DEVELOPMENT OF LATERAL-DIRECTIONAL TRANSFER FUNCTIONS FOR CLASS IV AIRCRAFT WITH LEVEL 1 FLYING QUALITIES

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<td>This report describes the computer program that was developed to support the effort currently being conducted at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. The output from the computer program is a set of transfer functions for trimmed flight conditions which can be used to describe representative F-18 time histories. The transfer functions meet the Level 1 Flying Qualities Requirements of MIL-F-8785C for Flight Phase Categories A and B of the F-18's flight envelope. These include roll angle, roll rate, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs. The computer program was written in Visual Basic and the coefficients to the transfer functions are written to an output file.</td>
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SUMMARY

This report describes the computer program that was developed to support the effort currently being conducted at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. The output from the computer program is a set of transfer functions for trimmed flight conditions which can be used to describe representative F-18 time histories. The transfer functions meet the Level 1 Flying Qualities Requirements of MIL-F-8785C for Flight Phase Categories A and B of the F-18's flight envelope. These include roll angle, roll rate, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs. The computer program was written in Visual Basic and the coefficients to the transfer functions are written to an output file.

This report includes a description of the transfer function development, the computer program structure and input/output content and format. A sample application is also included to aid the user in understanding the program application.
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A, B, C, D  Coefficients to transfer function
a_{ycg}  Lateral Acceleration at the center of gravity (ft/sec²)
b  Reference Wing Span (ft)
C_f, C_N, C_Y  Coefficient of Rolling Moment, Yawing Moment and Side Force
C_{l/\beta}  Coefficient of Rolling Moment with respect to sideslip, \frac{\partial C_l}{\partial \beta}
C_{n/\beta}  Change in Yawing Moment Coefficient with respect to sideslip, \frac{\partial C_n}{\partial \beta}
C_Y  Change in Side Force Coefficient with respect to sideslip, \frac{\partial C_l}{\partial \beta}
C_{l/r}  Change in Rolling Moment Coefficient with respect to yawing velocity, \frac{\partial C_l}{\partial (rb/2U)}
C_{n/r}  Change in Yawing Moment Coefficient with respect to yawing velocity, \frac{\partial C_n}{\partial (rb/2U)}
C_{l/\delta}  Change in Rolling Moment Coefficient with variation in control surface deflection, \frac{\partial C_l}{\partial \delta}

DLL  Dynamic Link Library
DOF  Degrees of Freedom
EOM  Equations of Motion
F_s, F_p  Lateral Stick and Pedal Force input (lbs)
g  Acceleration due to gravity (ft/sec²)
H  High Speed Category
I_{xx}, I_{yy}, I_{zz}  Body Axis Moments of Inertia (slug-ft²)
I_{xz}  Product of Inertia (slug-ft²)
L  Rolling Moment (ft-lbs)
L  Low Speed Category
L( )  \frac{1}{I_{xx}} \frac{\partial L}{\partial \delta}
L_i  \frac{L_i + \left( \frac{I_{xz}}{I_{xx}} \right) N_i}{1 + \left( \frac{I_{xz}^2}{I_{xx} I_{zz}} \right)}
L_{Fa}  Roll to Lateral Stick Transfer Function Command Gain (deg/sec²/ft)
m  Mass (slugs)
M  Medium Speed Category
N  Yawing Moment (ft-lbs)
N_{i_{1,2}}  Numerator of the transfer function to rudder pedal or lateral stick input
\[ N(\theta) = \frac{1}{1_{zz}} \frac{\partial N}{\partial \theta} \]
\[ N_1' = N_1 + \left( \frac{1_{xz}}{1_{zz}} \right) L_i \]
\[ 1 - \left( \frac{1_{xz}}{1_{xx} 1_{zz}} \right) \]

\( p, q, r \) Body Axis Angular Rates (Roll, Pitch, Yaw) (rad/sec)

\( p_{SS} \) Steady State Roll Rate (deg/sec)

\( s \) Laplace Operator

\( S \) Reference Wing Area (ft²)

\( U \) Body Axis Velocity in the X direction (ft/sec)

\( U_0 \) Initial Body Axis Velocity in the X direction (ft/sec)

\( V \) Total Velocity (ft/sec)

\( V_L \) Very Low Speed Category

\( V_{max} \) Maximum Service Speed (ft/sec)

\( V_{min} \) Minimum Service Speed (ft/sec)

\( V_{omax} \) Maximum Operational Speed (ft/sec)

\( V_{omin} \) Minimum Operational Speed (ft/sec)

\( Y \) Side Force (lbs)

\( Y^* \) \( \frac{1}{mU} \frac{\partial Y}{\partial (\theta)} \)

\( \beta \) Sideslip Angle (rad)

\( \delta_{a,s,r} \) Aircraft Aileron, Stabilator and Rudder Deflection (rad)

\( \Delta\text{lat-dir} \) Denominator of the Lateral-Directional Transfer Function

\( \rho \) Air Density (slugs/ft³)

\( \phi \) Roll Angle (rad)

\( \psi \) Yaw Angle (rad)

\( \tau_R \) Roll Mode Time Constant (sec)

\( \tau_s \) Spiral Mode Time Constant (sec)

\( \omega_d \) Dutch Roll Frequency (rad/sec)

\( \omega_{\psi} \) Undamped Natural Frequency of Numerator Quadratic in \( \psi / F_s \)

\( \zeta_d \) Transfer Function Numerator (rad/sec)

\( \zeta_{1\psi} \) Dutch Roll Damping

\( \zeta_{1\phi} \) Damping Ratio of Numerator Quadratic in \( \phi / F_s \)

\( \zeta_{1\theta} \) Transfer Function Numerator

**SUBSCRIPTS**

\( l \) Rolling Moment Parameter

\( n \) Yawing Moment Parameter

\( p \) Roll Rate Parameter

\( r \) Yaw Rate Parameter

\( v \) Body Axis y-Velocity Parameter

\( y \) Side Force Parameter

\( \beta \) Sideslip Parameter

\( \delta_a \) Aileron Deflection Parameter

\( \delta_r \) Rudder Deflection Parameter

\( \delta_s \) Stabilator Deflection Parameter

\( \varphi \) Roll Angle Parameter
1.0 INTRODUCTION

C. S. Draper Laboratory, Inc. is currently conducting a research program to design, develop and evaluate a hybrid, learning augmented, lateral-directional flight control system for a nonlinear aircraft model of the F-18. This effort is to support the technology program entitled "Aircraft Vehicle Technology Block", Section 8.0, "Dynamics of Flight", Task Area 8.4, "Advanced Flight Controls". The control system performance will be tested against a linearized reference model representative of the F-18 with Level 1 lateral-directional flying qualities throughout the flight envelope. The reference model will provide Level 1 transient responses to stick and pedal inputs. This report describes the approach, basic assumptions, and the computer code used to develop the reference model.

2.0 APPROACH

The objective of this effort was to develop a lateral-directional reference model that would provide time histories that demonstrate Level 1 lateral-directional flying qualities throughout the flight envelope of the F-18 modeled at C. S. Draper Laboratory, Inc. The approach taken was to provide simplified transfer functions through pole-zero placement that are representative of the F-18. The simplified transfer functions were designed to meet the Level 1 lateral-directional flying qualities requirements outlined in MIL-F-8785C (Reference 1) for Flight Phase Categories A and B. Only those requirements which could be represented by transfer functions were addressed in this effort. The reference transfer functions were then used to generate the required time histories to different stick and pedal inputs at any trimmed flight condition. For simplification it was assumed that the reference model could be represented by the classical lateral-directional 3 degree-of-freedom (DOF) equations of motion (EOM), as described in Reference 2. With this assumption there was no coupling between the longitudinal EOM and the lateral-directional EOM. By using the classical lateral-directional 3 DOF EOM, the modal characteristics and the resulting transfer functions were described purely by the roll mode time constant (τₔ), the spiral mode time constant (τₛ), and the Dutch roll frequency (ωₜ) and damping (ζₜ).

The poles or the modal characteristics of the transfer functions were taken from Reference 3 as a function of Mach and altitude. In those instances where the modal characteristics do not meet the Level 1 Flying Qualities Requirements of MIL-F-8785C, the values were modified to the appropriate maximum or minimum values. This was based on the assumption that the new control system would augment the F-18 model dynamics to meet MIL-F-8785C requirements. For simplification the spiral mode time constant was set to zero throughout the flight envelope. Although most of MIL-F-8785C requirements could be satisfied through the roll response to lateral stick force transfer function, the intent of this effort was to provide multiple Level 1 reference time histories for the hybrid lateral-directional flight control system. The transfer functions gains and zeros were either placed or calculated to provide Level 1 Flying Qualities. The values for the numerator gains and zeros depended on the transfer function being evaluated. The following paragraphs will describe how these transfer functions numerators and gains were computed.
2.1 ASSUMPTIONS

This section presents the basic assumptions used to simplify the equations of motion in order to generate the transfer functions calculated by the computer program (F18LDTF). These are standard assumptions as applied in Reference 2.

