Flight Control for the F-8 Oblique Wing Research Aircraft

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ABSTRACT: This paper discusses multivariable flight control laws for the F-8 Oblique Wing Research Aircraft. The control laws are developed using a loopshaping methodology to support the NASA/Navy program to ultimately flight test a supersonic aircraft with an oblique wing with as much as 65-deg wing skew. The objective of the control laws is to obtain decoupling of the longitudinal and lateral-directional motions of the unsymmetrical aircraft, as well as to satisfy conventional flight control objectives, including gust attenuation, good command tracking, good handling qualities, and stability robustness with respect to model uncertainty. A multivariable proportional-plus-integral element is the basic ingredient of the control laws, along with sensor blending into regulated variables and pilot command precompensation. Various analyses, including frequency and time responses, are presented. Stability robustness properties of the control laws are presented using structured and unstructured singular-value techniques. Responses of the controlled aircraft due to pilot inputs are illustrated using time histories.

Introduction

NASA and the Navy are sponsoring a research program to ultimately flight test a supersonic oblique wing aircraft [1], [2]. The wing will have a pivot to allow zero skew angle for low speed and landing approach and as much as 65-deg wing skew for supersonic flight. Such an aircraft promises several advantages over a similar aircraft with symmetric variable sweep [3]. Some specific advantages include: (1) reduced supersonic wave drag as compared to conventional geometry designs, (2) a more versatile (i.e., a loiter configuration with zero wing sweep versus a dash configuration with large wing sweep), more efficient (i.e., fuel savings due to different configurations) aircraft over a wide range of operating conditions, and (3) a single pivot is structurally more advantageous (i.e., hinge moments and forces balance) than other variable-sweep symmetric aircraft [4].

This paper discusses the development of multivariable control laws for the F-8 Oblique Wing Research Aircraft. Point designs for the five flight conditions in Table I have been developed to date. Gain schedules will be developed for the full flight envelope in the future. The aircraft control laws were implemented and flown on NASA Ames' moving base simulator in January 1987. This work was performed as part of Rockwell's NAAO (North American Aircraft Operations) feasibility and preliminary design activities in support of this research program [5], [6]. A sketch of the aircraft is shown in Fig. 1. It is equipped with conventional ailerons, elevator, and rudder. In a large wing skew configuration, the ailerons have very little roll control power because of their small moment arms relative to the aircraft center of mass. Thus, a rolling tail was employed for roll control in these configurations. Sensors used as part of the control laws are three body angular rate gyros (roll, pitch, yaw), normal and lateral accelerometers, and an inertial reference system for roll and pitch Euler angles. The pilot commands the control laws with conventional longitudinal and lateral stick and rudder pedals.

The remainder of the paper is divided into five sections. The next section discusses the flight control problem. The following section describes mathematical models used for design and analysis. Discussion of the control law design is contained in the next section. Analysis of the control laws is then covered. The final section contains conclusions.

Flight Control Problem

The key objective of the control laws is to decouple the longitudinal and lateral-directional motions of the aircraft. Without the control laws, all motions of the aircraft (with a highly skewed oblique wing) are highly coupled and it would not be possible to meet conventional handling qualities specifications. Other objectives for control of the oblique wing aircraft include gust attenuation, desensitization, good command tracking, stability augmentation, good handling qualities, and stability robustness with respect to model uncertainty.

A control structure for controlling the oblique wing aircraft is shown in Fig. 2. The matrix transfer function for the aircraft, actuator, and digital implementation dynamics is denoted as $M(s)$. There are five control surface actuator commands: left elevator, right elevator, rudder, left aileron, and right aileron, which are denoted as $\delta_l$, $\delta_r$, $\delta_r$, $\delta_a$, and $\delta_{a_r}$, respectively. There are seven sensor outputs: roll rate, pitch rate, yaw rate, lateral acceleration, normal acceleration, roll angle, and pitch angle, which are denoted as $p$, $q$, $r$, $n$, $n$, $\phi$, and $\theta$, respectively. The matrix transfer functions indicated by $R(s)$, $M(s)$, $K(s)$, and $P(s)$ are portions of the control law. $R(s)$ combines the seven sensor outputs into three regulated variables that rep-

