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Survey on the Aerodynamics of Battle-Damaged Combat Aircraft

Lincoln P. Erm

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DSTO-GD-0184

ABSTRACT

A literature survey on the aerodynamics of battle-damaged combat aircraft is presented in this report. The survey considers experimental investigations carried out in wind tunnels using either scaled or full-sized models of complete aircraft or components of aircraft that have either simulated damage or actual gunfire damage. The survey could assist in the planning of a possible experimental program at AMRL to obtain aerodynamic data for battle-damaged aircraft. The data could be used in modelling the flight-dynamic behaviour of damaged aircraft.

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Executive Summary

In times of conflict, modern combat aircraft may be damaged and there is a need to know how the damage affects an aircraft's flying capabilities. Previous damage studies at AMRL have concentrated almost solely on how the damage affects the structural integrity of an aircraft, rather than on how the damage affects the flight dynamics of the aircraft. The main concern has been whether damaged aircraft structures can safely withstand the loading expected during limited or full combat. However, both the flight dynamic and structural aspects of battle damage are important. Minor damage from a structural viewpoint, such as a missing or damaged leading-edge flap, may be major damage from a flight-dynamic viewpoint.

Flight-dynamic simulation codes are available at AMRL that enable the flight behaviour of undamaged aircraft to be predicted. These codes incorporate a data base that contains a wide range of static aerodynamic characteristics, such as force coefficients, moment coefficients and aerodynamic derivatives, for an undamaged aircraft. If the static aerodynamic characteristics in the data bases of the codes are replaced with data applicable to a damaged aircraft, then the codes could be used to predict the flight behaviour of that aircraft. To obtain the required data to insert into the code, it would be necessary to carry out wind-tunnel experiments at AMRL using models of damaged aircraft.

As a starting point in an investigation into the flight dynamics of damaged aircraft, a literature survey has been undertaken on the aerodynamics of damaged aircraft. The survey considers experimental investigations carried out in wind tunnels using either scaled or full-sized models of complete aircraft or components of aircraft that have either simulated damage or actual gunfire damage. The survey could be used as a guide when formulating an experimental program to measure static aerodynamic characteristics of damaged aircraft. Factors that could be considered include what types of damage to investigate, what parameters to measure, what range of operating conditions to use and the pitfalls to avoid. The survey is the basis of this report.

The outcome of this work could be an improved ability of the ADF to assess the operational capability, from a flight-dynamic viewpoint, of damaged aircraft. The study might help establish whether a damaged aircraft could complete a mission, whether the aircraft could take off again and be used in combat, or whether the aircraft could take off and fly to a main base for substantial repairs.

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NOTATION

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Notation

c	Chord length, (m).
C_D	Drag coefficient.
C_l	Rolling-moment coefficient.
C_L	Lift coefficient.
C_m	Pitching-moment coefficient.
C_n	Yawing-moment coefficient.
C_Y	Side-force coefficient.
D	Drag force, (N).
L	Lift force, (N).
M	Mach number.

α	Angle of incidence, (deg).
β	Angle of sideslip, (deg).
δ_i	Angle of deflection of a control surface, i = 1, 2, 3, ... (deg).
ΔC_L	Difference between the lift coefficient on a wing with and without patches.

Derivatives

$C_{l\beta}$	Lateral stability parameter, $\partial C_l / \partial \beta$.
$C_{L\alpha}$	Lift curve slope, $dC_L / d\alpha$.
$C_{n\beta}$	Directional stability parameter, $\partial C_n / \partial \beta$.
$\partial C_m / \partial C_L$	Longitudinal stability parameter.
$\Delta C_m / \Delta C_L$	Longitudinal stability parameter.

1. Introduction

When modern combat aircraft are damaged in battle, answers are required to questions such as (1) can the aircraft complete a mission if it is damaged in a given way, (2) can the aircraft take off again and be used in combat, but with a reduced capability, (3) is it safe for the aircraft to take off and fly to another location to be repaired, and (4) will the damage cause the loss of the aircraft?

