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Effect of Delta Wing Shape on Aerodynamic Characteristics at Low Speed

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Abstract

The paper concentrated on effect of sweep angle of delta wing at very low speed of 5 m/s and attack angle of 20 degrees. Sweep angle changed inducing a change of shape of delta wing. Aerodynamic characteristics of delta wing were estimated by changing sweep angles (32, 45, and 60 degrees) within attack angle of 20 degrees and air velocity of 5 m/s. Firstly, experimental configuration was conducted to validate numerical results solving with help of ANSYS software. Results showed a good agreement between numerical and experimental method. Then, simulation method was used to carry out effect of delta wing shape on aerodynamic characteristics at low speed. From obtained results, it was remarked that, increasing sweep angle of delta wing from 32 to 60 degrees made reduce drag and lift forces. Aerodynamic quality of delta wing with high sweep angle was higher than that of a delta wing with small sweep angle.

Keywords: Aerodynamic characteristic, ANSYS, delta wing, low speed, sweep angle.

1. Introduction

Until 1930s, most aircraft wings were designed in a rectangular, trapezoidal or elliptical shape, with this shape suitable only for aircraft traveling at subsonic speeds. At higher speeds, compression effect due to wave formation hit aircraft strongly, including stability and control problems and a huge increase in drag. "Swept back" wing had partially solved this problem, helping aircraft reduced drag and achieved higher speeds. Delta wing was a triangular wing, a special form of "Swept back" wing, which was named delta because of its resemblance to Greek letter delta (*Δ*). Delta wing was a low aspect ratio, so it only stalled at high angles of attack with high induced drag. There were vortices upon delta wing that induced lift named vortex lift. Jones *et al.* [1] showed relative theory for vortex breakdown on 700 and 760 Delta wing. A transition in criticality of Delta wing vortex was also shown to be linked with appearance of breakdown. These vortices were an unsteady phenomenon of aerodynamic that were studied in much research. Gursul *et al.* [2] summarized brief introduction to delta wing aerodynamics, vortex breakdown, shear layer instabilities and requirements from experiments and Computational Fluid Dynamics (CFD).

Al-Garni *et al.* [3] carried out an experimental and numerical investigation of aerodynamic characteristics of 650 delta wing and 650/400 double-delta wing in comparison with theory of Polhamus. Comparison of result showed good agreement between different experimental studies as well as good agreement with computational fluid dynamics predictions and theoretical calculations.

Nakamura and Yamada [4] conducted experiments of a delta wing's spin phenomena at low-speed wind tunnel of Nagoya University with its exit test section inclined vertically. It was evident from these pressure distributions and flow visualizations that a leading-edge separation vortex made an important role in spin phenomena of delta wing.

Many supersonic aircrafts used delta wing, and they often flied at high angles of attack. For example, in landing or taking off phase, they needed to fly at very high angle of attack due to their poor aerodynamic performance at low speeds. When an aircraft with delta wing flied at high attack angle in low speeds, there appeared two large counter-rotating leading-edge vortices which induced an important lift force [5-15].

Trussa [5] investigated low-speed aerodynamic characteristics of a novel delta wing layout with deflected wing tips. Novel delta wing had a leading-edge sweep of 60 degrees, a high-speed aerofoil with a rounded leading-edge and wing tips that could rotate a full 1800 about a hinge. Wang *et al.* [6] estimated aerodynamics of a NACA0012 aerofoil at chord-based Reynolds numbers from $5.3*10^3$ to 2.0*104 with different turbulent intensity from 0.6% to 6.0%. Authors observed that turbulent intensity had a more pronounced effect at lower Reynolds number than at higher Reynolds number on shear layer separation, reattachment, transition, and formation of separation bubble. Zhang *et al.* [7] studied experimentally effect of taper ratio on aerodynamic performance of cropped non-slender delta wings with taper ratio of 0-0.79. Gordnier and Visbal [8] estimated flow over a 50-degree Delta wing by solving full Navier-Stokes equations. Behaviour of vortex upon delta wing was carried out at different attack angle.

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Dsouza and Basawaraj [9] investigated numerically aerodynamic characteristics of 65 degrees/40 degrees double-delta wing at various angles of attack at subsonic conditions.

Oyama *et al.* [10] presented computational method of subsonic to supersonic flows over a delta wing at high angles of attack and corresponding aerodynamic characteristics. Authors remarked that flow type change did not significantly change aerodynamic characteristics of delta wing such as normal force, pitching and rolling moments, except in transition region. Numerical investigation of high attack angle flow on 76 degrees/45 degrees double delta wing in incompressible flow was caried out by [11]

Hoang *et al.* [12] investigated experimentally and numerically aerodynamic characteristics of 74.5-degree slender delta wing. The apparition of vortices upon delta wing caused negative pressure distribution on the wing which reached a maximum absolute value at vortex core. Aerodynamic characteristics of this high swept-back Delta wing were investigated at air velocity of 10 m/s and attack angle of 20 degrees in changing rolling angle of wing from 0 to 20 degrees. Nguyen *et al.* [13] also carried out effect of turbulent flow to dynamic characteristic of high sweep-back angle delta wing in subsonic flow.

