LONGITUDINAL STABILITY AND CONTROL DERIVATIVES OF A JET FIGHTER AIRPLANE EXTRACTED FROM FLIGHT TEST DATA BY UTILIZING MAXIMUM LIKELIHOOD ESTIMATION

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**Abstract**

A method of parameter extraction for stability and control derivatives of aircraft from flight test data, implementing maximum likelihood estimation, has been developed and successfully applied to actual longitudinal flight test data from a modern sophisticated jet fighter. The results of this application establish the merits of the estimation technique and its computer implementation (allowing full analyst interaction with the program) as well as provide data for the validation of a portion of the Langley differential maneuvering simulator (DMS). The results are presented for all flight test runs in tabular form and as time history comparisons between the estimated states and the actual flight test data. Comparisons between extracted and manufacturer’s values for five major derivatives are presented and reveal good agreement for these principal derivatives with the exception of the static longitudinal stability derivative \( C_{m\alpha} \). This particular derivative is extensively investigated by utilizing the interactive capabilities of the computer program. The results of this investigation verify the numbers extracted by maximum likelihood estimation.
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SUMMARY

A method of parameter extraction for stability and control derivatives of aircraft from flight test data, implementing maximum likelihood estimation, has been developed and successfully applied to actual longitudinal flight test data from a modern sophisticated jet fighter. The results of this application establish the merits of the estimation technique and its computer implementation (allowing full analyst interaction with the program) as well as provide data for the validation of a portion of the Langley differential maneuvering simulator (DMS). The results are presented for all flight test runs in tabular form and as time history comparisons between the estimated states and the actual flight test data. Comparisons between extracted and manufacturer's values for five major derivatives are presented and reveal good agreement for these principal derivatives with the exception of the static longitudinal stability derivative $C_{m\alpha}$. This particular derivative is extensively investigated by utilizing the interactive capabilities of the computer program. The results of this investigation verify the numbers extracted by maximum likelihood estimation.

INTRODUCTION

A method of parameter extraction for stability and control derivatives of aircraft from flight test data has been developed at the Langley Research Center (ref. 1). This method utilizes maximum likelihood estimation, an advanced mathematical theory, and has been fully implemented on the Langley Research Center real-time digital complex (ref. 2). The casting of the digital program in such a framework permits the analyst to interact with the program through a control console and cathode ray display.

Applying the computer program to actual flight test data from a modern sophisticated jet fighter airplane (fig. 1) serves a dual purpose: first, to establish the merits of the computer program and, second, to provide additional means of validating the Langley
The differential maneuvering simulator (DMS) program (ref. 3). The successful extraction of stability derivatives from real-world flight test data goes a step beyond the use of analytically generated data toward establishing the creditability and merits of any estimation technique. The documentation of the aerodynamic characteristics of the test airplane (ref. 4) is extensive and is currently being used as a prime source for the DMS program package. The DMS provides dual-cockpit fixed-base simulation in which the two piloted vehicles can be operated jointly or individually in either a cooperative mode or an uncooperative mode. The flight tests themselves and the parameters extracted serve as additional means of validating the DMS for this particular airplane.

The flight test runs utilized in this study are longitudinal responses generated by stabilator deflections in the neighborhood of ±5°. The changes in angle of attack and pitching velocity are typically ±10° and ±20° per second, respectively. Normal acceleration responses are between +4g and -1g. The parameters extracted were the standard body-axis longitudinal stability and control derivatives.

**SYMBOLES**

Measurements and calculations were made in the U.S. Customary Units. They are presented herein in the International System of Units (SI) with the equivalent values in the U.S. Customary Units given parenthetically.

\[ a_z \text{ normal acceleration (positive down), g units} \]

\[ C_m \text{ pitching-moment coefficient} \]

\[ C_{m,o} \text{ pitching-moment coefficient at } \alpha = \delta = 0 \]

\[ C_{mq} = \frac{\partial C_m}{\partial \left( \frac{qC}{2V} \right)} \text{ per radian} \]

\[ C_{mq} + C_{m\dot{\alpha}} \text{ damping-in-pitch derivative, } \frac{\partial C_m}{\partial \left( \frac{qC}{2V} \right)} + \frac{\partial C_m}{\partial \left( \frac{\dot{C}}{2V} \right)} \text{ per radian} \]

\[ C_{m\alpha} \text{ static longitudinal stability derivative, } \frac{\partial C_m}{\partial \alpha} \text{ per radian} \]

\[ C_{m\dot{\alpha}} = \frac{\partial C_m}{\partial \left( \frac{\dot{C}}{2V} \right)} \text{ per radian} \]
\[(C_m)_{\alpha_T, \delta_T}\quad \text{pitching-moment coefficient at } \alpha = \alpha_T, \quad \delta = \delta_T\]