In the past, studies at the Aeronautical and Maritime Research Laboratory (AMRL) on the flying capabilities of damaged aircraft have mainly concentrated on the structural integrity of aircraft, rather than the flight dynamics of aircraft. However, all aspects of battle damage are important and minor damage from a structural viewpoint may be major damage from a flight-dynamic viewpoint. For example, an aircraft may be structurally sound if say a leading-edge flap is damaged or blown away, but from a flight-dynamic perspective, such damage may be catastrophic. To address this shortcoming, a study of the effects of battle damage on the flight dynamics of damaged combat aircraft has commenced at AMRL.

Flight-dynamic simulation codes, such as the program CASTLE for the F/A-18 aircraft (Reference 1), are currently available at AMRL, enabling the flight-dynamic behaviour of undamaged aircraft to be investigated. The codes incorporate a data base consisting of static aerodynamic characteristics, such as force coefficients (C_L, C_D, C_Y), moment coefficients (C_l, C_m and C_n) and aerodynamic derivatives ($C_{l\beta}$, $C_{n\beta}$), for a range of aerodynamic flow angles (α, β) and velocities. If the data in the data base were changed to correspond to a damaged aircraft, then the code could be used to predict the performance of that aircraft. The data for the damaged aircraft would have to be obtained experimentally. It would be necessary to undertake wind-tunnel experiments to measure the static aerodynamic characteristics of the damaged aircraft. Complementary water-tunnel flow-visualisation tests might also be needed to see how the damage affects the flow around the aircraft.

The codes could then be used to provide answers to the above questions and to study operational problems in handling damaged aircraft. For example, battle damage may introduce adverse coupling effects between the longitudinal and lateral modes of the aircraft motion. The loss of a large portion of a horizontal tail would mean that when the pilot commanded a pitching moment, the aircraft would also experience unexpected, and unwanted, yawing and rolling moments and also possibly a side force (Reference 2).

As a starting point to the study of the flight dynamics of damaged aircraft, a literature survey on the aerodynamics of damaged aircraft has been undertaken. The survey could be used as a guide when formulating a possible experimental program at AMRL to measure static aerodynamic characteristics of models of damaged aircraft to use in data bases of flight-dynamic simulation codes. The survey is the basis of this report.

2. Survey of Literature

Despite the importance of knowing how battle damage affects aerodynamic characteristics of aircraft, very little published work on the topic is available. The scope of the reported work has been varied, but all cases examined have been concerned with experimental investigations carried out in wind tunnels, rather than with CFD studies of the problem. Various types of aircraft have been used in the studies, and measurements have been taken on models of aircraft and on full-scale aircraft, for both subsonic and supersonic flows. In some cases a complete aircraft was used, and in other cases a component of an aircraft, such as a wing, was used. The damage to the aircraft has been either simulated, such as holes drilled in an aircraft wing, or else has been produced by actual gunfire. The damage has not been restricted to holes blown in surfaces or missing parts of an aircraft, but also includes cases where a control surface has been jammed at an angle or left floating. The aim of the experimental programs has often been to provide data suitable for use in vulnerability assessments of military aircraft or in flight-dynamic studies.

