Control Power Design Requirements for Aircraft Flying Qualities

by

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AAE 590 – Control Power Requirements

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1   Introduction

The difference between a good flying airplane and poor flying airplane can best be understood by studying flying qualities. Since the beginning of flight, designers have studied what qualities make an airplane easy to fly. Early on, simply creating a stable aircraft was the main goal. As flight mechanics became more advanced, so did our understanding of desirable flight characteristics. From flying quality research came new standards developed for military and civil aircraft to ensure new designs would have favorable qualities. Among the most influential of these standards was MIL-F-8785 used for design of military aircraft. From MIL-F-8785c, the purpose of the document is to, "…assure flying qualities that provide adequate mission performance and flight safety regardless of design implementation or flight control system mechanization." Though currently replaced with MIL-STD-1797, the majority of MIL-F-8785 is included as suggested requirements in MIL-STD-1797. The Federal Aviation Administration (FAA) defines similar flying qualities requirements in the Federal Aviation Regulations (FARs) parts 25 and 23.

The following tables define flying quality levels, aircraft classification, and flight phase as defined in MIL-F-8785c.

Table 1. Levels of Flying Qualities

Flying Quality Levels	
Level 1	Flying qualities clearly adequate for the mission Flight Phase
Level 2	Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists
Level 3	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.

Table 2. Aircraft Classifications

Classification	Aircraft Type	Examples
Class I	Small, light airplanes	Light utility, primary trainer, light observation
Class II	Medium-weight, low-to-medium maneuverability	Heavy utility/search and rescue, light or medium transport/cargo/tanker, recon, tactical bomber
Class III	Large, heavy, low-to medium maneuverability	Heavy transport/cargo/tanker, heavy bomber
Class IV	High maneuverability	Fighter/interceptor, attack, tactical recon

Table 3. Flight Phase Categories

	Description	Include in category:
Category A	Those non-terminal flight phases that require rapid maneuvering, precision tracking or precise flight path control.	Air-to-air combat, ground attack, weapon deliver/launch, aerial recovery reconnaissance, in-flight refueling, terrain following, anti-submarine search, close formation flying
Category B	Those non-terminal flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required.	Climb, cruise, loiter, in-flight refueling (tanker) descent, emergency descent, emergency deceleration, aerial delivery
Category C	Terminal flight phases are normal accomplished using gradual maneuvers and usually require accurate flight path control.	Takeoff, catapult takeoff, approach, wave-off/go-around, landing

This document details functions created in MATLAB for use with FlatEarth Version 9.5 to study tradeoffs in flying qualities for control power requirements. The requirements studied are those on roll rate, crosswind control, asymmetric thrust control, longitudinal control during maneuvering, longitudinal control margin, and longitudinal control during takeoff. Included are functions to determine flying qualities and examples of possible uses of each function for preliminary control surface design. The user is encouraged to develop further uses for the functions.

2 Lateral-Directional Flying Qualities

2.1 <u>Roll Effectiveness</u>

The function "FQRoll1" determines flying level qualities for roll effectiveness based on MIL-F-8785c section 3.3.4 requirements. MIL-F-8785c contains tables broken down by airplane class, flight phase category, roll angle, speed range, and flying qualities level. The entries in the tables are the roll times required to achieve the given flying qualities level. For example, a class I airplane in flight phase A must roll from 0 degrees to 60 degrees in less than or equal to 1.3 seconds to achieve a level 1.

The inputs required for "FQRoll1" are the aileron deflection angle in radians, and the lateral directional linear state space system. The function uses the inputs of airplane class, flight phase, and speed range to determine the flying qualities level. These variables are input as follows into the function:

For Flight Phase Category   A use phase = 1
                                               B use phase = 2
                                               C use phase = 3
  For Airplane Class I use class=1;
                                    II-L use class = 21;
                                     II-C use class = 22;
                                     III use class = 3;
                                     IV   use class = 4;
  For Speed Range Very Low use spd_range = 1
                                    Low use spd_range = 2
                                    Medium use spd_range = 3
                                    High use spd_range = 4

In order to determine the flying qualities level, the time to roll is first determined. To accomplish this, a step input is applied to the lateral directional state space system with a magnitude of the maximum aileron deflection angle. The step function gives the values of phi (roll angle) and the times for the simulation. These roll times are compared to tables taken from MIL-F-8785c shown in the tables below to determine the flying qualities level.

Table 4. Roll Performance for Class I and Class II

Airplane Class	Level	CATEGORY A		CATEGORY B		CATEGORY C	
		60 deg	45 deg	60 deg	45 deg	30 deg	25 deg
I	1	1.3		1.7			1.3
I	2	1.7		2.5			1.8
I	3	2.6		3.4			2.6
II-L	1		1.4		1.9	1.8	
II-L	2		1.9		2.8	2.5	
II-L	3		2.8		3.8	3.6	
II-C	1		1.4		1.9		1
II-C	2		1.9		2.8		1.5
II-C	3		2.8		3.8		2
Source: MIL-STD-1797A							

Table 5. Class II Speed Range Definitions

SPEED RANGE SYMBOL	EQUIVALENT AIRSPEED RANGE
L	Vmin < V < 1-8 Vmin
M	1.8 Vmin < V < 0.7 Vmax
H	0.7 Vmax < V < Vmax

Table 6. Roll Performance for Class III

Time to achieve 30 deg bank angle change (seconds)				
LEVEL	SPEED RANGE	CATEGORY A	CATEGORY B	CATEGORY C
1	L	1.8	2.3	2.5
	M	1.5	2	2.5
	H	2	2.3	2.5
	L	2.4	3.9	4
2	M	2	3.3	4
	H	2.5	3.9	4
3	ALL	3	5	6
Source: MIL-STD-1797A				

Table 7. Class IV Speed Range Definitions

SPEED RANGE SYMBOL	EQUIVALENT AIRSPEED RANGE
VL	Vmin < V < Vmin + 20 kt
L	Vmin + 20 KTS < V < 1.4 Vmin
M	1.4 Vmin < V < 0.7 Vmax
H	0.7 Vmax < V < Vmax

Table 8. Roll Performance for Class IV

LEVEL	SPEED RANGE	CATEGORY A			CATEGORY B	CATEGORY C
		30 deg	50 deg	90 deg	90 deg	30 deg
1	VL	1.1			2.0	1.1
	L	1.1			1.7	1.1
	M			1.3	1.7	1.1
	H		1.1		1.7	1.1
2	VL	1.6			2.8	1.3
	L	1.5			2.5	1.3
	M			1.7	2.5	1.3
	H		1.3		2.5	1.3
3	VL	2.6			3.7	2.0
	L	2.0			3.4	2.0
	M			2.6	3.4	2.0
	H		2.6		3.4	2.0
Source: MIL-STD-1797A						

For a given airplane class and speed range, a 3 x 3 table of roll times exists in the function "FQRoll1". Each row of a table is a different flying qualities level while each column is a different flight phase category. Using the user inputs of airplane class, flight phase, and speed range, the function determines the correct table to use through a series of "if" statements. The function also determines the correct roll angle based on the class and phase of aircraft. If the calculated roll time exceeds the maximum value in the tables, the flying qualities level output is 0 indicating the data is out of range of MIL-F-8785c.

If the plot flag is set to 1, a plot of simulation roll angle vs time is created. On this plot, the time at which the airplane rolls through the specified angle is shown to determine flying qualities level. Note that it is the user's responsibility to check flying qualities tables to ensure proper roll angle for the airplane class and flight phase has been selected. The outputs of "FQRoll1" are the flying qualities level, the time required to roll through the input angle, the linear simulation roll angle and time outputs, time required for level 1, and simulation roll angle vs time plots.

During the preliminary design of an aircraft, "FQRoll1" can be used to quickly determine the roll control power of an aircraft while varying design parameters for the aileron such as aileron chord and aileron position on the wing. The MATLAB script "FQRoll1_example" gives an example of how this function may be used in the design process.