Assumption 1. The airplane is assumed to be a rigid body.
Assumption 2. The earth is assumed to be an inertial frame of reference.
Assumption 3. The mass and mass distribution of the airplane are assumed to be constant.
Assumption 4. The XZ plane is assumed to be the plane of symmetry.
Assumption 5. The disturbances from the steady flight conditions are assumed to be small enough that the small angle approximations are applicable.
Assumption 6. The steady lateral trim conditions are assumed to be such that initial roll (p) and yaw (r) rates, roll angle (φ) and sideslip angle (β) are zero and the longitudinal forces and moments due to lateral perturbations about such trim conditions are assumed negligible.
Assumption 7. The air flow is assumed to be quasi steady.
Assumption 8. The variation of atmospheric properties such as density are assumed to be negligible.
Assumption 9. The earth is assumed to be flat such that the effects associated with the rotation of the vertical axis of the airplane while moving in the inertial frame are assumed negligible. In addition the airplane is trimmed for straight and level flight with pitch rate (q) = 0
Assumption 10. The equations of motion are based on a stability axis system.
Assumption 11. In the steady flight condition, the flight path of the airplane is assumed to be horizontal.

In addition the following auxiliary relationships were applied:

\[ p = \dot{\phi} \]  \hspace{1cm} (1)
\[ r = \dot{\psi} \]  \hspace{1cm} (2)
\[ a_{ycg} = U_0 \dot{\beta} - g \phi + U_0 r \]  \hspace{1cm} (3)

2.2 DERIVATION OF THE EQUATIONS OF MOTION

The assumptions and auxiliary equations cited in the previous section permits the decoupling of the longitudinal and lateral-directional EOM. In addition the 3-DOF Dutch roll approximation was applied since it complemented the assumption that \( \tau_z = 0 \) throughout the flight envelope. The assumptions used in the 3-DOF Dutch Roll approximations are:

Assumption 12. The rolling acceleration due to yaw rate, \( L_r \), is negligible.
Assumption 13. The yawing acceleration due to roll rate, \( N_{\phi} r \), is negligible.
Assumption 14. The contribution of gravity term to the side force equation, \( \frac{g \phi}{U_0} \), is negligible.

The resulting equations for the F-18 modeled in the computer program are as follows:
\[(s - Y_v)\beta(s) + r(s) = (Y_{\delta_h}^*)\delta_h(s) + (Y_{\delta_p}^*)\delta_p(s) + (Y_{\delta_r}^*)\delta_r(s) \quad (4)\]

\[-L_{\delta}^*\beta(s) + s(s - L_p^*)\psi(s) = (L_{\delta_h}^*)\delta_h(s) + (L_{\delta_p}^*)\delta_p(s) + (L_{\delta_r}^*)\delta_r(s) \quad (5)\]

\[-N_{\delta}^*\beta(s) + (s - N_r^*)r(s) = (N_{\delta_h}^*)\delta_h(s) + (N_{\delta_p}^*)\delta_p(s) + (N_{\delta_r}^*)\delta_r(s) \quad (6)\]

The transfer functions were obtained by solving the Laplace transformed perturbation equation for the output variable of interest with all other inputs considered to be zero. The equations for the lateraldirectional responses to controller inputs were defined as follows:

\[\beta(s)/\delta(s) = (A_{\beta} s + B_{\beta})/\Delta\text{lat-dir} \quad (7)\]

\[r(s)/\delta(s) = (A_r s + B_r)/\Delta\text{lat-dir} \quad (8)\]

\[\psi(s)/\delta(s) = (A_{\psi} s^2 + B_{\psi}s + C_{\psi})/\Delta\text{lat-dir} \quad (9)\]

\[p(s)/\delta(s) = s(\lambda_{\varphi} s^2 + B_{\varphi}s + C_{\varphi})/\Delta\text{lat-dir} \quad (10)\]

The roll angle, roll rate and sideslip response to aileron command (\(\varphi/\delta_a\), \(p/\delta_a\), and \(\beta/\delta_a\) respectively) were defined by pole-zero placement to meet the Level 1 lateral-directional flying qualities requirements of MIL-F-8785C. This was done by using F-18 data (Reference 3) to define the denominator of the transfer function and set the numerator zeros and gains to satisfy MIL-F-8785C. The remaining transfer functions were defined from F-18 aerodynamic data from Reference 4. Table 1 provides the coefficients for the numerators of the transfer functions in terms of the primed dimensional stability derivatives as defined in Reference 2. In addition many of MIL-F-8785C requirements are stated in terms of responses to lateral stick force or pedal force inputs. In order to model the transfer functions as responses to force inputs, simplified linear relations between force inputs and control deflections were derived and applied as a gain to the transfer functions. By using this method the roll and yaw contributions due to the stabilator were combined with the aileron inputs to yield the yaw rate response to lateral stick force inputs.

### Table 1

LATERAL-DIRECTIONAL NUMERATOR TRANSFER FUNCTION COEFFICIENTS

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<td>(N_{\delta}^\beta)</td>
<td>(Y_{\delta}^\beta)</td>
<td>(Y_{\delta}^\beta (-N_{\delta}^\beta / Y_{\delta}^\beta))</td>
<td>(L_{\delta}^\beta (-Y_{\delta} - N_{\delta}^\beta / Y_{\delta}^\beta))</td>
</tr>
<tr>
<td>(N_{\delta}^\psi)</td>
<td>(N_{\delta}^\psi)</td>
<td>(N_{\delta}^\psi (-Y_{\delta} + (Y_{\delta}^\psi / N_{\delta})N_{\psi}^\psi))</td>
<td>(L_{\delta}^\psi \left(N_{\delta}^\psi \frac{1}{L_{\delta}^\psi N_{\psi}^\psi} + Y_{\delta} N_{\psi}^\psi + (Y_{\delta}^\psi / L_{\delta}^\psi)N_{\psi}^\psi\right))</td>
</tr>
<tr>
<td>(N_{\delta}^p)</td>
<td>(N_{\delta}^p)</td>
<td>(N_{\delta}^p (-Y_{\delta} - N_{\delta}^p / Y_{\delta}^\beta))</td>
<td>(L_{\delta}^p \left(N_{\delta}^p \frac{1}{L_{\delta}^p N_{\psi}^\psi} + Y_{\delta} N_{\psi}^\psi + (Y_{\delta}^\psi / L_{\delta}^\psi)N_{\psi}^\psi\right))</td>
</tr>
<tr>
<td>(N_{\delta}^r)</td>
<td>(N_{\delta}^r)</td>
<td>(N_{\delta}^r (-Y_{\delta} + (Y_{\delta}^r / N_{\delta})N_{\psi}^r))</td>
<td>(L_{\delta}^r \left(N_{\delta}^r \frac{1}{L_{\delta}^r N_{\psi}^r} + Y_{\delta} N_{\psi}^r + (Y_{\delta}^r / L_{\delta}^r)N_{\psi}^r\right))</td>
</tr>
</tbody>
</table>

\(A, B, C, D = \) coefficients of the transfer functions

\(\Delta\text{lat-dir} = \) denominator of the transfer function
2.3 MODAL CHARACTERISTICS

The modal characteristics are defined as the roots of the characteristic equation of the transfer function denominator. Equation (11) describes the modal characteristics of the reference model used in this computer code and was used to satisfy the following MIL-F-8785C requirements:

- 3.3.1.1 Lateral-Directional Oscillations (Dutch Roll)
- 3.3.1.2 Roll Mode
- 3.3.1.3 Spiral Stability

As stated earlier the spiral mode time constant \( \tau_s \) was set to zero throughout the flight envelope which meets the flying qualities specification requirement in MIL-F-8785C Paragraph 3.3.1.3 since \( \tau_s \) is neutrally stable. The values for the remaining roots of the characteristic equation were from Reference \( 3 \) as a function of Mach and altitude to provide values representative of the F-18. The Dutch roll frequency and damping were tested against the specification minimum values of \( \omega_d > 1.0 \) rad/sec and \( \zeta_d > 0.4 \) (MIL-F-8785C Paragraph 3.3.1.1). If \( \omega_d \) and \( \zeta_d \) did not meet the minimum values then the program set the data to those minimum values. If \( \tau_R \) exceeded the maximum specification value of 1.0 seconds (MIL-F-8785C Paragraph 3.3.1.2) the program sets \( \tau_R = 1.0 \). Although no minimum value is called out in the specifications, past experience (Reference \( 5 \)) has shown that designers should avoid too low an augmented value for \( \tau_R \) to prevent roll ratcheting. Since the F-18 by design has relatively low values for \( \tau_R \), a minimum of 0.3 seconds was selected to prevent potential roll ratcheting in the hybrid control system.