Tran *et al.* [14] estimated effect of turbulent inlet flow and effect of taper ratios to vortices formation, aerodynamic characteristics of Delta wing of 45 degrees swept-back leading-edge angle at very low speed both experimentally and numerically method. Authors remarked that two vortices grow up and tended to move inward when attack angle increased; vortices were broken strongly in high attack angles; and aerodynamic quality of delta wings change insignificantly when changing turbulent intensity at inlet.

Tosti [15] experimented delta wings with sweep angle varying from 45 to 80 degrees. He found that critical angle of attack trend increased, and maximum lift also increased. However, the change was not nonlinear. When angle of attack increases from 44.9 to 56.3 degrees, critical sweep angle and maximum lift coefficient increased accordingly. If sweep angle continued to increase, angle of attack increased, limit and maximum lift coefficient was reduced. The same for drag coefficient, as sweep angle increased, drag coefficient decreased. With classification of swept angle, there were different types of wings:

- Zero sweep angle: conventional flat wing,

- Swept angle from 0 to 20 degrees: stall phenomenon was similar that of fixed wing; Vortices appeared inconspicuous on wings,

- Sweep angle from 30 to 40 degrees: Vortices on wing appeared significantly and increased lift force,

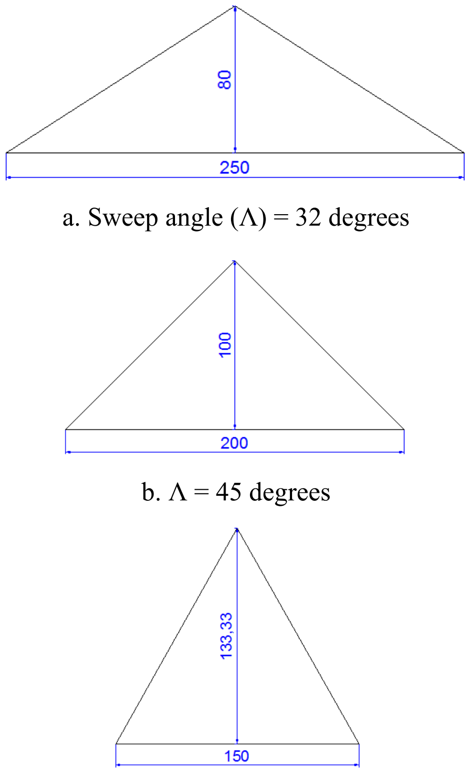
- Sweep angle greater than 50 degrees: Flow on and around the wing was dominated by vortices emerging from leading-edge point; Stall phenomenon occurred due to phenomenon of vortices breakdown.

Hoang *et al.* [16] investigated experimentally and numerically aerodynamic characteristics of 74.5-degrees slender delta wing. The apparition of vortices upon delta wings caused negative pressure distribution on the wing which reached a maximum absolute value at vortex core. Aerodynamic characteristics of this high swept-back Delta wing were investigated at air velocity of 10 m/s and attack angle of 20 degree in changing rolling angle of wing from 0 to 20 degree.

2. Methodology

2.1. Delta Wing Model

Delta wing model had a triangular shape with sweep angle of varying from 32 to 60 degrees as shown in Fig. 1.



a. Sweep angle (Λ) = 32 degrees

b. Λ = 45 degrees

c. Λ = 60 degrees

Fig. 1. Delta wing model

- Sweep angle of 32 degrees: delta wing had span of 0.25 m, root chord length of 0.08 m and thickness of 0.005 m (Fig. 1a),

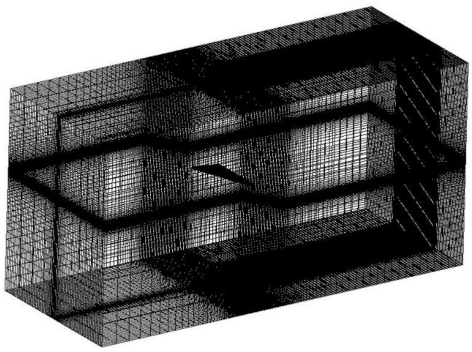
- Sweep angle of 45 degrees: delta wing had span of 0.20 m, root chord length of 0.10 m and thickness of 0.005 m (Fig. 1b),

- Sweep angle of 60 degrees: delta wing had span of 0.15 m, root chord length of 0.1333 m and thickness of 0.005 m (Fig. 1c).