In the example script, the MPX5 aircraft basic constants and FlatEarth 9.5 are used when calculating stability derivatives using the "Make_Constants.m" code. The aircraft is defined to be class I and in flight phase A. Because this is a class I aircraft, the speed range does not need to be defined. The user is also required to input the maximum aileron deflection. The three design variables for the aileron are the inboard/outboard location on the wing and the aileron chord to wing chord ratio. These values in the script override the values found in the MPX5 basic constants script. In this example, the inboard position was moved from 55% span to 72% span and the outboard value was left at 96% span. The aileron chord to wing cord ratio was varied from 0.05 to 0.40 to see how the change in aileron chord changes the flying qualities level. The limitations of the methods used to estimate control derivative parameters requires the ratio of aileron chord to wing chord to be no smaller than 0.05.

The next section of code in FQRoll1_example.m performs the calculations. First, the roll angle and aileron deflection angle are converted to radians. The script then moves into a for loop to determine flying qualities level for each value of the aileron chord. Changing the design of the aileron also changes the values of the variation of airplane rolling moment with aileron deflection $C_{l\delta a}$ and the variation of airplane yawing moment coefficient with aileron deflection $C_{n\delta a}$. To do this, the FlatEarth functions "Cl_da" and "Cn_da" are called to redefine constant(41) and constant(52). The constant variable was created while running "Make_Constants.m" of the Flat Earth code. Because the lateral direction characteristics of the airplane have been altered, each iteration in the for loop requires the system be linearized. This linearization defines the state space system LDsys which is a required input to "FQroll1". Finally, with all the inputs defined, "FQRoll1" is called and the flying qualities level is calculated for each value of the ratio of aileron chord to wing chord. Should the user not input a vector of values for any of the design variables, the example script recognizes this and sets the plot flag equal to 1 for FQRoll1. Figure 1 below shows an example output for MPX5 with the aileron chord to wing chord ratio of 0.25.
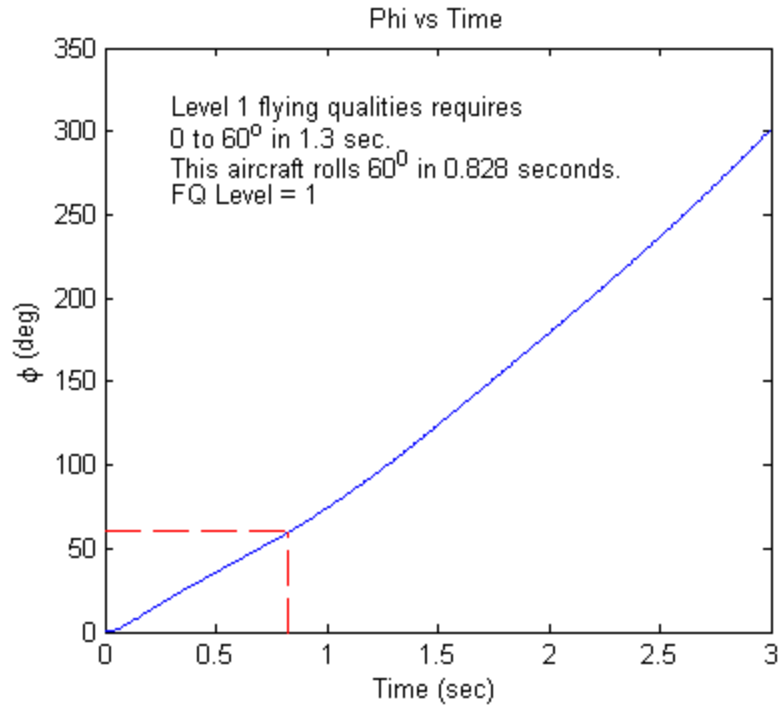
Figure 1. Roll angle vs Time

The final section of code plots the time to bank to the specified roll angle vs the design variable of interest. In this case, the variable of interest is the aileron cord to wing cord ratio. The plot is split with a dashed line indicating the boundary between level 1 and level 2 flying qualities. If desired, the aileron chord to wing chord ratio can be replaced with the aileron chord. Figure 2 below gives the output from the script "FQRoll1_example". The plot shows the tradeoff between the aileron size and the roll time aiding in design decisions.
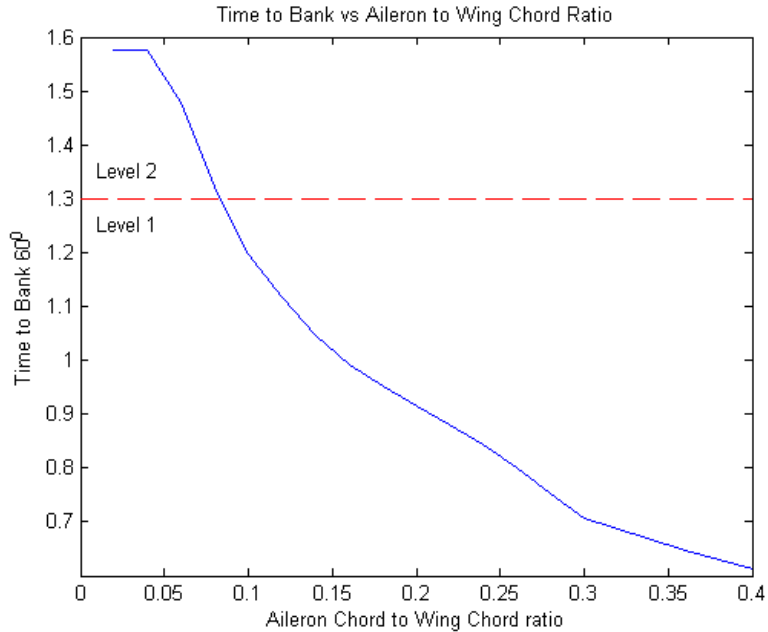
Figure 2. Output from FQRoll1_example

2.2 Lateral Directional Control in Crosswinds

MIL-F-8785c section 3.3.7 states "It shall be possible to take off and land with normal pilot skill and technique in 90 degree crosswinds from either side, of velocities up to those specified in Table 9."

Table 9. Crosswind Velocity

Level	Class	Crosswind
1 and 2	I	20 knots
	II, III, & IV	30 knots
	Water-based airplanes	20 knots
3	All	one-half the values for Levels 1 and 2
Source: MIL-F-8785c		

Using this requirement from MIL-F-8785c, the function FQYaw1 was created to evaluate the flying qualities level in a crosswind. The function calculates the required rudder and aileron for straight flight with sideslip in a crosswind. With plots enabled, rudder deflection, aileron deflection, and phi vs Beta and Crosswind Velocity plots are created. This function returns the flying qualities level as defined in MIL-F-8785c. The function uses the following inputs:

W - Aircraft weight (lbs)
rho - air density slugs/ft^3
U1 - Trim Flight Speed (ft/sec)
S_w - Reference Wing Area (ft^2)

b_w - Reference Wing Chord (ft)
Cyb - Variation of airplane side force coefficient with dimensionless rate of change of angle of sideslip (1/rad)
Cyda - Variation of side force coefficient with aileron angle (1/rad)
Cydr - Variation of side force coefficient with rudder angle (1/rad)
Clb - Variation of rolling moment coefficient with angle of sideslip (1/rad)
Clda - Variation of rolling moment coefficient with aileron angle (1/rad)
Cldr - Variation of rolling moment coefficient with rudder angle (1/rad)
Cnb - Variation of yawing moment coefficient with angle of sideslip(1/rad)
Cnda - Variation of yawing moment coefficient with aileron angle (1/rad)
Cndr - Variation of yawing moment coefficient with rudder angle (1/rad)
gamma - Flight Path Angle (deg)
LT1 - Moment due to Thrust about X (ft-lbf);
NT1 - Moment due to Thrust about Z (ft-lbf);
FyT1 - Thrust Force Component along Y (ft-lbf);
DND1 - Additional yawing moment due to drag from failed engine
　　　NOTE: The contribution of DND1 may be estimated by using NT1=FOEI*NT1
　　　and setting DND1=0. See Table 10 below [Reference 1]

