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A Review on Methods Used for Estimation of Aerodynamic of Damaged Aircraft

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Abstract

In this study a comprehensive review on methods used by aerospace researchers for the estimation of aerodynamic data for aircraft that sustained damage are illustrated. Design of flight control laws, verification of performance predictions, and the implementation of flight simulations are tasks that require a mathematical model of the aircraft dynamics. The importance of study of damaged aircraft aerodynamic is to generate a good aircraft model to account for various damage effects including the changes in aerodynamic, mass and centre of gravity shift. All aspects of damage are important and minor damage from structural viewpoint may be major damage from a flight dynamic viewpoint. The review mainly focused on: wind tunnels investigations and simulation codes.

Keywords: Aerodynamic, Damaged aircraft, Wind tunnels.

1. Introduction

The control of aircraft has been of paramount concern since the beginning of flight. The dynamic models are characterized by coefficients (aerodynamic derivatives) whose values must be determined from wind tunnels and computational fluid dynamics. To generate a good aircraft model, it is important to have a good estimate of the aerodynamic parameters that closely represents the characteristics of the actual aircraft. In damage events, significant portion of the aircraft's aerodynamic lifting surface may become separated or damage to the aircraft's frame as shown in figure (1), and as a result these may cause the aircraft unstable due to the change of flight envelope.

A flight dynamics model of damaged aircraft is important to develop to account for various damage effects including the changes in aerodynamics, mass, inertia and centre of gravity shift. Understanding the aircraft aerodynamics characteristics during a damage event is critical to developing flight control strategies for stability recovery of damaged aircraft.

Figure1: Wing and horizontal stabilizer damage. [1]

When the aircraft is damaged then several problems may arise and answers are required to questions such as:

a. Can the aircraft complete a mission if it is damaged in a given way?
b. Can aircraft take off again but with reduced capability?
c. Is it safe for the aircraft to take off and fly to another location to be repaired?
d. Will the damage cause the loss of the aircraft?

2. Investigation methods

To know the damage effect on aircraft's flying capabilities the wind tunnels investigations and simulation codes are carried out to calculate the new aerodynamic and stability derivatives so as to design a proper reconfigurable flight control system.

2.1 Wind tunnels investigations:

Hayes [2] at Langley Research Centre on 1968 conducted investigations in a supersonic wind tunnel to determine the effects of simulated wing damage on the static aerodynamic characteristics of a swept wing aircraft model as in figure (2).His model is an ogive-cylinder fuselage with a mid-swept wing and slap vertical tail. Damage was simulated by removing the leading edge section of a wing, the trailing edge section or the complete wing. Removal of the leading edge resulted in an 11% reduction of the total wing area and the lift curve slope is decreased by 10%. However, the lift curve slope decreased by only 13% in case of trailing edge removal while the area resulted in a 17% reduction. Coefficients $(C_L, C_D, C_Y, C_m, C_l, C_n)$ as well as parameters $(C_{L\alpha}, L/D, \Delta C_m / \Delta C_L)$ were determined for a range of values of angles of attack $\left(-4^0 < \alpha < 22^0\right)$, side slip angles $\left(-5^0 < \beta < 10^0\right)$ and Mach numbers $(1.70 \le M \le 2.86)$ for constant Reynolds number of $7.38 * 10^6$.

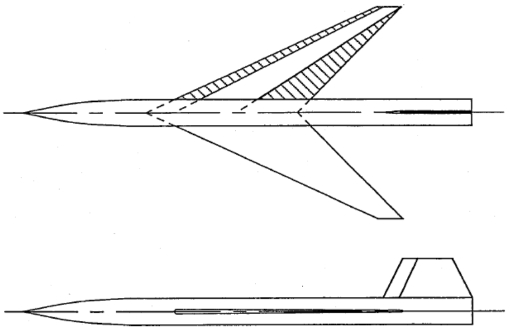

Figure 2: Swept wing aircraft model showing regions of damage (shaded area).

Betzina and Brown [3] measured static aerodynamic characteristics of a McDonnell-Douglas A-4B aircraft with both simulated and actual gunfire damage to the starboard wing. A full scale aircraft was used for experiments which were carried in the NASA-Ames $40*80$ ft wind tunnel. A standard fuselage and three different wings were attached to it for the tests. The first wing tested was an undamaged one in which holes had been cut and detachable cover plates installed at various locations. Removal of one or more cover plates gave one of fourteen different simulated damage cases. The other two wings used had been damaged by actual gunfire. Coefficients $(C_L, C_D, C_Y, C_m, C_l, C_n)$ were determined for a range of values of angles of attack $\left(-4^0 < \alpha < 26^0\right)$ for the different wings with all other variables held constant.

Spearman [4] summaries transonic wind tunnel tests carried out at the Longley Research Centre using models of undamaged and damaged aircraft to investigate the effects of damage on the aircraft’s static aerodynamic characteristics. Three types of aircraft models were used, namely a swept wing aircraft, a delta wing aircraft and a trapezoidal wing aircraft. Damage to the aircraft was simulated by the removal of all or part of a wing, horizontal tail or vertical tail. Figure (4) shows the damage to the trapezoidal wing aircraft.

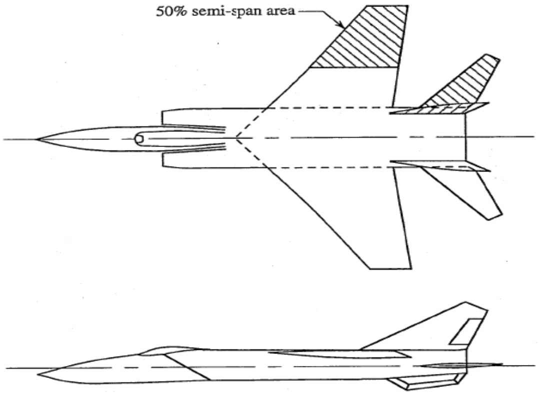

Figure 3: Trapezoidal wing aircraft showing the region of damage (shaded area).

