References

[1]Balas, M. J., "Trends in Large Space Structure Control Theory: Fondest Hopes, Wildest Dreams," *IEEE Transactions on Automatic Control*, Vol. AC-27, No. 3, 1982, pp. 522–535.

[2]Kimura, H., "Pole Assignment By Gain Output Feedback," *IEEE Transactions on Automatic Control*, Vol. AC-20, No. 4, 1975, pp. 509–516.

[3]Davison, E. J., and Wang, S. H., "On Pole Assignment in Linear Multivariable Systems Using Output Feedback," *IEEE Transactions on Automatic Control*, Vol. AC-20, No. 4, 1975, pp. 516–518.

[4]Srinathkumar, S., "Eigenvalue/Eigenvector Assignment Using Output Feedback," *IEEE Transactions on Automatic Control*, Vol. AC-23, No. 1, Feb. 1978, pp. 79–81.

[5]Juang, J. N., Lim, K. B., and Junkins, J. L., "Robust Eigensystem Assignment for Flexible Structures," *Journal of Guidance, Control, and Dynamics*, Vol. 12, No. 3, 1989, pp. 381–387.

[6]Aubrun, J. N., "Theory of Control of Structures by Low-Authority Controllers," *Journal of Guidance and Control*, Vol. 3, No. 5, 1980, pp. 444–451.

[7]Balas, M. J., "Direct Velocity Feedback Control of Large Space Structures," *Journal of Guidance and Control*, Vol. 2, No. 3, 1979, pp. 157–180.

[8]Balas, M. J., "Direct Output Feedback Control of Large Space Structures," *Journal of the Astronautical Sciences*, Vol. 27, No. 2, 1979, pp. 252, 253.

[9]Martinovic, Z. W., et al., "Analytical and Experimental Investigation of Output Feedback vs Linear Quadratic Regulator," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 1, 1990, pp. 160–167.

[10]Creamer, N. G., "An Identification Method for Damped Structures," *Proceedings of the 1987 SEM Spring Conference on Experimental Mechanics*, Houston, TX, June 1987, pp. 260–267.

Lateral-Direction Tracking Requirements from Simulation Data

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Nomenclature

F_{as} = lateral stick input
L_{Fas} = lateral stick to roll rate sensitivity
p = roll rate
β = sideslip angle
δ_a, δ_{sp} = aileron and spoilers deflection
τ_{ap} = low-order equivalent system time delay
τ_s, τ_r = spiral and roll modes time constants
ω_ϕ, ζ_ϕ = roll transfer function zero natural frequency and damping
ω_d, ζ_d = dutch-roll natural frequency and damping

Introduction

THE primary lateral-directional control task is the control of bank angle by use of lateral stick. The precision of tracking is highly dependent on the numerator/denominator dipole cancellation in the roll transfer function for conventional aircraft as well as for highly augmented ones, which possess an equivalent low-order transfer function in the appropriate frequency range. The Northrop criterion[1] has been used to relate flying qualities characteristics to the amount of dipole cancellation via the parameter ω_ϕ/ω_d. In the present work, a fixed-base simulation has been carried out to further validate the method by relating pilot comments and tracking error data to the analytical level boundaries provided by the criterion.[2] A general agreement has been found with the left-hand boundaries limits, whereas the boundary position on the right-hand side of the criterion appears disputable.

Lateral-Directional Tracking Requirements

The primary lateral-directional tracking task involves bank-angle control by lateral stick. For highly augmented aircraft, an equivalent system transfer function can be obtained by reducing the high-order dynamics over the frequency range of interest (usually between 0.1 and 10 rad/s) using, for example, low-order equivalent systems techniques[3] to yield

$$\frac{p(s)}{F_{as}(s)} = \frac{L_{Fas}\, s[s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi{}^2]e^{-\tau_{ap}s}}{[s + (1/\tau_s)][s + (1/\tau_r)](s^2 + 2\zeta_d\,\omega_d\,s + \omega_d{}^2)} \tag{1}$$