Table 10. DND1 estimation

Type of Power Plant	Fixed Pitch	Variable Pitch	Low BPR	High BPR
FOEI	1.25	1.1	1.15	1.25

max_dr - Maximum Rudder Deflection (Degrees)
flag - Plot Flag. flag = 1 - Output Plots flag =0 Do not output plots
class - Airplane class

The following are outputs from "FQYaw1"

level – Flying quality level
d_dr – Additional rudder deflection needed for level 1

　　　With the input of aircraft class, the function first determines the correct crosswind to apply. The maximum sideslip angle in crosswind is then determined. The function next calculates phi (deg), aileron deflection (deg), and rudder deflection (deg) required to fly given sideslip angle beta using equations 4.71a-c in Reference 1. Rearranging these equations yields the following system:

$$
\begin{bmatrix} \dfrac{W\cos(\gamma)}{\bar{q}S_w} & C_{y\delta a} & C_{y\delta r} \\ 0 & C_{l\delta a} & C_{l\delta r} \\ 0 & C_{n\delta a} & C_{n\delta r} \end{bmatrix} \begin{bmatrix} \sin(\phi) \\ \delta a \\ \delta r \end{bmatrix} = \begin{bmatrix} -C_{y\beta}\beta - \dfrac{F_{y_T}}{\bar{q}S_w} \\ -C_{l\beta}\beta - \dfrac{L_T}{\bar{q}S_w b_w} \\ -C_{n\beta}\beta - \dfrac{N_T - \Delta N_D}{\bar{q}S_w b_w} \end{bmatrix}
$$

Equation 1

The crosswind velocity in knots is determined using:

$$Xwindvel = sin(\beta) * U1 * .5925$$

Equation 2

Finally, the function interpolates to find the required rudder deflection for a given crosswind velocity. This value is then compared to Table 9 to determine flying qualities level. This flying qualities level output from the function. The function also outputs the required difference in rudder deflection required to achieve level 1 flying qualities. For example, if only 20 degrees of rudder deflection is available, but 22 degrees is required for level 1, the function will output 2 degree difference. If the plot flag is on, the function will produce plots of rudder deflection, aileron deflection, and roll angle vs sideslip angle and crosswind velocity.

The MATLAB script "FQYaw1_example.m" uses the function "FQYaw" to determine flying quality levels. In the example, the MPX5 aircraft and version 9.5 of FlatEarth are used. From the outputs of FQYaw2, the MPX5 has level 3 flying qualities in a crosswind. The aircraft was only able to maintain sideslip for a crosswind of 12 knots. The sample output is shown below in Figure 3 and Figure 4.
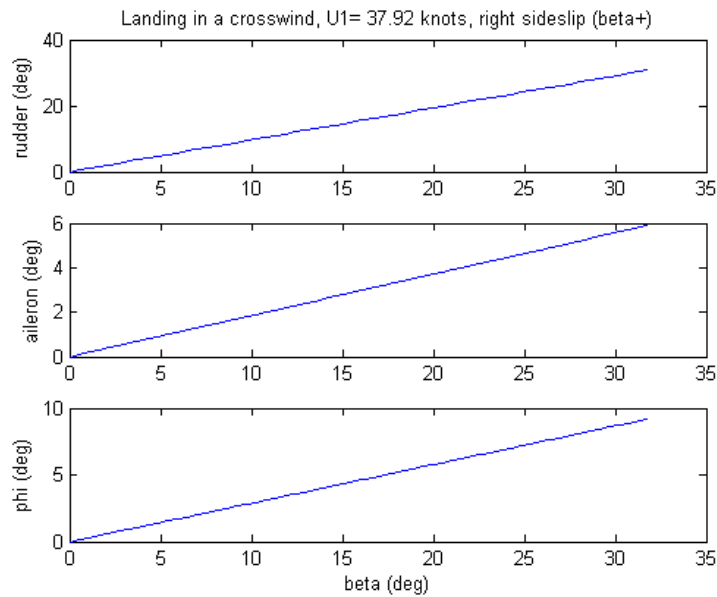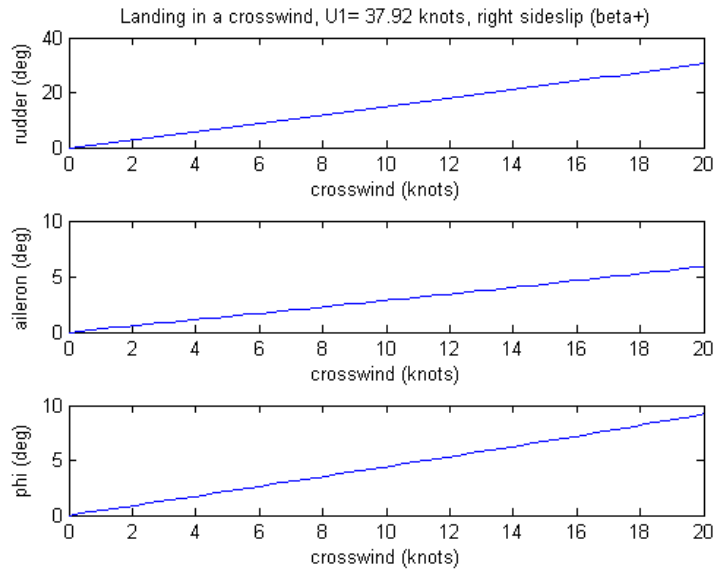

Figure 3. FQYaw1_example output vs beta

Figure 4. FQYaw2_example output vs crosswind

2.3 Lateral-Directional Control with Asymmetric Thrust

In addition to maintain lateral control in a crosswind, the aircraft must be able to maintain lateral control in an asymmetric thrust condition. Asymmetric thrust usually results when a multi-engine aircraft loses one or more engines. MIL-F-8785c section 3.3.9 states: "Following sudden asymmetric loss of thrust from any factor, the airplane shall be safely controllable in the crosswinds of [Table 9]." The equations used to solve the asymmetric thrust case are identical to those used for solving the crosswind problem and are given in Equation 1. The difference is in this case, the moment N_T will be non-zero as the asymmetric thrust causes the aircraft to yaw about the body z-axis.

The function "FQYaw2" was created to study the effect of asymmetric thrust. This function calculates the required rudder and aileron for zero sideslip in an asymmetric thrust situation. The function uses the following inputs:

W - Aircraft weight (lbs)
rho - air density slugs/ft^3
U1 - Trim Flight Speed (ft/sec)
S_w - Reference Wing Area (ft^2)
b_w - Reference Wing Chord (ft)
Cyb - Variation of airplane side force coefficient with dimensionless rate
    of change of angle of sideslip (1/rad)
Cyda - Variation of side force coefficient with aileron angle (1/rad)
Cydr - Variation of side force coefficient with rudder angle (1/rad)
Clb - Variation of rolling moment coefficient with angle of sideslip
    (1/rad)
Clda - Variation of rolling moment coefficient with aileron angle (1/rad)
Cldr - Variation of rolling moment coefficient with rudder angle (1/rad)
Cnb - Variation of yawing moment coefficient with angle of sideslip(1/rad)
Cnda - Variation of yawing moment coefficient with aileron angle (1/rad)
Cndr - Variation of yawing moment coefficient with rudder angle (1/rad)
gamma - Flight Path Angle (deg)
LT1 - Moment due to Thrust about X (ft-lbf);

NT1 - Moment due to Thrust about Z (ft-lbf);
FyT1 - Thrust Force Component along Y (ft-lbf);
DND1 - Additional yawing moment due to drag from failed engine
        NOTE: The contribution of DND1 may be estimated by using NT1=FOEI*NT1
        and setting DND1=0. See Table 10 [Reference 1]
max_dr - Maximum Rudder Deflection (Degrees)
max_da - Maximum Aileron Deflection (Degrees)

The following are the outputs from "FQYaw2":

level – Flying quality level
d_dr – Additional rudder deflection needed for level 1
dr – Rudder deflection
da - Aileron deflection
phi – Roll angle

