NASA Technical Memorandum 88269

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August 1986

National Aeronautics and
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Ames Research Center, Dryden Flight Research Facility, Edwards, California

1986

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MODEL-FOLLOWING CONTROL FOR AN OBLIQUE-WING AIRCRAFT

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Abstract

A variable-skew oblique wing offers a substantial aerodynamic performance advantage for aircraft missions that require both high efficiency in subsonic flight and supersonic dash or cruise. The most obvious characteristic of the oblique-wing concept is the asymmetry associated with wing-skew angle which results in significant aerodynamic and inertial cross-coupling between the aircraft longitudinal and lateral-directional axes. This paper presents a technique for synthesizing a decoupling controller while providing the desired stability augmentation.

The proposed synthesis procedure uses the concept of explicit model following. Linear quadratic optimization techniques are used to design the linear feedback system. The effectiveness of the control laws developed in achieving the desired decoupling is illustrated for a given flight condition by application to linearized equations of motion, and also to the nonlinear equations of six degrees of freedom of motion with nonlinear aerodynamic data.

Nomenclature

A,B	system matrices
h	altitude
J	cost functional
K	gain matrix
M	Mach number
OWRA	oblique-wing research aircraft
p	roll rate, deg/sec
Q,D	state weighting matrix
q	pitch rate, deg/sec
R	control weighting matrix
r	yaw rate, deg/sec
s	complex frequency
t	time
u	input vector
v	velocity, ft/sec
x	state vector
α	angle of attack, deg
β	sideslip angle, deg
δ	control surface deflection
θ	pitch angle, deg
Λ	wing skew angle, deg
ϕ	bank angle, deg

Subscripts

aL	left aileron
aR	right aileron
hL	left horizontal tail
hR	right horizontal tail
m	model
p	aircraft

Superscripts

m	number of inputs
n	number of states
T	matrix transpose

Introduction

The advantages of an oblique wing were first noted in the 1940's. However, not until recently have the interest, technology, and mission of an oblique-wing design evolved into a full-scale flight research program. Dryden Flight Research Facility of NASA Ames Research Center and the U.S. Navy are developing an oblique-wing research aircraft (OWRA). Gregory,[1] and Wiler and White[2] have outlined potential advantages and disadvantages of this type of airplane. Theoretical and wind tunnel studies have shown that a variable-skew oblique wing offers a substantial aerodynamic performance advantage for aircraft missions that require both high efficiency in subsonic flight and supersonic dash or cruise.

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The most obvious disadvantage of the oblique-wing concept is the asymmetry associated with wing-skew angle. This asymmetry results in significant aerodynamic and inertial cross-coupling between the aircraft longitudinal and lateral-directional axes.

The test bed for OWRA will be the NASA F-8 digital fly-by-wire aircraft. This aircraft will be modified by the removal of the current high wing and installation of a composite wing-and-pivot assembly. A major part of the OWRA program will be the synthesis of a flight control system which will provide acceptable stabilization and decoupling across the Mach, angle-of-attack, and wing-skew envelope. These aircraft stability and decoupling requirements are ideally suited for the application of modern control theory techniques to the solution of problems associated with OWRA.

The potential advantages of the oblique-wing concept can only be realized by development of related technologies. Foremost among these is the control system architecture to compensate for cross-coupled aircraft responses, while presenting the crew with the feel of a conventional airplane. Current typical design procedures synthesize aircraft controllers based on solutions of two, or at most, three degrees of freedom. However, the added OWRA stabilization and decoupling problems require at least five degrees of freedom simultaneously.

Model following has been a popular method for the design of multivariable control systems, and shown to be amenable to the solution of many aircraft control problems. Commencing with the work of Kalman[3] and Tyler,[4] extensive use has been made of the linear optimal control theory in design of model-following controllers. Yore[5] used this method for simultaneous stability augmentation and mode decoupling. While optimal control theory provides an extremely flexible synthesis technique, various structural approaches have been adopted in synthesizing model-following controllers.[6] A controller based on perfect model following (such as perfect matching of the dynamics of the compensated plant to those of the model) was presented by Alag, Kempel, and Pahle[7] for control of OWRA. Though the desired degree of decoupling was achieved, the control surface activity was excessive and alternate controller development was required.