Table 1

| Flight Conditions |
|-------------------|---------|-----|
| $M$               | $h_r$   | $\alpha_r$ |
| 0.9               | 500     | 65  |
| 1.6               | 29K     | 65  |
| 1.2               | 29K     | 65  |
| 1.4               | 29K     | 55  |
| 0.8               | 20K     | 45  |

Fig. 1. F-8 Oblique Wing Research Aircraft sketch.
resent the basic flight control objectives for the three axes. The pilot commands the roll variable with the lateral stick, the yaw variable with the rudder pedals, and the pitch variable with the longitudinal stick. M(s) is the surface management transfer function, which produces the five individual surface commands from three commands representing effective aileron, elevator, and rudder. Finally, K(s) is the feedback compensator and P(s) the precompensator.

**Regulated Variables**

The basic flight control objectives involve three loops: roll, pitch, and yaw. Regulated variables, which must be some combination of measured variables, are defined as follows.

The regulated variable for the roll axis is roll rate plus a small gain (0.02 sec⁻¹) times the roll Euler angle. This choice expresses the desired to command roll rate with the lateral stick and to regulate roll rate to zero when there is no lateral stick command. The small gain on roll angle provides a stable closed-loop spiral mode and is probably not necessary since a sufficiently small unstable drift is permitted by the military handling qualities specifications.

The regulated variable for the pitch axis will be a combination of pitch rate and low-passed nz plus a small gain times the sine of the pitch Euler angle. Low-passed normal acceleration provides gust attenuation while avoiding undesirable flexure effects, and pitch rate is used for stability augmentation. The relative gain between pitch rate and normal acceleration [12.6 g/(rad/sec)] was chosen to obtain a desirable stick gradient variation with speed. The break frequency for the nz low pass was set as high as possible but limited by the nonminimum-phase characteristics of the nz measurement. The value of 3 rad/sec for the break frequency was selected. The small gain (0.3 g) on the sine of the pitch angle provides a stable closed-loop phugoid.

For the yaw axis, the variable ny is first defined from kinematic relations as follows:

\[
ny = Vg(r \cos \alpha_0 \cos \beta_0 - p \cos \beta_0 \sin \phi)
\]

where V is the velocity of the aircraft, g the gravitational acceleration, p the roll rate, r the yaw rate, and \( \phi \) the roll Euler angle. The symbols \( \beta_0 \) and \( \alpha_0 \) denote constants for the flight condition (possibly gain scheduled). For the purpose of control, ny can be thought of as a variable that is proportional to the difference between the actual turn rate and the turn rate associated with a coordinated turn. The regulated variable for the yaw axis will be a complementary blend of lead/lag-compensated lateral acceleration together with ny. The lead/lag compensator is a stable low-order approximation to \( G_{ny}(s)/G_{ny}(s) \), where the transfer functions indicated are from rudder to ny and ny. The lead/lag compensator improves stability augmentation. The complementary filter (with break frequency at 1 rad/sec) results in a regulated variable, which is ny for stability augmentation at high frequency and lateral acceleration for coordinated turns at low frequency. The complementary filter break frequency was set as high as possible but was limited by the nonminimum-phase characteristics of the ny measurement.

**Surface Management**

The surface management transfer function forms the individual surface commands from effective aileron, elevator, and rudder commands. For a zero skew condition, this function would just deflect the ailerons differentially for an aileron command, deflect the elevators symmetrically for an elevator command, and deflect the rudder for a rudder command. For a highly skewed wing condition, the surface management just deflects the horizontal tail differentially for the aileron command and symmetrically for the elevator command.

**Bandwidth Considerations**

The open-loop rigid-body aircraft has two underdamped modes (four poles) with frequencies between 3 and 7 rad/sec, depending on the flight condition. These two modes are similar to a symmetric aircraft’s short-period and dutch-roll modes. Stability augmentation of these modes requires bandwidths in excess of 7 rad/sec. Gust rejection, desensitization, and decoupling of pilot inputs are all improved with increasing bandwidth. The limiting factor for bandwidth is model uncertainty (especially at high frequencies) and uncompensable nonminimum-phase elements in the feedback loop. The primary contributor to model uncertainty is unsteady aerodynamics and structural flexure. A goal of 10-rad/sec bandwidth was selected based on having adequate roll-off for an elastic mode in the neighborhood of 40-50 rad/sec. A 50-Hz sample rate for the digital implementation is consistent with this bandwidth goal.