Hayes (Reference 3) conducted an investigation in a supersonic wind tunnel to determine the effects of simulated wing damage on the static aerodynamic characteristics of a generic swept-wing aircraft model. The model, shown in Figure 1, consisted of an ogive-cylinder fuselage, swept wings and a vertical tail. Damage was simulated by removing either 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 in the total wing area and removal of the trailing edge resulted in a 17% reduction. Coefficients, C_L, C_D, C_Y, C_l, C_m and C_n, as well as parameters, L/D, $C_{L\alpha}$ and $\Delta C_m/\Delta C_L$, were determined for a range of values of α, β and M ($-4^\circ < \alpha < 22^\circ$), ($-5^\circ < \beta < 10^\circ$), ($1.70 \leq M \leq 2.86$) for a constant Reynolds number of $7.38 \times 10^6/\mathrm{m}$. It was found that removing either the leading edge, the trailing edge or the complete wing led to a decrease in the slope of the lift curve and in the maximum lift/drag ratio. At the lower Mach numbers, removal of the trailing edge caused a rolling moment slightly larger than that caused by the removal of the leading edge, but the effect was reversed at higher Mach numbers, even though the trailing edge has more area than the leading edge. When the leading or trailing edge was removed, it was possible to trim the aircraft by altering the angle of sideslip, while maintaining angles of incidence and sideslip within reasonable limits, but trim could not be achieved when the entire wing was removed.

Betzina & Brown (Reference 4) 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 the experiments which were carried out in the NASA-Ames 40 × 80 foot wind tunnel. Three different wings were attached to the aircraft for the tests. One of the wings had sections removed from the upper and lower surfaces and these were replaced with eleven detachable panels, as shown in Figure 2. By removing different combinations of panels, fourteen different simulated damage cases could be obtained. This wing was tested both with and

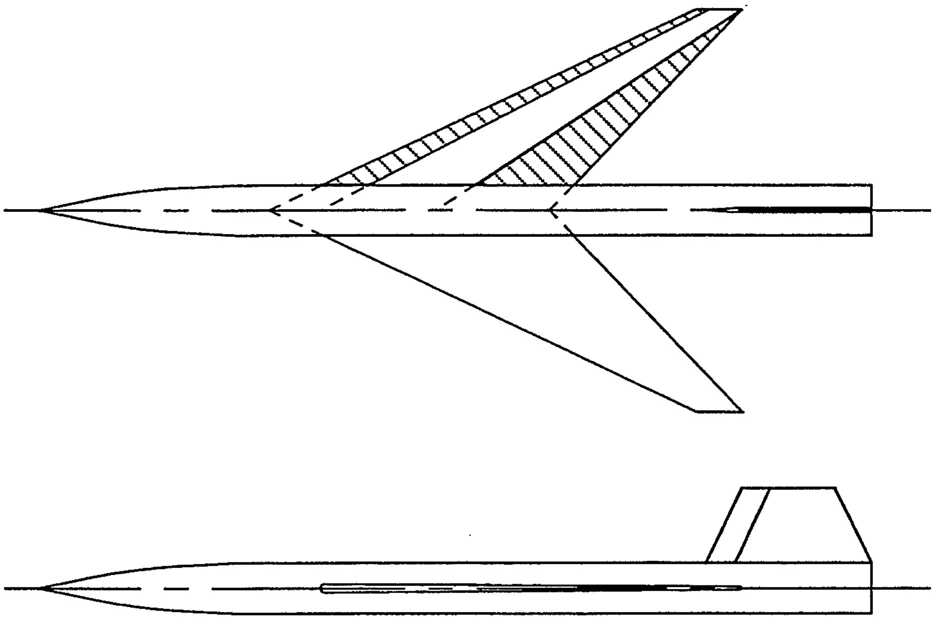

Figure 1 Generic swept-wing aircraft model, showing regions of damage (shaded) – based on a diagram given in Reference 3.