This paper presents the use of models in design of linear feedback systems by means of linear-quadratic optimization. The linear control law developed provides the decoupling as well as the desired stability augmentation. The effectiveness of the control law is illustrated by time responses from linearized equations of motion, and nonlinear equations of six degrees of freedom of aircraft motion for a given flight condition.

Model-Following Systems

Problem Definition

The concept of model following is useful when an ideal set of plant equations of motion can be specified. The objective of model-following flight control is to force the aircraft to respond as the model would respond to a given pilot command. More precisely, the model-following problem can be stated as follows.

Given the linearized aircraft dynamics,

$$\dot{x}_p = A_p x_p + B_p u_p \tag{1}$$

where $x_p \epsilon R^n$, $u_p \epsilon R^m$, A_p, and B_p are matrices of appropriate dimensions, find the control u_p such that the aircraft states x_p approximate "reasonably well" model state vector x_m. The model state vector x_m is defined by the equation:

$$\dot{x}_m = A_m x_m + B_m u_m \tag{2}$$

where $x_m \epsilon R^n$, $u_m \epsilon R^m$, A_m, and B_m are matrices of appropriate dimensions.

For OWRA, the state and input vectors are given by

$$x = \begin{bmatrix} v \\ \alpha \\ \beta \\ \phi \\ \theta \\ p \\ q \\ r \end{bmatrix} \quad \begin{array}{l} \text{velocity, ft/sec} \\ \text{angle-of-attack, deg} \\ \text{sideslip angle, deg} \\ \text{bank angle, deg} \\ \text{pitch angle, deg} \\ \text{roll rate, deg/sec} \\ \text{pitch rate, deg/sec} \\ \text{yaw rate, deg/sec} \end{array}$$

$$u = \begin{bmatrix} \delta_{hL} \\ \delta_{hR} \\ \delta_{aL} \\ \delta_{aR} \\ \delta_R \end{bmatrix} \quad \begin{array}{l} \text{left horizontal tail deflection, deg} \\ \text{right horizontal tail deflection, deg} \\ \text{left aileron deflection, deg} \\ \text{right aileron deflection, deg} \\ \text{rudder deflection, deg} \end{array}$$

The desired model of the aircraft, defined by matrices A_m and B_m, as well as the aircraft matrices A_p and B_p, are given in Table 1. The desired model used in this study is a modification of the zero-wing-skew configuration at the same flight condition. The aircraft matrices correspond to a flight condition of Mach 0.8 and an altitude of 20,000 ft at 45° wing skew. The elements of A_m were modified to increase the short period and dutch-roll mode damping, and to provide improved roll and spiral mode characteristics.

Explicit Model-Following Systems

There are two configurations of model following, known as implicit model following and explicit model following. As Fig. 1 shows, in implicit model following, the control inputs to the plant are formed from the aircraft states and pilot input. No dynamic coupling exists between the model states and the closed-loop plant; the model state x_m appears only in the performance index.

Figure 2 illustrates the explicit model following in which the model states must be generated for use in forming the control input. Explicit model following requires the simulation of the model as a part of feedforward controller. Alignment of plant and model in the presence of

uncertainties, such as unknown parameters and random disturbances, requires this type of control. This enables a continuous correction of the errors between model and plant states even in the presence of unknown disturbances.

The dynamics of the plant and model are governed by the following linear state equations:

$$\dot{x}_p = A_p x_p + B_p u_p \tag{1}$$

$$\dot{x}_m = A_m x_m + B_m u_m \tag{2}$$

Defining an augmented state vector x, the dynamics of the system are expressed as

$$\dot{x} = Ax + Bu_p \tag{3}$$

where

$$x = \begin{bmatrix} x_p \\ x_m \\ u_m \end{bmatrix} \quad A = \begin{bmatrix} A_p & 0 & 0 \\ 0 & A_m & B_m \\ 0 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} B_p \\ 0 \\ 0 \end{bmatrix} \tag{4}$$

The pilot input u_m is modeled as a constant, an assumption that does not overly distort the reality of the situation and allows a complete analysis of the problem from a theoretical viewpoint.