2.4 ROLL REQUIREMENTS

The roll angle and roll rate response to lateral stick force inputs were used to satisfy the following MIL-F-8785C requirements:

- 3.3.2.2 Roll Rate Oscillations
- 3.3.2.2.1 Additional Roll Rate Requirement For Small Inputs
- 3.3.2.3 Bank Angle Oscillations
- 3.3.4.1 Roll Performance for Class IV Airplanes
- 3.3.4.1.3 Roll Response
- 3.3.4.4 Linearity of Roll Response

The roll response to lateral stick force inputs \( \phi / F_s \) and the roll rate response to lateral stick force inputs \( \dot{\phi} / F_s \) were represented by the following equations:

\[
\frac{\phi}{F_s} = \frac{L_{fa}(s^2 + 2\zeta_\phi \omega_s s + \omega_\phi^2)}{(s)(s + 1/\tau_R)(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \tag{12}
\]

\[
\frac{\dot{\phi}}{F_s} = \frac{L_{fa}(s^2 + 2\zeta_\phi \omega_s s + \omega_\phi^2)}{(s)(s + 1/\tau_R)(s^2 + 2\zeta_d \omega_d s + \omega_d^2)} \tag{13}
\]

where:

- \( L_{fa} \) = command gain to stick force

To meet the roll oscillation requirement stated in paragraphs 3.3.2.2, 3.3.2.2.1, and 3.3.2.3 of MIL-F-8785C the complex roots of the numerator and denominator were canceled \( \omega_d = \omega_\phi \) and \( \zeta_d = \zeta_\phi \). By
canceling the complex roots the Dutch roll mode was not excited and thus inherently satisfied the above requirements.

The resulting equation for the roll rate response was:

$$\frac{p}{F_s} = \frac{L_{Fa}}{(s + 1/\tau_R)}$$

(14)

The term $L_{Fa}$ was then calculated from the steady-state roll equation ($p_{ss}$) where:

$$p_{ss} = L_{Fa}(\tau_R)F_s$$

(15)

By rearranging Equation (15) the computer program solves for $L_{Fa}$ using Equation 16.

$$L_{Fa} = \frac{p_{ss}}{\tau_R F_s}$$

(16)

The data for $p_{ss}$ was taken from Reference 6, which contained data for predicted maximum steady state roll as a function of Mach and altitude. The lateral stick force input was modeled to reflect that for Class IV aircraft aileron effectiveness which is nonlinear with deflection (i.e. large deflections produce an incrementally larger rolling moment than do small deflections). This was achieved by modeling a nonlinear stick shaping curve within the region recommended in Reference 5 and is shown in Figure 1. Reference 5 indicated that designing within this region, excessive roll sensitivity can be avoided while maintaining adequate roll control power.
Paragraph 3.3.4.1 is a measure of time to change bank angle (φ) within a specified time as shown in Table 2. Table 3 contains the speed range definitions for Level 1 Class IV airplanes. Paragraph 3.3.4.1.3 states that "Stick-controlled Class IV airplanes in Category A Flight Phase shall have a roll response to roll control force not greater than 15 degrees in 1 second per pound for Level 1...". To meet paragraphs 3.3.4.1 and 3.3.4.1.3 of MIL-F-8785C \( L_f^a \) is substituted into equation (12) since these two requirements are a function of roll or bank angle. The computer program calculates the roll response for the given time span and force input and tests the resulting values against the specification requirements for stick sensitivity and roll performance. If the value for \( L_f^a \) did not satisfy those two requirements the value for \( L_f^a \) was either increased or decreased so that the specification requirements were satisfied.

**TABLE 2. LEVEL 1 ROLL PERFORMANCE FOR CLASS IV AIRPLANES**

**FLIGHT PHASE CATEGORY A**

<table>
<thead>
<tr>
<th>TIME TO ACHIEVE THE FOLLOWING BANK ANGLE CHANGE (sec)</th>
<th>SPEED RANGE</th>
<th>30°</th>
<th>50°</th>
<th>90°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vl</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M</td>
<td>1.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3. LEVEL 1 AIRSPEED RANGE DEFINITIONS FOR CLASS IV AIRPLANES**

<table>
<thead>
<tr>
<th>SPEED RANGE SYMBOL</th>
<th>EQUIVALENT AIRSPEED RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VL</td>
<td>( V_{0\min} \leq V &lt; V_{\min} + 20KTS )</td>
</tr>
<tr>
<td>L</td>
<td>( V_{\min} + 20KTS^{(1)} \leq V &lt; 1.4V_{\min} )</td>
</tr>
<tr>
<td>M</td>
<td>( 0.4V_{\min} \leq V &lt; 0.7V_{\max}^{(2)} )</td>
</tr>
<tr>
<td>H</td>
<td>( 0.7V_{\max}^{(2)} \leq V \leq V_{0\max} )</td>
</tr>
</tbody>
</table>

(1) or \( V_{0\min} \) whichever is greater
(2) or \( V_{0\max} \) whichever is less

The requirements of 3.3.4.4, Linearity of Roll Response would inherently be met by the low order representation of roll and roll rate transfer functions.

**2.5 SIDESLIP REQUIREMENTS**

The sideslip (\( \beta \)) response to lateral stick force input and rudder pedal force input was used to satisfy the following MIL-F-8785C requirements:

3.3.2.4 Sideslip Excursions
3.3.2.4.1 Additional Sideslip Requirement for Small Inputs
3.3.2.5 Control of Sideslip in Rolls
3.3.6.1 Yawing Moments in Steady Sideslips
Paragraphs 3.3.2.4, 3.3.2.4.1 and 3.3.2.5 were satisfied by assuming that the control system is capable of eliminating any sideslip generated by the lateral stick and basically setting the sideslip response to zero (0). An example procedure is outlined in Reference 5 that designs a stick crossfeed to the rudder pedals which would ideally eliminate the sideslip generated by the stick input.

Paragraph 3.3.6.1 was satisfied through the sideslip response to pedal force input (β/F_p) transfer function. In this effort the gain on the pedal to rudder deflection was set so that the right pedal (or positive input) would generate a left (or negative) rudder deflection and vice-versa.

The remaining transfer functions: roll and roll rate to pedal force input (ϕ / F_p and p / F_p), yaw rate to stick and pedal force inputs (τ / F_s and τ / F_p) and lateral acceleration at the center of gravity to stick and pedal force inputs (a_ycg / F_s and a_ycg / F_p) were included as a matter of completeness but were not tailored to meet any specification requirements. The coefficients of the transfer functions were calculated as shown in Table 1. The equation for lateral acceleration at the center of gravity to stick and pedal inputs were computed according to Equation (3). Table 4 lists the equations for the dimensional stability derivatives and the primed derivatives used in Table 1. The non-dimensional stability derivatives are provided as nonlinear table data as a function of Mach and angle of attack in Appendix C.

### TABLE 4. LATERAL-DIRECTIONAL STABILITY DERIVATIVES

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y_v</td>
<td>ρSU C_yβ / 2m</td>
<td>1 / sec</td>
</tr>
<tr>
<td>Y_y</td>
<td>ρSU^2 C_yδ / 2m</td>
<td>ft / sec^2</td>
</tr>
<tr>
<td>Y_y*</td>
<td>ρSU C_yδ / 2m</td>
<td>1 / sec</td>
</tr>
<tr>
<td>N_β</td>
<td>ρSU^2 b C_nβ / 2I_xz</td>
<td>1 / sec^2</td>
</tr>
<tr>
<td>N_r</td>
<td>ρSU^2 b C_nτ / 4I_xz</td>
<td>1 / sec</td>
</tr>
<tr>
<td>N_δ</td>
<td>ρSU^2 b C_νδ / 2I_xz</td>
<td>1 / sec^2</td>
</tr>
<tr>
<td>N_j</td>
<td>N_i + (I_{xz}/I_{zz})L_i / (1 - (I_{zz}/I_{xx}L_z))</td>
<td></td>
</tr>
<tr>
<td>L_β</td>
<td>ρSU^2 b C_νβ / 2I_xx</td>
<td>1 / sec^2</td>
</tr>
<tr>
<td>L_r</td>
<td>ρSU^2 b C_ντ / 4I_xx</td>
<td>1 / sec</td>
</tr>
<tr>
<td>L_δ</td>
<td>ρSU^2 b C_νδ / 2I_xx</td>
<td>1 / sec^2</td>
</tr>
<tr>
<td>L_j</td>
<td>L_i + (I_{xz}/I_{xx})N_i / (1 - (I_{zz}/I_{xx}L_z))</td>
<td></td>
</tr>
</tbody>
</table>
3.0 PROGRAM STRUCTURE

The computer program F18LDTF.EXE is a menu driven program written in Visual Basic Version 2.0 and runs in the Microsoft Windows™ Environment. The program is broken into two main sections, F18LDTF.BAS and F18LDTF.FRM shown in Figure 2. The following bold face sections describe each main section as well as code and subroutines corresponding to each menu option in alphabetical order. A program listing is in Appendix A. Modeled aircraft specifications and the permissible flight envelope are in Appendix B. The plots for the nonlinear data are shown in Appendix C. In addition to the program and data table, an input file with trim Mach, altitude and angle-of-attack is required to run the program. A sample input file is in Appendix D. Note that it includes a case outside of the permissible flight envelope to test for potential input errors. The output file lists the coefficients of the transfer functions for roll rate, roll angle, sideslip, yaw rate and lateral acceleration to lateral stick and pedal inputs for each flight condition evaluated. A sample output file corresponding to the input file of Appendix D is in Appendix E.