The purpose of the investigation was to determine the probability of completely losing the aircraft, and the extent of damage that the aircraft could be sustained while still completing the mission or at least returning to friendly place. Coefficients (C_L, C_m, C_l, C_n) as well as stability parameters $\left(C_{n_\beta}, {}^{\Delta C_m}\!/_{\Delta C_L}\right)$ were determined for a range of values of angles of attack $\left(-2^0 \le \alpha \le 4^0\right)$, side slip angles $\left(-4^0 \le \beta \le 4^0\right)$ and Mach numbers $\left(0 < M \le 2\right)$.For the configurations studied in the tests, it was found that losing even half of the wing would not necessarily causes the aircraft to be completely lost, as either enough rudder/aileron power was available or a small side slip could be implemented to offset the rolling moment and the aircraft remained statically stable in the longitudinal plane.

In 1986, Turhal [5] carried out wind tunnel tests using a $^{1}/_{16}$ scale model of an F-16 aircraft to investigate the effect of various types of control surface failure on aircraft's static stability. Three different failure cases were investigated:

a. Fixed deflection of a control surface.
b. Floating left flaperon.
c. Missing left flaperon.

Forces and moments were measured for each failure mode and aerodynamic coefficients ($C_L, C_D, C_Y, C_m, C_l, C_n$) were determined for a range of values of angles of attack, side slip angles and control surfaces deflections. The wind tunnel force and moment data were curve fitted to determine the aerodynamic derivatives as a function of α , β and control surfaces deflections.

Gautam H. Shah [6] at NASA Longley Research Centre conducted in a subsonic wind tunnel investigation to measure the aerodynamic effects of the damage to the lifting and stability/control surfaces of commercial aircraft configurations. The damage is in the form of partial or total loss of the wing, horizontal stabilizer and vertical tail as in figure (4).

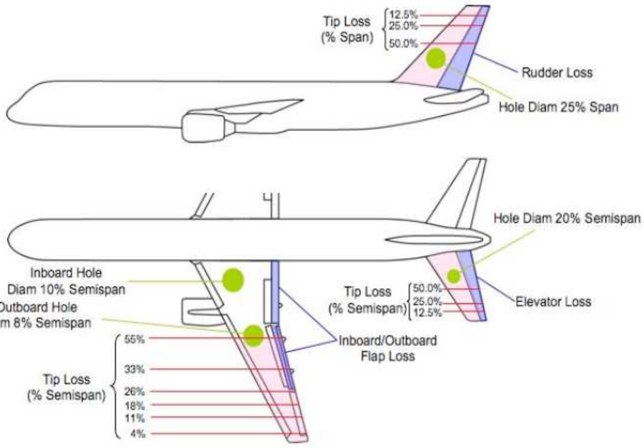

Figure 4: Model sketch and damage conditions tested.

His investigation is focused on:

a. Wing damage:

   Figure (5) shows lift coefficient versus angle attack for increasing levels of wing tip loss. The progressive reduction in lift curve slope is seen throughout the angle of attack range up to and beyond the stall at approximately $\alpha = 10^0$ .The effect of tip loss on effective dihedral C_{l_β} is shown in figure (6), as rolling moment coefficient versus sideslip for $\alpha = 0$, where a negative slope indicates static stability. In the low and moderate sideslip region, only a small reduction in stability is noted, though the effect increases for large damage cases at large negative (damaged wing forward) sideslip angles.

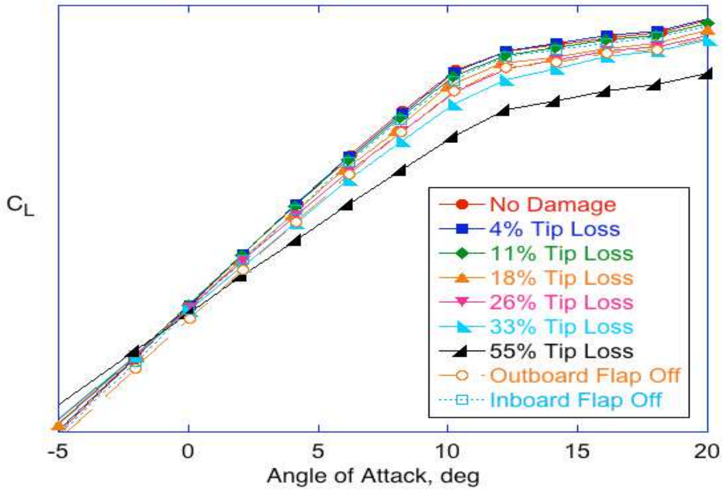

Figure 5: Lift coefficient.

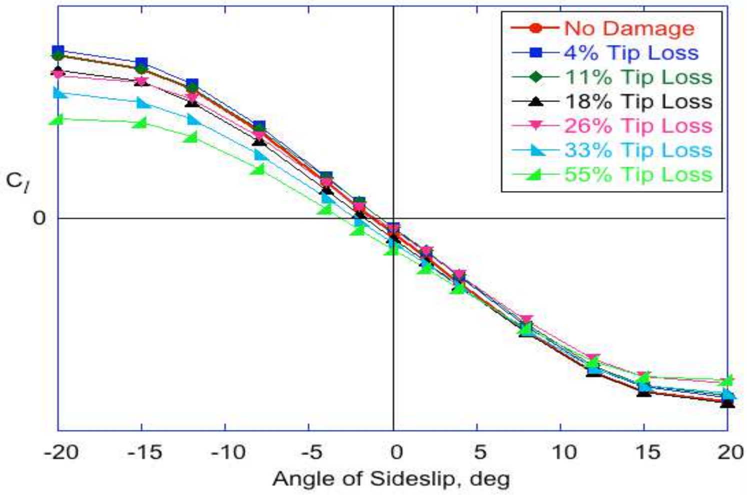

Figure 6: Rolling moment versus sideslip, $\alpha = 0$.

b. Horizontal tail damage:

He showed that for the several damage cases there is a progressive loss in stability (decreasing negative slope) with increasing loss of the stabilizer area as in figure(7). The effect on longitudinal dynamic stability is shown in figure (8) as pitch damping over the angle of attack range for damaged and undamaged cases.