When the complex dipole cancels out ($\omega_\phi = \omega_d$ and $\zeta_\phi = \zeta_d$), the roll-rate response is not contaminated by sideslip contribution in the dutch-roll mode and the response has the classical nonoscillatory behavior. If such cancellation does not occur, both open-loop and closed-loop lateral-directional tracking tasks are severely affected. The Northrop criterion, shown in Fig. 1, has been used in the past to relate pilot ratings and dipole cancellation by plotting the dutch-roll excitation parameter ω_ϕ/ω_d. The cancellation depends mainly on the zero-pole natural frequencies and, to a lesser extent, on the damping factors. Recalling Ref. 4, we can relate ω_ϕ and ω_d to $C_{n\delta a}$ and $C_{l\delta a}$ using

$$\omega_\delta^2 = N'_\beta\left(1 - \frac{N'_{\delta a}L'_\beta}{L'_{\delta a}N'_\beta}\right) \tag{2a}$$

$$\omega_d^2 = N'_\beta \tag{2b}$$

Hence, the importance of ω_ϕ/ω_d as the parameter that determines proverse (>1, or $C_{n\delta a}/C_{l\delta a} > 0$) or adverse ($<1$, or $C_{n\delta a}/C_{l\delta a} < 0$) yaw tendencies during roll control. The importance of ω_ϕ/ω_d is mainly felt during closed-loop tasks. From a root locus analysis of Eq. (1), it is clear that when the zero natural frequency is lower than the dutch-roll natural frequency, the closed-loop damping increases when the pilot closes the bank-angle error to aileron loop. Conversely, if ω_ϕ

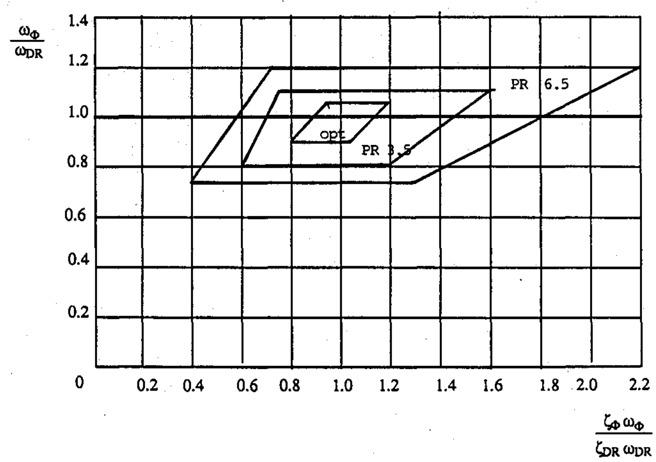

Fig. 1 Northrop criterion boundaries.

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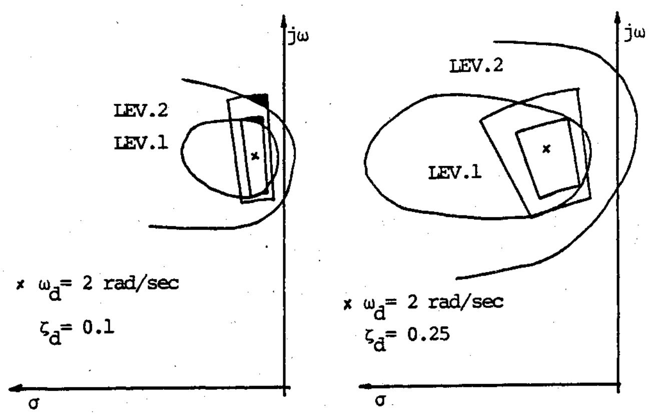

Fig. 2 Mapping of the Northrop criterion into the MIL-8785B boundaries sample location of ω_ϕ and ζ_ϕ for two sets of dutch-roll values.

is greater than ω_d, there is a decrease in closed-loop damping, which could lead to pilot-induced oscillations. Clearly, for highly damped dutch-roll, the effect of dipole cancellation is smaller.

A relation between the Northrop criterion and the more familiar MIL-8785B is shown in Fig. 2 where level 1 and 2 military specification boundaries are mapped into ω_ϕ zero location together with the Northrop requirements on a complex plane for various values of dutch-roll poles. For a given value of the dutch-roll natural frequency and damping, boundaries for ω_ϕ and ζ_ϕ are drawn in the complex plane and superimposed to MIL-8785B boundary levels.