        The MATLAB script "FQYaw2_example" uses the function "FQYaw2" to find flying qualities
level. The example script uses the basic constants script titled "Basic_Constants_Beech". This file uses a
twin engine aircraft to study flying qualities with an engine out case yielding asymmetric thrust. In the
script, the maximum aileron and rudder deflection angles, and engine distance from fuselage centerline
must be defined. Also defined is FOEI from Table 10, maximum and minimum flight speeds, and CL_{max}.
The script calls the function "Thrust2" to calculate the yawing moment caused by the single operating
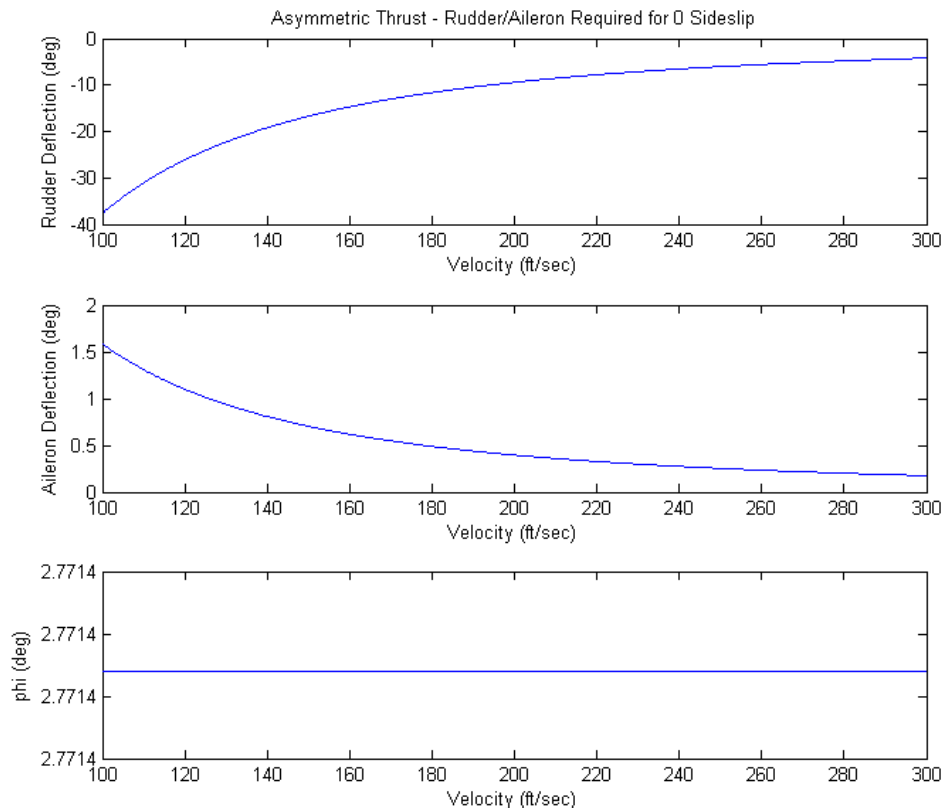engine offset from the fuselage centerline.

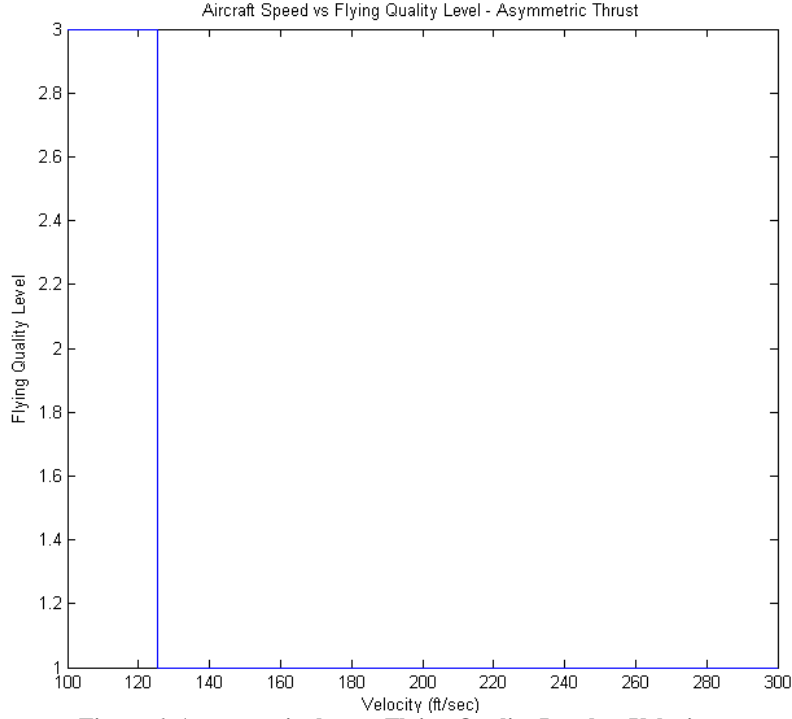**Figure 5. Asymmetric thrust: Rudder, Aileron, Phi angles.**

Figure 6. Asymmetric thrust: Flying Quality Level vs Velocity

3   Longitudinal Flying Qualities

3.1   <u>Elevator Effectiveness</u>

The function "FQPitch1" aids in determining flying qualities of the control power from the elevator.   The function uses inputs of load factor (n) and speed to determine the change in angle of attack and change in elevator angle from trim required to reach the desired load factor. In order to find the change of elevator angle and angle of attack from trim, the pitch trim and pitch pull-up maneuver equations are defined. By summing forces in the aircraft Z direction, Equation 3 results.

$$\sum F_z = ma_z = W - L = -mqV$$

Equation 3

$$(1)$$

Using the pitch rate definition in a pull-up given in Equation 4, the acceleration in a pull-up is calculated by Equation 5 where r is the radius of the pull-up. The pitch rate is made non-dimensional with Equation 6.

$$q = \frac{V}{r}$$

Equation 4

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$$a_z = \frac{-V^2}{r} = -qV$$

<div align="center">**Equation 5**</div>

$$\hat{q} = \frac{\bar{c}}{2V} q$$

<div align="center">**Equation 6**</div>

In order to calculate required change in elevator and angle of attack from trim, the trim values of angle of attack and elevator deflection must first be determined by solving the system of equations composed of Equation 7 and Equation 8 for angle of attack at trim α_1 and δe_1. Subtracting Equation 7 and Equation 8 from Equation 9 and Equation 10 yields the equations for change in angle of attack and elevator deflection from trim when solved. The resulting system is given by Equation 11. FQPitch1 solves Equation 11 and returns the changes in angle of attack and elevator deflection angle from trim required to achieve the pull-up load factor desired.

$$C_{L_1} = C_w = C_{Lo} + C_{L_\alpha}\alpha_1 + C_{L_{\delta e}}\delta e_1$$

<div align="center">**Equation 7**</div>

$$C_{m_1} = 0 = C_{mo} + C_{m_\alpha}\alpha_1 + C_{m_{\delta e}}\delta e_1$$

<div align="center">**Equation 8**</div>

$$C_{L_{man}} = nC_w = C_{Lo} + C_{L_\alpha}\alpha_{man} + C_{L_{\delta e}}\delta e_{man}$$

<div align="center">**Equation 9**</div>

$$C_{m_{man}} = 0 = C_{mo} + C_{m_\alpha}\alpha_{man} + C_{m_{\delta e}}\delta e_{man}$$

<div align="center">**Equation 10**</div>

$$\begin{bmatrix} C_{L_\alpha} & C_{L_{\delta e}} \\ C_{m_\alpha} & C_{m_{\delta e}} \end{bmatrix} \begin{pmatrix} \Delta\alpha \\ \Delta\delta e \end{pmatrix} = \begin{pmatrix} (n-1)C_w - C_{L_q}\hat{q} \\ -C_{m_q} \end{pmatrix}$$

<div align="center">**Equation 11**</div>

$$\Delta\alpha = \alpha_{man} - \alpha_{trim}$$

<div align="center">**Equation 12**</div>

$$\Delta\delta = \delta_{man} - \delta_{trim}$$

<div align="center">**Equation 13**</div>

The inputs to "FQPitch1" are as follows:

Cm_q - variation of aircraft pitching moment with pitch rate
Cm_de - variation of pitching moment with elevator deflection (1/rad)
Cm_0 - pitching moment coefficient at zero angle of attck
Cm_alpha - variation of pitching moment with angle of attack (1/rad)
CL_0 - lift coefficient for zero angle of attack
CL_alpha -variation of lift coefficient with angle of attack (1/rad)
CL_de - variation of lift coefficient with elevator deflection (1/rad)
Cl_alpha_h - 2-D Lift curve slope of horizontal tail
W - Weight (lbs)
rho - air density slugs/ft^3
S_w - Wing area (ft^2)
c_w - Wing Chord (ft)
U1 - Trim Speed (ft/s)
n - Load Factor
g - gravity (ft/s^2)

The MATLAB script FQPitch1_example is shown as an example of how FQPitch1 can be used to study flying qualities of an aircraft in design. The script requires the aircraft basic constants to be formed requiring "Basic_Constants_MPX5" and "Make_Constants" to be executed first. The user is required to input the maximum (most positive) and minimum (most negative) limits of the elevator deflection. In order to create the V-n diagram, the maximum and minimum load factors must be specified along with an estimate of CL_{max}. The stall speed is calculated using Equation 14. Cruise speed is set using Equation 15 and the dive speed is set at 1.5 times the cruise speed. The value of 36 in cruise speed determination is recommended for acrobatic airplanes as recommended by Roskam in Airplane Aerodynamic and Propulsion. The following section of code creates a generic V-n diagram for a plot overlay. It should be noted this is a rough flight envelope. For a detailed determination of flight envelope, see MIL-F-8785c section 3.1.8.
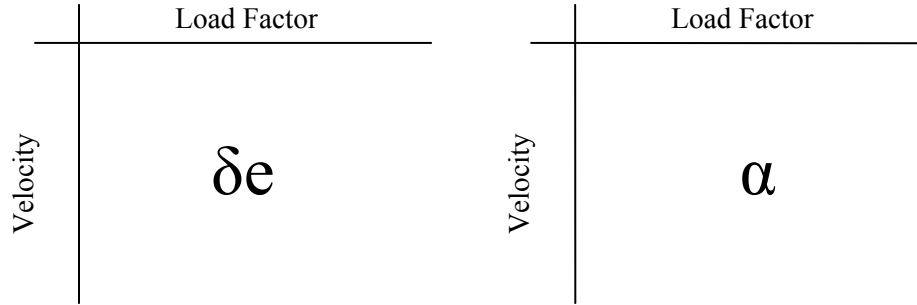
$$V_{stall} = \sqrt{\frac{2W}{\rho CL_{max} S_w}}$$

Equation 14

$$V_{cruise} = \sqrt{\frac{W}{S_w}}$$

Equation 15

The next section of code does all of the maneuver calculations. First, using FQPitch1, 2-D tables are created for elevator deflection and angle of attack from trim. The format of these tables is shown below.

Using 2D interpolation, the load factors at constant elevator deflection over the entire range of velocities is determined. These lines of constant elevator deflection are overlaid on the V-n diagram. The resulting plot is given below in Figure 7 below. In the example given for the MPX5, there is not enough elevator deflection to reach the maximum of the V-n diagram in speeds below 60 fps. Section 3.2.3.2 of MIL-F-8785c states the following states the maximum load factor should be achievable for a flying qualities level of 1 and half of the load factor for flying qualities level 2.
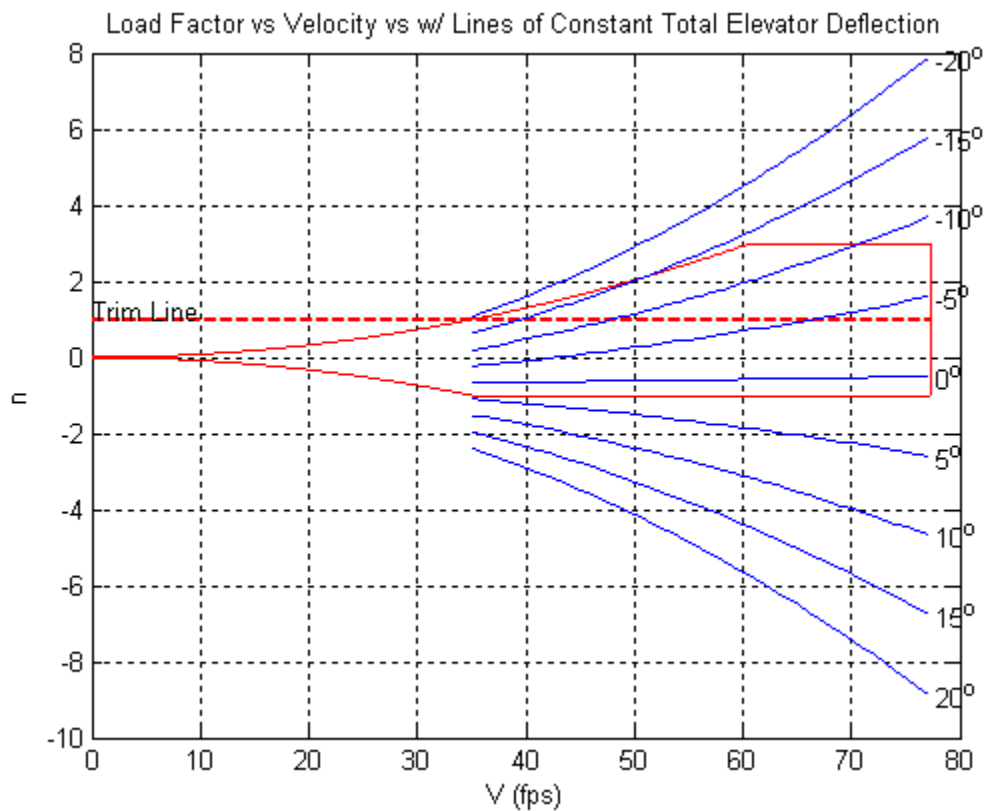

Figure 7. V-n diagram with constant total elevator deflection lines overlaid.

The 2D tables are used again to create a plot of elevator deflection at trim for different velocities. An example of this plot is given in Figure 8. Figure 9 is created for the user to ensure the angle of attack is not excessive at the desired trim velocities. Finally, Figure 10 gives the relation between elevator deflection from trim required and speed at constant load factors. From this figure, as speed decreases, a larger amount of elevator deflection is required to reach a given load factor.
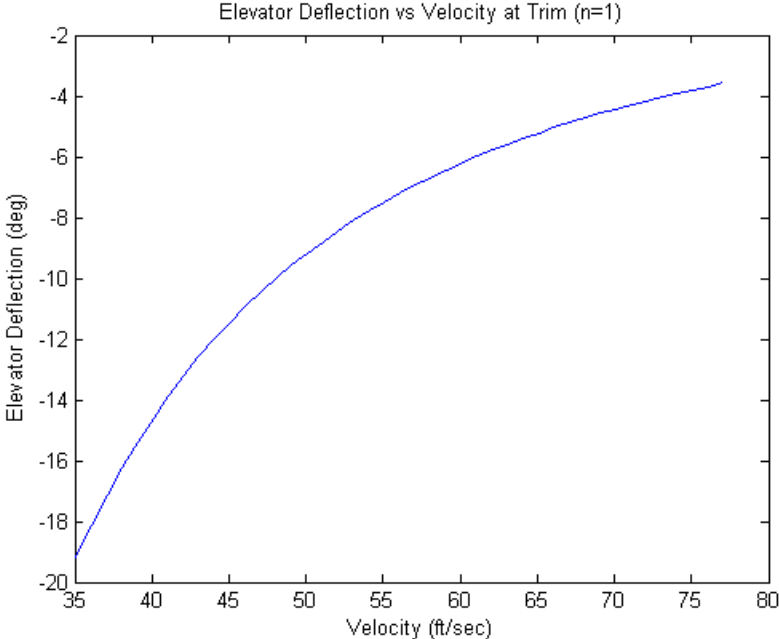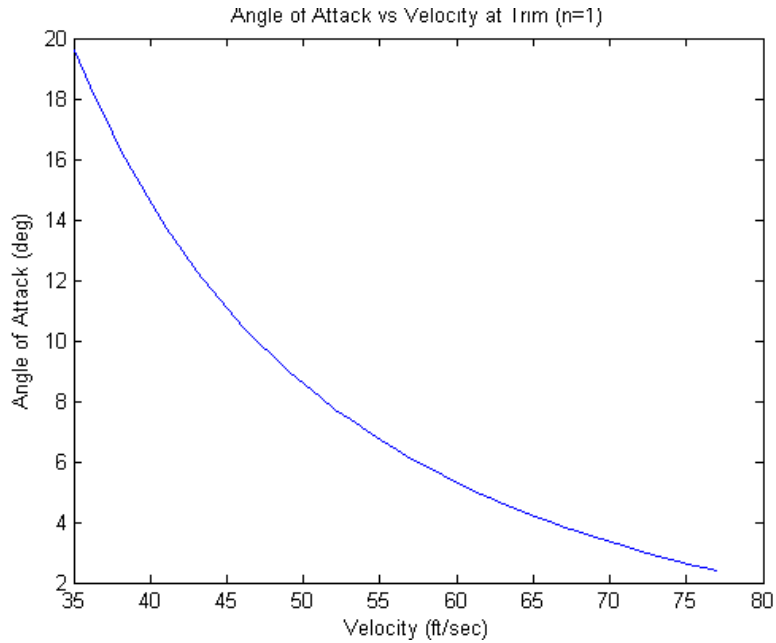