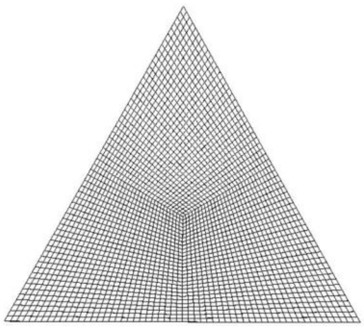
Delta wing was fixed with high attack angle of 20 degrees and put in air velocity of 5 m/s.

2.2. Simulation Setup

Delta wing was placed in a rectangular box with dimensions of 1 m x 0.4 m x 0.5 m. This was testing section of subsonic wind tunnel used for experimental research. Thus, we could easily compare simulation results with experimental results.



a. Computational domain



b. Delta wing

Fig. 2. Meshing grid

Since calculation only focused on surveying eddy area on delta wing, above rectangular computational domain was guaranteed to be accurate and contained all necessary results. In area closed to wing surface, many complicated phenomena occurred due to presence of large gradient. So, wing surface was meshed with high reliability. Entire computational domain was divided into about 1,500,000 elements (Fig. 2) using ICEM tools in ANSYS software.

Meshing grid also greatly affected results of problem, with high attack angle of delta wing, air flow was not adhered to surface of wing, but it separated surface of wing. Therefore, to be able to accurately calculate area close to surface of wing, meshing grid must mesh with value of y^+ approximately 1. Where y^+ was dimensionless distance to wing. It was used to check distance from wing to center of first grid. With $y^+ = 1$, value of y was determined as 0.05 mm. From that, computational domain was divided so that first mesh element has this value of y. Next mesh layers had development ratio about 1.1 to ensure y^+ of next mesh layers not too large.

The *k-ω* SST turbulence model was used to solve out governed equations of fluid flow.

2.3. Experimental Setup

AF6116 subsonic wind tunnel with Mach number 0.1 and test section of 1 m x 0.4 m x 0.5 m was used in experimental research. Only delta wing with sweep angle of 60 degree was chose to compare with numerical results. Experimental wing was made of plexiglass and was arranged with 39 pressure measuring holes (Fig. 3).

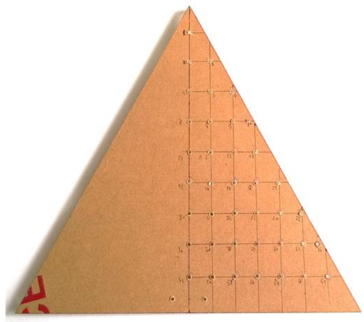


Fig. 3. Experimental wing

These measuring holes were arranged in 9 rows; distance between two consecutive row was 13.3 mm; distance between two holes consecutive on same row was 10 mm; and diameter of each measuring hole was 1.4 mm. Pressure was measured based on pitot tube principle with gauge value of pressure being average value of 60,000 pressures. From distribution of measured pressure on wing, lift and drag force were estimated by following formula:

$$\Delta F_i = (P_{i,Lower} - P_{i,Upper})\Delta S_i \quad (1)$$

$$\Delta L_i = \Delta F_i \times cos\alpha \quad (2)$$

$$\Delta D_i = \Delta F_i \times sin\alpha \quad (3)$$

$$L = \sum \Delta L_i \qquad C_L = L/\left(\tfrac{1}{2}\rho v^2 S\right) \quad (4)$$

$$D = \sum \Delta D_i \qquad C_D = D/\left(\tfrac{1}{2}\rho v^2 S\right) \quad (5)$$

where:

F is reaction force (N)

P is measure pressure (N/m^2)

A is attack angle (Degree)

L is lift force (N)

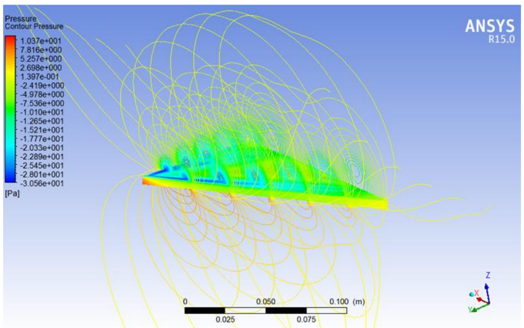
D is drag force (N)

CL is coefficient of lift

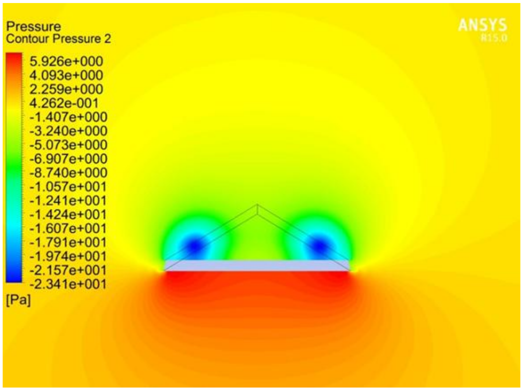
CD is coefficient of drag.

