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"Fast Simulation" in Evaluating Pilot/Aircraft Performance and Handling Qualities

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Abstract: A pilot/vehicle analysis and simulation is exercised using a model of a large transport aircraft. The methodology allows overall handling qualities assessment and performance predictions in specific aircraft maneuvers. The pilot model is adaptive in nature with a goal of modelling pilot behavior in the face of sudden changes in flight control system characteristics. A multi-axis stability and command augmentation system is designed and its robustness is evaluated in a low-level landing approach flight condition. The simulation technique, referred to as *fast simulation*, shows promise as a preliminary tool prior to conducting pilot-in-the-loop evaluation.

Keywords: aircraft control, automation, adaptive control, human-machine interface

1. INTRODUCTION

In making research recommendations for design issues in the Next Generation Air Transportation System, Sheridan, et al, (2006) discuss the role of simulation, both human-in-the-loop and so-called "fast time" where the latter description merely refers to the fact that the simulations are not done in real time. Quoting from the reference, *"Fast-time simulation experiments can be conducted where computational models of human operators are sufficiently well developed and robust, and where operator models can be connected to computer models of the automation, aircraft, etc."* While not intended to replace human-in-the-loop simulations, fast simulations can provide rapid, inexpensive preliminary evaluations of pilot/vehicle performance and handling qualities. The research to be discussed will utilize control theoretic models of the human pilot in fast simulations of pilot control of a large transport aircraft model. The research will demonstrate the utility of the fast simulation approach as a predictor of (1) pilot/vehicle performance, (2) vehicle handling qualities, and (3) adaptive pilot behaviour to sudden changes in the flight control system.

2. THE VEHICLE

Figure 1 shows the aircraft to be utilized. The model geometry and aerodynamic characteristics were obtained from de Castro (2003). Although de Castro did not provide for thrust commands in the model, they were included by the author. The vehicle is seen to be quite large, with a wing span and mass approximately 25% larger than those of a Boeing 747. The selection of a large transport aircraft was motivated by the fact that there is continuing interest in the handling qualities of such vehicle, see, for example, Field and Rossitto (1999), Shweyk and Rossitto (2000), and Hess and Joyce (2013). The flight condition under study will be a landing approach configuration (sea level) with a trim airspeed of 100 m/s. The aerodynamic model is linear, with uncoupled longitudinal and lateral dynamics. Three-dimensional atmospheric turbulence will be modelled, with disturbances in longitudinal gust velocity u_g (m/s), angle of attack, α_g (rad) and sideslip β (rad). The "effective" control inputs provided by the pilot and the stability and command augmentation system (SCAS) are elevator, aileron, rudder and engine thrust. The thesis of de Castro describes the allocation of the multiple aircraft control surfaces to each of these "effective" control inputs.

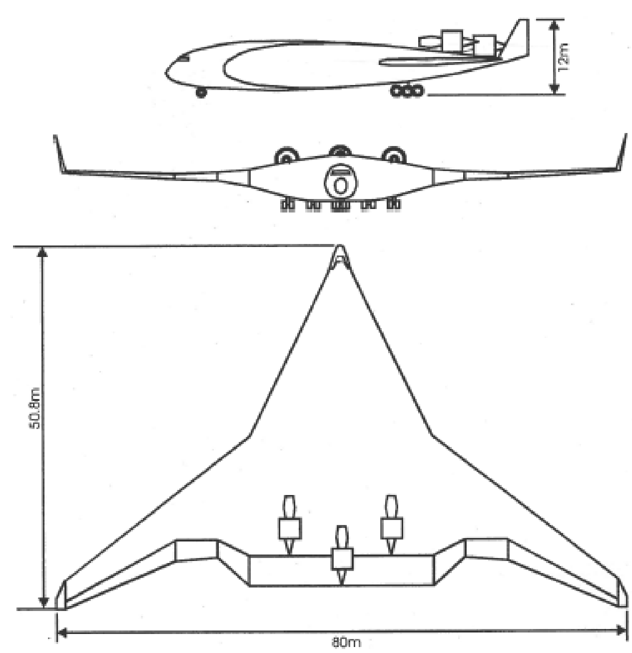

Fig. 1 The blended-wing body aircraft.