\[C_{m\delta} \quad \text{pitch-control-effectiveness derivative, } \frac{\partial C_m}{\partial \delta}, \text{ per radian}\]

\[C_X \quad \text{longitudinal-force coefficient}\]

\[C_{Xq} = \frac{\partial C_X}{\partial \left(\frac{q\bar{c}}{2V}\right)} \text{ per radian}\]

\[C_{X\alpha} = \frac{\partial C_X}{\partial \alpha} \text{ per radian}\]

\[(C_X)_{\alpha_T, \delta_T} \quad \text{longitudinal-force coefficient at } \alpha = \alpha_T, \quad \delta = \delta_T\]

\[C_Z \quad \text{normal-force coefficient}\]

\[C_{Z,0} \quad \text{normal-force coefficient at } \alpha = \delta = 0\]

\[C_{Zq} = \frac{\partial C_Z}{\partial \left(\frac{q\bar{c}}{2V}\right)} \text{ per radian}\]

\[C_{Z\alpha} = \frac{\partial C_Z}{\partial \alpha} \text{ per radian, slope of normal-force curve}\]

\[(C_Z)_{\alpha_T, \delta_T} \quad \text{normal-force coefficient at } \alpha = \alpha_T, \quad \delta = \delta_T\]

\[C_{Z\delta} = \frac{\partial C_Z}{\partial \delta} \text{ per radian}\]

\[\bar{c} \quad \text{mean aerodynamic chord, meters (ft)}\]

\[g \quad \text{acceleration due to gravity, meters/second}^2 \quad (\text{ft/sec}^2)\]

\[I_Y \quad \text{aircraft moment of inertia about the Y-axis, kilogram-meters}^2 \quad (\text{slug-ft}^2)\]

\[M \quad \text{Mach number}\]
m mass of fueled airplane, kilograms (slugs)

q pitching angular velocity, radians/second

\dot{q} pitching acceleration, radians/second^2

\bar{q} dynamic pressure, \( \frac{1}{2} \rho V^2 \), newtons/meter^2 (lb/ft^2)

S wing area, meters^2 (ft^2)

u velocity along horizontal body axis, meters/second (ft/sec)

\dot{u} acceleration along horizontal body axis, meters/second^2 (ft/sec^2)

V true airspeed, meters/second (ft/sec)

w velocity along vertical body axis, meters/second (ft/sec)

\dot{w} acceleration along vertical body axis, meters/second^2 (ft/sec^2)

\alpha angle of attack, radians

\dot{\alpha} rate of change of angle of attack, radians/second

\alpha_T trim angle of attack, radians

\delta stabilator deflection angle, radians

\delta_T stabilator deflection angle at trim, radians

\theta pitch angle, radians

\dot{\theta} rate of change of pitch angle, radians/second

\rho mass density of air, kilograms/meter^3 (slugs/ft^3)

\omega_n natural frequency of the pitching-moment oscillation for controls locked, radians/second
FLIGHT TESTS

The flight test data were provided by the U.S. Naval Air Test Center at Patuxent River, Maryland. The flight tests were conducted by Navy test pilots as part of an investigation with a McDonnell Douglas F-4 airplane. Five different longitudinal response runs were made: three during one flight test of the airplane and two during a second flight test. The first three runs were made at an altitude of approximately 1524 m (5000 ft) and at Mach numbers of about 0.6, 0.7, and 0.8, respectively. The other two runs were made at an altitude of approximately 6096 m (20 000 ft) and at Mach numbers of about 0.6 and 0.8, respectively. The stability augmentation system (SAS) was deactivated in order to provide full response for all the test runs.

For each of the test runs the procedure was identical. The airplane was trimmed by the pilot at the desired altitude and Mach number and held for a short period, and then a disturbing input was placed on the stabilators. The pilot task during the maneuver was to null any lateral motions. Since thrust was held constant during the maneuver and since altitude and Mach number were approximately constant throughout the maneuver, the translational modes of the airframe were not sufficiently excited to allow extraction of the longitudinal-force coefficient. A time history of the stabilator position for a typical test run is shown in figure 2(a). Shown in figure 2(b) are typical time histories of horizontal velocity $u$, vertical velocity $w$, pitching angular velocity $q$, and normal acceleration $a_z$. True airspeed was first determined from figure 1 of reference 5 using Mach number, pressure altitude, and temperature from flight tests and then resolved through angle-of-attack measurements to yield horizontal and vertical velocities.