3. Results

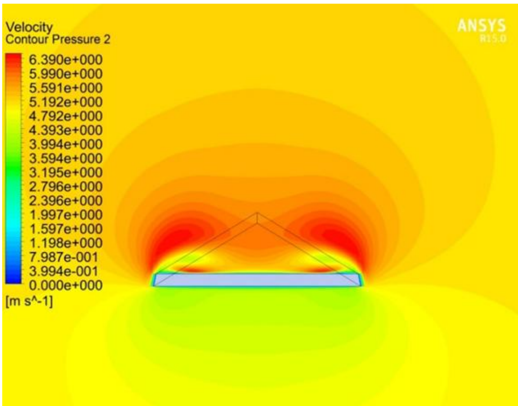
3.1. Attack Angle 20-Degrees, Velocity of 5 m/s and Sweep Angle 60-Degrees



a. Pressure around wing



b. Pressure at *y/cr* equal 0.5



c. Velocity at *y/cr* equal 0.5

Fig. 4. Air flow around 60-degrees delta wing

Pressure distribution of flow around delta wing was shown in Fig. 4. Pressure at lower surface had no remarkable phenomenon (Fig. 4a). Pressure at lower surface changed monotone, while pressure at upper surface had two areas of much lower pressure than ambient pressure, that was vortex regions (Fig. 4b). With other planes passing through the wing, similar results were obtained (Fig. 4a). Thus, there was apparition of two vortices upon the wing. These positions had minimum pressure, negative pressure, and were centre of vortex.

In regards of Fig. 4c, on upper surface of wing, there was a region of high air velocity moving around a lower velocity region. Thus, vortices appeared upon the wing. At the same time, these vortices created a region of high air velocity moving close to upper surface of wing. These were regions of high velocity and low pressure. This phenomenon created a large pressure difference between upper and lower pressure of wing, which inducted a vortex lift for delta wing [1].

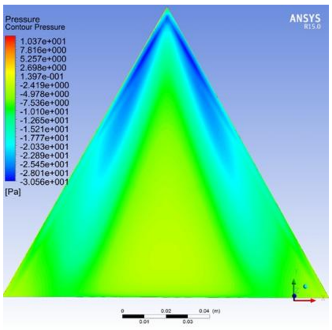
Pressure distribution on delta wing was shown in Fig. 5. Appearance of two vortices located on either side of wing affected air area below vortex closed to upper surface, forming negative pressure on the wing (Fig. 5a). On the lower surface, nothing special happened (Fig. 5b). Simulation results were in good accord with experimental results (Fig. 5c and Fig. 5d). Upon Delta wing appeared two areas of minimum pressure that could be explained by influence of two vortices. These high-velocity vortices created an area of low pressure on the upper surface. This was especially important in lift-generating mechanism of delta wing. At the same time, from *Cp* distribution, pressure difference between upper and lower surfaces was largest near leading edge of wing, while difference of *Cp* in middle part of wing was not large. As such, the lift for Delta wing was generated mainly near leading edge of wing. Both simulation and experiment described pressure variation on wing and pressure region affected by vortices.

Fig. 6 depicted correlation between spanwise pressure field at 8th measuring row (*y/cr* = 0.2, *cr* was root chord length of delta wing) of experimental and numerical results. Despite deviation, the trend of two graphs was the same.

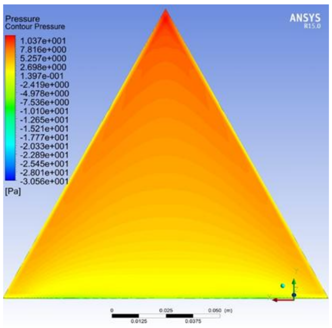
Table 1 summarized aerodynamic characteristics of delta wing for both experimental and numerical results. There was a relative error less than 18% between simulation and experiment. Main reason of this difference could be from both simulation setup (meshing grid, turbulence model,…) and experimental setup (condition of experiment, support, instrument of measurement,…).

Table 1. Aerodynamic characteristics of 60-degree delta wing

Parameter	EXP	SIM	Error (%)
Lift (N)	0.188	0.154	17.76%
Drag (N)	0.068	0.062	9.27%
L/D	2.747	2.49	9.53%

