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Multiaxis Pilot Ratings for Damaged Aircraft

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A systematic methodology for the prediction of loss of control for various maneuvers performed by a specific aircraft with various types and degrees of damage is presented. The study monitors the development of loss of control while the scale of the specific damage is increasing. This study also investigates the sensitivity of the specific aircraft to different types of damage while a specific maneuver is being performed. The result shows the existence of the critical degrees of specific damage that cause the pilot to lose control as represented by a pilot opinion rating (POR) of greater than 9 on the Cooper-Harper rating scale.

Introduction

THE assessment of loss of control of an aerodynamic surface damaged aircraft should receive further attention because of the safety and economic considerations. In many critical situations, knowledge about flying control status is desperately needed so that no human life is sacrificed while saving a seriously damaged aircraft and the valuable aircraft is not abandoned while it can still survive. It is obviously not practical to obtain such knowledge by carrying out real test flights for each specific type of aircraft with various types and degrees of surface damage. In the research, a computer simulation methodology is developed to obtain the data associated with the flying control status of various multiaxis maneuvers for a specific aircraft with various types and degrees of surface damage.

The pioneering work of Cooper and Harper[1] uses the evaluation data collected from human pilots to establish pilot opinion ratings (PORs) to empirically characterize the control performance of aircraft. Kleinman et al.[2] developed the index of performance to theoretically describe the status of flying control for the human pilot. Under several reasonable and necessary hypotheses, Hess[3] correlated the index of performance with POR for single-axis tasks. Based on Hess's work, McRuer and Schmidt[4] defined the mathematical relation between the index of performance and PORs by using Dander's data.[5] With these valuable previous works, this research thus develops a systematic methodology to achieve the following goals: 1) develop the multiaxis dynamic models for a specific aircraft with various types and degrees of damage, 2) relate Cooper-Harper pilot ratings to the index of performance for pilot closed-loop control of damaged aircraft dynamics by use of the optimal-control pilot model, and 3) monitor and predict the states of loss of control for various maneuvers performed by a specific aircraft with various types and degrees of damage, where the maneuver can be a straight and level flight, a steady level turn, a symmetric pull-up, or a combination of a steady level turn and a symmetric pull-up.

Overview of Developed Methodology

The Learjet 24B aircraft is used for the analysis in the study. The specific maneuvers used are straight and level flight, steady level turn, symmetric pull-up, and the combination of a symmetric pull-up and a steady level turn. These maneuvers can be mathematically defined. For straight and level flight, roll rate, pitch rate, and yaw rate are all zero. For a steady level turn, roll rate and pitch angle are zero. For a symmetric pull-up, roll rate, yaw rate, and bank angle are all zero. The steady-state downward velocity and the side velocity are zero for all for maneuvers.

The strategy for assessment of loss of control of this aircraft performing the specified maneuvers with various types and degrees of aerodynamic surface damage can be portrayed using the following procedures:

1) Develop the multiaxis dynamic model of each maneuver for each type and degree of damage, which includes a plant matrix and an input matrix.

2) Transform the developed dynamic models into associated three single-axis transfer functions by using the single-input, single-output (SISO) method.

3) Input the resulting single-axis transfer functions and disturbance function to the Kleinman optimal pilot model (OPM)[2] using a C-language computer program of the OPM developed by Kim[6] to obtain the single-axis performance index J.

4) Transform the single-axis J into its corresponding single-axis POR by utilization of the cost function/rating correlation model.[4]

5) Use the product rule[7] to integrate the single-axis PORs of a specific type and degree of damage into the associated multiaxis POR.

6) Determine the state of control of the aircraft by using the Cooper-Harper rating scale[1] to interpret the resulting multiaxis POR. The aircraft is said to exhibit total loss of control if its POR is larger than 9; otherwise, the aircraft is controllable.

Theoretical Development

To implement the described methodology, some theoretical development tasks are required. The first is the establishment of dynamic models of the aircraft with various types and degrees of damage for different maneuvers that are needed in the first procedure of the methodology. The second procedure is to convert the dynamic model into its three associated single-axis transfer functions. The third procedure is to integrate the single-axis PORs into the associated multi-axis POR by using the product rule.[7] Each development is presented in this section.

