# Class Project
# Atmospheric Flight Mechanics and Control
# ENG ME 403
# Spring 2018

Professor Hua Wang

March 15, 2018

## 1 Introduction and Rules

In this project you will analyze the dynamics of an existing aircraft and design a feedback control system for improving the aircraft dynamics. While well-documented Matlab scripts are essential components of the project, they are not the only components. Textual descriptions of your efforts and conclusions are also essential components. The reports should be typed.

Your reports will be graded on creativity, clarity, and organization in the analysis and in the writing. For example, all axes on all plots should be clearly labeled, legends should be used where necessary to distinguish curves, and figures and tables should have descriptive captions. You are not allowed to discuss this project with other students, present or past. You may, however, generically discuss the use of Matlab and the Control System Toolbox with others. Evidence of collaboration, such as identical script fragments or incorrect answers, will be referred to the College's Academic Conduct Committee. It is expected that each student's project will be unique.

## 2 First Report Due Thursday, April 12 at 3:30 p.m.

### 2.1 First report description

Your first report should include at least the following:

**Introduction** Give a brief description of the aircraft you have chosen including its purpose (fighter, passenger, etc.), its history, and its manufacturer (the Jane's books in the library are good for this.) You must either choose an aircraft from the appendix of *Flight Stability and Control* by Nelson[1] or use the Boeing 747-100 data from your textbook. If you plan to use Nelson's appendix, please refer to the handout that describes the proper use of the appendix data. State whether you will focus on longitudinal or lateral dynamics. You must carry out the complete calculation of the dimensional derivatives. You are *strongly* encouraged to perform all calculations within Matlab. **You will get 10% extra credit for each of the following choices: 1) Use Nelson's appendix; 2) Work on lateral dynamics.**

**Dynamic Characteristics** Restricting your attention to either lateral or longitudinal motion, compute the eigenvalues of the model for your plane and include these in a table. Then, make a

[1] A copy of this text is placed on reserve at the Science and Engineering Library

table comparing the plane's dynamic parameters (e.g., damping ratio, natural frequency, etc.) to the acceptable ranges in Nelson's text. Based on these ranges, give the flying performance level.

**Appendix** Include a table of the plane parameters and stability derivatives and your source for them. Include your calculations for the remaining coefficients needed for the equations of motion as well. Be thorough and calculate all the coefficients you can. Justify any quantities you will be neglecting.

### 2.2 First report checklist

- Eigenvalues and mode shapes (i.e., eigenvectors) in a table
- Frequencies, periods, time constants in a table
- Compare eigenvalues of $4 \times 4$ matrix to approximate formulae
- Plot transient responses (all 4 state variables) to more than one sets of initial conditions
- Every table and figure should be numbered and have a caption describing its content.
- Every figure should have axis labels with units of variables beings plotted
- Matlab scripts in appendix
- Organization is critical - use section and subsections headings and include a table of contents
- Describe in words, with as few equations as possible, what was done
- Table comparing dynamic parameters to flying qualities
- Give flying performance level
- Propose a control system

## 3 Second Report Due Tuesday, May 1 at 3:30 p.m.

### 3.1 Second report description

The second report shall be a stand-alone document describing your **entire** project and will be graded as such. Your second report should include a corrected version of your first report and at least the following sections:

**Define Control Objective** Now, explain the function of your control system. If the performance level is low, you may wish to design a stability augmentation system to improve the level. If the level is satisfactory, you may want to consider designing an autopilot. You may wish to include simulation results for stick-fixed flying to demonstrate the dynamic behavior of the plane and the goal of your control system. If relevant, give a quantitative description of the control objective in terms of flying qualities and modal properties, such as damping factors and periods.

**Feedback Controller Design** Use the methods discussed in class to design a control system to achieve the performance objective. Show by analysis and simulations that you have (or have not) achieved the objective. Try using the same feedback for a different flight condition, and see if the performance is still improved.

### 3.2 Second report checklist

- Include a corrected form of first report as a subset of this report
- Identify your transfer function $G(s)$
  - Why did you choose it?
  - Document its calculation
  - Compute step response
- Describe the goal of your control effort
- Create and describe a root locus plot of your $G(s)$ for proportional control
- Choose at least two control strategies (e.g. phase lead, PID)
- Implement your control strategy
  - Compute step response
  - Compute performance metrics
  - Compute steady-state errors

# ME403 Class Project

## Constructing $\dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bc}$ from Tables in Nelson's Book

1. Find the table containing data for your aircraft from Appendix B (pages 398-419). Only certain Mach numbers are given.
2. From the table, find coefficients ($C$'s), weight $W$, CG location, moments of inertia, and reference geometry given your Mach number ($M$), and altitude ($h$).
3. Find $a$ (sound speed) and $\rho$ (mass density) from Appendix A (either SI or English units).
4. Compute the following intermediate values

   $u_0 = Ma$ (Forward velocity)

   $Q = \frac{1}{2}\rho u_0^2$ (Dynamic pressure)

   $m = W / g$ (Aircraft mass)
5. Compute derivatives from:
   - Table 4.2 for longitudinal motion (see attached)
   - Table 5.1 for lateral motion (see attached)
   - Note: $C_D = C_{D_0}$
   - If a coefficient is not in table, assume it is zero
6. Compute $A$ and $B$ from:
   - Equations 4.53 & 4.54 for longitudinal motion (see attached)
   - Equations 5.29 & 5.30 for lateral motion (see attached)