In explicit model following, the control function u_p is required to minimize a performance index given by

$$J = \frac{1}{2}\int_0^\infty [(x_p - x_m)^T Q (x_p - x_m) + u_p^T R u_p]\, dt \tag{5}$$

where $Q \geq 0$, $R > 0$ are weighting matrices. Using the augmented state vector x, the index J can be rewritten as

$$J = \frac{1}{2}\int_0^\infty (x^T \tilde{Q} x + u_p^T R u_p)\, dt \tag{6}$$

where

$$\tilde{Q} = \begin{bmatrix} Q & -Q & 0 \\ -Q & Q & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{7}$$

If pair (A,B) is stabilizable and pair (A,D with $D^T D = \tilde{Q}$) detectable, the optimal control u_p which minimizes J is given by

$$u_p = Kx = K_{xp} x_p + K_{xm} x_m + K_{um} u_m \tag{8}$$

The model equations must be simulated as a part of the feedforward controller because the controller requires model states.

Results

The degree of coupling in the open-loop aircraft is illustrated by response to application of a 1° command input at 1 sec and returned to zero at 3 sec (either by elevator or aileron input). Figure 3 illustrates the open-loop system response of pitch and yaw angular rate and bank angle to an elevator command input. Significant yaw rate and bank angle are generated as a result of pitch command. Of particular interest is the large change in bank angle, indicating a high degree of cross-coupling.

Table 2 gives the gain matrices for the explicit model-following configuration. Figure 4 indicates the linear closed-loop system response for the command input with the explicit model-following gains. The aircraft response is indicated by the solid line, and the model response by the dashed line in Figs 3 and 4. The model-following response is considered satisfactory with considerable attenuation in the degree of coupling, as indicated by the bank angle response of the aircraft. The model response in bank angle is zero. Figure 5 indicates the closed-loop response for the same case but with the aircraft now represented by a nonlinear simulation of 6 degrees of freedom for the same flight condition. The nonlinearities include the constraints on the control surface rate and position.

Figure 6 indicates the response of the open-loop system to 1° aileron command input. Bank angle, yaw angular rate, and pitch angular rate are shown. The relative pitch coupling is not as severe for this case as the roll coupling is for the elevator command; however, coupling is still evident.

Figure 7 indicates the linear closed-loop system response to the same aileron command. A dashed line denotes the model response, and a solid line, the aircraft response. The relatively small coupling in the pitch axis was not considered severe, as indicated by the aircraft pitch-angular rate response. The model pitch-angular rate response was zero. The objective in this case was to provide adequate lateral-directional dynamics. Figure 8 shows the closed-loop response for the same case with aircraft nonlinear simulation.

Conclusions

The method presented describes a decoupled control for a highly coupled unsymmetric aircraft. The method develops an explicit model-following control law by means of linear quadratic optimization techniques. The results indicate that the method does obtain the decoupling incorporated in the ideal model for the flight condition considered.

Evaluation of the control system on nonlinear equations of six degrees of freedom of motion for the flight condition considered shows promising results for implementation as a candidate control system for the aircraft. Work is in progress to investigate gain scheduling requirements and to obtain piloted simulation results.

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[5]Yore, E., "Optimal Decoupling Control," 9th Joint Automatic Control Conference of the American Automatic Control Council, New York, 1968, pp. 327-336.

[6]Morrow, L.D. and Balasubramanian, R., "Real Model Following Control," J. Aircraft, Vol. 12, No. 12, Dec. 1975, pp. 996-998.

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TABLE 1. — AIRCRAFT AND MODEL MATRICES*

(a) Aircraft matrices

$$A_p = \begin{bmatrix} 0.0094 & 22.0707 & 10.5479 & -0.1341 & -32.1127 & 0.0057 & -0.0005 & -0.0265 \\ -0.0001 & -0.7826 & 0.0958 & 0.0000 & 0.0000 & 0.0030 & 0.9926 & -0.0003 \\ 0.0000 & -0.0592 & -0.2908 & 0.0387 & -0.0002 & 0.0259 & 0.0001 & -0.9920 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & 0.0247 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 33.1432 & -53.6933 & 0.0000 & 0.0000 & -3.1250 & 2.0552 & 1.7210 \\ -0.0002 & -8.6816 & 0.7975 & 0.0000 & 0.0000 & 0.1679 & -1.0352 & 0.1810 \\ 0.0000 & -1.0092 & 10.7521 & 0.0000 & 0.0000 & -0.0213 & 0.0080 & -0.7129 \end{bmatrix}$$

$$B_p = \begin{bmatrix} 0.0844 & -0.0309 & -0.2210 & -1.2572 & 3.6598 \\ -0.0974 & -0.0974 & -0.0198 & -0.0302 & 0.0000 \\ -0.0166 & 0.0166 & 0.0008 & -0.0005 & 0.0647 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 12.9804 & -22.2654 & 15.8467 & -11.8422 & 13.2774 \\ -9.4073 & -10.8655 & -1.2311 & 0.8797 & 0.5694 \\ 1.9854 & -2.2579 & 0.5262 & -0.3276 & -6.2493 \end{bmatrix}$$