**calc_rh o** - Subroutine that calculates the air density as a function of altitude. The equations are based on standard atmospheric relationships.

**Files** - Menu caption "Files". This subroutine activates the sub-menu options open_tig_Click, output_file_Click and flight_cond_Click. The intent of this option is to allow the user to use and define different input and output data as appropriate.

**flight_cond_Click** - Menu caption "Open Flight Conditions". Opens a user defined input file. Operates the same as a Windows™ file open command. The input file format is that the first line contains the run title. The following lines list trim Mach, altitude in feet, and angle-of-attack in radians separated by commas for each flight condition. There is no limit to the number of flight conditions to be listed.

**Form_Load** - Loads initial data and sets default values at the initial execution of the program. Also sets the error output file for the Dynamic Link Library (DLL) VBDREAD to "c:\f18ldtf\error.out".

**F18LDTF.BAS** - Declares the global variables and arrays, constant values and initializes the DLL TOPEN and TLOOK. TOPEN and TLOOK were modified from Reference 7 to provide a look-up routine for the nonlinear table data.

**F18LDTF.FRM** - Loads initial data and sets default values at the initial execution of the program. This is the code which also acts as the driver to execute the various menu driven subroutines to read the data tables, input files, calculate the transfer functions and write the transfer functions to an output file. Each menu option is activated by placing the mouse pointer over the menu option and clicking the left mouse button. Figure 3 shows the initial display when the program is activated.

**Exit_Click** - Menu caption "Exit". Exit program.

**mach_to_vel** - Subroutine that calculates velocity in ft/sec as a function of Mach and altitude. The equations are based on standard atmospheric relationships.

**open_tig_Click** - Menu caption "Open Tigs File". This option operates the same as a Windows™ file open command with the default nonlinear data table "c:\f18ldtf\f18ld.dat". The data table is to be used later in the Dynamic Link Library (DLL) VBDREAD.

**output_file_Click** - Menu caption "Output File Name". This option operates the same as a Windows™ file open command with the default output file name "c:\f18ldtf\f18tf.out". The user may change the name as appropriate.

**print_tf** - Subroutine that prints the Laplace transfer function in descending order of Laplace operator (s) to the output file. The x represents the order of the transfer function.
Figure 2. F-18LDTF Structure

Visual Basic Program Structure

Form, Load, Initialize Values
Files
Open Files
Set Up
Set Delimiters
Run, Click
Generate Transfer Functions
Shell, Click
Run Other Applications
Exit, Click
End Program

Set Global Values

F18LDTF.EXE

F18LDTF.BAS
Figure 3. F18LDTF Initial Screen

**F-18 Lateral-Directional Transfer Functions**

<table>
<thead>
<tr>
<th>Files</th>
<th>Set-Up</th>
<th>Generate Transfer Functions</th>
<th>Shell</th>
<th>Exit</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATA TABLE INPUT FILE</td>
<td>c:\f18ldtf\f18ld.dat</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATA TABLE OUTPUT FILE STATUS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DATA TABLE OUTPUT FILE</td>
<td>c:\f18ldtf\error.out</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NAWCADWAR-9500-4.3
run_Click - Menu caption "Generate Transfer Functions". This code does the actual computation of the transfer functions for each flight condition in the input file and writes the results to the output file named in output_file_Click. The default output file name is "c:\f18dtf\f18tf.out".

set comma_Click - Menu caption "Comma Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to a comma between values.

set space_Click - Menu caption "Space Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to a single space between values. This is the default setting.

set tab_Click - Menu caption "Tab Delimiters". This subroutine sets the delimiters of the coefficients for the transfer functions in the output file to tab positions 0, 20, 40, 60, and 80 as appropriate to the order of the transfer function.

Set Up - Menu caption "Set-up". This subroutine activates the sub-menu options set space, set comma, and set tab. The program defaults to a space delimiter. This option allows the user to customize the output file by defining the delimiters to be used in printing out the transfer functions.

shell_Click - Menu caption "Shell". This subroutine allows the user to exit the program to run other executable files and then return to the program.

speed_cat - Subroutine that determines the speed category (VL, L, M, and H) in which to test MIL-F-8785C Requirement 3.3.4.1. Subroutine inputs are Mach, altitude and velocity. The subroutine calls vmin and vmax to determine the speed limits for the given altitude as defined in the flight envelope in reference 6. These limits are then used to determine the speed category of the trim velocity.

stick_gain - Subroutine that calculates the linearized gains between the lateral stick force input and the aileron and stabilator deflections. The gains are based on the values from References 3 and 4.

test_drdamp - Subroutine that tests nonlinear table value for Dutch roll damping ($\zeta_d$). If $\zeta_d < 0.4$ then the code sets $\zeta_d = 0.4$.

test_envelope - Subroutine that tests whether or not the trim conditions are within the permissible flight envelope of the F-18 modeled in this program. The program tests against the envelope as a function of Mach and altitude. It does not test for stall angle-of-attack.

test_freq - Subroutine that tests nonlinear table value for Dutch roll frequency ($\omega_d$). If $\omega_d < 1.0$ rad/sec then the code sets $\omega_d = 1.0$ rad/sec.

test_phi - Subroutine that tests the roll sensitivity and time to roll requirements. If the time to roll requirement is not met then the numerator gain is increased by 10% until the requirements is met. If the roll sensitivity is too high the numerator gain is set to the maximum requirement value.

test_stick - Subroutine that determines the maximum stick force input to as a function of $p_{ss}$. The stick force is the same as the design curve shown in Figure 1.

vmax - Subroutine that computes the maximum speed as a function of altitude for the permissible flight envelope for the F-18 at a gross weight of 42097 lbs.

vmin - Subroutine that computes the minimum speed as a function of altitude for the permissible flight envelope for the F-18 at a gross weight of 42097 lbs.
4.0 PROGRAM OPERATION

4.1 SYSTEM REQUIREMENTS

The program was designed in the Microsoft® Visual Basic™ Version 2.0 programming system for Windows™ Ver. 2.0 higher. The program runs from mouse inputs and requires 1.2 MB disk space to load the distribution disk onto the host system. The distribution disk contains the executable code, the program source code, the custom controls (denoted with the extension "VBX") required to run the program, the dynamic-link library (DLL) executable and source codes for VBREAD that executes the table look-up routine for the F-18 data tables used in the program and a sample input file (F18TRIM.INP) and output file (F18TF.OUT).

4.2 INSTALLATION

The Setup program will install the program and source code in a directory called "f18ldtf". For reference purpose, it will be assumed that the floppy drive designation is A, the hard drive designation is C and the user is in the Windows™ environment. To install the program insert the floppy disk into the A drive. In the Program Manager, choose Run from the File Menu, and then type:

A:setup <RETURN>

The Setup program will create and copy the following files into the C:F18LDTF\ directory:

F18LDTF.BAS
F18LD.DAT
F18LDTF.EXE
F18LDTF.FRM
F18LDTF.MAK
F18TF.OUT
F18TRIM.INP
ERROR.OUT
VBREAD.DLL
VBREAD.FOR
VBREAD.DEF

Into C:WINDOWS\SYSTEM\ directory the following custom control files will be copied:

ANIBUTON.VBX
CMDDIALOG.VBX
GAUGE.VBX
GRAPH.VBX
GRID.VBX
KEYSTAT.VBX
MSCOMM.VBX
MSMASKED.VBX
OLECLIENT.VBX
PICCLIP.VBX
SPIN.VBX
THREED.VBX
VBRUN200.DLL
4.3 PROGRAM EXECUTION

The following instructions will describe how to invoke "F18LDTF" and run a sample session. To invoke the executable program go to the Program Manager in the Windows environment. Choose Run from the File Menu and type:

\texttt{C:\F18LDTF\F18LDTF <RETURN>}

Figure 3 shows what will appear on the screen at program execution. To run the program use the mouse to click on the various menu options. The following instructions will describe the recommended order in which to exercise the various menu options.

