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Original Research Article

Experimental Investigation of Vortical Flow Induced by Canard on a Diamond Wing Equipped with LEX

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ABSTRACT

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In this research, the effects of canard flow on a diamond wing equipped with LEX, the same as new-generation fighters, have been investigated, using a closed-circuit wind tunnel. All tests were performed at a speed of 12.5 meters per second, which is equivalent to Reynolds number 214000 based on model length. The pressure measurement is conducted by the five-hole probe, which is normalized by the dynamic pressure of the free stream velocity in four cross-sections over the wing. The results showed that at a low angle of attack, a strong vortex is produced at the leading edge of the wing, called the leading-edge vortex. As the leading-edge vortex moves downstream, the diameter of its core and distance from the wing surface increases. At higher angles of attack, LEX, canard, and body vortices are also present, which combine with the leading-edge vortex and cover a large cross-flow area over the wing. At these angles of attack, the movement of the vortical flow downstream leads to an increase in the pressure coefficient of the vortex core, which indicates the beginning of instability and vortex breakdown. The results showed that the pressure increase in the vortex core was not sudden and this results in that the breakdown phenomenon in the diamond wing equipped with LEX and canard occurs slowly.

Introduction

Predicting and understanding the flow pattern around modern fighter aircraft and Unmanned Aerial Vehicles (UAV) at moderate and high angles of attack is a key issue in increasing their efficiency and maneuverability. Today's new-generation aircraft usually have wings with a low sweep-back angle (40-60 degrees) and the general shape of their wings is diamond, lambda, or in more limited cases simple delta [1]. Compared to the simple delta wing (with the same sweep back angle), the diamond and lambda wings have deflections in the trailing-edge area, which leads to a reduction in the taper and aspect ratio of the wing [2]. Previous researchers [3] showed that such wings have higher performance, which is due to the reduction of wetted wing area and higher L/D. This issue increases the range and endurance of the aircraft in subsonic regimes [4]. Another desirable feature of diamond wings is the reduction of the radar cross-section. Due to the angled wing plates, the possibility of the waves returning to the transmitter is reduced and the stealth feature is maintained [5]. Therefore, in terms of design, aerodynamic considerations should be considered to achieve maximum performance with parameters related to reduced radar cross-section [6]. Knowing the delta wing has been the attention of researchers for years, but in the case of the diamond wing with a low sweep-back angle, the flow characteristics are different, and more limited