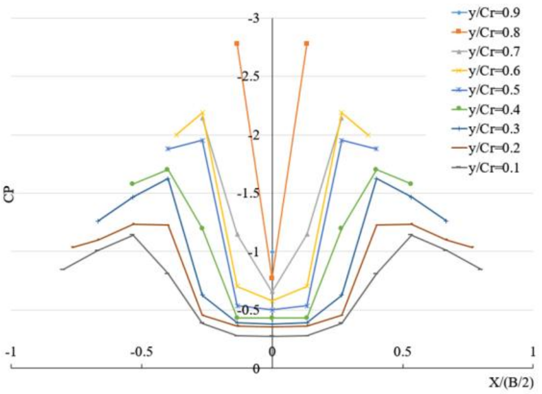


Upper surface

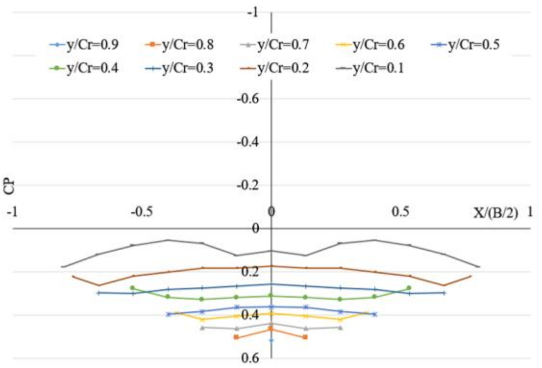


Lower surface

a. Simulation results – At *y/cr* equal 0.5



Upper surface



Lower surface

b. Experimental results

Fig. 5. Pressure on 60-degrees delta wing - at *y/cr* equal 0.5

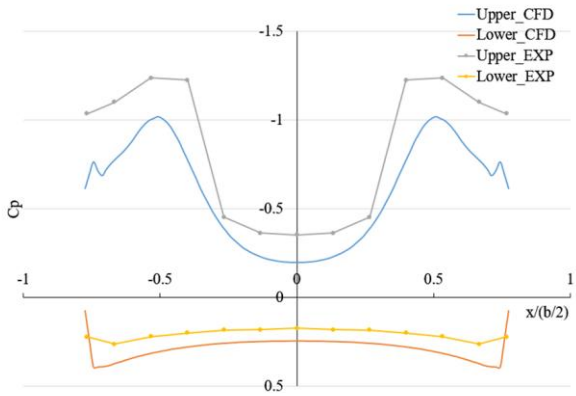


Fig. 6. Spanwise pressure of 60-degrees delta wing - at *y/cr* equal 0.2

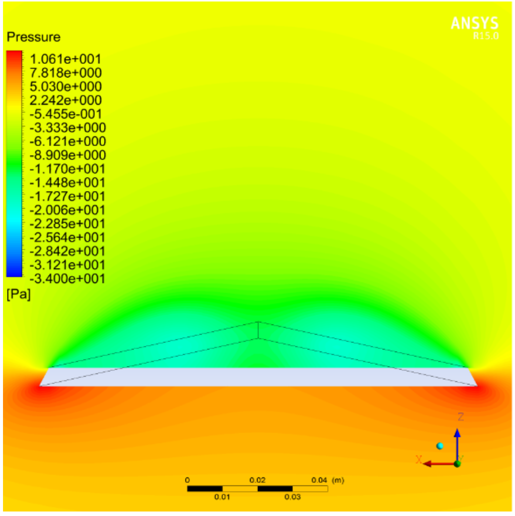
3.2. Effect of Delta Wing Shape

In precedent paragraph, simulation setup was validated by comparing with experimental results within less 18% relative error due to reason of both experimental setup and simulation setup. In this paragraph, only simulation method was used to carry out effect of shape of delta wing by changing sweep angle from 32 to 60 degrees (Fig. 1).

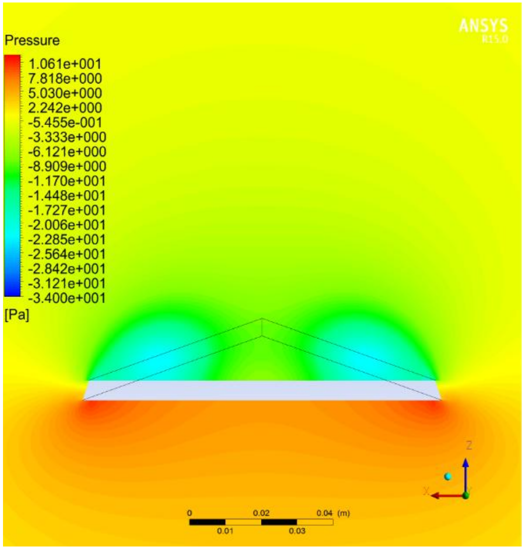
Fig. 7 and Fig. 8 presented distribution of pressure and velocity respectively at section of *y/cr* equal 0.5. Obtained results showed that for delta wing with 32-degrees sweep angle, vortices upon the wing were still weak, centre of vortices was wide. For wing with 45-degree sweep angle, formation of vortices upon the wing was clearly seen. Moreover, for wing with 60-degrees sweep angle, vortices appeared more clearly and stronger, centre of vortices narrowed, and values of pressure at centre of vortices were lower and decreased sharply.