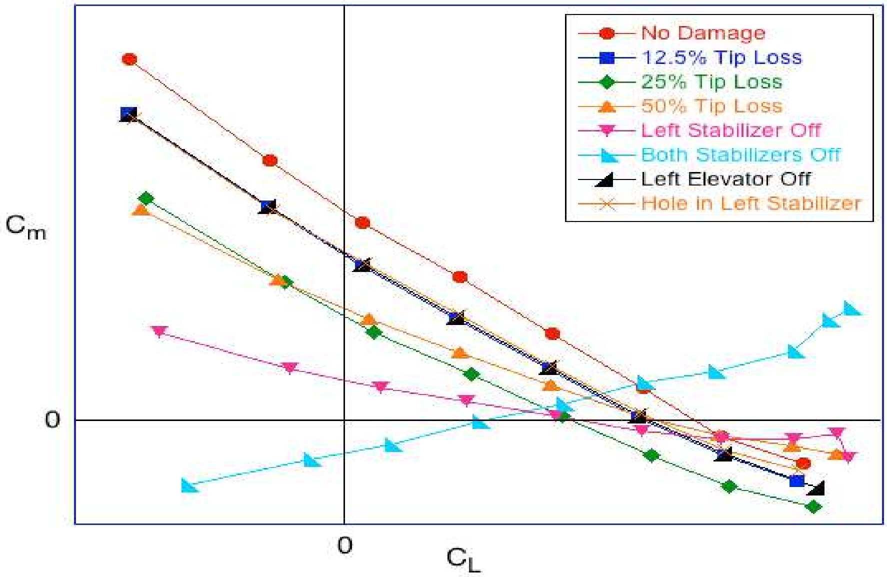

Figure 7: Static longitudinal stability.

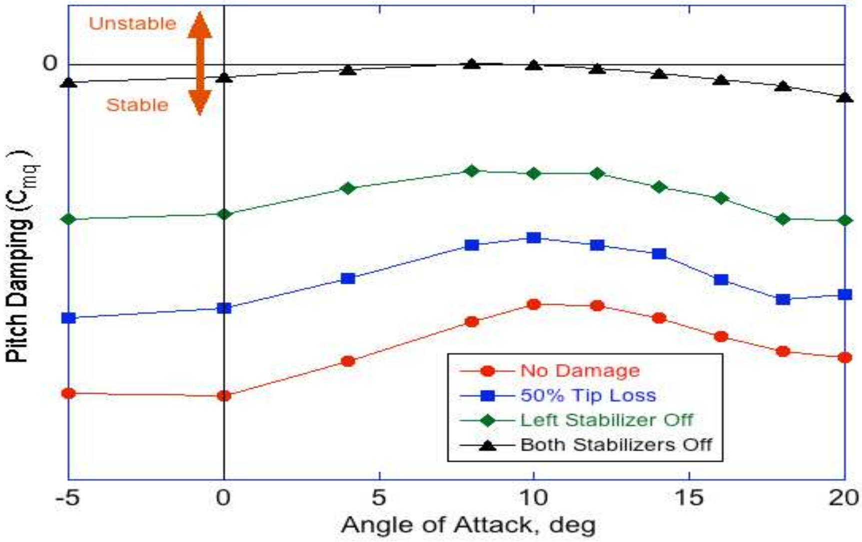

Figure 8: Pitch damping.

c. Vertical tail damage:

Figure (9) shows that at zero angle of attack, a progressive reduction in static directional stability (slope of C_n versus β) with increasing of damage area loss. Also the variation of directional stability over the entire angle of attack range is studied and the $C_{n\beta}$ is computed as the linear slope in yawing moment between side slip angles of $-4^0 to 4^0$ as in figure (10)

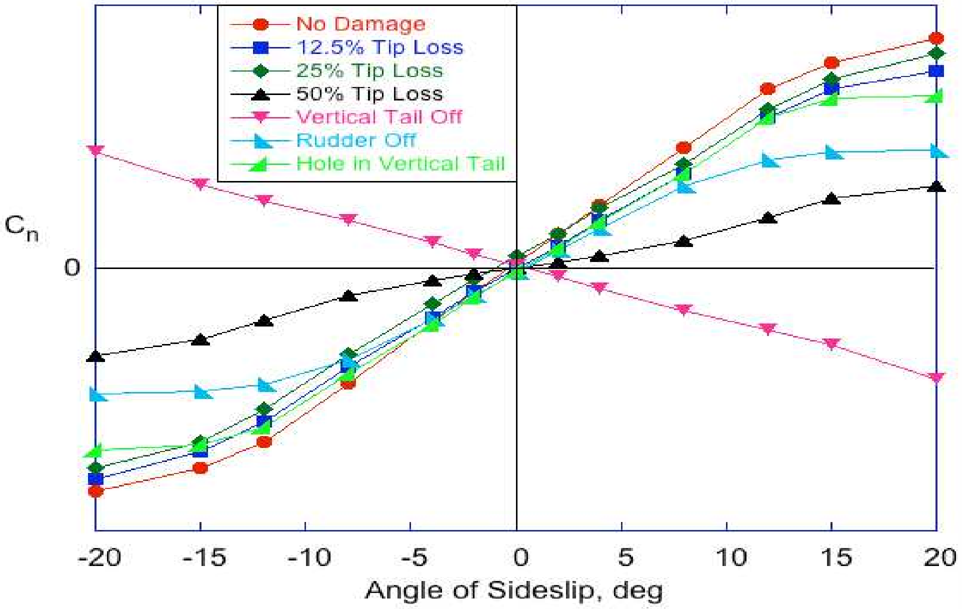

Figure 9: Yawing moment coefficient versus side slip angles at zero angle of attack ($\alpha = 0$).