Angle of attack was measured by means of a vane on a nose boom. The boom was assumed to be rigid. The readings were corrected for pitch by the Navy. Pitching velocity was measured by rate gyros located slightly forward and at the foot level of the pilot. Normal acceleration was measured by an accelerometer located in the left wheel well. The location of the instrumentation is shown in figure 1. However, the center-of-gravity offset of the accelerometer was negligible for longitudinal responses. (No documentation was available from the Navy as to the accuracy of the instrumentation.)

The data for each run were sampled at 0.1-sec intervals. Each of these points was used by the computer program but every other point is plotted in all time history figures to avoid crowding. No smoothing techniques were applied to the data provided. The data were supplied to Langley Research Center in tabular form but were transferred to magnetic tape for use with the computer program.
COMPUTATIONAL METHOD

The equations of motion used by the computer program for longitudinal motion are as follows:

\[
\dot{u} = -g \sin \theta - \omega q + \frac{1}{2} \frac{\rho V^2 S}{m} \left[ (C_X)_{\alpha_T}, \delta_T + C_{X\alpha}(\alpha - \alpha_T) + C_{Xq} \frac{q\dot{c}}{2V} \right]
\]

\[
\dot{\omega} = g \cos \theta + uq + \frac{1}{2} \frac{\rho V^2 S}{m} \left[ (C_Z)_{\alpha_T}, \delta_T + C_{Z\alpha}(\alpha - \alpha_T) + C_{Zq} \frac{qc}{2V} + C_{Z\delta}(\delta - \delta_T) \right]
\]

\[
\dot{q} = \frac{1}{2} \frac{\rho V^2 SC}{I_Y} \left[ (C_m)_{\alpha_T}, \delta_T + C_{m\alpha}(\alpha - \alpha_T) + C_{mq} \frac{\dot{\alpha} \dot{c}}{2V} + C_{mq} \frac{qc}{2V} + C_{m\delta}(\delta - \delta_T) \right]
\]

\[
\delta = q
\]

\[
a_z = \dot{\omega} - g \cos \theta - qu
\]

\[
\alpha = \frac{\dot{\omega}}{u}
\]

\[
\alpha = \tan^{-1} \frac{\omega}{u}
\]

\[
V = \sqrt{u^2 + \omega^2}
\]

Again, it should be noted that the form of input excitation (pitch doublet yielding the short-period motion) makes the extraction of longitudinal-force coefficients \((C_X)\) derivatives infeasible, since \(\dot{u}\) is negligible. However, the program extracts a set of \(C_X\) derivatives that provide a longitudinal response to match the flight data; thus, a proper representation of true airspeed is ensured.

The method of parameter estimation incorporated into the computer program is based on maximum likelihood estimation. This method is inherently iterative and requires an initial estimate for each derivative in order to begin the extraction process. Reference 1 describes in detail both the method of extraction and the computer program. It should be emphasized, however, that the procedure for extracting the derivatives is not straightforward. Engineering judgment tempered with estimator statistics, such as the variance of individual derivatives and intercorrelation coefficients, plays a significant role in the extraction procedure; thus, the capability of analyst program interaction is highly desirable.
RESULTS

Figure 3 illustrates the response of the mathematical model to a typical set of starting values; the flight data are included for comparison. Usually 8 to 10 iterations are required before initial convergence is obtained. From this base, engineering judgment and statistical information are used to eliminate all possible inconsistencies between aerodynamic principles and statistical results.

The conditions for the five flight tests are listed in table I. In figure 4 are presented the model responses generated by the final estimates of the stability derivatives for the five flight test runs and the respective flight test data. Again, it should be noted that the flight data displayed have not been filtered.

The total set of extracted stability and control derivatives for each flight test run and the standard deviation of each derivative are listed in table II. The intercept derivatives \( C_{Z,0} \) and \( C_{m,0} \) are defined at zero angle of attack and zero stabilator deflection.

From the set of extracted derivatives for the test airplane, the five principal derivatives \( C_{Z,\alpha}, C_{Z,\delta}, C_{m,\alpha}, C_{m,q} + C_{m,\delta}, \) and \( C_{m,\delta} \) are plotted as a function of Mach number and compared with the manufacturer's data for an earlier version in figures 5 to 9. (It should be noted that the center-of-gravity variation between the flight test runs is less than 0.55% about 31.80% \( \delta_\alpha \).) Aerodynamic differences between the two airplanes are believed to be small and, hence, two different sets of estimates of the principal derivatives exist to predict airplane response.