(b) Model matrices

$$A_m = \begin{bmatrix} -0.0077 & 23.5966 & 0.0000 & 0.0000 & -32.1129 & 0.0000 & 0.0000 & 0.0000 \\ -0.0001 & -1.1052 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.9909 & 0.0000 \\ 0.0000 & 0.0000 & -0.2852 & 0.9387 & 0.0000 & -0.0148 & 0.0000 & -0.9919 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & -0.0120 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.0000 & -44.3777 & 0.0000 & 0.0000 & -4.5000 & 0.0000 & 14.6000 \\ 0.0001 & -12.1514 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -4.0000 & 0.0000 \\ 0.0000 & 0.0000 & 12.1943 & 0.0000 & 0.0000 & 0.0000 & 0.1890 & -4.0000 \end{bmatrix}$$

$$B_m = \begin{bmatrix} -2.2032 & -2.2032 & -0.8354 & -0.8354 & 0.0000 \\ -0.0848 & -0.0848 & -0.0494 & -0.0494 & 0.0000 \\ -0.0166 & 0.0166 & 0.0000 & 0.0000 & 0.0647 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 11.2379 & -11.2379 & 29.0513 & -29.0513 & 9.6847 \\ -7.8229 & -7.8229 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & -6.6502 \end{bmatrix}$$

*$M = 0.8$; $h = 20{,}000$ ft; $\alpha_0 = 1.6°$; $\Lambda = 45°$

TABLE 2. – GAIN MATRICES*

$$K_{xp} = \begin{array}{c} \begin{array}{cccccccc} v & \alpha & \beta & \phi & \theta & p & q & r \end{array} \\ \begin{bmatrix} -0.0519 & -1.6309 & -0.0001 & -0.0432 & 2.1180 & -0.0214 & 0.2558 & -0.0239 \\ -0.0614 & -1.0436 & -0.6015 & 0.0630 & 1.9146 & 0.0475 & 0.3378 & 0.1859 \\ -0.0081 & -0.4667 & 0.1671 & -0.0406 & 0.4541 & -0.0268 & 0.0250 & -0.0426 \\ 0.0232 & 0.6063 & -0.0928 & 0.0333 & -0.6926 & 0.0213 & -0.0348 & 0.0273 \\ -0.0524 & -0.3968 & -0.1964 & -0.0009 & 0.7165 & -0.0090 & 0.0442 & 0.1586 \end{bmatrix} \end{array}$$

$$K_{xm} = \begin{array}{c} \begin{array}{cccccccc} v & \alpha & \beta & \phi & \theta & p & q & r \end{array} \\ \begin{bmatrix} 0.0520 & 1.4288 & -0.9317 & 0.9512 & 02.1145 & 0.0205 & -0.2196 & 0.0521 \\ 0.0615 & 1.2344 & 0.1713 & -0.0608 & -1.9159 & -0.0348 & -0.2036 & -0.1015 \\ 0.0082 & 0.3162 & -0.0769 & 0.0431 & -0.4550 & 0.0225 & -0.0428 & 0.0515 \\ -0.0232 & -0.4681 & 0.0552 & -0.0362 & 0.6935 & -0.0177 & 0.0487 & -0.0424 \\ 0.0524 & 0.4089 & -0.0353 & -0.0013 & -0.7161 & 0.0092 & -0.0130 & -0.0256 \end{bmatrix} \end{array}$$

$$K_{um} = \begin{array}{c} \begin{array}{ccccc} \delta_{hL} & \delta_{hR} & \delta_{aL} & \delta_{aR} & \delta_R \end{array} \\ \begin{bmatrix} 0.6121 & 0.2711 & 0.3173 & -0.5317 & -0.2012 \\ 0.0015 & 0.2122 & -0.3388 & 0.1843 & 0.0414 \\ 0.2607 & 0.0542 & 0.2295 & -0.2846 & -0.0907 \\ -0.2221 & -0.0384 & -0.1941 & 0.2630 & 0.0875 \\ -0.2622 & -0.1349 & -0.1708 & 0.1445 & 0.0993 \end{bmatrix} \end{array}$$