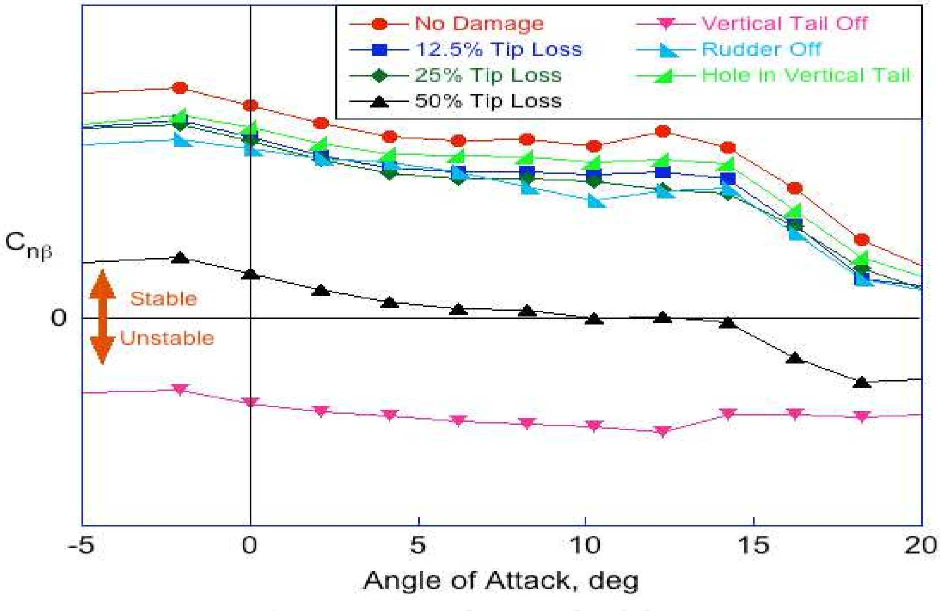

Figure 10: Static directional stability.

Djellal and Ouibrahim [7] on 2009 studied the effect of wing damage on aerodynamic behavior of the aircraft. Three models were used for these investigations. They considered that the damage is only located on the wing, which are from the aerodynamic point of view, the most critical components of the aircraft. The scenarios of damages were expressed in terms of diameters and localizations of the through holes of simulated damage in the wing. Damage size can be expressed in terms of a percentage diameter (d) to the local chord length (c).

Wing models with undamaged and damaged cases were investigated by considering moreover the variation of the holes diameter and its position on the span wise and the chordwise.

The models used for the investigations are:

a. Rectangular wing with a profile NACA 64_1-412 and a taper ratio $\lambda = 1$.
b. Aircraft wing model (trapezoidal wing) with NASA 23018 at the root section, NASA 23012 at tip section, taper ratio $\lambda = 0.5$ and without twist.
c. Triangular plan-form wing with a profile RAE 104, tapered, without sweep and twist.

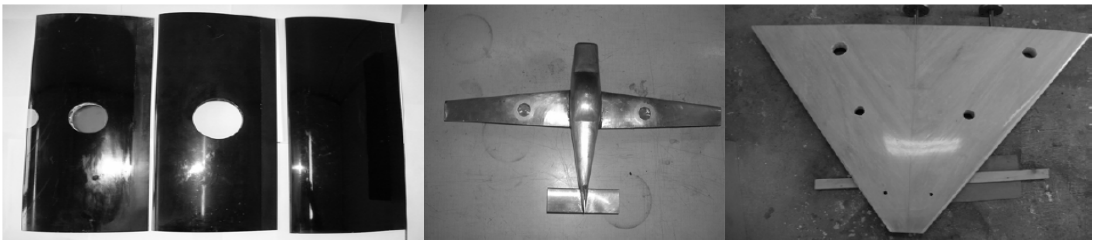

Figure 11: Damage for three models.

Their investigations are focused on the influence of damage to the aerodynamic behavior and presented as changes in coefficients, ΔC_L and ΔC_D in terms of:

$$\Delta C_L = C_{L\,damaged} - C_{L\,undamaged}$$

$$\Delta C_D = C_{D\,damaged} - C_{D\,undamaged}$$

For the aircraft wing model three damages of the same size ($40\%c$) centered at mid chord but located at three different wing spanwise locations: tip, mean aerodynamic chord, and root.

The magnitude of the damage effect is sensitive to its position along the span. As shown in figures (12) and (13) the degradation of the C_L and C_D increases from the tip to the root regions.

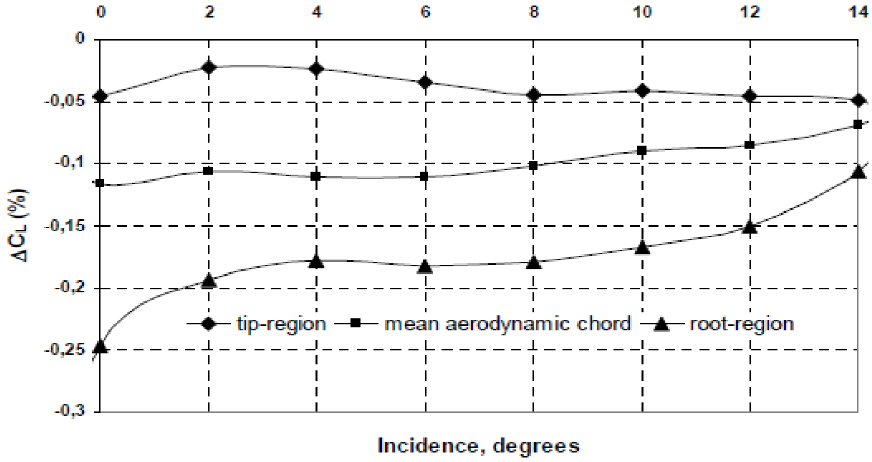

Figure 12: Rate of lift coefficient loss along the span.

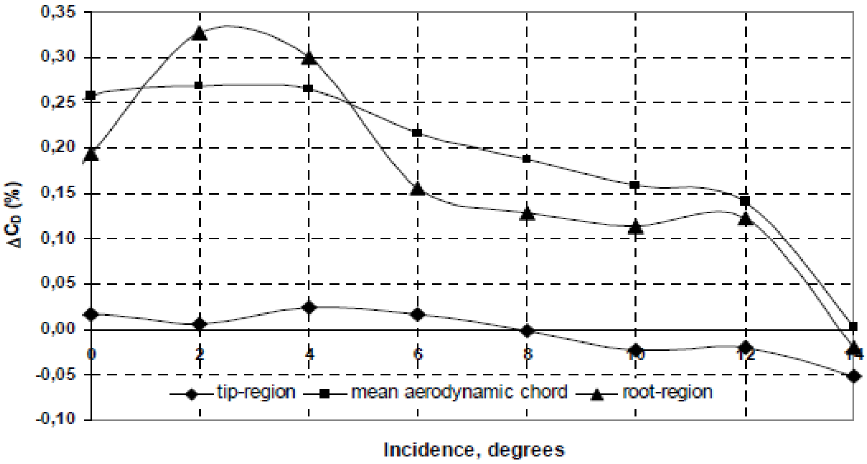

Figure 13: Rate of drag coefficient loss along the span.