Establishment of Dynamic Models

The variables used to define the geometric structure of a specific aerodynamic surface are illustrated by Fig. 1. The aspect ratio with damage, $\boldsymbol{A}$, is thus derived as

$$\boldsymbol{A} = b^2/(4\boldsymbol{S}) \times [1 + [L - \sqrt{L^2 + 4(L - l)(0.5S - \boldsymbol{S})/b}\,]/(L - l)]^2 \qquad (1)$$

where

b = control-surface span ($2a$)
S = area of undamaged control surface
$\boldsymbol{S}$ = area of damaged control surface
L = root chord length
l = tip chord length

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Table 1 Pilot model parameter values

	V_W	τ	τ_N	ρ_{y_1}	ρ_{y_2}	ρ_{y_3}	T_1	T_2
Θ	1	0.2	0.1	0.01	0.01	0.01	0.015	0.025
Φ	1	0.2	0.1	0.01	0.01	0.01	0.750	1.500
β	1	0.2	0.1	0.01	0.01	0.01	0.070	0.140

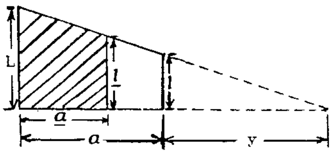

Fig. 1 Sketch of control surface.

By substituting A into the undamaged lift curve slope, the damaged subsonic lift curve slope, C_{L_α} of the specific control surface is obtained:

$$C_{L_\alpha} = 2\pi A/\{2 + \sqrt{[A^2/K^2(1 - M^2 + \tan^2 \Lambda) + 4]}\} \quad (2)$$

where

M = Mach number
K = ratio between lift curve slope and 2Π, 0.9 for studied aircraft because of its thin airfoils
Λ = sweep angle at half chord

The resulting C_{L_α} is substituted into the transform equations provided by Finck and Hoak,[8] and the various force and moment derivatives of the damaged aircraft are obtained. Each stability derivative is then converted into its dimensional stability derivative by being divided by the mass or mass moment of inertia of the aircraft.[8] Thus, the equations of motion of the damaged aircraft are obtained, and the usual state variable perturbation dynamic equations are formed.[9]

Multiaxis POR

The single-axis PORs are integrated into their multiaxis POR by use of the product rule:

$$R_m = 10 + \left(\frac{-1^{m+1}}{8.3^{m-1}}\right) \prod_{i=1}^{m} (R_i - 10) \quad (3)$$

where

R_m = multi-axis POR, ≤ 10
R_i = POR in axis i
m = number of axes

Some Details of Implementation

The Gates Learjet 24B aircraft is used for this research. The flight conditions, geometry and inertias, steady-state coefficients, and stability and control derivatives of this aircraft are given in Ref. 10. The specific types and degrees of damage are damage on wings, horizontal tail, or vertical tail, each with an increment of 6.25% loss of the specific surface area. Moreover, the maximum loss of any surface is limited to 50%. In addition, because this specific aircraft is a commercial one rather than a fighter, the steady-state pitch angle and bank angle should not be larger than 30 deg in practical situations. Therefore, the pitch and/or bank angles of the specified maneuvers are set to be 15 deg or 30 deg.

To perform the third procedure, several parameters are required to utilize Kim's optimal pilot model software.[6] They are neuromuscular constant τ_N, driving noise intensity V_W, human reaction time delay τ, noise ratios $\rho_{y_1}, \rho_{y_2}, \rho_{y_3}$, indifference thresholds T_1, T_2, and fractional attention f. The values of these parameters except f are given in Table 1[11]: The value of f is selected based on the data from the optimal pilot model of McRuer and Schmidt[4] and is between 0 and 1.

