to the left hand side as well close to the center line of delta wing. To study patterns of time-averaged flow data, for angles of attack of $\alpha = 25^\circ, 30^\circ, 35^\circ$ and five different values of yaw angle β , a laser sheet is located at $X/C=1.0$ throughout the experiment for PIV measurements. The distribution of time-averaged velocity vectors, $\langle V \rangle$ exhibits a localized swirl flow patterns with a high velocity magnitude around the centers of foci, F_1 and F_2 developing two identifiable recirculation cells. When angles of attack, α is set as $\alpha = 25^\circ, 30^\circ$ and 35° keeping yaw angle, β at 0° value, it is seen in all cases that the domain and the magnitude of time-averaged velocity vectors, $\langle V \rangle$ are symmetrical in macro scale as seen in Figure 4.49. But, the magnitude of time-averaged velocity vectors is gradually attenuated as angle of attack, α is increased. As also seen in the dye visualization experiment, when yaw angle is set to $\beta = 0^\circ$, there are similar flow structures on both sides of central cord axis of the delta wing. But, the magnitude of velocity vectors, $\langle V \rangle$ are higher and size of recirculation flow field is larger in the leeward side for higher angles of attack, α and higher yaw angles, β at $X/C=1.0$. Both central points of foci, F_1 and F_2 move towards the leeward side of the wing.

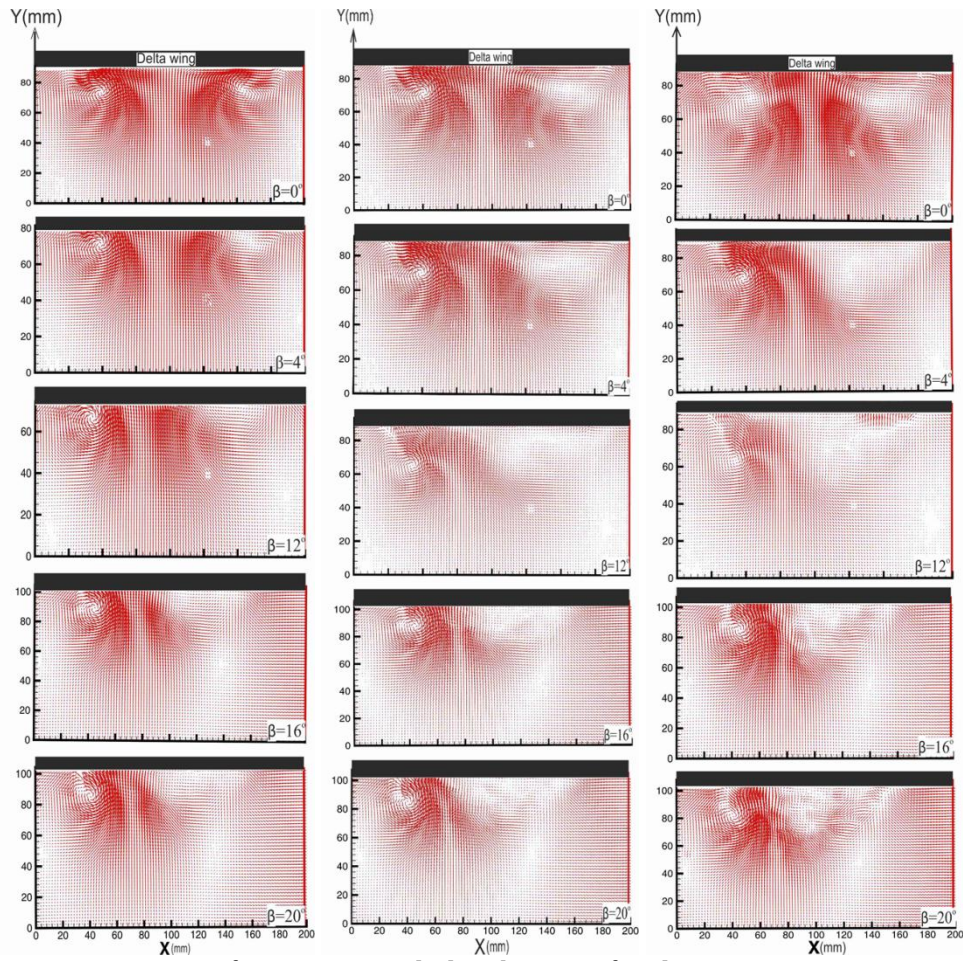


Fig.4.49. Patterns of time-averaged distribution of velocity vectors, $\langle V \rangle$ with variation of yaw angle, β for angle of attack, $\alpha = 25^\circ, 30^\circ$ and 35° . The laser sheet is located at $x/C = 1.0$