**Models**

A number of different models of the aircraft dynamics were used for the control law development. All of the models were obtained through Rockwell NAAO [7]. The simplest model was a standard eight-state linearized model of the rigid-body dynamics. The rigid-body model was augmented with linearized models of primary and secondary actuator dynamics, and digital implementation: antialiasing prefilters, time delays for sample and hold, and computational delay. The most complex model used was a simulation of the aircraft dynamics, including nonlinear kinematics and aerodynamics as well as actuator dynamics and was implemented at Rockwell NAAO. Models of the primary and secondary actuators also included deflection and rate limits.

Most of the control law development was carried out using the simple eight-state model. Figure 3 is a state-space model for the Mach = 0.8, altitude = 20,000 ft, \( \Lambda = 45 \) deg flight condition. The state-space model appears in the form

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\]
The state vector is \([ V, \beta, \alpha, p, q, \phi, \psi, \theta]^{T}\), the control input vector is \([ \delta z, \delta x, \delta y]^{T}\), and the two outputs are \(n)\) and \(n2\). Models of the actuator and digital implementation effects used to design lead compensation. The simulation was used for assessing the performance of the control laws in the presence of nonlinearities.

Model accuracy deteriorates at higher frequencies due to unmodeled aeroviscoelastic effects. Model uncertainty was parameterized with an unstructured multiplicative perturbation at the plant and a diagonal multiplicative perturbation at the control surfaces.

### Control Design

Having defined the regulated variables and the surface management, a plant transfer function can be introduced, which will be denoted by \(G(s) = R(s)A(s)B(s)\). The plant transfer function is a \(3 \times 3\) matrix transfer function connecting the effective aileron, elevator, and rudder-to-roll-, pitch-, and yaw-regulated variables.

It is easily shown [8] that the error between the regulated variable vector and the precompensated pilot command vector in response to pilot commands and disturbances (reflected to the regulated variable) is \(H(s)\). The open-loop transfer function is \(G(s)\) and \(H(s)\) are 3 \times 3 matrices. This makes the pre-compensation take the form of \(G(s)\) times the inverse of the aircraft dynamics, where the aircraft is approximated with a first-order transfer function \((Ks + H)^{-1}\), where \(K\) and \(H\) are 3 \times 3 matrices. The proportional-plus-integral (P+I) compensation provides the high gain at low frequency. The P-I compensation takes the form of the \(\frac{1}{s}\) times the inverse of the aircraft dynamics, where the aircraft is approximated with a first-order transfer function \((Ks + H)^{-1}\), where \(K\) and \(H\) are 3 \times 3 matrices. The proportional-plus-integral (P+I) compensation takes the form of the \(\frac{1}{s}\) times the inverse of the aircraft dynamics, where the aircraft is approximated with a first-order transfer function \((Ks + H)^{-1}\), where \(K\) and \(H\) are 3 \times 3 matrices.

### Proportional Plus Integral

The proportional-plus-integral (P+I) compensation provides the high gain at low frequency. The P-I compensation takes the form of the \(\frac{1}{s}\) times the inverse of the aircraft dynamics, where the aircraft is approximated with a first-order transfer function \((Ks + H)^{-1}\), where \(K\) and \(H\) are 3 \times 3 matrices. The proportional-plus-integral (P+I) compensation provides the high gain at low frequency. The P-I compensation takes the form of the \(\frac{1}{s}\) times the inverse of the aircraft dynamics, where the aircraft is approximated with a first-order transfer function \((Ks + H)^{-1}\), where \(K\) and \(H\) are 3 \times 3 matrices.

### Analysis

This section summarizes the analyses of the aircraft control laws. This paper concentrates on linear analyses, although nonlinear simulation was also used to verify flight worthiness of the control laws. The linear analyses were carried out using a state-space realization of the system involving 37 states. The only nonlinear effects included in the analyses discussed here were the primary and secondary actuator deflection and rate limits that were accounted for in the time simulations.

