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DECOUPLING CONTROL SYNTHESIS FOR AN OBLIQUE-WING AIRCRAFT

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Abstract

Interest in oblique-wing aircraft has surfaced periodically since the 1940's. This concept offers some substantial aerodynamic performance advantages but also has 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 a real model-following control system. Feedforward gains are selected on the assumption that perfect model-following conditions are satisfied. The feedback gains are obtained by using eigensystem assignment, and the aircraft is stabilized by using partial state feedback. The effectiveness of the control laws developed in achieving the desired decoupling is illustrated by application to linearized equations of motion of an oblique-wing aircraft for a given flight condition.

Nomenclature

A,B,C	system matrices
d	eigenvector of components, unspecified
e	error
I	identity matrix
j	$\sqrt{-1}$
K	feedback gain
L,M	matrices of appropriate dimension
OWRA	oblique-wing research aircraft
p	roll rate, deg/sec
q	pitch rate, deg/sec
RMF	real model-following
r	yaw rate, deg/sec
s	complex frequency
u	input vector
v	specified components of eigenvector
w	vector m-dimensional
x	state vector
y	output vector
Z	eigenvector achievable for specified components
α	angle of attack, deg
β	sideslip angle, deg
δ	control surface deflection
θ	pitch angle, deg
λ	eigenvalue
ϕ	bank angle, deg
$(\ldots)^{R_i}$	reordering operation

Subscripts

aL	left aileron
aR	right aileron
hL	left horizontal
hR	right horizontal
i	ith value
m	model
p	plant (aircraft)
R	set of real numbers
u	input vector
x	state vector

Superscripts

d	desired value
ℓ	number of outputs

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m	number of inputs
n	number of states
†	pseudo-inverse

Introduction

The advantages of an oblique wing were first noted in the 1940's. However, only recently has the interest, technology, and mission of an oblique-wing design evolved into a full-scale flight research program. The NASA Ames Research Center and the U.S. Navy are developing an oblique-wing research aircraft (OWRA). Gregory[1] has outlined a number of 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. 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. Current typical design procedures synthesize aircraft controllers based on 2- or at most 3-degree-of-freedom solutions. However, the OWRA stabilization and decoupling must consider at least 5 degrees of freedom simultaneously.

The basis for OWRA will be NASA's F-8 digital fly-by-wire aircraft. This aircraft will be modified by the removal of the current high wing and installation of a wing pivot and a composite wing. A major part of the OWRA program will be the synthesis of a control system that will provide acceptable stabilization and decoupling across the Mach, angle-of-attack, and wing-skew envelope. The aircraft thus offers an opportunity to apply modern control theory techniques to the solution of problems associated with OWRA.

Model-following has been a popular method for the design of multivariable control systems over the last two decades. In this method, the desired behavior of the plant is provided by an ideal model, and the problem is one of designing a suitable controller for the plant so that its response follows that of the model.

Yore[2] indicated the use of this method for simultaneous stability augmentation and mode decoupling. His synthesis procedure consisted of constructing an ideal model, designing feedback gains by quadratic optimization, and designing feedforward gains. A disadvantage of this method is that selection of feedback gain is an iterative and time-consuming process. The determination of this gain becomes a more complex problem when all states are not available and therefore output feedback is used.

Another technique for decoupled flight control design is the eigenstructure assignment.[3] In this technique, the performance specifications can be interpreted in terms of the eigenvalues and eigenvectors of the closed-loop system. Broussard and Berry[4] have established the equivalence of this technique to the design using model-following systems.

In this paper, the development of control laws for OWRA by integration of the two above-mentioned techniques is demonstrated. The results show the effectiveness of the controller in obtaining the decoupled response for a given flight condition and wing skew.

Problem Definition

The concept of model-following is useful when an ideal set of plant equations of motion can be specified. The ideal objective of model-following flight control is to force the aircraft to respond as the model would to a given pilot command. It is often desirable to simulate the model dynamics in the flight computer and to generate the aircraft control signal using the aircraft outputs, the pilot input commands, and the model states. This situation is sometimes referred to as the pilot flying the computer, while the computer is flying the aircraft.