5. CONCLUSION

In the present study, focuses are given on the basic features which are leading edge vortex bursting, its development and genesis of vortices over a delta wing which has a 70° sweep angle, Λ . Studies are performed both qualitatively and quantitatively using two kinds of experimental techniques. For these experimental studies, angles of attack are changed within the range of $25^\circ \leq \alpha \leq 35^\circ$ and yaw angles, β are varied within the range of $0^\circ \leq \beta \leq 20^\circ$. For quantitative observations, the experiments were fulfilled using the 2D PIV technique. Through these experiments, instantaneous flow data, time-averaged velocity vector $\langle V \rangle$, patterns of streamline $\langle \Psi \rangle$, vorticity contours $\langle \omega \rangle$, rms of transverse velocity, $[\langle v_{rms} \rangle / U]$ and rms of streamwise velocity, $[\langle u_{rms} \rangle / U]$ are analyzed in order to reveal the flow mechanism in end-view planes crossing the surface of delta wing vertically. Dye visualizations were performed in end-view planes in order to show that vortical flow structures are under the effect of yaw angles, β . In end-view plane, time-averaged flow data shows that there is a symmetrical flow structures over the delta wing in the case of zero yaw angles, β . These experimental results reveal that with increasing yaw angle, β symmetrical flow structure disrupts. Whereas breakdown locations of the windward side leading edge vortices move towards to the apex of the delta wing, leeward side vortex breakdown location moves far away from the trailing edge of the delta wing. The dye visualization technique in end-view plane shows that the strong Kelvin-Helmholtz vortices are developed and interact with the delta wing surface which can cause to unsteady loading such as buffeting which are increased with the enhancement of angle of attack, α and yaw angle, β . With increasing yaw angle, β symmetrical flow structure is disrupted continuously.

In this case, the corresponding streamline topology shows that there are two saddle points, S_1 and S_2 , and foci, F_1 and F_2 . Saddle points, S_1 and S_2 , are seemed well below the foci, F_1 and F_2 . The streamline patterns show a well-defined swirl pattern. The centers of the foci generally encounter with the central point's well defined reverse flow presented by time-averaged velocity vectors. The saddle points, S_1 and S_2 , and center of foci, F_1 and F_2 , gradually move downward and get closer to each other as angles of attack, α , are increased. Patterns of streamlines, $\langle \Psi \rangle$ of counter rotating flow recirculation are dissimilar in terms of size and magnitude. Differences between size and severity of vortices are easily seen in PIV results that are quantitatively visualized in terms of streamlines, $\langle \Psi \rangle$ and velocity vectors, $\langle V \rangle$. Time-averaged velocity vectors, $\langle V \rangle$ indicates a well-defined a pair of identical swirling flow cells for the case of zero yaw angle, β for all cases of angles of attack, that are considered in the present work. But, a well-defined recirculating flow region on the windward side gradually attenuates and diminishes and finally a single flow circulating loop is only seen in the image of velocity vector distributions $\langle V \rangle$ on the leeward side in the case of higher yaw angle, $\beta \geq 12^\circ$. Increasing yaw angle, β from $\beta=0^\circ$ to $\beta=4^\circ$ flow structures are subjected to small changes. Symmetrical flow structures are dramatically altered at a yaw angle of $\beta=20^\circ$ compared with the case of yaw angles from $\beta = 0^\circ$ to $\beta=4^\circ$. The distribution of time-averaged velocity vectors, $\langle V \rangle$ exhibits several small scales circulations presented by localized swirl patterns of streamlines.

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