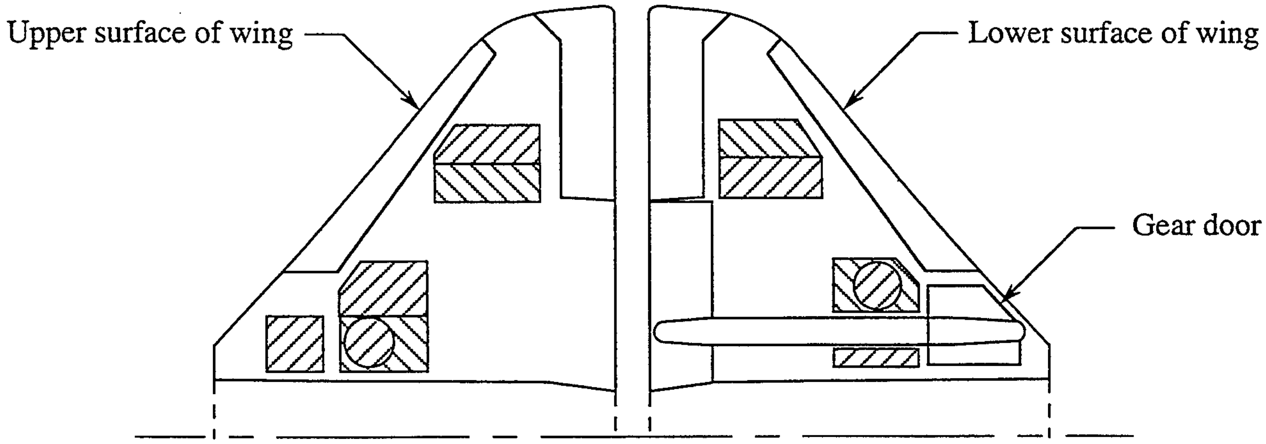

Figure 2 Upper and lower wing surfaces on an A-4B aircraft showing removable panels (shaded) – based on a diagram given in Reference 4.

without panels removed. The other two wings used had been damaged by actual gunfire. A 25 mm projectile was fired at one wing and a 30 mm projectile was fired at the other. The two projectiles were fired at the same region of each wing from an angle of 15° above and behind each wing. The 25 mm projectile created a large hole on the upper wing surface and blew off part of the landing gear fairing on the lower surface, creating a hole. The 30 mm projectile damaged mainly the lower wing surface, where the landing gear fairing was torn off. Coefficients C_L, C_D, C_l, C_m and C_n were determined for a range of values of α ($-4^{\circ} < \alpha < 26^{\circ}$) for the different wings. Control surface settings, δ_i (horizontal tail deflection, aileron deflection, flap deflection), were varied for measurements taken on the wing with panels. A comprehensive range of aerodynamic data was given in the report. The data were presented without analysis, as the objective of the work was to provide the necessary data for further analysis by McDonnell-Douglas.

Spearman (Reference 5) summarises transonic wind-tunnel tests carried out at the Langley Research Center 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 an aircraft was simulated by the removal of all or part of a wing, horizontal tail or vertical tail. An example of typical simulated damage is given diagrammatically in Figure 3 for the trapezoidal-wing aircraft. For a given set of measurements, the damage was confined to a specific region of the aircraft, e.g. a wing was not damaged at the same time as a horizontal tail. The investigation was undertaken to help determine the probability of an aircraft being lost in combat and to help determine the extent of damage that an aircraft can sustain and still complete a mission or return to friendly territory. Coefficients, C_L, C_l, C_m and C_n, as well as stability parameters, $C_{n\beta}$ and $\partial C_m/\partial C_L$, were determined for a range of values of α, β and M ($-2.0^{\circ} \leq \alpha \leq 4.0^{\circ}$), ($-4.0^{\circ} \leq \beta \leq 4.0^{\circ}$), ($0.0 \leq M \leq 2.0$). It was found that, for the delta-wing and the trapezoidal-wing aircraft at supersonic velocities, major damage to a wing, including the complete removal of a wing, may be sustained without necessarily losing the aircraft. Also, the loss of major parts of the horizontal tail may cause an aircraft to be catastrophically unstable in the subsonic range, but stable at low supersonic velocities. Thus, even though it may not be possible for a pilot to land the aircraft at subsonic velocities, the aircraft could possibly be flown to friendly territory at low supersonic velocities before the pilot must eject. Spearman also found that the loss of a major part of the vertical tail will result in the loss of an aircraft for both subsonic and supersonic velocities.