*M = 0.8; h = 20,000 ft; Λ = 45°

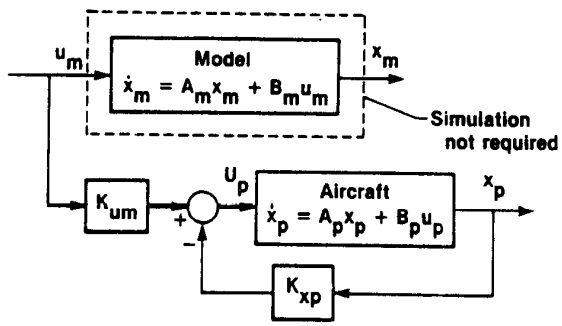


Fig. 1 Implicit model-following control law structure.

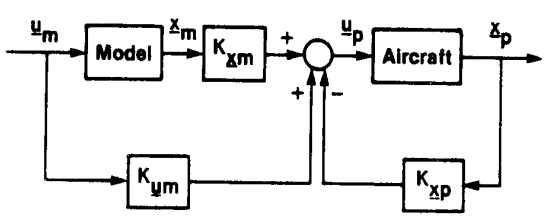
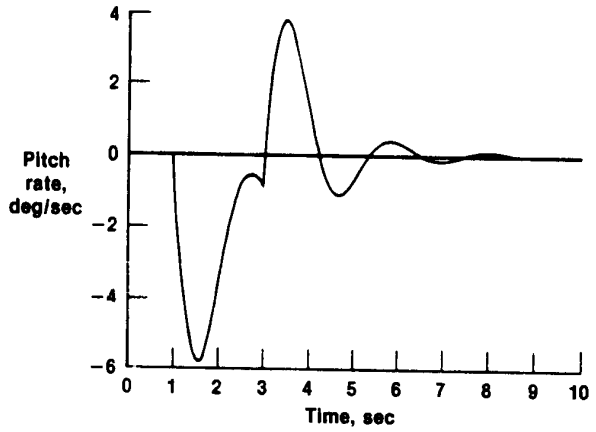
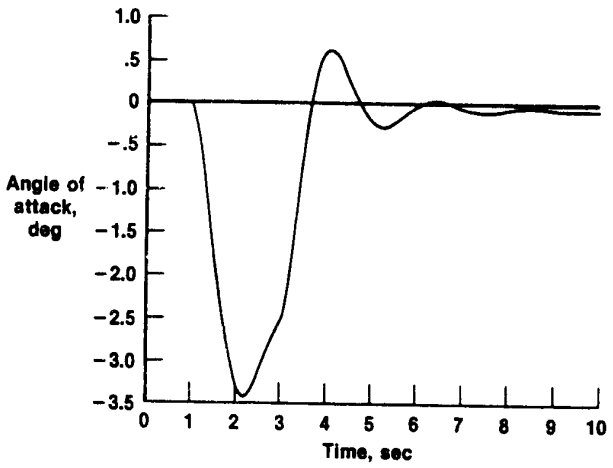


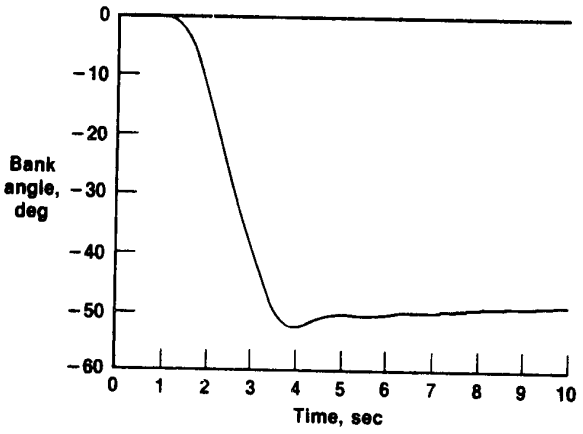
Fig. 2 Explicit model-following control law structure.



(a) Pitch rate.

