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The Influence of Battle Damage on the Aerodynamic Characteristics of a Model of an Aircraft

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Abstract: - We are here interested by the aerodynamics of battle damaged wings. In the tactical schemes of modern air conflicts, where the aircraft is subject to anti-aircraft hits, the frequency of operations is very high. Therefore, the battle damaged aircraft will have to be repaired rapidly to meet operational requirements within the time constraints imposed by the operational situation. Damage assessment, the study of losses of performance, and both the choice and application of adequate repairs belong to a vast program of study.
The first part of the present study deals with the influence of the simulated gunfire damage on the aerodynamic performance of the aircraft model. An experimental study with visualizations by smoke is carried out in the subsonic wind tunnel at the Polytechnic school (Algiers - Algeria).
The first results showed a degradation of the aerodynamic coefficients attributed to through flow penetration through the hole which disturbed the pressure field, increased the wake area, generated a form drag in addition to the pressure drag created by the presence of the hole internal surface. This loss of performance is a function of the hole diameter, spanwise position, and chordwise position.

Key-Words: Battle–damage, weak-jet, strong-jet, fineness, pressure drag, form drag, lift coefficient.

1 Introduction

The design and manufacturing of military aircrafts are affected not only by their ability to perform specified missions but also by the environment in which they perform their missions. The military aircraft is assumed to operate in a hostile environment, i.e. an environment with various operational anti – aircraft threats. As a result, the aircraft should be capable of sustaining some kind of battle damage. As a result of this, survivability is becoming one of the key aircraft design requirements. Survivability of an aircraft is dependant upon its vulnerability to damage caused by a variety of threats.

The vulnerability assessments generally tend to concentrate only on the structural integrity (reinforcement of the equipment, protection of the vital components... etc).

The aerodynamic integrity is of foremost importance for the continuous operation of an aircraft and should be a key requirement for the full assessment of vulnerability. Few detailed investigations of the aerodynamic effects of damage on the structure and particularly the wings have been carried out [1]. Published works to date are rare and focus mainly on two-dimensional wings [1, 2].

In this work, we are interested in a full aircraft configuration (light airplane model). We perform simulations of the damages and we present effects of those damages on the aerodynamic performances of the damaged model.

2 Damage Modeling

In view of the large number of variables involved in shooting damage, the damage range that can affect an airplane is wide. However, for the purpose of studying the effects of a damage, it is necessary to reduce the number of damage forms to a smaller representative number of damages so as to cut down experiment costs. In this study, we consider that the damage is located on the wings, which are from the aerodynamic point of view, the most critical components of the airplane.

The most common type of damage used in simulations is the circular hole [3]. The study of other shapes has not shown noticeable differences [4]. Damage size can be expressed in terms of a percentage ‘diameter to chord length’. When selecting a realistic range of gunfire damage sizes for the model, the structural strength of the wind tunnel models were also considered. The range of damage sizes was defined as going from 10%c to

40%c in 10%c increments [5].

In this study, three diameters are considered, 20%c, 30%c and 40%c. Given the nature of the gunfire threat, the wing may be damaged at any point along its chord and its span on either a half wing or a complete wing. Three locations along the span are considered: tip of the wing, fuselage, and midway locations. Along the chord, four locations are considered: leading edge, quarter of the chord, mid-chord, and trailing edge.

We only considered wings damaged at the chord quarter and at mid-chord since they are the most sensitive locations to damage [1]. For symmetry reasons, the present study analyses the damage on a full wing. A comparison with the damage of a half wing is presented.

3 Experimental Program

The experiments are carried out in the 0.6 m subsonic wind tunnel of the Fluid Mechanics Laboratory at Polytechnic school of Algiers. This is an open-section, closed return wind tunnel with a pipe diameter of 0.6 m with a maximum velocity of 48 m/s. Due to wind tunnel size it was decided to build the model 20 times smaller than full scale [6]. The shape, dimensions, and profiles of the airplane parts were designed according to aerodynamic and structural constraints. The model was fully made of aluminium on a four-axis numerically-controlled machine. The Wing was rectangular with a profile NACA 23018 at the root, NACA 23012 at the tip, with a taper ratio $\lambda = 0.5$, and without twist. The horizontal tail was also rectangular with a profile NACA 0012 along the span without dihedral. The same profile was used for the vertical tail (Fig.1).