**TABLE 3.2**
**The linearized small-disturbance longitudinal and lateral rigid body equation of motion**

**Longitudinal equations**

$$\left(\frac{d}{dt} - X_u\right)\Delta u - X_w\,\Delta w + (g\cos\theta_0)\,\Delta\theta = X_{\delta_e}\,\Delta\delta_e + X_{\delta_T}\,\Delta\delta_T$$

$$-Z_u\,\Delta u + \left[(1 - Z_{\dot w})\frac{d}{dt} - Z_w\right]\Delta w - \left[(u_0 + Z_q)\frac{d}{dt} - g\sin\theta_0\right]\Delta\theta = Z_{\delta_e}\,\Delta\delta_e + Z_{\delta_T}\,\Delta\delta_T$$

$$-M_u\,\Delta u - \left(M_{\dot w}\frac{d}{dt} + M_w\right)\Delta w + \left(\frac{d^2}{dt^2} - M_q\frac{d}{dt}\right)\Delta\theta = M_{\delta_e}\,\Delta\delta_e + M_{\delta_T}\,\Delta\delta_T$$

**Lateral equations**

$$\left(\frac{d}{dt} - Y_v\right)\Delta v - Y_p\,\Delta p + (u_0 - Y_r)\,\Delta r - (g\cos\theta_0)\,\Delta\phi = Y_{\delta_r}\,\Delta\delta_r$$

$$-L_v\,\Delta v + \left(\frac{d}{dt} - L_p\right)\Delta p - \left(\frac{I_{yz}}{I_x}\frac{d}{dt} + L_r\right)\Delta r = L_{\delta_a}\Delta\delta_a + L_{\delta_r}\Delta\delta_r$$

$$-N_v\,\Delta v - \left(\frac{I_{xz}}{I_z}\frac{d}{dt} + N_p\right)\Delta p + \left(\frac{d}{dt} - N_r\right)\Delta r = N_{\delta_a}\,\Delta\delta_a + N_{\delta_r}\,\Delta\delta_r$$

**TABLE 3.1**
**Summary of kinematic and dynamic equations**

| | |
|---|---|
| $X - mgS_\theta = m(\dot u + qw - rv)$<br>$Y + mgC_\theta S_\Phi = m(\dot v + ru - pw)$<br>$Z + mgC_\theta C_\Phi = m(\dot w + pv - qu)$ | Force equations |
| $L = I_x\dot p - I_{xz}\dot r + qr(I_z - I_y) - I_{xz}pq$<br>$M = I_y\dot q + rp(I_x - I_z) + I_{xz}(p^2 - r^2)$<br>$N = -I_{xz}\dot p + I_z\dot r + pq(I_y - I_x) + I_{xz}qr$ | Moment equations |
| $p = \dot\Phi - \dot\psi S_\theta$<br>$q = \dot\theta C_\Phi + \dot\psi C_\theta S_\Phi$<br>$r = \dot\psi C_\theta C_\Phi - \dot\theta S_\Phi$ | Body angular velocities in terms of Euler angles and Euler rates |
| $\dot\theta = qC_\Phi - rS_\Phi$<br>$\dot\Phi = p + qS_\Phi T_\theta + rC_\Phi T_\theta$<br>$\dot\psi = (qS_\Phi + rC_\Phi)\sec\theta$ | Euler rates in terms of Euler angles and body angular velocities |

Velocity of aircraft in the fixed frame in terms of Euler angles and body velocity components

$$\begin{bmatrix} \dfrac{dx}{dt} \\ \dfrac{dx}{dt} \\ \dfrac{dz}{dt} \end{bmatrix} = \begin{bmatrix} C_\theta C_\psi & S_\Phi S_\theta C_\psi - C_\Phi S_\psi & C_\psi S_\theta C_\psi + S_\Phi S_\psi \\ C_\theta S_\psi & S_\Phi S_\theta S_\psi + C_\Phi C_\psi & C_\Phi S_\theta S_\psi - S_\Phi C_\psi \\ -S_\theta & S_\Phi C_\theta & C_\Phi C_\theta \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix}$$

# LONGITUDINAL MOTION

**TABLE 4.2**
**Summary of longitudinal derivatives**

| | |
|---|---|
| $X_u = \dfrac{-(C_{D_u} + 2C_{D_0})QS}{mu_0}$ | $X_w = \dfrac{-(C_{D_\alpha} - C_{L_0})QS}{mu_0}$ |
| $Z_u = \dfrac{-(C_{L_u} + 2C_{L_0})QS}{mu_0}$ | |
| $Z_w = \dfrac{-(C_{L_\alpha} + C_{D_0})QS}{mu_0}$ | $Z_{\dot{w}} = C_{z_{\dot{\alpha}}} \dfrac{\bar{c}}{2u_0} QS/(u_0 m)$ |
| $Z_\alpha = u_0 Z_w$ | $Z_{\dot{\alpha}} = u_0 Z_{\dot{w}}$ |
| $Z_q = C_{Z_q} \dfrac{\bar{c}}{2u_0} QS/m$ | $Z_{\delta e} = C_{Z_{\delta e}} QS/m$ |
| $M_u = C_{m_u} \dfrac{(QS\bar{c})}{u_0 I_y}$ | |
| $M_w = C_{m_\alpha} \dfrac{(QS\bar{c})}{u_0 I_y}$ | $M_{\dot{w}} = C_{m_{\dot{\alpha}}} \dfrac{\bar{c}}{2u_0} \dfrac{QS\bar{c}}{u_0 I_y}$ |
| $M_\alpha = u_0 M_w$ | $M_{\dot{\alpha}} = u_0 M_{\dot{w}}$ |
| $M_q = C_{m_q} \dfrac{\bar{c}}{2u_0} (QS\bar{c})/I_y$ | $M_{\delta_e} = C_{m_{\delta_e}}(QS\bar{c})/I_y$ |