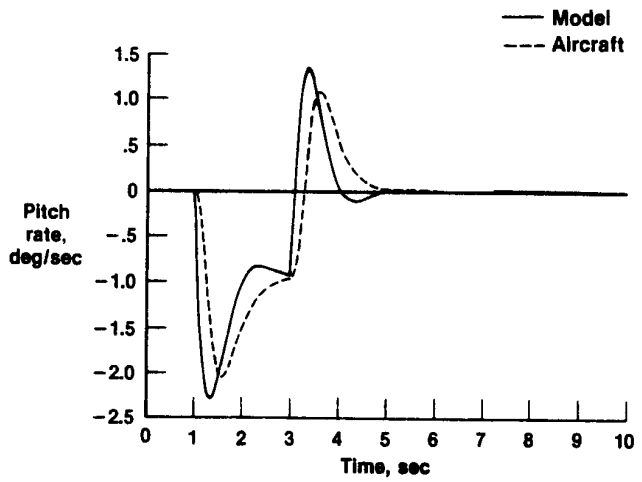


(b) Angle of attack.

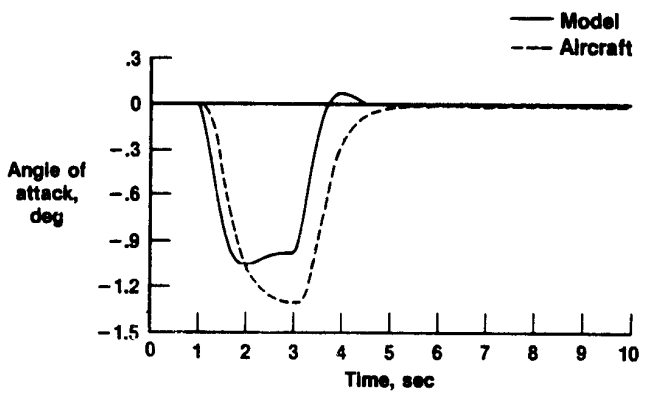


(c) Bank angle.

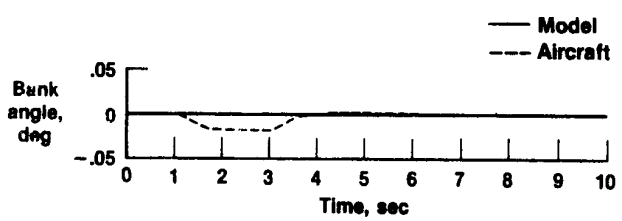
Fig. 3 Open-loop aircraft response to elevator command input.



(a) Pitch rate.



(b) Angle of attack.



(c) Bank angle.

Fig. 4 Model-following response to elevator command input.

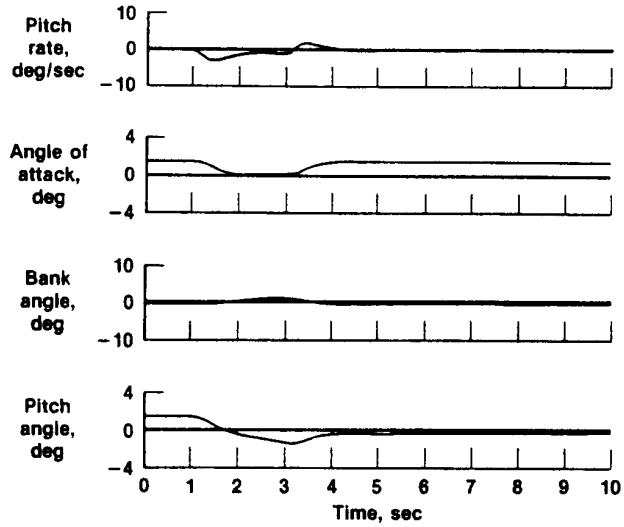
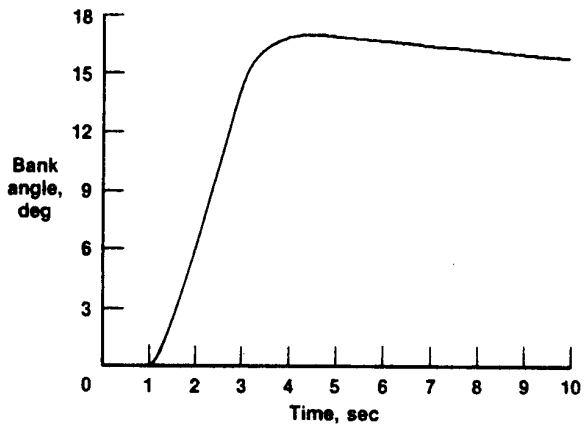
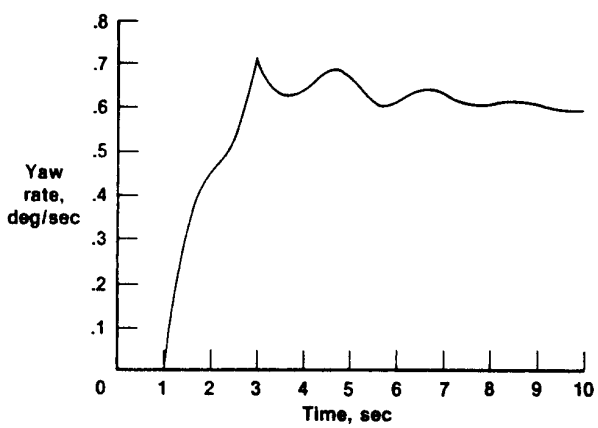