For a maximum velocity of 48 m/s, The Reynolds number based on the wing mean chord was $1.73X10^5$. Although this Re is much smaller than the full scale cruise value ($3.9X10^6$), it is still not below the critical values and the understanding of the flow behaviour and damage influence could be obtained. The model was mounted, via three struts, to a three-component balance (fig.2). The balance had a nominal accuracy of 0.05% on each component. The acquisition system gives repeatability of C_L to within 0.005, C_D to 0.002 and C_m to 0.002. The incidence is manually adjusted over the range [-20°, +40°]. The adjustment and the calibration of the balance are carried out according to well defined steps. Measurements are taken using three dynamometers whose electric signals are transmitted to the rack of measurement.

The values of the aerodynamic efforts are related directly to the values of the readers given in Newton on the indicators of the rack of measurement by suitable formulas.

Fig.1 : Model and its damages

Since an open working section tunnel is being used, there is no need for tunnel corrections [7]. And to contribute to the comprehension and the interpretation of the quantitative results, we use smoke through the damage to visualize the shape of the jet.

Fig.2 : Experimental setup

4 Undamaged state

In order to validate the experimental setup, preliminary tests were carried with the undamaged model. The results obtained were found to agree reasonably well with those found in the literature.

For instance, the lift coefficient reaches a maximum value of 0.983 for an angle of stall of 14°, which is considered a reasonable value for this type of profile (thin) at the corresponding Reynolds number ($3.9X10^6$) [8, 9]. Also, α_{ZL} the angle of zero lift is close to -2.5°, which is consistent with a non symmetric profile. The coefficient of drag reaches a minimal value $C_{Dmin} = 0.05027$ for the angle 0°.

The airplane drag coefficient C_D at C_{Lmax} is needed for takeoff and landing calculations. Varying widely, depending on the type of airplane and amount of flap, this coefficient may range from 0.1 to 0.5 [8]. For the model under study, the C_D at C_{Lmax} is 0.136. The interval of the values of C_D is between 0.108 and 0.264. They are normal values for a model of aircraft [8, 10]. The best flying conditions are obtained when the ratio C_L/C_D called fineness is maximal. The maximum value of the fineness, which is close to 11, is obtained for an angle of attack of 8°. This value is in the expected range for this type of aircraft [11] for an aspect ratio value AR = 9.478 [6]. The experimental value found is very close to the estimated value $(L/D)_{max} = 12$ in the conceptual design of the model [6].

5 Damaged State

The undamaged model was damaged by machining the wing with a circular hole normal to the chord.

Few data on the aerodynamic influence of the damage are available in the literature. To study this influence, we consider the case of a 40%c diameter damage located at the full wing mean aerodynamic chord. The hole is at the center of the mean chord profile.

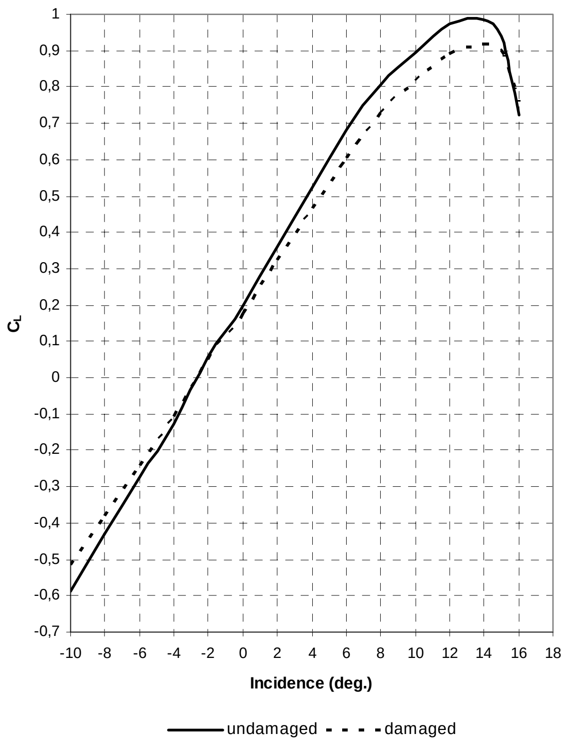

Fig.3 : Damage influence on C_L

Fig.3 presents a decrease in the value of C_{Lmax} and a reduction in the slope of lift. The angle of stall and the angle of zero lift remain unchanged.Over the incidence interval range, the damage increases the drag coefficient, while above the stall angle the tendency is reversed (fig. 4). Consequently, this results in a considerable loss in fineness (fig.5).