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information is available. To understand and analyze the flow of a diamond wing, first, the characteristics of a delta wing are investigated. The flow of a slender delta wing (sweep-back angle more than 60 degrees) with a sharp leading edge is such that the shear layer is separated from the leading edge. Then, the shear layer is rotated into the centerline of the wing and produces a coherent vortex shape [7, 8]. This vortex has a very high rotational speed in the core, which results in high-pressure suction [9]. Hence, the pressure difference between the bottom and top of the wing increases, which indicates an increment in lift force [10]. As the flow moves downstream, the vortex core diameter becomes larger. Also, it moves further away from the wing surface [11]. This allows the formation of the second vortex (secondary vortex) and even the third vortex at high angles of attack [12]. The formation of the second vortex changes the primary vortex trajectory towards the wing center line. Due to the secondary vortex separation, the main vortex trajectory is more inclined towards the center line of the wing, if the flow on the wing remains laminar [13]. Increasing the diameter of the vortex core over a certain value causes severe instability in the vortex, which is called vortex breakdown. This is associated with a dramatic reduction in lift force [14]. The vortex breakdown has several main characteristics, which include a sudden increase in the diameter of the vortex core, a sharp decrease in the axial velocity of the vortex, and the creation of a reverse flow that can affect downstream surfaces such as tails [15]. One of the important factors in the vortex breakdown is the sweep-back angle of the wing. Ekaterinaris and Schiff [16], and Wentz and Henry [17] showed that increasing the sweep-back angle of a wing leads to the delay of vortex breakdown. According to what was mentioned, the diamond wings used in the new generation aircraft have a low sweep-back angle; therefore, the vortex breakdown in such wings occurs at low angles of attack, which reduces their maneuverability. To overcome this problem, designers proposed vortex-generator surfaces. These aerodynamic objects (such as Leading-Edge Extension or LEX) generate vortices that shed towards downstream surfaces (here, the main wing), thereby reinforcing the energy in the wing boundary layer and delaying its separation [18][19]. Manshadi and Hashemi [20] showed that the use of LEX reduces the wake flow area in the last cross-section of a diamond wing by 14.2% compared to a wing without LEX, which is the reason for delaying the vortex breakdown. Shah [21] showed that a smaller LEX surface area leads to a decrease in the vortical flow-induced and the pitch-down moment of the aircraft increases. Hashemi and Manshadi [22] showed that the higher the LEX angle, the stronger the vortical flow, which is due to the larger amount of axial turbulence in the vortex core. By frequency analysis, they also found that LEX with a higher angle has a larger power spectrum density (PSD) value. Most new-generation aircraft and fighters use canard surfaces to take advantage of the strong longitudinal control and produce vortex flow at the same time. Using a canard (same as LEX) leads to the generation of vortical flow to prevent the separation of the boundary layer and the delay of vortex breakdown [23]. In this regard, many investigations have been carried out, like the work of Ghoreyshi et al. [24]. They showed that the use of canards at high angles of attack leads to a higher lift coefficient and a delay in the breakdown of the main wing vortex. Ignatyev and Khrabrov [25] showed that if the wing angle of attack is over 10 degrees, the canard increases the vertical force coefficient and reduces the pitch stability of the aircraft. Zhang et al. [26] showed that a canard with a sweep-back angle has a higher wing lift coefficient than a canard with a sweep-forward angle. The reason is the easier formation of secondary vortices on the wing. Manshadi et al. [27] showed that the canard installation position (horizontal distance) greatly affects aerodynamic efficiency and the lift-to-drag ratio of the wing. At angles of attack near the stall, the largest L/D is produced by the canard aligned with the main wing.

It can be seen that LEX and canard are two surfaces of vortex generators that can reduce wing vortex breakdown with low sweep-back angles. According to a review of studies, the effect of LEX and canard was investigated on delta and diamond wings separately. However, the effects of canard and LEX on a diamond wing similar to the new generation aircraft wing have not been performed yet, which is the novelty of this research. The present work has been done experimentally using the five-hole probe to analyze the vortical flow induced by these vortex generators. This method of research presents a new subject in the field of vortical flow knowledge, which is shown by the pressure coefficient in different cross-sections of the diamond wing and is the purpose of the research. The data adopted in this research can be a very suitable criterion for other works and complex flows with the generation of different vortices.

Experimental setup and investigated model

The model used in this research was designed by solid-work software and made by a 3D printer with high accuracy. This model includes a cylindrical body with 245 mm in length and 30 mm in diameter. According to Hashemi and Manshadi [22], the LEX angle is 16 degrees, which is located at the apex of the wing. The sweep-back angle of the diamond wing is 50 degrees, and its span and chord length are 234 and 175 mm, respectively. Two deflections with angles of 10 and 40 degrees have been made in the trailing edge, which are wing sweep-forward angles (Fig.1). The wing has a sharp edge of 45 degrees. The canard is located directly in front of the wing without horizontal distance [27]. The LEX cross-section is NACA 0012 airfoil with zero incidence angle [30] and a span length of 90 mm.

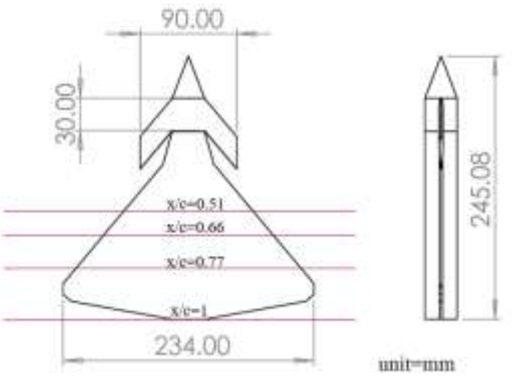


Fig. 1- Dimensions of the model used in the research.