Figure 8. Elevator deflection vs velocity at trim.

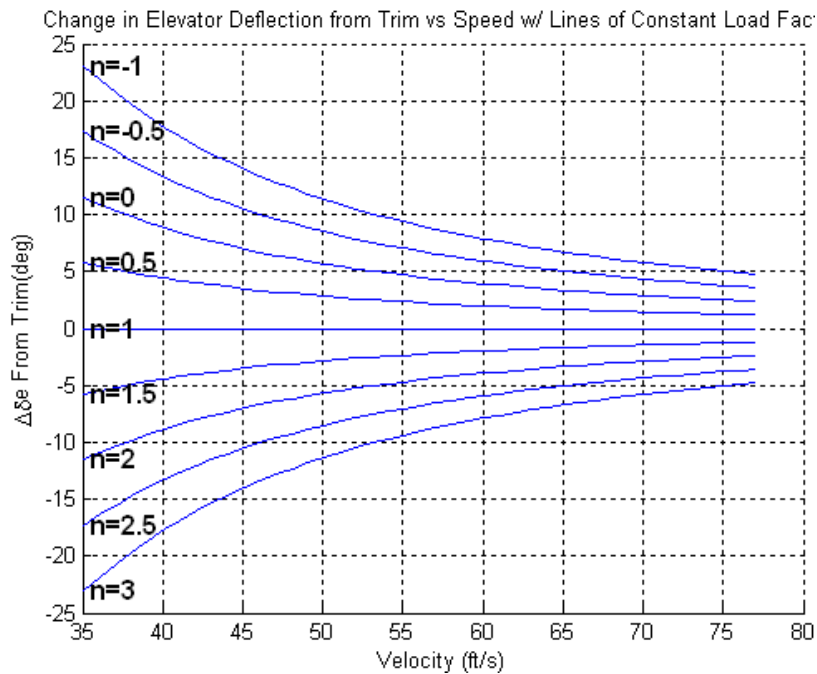**Figure 9. Angle of attack vs Velocity at trim.**

Figure 10. Change in elevator deflection from trim at constant load factor.

3.2 <u>Longitudinal Control Margin</u>

Adequate control margin assures enough elevator power to correct any unexpected disturbances during all phases of flight. MIL-STD-1797A defines control margin requirements in section 4.1.11.5. As a rationale for the requirement, MIL-STD-1797A gives the following:

"This overall requirement is intended to assure adequate control for safety in any situation not otherwise covered in the Standard. It is intended to permit recovery from unusual situations in,

and even beyond, the Permissible Flight Envelope--on the grounds that if a condition is attainable, someday it will be attained. Experience has shown that to be a reasonable assumption."

From MIL-STD-1797B, general numbers are placed on control margin in longitudinal control on pitch rate and acceleration. Table 11 below gives these values.

<div align="center">Table 11. Longitudinal Control margin guidance.</div>

Parameter	Tactical Utility	Safety Minimum
Pitch acceleration within the first second	Greater of: .07 rad/sec + pitch acceleration corrected for inertial coupling or .25 rad/sec/sec	.07 rad/sec/sec + pitch acceleration corrected for inertial coupling
Pitch rate at 2 sec	24 deg/sec	5 deg/sec

The flying qualities function "FQPitch2" determines flying qualities level for longitudinal control using the pitch rate at 2 seconds guidance. The inputs to the function are as follows:

de - Elevator deflection angle (rad)
Lsys - Longitudinal Directional Linear System (short period approximation)

The function uses the longitudinal linear system and applies a step input with magnitude of the maximum elevator deflection in radians. This system omits the effects of the phugoid mode to find the steady state pitch rate achieved. From this step response, the pitch rate at 2 seconds is determined through linear interpolation. If this pitch rate is faster than 24 deg/sec, the flying qualities level is 1. If it is between 24 deg/sec and 5 deg/sec, the level is defined as 2. If the pitch rate is less than 5 deg/sec, a flying quality level of 3 results. In addition to the pitch rate simulation, the response to the angle of attack (α) is also determined. The outputs to the function are as follows:

q_sim - Pitch rate from step input to elevator
t_sim1 - Time from pitch rate response to step input to elevator
alpha_sim - Alpha from step input to elevator
t_sim2 - Time from alpha response to step input to elevator
level - Flying quality level

The MATLAB script "FQPitch2_example.m" uses the function "FQPitch2" to determine control margin for the MPX5 aircraft. The script uses inputs of CL_max, simulation run time, and elevator deflection. These values are then used to calculate stall speed. Since this is the most extreme speed to trim the aircraft at, the stall speed is used to determine pitch rate available at trim. Next, the values are used in FlatEarth 9.5 to calculate aircraft constants and linearize full longitudinal system. From the longitudinal system, the short period system is extracted. The short period system uses 2 degrees of freedom: pitch rate and angle of attack. This short period system is then input to the function "FQPitch2". The example script uses the outputs of the function to plot pitch rate vs time and angle of attack vs time. The flying quality level is given in the title of the pitch rate vs time plot. An example output is given below in
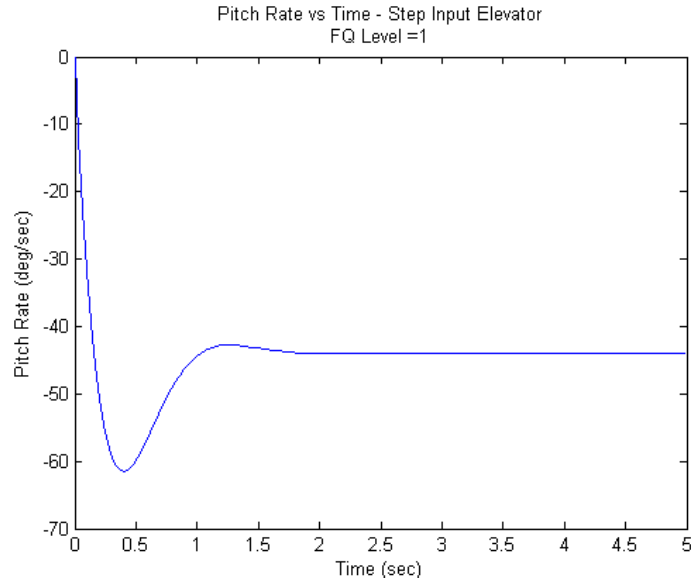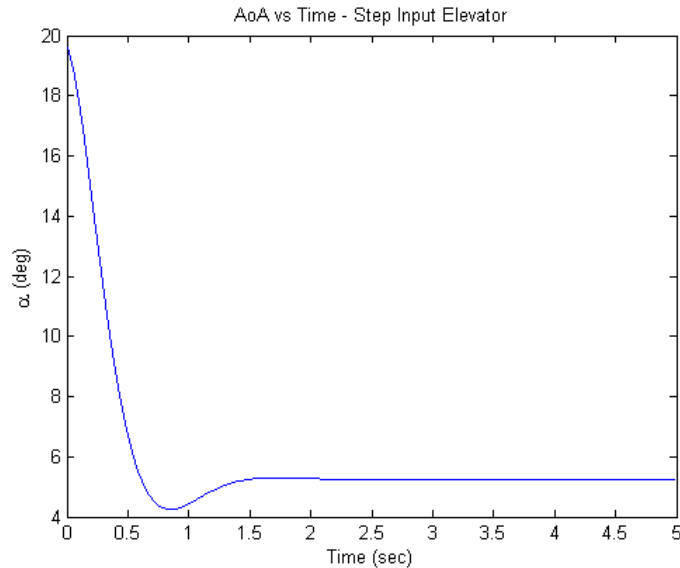
Figure 11. FQPitch2_example - Pitch Rate vs Time.