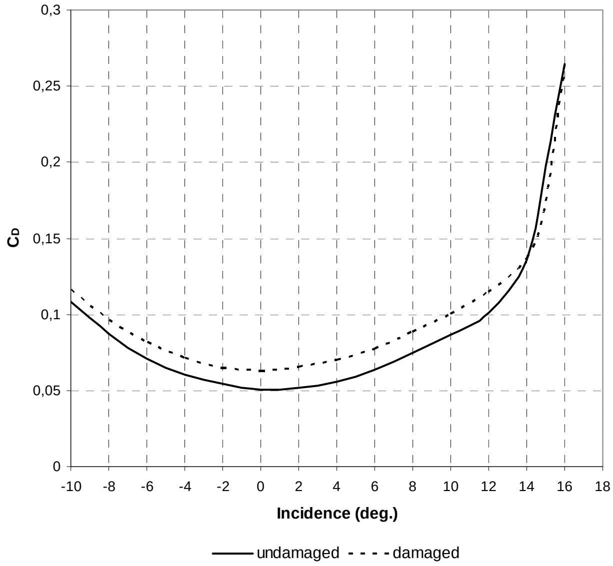

Fig.4 : Damage influence on C_D

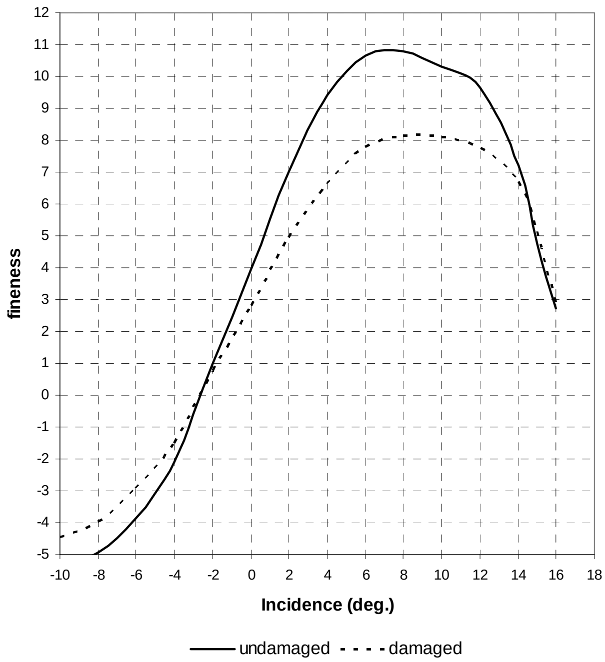

Fig.5 : Damage influence on C_L/C_D

For a more detailed understanding of the influence of damage, the results for the damaged model are presented as changes in coefficients, dC_L and dC_D, where:

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$$dC_L = C_{L_{damaged}} - C_{L_{undamaged}} \quad (1)$$

$$dC_D = C_{D_{damaged}} - C_{D_{undamaged}} \quad (2)$$

Fig.6 shows a reduction in the amplitude of C_L over the entire range of attack angle considered, i.e. dC_L is negative in the interval of positive lift and positive in the interval of negative lift. This reduction in C_L is due to the hole through flow which affects the distribution of pressure at the upper surface.

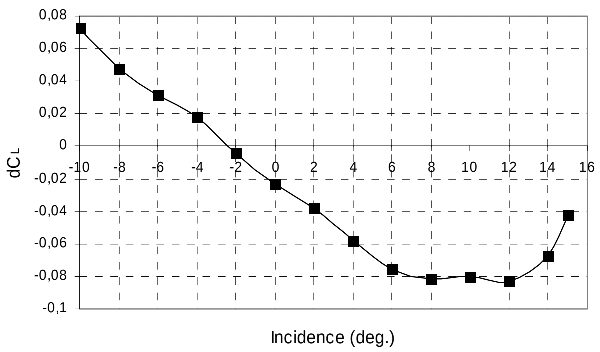

Fig.6 : Lift changes due to Damage

This lift loss is also caused by the decrease of the lifting area due to the physical removal of a portion of the wing.