More precisely, the model-following problem can be stated as follows. The linearized dynamics are given as

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

$$y_p = C x_p \tag{2}$$

where $x_p \in R^n$, $u_p \in R^m$, and $y_p \in R^\ell$, and A_p, B_p, and C are matrices of appropriate dimensions. The control u_p must be determined such that the plant output y_p approximates, reasonably well, some model output vector y_m defined by the equations:

$$\dot{x}_m = A_m x_m + B_m u_m \tag{3}$$

$$y_m = C x_m \tag{4}$$

where $x_m \in R^n$, $u_m \in R^m$, and $y_m \in R^\ell$, and A_m, B_m, and C are matrices of appropriate dimensions.

For OWRA, the state, input, and output vectors are given by

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

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

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

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 aircraft matrices correspond to a flight condition of 0.8 Mach number and an altitude of 6096 m at 45° wing skew. The model used in this study is a modification of the zero-wing-skew configuration at the same flight condition. A_m and B_m elements are modified to increase damping and to eliminate zero-wing-skew coupling terms. This model is preliminary and may not represent ideal dynamics but does incorporate the desired aircraft decoupling.

Model-Following Control System

There are two configurations of model-following; one is implicit model-following, and the other is real model-following (RMF). In implicit model-following, the model is not part of the system. In RMF, however, the model is part of the system as control law requires the states of the model. The technique of RMF has been shown to be amenable to the solution of many aircraft control problems.

Erzberger[5] established conditions for perfect model-following that enable an ideal match of the dynamics of the compensated plant with those of the model. However, the conditions for perfect model-following are never attainable in the real world. An asymptotic RMF control law was derived by Chan[6] for the class of plants and models whose output vectors are identically their state vectors. Chan showed that, even if the conditions for perfect model-following are not satisfied, use of perfect model-following gains can yield a control capable of keeping error between the model and plant to a "small" region of state space. Chan chose u_p as

$$u_p = u_1 + u_2 \tag{5}$$

where

$$u_1 = K_e \tag{6}$$

$$u_2 = B_p^{\dagger}(A_m - A_p)x_m + B_p^{\dagger}B_m u_m$$

$$= K_{xm}x_m + K_{um}u_m \tag{7}$$

and $B_p^{\dagger}$ is the pseudo-inverse of B_p, and K_{xm} and K_{um} are the feedforward gains using model states and command input. Also,

$$e = x_m - x_p \tag{8}$$

The control u_p will ensure perfect model-following, if it is possible. If perfect model-following is not possible, the error setting rates would depend on eigenvalues of the closed-loop system and can thus be controlled in RMF. Also, if only partial state feedback is possible in the plant, perfect real model-following is still possible.

For OWRA, because partial state feedback is to be used, the feedback gain K must be selected to ensure stability of the closed-loop aircraft and placement of its closed-loop eigenvalues at the desired location in the s-plane. The method of eigenstructure assignment will be used to select the gain K. This enables the desired eigenvectors and eigenvalues to be selected to ensure satisfactory tranisient response of the aircraft.

Eigensystem Synthesis

Two widely used synthesis techniques of modern control theory are the linear quadratic regulator design and the modal control theory involving pole placement or eigenvalue-eigenvector assignment.[7] One of the purposes of feedback control of aircraft is to improve or enhance the flying qualities of an aircraft. The difficulty in incorporating specifications such as damping, natural frequency, and decoupling within a quadratic performance index makes the eigensystem synthesis procedure a promising design alternative. The performance specifications can be interpreted in terms of desired closed-loop eigenvalues and eigenvectors. Moore[8] and others have shown how feedback can be used to place closed-loop eigenvalue and shape closed-loop eigenvectors. Cunningham[9], and Andry, Shapiro, and Chung,[10] and Sobel and Shapiro[11] have successfully demonstrated the use of eigenstructure assignment procedure for aircraft control system design.

The handling qualities data base may be used to obtain desired pole locations directly. The additional design objective of obtaining augmented dynamics similar to those obtained in flight leads to specifications on eigenvectors or desired mode shapes. For example, pitch attitude must be dominant for the short-period mode, and speed must be dominant for the phugoid mode.

Detailed discussions on eigenspace may be found in Ref. 11. However, some basic results for controllable and observable systems are summarized in the following discussion.[12]

Consider the system

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

$$y = Cx$$

where $x \in R^n$, $u \in R^m$, and $y \in R^{\ell}$, and A, B, and C are matrices of appropriate dimensions. If the system is controllable and observable, and the matrices B and C are full rank, the following results hold:

1. The positions of maximum (m,ℓ) closed-loop eigenvalues can be assigned arbitrarily with the stipulation that if λ_i is a complex closed-loop eigenvalue, its complex conjugate λ_i^* must also be a closed-loop eigenvalue.