During the tests, the model was without yaw and roll angles. Data measurement was done only from the right side of the model, due to the reduction of time and related costs. The five-hole probe was used to determine the pressure. This measurement device includes five metal tubes with a diameter of 1 mm, which are gathered together (Fig. 2).

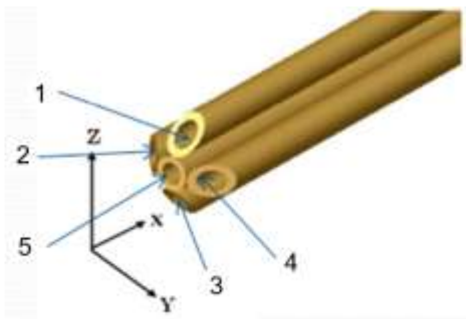


Fig. 2- Schematic of the five-hole probe numbering.

The five-hole probe needs to measure five pressure channels. For this purpose, a 15-channel pressure transducer was used. The sensors of the pressure channels device have an accuracy of ± 3 Pa that can measure the maximum pressure of ± 1270 Pa. The pressure data enters the computer using a 12-bit analog-to-digital voltage converter card. Based on the five-hole relations and similar work, the uncertainty values are shown in Table 1, the details of which are mentioned in references [28] [32].

Table 1- The uncertainties values in this research.

Parameter	Value (%)
Density (kg/m^3)	0.8
Free stream velocity (m/s)	0.4
Reynolds	0.7
Average velocity (m/s)	9
Velocity component (m/s)	9

The five-hole calibration has been performed to determine relationships between the pressures measured by the probe and the flow angles at the measurement location. These relationships are extracted as dimensionless coefficients that can be used according to flow angle. The dimensionless pressure coefficients have been determined and finally, the calibration curve obtained for the desired free stream velocity [28] [29] (Fig. 3).

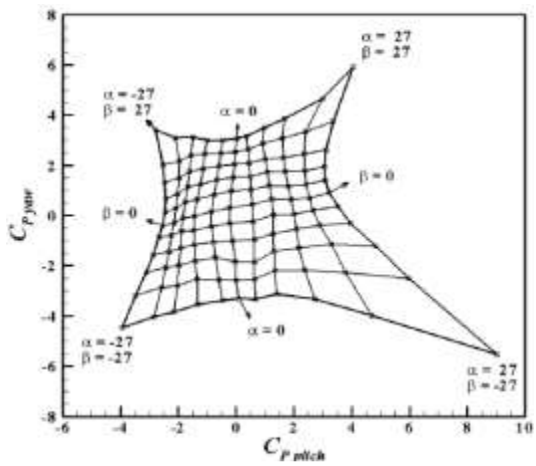


Fig. 3- Five-hole calibration curve.

The measurement cross-sections over the wing include x/c=0.51, 0.66, 0.77, 1 (Fig. 1, Table 2).

The probe is moved by a traverse device (with an accuracy of 0.01 mm) controlled by a computer.

Table 2- Test conditions

Parameter	Value
Free stream velocity	12.5 m/s
Reynolds number (based on the model length)	214000
Cross-sections	x/c=0.51, 0.66, 0.77, 1
Angles of Attack (AoA)	5-10-20 (degree)
Temperature	25°c
Dynamic viscosity	1.5×10^{-5} pa.s
Humidity	32%

All tests were conducted in the closed-circuit wind tunnel of Malek Ashtar University of Technology, Isfahan (Fig. 4). The tunnel test section has a cross-section of 270 × 380 mm2 and a length of 700 mm. The flow turbulence intensity of the tunnel has a value of less than 0.2%, which indicates the high quality of the wind tunnel [31].

To ensure the experimental results, the research model of Hashemi and Manshadi[32] has been used. For this purpose, the pressure coefficient distribution has been measured in one cross-section over a diamond wing equipped with LEX. The experimental validation performed is depicted in Fig. 5, according to which a good agreement between the data is observed.

Fig. 4- Closed-circuit wind tunnel used in the research.