Figure 12. FQPitch2_example - Alpha vs Time.

3.3 <u>Longitudinal Control During Takeoff</u>

Longitudinal control during takeoff is outlined in section 3.2.3.3 in MIL-F-8785c. The requirement states that elevator control must be sufficient to prevent undesirable attitudes during takeoff. For nose wheel aircraft, takeoff rotation must be possible at 90% of takeoff speed. For tail-wheel aircraft, the requirement states that any pitch attitude, up to level thrust line, must be obtainable for 50% of takeoff speed for Class I aircraft and takeoff speed for all other classes. These requirements apply to hard surface runways.

In order to determine performance at takeoff, a force balance is performed at the instant the aircraft begins to rotate. At this point, the nosewheel/tailwheel has just left the ground. Equation 16 through Equation 18 result when summing forces and moments. All subscripts "mg" indicate main gear.

The "g" subscripts indicate values are determined in ground effect. Equation 19 shows how to calculate the moment of inertia about the main gear rotation point and comes from Reference 2 page 43. Figure 13 below shows variable definitions and the forces and moments at takeoff. Pages 288-292 of Reference 1 have further details on using these equations.

$$T - D_g - \mu_g R_g = \frac{W}{g}\dot{U}$$

Equation 16

$$L_{wf_g} + L_{h_g} + R_g = W$$

Equation 17

$$-W\left(x_{mg_g} - x_{cg_g}\right) + D_g\left(z_{D_g} - z_{mg_g}\right) - T\left(x_{mg_g} - x_{ac_{wf}}\right) + M_{ac_{wf_g}} - L_{h_g}\left(x_{ac_h} - x_{mg_g}\right)$$
$$+ \frac{W}{g}U(z_{cg} - z_{mg}) = I_{yy_{mg}}\ddot{\theta}$$

Equation 18

$$I_{yy_{mg}} = I_{yy} + \frac{W}{g}\left(z_{cg}^2 + \left(x_{mg} - x_{cg}\right)^2\right)$$
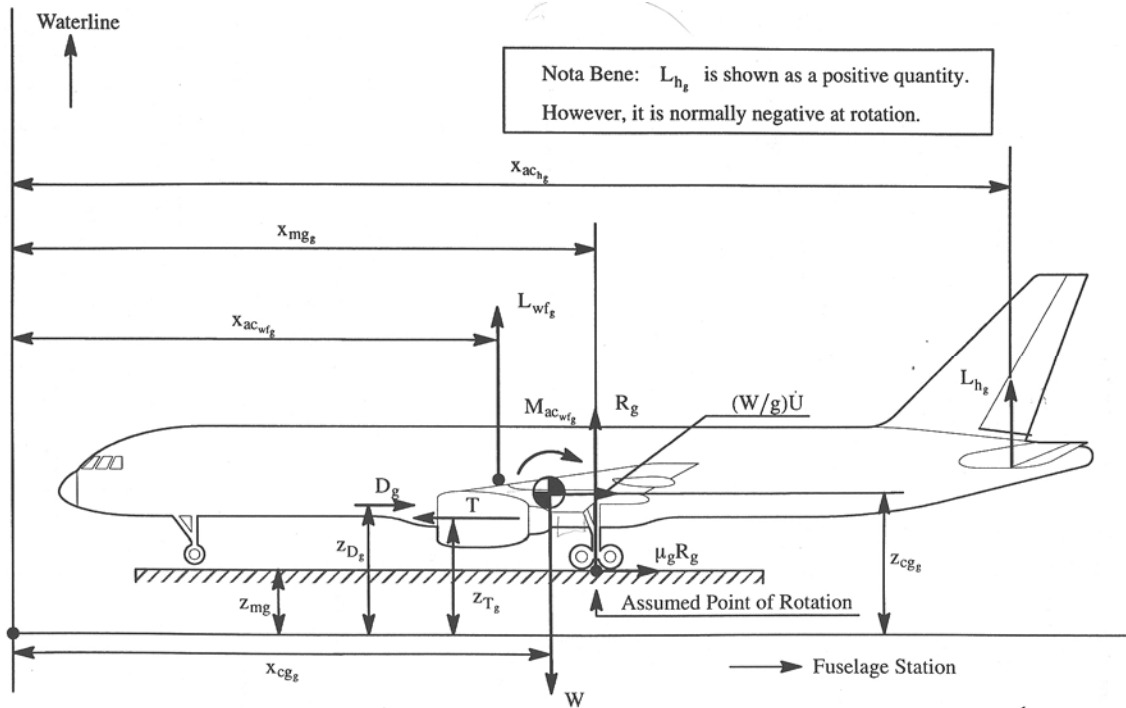
Equation 19

Figure 13. Forces and moments at takeoff. [Ref. 1]

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The equations above are rearranged and solutions for reaction at main gear (R), angular acceleration ($\ddot{\theta}$), and aircraft acceleration ($\dot{U}$) are determined. For nosewheel aircraft, a positive value of angular acceleration indicates the ability to rotate the aircraft and for tailwheel aircraft a negative value indicates the ability to rotate to level. For the coefficient of friction, a value of .02 is used to represent wheel-ground contact on a concrete or asphalt surface.

In addition to the requirements of MIL-F-8785c, Roskam gives further recommendations on angular acceleration at takeoff speed in Reference 1. Roskam states that the takeoff rotation process should not take more than 1-3 seconds to complete. With this in mind, suggest values for angular acceleration in preliminary design are given in Table 12 below.

Table 12. Suggest angular acceleration values at takeoff rotation.

	Angular Acceleration about Main Gear
Large Transports	6-8 deg/sec^2
Small Transports	8-10 deg/sec^2
Light Airplanes/Fighters	10-12 deg/sec^2

The function "FQPitch3" determines the ability for an aircraft to meet the requirements of MIL-F-87856c for control during takeoff. The function uses the following inputs:

CL_0_h - lift coefficient for zero angle of attack of horizontal tail
CL_0_wf - lift coefficient for zero angle of attack of wing/fuselage
CL_alpha_h -variation of lift coefficient with angle of attack horizontal tail (1/rad)
CL_de_h- variation of lift coefficient with elevator deflection horizontal tail (1/rad)
bhp_max - Maximum engine bhp
de - Elevator deflection (rad)
rho - Air density (slugs/ft^3)
Cd - Drag Coefficient
CL_alpha_w - -variation of lift coefficient with angle of attack wing/fuselage (1/rad)
Cm_0 - pitching moment coefficient at zero angle of attack
Cm_alpha - variation of pitching moment with angle of attack (1/rad)
Cm_de - variation of pitching moment with elevator deflection (1/rad)
ground_roll_angle - Tail-down angle of aircraft on runway (deg)
U1 - Aircraft speed (ft/sec)
S_w - Wing area (ft^2)
S_h - Horizontal tail area (ft^2)
x_m -Distance from nose of aircraft to arbitrary reference point (ft)
    measured positive aftward.
Xref - Distance from the leading edge of the wing mean aerodynamic chord
    to the arbitrary moment reference point. The equivalent force system
    for the aerodynamic force system is given about this point.
    Measured as positive aft,starting from the leading edge of
    the mean aero. chord. (ft)
Xcg - Distance from the leading edge of the wing mean aerodynamic chord
    to the center of gravity. Measured as positive aft, starting

from the leading edge of the mean aero. chord. (ft)
W - Aircraft weight (lb)
c_w - Wing cord (ft)
mu_mg - Coefficient of friction wheel-concrete
g - gravity (ft/sec^2)
eta - propeller efficiency
z_cg - Landing Gear height above ground (ft)
Iyy - Airplane moment of inertia about y-axis [slug-ft^2]
Xacwb - % Distance from the leading edge of the wing mean aerodynamic chord
        to the aerodynamic center of the wing and body.
Xach - Distance from the leading edge of the wing mean aerodynamic chord
      to the aerodynamic center of the horizontal tail
      (positive aftward) (ft)
x_mg_rot - Distance from leading edge of wing to main gear (ft)
z_d - Resultant Drag vertical distance above ground (ft)
z_t - Engine thrust vertical distance from ground (ft)
i_w - incidence angle of wing (rad)
i_h - incidence angle of horizontal tail (rad)
class - Aircraft class
gear_type - Landing gear type
        Gear Type = 1 Tricycle
        Gear Type = 2 Taildragger

   The function first uses the aircraft type and class inputs to determine the velocity to use for rotation
calculations. For a example, a class I taildragger will use a value of half of the takeoff speed to determine
if the aircraft can rotate to level at this speed. Next, the function calculates, at rotation, values for dynamic
pressure, thrust, drag, lift and moment coefficients, and the moment of inertia about the rotation point.
These values are determined assuming an amount of elevator is being applied. Using these values,
Equation 16 through Equation 18 are solved for main gear force reaction, angular acceleration, and
aircraft acceleration. The flying quality level is determined to be 1 if the value of angular acceleration is
greater than 3 deg/sec ^{2} with the correct sign based on landing gear type. The outputs from the function
are as follows:

R – Reaction force at main gear
U_dot – Aircraft acceleration
theta_dotdot_mg – Angular acceleration about main gear
level – flying quality level

   The MATLAB script "FQPitch3_example.m" uses the function "FQPitch3" to determine takeoff
performance for the MPX5 aircraft. The basic constants script for the MPX5 does not include all values
need to execute "FQPitch3" so these values are defined first. They include the maximum elevator
deflection, CL_max, class, landing gear type, aircraft angle during ground roll (tail down angle),
coefficient of friction, and maximum engine horsepower. Because the MPX5 is a tailwheel aircraft, the
landing gear type is set to 2. In addition, the main gear must be located on the aircraft. To do this, the
values of landing gear height above ground and distance from leading edge of wing to main gear are
defined. Figure 14 from Reference 3 gives typical values for taildown angle and main gear locations for a
taildragger aircraft. A bicycle landing gear arrangement is show in Figure 15 [3]. Additionally, the
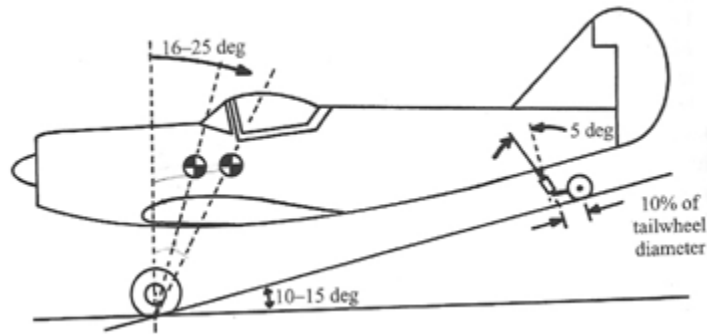vertical distance to the thrust and drag centerlines are defined.

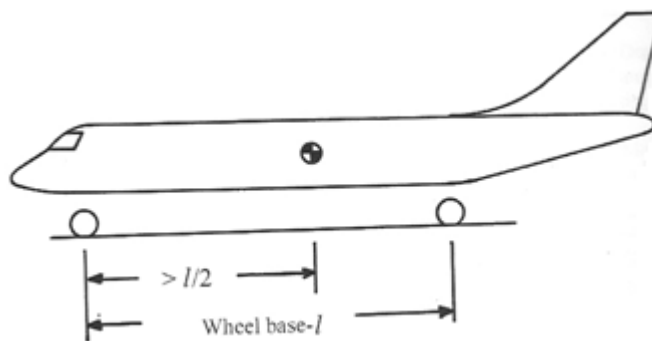**Figure 14. Taildragger landing gear. [Ref 3]**

Figure 15. Bicycle landing gear. [Ref 3]

With these user inputs defined, the next section of code performs the calculations. First, the stall speed is determined and used as the takeoff speed. This value is placed in a variable U1_vec. For this example, only one velocity is used, but a vector of velocities may be input in U1_vec. The script then moves into a for loop which runs for each value of velocity input. The values of CL_alpha and CL_0 for the wing and horizontal tail are calculated for each speed. CL_de of the horizontal tail is also determined. Another for loop is entered for each value of elevator deflection defined. The function "FQPitch3" is then called using the defined inputs resulting in values for main gear reaction, angular acceleration, and aircraft acceleration at each velocity and elevator deflection. The output of the script is a plot showing the value of angular acceleration vs elevator deflection. For taildragger aircraft, a negative angular acceleration indicates pitching the nose down to reach level for ground roll. The flying quality level and maximum angular acceleration achievable are given in the title.
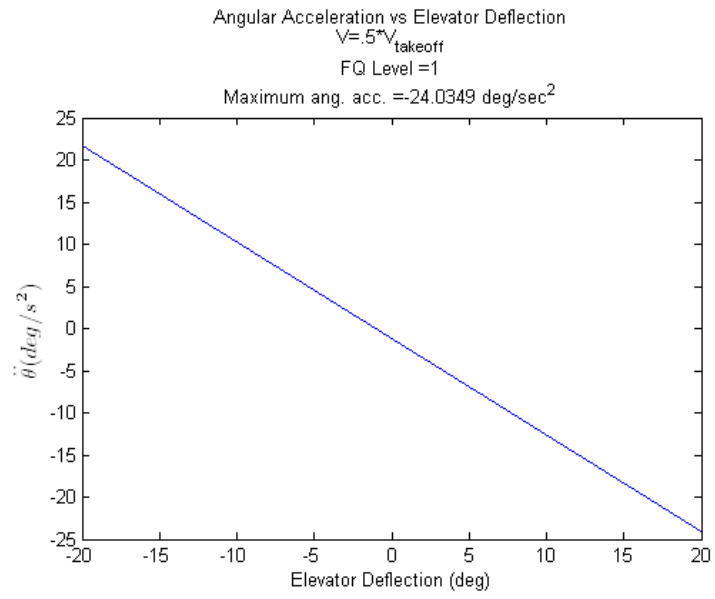
Figure 16. FQPitch3 - Angular acceleration vs elevator deflection.

4 References

[1] Roskam, Jan. "Airplane Flight Dynamics and Automatic Flight Controls", DARcorporation Lawrence, KS Second Printing, 1998.

[2] Roskam, Jan. "Airplane Design: Part VII Determination of Stability, Control, and Performance Characteristics: FAR and Military Requirements. DARcorporation. Lawrence, KS, 2002.

[3] Raymer, Daniel P. "Aircraft Design: A Conceptual Approach" AIAA Education Series. Reston, VA Fourth Edition, 2006.

[4] Anon.; MIL-F-8785c, Military Specification Flying Qualities of Piloted Airplanes; November 5, 1980; Air Force Flight Dynamics Laboratory, WPAFB, Dayton, OH.

[5] Anon.; MIL-STD-1797A, Flying Qualities of Piloted Aircraft; January 30, 1990; Air Force Flight Dynamics Laboratory, WPAFB, Dayton, OH.