2. The shape of maximum (m,r) eigenvectors can be altered. If the shape of a complex eigenvector v_i is altered, its complex conjugate v_i^* must be altered in the same way.

3. For each eigenvector whose shape is altered, minimum (m,r) eigenvector elements can be chosen arbitrarily.

4. Attainable eigenvectors must lie in the subspace spanned by the columns of $(\lambda_i I - A)^{-1}B$ of dimension m that is the number of independent control variables. A desired eigenvector v_i^d will, in general, not reside in the prescribed subspace and cannot be achieved. The achievable eigenvector v_i^a is obtained by orthogonal projection of v_i^d onto the subspace spanned by $(\lambda_i I - A)^{-1}B$. It will generally be true that only a few of the components in v_i are actually specified. The remainder can be arbitrary. To account for this, v_i is reordered and partitioned as follows:

$$(v_i)^{R_i} = \begin{pmatrix} v_i^* \\ d_i \end{pmatrix} \tag{9}$$

where

v_i^* = the specified subvector

d_i = the vector of unspecified components

$(\ldots)^{R_i}$ = the reordering operation

If we let

$$\begin{pmatrix} v_i^o \\ d_i \end{pmatrix} = \left[(\lambda_i I - A)^{-1}B\right]^{R_i} Z_i = \begin{pmatrix} L \\ M \end{pmatrix} Z_i \tag{10}$$

then, as shown in Ref. 13, Z_i may be selected to best approximate v_i^* with v_i^o. By the method of orthogonal projections, Z_i is obtained:

$$Z_i = (\bar{L}'L)^{-1}\bar{L}'v_i^* \tag{11}$$

As shown by Moore[8], the feedback gain K is given by

$$K = (w_1 w_2 \ldots w_n)(v_1 v_2 \ldots v_n)^{-1} \tag{12}$$

where w_i is obtained from the relation

$$(\lambda_i I - A)v_i = Bw_i \tag{13}$$

Results

To illustrate the degree of coupling in the open-loop system and decoupling in the closed-loop system, a one-degree control command was input for 2 sec as shown in Fig. 1. This command input was either elevator or aileron and was reduced to zero after 2 sec. Figures 2(a) to 2(c) illustrate the open-loop system response to an elevator command input for pitch rate, yaw rate, and bank angle, respectively. Significant yaw rate and bank angle are generated as a result of the pitch command, and of particular interest is the very large change in bank angle illustrating the significant cross-coupling.

Table 2 shows the desired eigenvector assignment specification, open- and closed-loop eigenvalues and desired eigenvalues, the feedback gain matrix K, and the feedforward gain matrices K_{xm} and K_{um}.

Figures 3(a) to 3(c) and 4 illustrate the closed-loop system response to the same elevator command input. The pitch rate in Fig. 3(a) is attenuated as compared with the open-loop response. However, the system is very closely following the desired model response as illustrated in Fig. 4. The yaw rate and bank angle are virtually nonexistent as illustrated in Figs. 3(b) and 3(c), thus achieving the desired decoupling.

Figures 5(a) to 5(c) illustrate the open-loop system response to a one-degree aileron command input. Pitch and yaw angular rate and bank angle are again shown. The relative pitch coupling is not as severe for the aileron command case as the roll coupling is for the elevator command; however, coupling is still present.

Figures 6(a) to 6(c), 7(a), and 7(b) illustrate the closed-loop system response to the same aileron command. Pitch rate is virtually nonexistent, and the desired yaw rate and bank angle are achieved, giving the desired decoupling.

Conclusions

A method is presented to obtain a decoupled control for a highly coupled asymmetric aircraft. The method utilizes a real model-following control law in which gains for perfect model-following are used even when the conditions for perfect model-following are not satisfied. The feedback gain, using output feedback, is computed by using eigenstructure assignment. The results indicate that the method does obtain the decoupling incorporated in the ideal model for the flight condition considered.

Future investigations will be conducted to evaluate the control algorithm under nonlinear 6-degree-of-freedom flight conditions. These investigations will consider such factors as nonlinear aerodynamic data, control system surface rate and position constraints, and system hysteresis.