In regards of distribution of pressure on wing at the upper surface Fig. 9 and at the lower surface Fig. 10. For a wing with 32-degrees sweep angle, upper pressure did not change much, area affected by vortices was large because vortices were close to upper surface of wing. For wings with 45-degrees sweep angle, around front of wing and leading-edge side, pressure was reduced in comparison with other areas of wing, this was due to presence of vortices upon wing. So, vortices upon the wing reduced pressure on surface of wing. For wing with sweep angle of more than 60 degrees, low pressure area was located near edges of wing (leading-edge sides), there was a difference of pressure on delta wing.

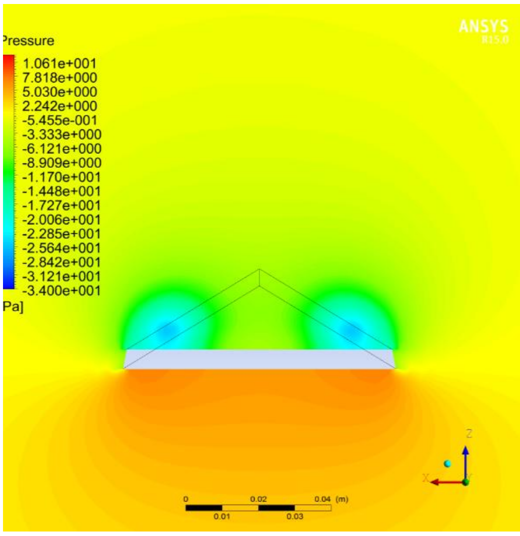
For more detail, streamline of air flow around delta wing was presented in Fig. 11. At angle of attack of 20 degrees for wing with sweep angle of 32 degrees, a stall phenomenon occurred; vortices on wing were irregular; separation flow was observed upon wing; and air flow became turbulence, like conventional wings. For delta wings with sweep angle 45-degrees and 60-degrees, stall phenomenon did not occur.



a. Λ = 32 degrees

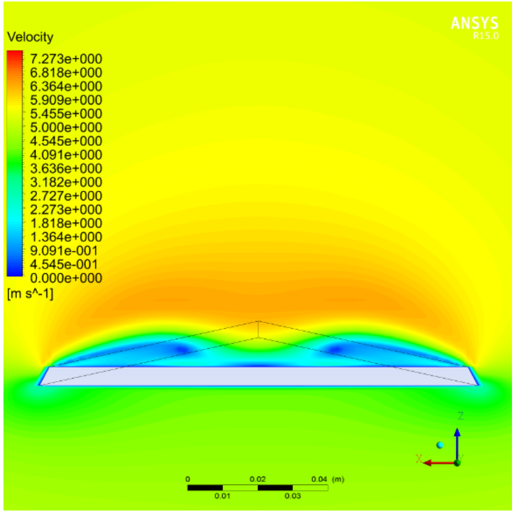


b. Λ = 45 degrees

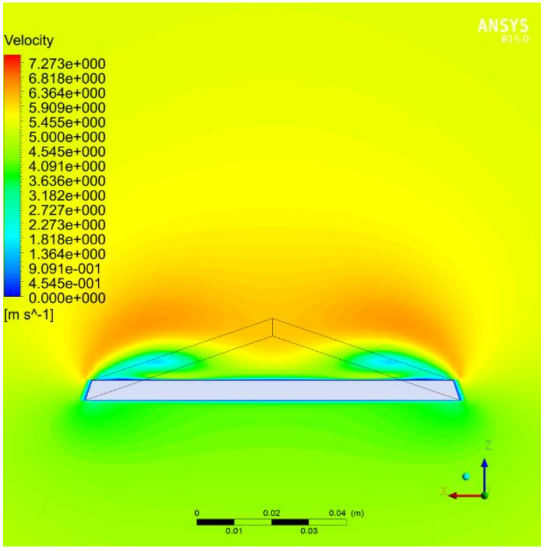


c. Λ = 60 degrees

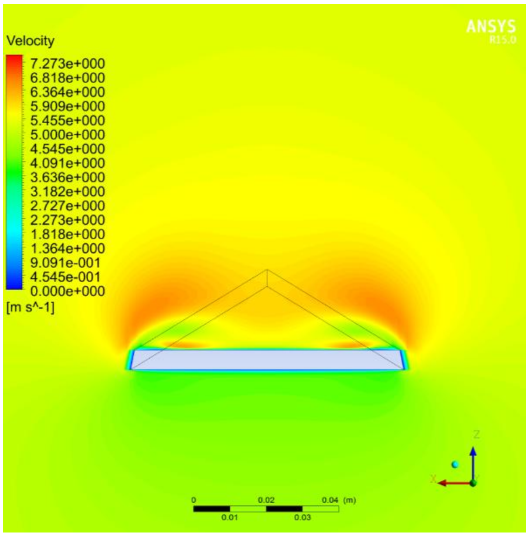
Fig. 7. Distribution of pressure - at *y/cr* equal 0.5