The shape of the through flow penetrating jet varies with the angle of incidence. At the angle of zero lift α_{ZL} = -2.5°, there are no losses. Indeed for this angle, there is no through flow as confirmed by smoke visualization. In our experiments we have confirmed the existence of through flow for 0° angle. Above this value and for all the attack angle range corresponding to positive lift, the direction of the flow is bottom to top. By generating a negative lift, the direction of the flow is reversed.

The jet penetrating by the hole takes two different forms. The first form is a 'weak-jet' which form an attached wake for small incidence angles (<4°) and the second form is a 'strong-jet' which form a separated wake for higher attack angles (>5°). This terminology is adopted from investigations into "jets-in-cross flow" [1].

Fig.7 shows an increase of the C_D over most of the incidence range except close to the stall angle where part of the jet goes through the hole. There are two mechanisms for the drag increase. For small angles of incidence, the attached jet increases friction drag while for higher angles of incidence, the strong jet forms a separated wake which increases form drag. An additional pressure drag is produced by the damaged hole which creates a positive pressure increment on the wing internal surface.

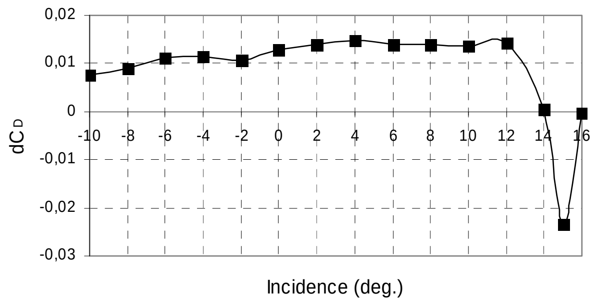

Fig.7 : Drag changes due to Damage

5.1 Effect of damage diameter

Three hole diameters, 20%c, 30%c, and 40%c, are considered in the present study. The hole center is located at mid-chord and in the area near the fuselage (root-region).

Fig.8 shows lift increments dC_L against incidence for three values of the diameter. Over the positive incidence range (α > -2.5°), an increase of the hole size results in a decrease of the lift coefficient. This is expected because a larger damage size allows a greater through flow, and perturbs even more the pressure distribution at the upper surface. Increasing the hole diameter changes the jet shape from weak-jet to strong-jet. This is accompanied by an increase of the lift loss rate (slope of the curve) [point X].

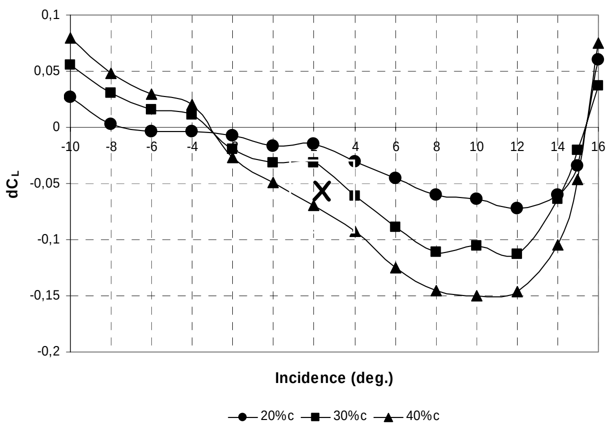

Fig.8 : Diameter influence on C_L

Fig.9 indicates that the drag increases with hole diameter over the entire incidence range. Indeed, an increase of the diameter increases the wake area size.