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TABLE 1. — AIRCRAFT AND MODEL MATRICES

Plant (aircraft) matrices

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

$$B_p = \begin{bmatrix} 0.0844 & -0.0309 & -0.2210 & -1.2572 & 3.6598 \\ -0.0974 & -0.0974 & -0.0198 & -0.0302 & 0.0000 \\ -0.0166 & 0.0166 & 0.0008 & -0.0005 & 0.0647 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\ 12.9804 & -22.2654 & 15.8467 & -11.8422 & 13.2774 \\ -9.4073 & -10.8655 & -1.2311 & 0.8797 & 0.5694 \\ 1.9854 & -2.2579 & 0.5262 & -0.3276 & -6.2499 \end{bmatrix}$$

Model matrices

$$A_m = \begin{bmatrix} -0.0077 & 23.5966 & 0.0000 & 0.0000 & -32.1129 & 0.0000 & 0.0000 & 0.0000 \\ -0.0001 & -1.1062 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.9909 & 0.0000 \\ 0.0000 & 0.0000 & -0.6000 & 0.0387 & 0.0000 & -0.0148 & 0.0000 & -0.9919 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & -0.0133 \\ 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 \\ 0.0000 & 0.0000 & -44.3777 & 0.0000 & 0.0000 & -10.0000 & 0.0000 & 0.0000 \\ 0.0001 & -12.1514 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -.0000 & 0.0000 \\ 0.0000 & 0.0000 & 12.1943 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -2.0000 \end{bmatrix}$$

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

TABLE 2. – EIGENSYSTEM ASSIGNMENT AND GAINS

Desired eigenvectors[a]

Short period		Dutch roll		Spiral	Roll subsidence
0	0	0	0	0	0
1	x	0	0	0	0
x	x	1	x	0	0
0	0	0	0	1	x
x	x	x	x	0	0
0	0	0	0	x	1
x	1	0	0	x	x
0	0	x	1	x	0

Eigenvalues

Condition	Open loop	Desired closed loop	Achieved closed loop
Short period	-1.0433 ± j2.8269	-2 ± j3.5	-2 ± j3.5
Dutch roll	-0.5463 ± j3.3816	-3 ± j4.0	-3 ± j4.0
Spiral	-0.0118	-0.1	-0.1
Roll subsidences	-2.7544	-7.0	-7.0
Phugoid	-0.0053 ± j0.0455		-0.0047 ± j0.0455

Feedback gain

$$K = \begin{array}{c} \begin{matrix} p & q & r & \phi & \alpha & \beta \end{matrix} \\ \begin{bmatrix} 0.1454 & -0.3471 & -1.4507 & 0.1476 & -0.5902 & -0.9587 \\ -0.0580 & 0.4180 & 1.0127 & -0.0915 & 1.0377 & 0.1151 \\ -0.3710 & 0.9639 & 2.2955 & -0.2967 & -5.0019 & 6.9733 \\ 0.1199 & 0.1133 & -0.0982 & 0.0194 & -7.2635 & 1.3083 \\ 0.0114 & -0.1653 & 0.1540 & 0.0210 & 0.6898 & -1.9884 \end{bmatrix} \end{array}$$

Feed forward gains

$$K_{xm} = B_p^{\dagger}(A_m - A_p)$$

$$K_{xm} = \begin{array}{c} \begin{matrix} v & \alpha & \beta & \phi & \theta & p & q & r \end{matrix} \\ \begin{bmatrix} 0.0010 & 6.5743 & -3.6200 & 0.0729 & -0.0003 & 0.1698 & -0.2893 & -0.3591 \\ -0.0006 & -3.6600 & 2.2241 & -0.0452 & 0.0002 & -0.0560 & 0.4205 & 0.2696 \\ -0.0019 & -9.0867 & 9.4682 & -0.1429 & 0.0004 & -0.5446 & 0.3861 & 0.5095 \\ 0.0002 & 7.0692 & 2.0716 & 0.0037 & -0.0002 & 0.1608 & -0.6155 & -0.0284 \\ 0.0004 & 2.1139 & -1.4962 & 0.0272 & -0.0001 & 0.0164 & -0.1778 & 0.0388 \end{bmatrix} \end{array}$$

$$K_{um} = B_p^{\dagger}B_m$$

$$K_{um} = \begin{bmatrix} -0.8204 & -0.5391 & -0.0271 & 0.7842 & -2.1203 \\ 1.0516 & 0.9978 & -0.1411 & -0.3323 & 1.3850 \\ 3.1869 & 1.6393 & 2.1149 & -1.9684 & 3.9478 \\ 0.0239 & 0.2235 & 0.8121 & 1.4435 & -0.1933 \\ -0.3735 & -0.4054 & 0.1779 & 0.1278 & 0.2326 \end{bmatrix}$$

[a] x is arbitrary.

