Numerical & Experimental Study of the Influence of Damage on the Aerodynamic Characteristics of Finite Wing

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ABSTRACT

In this paper the flow on a finite wing with star shape damage is numerically and experimentally investigated to understand the influences of damage on the aerodynamic characteristics of wing. To study the effects of different span positions, the damage was considered in tip, middle and root position of the wing span. The aerodynamic coefficients and their increments due to damage were extracted and the results were compared to each other and also to the results of experimental. Then flow visualizations were practiced to make evident the flow structure on the model and to help to understand the influences of each position of damage on the aerodynamic coefficients.

There was the flow through the damage which was driven by the pressure difference between the upper and lower wing surfaces. The flow could take two forms dependent on the angle of attack. The first form was a "weak-jet" which formed an attached wake and resulted in small changes in force and moment coefficients. The second form resulted from increased incidence. This was the "strong-jet" where through flow penetrated into the free stream flow with large separated wake and reverse flow. The effect on the force and moment coefficients was significant in this case. Generally comparing to an undamaged model, increasing incidence for a damaged model resulted increase loss of lift coefficient, increased drag coefficient and more negative pitching moment coefficient.

1. INTRODUCTION

Only a limited number of studies into the aerodynamics of damaged wings have been published in literature. Hayes studied the effect of damage on swept-wing airplane in 1968 [1]. In 1995 wind tunnel tests have been carried out on solid airfoil models subjected to damage simulating typical survivable gun fire type battle damage at different chord wise positions by Irwin and Render [2]. Irwin et al. in 1996 studied the aerodynamic effects and flow structure around the wings with damages on different positions of the chord [3]. Leishman et al. in 1997 studied the effect of ballistic damage on the aerodynamic of helicopter rotor airfoil [4]. In 2000, Irwin and Render studied the influence of mid-chord battle damage on the aerodynamic characteristics of two dimensional wings [5]. To assess the influence of Reynolds number, tests were carried out at two Reynolds numbers of \(2.5 \times 10^5\) and \(5 \times 10^5\). In 2005, Mani and Render studied the flow on a full span NACA 64-412 airfoil (two dimensional wing) with right triangle, inverse triangle and star shaped damaged at middle of the airfoil [6]. The results were compared to each other and also to the results of circular shaped damage from previous work.

As mentioned above limited amounts of numerical and experimental works have been conducted to study the aerodynamic effects of damage to wings. Besides in the researches have been already done up to now the effects of very simple forms of damages, the damage on infinitive airfoils and high speed flows have been considered, while examinations into low-speed characteristics on wing have failed to explain the aerodynamic effects. Therefore in this paper to achieve the real shape of damages and to study the influence of sharp corners of damage, low-speed flow on a wing with star shape damage was numerically and experimentally investigated. The results of qualitative and quantitative investigations into aerodynamic characteristics of the damaged wing are presented and are compared to the experimental results.
2. Computational Methodologies

This study is undertaken using Fluent software as a tool to predict the flow field around the body which uses a cell-centered finite volume method and has been proven to work well for different flow regimes [7]. To investigate the flow field, the Navier-Stokes equations are modeled by using Pressure-based method. The SIMPLE algorithm with under-relaxation coefficients is used in the overall discretization of the equations. The flow considered here is three-dimensional, stationary, viscous, and turbulent in which the RNG standard model has been used for turbulence modeling. To accommodate accurate turbulence modeling, the standard wall functions are selected. A first order accurate method is computed to establish the flow. A second order accurate method is computed to achieve the convergence of the solution.

The wing models of studies are a section of NACA 641-412 [8] with 200mm chord and 800mm span. The damage is star shape to study of the sharp corners. Two equilateral triangles with 54mm in length of side [9] were combined to form a star shape which has the most realistic approximation to the shape of real battle damage. The geometric center of the damage set at 150mm, 450mm and 650mm from the bottom of the span which named root, middle and tip positions of the span respectively. The damages were chosen in least complication with location on mid chord only, entry and exit holes identical shape through the wing and normal to the chord. Geometry of the damaged wing model and numerical simulation domain are shown in Fig. 1 and 2.

The entire solution domain is discretized by an unstructured grid of tetrahedral and wedge cells. The grid study has been done. A trade off between computation time and quality of result led to a grid with finer mesh near to solid surface and coarser mesh adjacent to inlet and outlet boundaries. The total number of cells is about 2,100,000 cells for clean wing and 2,350,000 cells for damaged wing. Fig. 3 shows the quality of the unstructured grid adjacent to the wing surface and inside of the damage. For evaluating the quality of the unstructured grid adjacent to the wing surface, the values of Y+ at the first of wall nodes were calculated. It was shown that most of them have the values more than 30 except for a negligible number of the grids.