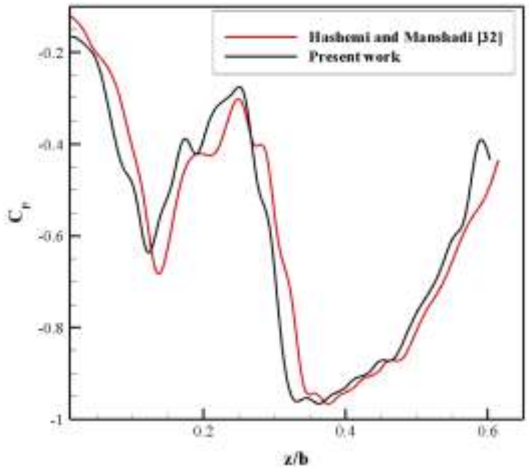


Fig. 5- The experimental validation.

Results

In this part, the results (pressure flow field) of the vortical flow on the diamond wing equipped with LEX 16° and canard by the five-hole are presented. The pressure coefficient (C_p) is normalized by the free stream dynamic pressure.

Vortical flow analyzing

The flow structure on the diamond wing with a low sweep-back angle includes flow separation due to the adverse pressure gradient. The free shear layer separated from the wing's outboard has turned towards the center line and formed a primary vortex structure. As can be seen in Fig. 6, at the x/c=0.51 cross-section, the primary vortex on the wing has induced a strong spanwise flow that has a high suction pressure in its core center. There is a complex vortex flow near the body that originates from the upstream surfaces (canard and LEX). The dominant vortex is the leading-edge (primary) vortex, which has produced a lower pressure coefficient than the canard and LEX vortex (Fig. 6). The important point is that the canard and LEX vortex have a greater distance from the wing surface than the primary vortex of the wing.

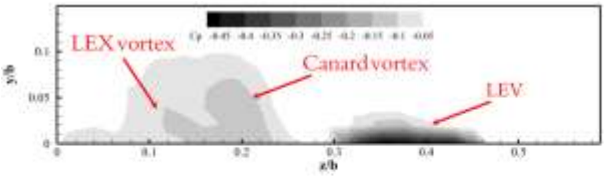


Fig. 6- Vortex flow formed on the diamond wing at x/c=0.51 cross-section (AoA=5°).

Fig. 7 shows pressure distribution over the wing at the cross-section x/c=0.51 and y/b=0.019 at the angle of attack 5 degrees. There is a substantial pressure drop at z/b=0.37 which indicates the high strength of the wing's primary vortex. The vortex strength is determined by the reduction in pressure coefficient in its core. The more significant pressure difference between over and under the wing indicates the production of more lift force [22] [32] [33]. Two vortices are observed at positions z/b=0.21 and z/b=0.13. The strength of the outer vortex is stronger than the inner vortex.

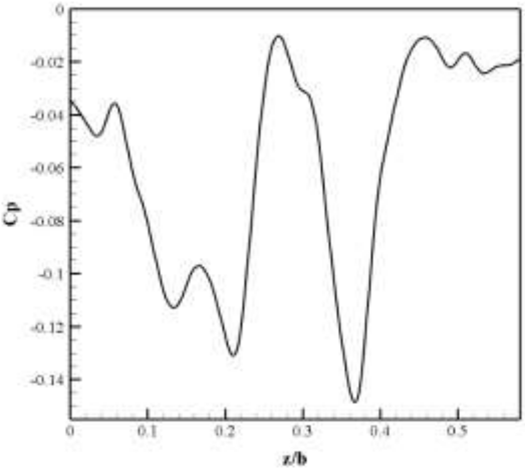


Fig. 7- Pressure distribution over the diamond wing at section x/c=0.51 and y/b=0.019 (AoA=5º).

The movement of the flow downstream leads to increasing strength of the primary vortex. Fig. 8 shows the pressure coefficient contour over the wing at the x/c=0.66 cross-section (AoA=5º). As can be seen, the vortices caused by the canard and LEX (close to the body) have merged. These vortices have created only a low-pressure area in the inboard section of the wing that has a smaller area than the previous cross-section. The dominant low-pressure area is in the outboard section of the wing and has a more substantial vortex flow that has developed toward the wing center line. It can be seen that a dual vortex structure has occurred close to the wing's leading edge (Fig. 9).