Irwin et al. (Reference 6) investigated the effects on aerofoil static aerodynamic characteristics of idealised gunfire damage, simulated by drilling circular holes in two-dimensional solid aerofoil sections, as shown in Figure 4. Aerofoils having chords of 100 and 200 mm were used and holes were located on the mid span of the aerofoil, at the leading and trailing edges as well as at the 25% and 50% chord positions, as shown. Holes were drilled normal to the chord line and holes of two different diameters were used, namely $0.1c$ and $0.2c$, where c is the chord length. The aerofoils were placed in a

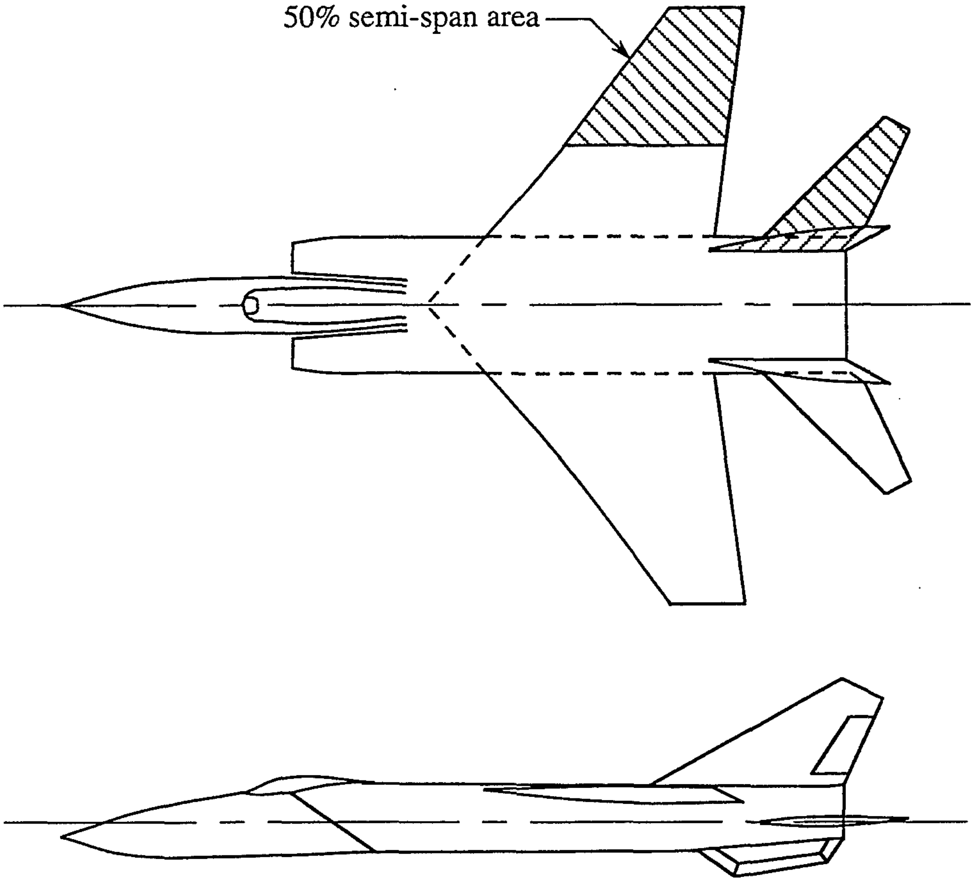

Figure 3 Trapezoidal-wing aircraft, showing regions of damage (shaded) – based on a diagram given in Reference 5.