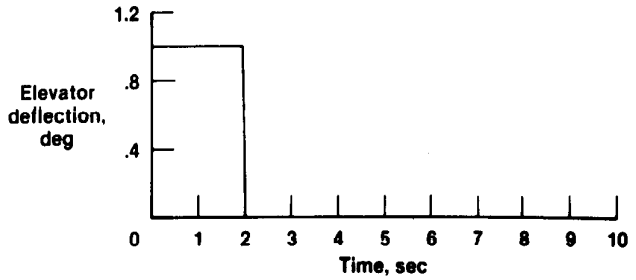
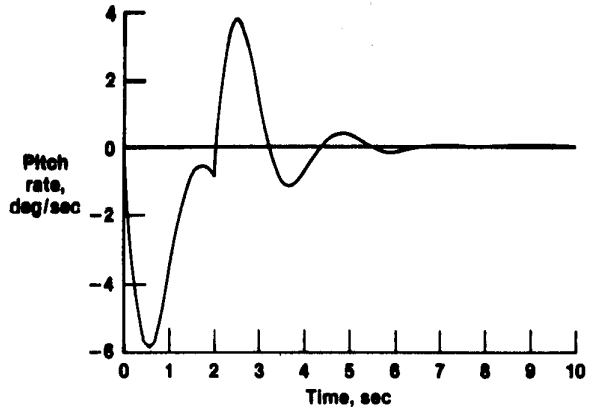
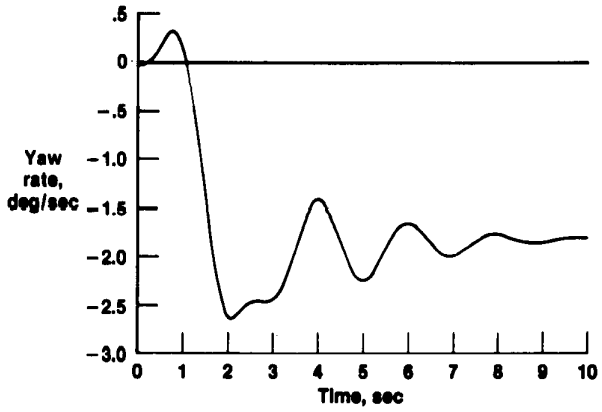


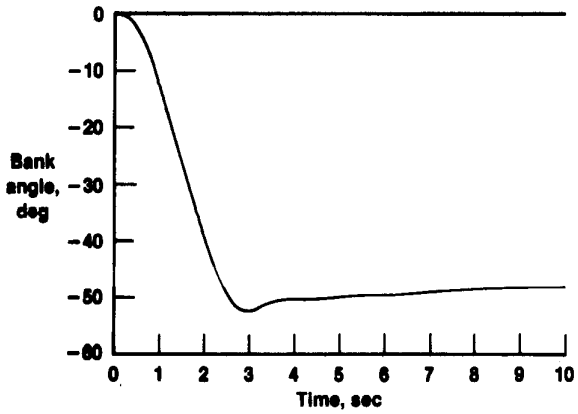
Fig. 1 Command input to system.



(a) Pitch rate.

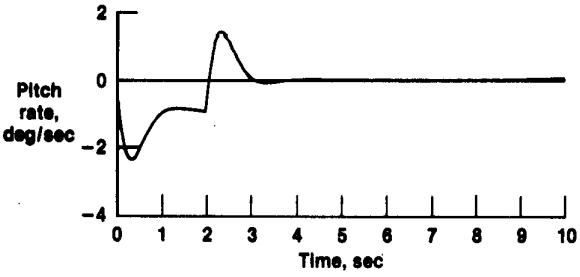


(b) Yaw rate.

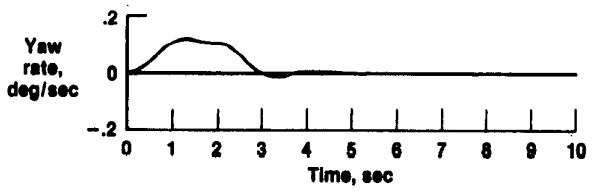


(c) Bank angle.

