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

\[ s \] 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

\[ \alpha \] angle of attack, deg

\[ \beta \] sideslip angle, deg

\[ \delta \] control surface deflection

\[ \theta \] pitch angle, deg

\[ \lambda \] eigenvalue

\[ \phi \] bank angle, deg

\[ (\ldots)^R \] reordering operation

Subscripts

\[ aL \] left aileron

\[ aR \] right aileron

\[ hL \] left horizontal

\[ hR \] right horizontal

\[ i \] \( i \)th value

\[ m \] model

\[ p \] plant (aircraft)

\[ R \] set of real numbers

\[ u \] input vector

\[ x \] state vector

Superscripts

\[ d \] desired value

\[ \lambda \] number of outputs

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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

\[ \dot{x}_p = A_p x_p + B_p u_p \]  \hspace{1cm} (1)

\[ y_p = C_p x_p \]  \hspace{1cm} (2)

where \( x_p \in \mathbb{R}^n, u_p \in \mathbb{R}^m, \) and \( y_p \in \mathbb{R}^s. \) \( A_p, B_p, \) and \( C_p \) 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:

\[ \dot{x}_m = A_m x_m + B_m u_m \]  \hspace{1cm} (3)

\[ y_m = C_m x_m \]  \hspace{1cm} (4)

where \( x_m \in \mathbb{R}^n, u_m \in \mathbb{R}^m, \) and \( y_m \in \mathbb{R}^s. \) \( A_m, B_m, \) and \( C_m \) are matrices of appropriate dimensions.

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

\[
\begin{align*}
\gamma & : \text{velocity, m/sec} \\
\alpha & : \text{angle of attack, deg} \\
\beta & : \text{sideslip angle, deg} \\
\phi & : \text{bank angle, deg} \\
\theta & : \text{pitch angle, deg} \\
p & : \text{roll rate, deg/sec} \\
q & : \text{pitch rate, deg/sec} \\
r & : \text{yaw rate, deg/sec} \\
\delta_L & : \text{left horizontal tail deflection, deg} \\
\delta_R & : \text{right horizontal tail deflection, deg} \\
\delta_{al} & : \text{left aileron deflection, deg} \\
\delta_{ar} & : \text{right aileron deflection, deg} \\
\delta_r & : \text{rudder deflection, deg} \\
p & : \text{roll rate, deg/sec} \\
q & : \text{pitch rate, deg/sec} \\
r & : \text{yaw rate, deg/sec} \\
\alpha & : \text{angle of attack, deg} \\
\beta & : \text{sideslip angle, deg}
\end{align*}
\]

\[ y = \begin{bmatrix} \gamma \\ \alpha \\ \beta \\ \phi \\ \theta \\ p \\ q \\ r \\ \delta_L \\ \delta_R \\ \delta_{al} \\ \delta_{ar} \\ \delta_r \\ p \\ q \\ r \\ \alpha \\ \beta \end{bmatrix} \]

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.
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 6036 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 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 for the class of plants and models whose output vectors are identical to 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

$$u_p = u_1 + u_2$$  \hspace{1cm} (5)

where

$$u_1 = K_e$$  \hspace{1cm} (6)

$$u_2 = B_p^T(A_m - A_p)x_m + B_p^T B_m U_m$$  \hspace{1cm} (7)

and $B_p^T$ is the pseudo-inverse of $B_p$, and $K_m$ and $K_u$ are the feedforward gains using model states and command input. Also,

$$e = x_m - x_p$$  \hspace{1cm} (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 ONWA, 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 transient 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. 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 and others have shown how feedback can be used to place closed-loop eigenvalue and shape closed-loop eigenvectors. Cunningham, Andry, Shapiro, and Chung 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 $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, and $y \in \mathbb{R}^l$, 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 $(m,s)$ closed-loop eigenvalues can be assigned arbitrarily with the stipulation that if $\lambda_i$ is a complex closed-loop eigenvalue, its complex conjugate $\bar{\lambda}_i$ must also be a closed-loop eigenvalue.