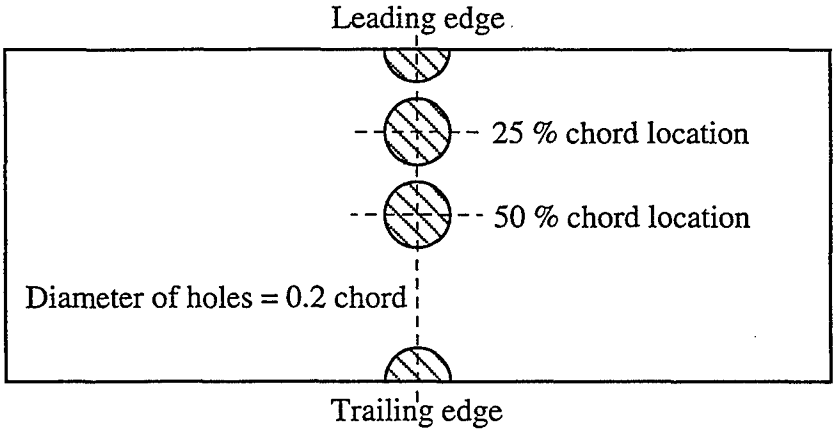

Figure 4 Simulated damage (shaded) in an aerofoil – based on a diagram given in Reference 6.

low-speed wind tunnel and only one hole in an aerofoil was used at a time for any given set of measurements. The flow patterns around the aerofoils were modified as a result of air flowing through a hole from a high pressure to a low pressure region and the aim of the investigation was to study how aerofoil characteristics change for different hole locations, hole sizes, aerofoil sizes and Reynolds numbers. Values of C_L, C_D and C_m were measured for a range of values of α ($-10^o < \alpha < 15^o$) for Reynolds numbers of 2.5×10^5 and/or 5.0×10^5. The researchers found that the holes at the 25% and 50% chord locations had more effect on the lift, drag and pitching moment coefficients than the leading-edge holes, whereas the trailing-edge holes were found to have little effect on the coefficients. The coefficients were affected very little by the holes of diameter 0.1*c*, and greater effects were evident for holes of diameter 0.2*c* (as logic suggests). There was a close correlation between data for the two chord sizes, provided that the data were first normalised by the ratio of the damaged wing area to the total wing area prior to damage. The coefficients were found to be largely independent of Reynolds number for the two Reynolds numbers used. The above findings apply to solid aerofoil sections and different results may have been obtained with hollow sections, which are more representative of actual aircraft wings.

Schemensky & Howell (References 7 and 8) developed an empirically-based computer program for determining the lift, drag and moment characteristics of aircraft that have sustained nuclear damage. The program can assess the effects on aircraft aerodynamics of damage such as rough, bent and burnt surfaces, loss of radomes and panels, and the asymmetric loss of wing or trim surfaces. The program is an extension of an existing code developed earlier by Schemensky (Reference 9), which was designed to predict baseline aerodynamic data for an undamaged aircraft. The new code incorporates additional subroutines for damage evaluation. The new program operates by first computing aerodynamic characteristics of a selected undamaged aircraft and then computing the incremental changes in the characteristics resulting from a selected type of damage. The characteristics of the damaged aircraft are obtained by simply adding the incremental components to those for the undamaged aircraft. To operate the program it is necessary for the user to specify details of the basic geometry of the aircraft. Two types of components are used to represent the geometry. The fuselage, canopy, stores and nacelles are represented by a series of bodies, while the wings, tails and pylons are represented by a series of single-panel aerofoil surfaces. It is also necessary for the user to model the damage into one or more categories, including surface roughness, forward-facing and rearward-facing steps, caved-in and missing panels, surface waviness, protuberances, body bluntness and missing parts of wing and tail surfaces.

The program determines the lift, drag and moment characteristics for each of the components of the undamaged aircraft and then sums individual characteristics (such as lift) to obtain total characteristics. The program computes characteristics using known relationships published in the literature. The program also computes incremental changes to the characteristics for each category of damage, and these are added to the estimates for the undamaged aircraft. Most of the empirical methods used to evaluate the damage are based on published relationships, although some methods were developed specifically to satisfy a need. To verify the accuracy of the computer program, predictions of C_L, C_D, C_l and C_m were made for a range of values of α and M, and the predictions were compared with experimental data. Comparisons were made for both damaged and undamaged aircraft and it was found that predictions and experimental data compared favourably thus giving credibility to the program. The experimental data of Hayes (Reference 3) and Betzina & Brown (Reference 4), discussed earlier, were used in the comparisons.