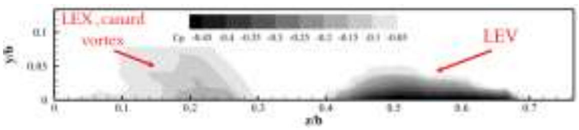


Fig. 8- Pressure coefficient contour over the diamond wing at x/c=0.66 cross-section and AoA=5°.

The dual vortex structure was shown by Gordnier and Visbal [33], and Hashemi and Manshadi [32]. Near the wing apex, a long-separated shear layer has formed a primary vortex that originates from the leading edge of the wing. The second vortex is formed near the primary vortex in the direction of rotation, which is a dual vortex structure. This vortex results from the interaction of the primary vortex and the boundary layer. When the secondary flow separates from the surface, it divides the primary shear layer into two vortices in the same direction. Comparing Fig. 7 and 9 shows that the pressure coefficient of the primary vortex has decreased and breakdown has not occurred. Fig. 10 and 11 illustrate the changes in the vertical and horizontal position of the primary vortex core. (In different cross-sections and AoA=5°). It should be noted that this position is obtained based on the lowest pressure coefficient.

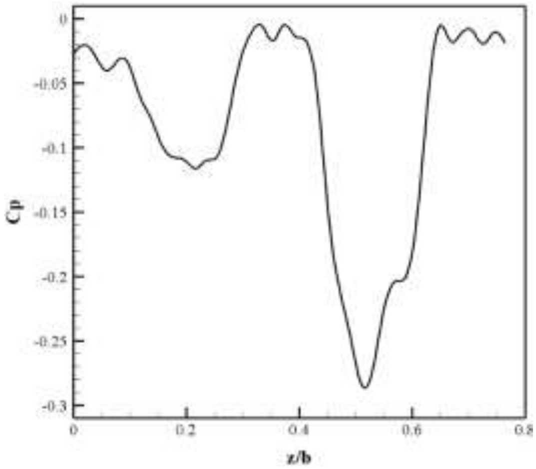


Fig. 9- Pressure distribution over the diamond wing at the cross-section x/c=0.66 and y/b=0.019 (AoA=5º).

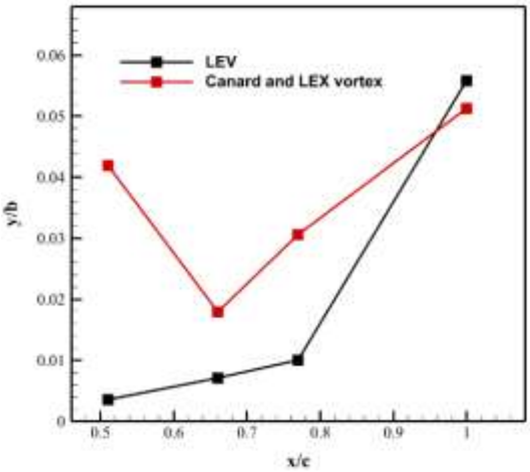


Fig. 10- The vertical distance of primary, canard, and LEX core vortices at various cross-sections (AoA=5º).