2.2 Simulation codes:

Zaiser [8] on Air University used Turhal's data in his studies on the stability characteristics of a combat aircraft with control surface failure. An investigation of the stability characteristics of an aircraft which has sustained damage to a primary control surface was performed. He developed polynomial functions which describe the aircraft static stability derivatives. The polynomials were examined to identify aerodynamic coupling which might be significant. The analysis was performed using wind tunnel data taken on an F-16 model in Turhal's tests. The aircraft stability and control derivatives were developed and analyzed to identify aerodynamic coupling with implications for an aircraft with failed control surfaces. The investigations were conducted at two flight conditions representative of the aircraft at cruise and landing approach velocities.

Nhan, Kalmanje, and John Kaneshige [9] at NASA Ames Research Centre performed aerodynamic modeling to the Generic Transport Model (GTM) to estimate the aerodynamic coefficients, stability and control derivatives. This damage effect is performed using a vortex lattice code. This computational fluid dynamics modeling is capable of rapidly computing the aerodynamic characteristics and control sensitivity of the damaged GTM due to various flight control surface inputs. The damage effects are modeled as partial losses of the left wing, left horizontal stabilizer and vertical tail as shown in figure (14).

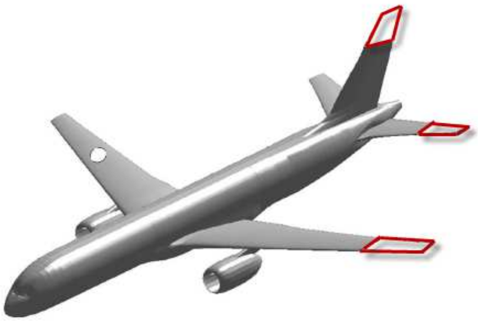

Figure 14: Damage to the Generic Transport Model (GTM).

Their studies showed that the effect of wing loss can be seen as a significant source of loss of the lift capability of a damaged aircraft as the lift coefficient can be reduced by as much as 25% for up to 50% span loss of the one of the wings as shown in figure (15) and the changing of the pitching moment due to the wing loss as in figure (16).

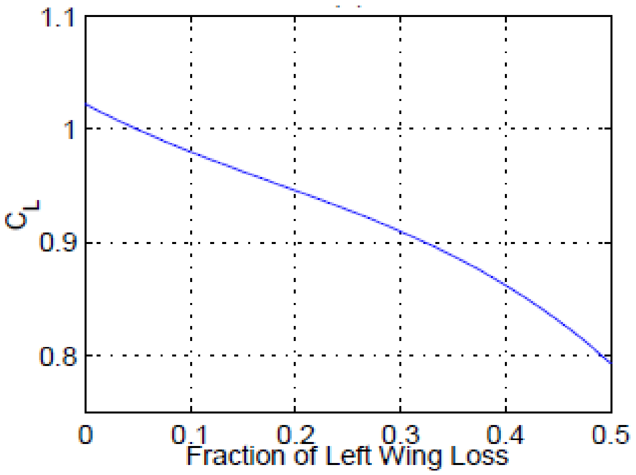

Figure 15: Lift coefficient reduction due to wing loss at $\alpha = 12^0$, $\beta = 0^0$.

Figure 16: Pitching moment coefficient due to wing loss at $\alpha = 12^0$, $\beta = 0^0$.

Nesrin.S.K, Nespeca.P, T.Marchelli, and M.Sarigul.Klijn [10] represented an approach to predict the flight dynamics and stability derivatives of structurally damaged transport category subsonic aircraft (C-17 Global master model) based on spanwise full loss damage model. In their study they derived the stability and control derivatives from the basic principles and theoretical aerodynamics. The damage is introduced using spanwise parameter dmg which represents the fraction of missing half span of the wing starting from the tip as in figure (17). From the basis of aerodynamic they defined new terms which showed the effect of damage on the basic wing geometry properties. These new definitions are used for the formulas of the stability coefficients and derivatives for the damaged aircraft.

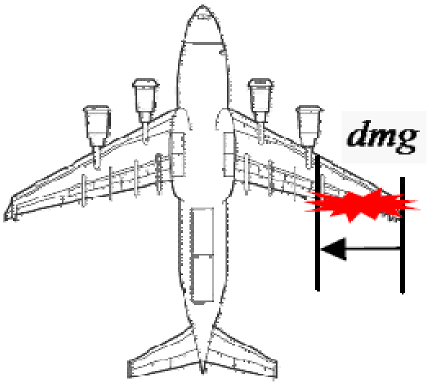

Figure 17: Spanwise losses of structure damage model.

Neal, Shahyar, Harold, Sally and Joseph [11] presented a computational study to assess the utility of the two different NASA unstructured Navier-Stokes flow solvers, USM3D and FUN3D, for capturing the degradation in static stability and aerodynamic performance of transport aircraft configuration due to airframe damage. The damage which studied is the loss in wing, horizontal stabilizer, and vertical tail. Their study demonstrated that high fidelity Navier-Stokes flow solvers could augment flight simulation models with additional aerodynamic data for various airframe damage scenarios.The goal of their study is to evaluate the accuracy and utility of the respective numerical tools by correlating with the damaged aircraft experimental data shown in [6].

Tetrahedral grids were constructed on the full span (no damage) and with damage in wing, horizontal and vertical tail as seen in figures (18, 19 and 20)

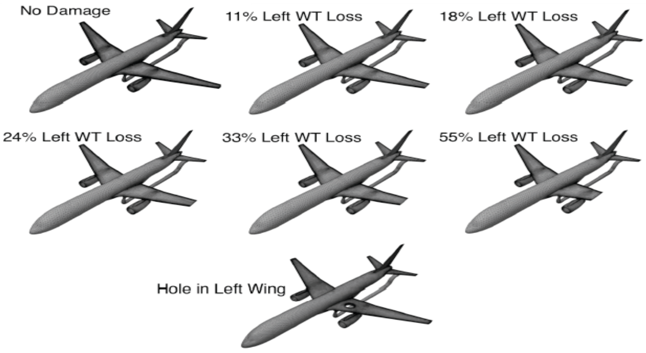

Figure 18: Wing tip damage configurations.