Modern combat aircraft are critically dependent on flight control systems, including flight control surfaces, for stabilisation and for achieving high levels of performance. However, damage to flight control systems is relatively common (Reference 10) and, based on recoverable combat data, flight control systems have contributed to up to 20% of aircraft losses in combat (Reference 11). A survey of how aircraft flight characteristics are affected by damaged flight control surfaces is thus of considerable importance.

A feature of modern combat aircraft is that they have damage-adaptive or self-repairing flight control systems. If an aircraft with such a system loses a control surface then it is not necessarily uncontrollable, since the flight control system may be able to reconfigure the remaining undamaged control surfaces to enable an aircraft to carry out a mission, or at least to allow it to return to base for repairs.

Work in this general field was undertaken by Turhal (Reference 12), who carried out wind-tunnel tests using a 1/20 scale model of an F-16 aircraft to investigate the effect of various types of control surface failure on the aircraft's static stability. Three different failure cases were investigated, namely (1) fixed deflection of a control surface, (2) floating left flaperon and (3) missing left flaperon, with each configuration representing a potential failure mode. Forces and moments were measured for each failure mode and aerodynamic coefficients, C_L, C_D, C_Y, C_l, C_m and C_n were determined for a range of values of α, β and δ_i (leading edge flap deflection, trailing edge flaperon deflection, horizontal tail deflection and rudder deflection). The wind tunnel force and moment data were curve fitted to determine aerodynamic derivatives as a function of α, β and δ_i. Using the curve-fitted data in an optimisation program, an attempt was made to determine the "best" settings (i.e. the settings corresponding to minimum drag) of undamaged control surfaces necessary to return the aircraft to equilibrium conditions. However, the optimisation program yielded unrealistic solutions, e.g. unreasonably high angles of attack and sideslip were found for a reconfigured aircraft. The attempt was unsuccessful due to problems with the form of the polynomials used when curve fitting aerodynamic derivatives. Turhal also carried out oil flow-visualisation experiments to obtain an understanding of the flow characteristics around the F-16 aircraft for each failure configuration.

Zaiser (Reference 2) used Turhal's data in his studies on the stability characteristics of a combat aircraft with control surface failure. Zaiser reduced Turhal's data and developed polynomial functions which describe the aircraft static stability derivatives.

The polynomials were examined to identify aerodynamic coupling which might be significant. After deriving the equilibrium equations for rectilinear flight in terms of the static stability derivatives, Zaiser defined the regions in α/β space in which equilibrium could be maintained when the aircraft sustained a failure to the rudder.

Roy (Reference 13) extended Zaiser's work and investigated the dynamic stability characteristics of an F-16 aircraft that had sustained damage to its rudder actuator. Roy used Zaiser's data and derived a linearised model of the damaged aircraft, taking into account static aerodynamic coupling associated with asymmetric trim orientation. Regions in α/β space where trim can be achieved were selected as input into the linearised aircraft model. For the aircraft at cruise speed, and for several trim conditions, the model was used to determine the region in α/β space where the aircraft was dynamically stable.

Another aspect of work on battle-damaged aircraft is concerned with the flight dynamics of patched aircraft, where battle-damage repair includes the application of an external patch. Currently the flight behaviour of patched aircraft is not as important an issue as that for damaged aircraft and attention is to be focussed on unpatched damaged aircraft. A patched aircraft may have reduced capabilities but it will still fly. A possible future detailed study of the flight behaviour of patched aircraft might show what patched areas are critical to increasing the drag and thus the fuel consumption of an aircraft. The study might also show which patched areas adversely affect the flow around the aircraft (such as patching near the LEX fence on an F/A-18 aircraft) and perhaps these areas should not be patched or else the patching technique should be modified.