#### Closed-Loop Poles

The closed-loop poles of the feedback system for the five flight conditions were found to be stable and have adequate damping ratios. The damping ratios are larger than 0.47 for all five flight conditions.
Analysis of Multivariable Frequency-Response Properties

Multivariable frequency-response analyses are discussed for nominal performance and stability robustness, but, first, some notation needs to be developed. To develop the notation for the multivariable frequency-response analyses, recall the closed-loop system shown in Fig. 2. Three transfer functions are of interest:

\[ S(s) = [I + R(s) A(s) M(s) K(s)]^{-1} \]

\[ T_s(s) = M(s) K(s) R(s) A(s) \]

\[ T_s(s) = A(s) M(s) K(s) R(s) \]

\[ T(s) = [I + M(s) K(s) R(s) A(s)]^{-1} \]

where \( S(s) \) is the sensitivity matrix associated with the regulated variables, \( T_s(s) \) the complementary sensitivity associated with the five actuator commands, and \( T(s) \) the complementary sensitivity associated with the seven outputs (or measurements).

For good nominal performance, it is desirable for the singular values of \( S(j \omega) \) to be less than 1 below the bandwidth of the closed-loop system and less than, say, 2 for any frequency, in particular, around and above crossover. A typical plot of the sensitivity singular values is shown in Fig. 4 for the \( M = 0.8 \), \( h = 20K \), \( \Lambda = 45 \) deg flight condition. It can be seen that good disturbance rejection and desensitization as well as decoupling have been achieved for frequencies below the bandwidth of 10 rad/sec. Around 30 rad/sec, the peak in the singular values of the sensitivity is approximately 2.

For good stability robustness with respect to unstructured multiplicative perturbations at the five actuator commands, it is desirable for the singular values of \( T_s(j \omega) \) (the complementary sensitivity) to be sufficiently small. A typical plot of the singular values of the complementary sensitivity is shown in Fig. 5 for the \( M = 0.8 \), \( h = 20K \), \( \Lambda = 45 \) deg flight condition. Two of the singular values of \( T_s(s) \) are zero since there is only three loops. It can be seen that they are less than \( 2(0.05 \omega + 1)^{-2} \) for all \( \omega \). That is, the peaks are less than 2 and starting at 20 rad/sec, the singular values roll off with a slope of \(-2\) or more. These are generally considered to be good characteristics for complementary sensitivity. The peak of 2 implies diagonal perturbations as large as 0.2, 0.5, and 0.8 percent can be tolerated at any frequency; at higher frequencies, perturbation magnitudes as large as \( \omega^2/800 \) can be tolerated.

Analysis of Handling Qualities

Low-order equivalent systems analysis was conducted to analyze the in-axis handling qualities of the closed-loop system. Decoupling response of the control laws will be discussed in a later section. The in-axis transfer functions investigated are the roll-rate response to lateral stick inputs, lateral acceleration and sideslip response to pedal inputs, and normal acceleration and pitch-rate response to longitudinal stick inputs. The accelerations were computed at the appropriate center of rotation. These transfer functions were fit with the previously presented MIL-F-8785C-specified transfer functions with allowances made for time delays.

The results are contained in Table 2 and typical frequency-response fits are shown in Fig. 7 for the \( M = 0.8 \), \( h = 20K \), \( \Lambda = 45 \) deg flight condition. The solid curves shown in Fig. 7 are for the actual (high-order) responses and the dotted curves are for the approximate (low-order) responses. The equivalent systems fits can be seen to be quite good for all transfer functions, therefore, the equivalent parameters should be meaningful. The level 1 requirements referred to in the following are for class IV, category A flight phases of MIL-F-8785C [10]. The control laws satisfy level 1 requirements for all but the equivalent short-period frequency for one flight condition, for which the frequency is 10 percent too large.

Time Histories

The pilot objectives were taken to be: maintain wings level, heading hold, altitude hold, and velocity hold. To mimic the pilot, outer-loop control laws were designed to satisfy these four objectives. Careful attention was paid to maintain bandwidths of these outer loops within limits of what a human pilot could perform. Bandwidths were selected as 1 rad/sec for heading and bank angle, 0.5 rad/sec for velocity, and 0.3 rad/sec for altitude. Two maneuvers were simulated for two different trim conditions: 1-g straight and level and a 4-g steady pullup. The maneuvers were 0.5-g incremental pulse in \( nz \) and a 50-deg banked turn. Selected results for the 0.5-g incremental \( nz \) pulse are shown in Fig. 8, and the results for the 50-deg banked turn are shown in Fig. 9. The solid curves shown in Figs. 8 and 9 are for all the maneuvers.
Table 2