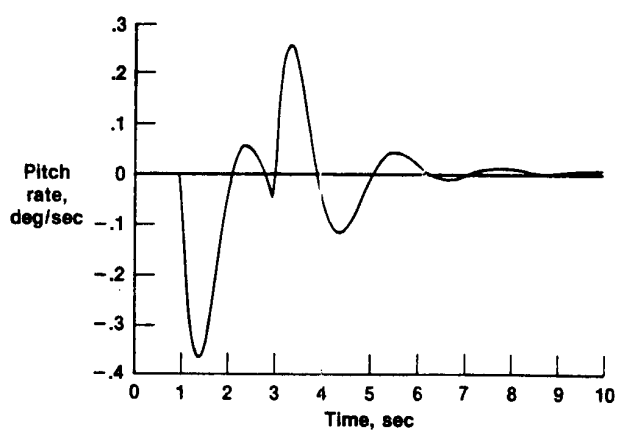
Fig. 5 Nonlinear model-following response to elevator command input.



(a) Bank angle.

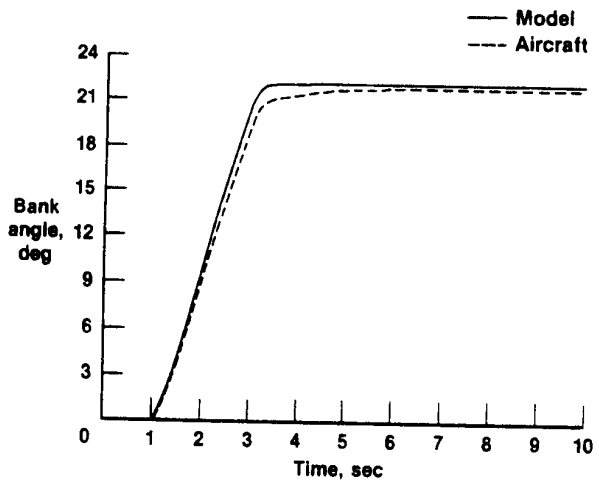


(b) Yaw rate.

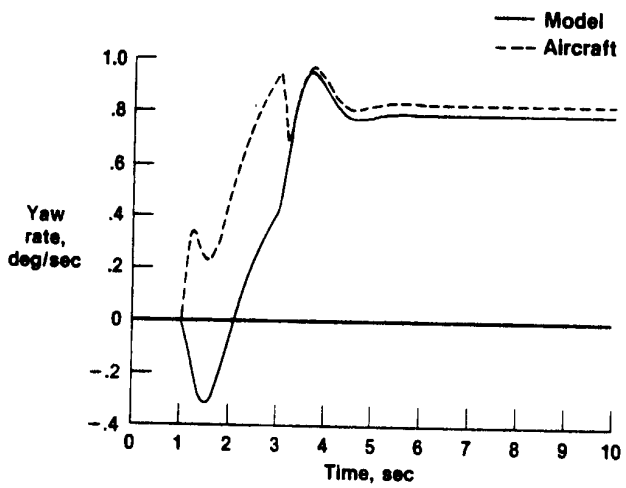


(c) Pitch rate.