The five principal derivatives taken from the manufacturer's data were fixed as constants in the program and the minor derivatives \( (C_{X,\alpha, T, \delta}, C_{X, \alpha}, C_{X, q}, (C_{Z, \alpha, T, \delta}, C_{Z, q, (C_{m, \alpha, T, \delta),}) \) were extracted from the flight data by the maximum likelihood algorithm. This procedure yielded the model responses presented in figure 10 for the five flight test runs. These results clearly indicate an error in both frequency and amplitude for normal acceleration \( a_z \) and an error in amplitude for vertical velocity \( w \). The issue now is to uncover the manufacturer's estimates that give rise to the errors. Examination of figures 5 to 9 reveals that the largest discrepancy occurs in the estimates of the static longitudinal stability derivative \( C_{m, \alpha} \) and, therefore, the error analysis was begun with this derivative.

The principal derivatives taken from the extracted set were used in conjunction with the manufacturer's values of \( C_{m, \alpha} \) to generate the responses shown in figure 11; the minor derivatives were extracted in the usual manner. These results clearly indicate an error in frequency for all the variables.

In a final attempt to use the manufacturer's value of \( C_{m, \alpha} \), this derivative was fixed at the manufacturer's value and the algorithm was allowed to select the values of
all other derivatives. This procedure converged for all flight test runs with the exception of test run 4, which diverged. The resulting model responses with the respective flight test data are presented in figure 12 for test runs 1, 2, 3, and 5. Again, an error exists in both frequency and amplitude for normal acceleration \( a_z \) and an error exists in amplitude for vertical velocity \( w \).

On the basis of these results, it is concluded that the flight test data require a much lower value for the static longitudinal stability derivative \( C_{m\alpha} \) than that presented by the manufacturer. As further verification of this conclusion, values of the static longitudinal stability derivative were calculated by using the following equation:

\[
|C_{m\alpha}| = \frac{\omega_n^2 I_Y}{q S \sigma_c}
\]  

These calculations were made from the flight test data after input excitation had essentially ceased. The results of these calculations are presented in figure 7. The calculations yielded values of \( C_{m\alpha} \) which agreed more closely with the extracted values than with the manufacturer's data.

At this point in the error analysis, at least one discrepancy has been shown to be significant. To determine discrepancies among the remaining four principal derivatives, the following procedure was used. The four principal derivatives taken from the manufacturer's data were fixed as constants in the program, and the minor derivatives as well as \( C_{m\alpha} \) were extracted in the usual manner. This procedure yielded the model responses presented in figure 13 and the variation of \( C_{m\alpha} \) with Mach number presented in figure 14. Although the model responses for this procedure are quite good, the least-squares residual for fitting the flight data is inferior to that of the extracted set presented in table II. Therefore, it is believed that good agreement exists for all principal derivatives with the exception of the static longitudinal stability derivative \( C_{m\alpha} \). Also, it should be noted that this procedure yielded values for \( C_{m\alpha} \) that agreed more closely with the extracted values than with the manufacturer's data.

**CONCLUDING REMARKS**

It is believed that the agreement between the extracted values and the manufacturer's data for four of the five principal derivatives \( \{C_{Z\alpha}, C_{Z\delta}, C_{m_q} + C_{m\delta}, C_{m\delta}\} \), and the extensive investigation carried out on the fifth principal derivative \( C_{m\alpha} \) establish not only the merits of maximum likelihood estimation in a real-world environment but also the merits of the interactive capabilities of the computer implementation utilized to carry out the investigation. The investigation of \( C_{m\alpha} \) revealed that the flight test data require
a much lower value for the static longitudinal stability derivative than that presented by the manufacturer.

The present study also provided some of the data to validate the Langley differential maneuvering simulator (DMS) program.

Langley Research Center,
National Aeronautics and Space Administration,

REFERENCES


TABLE I.- FLIGHT TEST CONDITIONS

<table>
<thead>
<tr>
<th>Test run</th>
<th>Altitude</th>
<th>Mach number</th>
<th>Input</th>
<th>Excitation</th>
<th>Center of gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>m</td>
<td>ft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1524</td>
<td>5000</td>
<td>0.6</td>
<td>Pitch doublet</td>
<td>31.80% c</td>
</tr>
<tr>
<td>2</td>
<td>1524</td>
<td>5000</td>
<td>0.7</td>
<td>Pitch doublet</td>
<td>31.47% c</td>
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<tr>
<td>3</td>
<td>1524</td>
<td>5000</td>
<td>0.8</td>
<td>Pitch doublet</td>
<td>31.27% c</td>
</tr>
<tr>
<td>4</td>
<td>6096</td>
<td>20000</td>
<td>0.6</td>
<td>Pitch doublet</td>
<td>32.22% c</td>
</tr>
<tr>
<td>5</td>
<td>6096</td>
<td>20000</td>
<td>0.8</td>
<td>Pitch doublet</td>
<td>31.52% c</td>
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</table>
### TABLE II.- EXTRACTED STABILITY AND CONTROL DERIVATIVES