$$\mathbf{x} = \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \end{bmatrix}, \qquad \boldsymbol{\eta} = \begin{bmatrix} \Delta\delta \\ \Delta\delta_T \end{bmatrix} \tag{4.52}$$

and the matrices **A** and **B** are given by

$$\mathbf{A} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{4.53}$$

$$\mathbf{B} = \begin{bmatrix} X_\delta & X_{\delta_T} \\ Z_\delta & X_{\delta_T} \\ M_\delta + M_{\dot{w}} Z_\delta & M_{\delta_T} + M_{\dot{w}} Z_{\delta_T} \\ 0 & 0 \end{bmatrix} \tag{4.54}$$

# LATERAL MOTION

**TABLE 5.1**
**Summary of lateral directional derivatives**

| | | |
|---|---|---|
| $Y_\beta = \dfrac{QSC_{y_\beta}}{m}$ (ft/s² or m/s²) | $N_\beta = \dfrac{QSbC_{n_\beta}}{I_z}$ ($s^{-2}$) | $L_\beta = \dfrac{QSbC_{l_\beta}}{I_x}$ ($s^{-2}$) |
| $Y_p = \dfrac{QSbC_{y_p}}{2mu_0}$ (ft/s) or (m/s) | $N_p = \dfrac{QSb^2C_{n_p}}{2I_zu_0}$ ($s^{-1}$) | |
| $L_p = \dfrac{QSb^2C_{l_p}}{2I_xu_0}$ ($s^{-1}$) | | |
| $Y_r = \dfrac{QSbC_{y_r}}{2mu_0}$ (ft/s) or (m/s) | $N_r = \dfrac{QSb^2C_{n_r}}{2I_zu_0}$ ($s^{-1}$) | |
| $L_r = \dfrac{QSb^2C_{l_r}}{2I_xu_0}$ ($s^{-1}$) | | |
| $Y_{\delta a} = \dfrac{QSC_{y_{\delta_a}}}{m}$ (ft/s²) or (m/s²) | $Y_{\delta_r} = \dfrac{QSC_{y_{\delta_r}}}{m}$ (ft/s²) or (m/s²) | |
| $N_{\delta a} = \dfrac{QSbC_{n_{\delta_a}}}{I_z}$ ($s^{-2}$) | $N_{\delta r} = \dfrac{QSbC_{n_{\delta_r}}}{I_z}$ ($s^{-2}$) | |
| $L_{\delta a} = \dfrac{QSbC_{l_{\delta_a}}}{I_x}$ ($s^{-2}$) | $L_{\delta r} = \dfrac{QSbC_{l_{\delta_r}}}{I_x}$ ($s^{-2}$) | |

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\boldsymbol{\eta} \tag{5.28}$$

The matrices **A** and **B** are defined as follows:

$$\mathbf{A} = \begin{bmatrix} Y_v & Y_p & -(u_0 - Y_r) & g\cos\theta_0 \\ L_v^* + \dfrac{I_{xz}}{I_x}N_v^* & L_p^* + \dfrac{I_{xz}}{I_x}N_p^* & L_r^* + \dfrac{I_{xz}}{I_x}N_r^* & 0 \\ N_v^* + \dfrac{I_{xz}}{I_z}L_v^* & N_p^* + \dfrac{I_{xz}}{I_z}L_p^* & N_r^* + \dfrac{I_{xz}}{I_z}L_r^* & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{5.29}$$

$$\mathbf{B} = \begin{bmatrix} 0 & Y_{\delta_r} \\ L_{\delta_a}^* + \dfrac{I_{xz}}{I_x}N_{\delta_a}^* & L_{\delta_r}^* + \dfrac{I_{xz}}{I_x}N_{\delta_r}^* \\ N_{\delta_a}^* + \dfrac{I_{xz}}{I_z}L_{\delta_a}^* & N_{\delta_r}^* + \dfrac{I_{xz}}{I_z}L_{\delta_r}^* \\ 0 & 0 \end{bmatrix} \tag{5.30}$$

$$\mathbf{x} = \begin{bmatrix} \Delta v \\ \Delta p \\ \Delta r \\ \Delta\phi \end{bmatrix} \quad \text{and} \quad \boldsymbol{\eta} = \begin{bmatrix} \Delta\delta_a \\ \Delta\delta_r \end{bmatrix} \tag{5.31}$$

The starred derivatives are defined as follows:

$$L_v^* = \frac{L_v}{[1 - (I_{xz}^2/(I_xI_z))]} \qquad N_v^* = \frac{N_v}{[1 - (I_{xz}^2/(I_xI_z))]} \quad \text{and the like.} \tag{5.32}$$

## 4.7 FLYING QUALITIES

In the previous sections we examined the stick fixed longitudinal characteristics of an airplane. The damping and frequency of both the short- and long-period motions were determined in terms of the aerodynamic stability derivatives. Because the stability derivatives are a function of the geometric and aerodynamic characteristics of the airplane, designers have some control over the longitudinal dynamics by their selection of the vehicle's geometric and aerodynamic characteristics. For example, increasing the tail size would increase both the static stability of the airplane and the damping of the short-period motion.* However, the increased tail area also would increase the weight and drag of the airplane and thereby reduce the airplane's performance, The designer is faced with the challenge of providing an airplane with optimum performance that is both safe and easy to fly. To achieve such a goal, the designer needs to know what degree of stability and control is required for the pilot to consider the airplane safe and flyable.