From the figure we can see that the criterion is more demanding in the region to the left of the pole, whereas it is insufficient, especially for low-damping cases, in the corners to the right of the pole (the left plot has a level 2 dutch-roll damping). An important aspect of the Northrop criterion is that it implicitly accounts for the usable zero location areas in the complex plane due to increases in dutch-roll natural frequency and damping.

We must point out that, in analyzing lateral-directional tracking performance due to dipole effects, other parameters must be taken into account, which characterize the global lateral-directional flying qualities such as $1/\tau_r$, $1/\tau_s$, τ_{ap}, and $|\phi/\beta|_d$.[5] Therefore, careful application of the criterion requires meeting military specification requirements in terms of roll, spiral, and dutch-roll modes as well as loop equivalent time delay and small to medium values of dutch-roll magnitude contribution to the rolling and sideslipping degrees of freedom.

Simulation

A limited fixed-based simulation of the lateral tracking task was performed using Aeritalia's two-dome simulator. The AMX aircraft was used in the simulation and it is a subsonic dedicated attack fighter with conventional flight control system. The aircraft is statically stable and it has a limited authority stability augmentation system, which only marginally affects the dynamic characteristics. The flight control system is a three-axis fly-by-wire managed by a digital computer along with conventional electrohydraulic channels.

The simulation consisted of a formation flight with respect to a leader flying the same trajectory and whose image was computer generated. The single test pilot was asked to maintain the fixed vector displayed on the head-up display exactly on the nozzle of the model, in level flight as well as in a 45-deg bank maneuver. During the simulation, which lasted for 30 s, the yaw control was free and minimum use of longitudinal control was required. The rms and integral errors on lateral and vertical translations and roll rotation, as well as lateral and longitudinal stick activities, were monitored to provide a measure of the pilot capability to track the leader aircraft, to compare the various configurations and to establish a correlation with the analytical results from the Northrop criterion.

Nine configurations were flown, corresponding to nominal case and degraded states; their characteristics and pilot comments are given in Table 1. Figure 3 shows the simulation results in terms of flying quality levels as determined using the Northrop criterion chart. The nominal condition (case 1 FFCS) was found slightly difficult to control due to sluggish roll response, although the roll-time constant meets level 1 flying qualities.

Better comments were given for configurations 3 and 9. In fact, the absence of roll damper leads to lower roll-time constant and relative improvement in roll control. The most difficult configurations were 4 and 5 because of the low damping

Table 1 Pilot comments from simulation

Configuration	Description	Pilot comments
1) FFCS	Full flight control system	Acceptable but not easy to control in roll due to sluggish response
2) C/F OFF	Cross-feed off	Difficult to control due to roll and yaw oscillations developed during task
3) R/D OFF	Roll damper off	Easier than 1 because of faster roll response and capability of stop bank angle quickly
4) Y/D OFF	Yaw damper off	Very difficult to perform tracking because of unstable oscillations
5) R/D and Y/D OFF	Both dampers off	Same as 4
6) C/F and R/D OFF	Cross-feed and roll damper off	Yaw oscillations, better roll control than 2
7) C/F and Y/D OFF	Cross-feed and yaw dampers off	Strong yaw oscillations, similar to 6
8) C/F + R/D + Y/D OFF	Cross-feed roll and yaw dampers off	More difficult than 6 because of higher oscillations
9) G = G*2/3	Reduced aileron-spoiler gain	Easier than case 1

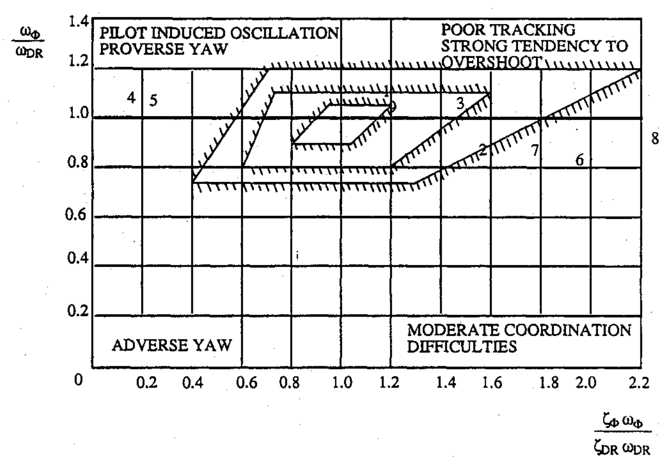

Fig. 3 Simulation results.