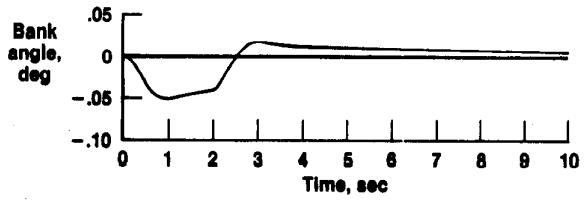
Fig. 2 Open-loop system response to elevator command input.



(a) Pitch rate.



(b) Yaw rate.



(c) Bank angle.

Fig. 3 Closed-loop system response to elevator command input.

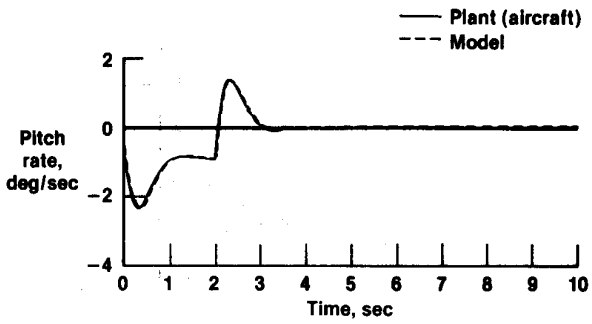
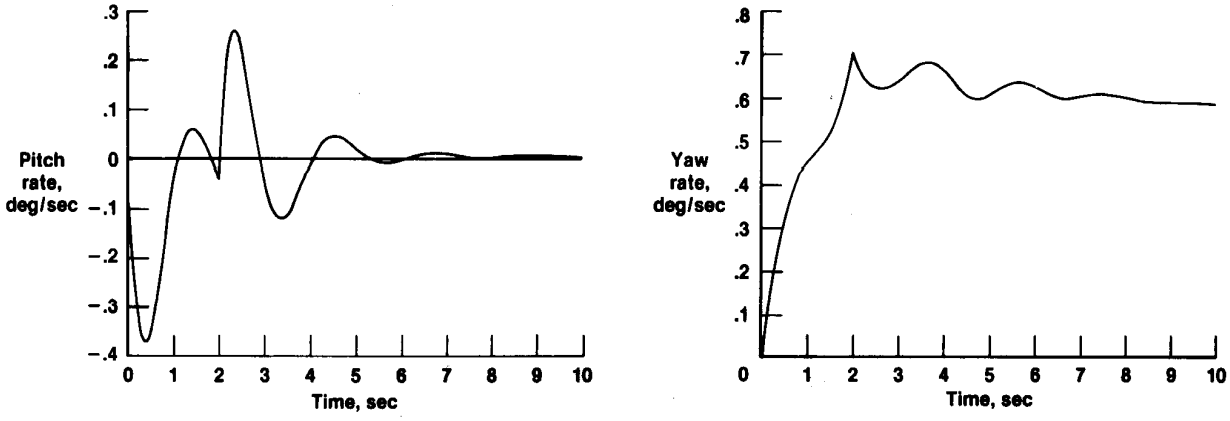
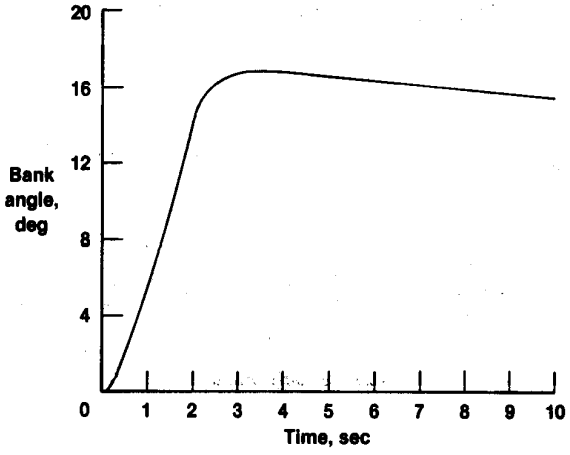


Fig. 4 Model-following response to elevator command input.



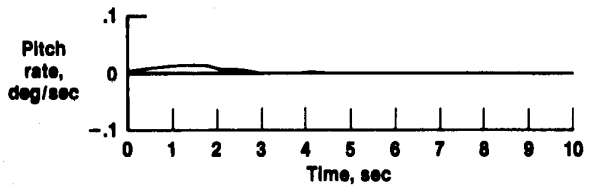
(a) Pitch rate.