Three types of boundary conditions were used: wall, velocity inlet and, pressure outlet. In this paper wind tunnel was simulated. The length of width and height were considered the same size of the test section of the wind tunnel in experimental arrangement, Fig. 2. To study of tip vortex and damage vortices interaction, there is space between tip of wing and wall.

The fluid is air. The flow velocity is 40 m/s, the temperature is 290K, the turbulence intensity is 0.15%, which relates to the experimental test condition of the model that here is numerically investigated. The characteristic length scale (the length of chord) is 0.2 m, and the operating pressure is 101325Pa.
3. DISCUSSION AND RESULTS

Flow visualization and force measurement of the numerical flow simulation for any span position of the damage are presented. A comparison between numerical and experimental results for middle damage is done to validate the numerical model.

3.1 Flow visualizations at low and high angle of attack

Because of the pressure difference between upper and lower surfaces of the wing, the flow passes through the damage. The flow through the damage is formed in two types and is dependent on the angle of attack. The types are called by the names "weak-jet" and "strong-jet" that in references [5, 6 and 9] also identified.

Fig. 4 is a picture of upper view of damaged wing in \( \alpha = 0^\circ \) from experiment. In this case damage is placed at middle position of the span and it can be compared with numerical results Fig. 5. In this figure there is a weak primary separation in front of the damage (1). In addition small vortices behind the rear apexes signify one jet which exits from the rear part of the hole (2), as it is evident from the Fig. 6 in numerical result.

The vortices at this incidence are fairly weak, but their presence is confirmed by the region of reverse flow located between them as it is evident in Fig. 4 & 5.

In this angle of attack, flow shows the characteristics of "weak-jet" that the flow exited at the rear part of the hole and immediately bent over and attached to the upper surface, forming a wake, as shown in Fig. 6.

As the angle of attack is increased, the pressure differential increase too and results "strong-jet", with more significant effects on the flow over the wing. This is illustrated by Fig. 7, 8 & 9.

The primary separation due to damage occurs in the front of damage (1) and the secondary separation due to out coming flow from rear part of the damage is located near the two rear side apexes of the star (2). The flow is continued after damage and entrained into the big vortices (3). These two big vortices are formed by reverse flow from under side of the model (4) and direct flow over the model upon meeting the damage jet. This reverse flow separates (5) and is entrained into the jet. The width of the jet is indicated by the two small vortices behind the two rear side apexes of the star that are produced by the out coming flow (6).

The main characteristic of this damage is interpreted by the reality that the jet flow has penetrated more deeply the external flow and entrains the reverse flow (4) as shown in Fig. 7 & 8.

All of these phenomena are causing a separated region to appear. This region existed between the jet and upper wing surface, extending from immediately behind the damage to the trailing edge as shown in Fig. 9. This is the characteristic of a "strong-jet".

3.2 Flow Visualisation on damage in different span positions

Fig. 10 & 11 are shown to study the effects of different span positions of damage. It can be seen that contra rotating vortices behind the damage are not symmetric at tip position in Fig. 10 as compared with the middle and root positions of the span in Fig. 7 and 11.

Fig. 10 is the picture of path lines colored by velocity magnitude of the damaged wing at 6 degrees incidence in the tip position of the span. The lower side of figure is pointing toward the wing tip. The Pressure difference between upper and lower surfaces of wing forms the tip vortices and the spanwise secondary flow which prevent typical extension of vortices on wing's upper surface. Both of the large vortices behind the damage can be recognized with the differences existed between the shapes of the vortices. The vortex in near the wing tip is different as compared to the other vortex. The flow behind the damage in tip position is affected by the tip vortices of the wing and interacts with the spanwise secondary flow, so one side of flow behind the damage has a different reverse flow and vortex strength. Therefore the vortex at the tip side deviates and trends to root side of the wing and forms asymmetrical contra rotating vortices.
Figure 4. Experimental result of star damaged wing at $\alpha=0^\circ$.

Figure 5. Numerical result, upper view of path lines colored by velocity magnitude $\alpha=0^\circ$.

Figure 6. Numerical result, side view of path lines colored by velocity magnitude $\alpha=0^\circ$.

Figure 7. Experimental result of star damaged wing at $\alpha=6^\circ$.

Figure 8. Numerical result, upper view of path lines colored by velocity magnitude $\alpha=6^\circ$.

Figure 9. Numerical result, side view of path lines colored by velocity magnitude $\alpha=6^\circ$.
Since the spanwise pressure distribution is nearly elliptical and the amount of the pressure difference between upper and lower surfaces adjacent to wing tip is less than the middle and root positions of the wing, the strength of jet in tip damage is less than the middle and root positions of the wing. So the vortex at the tip side deviates and trends to root side under effects of the tip vortices and spanwise secondary flow.