Also, in the third procedure, the input of driving noise-shaping filters ($Y_{W,i}$ of the i axis, where i can be θ, ϕ, or β) for the three axes are required by Kim's optimal pilot model software. These driving noise-shaping filters are modeled as a second-order Markov process[4] based on Dander's data and are given as follows:

$$Y_{W,\theta}(s) = 0.2219/(s^2 + 0.7s + 0.25) \quad (4)$$

$$Y_{W,\phi}(s) = 13.3/(s^2 + 0.7s + 0.25) \quad (5)$$

$$Y_{W,\beta}(s) = 0.53/(s^2 + 0.7s + 0.25) \quad (6)$$

The commanded attitude of the associated axis is thus the product of the driving noise-shaping filter of the associated axis and the external disturbance and is calculated by the software automatically. It is important to know that Gaussian white noise is used as the external disturbance. Moreover, in this research, the external disturbance is Gaussian distributed with a mean of zero and a variance that is a delta function of time.

In the fourth procedure, the single-axis index of performance J_i of the i axis is transformed into its corresponding POR by use of the following equation[11]:

$$\text{POR}_i = 7.7 + 3.7 \log_{10}(\bar{J}_i) \quad (7)$$

and $\text{POR}_i \leq 10$. Here, $\bar{J}_i$ is obtained by the equation

$$\bar{J}_i = J_i/\sigma_c^2 \quad (8)$$

where σ^2 is the mean-square output error due to the driving noise and is equal to 0.14, 500, and 0.81 for θ, ϕ, and β axes, respectively.[11] Then, as mentioned above, the obtained single-axis PORs are integrated into a multiaxis POR in the fifth procedure by use of the product rule; the state of control of the aircraft is therefore determined by using the Cooper-Harper rating scale to interpret this obtained POR.

Analysis of Resulting Data

The resulting data are plotted for straight and level flight, steady level turn, symmetric pull-up, and the combination of steady level

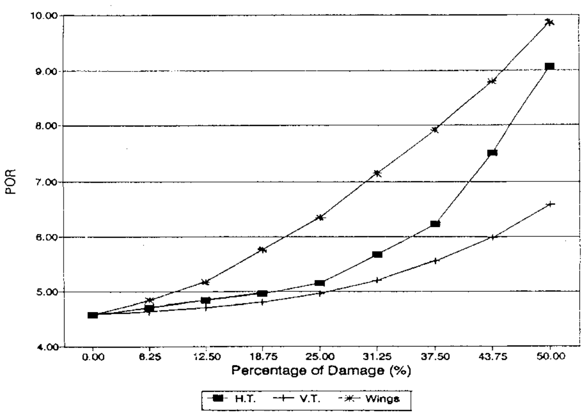

Fig. 2 POR of straight and level flight vs damage.

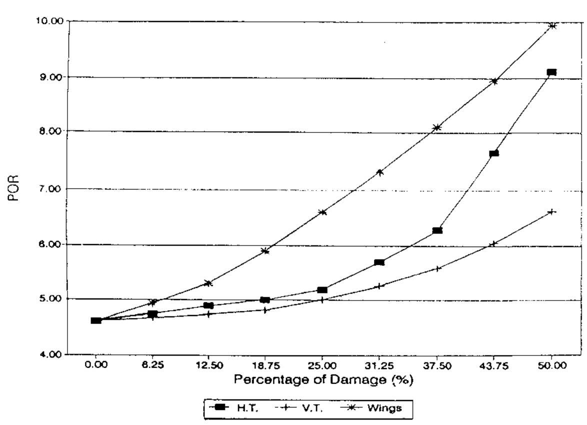

Fig. 3 POR of symmetric pull-up at $\Theta_0 = 15$ deg vs damage.

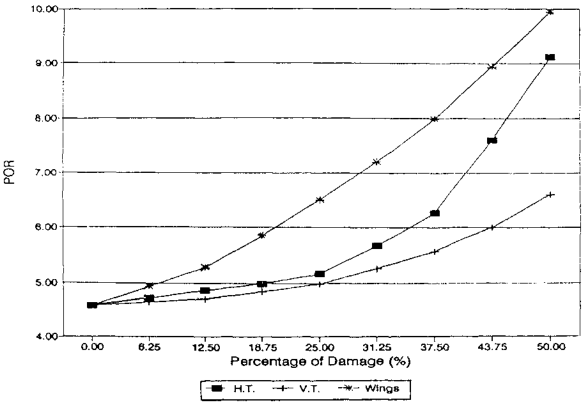

Fig. 4 POR of steady level turn at Φ_0 = 15 deg vs damage.