2. The shape of maximum $(m,s)$ eigenvectors can be altered. If the shape of a complex eigenvector $v_i$ is altered, its complex conjugate $\bar{v}_i$ must be altered in the same way.

3. For each eigenvector whose shape is altered, minimum $(m,s)$ eigenvector elements can be chosen arbitrarily.
4. Attainable eigenvectors must lie in the subspace spanned by the columns of \((\lambda I - A)^{-1}B\) of dimension \(m\) that is the number of independent control variables. A desired eigenvector \(v_d^i\) will, in general, not reside in the prescribed subspace and cannot be achieved. The achievable eigenvector \(v_1^*\) is obtained by orthogonal projection of \(v_d^i\) onto the subspace spanned by \((\lambda I - A)^{-1}B\). It will generally be true that only a few of the components in \(v_1^*\) are actually specified. The remainder can be arbitrary. To account for this, \(v_1^*\) is reordered and partitioned as follows:

\[
(v_1^*)^R_l = \begin{pmatrix} v_1^* \\ d_1 \end{pmatrix}
\]

(9)

where

\[
v_1^* \text{ is the specified subvector}
\]

\[
d_1 \text{ is the vector of unspecified components}
\]

\[
(\ldots)^R_l \text{ is the reordering operation}
\]

If we let

\[
\begin{pmatrix} v_1^0 \\ d_1 \end{pmatrix} = [(\lambda I - A)^{-1}B]^{R_l}Z_l = \begin{pmatrix} \frac{L}{M} \end{pmatrix}Z_l
\]

(10)

then, as shown in Ref. 13, \(Z_l\) may be selected to best approximate \(v_1^*\) with \(v_1^0\). By the method of orthogonal projections, \(Z_l\) is obtained:

\[
Z_l = (L' L)^{-1} L' v_1^*
\]

(11)

As shown by Moore8, the feedback gain \(K\) is given by

\[
K = (w_1 w_2 \ldots w_n)(v_1 v_2 \ldots v_n)^{-1}
\]

(12)

where \(w_i\) is obtained from the relation

\[
(\lambda I - A)v_i = Bw_i
\]

Results

To illustrate the degree of coupling in the open-loop system and decoupling in the closed-loop system, a one-degree-of-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 eigencstructure 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.

References


TABLE 1. AIRCRAFT AND MODEL MATRICES

Plant (aircraft) matrices

\[
\begin{bmatrix}
0.0094 & 22.0707 & 10.5479 & -0.1341 & -32.1127 & 0.0057 & -0.0005 & -0.0265 \\
-0.0001 & -0.7826 & 0.0958 & 0.0000 & 0.0000 & 0.0030 & 0.9926 & -0.0003 \\
0.0000 & -0.0592 & -0.2908 & 0.0387 & -0.0002 & 0.0259 & 0.0001 & -0.9920 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & 0.00247 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 \\
0.0000 & 33.1432 & -53.6933 & 0.0000 & 0.0000 & -3.1250 & 2.0552 & 1.7210 \\
-0.0002 & -8.6816 & 0.7975 & 0.0000 & 0.0000 & 0.1679 & -1.0352 & 0.1810 \\
0.0000 & -1.0929 & 10.7621 & 0.0000 & 0.0000 & -0.0213 & 0.0000 & -0.7129
\end{bmatrix}
\]

Model matrices

\[
\begin{bmatrix}
-0.0078 & 23.5966 & 0.0000 & 0.0000 & -32.1129 & 0.0000 & 0.0000 & 0.0000 \\
-0.0001 & -1.1062 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.9909 & 0.0000 \\
0.0000 & 0.0000 & -0.6000 & 0.0387 & 0.0000 & -0.0146 & 0.0000 & -0.9919 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 & -0.0133 \\
0.0000 & 0.0000 & -44.3777 & 0.0000 & 0.0000 & 0.0000 & 1.0000 & 0.0000 \\
0.0001 & -12.1514 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -10.0000 & 0.0000 \\
0.0000 & 0.0000 & 12.1943 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & -2.0000
\end{bmatrix}
\]

\[
\begin{bmatrix}
-2.2032 & -2.2032 & -0.8354 & 0.0354 & 0.0000 \\
-0.0848 & -0.0848 & -0.0494 & 0.0494 & 0.0000 \\
0.0166 & 0.0166 & 0.0000 & 0.0000 & 0.0647 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
-7.8229 & -7.8229 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & -6.6502
\end{bmatrix}
\]
### TABLE 2. -- EIGENSYSTEM ASSIGNMENT AND GAINS