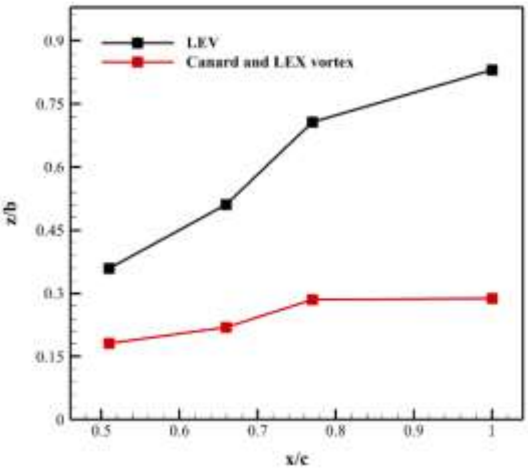
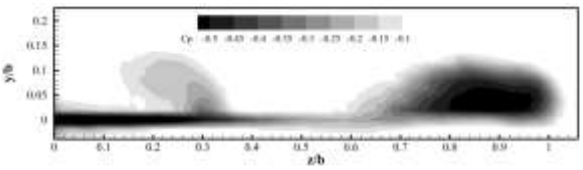
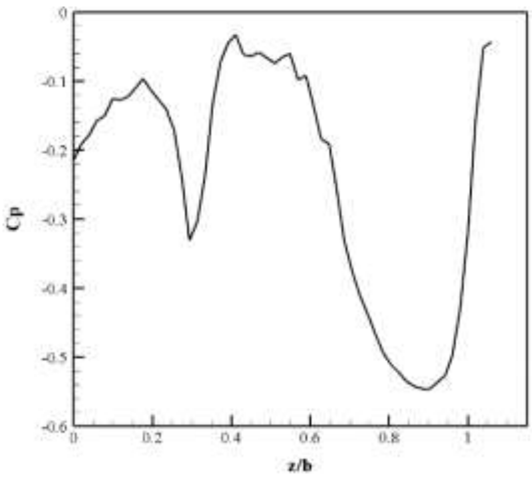


Fig. 11- The horizontal distance of primary, canard, and LEX core vortices at various cross-sections (AoA=5º).

According to Fig. 10, the canard and LEX vortices have a greater distance from the wing surface than the leading-edge vortex (at cross-section x/c=0.51). However, this value decreases at cross-section x/c=0.66 and then increases by moving downstream. The leading-edge vortex core moves further from the wing surface as it sheds downstream. The growth of vortices is slow between cross-sections x/c=0.51 to x/c=0.77, but there is a sudden increase in the x/c=1. As can be seen in Fig. 11, the movement of all vortices towards the wing trailing edge has led to an increase in the horizontal distance of the vortex core. In other words, the trajectory of the vortice core begins from the wing apex and goes downstream towards the outboard side of the wing. The horizontal distance of the LEX and canard vortices at the near trailing-edge cross-sections of the wing remains almost constant. Fig. 12 shows the pressure coefficient contour and pressure distribution (at y/b=0.019) over the wing at x/c=1.



A) Pressure coefficient contour



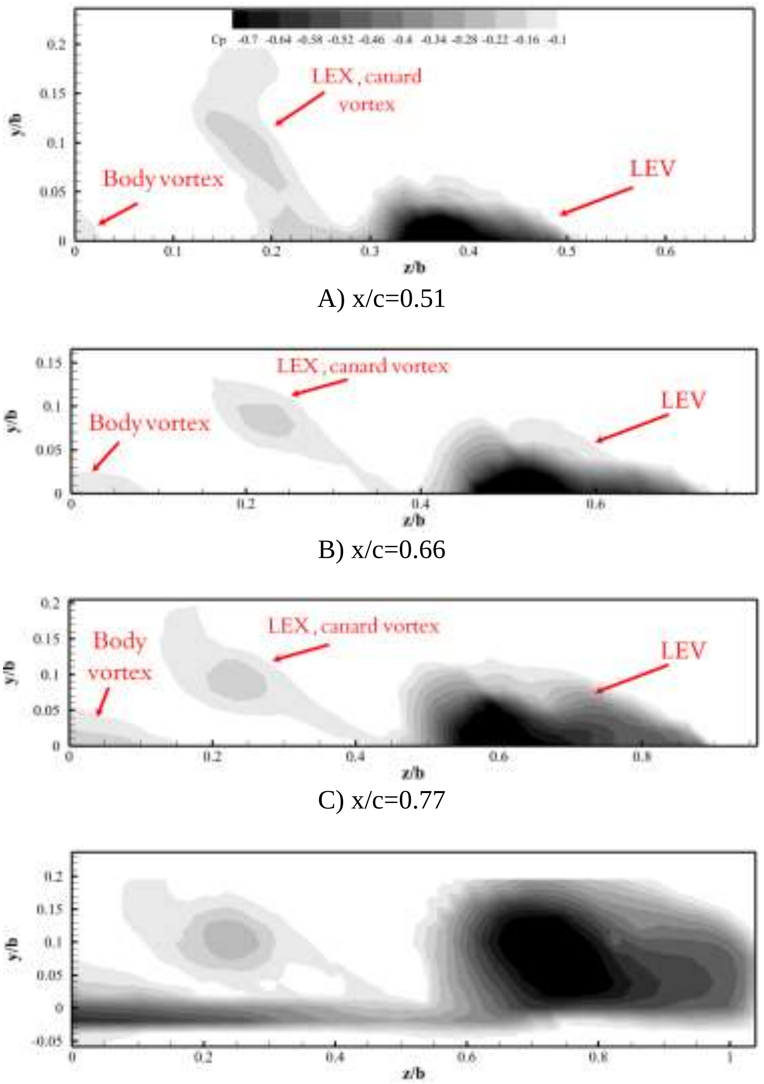
b) Pressure coefficient distribution at y/b=0.019