1. Move the mouse to "Files" and select the option "Open Tigs File". The default file "c:\f18ldtf\f18ld.dat" will appear. Click the "OK" button. When the data file is read in, the message "DLL LIB TOPEN COMPLETE" will appear on the screen in the "STATUS" text box.

2. Move the mouse to "Files" and the option "Open Flight Conditions" and click on. This option operates the same as a Windows\textsuperscript{TM} file open command. The sample input file is in "c:\f18ldtf\f18trim.inp". The user may create their own input file for transfer function file generation. Click the "OK" button when the appropriate input file is highlighted. In the "STATUS" text box a message will appear stating input flight condition file is open.

3. Move the mouse to "Set Up". The default delimiter between the coefficients of the transfer function is a space. If the user requires a different delimiter the user may select the option for a comma, space or tab delimiter. A message will appear in the "STATUS" text box stating which delimiter was selected. If the space is a satisfactory delimiter then the user may skip this option.

4. Select the "Generate Transfer Functions" option. While the program is reading in the flight conditions and generating the transfer functions the message "Generating Transfer Functions" will appear in the "STATUS" text box. In the box below the "STATUS" text box the message "Case Number x" will appear for each flight condition case. Upon completion, the message "Generation of Transfer Functions Complete" and "Transfer Functions Saved to File F18TF.OUT" will appear in the "STATUS" text boxes.

5. Select "Exit" to leave the program.

6. If the user desires to run additional executable, batch or command files, the "Shell" option may be invoked. This is useful if the user would like to view or edit the output file prior to exiting the program.
5.0 CONCLUSIONS

This report documents the development of a computer program that generates Level 1 lateral-directional transfer functions for a Class IV airplane that meet requirements of MIL-F-8785C given a trim Mach, altitude and angle-of-attack flight conditions. The data used to generate the transfer functions were representative of an F-18 and will support the effort being done at C. S. Draper Laboratory, Inc. to develop a hybrid, learning augmented, lateral-directional flight control system. Also presented in this report is the structure of the computer code, instructions for running the program, sample input and sample output.
REFERENCES


Option Explicit
Declare Sub TOPEN Lib "VBRDAD.DLL" (ByVal INFILE As String, ByVal OUTFILE As String)
Declare Sub trcok Lib "VBRDAD.DLL" (Table As integer, X As Single, Y As Single, Z As Single, FXZ As Single)
' Declare Global Variables
Global mach As Single, alt As Single, alpha As Single
Global tau As Single, pmax As Single, dfreq As Single, dcdamp As Single
Global cydr As Single, cldr As Single, cmd As Single, cr As Single, c1r As Single
Global cyda As Single, clda As Single, cmda As Single, clb As Single
Global cyb As Single, cdyb As Single, cldb As Single, cmdb As Single
Global fstick, fpdal, bprime_fstick, tab_flag, phit
Global File_com_file$, sep$, speedcat$, ncave, test_case_flag
'
' The following are the arrays that define the transfer functions used to define
' the Level 1 Flying Qualities. Those values corresponding to array name(x) are
' the values of the numerator of the transfer function in descending order of s and
' the values corresponding to denominator(x) are the values of the denominator of
' the transfer functions.
Global p_to_fstick(4), phi_to_fstick(3), beta_to_frud(2), r_to_frud(5)
Global p_to_frud(5), phi_to_frud(5), beta_to_fstick(2), r_to_fstick(5)
Global eyec_to_frud(5), eyec_to_fstick(5), denominator(5), f(5)
'
' Declare Global Constants
Global Const tab_num_taur = 1
Global Const tab_num_freq = 2
Global Const tab_num_damp = 3
Global Const tab_num_pmax = 4
Global Const tab_num_cydr = 5
Global Const tab_num_cldr = 6
Global Const tab_num_cmd = 7
Global Const tab_num_cnr = 8
Global Const tab_num_cdr = 9
Global Const tab_num_cyda = 10
Global Const tab_num_clda = 11
Global Const tab_num_cmda = 12
Global Const tab_num_cyb = 13
Global Const tab_num_cnb = 14
Global Const tab_num_clb = 15
Global Const tab_num_cyds = 16
Global Const tab_num_clds = 17
Global Const tab_num_cnbs = 18
Global Const Z = 1
Global Const num_files = 3
Global Const dot$ = ","
Global Const blank$ = " "
Global Const comama$ = ","
Global Const tmax = 124000 'slug-sq.ft
Global Const txx = 143000 'slug-sq.ft
Global Const tfx = -2971 'slug-sq.ft
Global Const ts = 37.44 'ft
Global Const b = 400 'sq. ft
Global Const mass = 1300.4
Global Const force_to_rud_gain = -0.00262 'rad per lb right pedal => left rudder &
vice versa
Global Const rad_to_deg = 57.29578
Global Const g = 32.174 'ft/sec^2
Sub calc_rho (alt, rho)
    ' CALCULATE DENSITY
    T88 = 288.15
    THERAT = 10 - alt * atm_con
    If (alt >= 36088) Then THERAT = .75134679
    DELRAT = (T88 / (T88 - .00198 * alt)) ^ (-.256)
    rho = (DELRAT / THERAT) * .002377
End Sub

Sub Exit_Click ()
End Sub

Sub flight_cond_Click ()
    cmdialog1.Filename = "c:\f18ldt\f18ldr\f18ldr.lnp" 'Default name
    cmdialog1.Action = 1
    Flt_con_file$ = cmdialog1.Filename
    Open Flt_con_file$ For Input As #3
    Text2.Text = "Flt. Cond. File = " + cmdialog1.Filename + " Open"
End Sub

Sub Form_Load ()
    Text2.Text = "c:\f18ldt\error.out"
    OUTFILE = Text2.Text
    'define initial constants
    denominator(1) = 1
    denominator(5) = 0
    tab_flag = 0
    sep$ = blank$
    speedat$ = "VL"
    Mach_min_val = .19
    Mach_max_val = 1.1
    phi = 1.
    fstick = 13' max lateral stick input (lbf)
End Sub

Sub mach_to_val (mach, alt, vel)
    ' CALCULATE VELOCITY (FT/SEC) FROM MACH AND ALT
    THERAT = 10 - alt * atm_con
    
    NOTE: CONSTANT TEMP AFTER 36089 FT (US STD ATM)
End Sub

If (alt >= 36088) Then THERAT = .75134679
DIVCON = Sqr(1.4 + 32.2 + 53.35 + THERAT * 518.6)
vel = DIVCON * mach
End Sub

Sub output_file_Click ()
    cmdialogl.Filename = "c:\f18ldt\f18ldt.out" 'Default name
    cmdialog3.Action = 1
    Open cmdialog3.Filename For Output As 92
End Sub

Sub print_tf2 (tf$i)
    For i = 1 To 2
        f$i = Format(tf$i, "###0.000000")
        Next i
    If tab_flag = 0 Then
        Print 92, f$1; sep$; f$2
    ElseIf tab_flag = 1 Then
        Print 92, f$1; Tab(20); f$2
    End If
End Sub

Sub print_tf3 (tf$)
    For i = 1 To 3
        f$i = Format(tf$i, "19.10")
        Next i
    If tab_flag = 0 Then
        Print 92, f$1; sep$; f$2
    ElseIf tab_flag = 1 Then
        Print 92, f$1; Tab(20); f$2
    End If
End Sub
Simplifying approximations were made in generating the transfer functions to yield Level 1 time histories that should by within the F-18's capabilities to achieve.

Note that these transfer functions are applicable to trimmed flight conditions with flight path angle = 0 so that the Mach, alt and angle-of-attack values correspond to those trimmed values.

One such simplifying approximation is that the spiral mode = 0 throughout the flight envelope.

The roll characteristics are based on the approximation that:

\[
p_{\text{fashion, roll}} = \frac{\theta_{\text{fashion, roll}}}{\phi_{\text{fashion, roll}}} = \sin(\phi_{\text{fashion, roll}})
\]

This will be the low-order transfer functions for the \( p \) and \( \phi \) transfer functions with the additional assumptions that the \( p \) and \( \phi \) numerator \( \text{freq} \) & \( \text{damping} \) = dutch roll \( \text{freq} \) & \( \text{damping} \).