The state and control variables for the aircraft model are given by

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$$\dot{x} = Ax + Bu$$

$$x = \{u, \alpha, q, \theta, \beta, p, r, \phi, \psi\}^T \qquad (1)$$

$$u_c = \{\delta_e, \delta_a, \delta_r, \delta_T, u_g, \alpha_g, \beta_g\}^T$$

Where,

u = airspeed (from trim), m/s

α = angle of attack, rad

q = pitch rate, rad/s

θ = pitch attitude, rad

β = sideslip angle, rad

p = roll rate, rad/s

r = yaw rate, rad/s

ψ = heading, rad

δ_e = elevator angle, rad

δ_a = aileron angle, rad

δ_r = rudder angle, rad

δ_T = thrust (from trim), N

u_g = longitudinal velocity turbulence input, m/s

α_g = angle of attach turbulence input, rad

β_g = sideslip angle turbulence input, rad

$$A = \begin{bmatrix} -2.38e-2 & -11.39 & -14.766 & -0.6992 & 0 & 0 & 0 & 0 & 0 \\ -2e-3 & -0.7535 & 0.9744 & -1.45e-2 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.256 & -0.2153 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -1.94e-2 & 5.3e-2 & -1.0095 & 9.81e-2 & 0 \\ 0 & 0 & 0 & 0 & -0.7069 & -1.2803 & -8.73e-2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.13e-2 & 1.45e-2 & -4.59e-2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1.0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 2.69e-6 & 2.38e-2 & 11.39 & 0 \\ -0.1667 & 0 & 0 & 0 & 2.0e-3 & 0.7535 & 0 \\ -1.89 & 0 & 0 & -1.0e-7 & 0 & 0.256 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 2.1e-3 & 6.4e-3 & 0 & 0 & 0 & 1.94e-2 \\ 0 & -0.5647 & 0.1035 & 0 & 0 & 0 & 0.7069 \\ 0 & 9.9e-3 & -4.22e-2 & 0 & 0 & 0 & -2.13e-2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Second-order amplitude and rate-limited actuators were included in the analyses and fast simulations. The linear actuator dynamics were described by

$$\frac{\delta_{act}}{\delta_{comm}}(s) = \frac{50^2}{s^2 + 2(0.707)50s + 50^2} rad/rad \qquad (2)$$

Amplitude limits were set to ± 0.52 rad (±30 deg) with rate limits of 0.87 rad/s (± 50 deg/s). A simple engine model for the turbo-fan engines was created as

$$\frac{\delta_T}{\delta_{comm}}(s) = \frac{1}{s+1} N/N \qquad (3)$$

3. THE PILOT MODEL(S)

The literature is replete with discussions of mathematical models of the human pilot for tracking studies. A useful background can be found in Hess, (1997). The analytical pilot models to be utilized in the study are the multi-axis structural and adaptive pilot models of Hess, (1997a), (2016). In fast simulations in which changes in SCAS characteristics are considered, the adaptive model is employed. This model is based upon the pursuit pilot model described by Hess (2006). Here "pursuit" refers to the fact that the pilot model assumes that the pilot can independently sense system output-rate, as opposed to system error-rate. As will be seen, the structural model will provide estimates of aircraft handling qualities and performance with a "healthy aircraft" and the adaptive model will demonstrate the ability of the pilot to accommodate SCAS changes.

Figures 2 and 3 show the two pilot model structures in block diagram format. These models are for the inner-most loops under pilot control, i.e., pitch and roll attitude. Models describing pilot behaviour in the outer response loops, i.e. controlling altitude-rate and altitude in the longitudinal modes, and heading in the lateral modes were also provided and consisted of pure gains or simple integrations. Details of the pilot models are included in Appendix A. In Fig. 2, and for the current application, switches 1, 2, and 3 are in the "down" position, and switch 4 is in the "middle" position, i.e., no vestibular feedback was considered. The element Y_{NM} is a simple second-order model of the neuromuscular system of the pilot's arm, and Y_{FS} is a second-order model of the force/feel systems in the aircraft's cockpit inceptors (column and wheel). Details of selecting the remaining model parameters in Fig. 2 can be found in Hess (1977). The relative simplicity of the non-adaptive structure of the model of Fig. 3 as compared to that of Fig. 2 means that no force/feel systems are modelled, and no explicit time delay is included. Details about the Fig. 3 model can be found in Hess (2006) with the adaptive logic presented in Hess (2016). The need for two separate pilot models can be explained by the fact that inclusion of adaptive logic in the pilot model of Fig. 2 was unduly complex, and the g the simpler model of Fig. 3 was instead utilized. The structural model of Fig. 2 was retained to make handling qualities estimates. These estimates were obtained by creating what is referred to as a "handling qualities sensitivity function" (HQSF) defined as

$$HQSF = \left| \frac{1}{K_e} \cdot \frac{U_M}{C}(j\omega) \right| \qquad (4)$$

and plotting the HQSF vs ω on linear scales. Fig. 4 shows bounds defining predicted handling qualities levels using the Cooper-Harper pilot rating scale (1969). The bounds of Fig. 4 have been simplified somewhat from those of Hess (1997) for the purposes of clarity. As an example, the solid curve is representing an HQSF predicting Level 2 handling qualities.

Two levels of handling qualities can be examined. The first has been termed "task-independent" and the second "task-dependent." Task-independent handling qualities are obtained by forcing 2.0 rad/s crossover frequencies in the pilot model