<table>
<thead>
<tr>
<th>Derivative</th>
<th>Test run 1 (c.g. = 31.80% C)</th>
<th>Test run 2 (c.g. = 31.47% C)</th>
<th>Test run 3 (c.g. = 31.27% C)</th>
<th>Test run 4 (c.g. = 32.22% C)</th>
<th>Test run 5 (c.g. = 31.52% C)</th>
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<tbody>
<tr>
<td></td>
<td>Extracted value</td>
<td>Standard deviation</td>
<td>Extracted value</td>
<td>Standard deviation</td>
<td>Extracted value</td>
</tr>
<tr>
<td>$C_m, o$</td>
<td>0.0193</td>
<td>0.00008</td>
<td>0.0156</td>
<td>0.00008</td>
<td>0.0148</td>
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<tr>
<td>$C_m, a$</td>
<td>-0.106</td>
<td>0.0017</td>
<td>-0.126</td>
<td>0.0026</td>
<td>-0.167</td>
</tr>
<tr>
<td>$C_m q + C_m d$</td>
<td>-3.32</td>
<td>0.06</td>
<td>-3.11</td>
<td>0.08</td>
<td>-3.30</td>
</tr>
<tr>
<td>$C_m d$</td>
<td>0.576</td>
<td>0.009</td>
<td>0.555</td>
<td>0.015</td>
<td>0.540</td>
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<tr>
<td>$C_z, o$</td>
<td>-0.080</td>
<td>0.004</td>
<td>-0.086</td>
<td>0.004</td>
<td>-0.106</td>
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<td>$C_z a$</td>
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<td>0.07</td>
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<td>-3.64</td>
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<td>$C_z d$</td>
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<td>0.334</td>
<td>0.019</td>
<td>0.325</td>
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<tr>
<td>$C_z q$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Unidentifiable due to insensitivity
Figure 1. Diagram of test airplane.

Figure 2. (a) Time history of stabilator deflection angle.

Figure 2.- Typical flight data.
(b) Time histories of horizontal velocity, vertical velocity, pitching velocity, and normal acceleration.

Figure 2.- Concluded.
Figure 3. - Responses to typical starting values.
(a) Test run 1.

Figure 4.- Final model responses generated by extracted derivative estimates.
Figure 4.- Continued.

(b) Test run 2.
Figure 4.- Continued.

(c) Test run 3.
(d) Test run 4.

Figure 4.- Continued.
(e) Test run 5.

Figure 4.- Concluded.
Figure 5.- Variation of $C_{Z\alpha}$ with Mach number.

Figure 6.- Variation of $C_{Z\delta}$ with Mach number.
Figure 7.- Variation of $C_{m\alpha}$ with Mach number.
All data corrected to c.g. = 31% $c$. 
Figure 8. Variation of $C_{mq} + C_{m\alpha}$ with Mach number.
Figure 9.- Variation of $C_{m\delta}$ with Mach number.
(a) Test run 1.

Figure 10.- Final model responses generated by using manufacturer's derivative estimates.
Figure 10.- Continued.

(b) Test run 2.
(c) Test run 3.

Figure 10.- Continued.
(d) Test run 4.

Figure 10.- Continued.
(e) Test run 5.

Figure 10.- Concluded.
Figure 11. Final model responses generated by using manufacturer's $C_{m\alpha}$, and other principal derivatives from extracted estimates.
Figure 11.- Continued.

(b) Test run 2.
(c) Test run 3.

Figure 11.- Continued.
(d) Test run 4.

Figure 11.- Continued.
(e) Test run 5.

Figure 11.- Concluded.
(a) Test run 1.

Figure 12.—Final model responses generated by using manufacturer’s $C_{m \alpha}$, and other derivatives selected by algorithm.
Figure 12.- Continued.

(b) Test run 2.
(c) Test run 3.

Figure 12.- Continued.
Figure 12.- Concluded.
Figure 13.- Final model responses generated by using algorithm-selected $C_{m\alpha}$, and manufacturer's principal derivatives.
(b) Test run 2.

Figure 13.- Continued.
(c) Test run 3.

Figure 13.- Continued.
Figure 13.- Continued.

(d) Test run 4.
(e) Test run 5.

Figure 13.- Concluded.
Figure 14.- Variation of $C_{m\alpha}$ with Mach number.
"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—National Aeronautics and Space Act of 1958

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