The flying qualities of an airplane are related to the stability and control characteristics and can be defined as those stability and control characteristics important in forming the pilot's impression of the airplane. The pilot forms a subjective opinion about the ease or difficulty of controlling the airplane in steady and maneuvering flight. In addition to the longitudinal dynamics, the pilot's impression of the airplane is influenced by the feel of the airplane, which is provided by the stick force and stick force gradients. The Department of Defense and Federal Aviation Administration has a list of specifications dealing with airplane flying qualities. These requirements are used by the procuring and regulatory agencies to determine whether an airplane is acceptable for certification. The purpose of these requirements is to ensure that the airplane has flying qualities that place no limitation in the vehicle's flight safety nor restrict the ability of the airplane to perform its intended mission. The specification of the requirements for airplane flying qualities can be found in [4.5].

As one might guess, the flying qualities expected by the pilot depend on the type of aircraft and the flight phase. Aircraft are classified according to size and maneuverability as shown in Table 4.7. The flight phase is divided into three categories as shown in Table 4.8. Category A deals exclusively with military aircraft. Most of the flight phases listed in categories B and C are applicable to either commercial or military aircraft. The flying qualities are specified in terms of three levels:

Level 1 Flying qualities clearly adequate for the mission flight phase.

Level 2 Flying qualities adequate to accomplish the mission flight phase but with some increase in pilot workload and/or degradation in mission effectiveness or both.

* Because the aerodynamic derivatives also are a function of the Mach number, the designer can optimize the dynamic characteristics for only one flight regime. To provide suitable dynamic characteristics over the entire flight envelope, the designer must provide artificial damping by using stability augmentation.



**TABLE 4.7**
**Classification of airplanes**

| | |
|---|---|
| Class I | Small, light airplanes, such as light utility, primary trainer, and light observation craft |
| Class II | Medium-weight, low-to-medium maneuverability airplanes, such as heavy utility/search and rescue, light or medium transport/cargo/tanker, reconnaissance, tactical bomber, heavy attack and trainer for Class II |
| Class III | Large, heavy, low-to-medium maneuverability airplanes, such as heavy transport/cargo/tanker, heavy bomber and trainer for Class III |
| Class IV | High-maneuverability airplanes, such as fighter/interceptor, attack, tactical reconnaissance, observation and trainer for Class IV |

**TABLE 4.8**
**Flight phase categories**

| | |
|---|---|
| **Nonterminal flight phase** | |
| Category A | Nonterminal flight phase that require rapid maneuvering, precision tracking, or precise flight-path control. Included in the category are air-to-air combat, ground attack, weapon delivery/launch, aerial recovery, reconnaissance, in-flight refueling (receiver), terrain-following, antisubmarine search, and close-formation flying |
| Category B | Nonterminal flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in the category are climb, cruise, loiter, in-flight refueling (tanker), descent, emergency descent, emergency deceleration, and aerial delivery. |
| **Terminal flight phases** | |
| Category C | Terminal flight phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this category are takeoff, catapult takeoff, approach, wave-off/go-around and landing. |

Level 3 Flying qualities such that the airplane can be controlled safely but pilot workload is excessive and/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.

The levels are determined on the basis of the pilot's opinion of the flying characteristics of the airplane.

### 4.7.1 Pilot Opinion

Handling or flying qualities of an airplane are related to the dynamic and control characteristics of the airplane. For example, the short- and long-period damping ratios and undamped natural frequencies influence the pilot's opinion of how easy or difficult the airplane is to fly. Although we can calculate these qualities, the question that needs to be answered is what values should $\zeta$ and $\omega_n$ take so that the pilot finds the airplane easy to fly. Researchers have studied this problem using ground-based simulators and flight test aircraft. To establish relationships between

TABLE 4.9
**Cooper-Harper scale**

| Pilot rating | Aircraft characteristic | Demand of pilot | Overall assessment |
|---|---|---|---|
| 1 | Excellent, highly desirable | Pilot compensation not a factor for desired performance | Good flying qualities |
| 2 | Good, negligible deficiencies | Pilot compensation not a factor for desired performance | |
| 3 | Fair, some mildly unpleasant deficiencies | Minimal pilot compensation required for desired performance | |
| 4 | Minor but annoying deficiencies | Desired performance requires moderate pilot compensation | Flying qualities warrant improvement |
| 5 | Moderately objectionable deficiencies | Adequate performance requires considerable pilot compensation | |
| 6 | Very objectionable but tolerable deficiencies | Adequate performance requires extensive pilot compensation | |
| 7 | Major deficiencies | Adequate performance not attainable with maximum tolerable pilot compensation; controllability not in question | Flying quality deficiencies require improvement |
| 8 | Major deficiencies | Considerable pilot compensation is required for control | |
| 9 | Major deficiencies | Intense pilot compensation is required to retain control | |
| 10 | Major deficiencies | Control will be lost during some portion of required operation | Improvement mandatory |

the stability and control parameters of the airplane and the pilot's opinion of the airplane a pilot rating system was developed. A variety of rating scales have been used over the years; however, the rating system proposed by Cooper and Harper [4.6] has found widespread acceptance. The Cooper-Harper scale is presented in Table 4.9. The rating scale goes from 1 to 10 with low numbers corresponding to good flying or handling qualities. The scale is an indication of the difficulty in achieving the desired performance that the pilot expects.