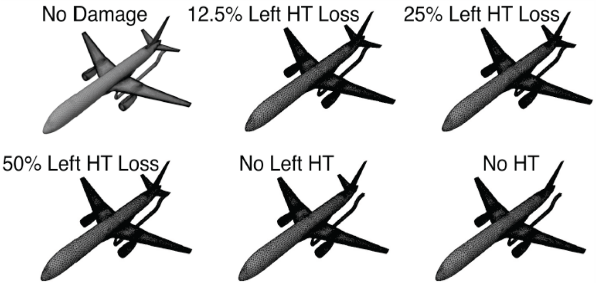

Figure 19: Horizontal tail damage configurations.

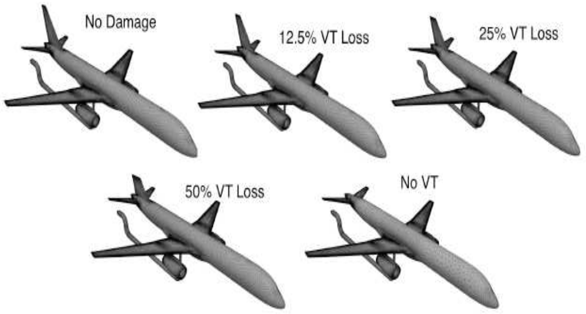

Figure 20: Vertical tail damage configurations.

The effect of wing tip losses in lift coefficient is presented in figure (21) and the overall trend of lift losses with the increasing tip loss is well captured. Also the effect of rolling moment coefficient against sideslip angles at zero angle of attack is illustrated as in figure (22).

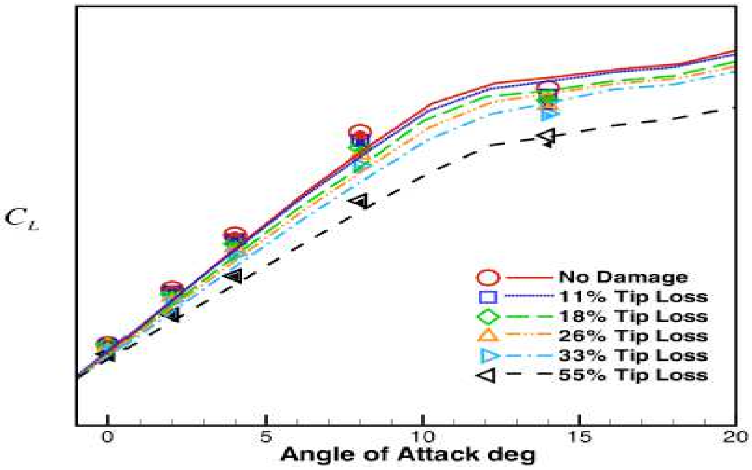

Figure 21: Effect of left wing damage on lift coefficient at $\beta = 0^0$, USM3D (open symbols), FUN3D (solid symbols), experiment (line symbols).

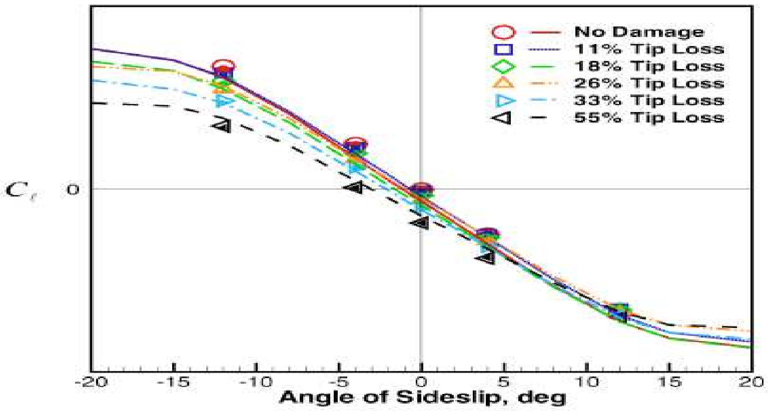

Figure 22: Effect of left wing damage on rolling moment coefficient at $\alpha = 0^0$, USM3D (open symbols), FUN3D (solid symbols), experiment (line symbols).

The effect of horizontal stabilizer damage in longitudinal stability is illustrated in figure (23) in terms of lift and pitching moment coefficients.

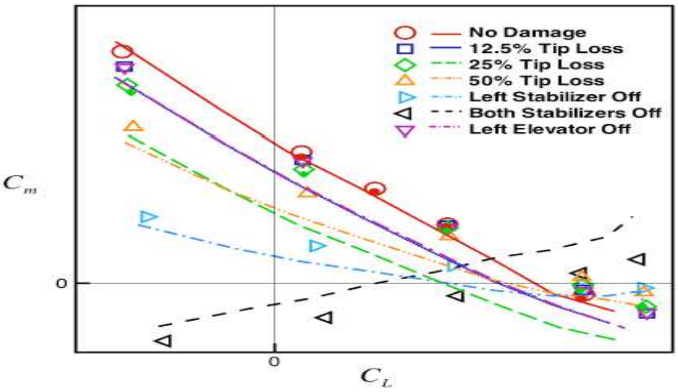

Figure 23: Effect of horizontal stabilizer damage on pitching moment coefficient at $\beta = 0^0$, USM3D (open symbols), FUN3D (solid symbols), experiment (line symbol).

The effect of vertical tail loss in yawing moment coefficient versus angle of sideslip at zero angle of attack is presented in figure (24) and an excellent correlation with the experimental data is observed for the two flow solvers. The static directional static stability (C_{n_β}) is plotted against angle of attack range to yield the stability of the aircraft as in figure (25).