The dutch roll characteristics are based on the 3 Degree-of-Freedom Dutch Roll approximation to provide the numerator characteristics for the beta and \( r \) transfer functions to both the lateral stick and rudder input. This approximation was also used to generate the roll response to pedal inputs.

```
Input #3, title$ # Text3.Text = "Generating Transfer Functions"
Print #2, title$
Print #2, blank$
ncase = 0

Ixs_div_IX = Ixs / Ixx
Ixs_div_IX = Ixs / Ixx
one_minus_Ixs_div_IXs = 1 - Ixs_div_IX * Ixs_div_IX

' Read in mach, altitude and angle-of-attack

Do While Not EOF(3)
Input #3, mach, alt, alpha
ncase = ncase + 1
fmsach = Format(mach, "$0.000$")
fall = Format(alt, "$000.000$")
fallpha = Format(alpha, "$0.000")
fcnase = Format(ncase, "$0000$")

Text4.Text = "Case Number "$ + fcnase

Print #2, "Case Number "; fcnase
Print #2, "mach "; fmsach; " alt "; fall; " alpha(rad) "; fallpha

' Test that trim condition is within the flight envelope for the F-18 otherwise go to next flight condition

Call test_envelopes(alt, mach, env_flag)
```

If env_flag = 1 Then
Print #2, "Trim flight conditions outside of permissible flight envelope"
GoTo 10

End If

Call mach_to_vel(mach, alt, vel)
U0 = vel * Cos(alpha)

Call calc_rho(alt, rho)
q = .5 * rho * U0 * U0

Determining the speed category
test for time to bank
Call speed_cat(mach, alt, vel, speedcat$

Do table look-ups

Call tlook(tab_num_taur, mach, alt, z, taur)
Call tlook(tab_num_freq, mach, alt, z, drfreq)
Call tlook(tab_num_damp, mach, alt, z, drdamp)
Call tlook(tab_num_pasmax, mach, alt, z, pasmax)
Call tlook(tab_num_cydr, mach, alpha, z, cydr)
Call tlook(tab_num_cldr, mach, alpha, z, cldr)
Call tlook(tab_num_cndr, mach, alpha, z, cndr)
Call tlook(tab_num_cdr, mach, alpha, z, cndr)
Call tlook(tab_num_cyda, mach, alpha, z, cyda)
Call tlook(tab_num_clda, mach, alpha, z, clda)
Call tlook(tab_num_cnda, mach, alpha, z, cnda)
Call tlook(tab_num_cnda, mach, alpha, z, cnda)
Call tlook(tab_num_cydb, mach, alpha, z, cyb)
Call tlook(tab_num_cydb, mach, alpha, z, cyb)

Call test_taur(taur)
Call test_FREQ(drfreq)
Call test_drdamp(drdamp)

Determine the coefficients for the denominator of
the transfer functions in descending order of s.
The denominator is an expanded representation of
The $DOP$ Dutch Roll Approximation where in the
$s$ domain the denominator is as follows:
s = (s(taur)+s5^{2} + 2*drdamp*drfreq*s + drfreq)^2

denominator(1) = 1 and denominator(5) = 0 already set in

Form Load

\[ two_s_w = 2 + drdamp * drfreq \]
\[ wn1 = drfreq * drfreq \]
\[ denominator(2) = two_s_w + taur \]
\[ numerator(3) = wn1 + taur * two_s_w \]
\[ denominator(4) = taur + wn2 \]

Format denominator values

Print #2, blank$
Print #2, " Denominator to Lateral-Directional Transfer Functions."
Print #2, " Coefficients are in descending order of s."
Print #2, blank$

Call print_tfs(denominator())

LPrime_fstick = pasmax / (tau * fstick)
Call test_tphi(LPrime_fstick, taur, pasmax, speedcat$

p_to_fstick(1) = LPrime_fstick
p_to_fstick(2) = LPrime_fstick * two_s_w
p_to_fstick(3) = LPrime_fstick * wn2
p_to_fstick(4) = 0

phi_to_fstick(1) = LPrime_fstick
phi_to_fstick(2) = LPrime_fstick * two_s_w
phi_to_fstick(3) = LPrime_fstick * wn2

Print #2, blank$
Print #2, " p to lateral stick force transfer function numerator"
Call print_tfs(p_to_fstick())

Print #2, blank$
Print #2, " phi to lateral stick force transfer function numerator"
Call print_tfs(phi_to_fstick())

The Dutch Roll requirement will be met with a three degree of freedom
dutch roll approximation for sideslip to rudder input

The denominator will be represented by the dutch roll frequency and
damping.

The numerator will be represented by a first order transfer function.
In "Aircraft Dynamics and Automatic Control" by McRuer, Ashkenas, and Graham
the numerator is defined as $(dudrstar)*(s-Mr’-(dudrstar))$. Where

\[ Yadc = Ydr/90 \]
\[ Mr’ = Mr + ([ixs/ixs]1dcr/\{(1-ixs’2)/(ixs’2)\}) \]
\[ Mdr’ = Mr + ([ixs/ixs]1dcr/\{(1-ixs’2)/(ixs’2)\}) \]

Pedal Gain is based on the FA - 18 like gearing used in the generic
fighter model hosted in the FASTER lab here at NAWC-AD WAR
Calculate dimensional derivatives

Ydrstar = cydr * rho * S * Uo / (2 * mass)
Ydstar = cyda * rho * S * Uo / (2 * mass)
Ydstar = cyds * rho * S * Uo / (2 * mass)
Tv = cyb * rho * S * Uo / (2 * mass)
Wc = cnc * q * S * span / span / (2 * Uo * iss) 
Lr = clr * q * S * span / span / (2 * Uo * iss) 
Mb = cbn * q * S * span / iss 
Lb = cbl * q * S * span / span / iss 
Mdr = cmdr * q * S * span / span / iss 
Ldr = cdr * q * S * span / span / iss 
Mda = cnda * q * S * span / span / iss 
Lda = cnda * q * S * span / iss 
Mds = cnda * q * S * span / iss 
Lds = cnda * q * S * span / iss 

Mrprime = (Mc + (ixs * xis) / Lr) / one_minus_ixs2_div_ixs 
Mdrprime = (Mdr + (ixs * xis) / Ld) / one_minus_ixs2_div_ixs 
Ldrprime = (Ldr + (ixs * xis) / Mdr) / one_minus_ixs2_div_ixs 

Mbpri = (Mb + (ixs * xis) / Lb) / one_minus_ixs2_div_ixs 
Lbpri = (Lb + (ixs * xis) / Mb) / one_minus_ixs2_div_ixs 
Mdpri = (Mdp + (ixs * xis) / Lda) / one_minus_ixs2_div_ixs 
Ldpri = (Ldp + (ixs * xis) / Mdp) / one_minus_ixs2_div_ixs 

A-6

Computer transfer function numerators

' Test to prevent division by 0
If Ldrprime = 0 Then
  phi_to_frud(1) = 0
  phi_to_frud(2) = 0
  phi_to_frud(3) = 0
  Ydrstar = Ldrprime = Ydstar = Lbprime = Mrprime / 0.00001' Set
  Ldrprime to Small Number
End If

Else
  phi_to_frud(1) = force_to_rud_gain * rad_to_deg * Ldrprime
  phi_to_frud(2) = force_to_rud_gain * rad_to_deg * Ldprime
  phi_to_frud(3) = force_to_rud_gain * rad_to_deg * Ldprime + (1 - Ldprime / Mrprime) + Yv * Mrprime - Ydstar + Lbprime + Mrprime / Ldprime
End If

p_to_frud(1) = phi_to_frud(1)
p_to_frud(2) = phi_to_frud(2)
p_to_frud(3) = phi_to_frud(3)
p_to_frud(4) = 0

If Ydstar = 0 Then
  beta_to_frud(1) = 0
  beta_to_frud(2) = 0
End If

Else
  beta_to_frud(1) = force_to_rud_gain * rad_to_deg * Ydstar
  beta_to_frud(2) = force_to_rud_gain * rad_to_deg * Ydstar + (-Mrprime - (Mbpri / Ydstar))
End If

beta_to_fstick(1) = 0 'to assure 0 sideslip in rolls by effectively subtracting
any beta
beta_to_fstick(2) = 0 'generated and thus setting the response to zero

r_to_frud(1) = force_to_rud_gain * rad_to_deg * Mdrprime
r_to_frud(2) = force_to_rud_gain * rad_to_deg * Mdrprime + (-Tv - (Ydstar / Mdrprime) + Mrprime)

r_to_frud(1) (x - yst + r_to_sill) * rad_to_deg
r_to_fstick(2) = (x - yst + r_to_sill) * rad_to_deg

An auxiliary relationship that is provided for simultaneous time history matching
in the acceleration in the y direction due to rudder & stick inputs.
the equation for yacc = 0.9betadot - gphi - dot

acc_to_frud(1) = (Uo + beta_to_frud(1) - g * phi_to_frud(1)) / rad_to_deg
acc_to_frud(2) = (Uo + beta_to_frud(2) - g * phi_to_frud(2) + Uo * r_to_frud(1)) / rad_to_deg
acc_to_frud(3) = (-g * phi_to_frud(3) + Uo * r_to_frud(3)) / rad_to_deg

acc_to_fstick(1) = (Uo * beta_to_fstick(1) - g * phi_to_fstick(1)) / rad_to_deg
acc_to_fstick(2) = (Uo * beta_to_fstick(2) - g * phi_to_fstick(2) + Uo * r_to_fstick(1)) / rad_to_deg
acc_to_fstick(3) = (-g * phi_to_fstick(3) + Uo * r_to_fstick(3)) / rad_to_deg