Flying qualities research provides the designer information to assess the flying qualities of a new design early in the design process. If the flying qualities are found to be inadequate then the designer can improve the handing qualities by making design changes that influence the dynamic characteristics of the airplane. A designer that follows the flying qualities guidelines can be confident that when the airplane finally is built it will have flying qualities acceptable to its pilots.

Extensive research programs have been conducted by the government and the aviation industry to quantify the stability and control characteristics of the airplane with the pilot's opinion of the airplane's flying qualities. Figure 4.15 is an example of the type of data generated from flying qualities research. The figure shows the relationship between the level of flying qualities and the damping ratio and undamped natural frequency of the short-period mode. This kind of figure is sometimes referred to as a thumbprint plot. Table 4.10 is a summary of the longitudinal

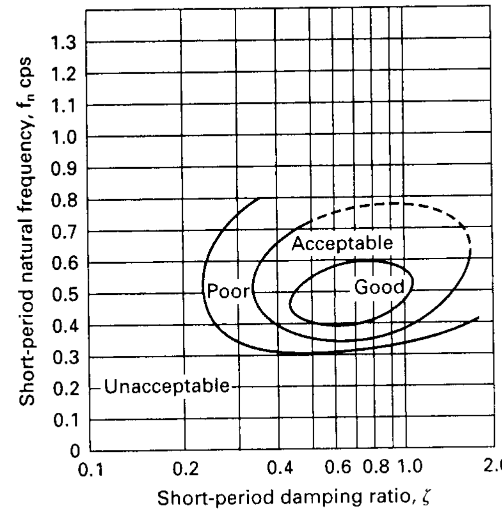



**FIGURE 4.15**
Short-period flying qualities.

TABLE 4.10
**Longitudinal flying qualities**

| Phugoid mode | |
|---|---|
| Level 1 | $\zeta > 0.04$ |
| Level 2 | $\zeta > 0$ |
| Level 3 | $T_2 > 55$ s |

| Short-period mode | | | | |
|---|---|---|---|---|
| | Categories A and C | | Category B | |
| | $\zeta_{sp}$ | $\zeta_{sp}$ | $\zeta_{sp}$ | $\zeta_{sp}$ |
| Level | min | max | min | max |
| 1 | 0.35 | 1.30 | 0.3 | 2.0 |
| 2 | 0.25 | 2.00 | 0.2 | 2.0 |
| 3 | 0.15 | — | 0.15 | — |

specifications for the phugoid and short-period motions that is valid for all classes of aircraft.

The information provided by Table 4.10 provides the designer with valuable design data. As we showed earlier, the longitudinal response characteristics of an airplane are related to its stability derivatives. Because the stability derivatives are related to the airplane's geometric and aerodynamic characteristics it is possible for the designer to consider flying qualities in the preliminary design phase.

**EXAMPLE PROBLEM 4.4.** A fighter aircraft has the aerodynamic, mass, and geometric characteristics that follow. Determine the short-period flying qualities at sea level, at 25,000 ft, and at 50,000 ft for a true airspeed of 800 ft/s. How can the designer improve the flying qualities of this airplane?

$$\begin{array}{ll} W = 17\,580 \text{ lb} & I_y = 25\,900 \text{ slug}\cdot\text{ft}^2 \\ S = 260 \text{ ft}^2 & \bar{c} = 10.8 \text{ ft} \\ C_{L_\alpha} = 4.0 \text{ rad}^{-1} & C_{m_q} = -4.3 \text{ rad}^{-1} \\ C_{m_\alpha} = -0.4 \text{ rad}^{-1} & C_{m_{\dot\alpha}} = -1.7 \text{ rad}^{-1} \end{array}$$

***Solution.*** The approximate formulas for the short-period damping ratio and frequency are given by Equations (4.80) and (4.81):

$$\omega_{n_{sp}} = \sqrt{\frac{Z_\alpha M_q}{u_0} - M_\alpha}$$

$$\zeta_{sp} = -\frac{(M_q + M_{\dot\alpha} + Z_\alpha/u_0)}{2\omega_{n_{sp}}}$$

where $Z_\alpha = -C_{L_\alpha} QS/m$

$$M_q = C_{m_q}\left(\frac{\bar{c}}{2u_0}\right)\frac{QS\bar{c}}{I_y}$$

$$M_\alpha = C_{m_\alpha}\frac{QS\bar{c}}{I_y}$$

$$M_{\dot\alpha} = C_{m_{\dot\alpha}}\left(\frac{\bar{c}}{2u_0}\right)\frac{QS\bar{c}}{I_y}$$

If we neglect the effect of Mach number changes in the stability coefficients, the damping ratio and frequency can easily be calculated from the preceding equations. Figure 4.16 is a plot of $\zeta_{sp}$ and $\omega_{n_{sp}}$ as functions of the altitude. Comparing the estimated short-period damping ratio and frequency with the pilot opinion contours in Figure 4.15, we see that this airplane has poor handling qualities at sea level that deteriorate to unacceptable characteristics at altitude.