Equivalent Systems Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$</td>
<td>0.9 1.6 1.2 1.4 0.8</td>
</tr>
<tr>
<td>$h$, ft</td>
<td>500 29K 29K 29K 20K</td>
</tr>
<tr>
<td>$\Lambda$, deg</td>
<td>65.0 65.0 65.0 55.0 45.0</td>
</tr>
<tr>
<td>$T_E$, sec</td>
<td>0.24 0.24 0.24 0.25 0.24</td>
</tr>
<tr>
<td>$r_p$, msec</td>
<td>95.0 97.0 97.0 93.0 93.0</td>
</tr>
<tr>
<td>$\omega_{\delta q}$ rps</td>
<td>10.0 10.0 10.0 8.9 5.4</td>
</tr>
<tr>
<td>$\delta_{\delta q}$</td>
<td>0.71 0.84 0.87 0.68 0.89</td>
</tr>
<tr>
<td>$\omega_{\psi}$ rps</td>
<td>3.4 15.0 12.0 2.2 0.0</td>
</tr>
<tr>
<td>$\omega_{\phi}$ rps</td>
<td>10.0 8.9 8.2 8.2 5.1</td>
</tr>
<tr>
<td>$\omega_\psi$ rps</td>
<td>0.66 0.74 0.70 0.63 0.78</td>
</tr>
<tr>
<td>$T_p$, msec</td>
<td>17.0 17.0 13.0 13.0 0.0</td>
</tr>
<tr>
<td>$\phi$, rps</td>
<td>0.72 0.48 0.40 0.92 0.75</td>
</tr>
<tr>
<td>$\omega_{\omega}$ rps</td>
<td>11.0 3.8 3.8 3.6 2.8</td>
</tr>
<tr>
<td>$\delta_{\phi}$</td>
<td>1.1 0.76 0.81 0.74 0.80</td>
</tr>
<tr>
<td>$\omega_\phi/(n/\alpha)$ (rad)$^{-1}$/(g/(rad))</td>
<td>56.0 96.0 84.0 97.0 95.0</td>
</tr>
<tr>
<td>$\omega_\phi/(n/\alpha)$ (rad)$^{-1}$/(g/(rad))</td>
<td>58.0 98.0 98.0 98.0 99.0</td>
</tr>
<tr>
<td>$n/(\alpha)$ g/(rad)</td>
<td>30.0 31.0 21.0 39.0 21.0</td>
</tr>
<tr>
<td>$\omega_\phi/(n/\alpha)$ (rad)$^{-1}$/(g/(rad))</td>
<td>4.03 0.466 0.688 0.322 0.373</td>
</tr>
</tbody>
</table>

Fig. 7. Equivalent system fits for handling qualities evaluation.

Fig. 8. Response of longitudinal maneuver.

Fig. 9. Response to lateral-directional maneuver.

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trim. Note that the responses due to an nz pulse show small differences (as expected), as do the φ responses due to the banked-turn input. However, the decoupling deteriorates at the elevated g’s condition.

Conclusions

This paper discussed control laws for the F-8 Oblique Wing Research Aircraft. The loopshaping procedure for designing the control laws was presented. The performance and stability robustness objectives for the control laws were presented in terms of singular values and structured singular values of specific frequency responses. The handling qualities of the closed-loop system were analyzed with the equivalent systems technique. Time histories of the closed-loop response to pilot inputs were examined. The analyses using highest fidelity models available showed that the design goals were achieved.

References

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[13] Martin J. Klepi received the B.S.M.E. degree from Stanford University in 1958 and the M.S.M.E. and E.M.E. degrees from the University of Southern California in 1963 and 1969, respectively. Since 1958, he has worked at Rockwell on analysis and synthesis for control systems and dynamics of manned and unmanned aircraft and space vehicles. In 1971, he joined the B-1 project, where his duties have included analysis and synthesis for flexible vehicle effects on the flight control augmentation system and for the structural mode control system (SMCS). He has designed and implemented the flight-test program for the B-1 SMCS. For the last five years, he has been responsible for vehicle modeling and design of multivariable control laws to satisfy military specifications.