Print #2, blank$
Print #2, "beta to lateral stick force transfer function numerator"

Call print_tf2(beta_to_fstick())

Print #2, blank$
Print #2, "x to lateral stick force transfer function numerator"

Call print_tf2(r_to_fstick())

Print #2, blank$
Print #2, "yacc to lateral stick force transfer function numerator"

Call print_tf3(acc_to_fstick())

Print #2, blank$
Print #2, "p to pedal force transfer function numerator"

Call print_tf4(p_to_frud())

Print #2, blank$
Print #2, "phi to pedal force transfer function numerator"
Call print_tf3(phi_to_frud())
Print #2, blank$
Print #2, "beta to pedal force transfer function numerator"
Call print_tf2(beta_to_frud())
Print #2, blank$
Print #2, "r to pedal force transfer function numerator"
Call print_tf2(r_to_frud())
Print #2, blank$
Print #2, "acog to pedal force transfer function numerator"
Call print_tf2(acog_to_frud())
10 Print #2, blank$
Loop
Close #2
Close #3
Text3.Text = "Generation of Transfer Functions Complete"
Text4.Text = "Transfer Functions Saved to File " + cdialog1.filename
End Sub

Sub save_mod_Click ()
End Sub

Sub set_comma_Click ()
sep$ = comma$
tab_flag = 0
Text3.Text = "Delimiters Set To Commas"
End Sub

Sub set_space_Click ()
sep$ = blank$
tab_flag = 0
Text3.Text = "Delimiters Set To Spaces"
End Sub

Sub set_tab_Click ()
tab_flag = 1
Text3.Text = "Delimiters Set To Tabs"
End Sub

Sub shell_Click ()
' ... set dialog default extension filename ...
cdialog2DialogTitle = "Executable Files"
cdialog2.Filter = "Exe Files (*.exe)|*.exe|Com Files (*.com)|*.com|Batch Files (*.bat)|*.bat"
cdialog2.filename = "*.exe"
cdialog2.Action = 1 'opens file
' ... open the selected file ...
x = Shell(cdialog2.filename, 3)

End Sub

Sub speed_cat (mach, alt, vel, speedcat$)
Call vmin(alt, Mach_min_val)
Call vmax(alt, Mach_max_val)
Call mach_to_vel(Mach_min_val, alt, vmin_val)
Call mach_to_vel(Mach_max_val, alt, vmax_val)
vmin20 = vmin_val + 33.77778
v0min = 1.4 * vmin_val
v7max = .7 * vmax_val
If vel >= vmin_val And vel < vmin20 Then
speedcat$ = "VL"
ElseIf vel >= vmin20 And vel < v0min Then
speedcat$ = "L"
ElseIf vel >= v0min And vel < v7max Then
speedcat$ = "H"
ElseIf vel >= v7max And vel <= vmax_val Then
speedcat$ = "H"
End If
End Sub

Sub stick_gain (fstick, gains, gains)
' This gain is computed from data used in NAWC-AC FASTER
' LAB. This is needed to compute the stick force gain necessary
' to generate the transfer functions.
' From NDC A7813 VOL. 1 REV B page 9-14
' the stick force to stick deflection gain is 3.6667 lb/in
' Compute stick deflection from the force
stick_in = fstick / lb_per_in
sign_stick = Sgn(fstick)
gains = sign_stick * stk_to_stab / lb_per_in, units = (rad/in)*(in/lb)
    'stk_to_stab = .04 rad/in
If Abs(stick_in) <= 1 Then
    gains = sign_stick * stk_to_sill / lb_per_in, units = (rad/in)*(in/lb)
    'stk_to_sill = .075 rad/in
Else
    gains = sign_stick * stk_to_sill2 / lb_per_in, units = (rad/in)*(in/lb)
    'stk_to_sill2 = .125 rad/in
End If

End Sub

Sub test_drdamp (damp)
If damp < .4 Then
damp = .4
End If
End Sub

Sub test_envelope (alt, mach, env_flag)
    ' Tests that trim flight conditions are
    ' within the permissible flight envelope.
    ' If not will skip this case and go
    ' to next trim case in input file.
    Call vmin(alt, mach_min) ' Determines min Mach for altitude
    Call vmax(alt, mach_max) ' Determines max Mach for altitude
If mach < mach_min Or mach > mach_max Then
    env_flag = 1
Else
    env_flag = 0
End If
End Sub

Sub test_freq (freq)
If freq < 18 Then
    freq = 18
End If
End Sub

Sub test_phi (lf, tau, psemax, speedcat$)
lf_odd = lf
    ft30 = Format(t30, "####.00")
    ft50 = Format(t50, "####.00")
    ft90 = Format(t90, "####.00")
tau_term = 1 - Exp(-1 * tau) ' unit step response in 1 second
100 phi = If * (1 - Exp(-1 * tau))
If phi <= 15 Then ' test for stick sensitivity
    lf = 15 / tau_term
    phi = If * (1 - Exp(-1 * tau))
End If
End Select
End Sub

Select Case speedcat$
    Case "VL", "L", ' test for 30 deg bank angle change
        phi30 = fstick * If * (1 - Exp(-t30 * tau))
        If phi30 < 30 Then
            lf = 1.1 * If
            GoTo 100 ' check that If still meets stick sensitivity req'ts
        End If
    Case "M" ' test for 90 deg bank angle change
        phi90 = fstick * If * (1 - Exp(-t90 * tau))
        If phi90 < 90 Then
            lf = 1.1 * If
            GoTo 100 ' check that If still meets stick sensitivity req'ts
        End If
    Case "H" ' test for 50 deg bank angle change
        phi50 = fstick * If * (1 - Exp(-t50 * tau))
        If phi50 < 50 Then
            lf = 1.1 * If ' check that If still meets stick sensitivity req'ts
            GoTo 100
        End If
End Select
End Sub

Sub test_stick (fstick, pss)
    ' maximum input stick force is a function of pss to
    ' to help in preventing too much roll sensitivity
    ' the curve fits with in the region specified in
    ' figure 194 pg 480 MIL-SPEC-8785A
If pss >= 80 And pss < 200 Then
fstick = 9 + .03333 * (ps - 80)

Elseif ps >= 18.75 And ps < 80 Then
  fstick = 5 + .06531 * (ps - 18.75)

Elseif ps < 18.75 Then
  fstick = 1 + .21333 * ps

End If

End Sub

Sub test_taur (tau)

  If tau < .3 Then tau = .3
  If tau > 10 Then tau = 10

End Sub

Sub vmax (alt, Mach_max_val)

  ' this subroutine computes the values for
  ' the maximum speed for the permissible flight
  ' envelope for the F-15 for a gross weight of
  ' 42,097 lbs. The values computed here will be
  ' used to determine the values for the time to roll requirements

  If alt < 20000 Then
    Mach_max_val = 1.1 + .000027 * alt
  Elseif alt >= 20000 And alt < 35000 Then
    Mach_max_val = 1.64 + .000024 * (alt - 20000)
  Elseif alt >= 35000 And alt < 45000 Then
    Mach_max_val = 2*
  Elseif alt >= 45000 And alt < 50000 Then
    Mach_max_val = 2 + .000066 * (alt - 45000)
  Elseif alt >= 50000 And alt <= 51000 Then
    Mach_max_val = 1.64 - .00008 * (alt - 50000)
  Elseif alt >= 51000 And alt < 53000 Then
    Mach_max_val = 1 - .00003 * (alt - 51000)
  Elseif alt >= 53000 Then
    Mach_max_val = .94
  End If

End Sub

Sub vmin (alt, Mach_min_val)

  ' this subroutine computes the values for
  ' the minimum speed for the permissible flight
  ' envelope for the F-15 for a gross weight of
  ' 42,097 lbs. The values computed here will be
  ' used to determine the values for the time to roll requirements

  If alt < 20000 Then
    Mach_min_val = .19 + .0000046 * alt
  Elseif 20000 >= alt And alt < 30000 Then
    Mach_min_val = .28 + .0000064 * (alt - 20000)
  Elseif alt >= 30000 And alt < 34000 Then
    Mach_min_val = .34 + .0000155 * (alt - 30000)
  Elseif alt >= 34000 And alt < 43000 Then
    Mach_min_val = .4 + .00001556 * (alt - 34000)
  Elseif alt >= 43000 And alt < 50000 Then
    Mach_min_val = .54 + .00001176 * (alt - 43000)
  Elseif alt >= 50000 And alt < 53000 Then
    Mach_min_val = .74 + .0000083 * (alt - 50000)
  Elseif alt >= 53000 Then
    Mach_min_val = .86
  End If