**Desired eigenvectors**

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<tr>
<th>Short period</th>
<th>Dutch roll</th>
<th>Spiral</th>
<th>Roll subsidence</th>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>1</td>
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<tr>
<td>x</td>
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<td>x</td>
<td>0</td>
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**Eigenvalues**

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<th>Condition</th>
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<th>Desired closed loop</th>
<th>Achieved closed loop</th>
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</thead>
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<tr>
<td>Short period</td>
<td>-1.0433 ± j2.8269</td>
<td>-2 ± j3.5</td>
<td>-2 ± j3.5</td>
</tr>
<tr>
<td>Dutch roll</td>
<td>-0.5463 ± j3.3816</td>
<td>-3 ± j4.0</td>
<td>-3 ± j4.0</td>
</tr>
<tr>
<td>Spiral</td>
<td>-0.0118</td>
<td>-0.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>Roll subsidence</td>
<td>-2.7544</td>
<td>-7.0</td>
<td>-7.0</td>
</tr>
<tr>
<td>Phugoid</td>
<td>-0.0053 ± j0.0455</td>
<td>-0.0047 ± j0.0455</td>
<td></td>
</tr>
</tbody>
</table>

**Feedback gain**

\[
K = \begin{bmatrix}
0.1454 & -0.3471 & -1.4507 & 0.1476 & -0.5902 & -0.9587 \\
-0.0580 & 0.4180 & 1.0127 & -0.0915 & 1.0377 & 0.1151 \\
-0.3710 & 0.9639 & 2.2955 & -0.2967 & 5.0019 & 6.9733 \\
0.1199 & 0.1133 & -0.0982 & 0.0194 & -7.2635 & 1.3083 \\
0.0114 & -0.1653 & 0.1540 & 0.0210 & 0.6898 & -1.9884
\end{bmatrix}
\]

**Feed forward gains**

\[
K_{xm} = B_p (A_m - A_p)
\]

\[
K_{xm} = \begin{bmatrix}
0.0010 & 6.5743 & -3.6200 & 0.0729 & -0.0003 & 0.1698 & -0.2893 & -0.3591 \\
-0.0006 & -3.6600 & 2.2241 & -0.0452 & 0.0002 & -0.0560 & 0.4205 & 0.2696 \\
-0.0019 & 9.0867 & 9.4602 & -0.1429 & 0.0004 & -0.5446 & 0.3861 & 0.5095 \\
0.0002 & 7.0692 & 2.0716 & 0.0037 & -0.0002 & 0.1608 & -0.6155 & -0.0284 \\
0.0004 & 2.1139 & -1.4962 & 0.0272 & -0.0001 & 0.0164 & -0.1778 & 0.0388
\end{bmatrix}
\]

\[
K_{um} = B_p B_m
\]

\[
K_{um} = \begin{bmatrix}
-0.8204 & -0.5391 & -0.0271 & 0.7842 & -2.1203 \\
1.0516 & 0.9978 & -0.1411 & -0.1323 & 1.3850 \\
3.1869 & 1.6393 & 2.1149 & -1.9684 & 3.9478 \\
0.0239 & 0.2235 & 0.8121 & 1.4435 & -0.1933 \\
-0.3735 & 0.4054 & 0.1779 & 0.1278 & 0.2326
\end{bmatrix}
\]

\*x is arbitrary.*

---

![Fig. 1 Command input to system.](image_url)
Fig. 2 Open-loop system response to elevator command input.

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

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