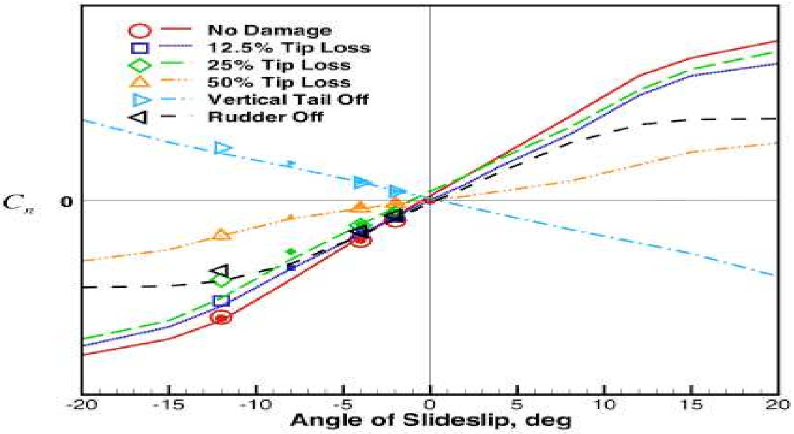

Figure 24: Effect of vertical tail damage on yawing moment coefficient at $\alpha = 0^0$, USM3D (open symbols), FUN3D (solid symbols), experiment (line symbols).

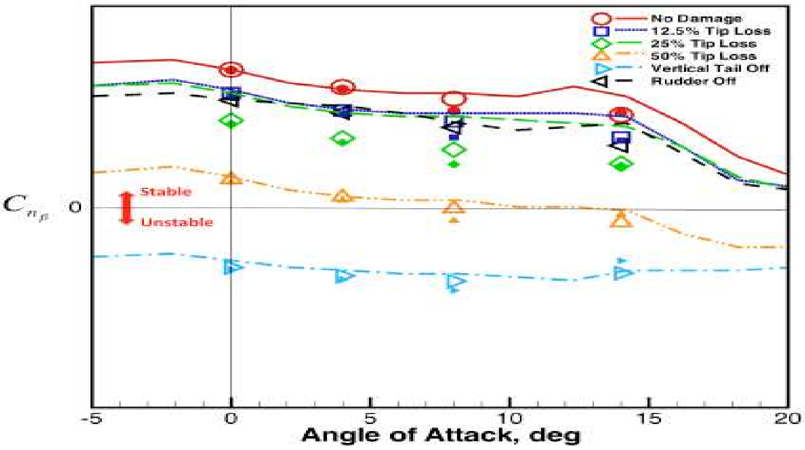

Figure 35: Effect of vertical tail damage on static directional stability, USM3D (open symbols), FUN3D (solid symbols), experiment (line symbols).

B.A.Siddiqui, A.H.Kasim, and A.Z.al-Garani [12] modeled aircraft in Missile DATCOM to predict the lift, drag and pitching moment coefficients and validate the results with [2]. A new technique is proposed for the determination of the aerodynamic derivatives using the data from missile DATCOM and experimental wind tunnel data [2].The model used for the modeling in DATCOM is the same as that used by [2]. A fuselage was of circular cross section having a fineness ratio of 13.8 with an ogive nose. A swept wing was mounted in a mid-wing position. There is no horizontal tail, but a swept vertical tail with a sharp wedge of constant chord at leading edge as seen in figure (26).

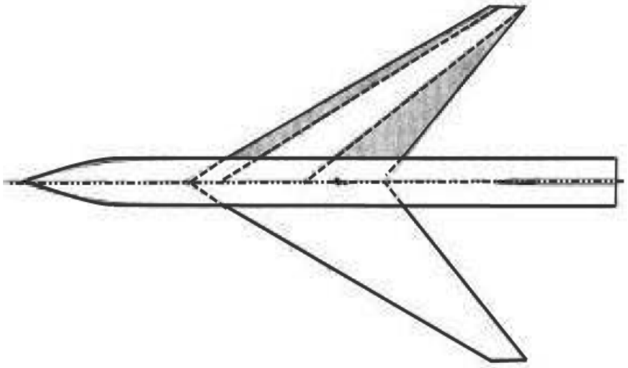

Figure 26: Aircraft model (damage: shaded area).

Damaged aircraft configurations were achieved by:

a. Removal of starboard leading edge portion (forward portion shaded area), this resulted in a 11% reduction in total exposed wing area.
b. Removal of the trailing edge portion of the starboard panel (aft shaded area), this resulted in a 17% reduction in total exposed wing area.
c. Removal of the entire starboard wing panel.

Their steps for this technique are:

a. Get geometric dimensions of the aircraft.
b. Get experimetal aerodynamic data of the complete aircraft.
c. Test a major part of the heathy aircraft in wind tunnel (wing).
d. Model the healthy aircraft in DATCOM to predict the aerodynamics.

e. Improve this DATCOM prediction for the healthy aircraft by wind tunnel study of the wing alone.
f. Model the damaged aircraft in DATCOM.
g. Improve the model in step (f) with wind tunnel data for healthy half wing.
h. Subtract the DATCOM prediction of the healthy aircraft from DATCOM prediction of the damaged aircraft.
i. Add the difference in step (h) and add to healthy complete aircraft aerodynamics in step (b).

A comparison for the various damage cofigurations for the proposed techniques with DATCOM and experimental data are plotted as shown in figures (27, 28 and 29).

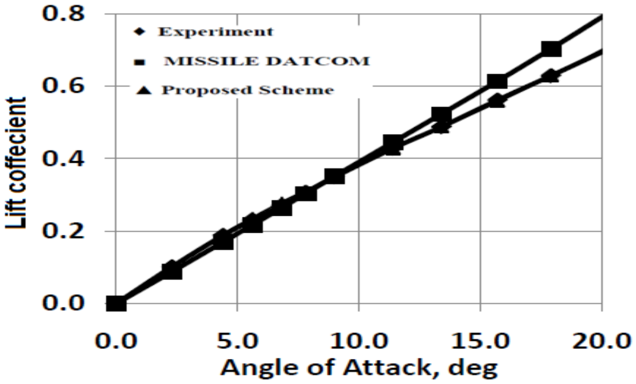

Figure (27): Comparison of lift coefficient for proposed technique and DATCOM predictions with experimental data for wing leading edge damaged aircraft.