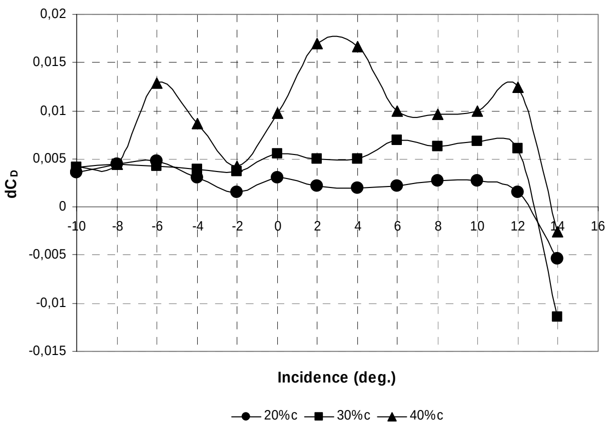

Fig.9 : Diameter influence on C_D

Fig.9 shows that the magnitude of the wavy curves increases with the hole diameter. This 'waviness' may be in part due to the underlying flow mechanisms. From these observations, it seems logical that the fineness falls with the increase of damage diameter (fig.10).

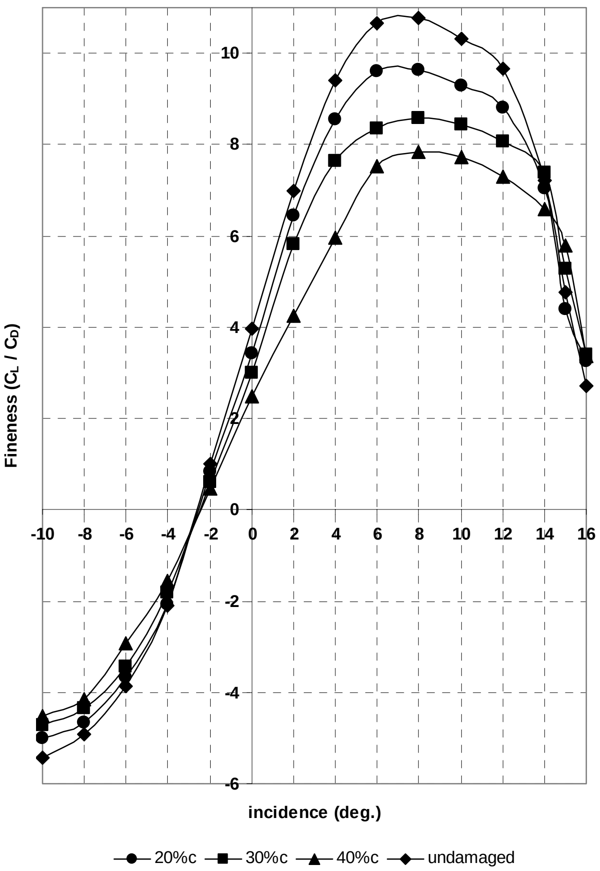

Fig.10 : Diameter influence on Fineness

As a comparison, tables 1 and 2 provide the percentages of both lift loss and drag increase respectively. Three diameters are considered.

Case	C_{Lmax}	dC_{Lmax}	percentage
Undamaged	0.983	-	-
20%c Damage	0.955	-0.034	3.5 %
30%c Damage	0.920	-0.069	7.01 %
40%c Damage	0.916	-0.083	8.44 %

Table 1 : percentage of lift loss

Case	C_{Dmin}	dC_{Dmin}	percentage
Undamaged	0.0502	-	-
20%c Damage	0.0516	0.0021	4.06 %
30%c Damage	0.0538	0.0036	6.69 %
40%c Damage	0.0631	0.0064	10.14 %

Table 2 : percentage of drag increase

According to the tables, the drag is strongly affected by the presence of damage.

5.2 Spanwise influence of damage

Here we compare the results from three damages of the same size (40%c) with center at mid-chord but located at three different wing spanwise locations: tip, mean aerodynamic chord, and root.

The results show that the lift loss is minimal at the tip and increases towards the root (fig.11). Indeed, it is well known that the lift distribution is elliptic with maximum at the symmetry axis of the fuselage. Therefore, a perturbation will have more effect near the fuselage.