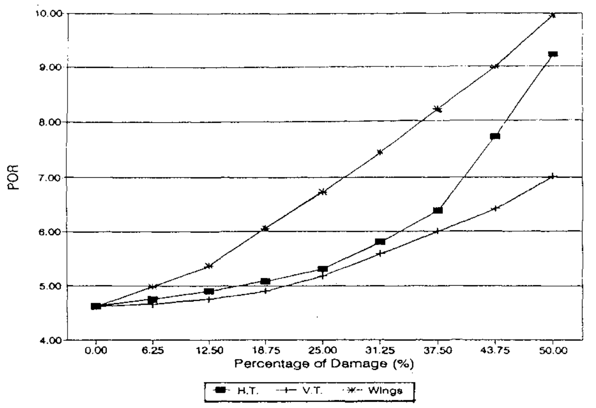

Fig. 5 POR of combinational maneuver with both Θ_0 and Φ_0 at 15 deg vs damage.

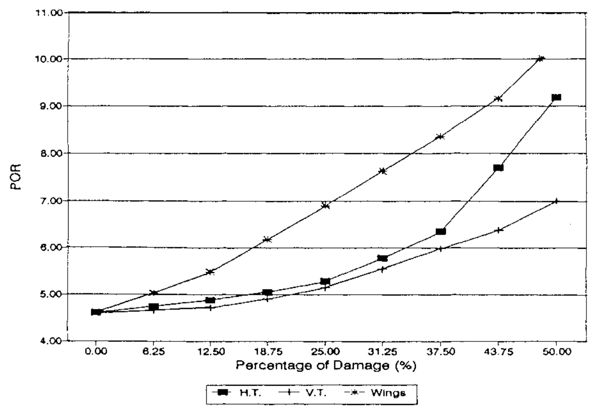

Fig. 6 POR of steady level turn at Φ_0 = 30 deg vs damage.

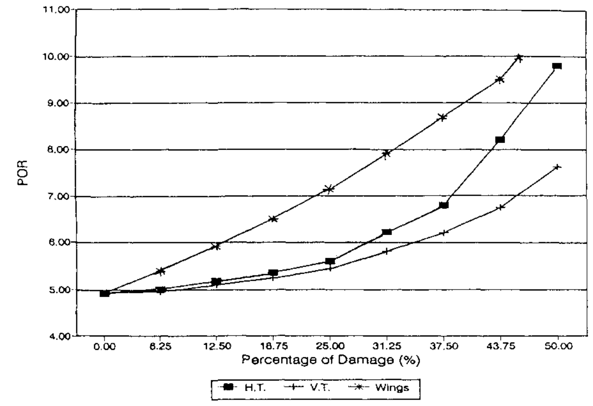

Fig. 7 POR of combinational maneuver with both Θ_0 and Φ_0 at 30 deg vs damage.

turn and symmetric pull-up in Figs. 2–7. From these figures, the computer simulation shows the same trend for all these maneuvers. Namely, loss of control increases whereas the surface damage on the wing, horizontal tail, or vertical tail increases.

The resulting data suggest that the Gates Learjet 24B aircraft is capable of surviving serious surface damage. To perform tasks with small pitch and bank angles that are not more than 15 deg, the aircraft remains controllable even though the surface damage of either type is about 43.75% loss. In addition, coincidently, with the same proportional surface loss, the specific aircraft is more sensitive to wing damage than to tail surface damage if the damage scales are all less than 37.50% for all four types of maneuvers. However, if the damage scales are more than 37.50%, the aircraft is more sensitive to horizontal tail loss. This dramatic increase in sensitivity to horizontal tail loss occurs because the variation of pitching moment coefficient with α, $C_{m\alpha}$, changes its sign from negative to positive whereas the damage scale is 37.50%; this change abruptly reduces the controllability of the aircraft. However, among all types of surface damage, the resulting data suggest that wing loss is still the most serious condition for this aircraft for all types of maneuvers studied.