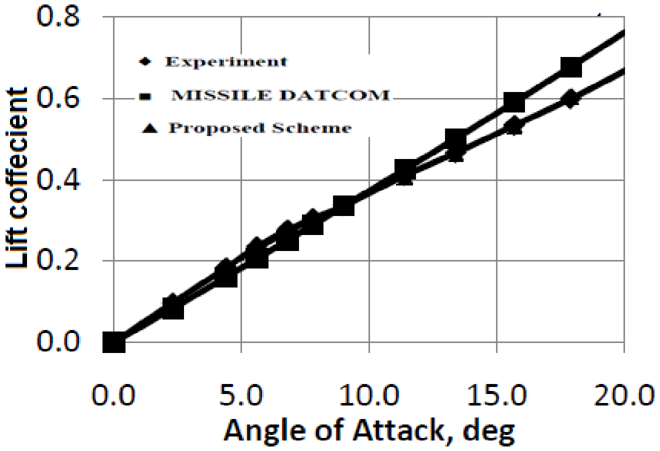

Figure 28: Comparison of lift coefficient for proposed technique and DATCOM predictions with experimental data for wing trailing edge damaged aircraft.

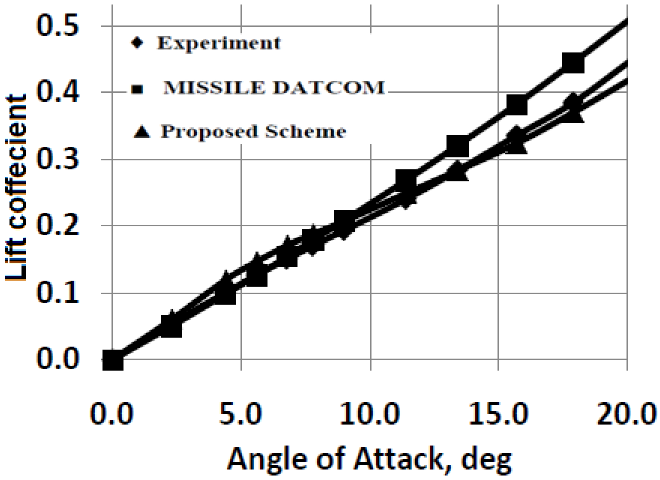

Figure 29: Comparison of lift coefficient for proposed technique and DATCOM predictions with experimental data for wing panel removal damage.

Jinwhan kim, Karthik, and Menon [13] discussed an estimation of aerodynamic model of damaged aircraft using differential vortex lattice method (DVLM) tightly coupled with extended Kalman filters in order to enable the assessment of aircraft performance.Their study is developed as; first, a rapid approach for deriving aerodynamic models of damaged aircraft via DVLM, and second is to use extended Kalman filtering for online estimation of damaged aircraft parameters based on DVLM. The DVLM proposed in their study allows the calculation of the forces on the damaged aircraft using differential circulation (Γ) strength components in the vicinity of the damaged section. And the using of DVLM reduces the dimension of the problem by exploiting the knowledge about the circulation over the aircraft structure before the damage. The problem is formulated in terms of the changes in the circulation on the panels in the neighborhood of the damage.

For the formulation of the DVLM the surface panels are divided into three groups as in figure (30):

a. Group 1 contains undamaged panels that are some distance away from the damaged section, where the effect of damage can be assumed to be negligible or insignificant.
b. Group 2 contains damaged panels which have been taken off from the airframe.
c. Group 3 contains undamaged panels that are in the close neighborhood of the damaged area. The effect of the damage can be felt strongly and clearly over these panels.

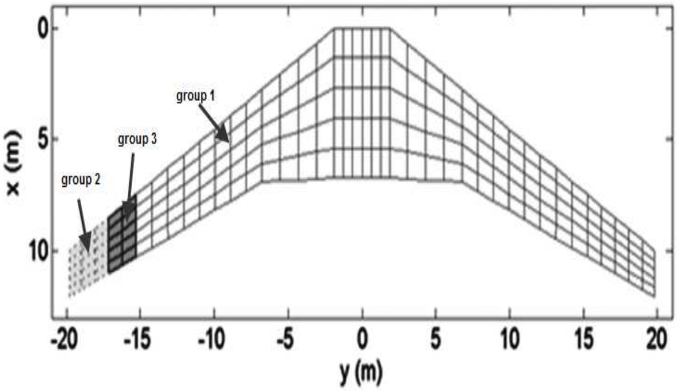

Figure 30: Panels group used in DVLM formulation.

Two cases of damage for the numerical calculation are considered: wing tip damage and a hole in the wing. The pressure distributions is evaluated and integrated to produce aerodynamic forces. These forces can be normalized with respect to dynamic pressure and reference area to obtain the lift, drag and side force coefficients. The formulation of using DVLM is as in figure (31).

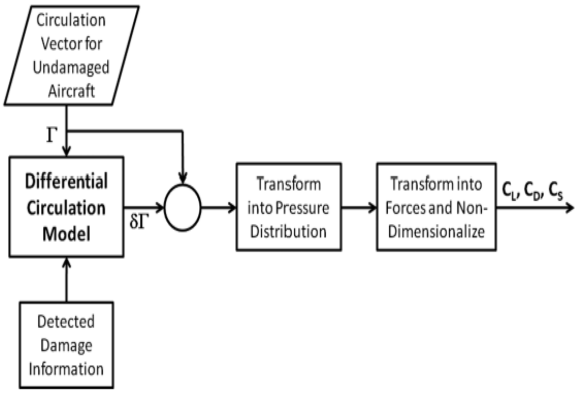

Figure 31: DVLM procedure.

3. Conclusion

The review shows the considerable work done over the last years to estimate the aerodynamic of damaged aircraft. The damage effect aerodynamic modeling has been performed to provide an understanding of the control and stability of an asymmetric damaged aircraft Various damage modeling are used (wing, horizontal and vertical tail) for investigation of damage on aircraft lift, drag and moments coefficients. The most researches at last ten years conducted by mean of computation code rather than wind tunnels because of computers availability.

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