To improve the flying qualities of this airplane, the designer needs to provide more short-period damping. This could be accomplished by increasing the tail area or the tail moment arm. Such geometric changes would increase the stability coefficients $C_{m_\alpha}$, $C_{m_q}$, and $C_{m_{\dot\alpha}}$. Unfortunately, this cannot be accomplished without a penalty in flight performance. The larger tail area results in increased structural weight and empennage drag. For low-speed aircraft geometric design changes usually can be used to provide suitable flying qualities; for aircraft that have an extensive flight envelope such as fighters it is not possible to provide good flying qualities over the entire flight regime

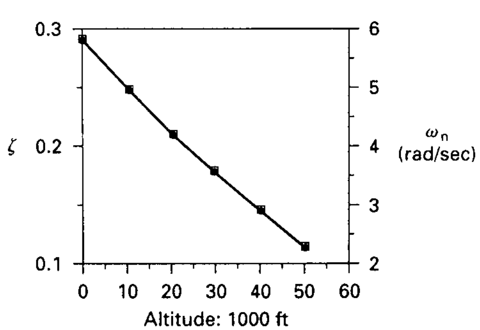



**FIGURE 4.16**
Variation of $\zeta_{sp}$ and $\omega_{n_{sp}}$ as a function of altitude.

from geometric considerations alone. This can be accomplished, however, by using a stability augmentation system.

## 4.8 FLIGHT SIMULATION

To determine the flying quality specifications described in a previous section requires some very elaborate test facilities. Both ground-based and in-flight simulators are used to evaluate pilot opinion on aircraft response characteristics, stick force requirements, and human factor data such as instrument design, size, and location.

The ground-based flight simulator provides the pilot with the "feel" of flight by using a combination of simulator motions and visual images. The more sophisticated flight simulators provide six degrees of freedom to the simulator cockpit. Hydraulic servo actuators are attached to the bottom of the simulator cabin and driven by computers to produce the desired motion. The visual images produced on the windshield of the simulator are created by projecting images from a camera mounted over a detailed terrain board or by computer-generated images. Figure 4.17 is a sketch of a five degree of freedom ground-based simulator used by the

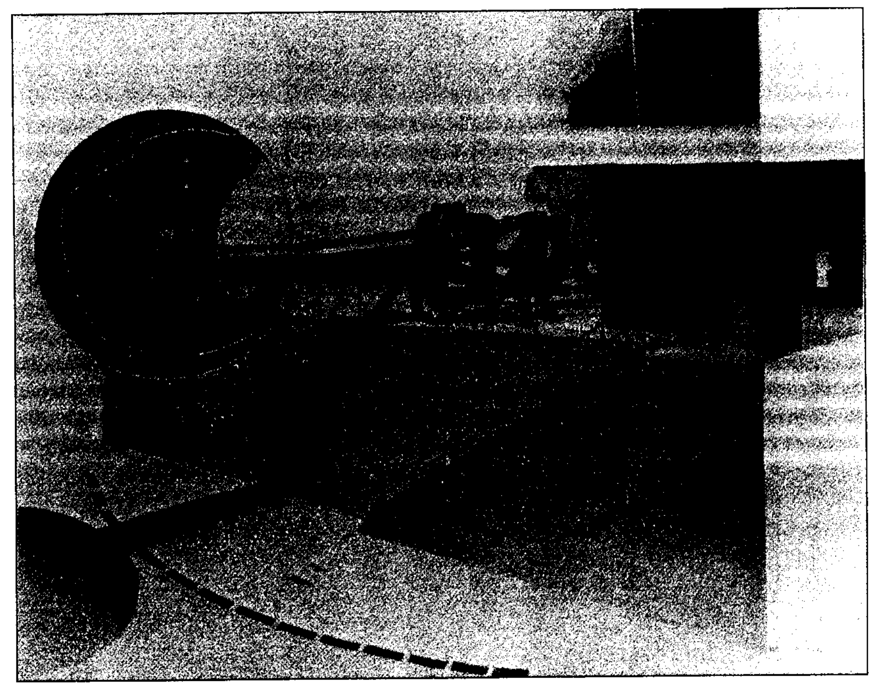


**FIGURE 4.17**
Sketch of United States Air Force Large Amplitude Multimode Aerospace Research Simulator (LAMARS). Courtesy of the Flight Control Division, Flight Dynamics Directorate, Wright Laboratory.

MIL-F-8785C
5 November 1980
SUPERSEDING
MIL-F-8785B
7 August 1969

# MILITARY SPECIFICATION

## FLYING QUALITIES OF PILOTED AIRPLANES

This specification is approved for use by all Departments and Agencies of the Department of Defense.

## 1. SCOPE

1.1 Scope. This specification contains the requirements for the flying and handling qualities, in flight and on the ground, of U.S. Military, manned, piloted airplanes except for flight at airspeeds below $V_{con}$ (MIL-F-83300). It is intended to assure flying qualities that provide adequate mission performance and flight safety regardless of design implementation or flight control system mechanization. The structure of the specification allows its use to guide these aspects in design tradeoffs, analyses and tests.