Fig. 12- Pressure contour and pressure coefficient distribution over the diamond wing at x/c=1 cross section and 5° angle of attack.

There is a wide low-pressure area at the tip of the wing, which also scatters a large cross-flow. Since the last cross-section is located after the forward-sweep angle in the wing trailing edge, there is a wingtip vortex that is combined with the leading-edge vortex. The combination of two vortices has increased their energy, and as a result, a significant pressure drop occurs in the core of the merged vortex compared to the previous section.

Effect of angle of attack on vortical flow and vortex breakdown

By following Fig. 13 A and 6, it is observed that at the cross-section x/c=0.51, increasing the angle of attack from 5 to 10 degrees has led to a lower pressure coefficient in the leading-edge vortex. Also, this vortex covers more area over the wing. In all cross-sections, the radius and vertical distance of the leading-edge vortex grows as the angle of attack increases. That is consistent with Nakamura and Ushimaru's research [35]. The dual vortex structure is observed at cross-sections x/c=0.66 and x/c=0.77 (Fig. 14). The pressure coefficient of this vortex is lower in the downstream sections. The dual vortex structure is combined with the leading-edge vortex (at x/c=1), with a lower pressure coefficient and more surface area. At all cross-sections, as the flow moves downstream, the pressure coefficient drops, which indicates the breakdown has not occurred. A new low-pressure area is observed near the body, which is a very weak vortex (forebody vortex) at 10-degree angles of attack. This vortex, like the leading-edge vortex, becomes stronger and covers more area by moving downstream. The dual vortex structure trajectory is also from the inboard side of the wing to the outboard side. Fig. 15 shows the pressure coefficient over the wing (AoA=20º) at the cross-section x/c=0.51. By comparing Fig. 15 and 13 A show that, the higher angle of attack leads to a reduction in the pressure coefficient of the leading-edge vortex. Increasing the suction of the leading-edge vortex and the distance of its core from the wing surface has led to the combination of the canard and leading-edge vortices. This vortex has created a low-pressure area near the inboard side of the body. According to Fig. 16, close to the body of the model (z/b=0), there is a continuity of the pressure coefficient line until reaching the leading-edge vortex, which shows the interaction between this vortex,



A) x/c=0.51
B) x/c=0.66
C) x/c=0.77
D) x/c=1

Fig. 13- The vortical flow contour from the cross-section x/c=0.51 to x/c=1 at the angle of attack of 10 degrees.

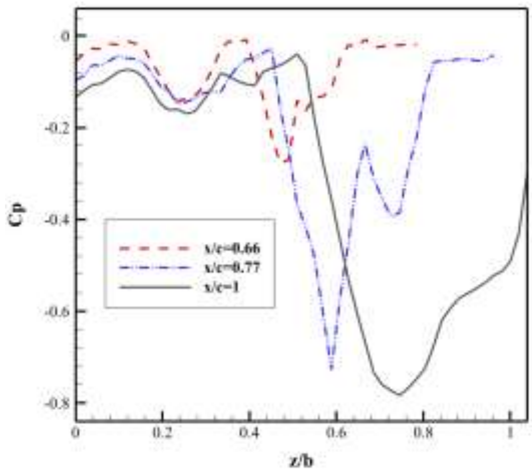


Fig. 14- Distribution of pressure coefficient in different sections (y/b=0.058 and AoA=10).

and forebody, canard, and LEX vortices. Up to x/c=0.66, the pressure coefficient decreases, but after that, this process reverses, which illustrates the vortex breakdown phenomenon. It should be noted that the breakdown did not occur suddenly, that is a characteristic of the diamond wing equipped with canard and LEX. Therefore, the vortical flow has been preserved to some extent, but its strength has been reduced slightly.