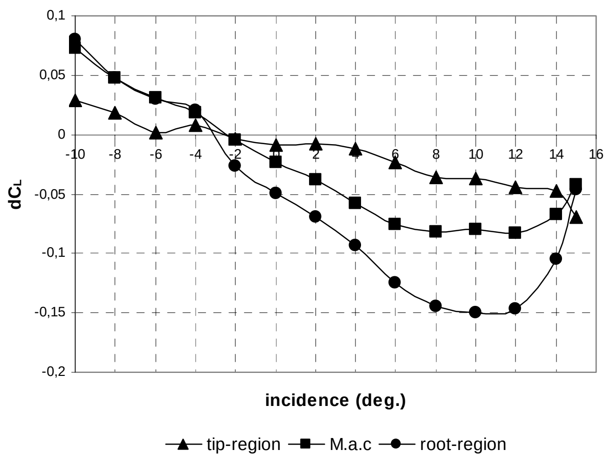

Fig.11 : Spanwise influence of damage on C_L

Fig.12 represents the drag coefficient increments against incidence for the three damage locations considered. The drag increase is negligible at the tip region. It is even smaller for smaller diameters (20%c and 30%c). The drag increases towards the root-region.

The same waviness trend of the curve is visible for damage at the root region. For this location, the flow mechanisms are very disturbed by the wing-body aerodynamic interference.

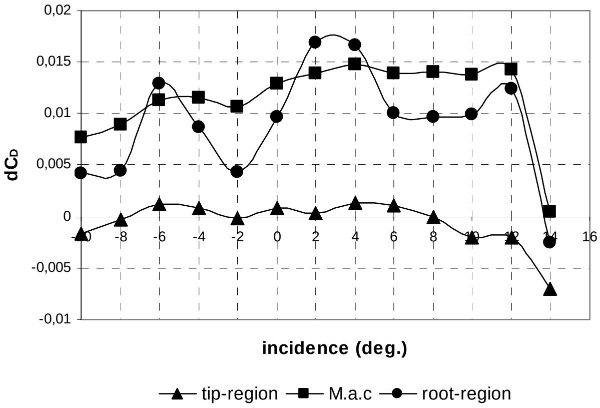

Fig.12 : Spanwise influence of damage on C_D

5.3 Chordwise influence of damage

In this section, we compare the effects of the damage located at quarter chord with the damage located at mid-chord, for all diameters and localisations. We take the example of a damage of diameter 40%c located at the root region.

Fig.13 shows the lift changes dC_L for the two cases. Lift loss for the quarter chord damage is higher than the mid-chord damage. This is expected because when we approach the leading edge, the suction pressure on the upper surface is strongly reduced affecting consequently the lift coefficient.

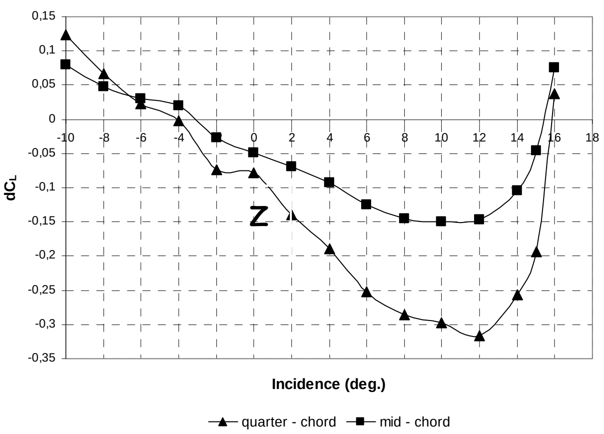

Fig.13 : Chordwise influence of damage on C_L

For the angles of positive incidence, the slope is accentuated in the case of the damage located at the quarter-chord (point Z). The visualisation showed that these significant changes in coefficient values coincided with the transition from weak to strong jet. Fig.14 compare the increase in drag for the quarter chord and mid -chord.