Moreover, based on the resulting data, some criteria can be established for this Learjet 24B as follows:

1) When performing straight and level flight, symmetric pull-up with Θ_0 not more than 30 deg, steady level turn with Φ_0 not more than 30 deg, or the defined combinational maneuver with neither Θ_0 nor Φ_0 more than 30 deg, the specific aircraft should be abandoned if the wing loss is more than 43.75% or the horizontal tail loss is about 50%.

2) When performing steady level turn with Φ_0 between 15 deg and 30 deg, the specific aircraft should reduce its Φ_0 to 15 deg or less if the wing loss is about 42% or the horizontal tail loss is about 49%.

3) When performing the defined combinational maneuver with both Θ_0 and Φ_0 between 15 deg and 30 deg, the specific aircraft should reduce both Θ_0 and Φ_0 to 15 deg or less or simply reduce its maneuver to the steady level turn with the same Φ_0 if the wing loss is about 40% or the horizontal tail loss is about 45%.

4) When performing straight and level flight, symmetric pull-up with Θ_0 not more than 30 deg, steady level turn with Φ_0 not more than 30 deg, or the defined combinational maneuver with neither Θ_0 nor Φ_0 more than 30 deg, the specific aircraft should not be abandoned even though the vertical tail loss is 50% or less.

Conclusions

The assessment of loss of control of aircraft should be conducted so that the tragedies of human lives being sacrificed to save a seriously damaged aircraft can be avoided. Moreover, the damaged aircraft is not abandoned while it can still survive. This research thus develops a systematic methodology to evaluate the controllability for a specific aircraft, the Learjet 24B, with various types and degrees of aerodynamic surface damage.

The general dynamic models of the aircraft with/without various types and degrees of damage have been developed in this research. These dynamic models, the optimal pilot model, the cost function/rating correlation model, and the Cooper-Harper rating scale, are then successfully integrated into this methodology. Consequently, based on computer simulation, the controllability of the specific aircraft with specific surface damage is monitored and predicted while the aircraft is performing straight and level flight, symmetric pull-up, steady level turn, or the combination of symmetric pull-up and steady level turn. Moreover, safety criteria for operating the specific aircraft are established. With these simple and clear criteria, the pilot can make a decision quickly and correctly to save the aircraft or to safe his or her life. This assumes the pilot has knowledge of the type and amount of damage from a failure identification system.

Although beyond the scope of this work, nonlinear aerodynamics and dynamics as well as autopilot engagement when damage occurs would likely have important influences on pilot ratings.

Appendix: Flight Conditions and Aerodynamic, Inertial, and Geometric Data

Velocity = 677 ft/s	Altitude = 40,000 ft
Air density = 0.000588 slug/ft^3	Weight = 13,000 lb
$I_{xx} = 28{,}000$ slug/ft^2	$I_{yy} = 18{,}800$ slug/ft^2
$I_{zz} = 47{,}000$ slug/ft^2	$I_{xz} = 1300$ slug/ft^2
Wing area = 230 ft^2	Wing span = 34 ft
Wing mean geometric chord = 7 ft	

$C_{L_0} = 0.41$	$C_{D_0} = 0.03$	$C_{m_\alpha} = -0.64$
$C_{m_{\dot{\alpha}}} = -6.70$	$C_{m_q} = -15.50$	$C_{L_u} = 0.40$
$C_{L_\alpha} = 5.84$	$C_{L_{\dot{\alpha}}} = 2.20$	$C_{L_q} = 4.70$
$C_{D_\alpha} = 0.30$	$C_{L_{\delta e}} = 0.46$	$C_{m_{\delta e}} = -1.24$
$C_{l_\beta} = -0.11$	$C_{l_p} = -0.45$	$C_{l_r} = 0.16$
$C_{l_{\delta a}} = 0.18$	$C_{l_{\delta r}} = 0.02$	$C_{n_\beta} = 0.13$
$C_{n_p} = -0.01$	$C_{n_r} = -0.20$	$C_{n_{\delta a}} = -0.02$
$C_{n_{\delta r}} = -0.07$	$C_{y_\beta} = -0.73$	$C_{y_p} = 0$
$C_{y_r} = 0.40$	$C_{y_{\delta a}} = 0$	$C_{y_{\delta r}} = 0.14$

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