(b) Yaw rate.

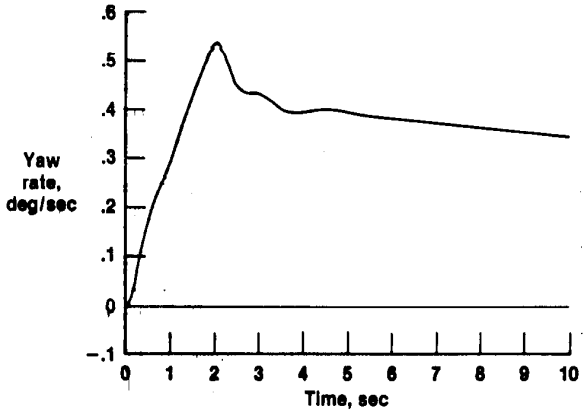


(c) Bank angle.

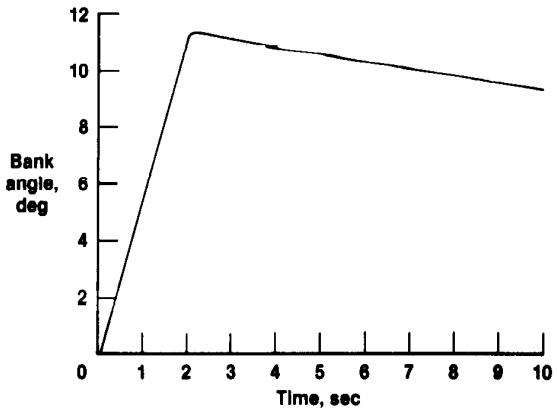
Fig. 5 Open-loop system response to aileron command input.



(a) Pitch rate.

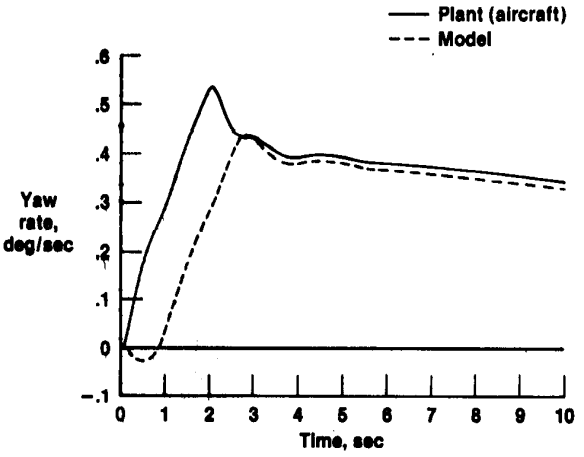


(b) Yaw rate.

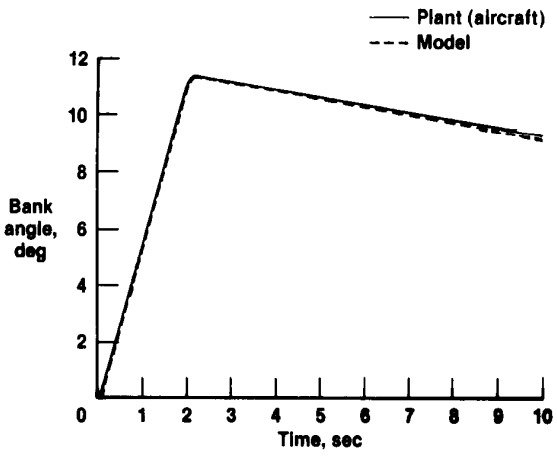


(c) Bank angle.

Fig. 6 Closed-loop system response to aileron command input.



(a) Yaw rate.



(b) Bank angle.

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

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15. Supplementary Notes

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16. Abstract

Interest in oblique-wing aircraft has surfaced periodically since the 1940's. This concept offers some substantial aerodynamic performance advantages but also has 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 a real model-following control system. Feedforward gains are selected on the assumption that perfect model-following conditions are satisfied. The feedback gains are obtained by using eigensystem assignment, and the aircraft is stabilized by using partial state feedback. The effectiveness of the control laws developed in achieving the desired decoupling is illustrated by application to linearized equations of motion of an oblique-wing aircraft for a given flight condition.

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