1.2 Application. The flying qualities of all airplanes proposed or contracted for shall be in accordance with the provisions of this specification. The requirements apply as stated to the combination of airframe and related subsystems. Stability augmentation and control augmentation are specifically to be included when provided in the airplane. The automatic flight control system is also to be considered to the extent stated in MIL-F-9490 or MIL-C-18244, whichever applies. The requirements are written in terms of cockpit flight controls that produce essentially pitching, yawing and rolling moments. This approach is not meant to preclude other modes of control for special purposes. Additional or alternative requirements may be imposed by the procuring activity in order to fit better the intended use or the particular design.

1.3 Classification of airplanes. For the purpose of this specification, an airplane shall be placed in one of the following Classes:

Class I  Small, light airplanes such as
- Light utility
- Primary trainer
- Light observation

Beneficial comments (recommendations, additions, deletions) and any pertinent data which may be of use in improving this document should be addressed to: ASD/ENESS, Wright-Patterson AFB, OH 45433 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FSC 15GP

Class II Medium weight, low-to-medium maneuverability airplanes such as
- Heavy utility/search and rescue
- Light or medium transport/cargo/tanker
- Early warning/electronic countermeasures/airborne command, control, or communications relay
- Antisubmarine
- Assault transport
- Reconnaissance
- Tactical bomber
- Heavy attack
- Trainer for Class II

Class III Large, heavy, low-to-medium maneuverability airplanes such as
- Heavy transport/cargo/tanker
- Heavy bomber
- Patrol/early warning/electronic countermeasures/airborne command, control, or communications relay
- Trainer for Class III

Class IV High-maneuverability airplanes such as
- Fighter/interceptor
- Attack
- Tactical reconnaissance
- Observation
- Trainer for Class IV

The procuring activity will assign an airplane to one of these Classes, and the requirements for that Class shall apply. When no Class is specified in a requirement, the requirement shall apply to all Classes. When operational missions so dictate, an airplane of one Class may be required by the procuring activity to meet selected requirements ordinarily specified for airplanes of another Class.

1.3.1 Land- or carrier-based designation. The letter -L following a Class designation identifies an airplane as land-based; carrier-based airplanes are similarly identified by -C. When no such differentiation is made in a requirement, the requirement shall apply to both land-based and carrier-based airplanes.

1.4 Flight Phase Categories. The Flight Phases have been combined into three Categories which are referred to in the requirement statements. These Flight Phases shall be considered in the context of total missions so that there will be no gap between successive Phases of any flight and so that transition will be smooth. In certain cases, requirements are directed at specific Flight Phases identified in the requirement. When no Flight Phase or Category is stated in a requirement, that requirement shall apply to all three Categories. Flight Phases descriptive of most military airplane missions are:

Nonterminal Flight Phases:

Category A - Those nonterminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control. Included in this Category are:

a. Air-to-air combat (CO)

b. Ground attack (GA)

c. Weapon delivery/launch (WD)

d. Aerial recovery (AR)

e. Reconnaissance (RC)

f. In-flight refueling (receiver) (RR)

g. Terrain following (TF)

h. Antisubmarine search (AS)

i. Close formation flying (FF).

Category B - Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in this Category are:

a. Climb (CL)

b. Cruise (CR)

c. Loiter (LO)

d. In-flight refueling (tanker) (RT)

e. Descent (D)

f. Emergency descent (ED)

g. Emergency deceleration (DE)

h. Aerial delivery (AD).

<u>Terminal Flight Phases</u>:

Category C - Terminal Flight Phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this Category are:

a. Takeoff (TO)

b. Catapult takeoff (CT)

c. Approach (PA)

d. Wave-off/go-around (WO)

e. Landing (L)

When necessary, recategorization or addition of Flight Phases or delineation of requirements for special situations, e.g., zoom climbs, will be accomplished by the procuring activity.

1.5 Levels of flying qualities. Where possible, the requirements of section 3 have been stated in terms of three values of the stability or control parameter being specified. Each value is a minimum condition to meet one of three Levels of acceptability related to the ability to complete the operational missions for which the airplane is designed. The Levels are:

| | |
|---|---|
| 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. |

2. APPLICABLE DOCUMENTS

2.1 Issues of documents. The following documents, of the issue in effect on the date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein:

SPECIFICATIONS

MILITARY

| | |
|---|---|
| MIL-D-8708 | Demonstration Requirements for Airplanes |
| MIL-A-8861 | Airplane Strength and Rigidity Flight Loads |
| MIL-F-9490 | Flight Control Systems - Design, Installation and Test of, Piloted Aircraft, General Specification for |
| MIL-C-18244 | Control and Stabilization Systems, Automatic, Piloted Aircraft, General Specification for |
| MIL-F-18372 | Flight Control Systems, Design, Installation and Test of, Aircraft (General Specification for) |
| MIL-W-25140 | Weight and Balance Control Data (for Airplanes and Rotorcraft) |
| MIL-F-83300 | Flying Qualities of Piloted V/STOL Aircraft |
| MIL-S-83691 | Stall/Post-Stall/Spin Flight Test Demonstration Requirements for Airplanes |

STANDARDS

| | |
|---|---|
| MIL-STD-756 | Reliability Prediction |

(Copies of specifications and standards required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