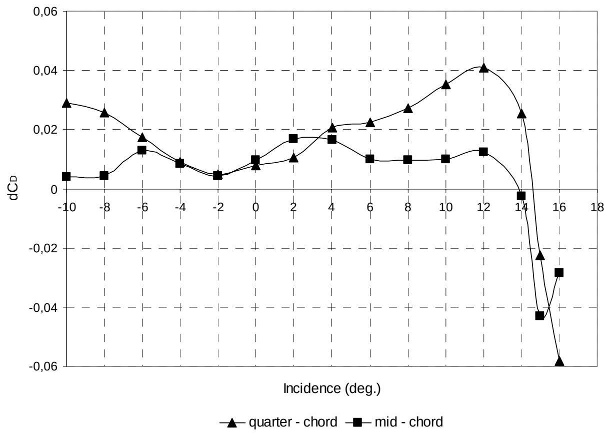

Fig.14 : Comparison between quarter-chord and mid-chord

The drag increase is higher for the quarter chord damage, where the chord wise extent of the wake is greater than seen for the mid-chord. The same tendencies are obtained for the other holes diameters (20%c, 30%c) and the other locations (M.a.c, tip).

5.4 Comparison of damage influence between full wing and half wing

Given the nature of the gunfire threat, the wing may be damaged on either a half wing or a complete wing. In this section, the results for a damaged half wing are compared with those for a symmetrically damaged full wing. We consider the case of a 40%c diameter damage located at mid-chord and in the root region.

Fig.15 represents the lift coefficient increments for the two cases. For the angles of positive incidence ($-2.5° < \alpha \leq 14°$), the loss of lift coefficient in full wing damage is higher than the half wing case. The presence of two holes in the wing means a larger through flow, more disturbed pressure field and thus more adverse influence on the lift.

It is worth mentioning that a single damage (only one half-wing) generates a roll moment due to lift-forces imbalance. This may be the source of a lateral instability. Moreover this roll moment increases with incidence angle. A six component balance would be required in order to estimate this roll moment.

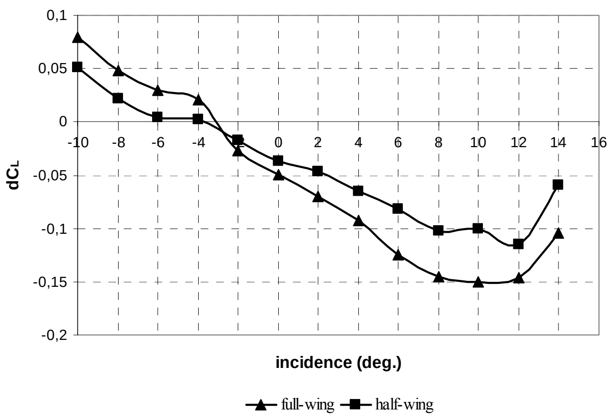

Fig.15 : Damage effect on Lift ; comparison between full wing and half wing

Also shown in fig.16 are the drag coefficient increments for both full wing damage and half wing damage. Over the entire incidence range, the drag increase in full wing damage is higher than the half wing case. More form drag and pressure drag are created by the presence of the two holes.

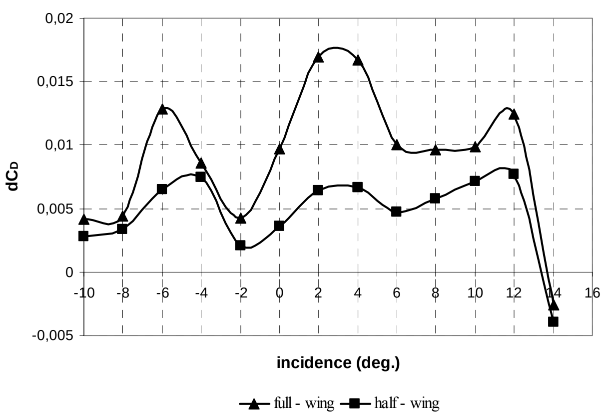

Fig.16 : Damage effect on Drag ; comparison between full wing and half wing

4 Conclusion

The presence of damage decreases the lift and produces more drag. Consequently, there is a loss in the aerodynamic performance of the aircraft.

This influence on aerodynamic coefficients can be attributed to through flow through the hole which creates a pressure field disruption. This through flow driven by the pressure differential between the upper and lower wing surface increases the wake area thus the friction and the form drag. An additional pressure drag is produced by the damaged hole which creates a positive pressure increment on the wing internal surface.

The effect on force coefficients increases with the type of the jet which is function of the angle of incidence and the diameter of the damage hole.

This study has shown that loss of performance increases when the damage size increases and when the damage location moves towards either the fuselage or the leading edge.

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