a. Λ = 32 degrees

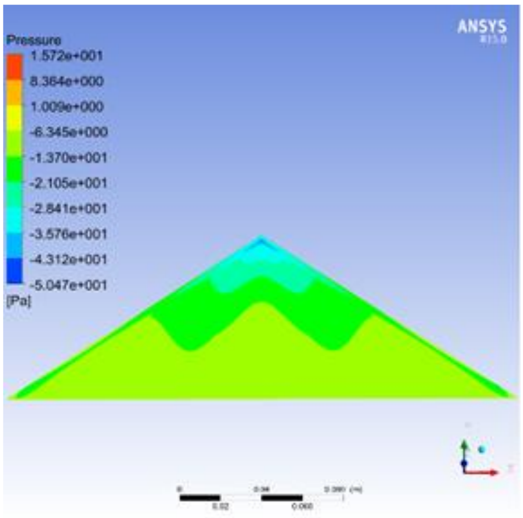


b. Λ = 45 degrees

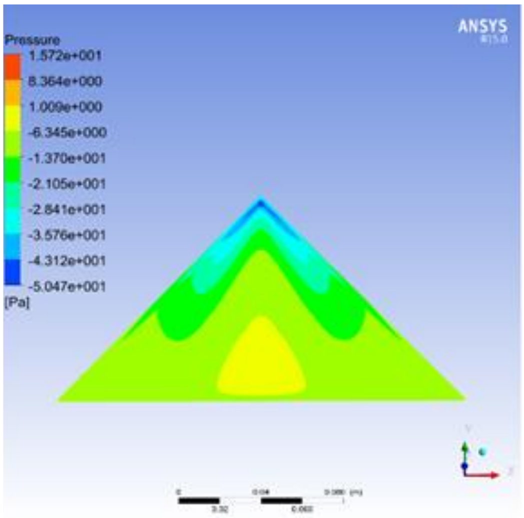


c. Λ = 60 degrees

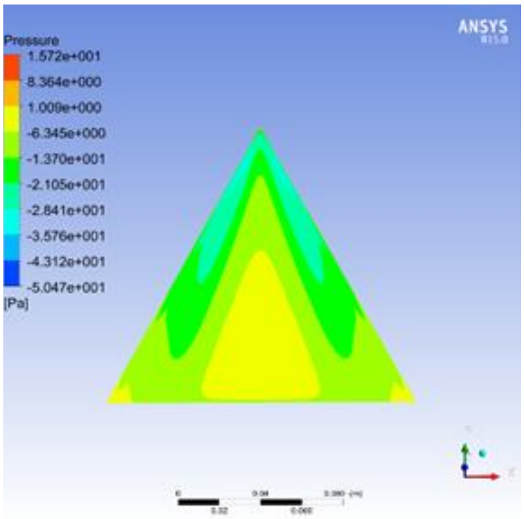
Fig. 8. Distribution of velocity - at *y/cr* equal 0.5