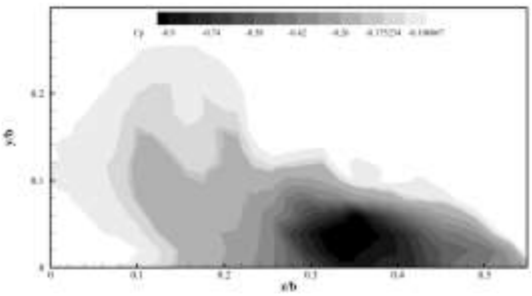


Fig. 15- Pressure coefficient contour at cross-section x/c=0.51 and AoA=20.

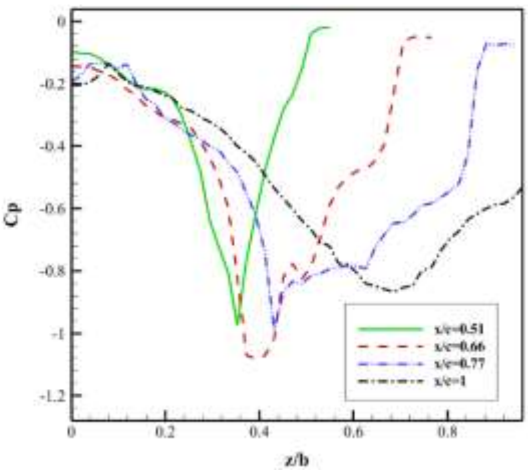


Fig. 16- Distribution of pressure coefficient in different cross-sections (y/b=0.058 and AoA=20).

Conclusion

In this research, an experimental investigation of the canard effect has been conducted on the flow pattern of a diamond wing equipped with LEX. According to the literature review, the investigation of the vortical flow induced by the canard on a low sweep-back diamond wing has not been performed, which is of interest to the present authors. The wing model has a low sweep-back angle with a leading edge that is sharp (45 degrees). The canard airfoil section is NACA 0012, which is installed in front of the main wing and LEX without any additional horizontal distance. All the tests have been performed in the closed-circuit wind tunnel at a free stream velocity of 12.5 meters per second (Reynolds number of 214000 based on the model length) and at angles of attack 5, 10, and 20 degrees. The pressure coefficient over the wing was measured by the five-hole prob at four cross-sections. The purpose of the work is to analyze the pressure of the vortex flow and the effects of increasing the angle of attack on the vortex breakdown phenomenon. The results showed that at AoA=5º, the free shear layer rotated from the pressure side to the suction side of the wing, which produced a strong spanwise flow and leading-edge vortex. At the wing apex, there were canard and LEX vortices that were located far from the wing surface compared to the leading-edge vortex. The diameter of the leading-edge vortex core has grown and has moved away from the wing surface by moving downstream. Also, the LEX and canard vortices are exposed to the strong suction of the leading-edge vortex; as a result, they are pulled toward the wing surface. At the wing trailing edge, the combination of the leading edge and the wing tip vortices has produced a strong vortical flow. A new vortex is formed near the body, called the forebody vortex, at higher angles of attack. The leading-edge vortex combined with the LEX, canard, and body vortices produced a high-pressure suction area. As the flow moves downstream, the pressure coefficient increases, which illustrates the vortex breakdown. The gradual increase in the pressure coefficient indicates that the vortex breakdown phenomenon is not sudden in the diamond wing equipped with LEX and canard.

Nomenclature

x	Streamwise coordination
y	Spanwise coordination
z	Normal coordination
Cp	Pressure coefficient
Re	Reynolds number
c	chord
b	Semi-span
AoA	Angle of Attack (degree)
LEV	Leading-edge Vortex

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