End Sub
APPENDIX B

MODELED AIRCRAFT SPECIFICATIONS
TABLE B1. BASIC AIRCRAFT PARAMETERS

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>UNITS</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Weight</td>
<td>lbs</td>
<td>42097</td>
</tr>
<tr>
<td>Mass</td>
<td>slugs</td>
<td>1308.4</td>
</tr>
<tr>
<td>$I_{xx}$</td>
<td>slug-ft²</td>
<td>12400</td>
</tr>
<tr>
<td>$I_{zz}$</td>
<td>slug-ft²</td>
<td>14300</td>
</tr>
<tr>
<td>$I_{xz}$</td>
<td>slug-ft²</td>
<td>-2971</td>
</tr>
<tr>
<td>S</td>
<td>ft²</td>
<td>400</td>
</tr>
<tr>
<td>b</td>
<td>ft</td>
<td>37.44</td>
</tr>
</tbody>
</table>

FIGURE B1. PERMISSIBLE FLIGHT ENVELOPE

PERMISSIBLE

GROSS WEIGHT
42,097 Lb

Altitude - 1000 Ft

Mach Number

B-2
FIGURE B2. LATERAL STICK FORCE VS. STICK DEFLECTION
(REFERENCE 3)

Stabilator Deflection vs Lateral Stick Deflection

FIGURE B3. PEDAL FORCE VS. PEDAL DEFLECTION
(REFERENCE 3)

DIRECTIONAL PEDAL FORCE VS PEDAL DEFLECTION
FIGURE B4. DIFFERENTIAL STABILATOR GEARING CURVE
(REFERENCE 4)

FIGURE B5. AILERON GEARING CURVE
(REFERENCE 4)
FIGURE B6. RUDDER GEARING CURVE
(REFERENCE 4)
APPENDIX C

NONLINEAR DATA PLOTS
FIGURE C3. DUTCH ROLL DAMPING
FIGURE C4. P STEADY-STATE MAX (DEG/SEC)
FIGURE C6. VARIATION OF ROLLING MOMENT WITH RUDDER DEFL. (°/RAD)

MACH

0.0000
0.60000
0.80000
1.00000

△ △ △ △ △

ANGLE OF ATTACK

0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35

C-7
FIGURE C7. VARIATION OF YAWING MOMENT WITH RUDDER DEFLECT. (1/RAD)
Figure C9. Variation of Rolling Moment with Yaw Rate (1/\text{rad})

Mach
- 2.0
- 1.5
- 1.0
- 0.5
- 0.0

\( \alpha \)
- 3.5
- 3.0
- 2.5
- 2.0
- 1.5
- 1.0
- 0.5
- 0.0

\text{CL}_{r}
FIGURE C.10. VARIATION OF SIDE FORCE WITH AILERON DEFL.

(C/RAD)

---

C-11
Figure C12: Variation of Laminar Moment with Aileron Defl. (1/RAD)
FIGURE C15. VARIATION OF ROLLING MOMENT WITH SIDESLIP

C-16
FIGURE C.17. VARIATION OF ROLLING MOMENT WITH STABILIZER DEFIL. (1/RAD)
FIGURE C18. VARIATION OF YAWING MOMENT WITH STABILIZER DEFL. \((1/\text{RAD})\)
APPENDIX D

SAMPLE INPUT FILE
TABLE D1. SAMPLE FLIGHT CONDITIONS

<table>
<thead>
<tr>
<th>CASE NUMBER</th>
<th>MACH</th>
<th>ALTITUDE (FT)</th>
<th>ANGLE OF ATTACK (RAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.2</td>
<td>1000</td>
<td>.1414</td>
</tr>
<tr>
<td>2</td>
<td>.6</td>
<td>35000</td>
<td>.1093</td>
</tr>
<tr>
<td>3</td>
<td>.9</td>
<td>10000</td>
<td>.0171</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>35000</td>
<td>.05</td>
</tr>
</tbody>
</table>

Note: Case 4 is not a valid flight condition.

FIGURE D1. INPUT FILE FORMAT

Title
Mach, Altitude, Angle-Of-Attack

where each subscript refers to each flight condition

FIGURE D2. SAMPLE INPUT FILE

TEST FILE FOR F-18 TRANSFER FUNCTION PROGRAM 3/16/94

.2,1000,.1414
.6,35000,.1093
.9,10000,.0171
0,35000,.05
APPENDIX E

SAMPLE OUTPUT FILE
TEST FILE FOR F-18 TRANSFER FUNCTION PROGRAM 3/16/94

Case Number 1
mach = .200  alt = 1000.0  alpha(rad) = .141

Denominator to Lateral-Directional Transfer Functions.
Coefficients are in descending order of s.

\[
\begin{align*}
1.000000 & 1.719688 & 3.037692 & 1.144893 & 0.000000 \\
p \text{ to lateral stick force transfer function numerator} & 13.966980 & 17.499701 & 34.259322 & 0.000000 \\
\phi \text{ to lateral stick force transfer function numerator} & 13.966980 & 17.499701 & 34.259322 & .000000 \\
\beta \text{ to lateral stick force transfer function numerator} & 0.000000 & 0.000000 & .000000 & .000000 \\
r \text{ to lateral stick force transfer function numerator} & 0.327676 & 0.001629 & .000000 & .000000 \\
\alpha_{ycg} \text{ to lateral stick force transfer function numerator} & -7.843049 & -8.566533 & -19.231792 & .000000 \\
p \text{ to pedal force transfer function numerator} & -0.013788 & -0.000792 & 0.111820 & 0.000000 \\
\phi \text{ to pedal force transfer function numerator} & -0.013788 & -0.000792 & 0.111820 & 0.000000 \\
\beta \text{ to pedal force transfer function numerator} & -0.000385 & -0.068454 & 0.000000 & 0.000000 \\
r \text{ to pedal force transfer function numerator} & 0.068420 & 0.000526 & 0.000000 & 0.000000 \\
\alpha_{ycg} \text{ to pedal force transfer function numerator} & 0.006261 & 0.000313 & 0.060769 & 0.000000
\end{align*}
\]

Case Number 2
mach = .600  alt = 35000.0  alpha(rad) = .109

Denominator to Lateral-Directional Transfer Functions.
Coefficients are in descending order of s.

\[
\begin{align*}
1.000000 & 1.616000 & 2.561680 & 0.967872 & 0.000000 \\
p \text{ to lateral stick force transfer function numerator} & 29.709662 & 33.750175 & 59.906559 & 0.000000 \\
\phi \text{ to lateral stick force transfer function numerator} & 29.709662 & 33.750175 & 59.906559 & 0.000000 \\
\beta \text{ to lateral stick force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
r \text{ to lateral stick force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\alpha_{ycg} \text{ to lateral stick force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
p \text{ to pedal force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\phi \text{ to pedal force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\beta \text{ to pedal force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
r \text{ to pedal force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\
\alpha_{ycg} \text{ to pedal force transfer function numerator} & 0.000000 & 0.000000 & 0.000000 & 0.000000
\end{align*}
\]
beta to lateral stick force transfer function numerator
0.000000 0.000000

r to lateral stick force transfer function numerator
0.210279 0.003787

aycg to lateral stick force transfer function numerator
-16.683230 -16.822641 -33.601716

p to pedal force transfer function numerator
-.001718 .000252 .306057 .000000

phi to pedal force transfer function numerator
-.001718 .000252 .306057

beta to pedal force transfer function numerator
-.000113 -.072688

r to pedal force transfer function numerator
.072675 .000538

aycg to pedal force transfer function numerator
-.000177 -.00277 -.166413

Case Number 3
mach = .900 alt = 10000.0 alpha(rad) = .017

Denominator to Lateral-Directional Transfer Functions. Coefficients are in descending order of s.

1.000000 5.293200 18.167690 5.604424 .000000

p to lateral stick force transfer function numerator
44.700194 221.409001 736.820090 .000000

phi to lateral stick force transfer function numerator
44.700194 221.409001 736.820090

beta to lateral stick force transfer function numerator
0.000000 .000000

r to lateral stick force transfer function numerator
2.462298 .047704

aycg to lateral stick force transfer function numerator
-25.101046 -82.655994 -412.948207

p to pedal force transfer function numerator
-.050856 -.014647 3.596983 .000000

phi to pedal force transfer function numerator
-.050856 -.014647 3.596983

beta to pedal force transfer function numerator
Case Number 4
mach = .000 alt = 35000.0 alpha(rad) = .050
Trim flight conditions outside of permissible flight envelope
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