a. Λ = 32 degrees

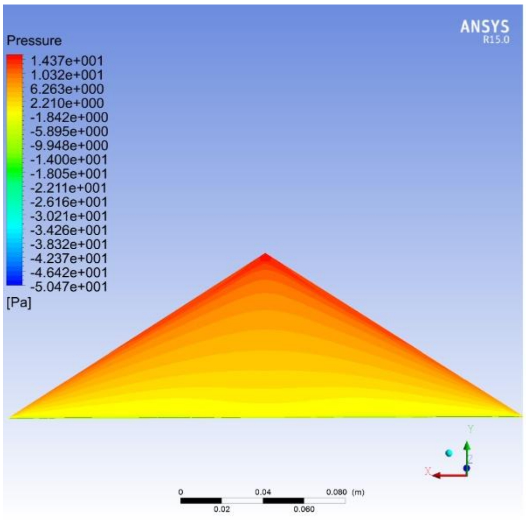


b. Λ = 45 degrees

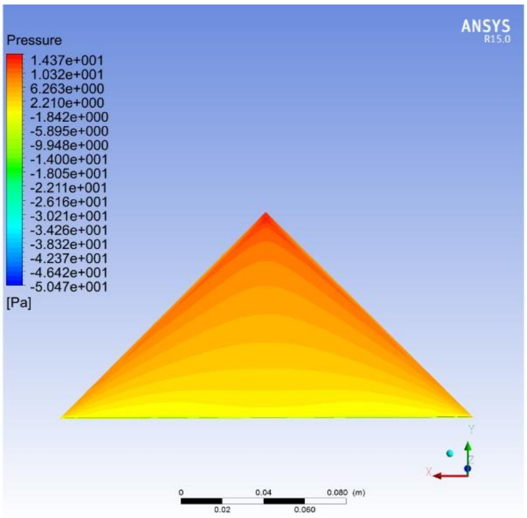


c. Λ = 60 degrees

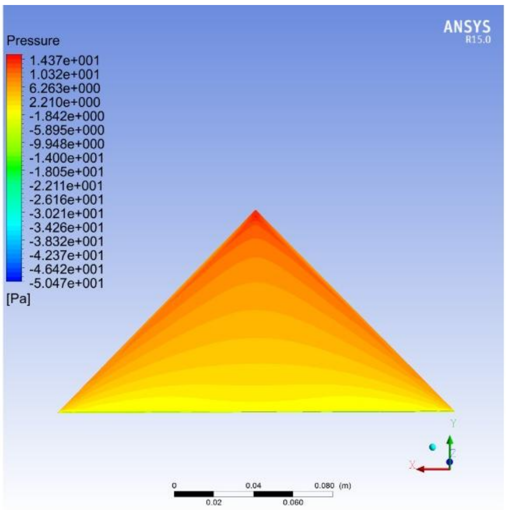
Fig. 9. Distribution of pressure on delta wing – Upper surface



a. Λ = 32 degrees

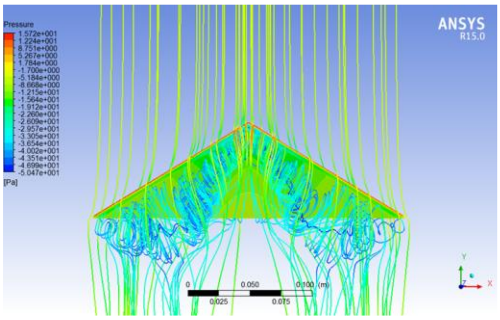


b. Λ = 45 degrees

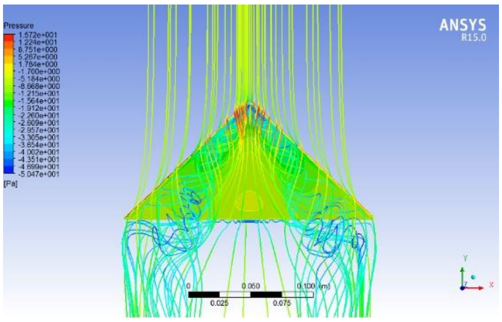


c. Λ = 60 degrees

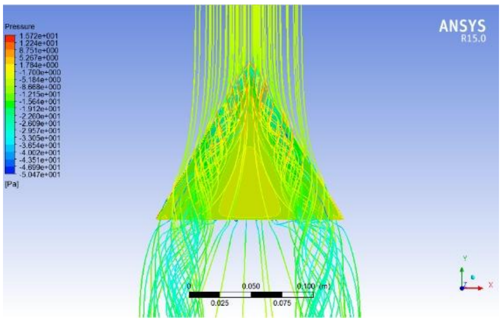
Fig. 10. Distribution of pressure on delta wing – Lower surface



a. Λ = 32 degrees



b. Λ = 45 degrees



c. Λ = 60 degrees

Fig. 11. Streamlines

From obtained results of aerodynamic characteristics of delta wing at angle of attack of 20 degrees shown in Table 2, increasing sweep angle of delta wing from 32 degrees to 60 degrees reduced drag and lift force of delta wing, in which lift force decreased gradually. However, aerodynamic quality of delta wing increased. Aerodynamic quality of delta wing with a large sweep angle was higher than that of a small reverse angle.

Table 2. Aerodynamic characteristics of delta wing

Parameter	Λ = 32 degrees	Λ = 32 degrees	Λ = 32 degrees
Lift (N)	**0.17016**	0.16110	0.15580
Drag (N)	0.08298	0.07105	**0.06254**
L/D	2.05054	2.2672	**2.4909**

4. Conclusion

By using numerical simulation and experimental method, aerodynamic characteristics of delta wing were calculated and represented. Both numerical and experimental methods had a common result and giving a clearer view of behaviour of air passing through delta wing as well as problems that delta wings could face when operating in different modes. That was helpful in applying, using delta wings in practice effectively and safely.

Difference between simulation results and experimental results was about 20%. This difference was due to major reasons such as support of delta wing in test section of wind tunnel, effect of boundary condition from wall, error in experimental correlation, as well as meshing and selection of turbulence model were not enough to fully describe above vortex phenomenon. However, 20% was an acceptable error. Therefore, this research will be continued on basis of adjusting and reducing major factors that may cause errors for experimental as well as simulation process.

Upcoming research direction of this subject is effect of attack, pitch, and rotation angle in comparison between experiment and simulation to give a complete overview about aerodynamic characteristics of delta wing.

Acknowledgments

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