3.3 Force and moment coefficients

A general study of the principle aerodynamic coefficients showed that at any span position of the damage, the coefficient of lift decreased and the coefficient of drag increased. The presence of damage produced more dive pitching moment.

For a better understanding of the influence of damage on the aerodynamic characteristics, the change of each aerodynamic coefficient at each incidence for any position of damage was defined as:

\[
\begin{align*}
    dC_l &= (C_l)_{\text{damaged}} - (C_l)_{\text{undamaged}} \\
    dC_d &= (C_d)_{\text{damaged}} - (C_d)_{\text{undamaged}} \\
    dC_m &= (C_m)_{\text{damaged}} - (C_m)_{\text{undamaged}}
\end{align*}
\]

Fig. 12, 13 & 14 represent the aerodynamic coefficients increments due to any span positions of the damage. Up to 2 degrees incidence, small increments were seen. This corresponded with the incidence rang identified for the "weak-jet" characteristics with minimal flow disruption and the damage jet remaining attached to the wing surface such as the flow could be seen on the undamaged wing.

It can be seen that increasing jet strength with incidence to 6 degrees results in increased loss of lift coefficient, increased drag coefficient and more negative pitching moment coefficient increments because "strong-jet" was observed on the wing surface. Associated with this form of jet, there were more effects on the flow. Generally, increasing the incidence of a wing, results in a greater pressure difference between upper and lower surfaces of the wing so that in presence of the damage it is likely to have a larger through flow and more influence on the lift coefficient as shown in figure 12.

In Fig. 13, the rate of change of \(dC_d\) changed dramatically from 2 to 6 degrees of incidence for all positions. The part of the flow through the damage circulated within the wing internal box cavity before emerging through the exit hole. In doing so, its momentum change would have resulted in a positive pressure increment on the surfaces of the internal structure. Increased angle of attack resulted in increased internal flow, giving increased internal pressure drag, and hence increased drag coefficient.

As can be seen in Fig. 12, 13 & 14, the damage in different span positions has different effects on aerodynamic characteristic, because the different span position of the damage affects the pressure distribution in different ways. It can be seen that the tip damage is less effective than the other positions.
Since the spanwise pressure distribution is nearly elliptical and the amount of the pressure difference between upper and lower surfaces adjacent to wing tip is less than the middle and root positions of the wing, the strength of jet in tip damage is decreased. So that the damage in tip position of the wing has less effect on aerodynamic coefficient increments as compared with the damages in the root and middle positions.

4. COMPARISON OF NUMERICAL RESULTS WITH EXPERIMENTAL DATA

Fig. 15 represents the lift coefficient increments against the incidence for damaged wing with a comparison between numerical and experimental results. Uncertainty and repeatability for both damaged and undamaged wing were determined and they were $dC_l = \pm 0.009$, $dC_d = \pm 0.0007$ and $dC_m = \pm 0.0007$.

There is a good agreement between numerical and experimental results at 2 and 6 degree incidences but some differences are existed between the results at lower incidences. This may be the result of turbulence model or the assumption that the whole flow is turbulent. As we know in real flows there is always a laminar region before the transition to turbulence. This deflection in numerical modeling can be the cause of these differences especially in lower incidences that this laminar region has more extension on the wing's surface. On the other hand the turbulent models have their own characteristics and it is known that there is no universally accepted model that can be used for all flow regimes.

5. CONCLUSION

1) The flow through the damage was formed in two types and was dependent on the angle of attack at all three positions of the damage. These types are called "weak-jet" and "strong-jet".
2) For the damage in middle position of the span, the large contra rotating vortices behind the damage were formed symmetrically.

3) The Study of the effects for different span positions showed that the damage in tip position, compared to the middle and root, made the asymmetric large contra rotating vortices behind the damage so that one side of flow behind the damage has a different reverse flow and vortex strength.

4) Since the spanwise pressure distribution is nearly elliptical, more pressure difference between upper and lower surfaces of the wing in root position produced the strong jet as compared with the tip damage. So the jet flow is less affected by the interaction between boundary layer of the wall and the boundary layer of wing surface and forms as symmetric vortices.

5) The large vortices behind the damage at tip position were affected by the tip vortex and the secondary spanwise flow to form an asymmetrical view with a tendency to root.

6) Increasing the incidence resulted, generally, in greater lift loss, higher drag and more negative pitching moment at any position of the damage. The effects of three dimensional flows and the lack of symmetry in the forms of large vortices were clearer in higher incidence.

REFERENCES