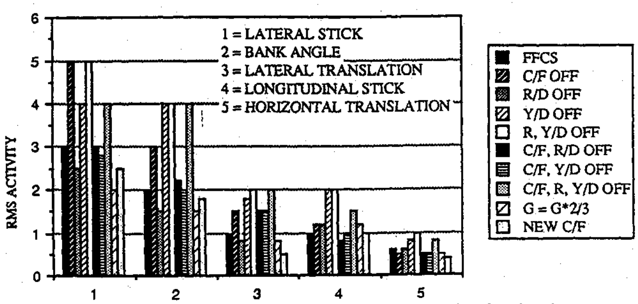

Fig. 4 RMS activity trends for simulated configurations.

(level 2) and $\omega_\phi > \omega_d$ leading to pilot-induced oscillations. Configurations 6 and 7, possessing adverse yaw, were considered difficult; however, their dynamics were to satisfy level 2 flying qualities and this result is shown in Fig. 3. Configuration 9, with reduced gain ailerons/spoilers, had the best ratings due to control effectiveness ratio values given by $C_{n\delta a}/C_{l\delta a} < 0$ for δ_{sp} (proverse yaw). Hence, the reduction of spoilers deflection leads to a decrease in proverse yaw yielding a natural frequency ratio ω_ϕ/ω_d close to unity.

Rms activity of the main variables during tracking is shown in Fig. 4 and trends consistent with pilot comments can be identified. Configurations 2, 4, 5, and 8 consistently show a higher level of stick activity and poorer tracking performance, whereas configurations 1, 3, and 9 clearly possess better flying qualities characteristics.

Conclusions

A limited fixed-base simulation has been performed in order to evaluate the capabilities of the Northrop criterion to relate flying qualities levels and the amount of pole-zero cancellation in the roll axis during tracking tasks. The objective was part of an effort, by the AGARD Flight Mechanics Panel, working group 17, directed toward the analysis of flying qualities techniques for highly augmented aircraft. The validation, although limited, has shown the capability of the method, provided the other parameters involved in the task have level 1 values.

References

[1]Hoh, R., Mitchell, D., and Hodgkinson, J., "Flying Qualities of Air Vehicles: Proposed MIL STD and Handbook," Air Force Wright Aeronautics Lab, Wright-Patterson AFB, AFWAL-TR-82-3081, Vol. 2, Nov. 1982.

[2]Various authors, "Handling Qualities of Unstable Aircraft," AGARD-FMP-WG-17, NATO, 7 Rue Ancelle, 92200 Nevilly-Sur-Seine, France, AGARDograph (to be published).

[3]Hodgkinson, J., and La Manna, W. J., "Equivalent System Approaches to Handling Qualities Analysis and Design Problems of Augmented Aircraft," MCAIR-77-016, Aug. 1977, pp. 1–9.

[4]McRuer, D., Ashkenas, I., and Graham, D., *Aircraft Dynamics and Automatic Control,* Princeton Univ. Press, Princeton, NJ, 1974.

[5]Innocenti, M., and Thukral, A., "Roll Response Criteria for Highly Maneuverable Aircraft Using Gibson's Method," AIAA Paper 89-3391, Aug. 1989, pp. 385–389.

Errata

Fast Orbit Propagator for Graphical Display

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THE following error was inadvertently introduced during the typesetting and production of this paper.

Eq. (9) should read as follows:

$$\bar{\omega}(t) = \bar{\omega}(t_0) + (3/2)J_2R^2\bar{p}^{-2}\bar{n}[2-(5/2)\sin^2\bar{i}](t-t_0) \qquad (9)$$