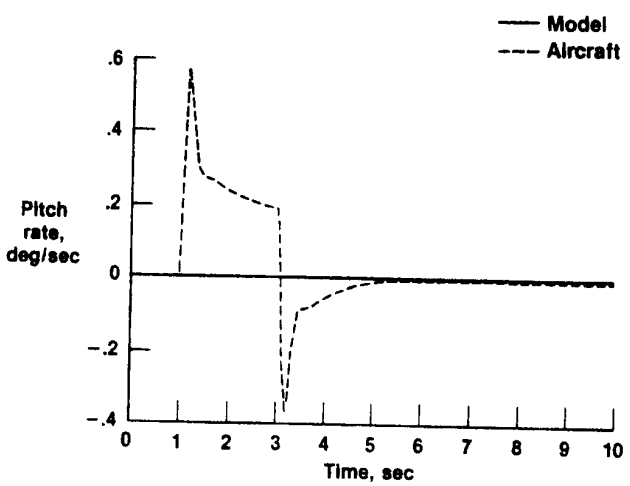
Fig. 6 Open-loop aircraft response to aileron command input.



(a) Bank angle.



(b) Yaw rate.



(c) Pitch rate.

Fig. 7 Model-following response to aileron command input.

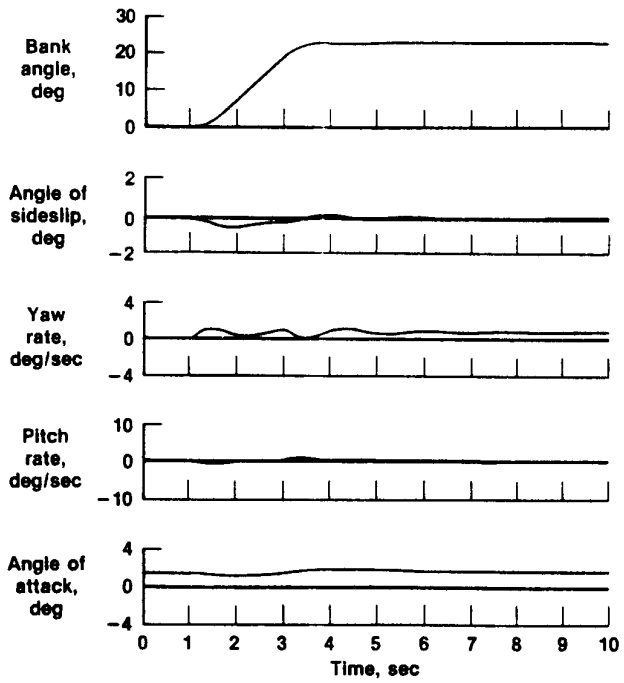


Fig. 8 Nonlinear model-following response to aileron command.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-88269		

4. Title and Subtitle	5. Report Date
MODEL-FOLLOWING CONTROL FOR AN OBLIQUE-WING AIRCRAFT	August 1986
	6. Performing Organization Code
7. Author(s) Gurbux S. Alag, Robert W. Kempel, Joseph W. Pahle, John J. Bresina, and Febo Bartoli	8. Performing Organization Report No. H-1362
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273 Edwards, CA 93523-5000	10. Work Unit No. RTOP 533-06-01
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	13. Type of Report and Period Covered Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared as AIAA Paper 86-2244CP for presentation at AIAA Conference on Guidance and Control, Williamsburg, Virginia, August 18-20, 1986.

16. Abstract

A variable-skew oblique wing offers a substantial aerodynamic performance advantage for aircraft missions that require both high efficiency in subsonic flight and supersonic dash or cruise. The most obvious characteristic of the oblique-wing concept is the asymmetry associated with wing-skew angle which results in significant aerodynamic and inertial cross-coupling between the aircraft longitudinal and lateral-directional axes. This paper presents a technique for synthesizing a decoupling controller while providing the desired stability augmentation.

The proposed synthesis procedure uses the concept of explicit model following. Linear quadratic optimization techniques are used to design the linear feedback system. The effectiveness of the control laws developed in achieving the desired decoupling is illustrated for a given flight condition by application to linearized equations of motion, and also to the nonlinear equations of six degrees of freedom of motion with nonlinear aerodynamic data.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Asymmetric aircraft control Flight control systems Model-following control system Multi-variable control system	Unclassified — Unlimited STAR category 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	10	A02

For sale by the National Technical Information Service, Springfield, Virginia 22161.