Recent work on the aerodynamic effects of wing patches has been undertaken by Carnegie (Reference 14). He investigated the effects of patches (plates) on the aerodynamics of the wing of a CF-18 aircraft. Boundary layer data were obtained for plates of various thicknesses (up to 12.7 mm) and the data were used to develop a set of correlation curves for describing the main effects of the plates on boundary layers. The curves were incorporated into a computer code which was used to analyse the effects of the patches on the flow over the CF-18 wing profile. Carnegie found that patch thickness was the parameter having the most influence on the aerodynamics of the CF-18 aerofoil. Results were plotted for $\alpha = 1^\circ$ to 3.9° and the computations showed that the wing boundary layer remained attached throughout this range of α. For $\alpha < 3^\circ$ and for 12.7 mm thick plates, a moderate reduction in C_L of 0.04 was found. For $\alpha > 3^\circ$, the reduction in C_L was as large as 0.21. At $\alpha = 4^\circ$, the boundary layer separated near the leading edge of the wing and unrealistic results were obtained (negative C_L). Carnegie also found that the effect of plates on drag was generally much greater and could double C_D for plates of thickness 12.7 mm.

3. General Discussion and Concluding Remarks

The foregoing literature survey on the aerodynamics of battle-damaged combat aircraft has shown the empirical nature of the various approaches, and how the results are configuration dependent. Possible future work at AMRL to obtain aerodynamic data for battle-damaged aircraft would be concerned specifically with Australian Defence Force aircraft and conditions, and some attempt would need to be made to tailor any tests to Australian needs.

Experimental details that would be considered include what types of damage to investigate, what parameters to measure, what range of operating conditions to use and the pitfalls to avoid. Reports on the repair of battle-damaged aircraft might also be able to provide information such as the location and extent of damage resulting from various types of attack. They might indicate whether damage from cannon fire is randomly distributed on an aircraft, the number of hits expected and the extent of damage from each hit. They might also indicate whether heat-seeking missiles primarily damage the tail of an aircraft (near the hot engine outlets) and the extent of damage caused by the missiles. When choosing the locations of holes in say an aircraft wing, it would be pointless to have holes at locations where there are major structural members or fuel tanks. The adverse effects on the aircraft of fractured load-bearing members or ruptured fuel tanks, associated with the formation of the holes, would most likely be far more severe than the aerodynamic effects of the holes.

The static aerodynamic characteristics of interest to AMRL would be for damaged F/A-18, F-111 or PC-9 aircraft, but no such data were found during the literature search. The data bases in simulation codes are extensive and it would be a formidable task to measure a complete range of data for an aircraft with a given type of damage. Furthermore, a different set of measurements would be required for each particular type of damage for each of the aircraft. Data from outside sources would have to be sought to supplement any measurements taken at AMRL. Simulation codes often contain data from flight tests on full-scale aircraft, but it is unlikely that such data will be available for damaged aircraft. It might be necessary to confine any future work at AMRL to a very restricted range of damage and flight conditions.

Current flight-dynamic models are useful when assessing the effects on aircraft performance of some types of damage, such as jammed or floating control surfaces, because these conditions are covered in their existing data bases. However, it would be inappropriate to use such models to analyse the effects of a missing control surface, since the data bases in the models do not apply in this case.

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A literature survey on the aerodynamics of battle-damaged combat aircraft is presented in this report. The survey considers experimental investigations carried out in wind tunnels using either scaled or full-sized models of complete aircraft or components of aircraft that have either simulated damage or actual gunfire damage. The survey could assist in the planning of a possible experimental program at AMRL to obtain aerodynamic data for battle-damaged aircraft. The data could be used in modelling the flight-dynamic behaviour of damaged aircraft.