3.2 <u>Longitudinal flying qualities</u>

3.2.1 <u>Longitudinal stability with respect to speed</u>

3.2.1.1 <u>Longitudinal static stability</u>. For Levels 1 and 2 there shall be no tendency for airspeed to diverge aperiodically when the airplane is disturbed from trim with the cockpit controls fixed and with them free. This requirement will be considered satisfied if the variations of pitch control force and pitch control position with airspeed are smooth and the local gradients stable, with:

a. Trimmer and throttle controls not moved from the trim settings by the crew, and

b. 1g acceleration normal to the flight path, and

c. Constant altitude

over a range about the trim speed of ±15 percent or ±50 knots equivalent airspeed, whichever is less (except where limited by the boundaries of the Service Flight Envelopes). Alternatively, this requirement will be considered satisfied if stability with respect to speed is provided through the flight control system, even though the resulting pitch control force and deflection gradients may be zero. For Level 3 the requirements may be relaxed, subject to approval by the procuring activity of the maximum instability to be allowed for the particular case. In no event shall its time to double amplitude be less than 6 seconds. In the presence of one or more other Level 3 flying qualities, no static longitudinal instability will be permitted unless the flight safety of that combination of characteristics has been demonstrated to the satisfaction of the procuring activity. Stable gradients mean that the pitch controller deflection and force increments required to maintain straight, steady flight at a different speed are in the same sense as those required to initiate the speed change; that is, airplane-nose-down control to fly at a faster speed, airplane-nose-up control to fly at a slower speed. The term gradient does not include that portion of the control force or control position versus airspeed curve within the breakout force range.

3.2.1.1.1 <u>Relaxation in transonic flight</u>. The requirements of 3.2.1.1 may be relaxed in the transonic speed range provided any divergent airplane motions or reversals in slope of pitch control force and position with speed are gradual and not objectionable to the pilot. In no case, however, shall the requirements of 3.2.1.1 be relaxed more than the following:

a. Levels 1 and 2 - For center-stick controllers, no local force gradient shall be more unstable than 3 pounds per 0.01 M nor shall the force change exceed 10 pounds in the unstable direction. The corresponding limits for wheel controllers are 5 pounds per 0.01 M and 15 pounds, respectively

b. Level 3 - For center-stick controllers, no local force gradient shall be more unstable than 6 pounds per 0.01 M nor shall the force ever exceed 20 pounds in the unstable direction. The corresponding limits for wheel controllers are 10 pounds per 0.01 M and 30 pounds, respectively.

This relaxation does not apply to Level 1 for any Flight Phase which requires prolonged transonic operation.

3.2.1.1.2 Pitch control force variations during rapid speed changes. When the airplane is accelerated and decelerated rapidly through the operational speed range and through the transonic speed range by the most critical combination of changes in power, actuation of deceleration devices, steep turns and pullups, the magnitude and rate of the associated trim change shall not be so great as to cause difficulty in maintaining the desired load factor by normal pilot techniques.

3.2.1.2 Phugoid stability. The long-period airspeed oscillations which occur when the airplane seeks a stabilized airspeed following a disturbance shall meet the following requirements:

a. Level 1 ----- $\zeta_p$ at least 0.04

b. Level 2 ----- $\zeta_p$ at least 0

c. Level 3 ----- $T_2$ at least 55 seconds

These requirements apply with the pitch control free and also with it fixed. They need not be met transonically in cases where 3.2.1.1.1 permits relaxation of the static stability requirement.

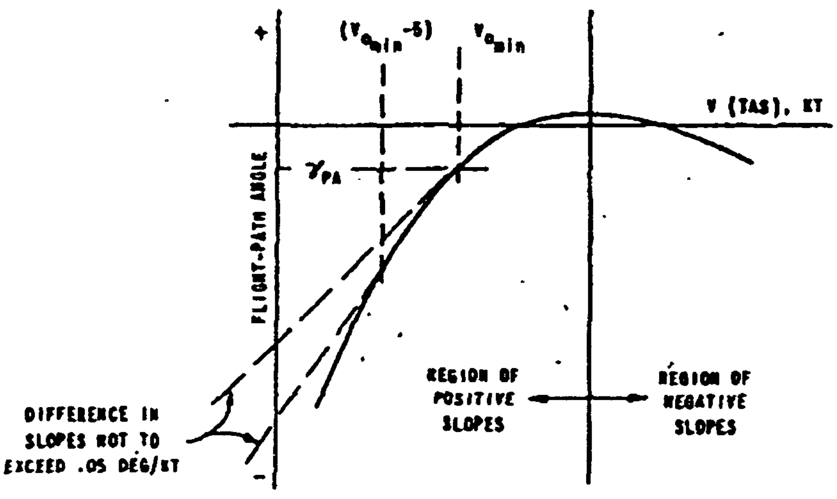
3.2.1.3 Flight-path stability. Flight-path stability is defined in terms of flight-path-angle change where the airspeed is changed by the use of pitch control only (throttle setting not changed by the crew). For the landing approach Flight Phase, the curve of flight-path angle versus true airspeed shall have a local slope at $V_{o_{min}}$ which is negative or less positive than:

a. Level 1 ----- 0.06 degrees/knot

b. Level 2 ----- 0.15 degrees/knot

c. Level 3 ----- 0.24 degrees/knot.

The thrust setting shall be that required for the normal approach glide path at $V_{o_{min}}$. The slope of the curve of flight-path angle versus airspeed at 5 knots slower than $V_{o_{min}}$ shall not be more than 0.05 degrees per knot more positive than the slope at $V_{o_{min}}$, as illustrated by:



3.2.2 Longitudinal maneuvering characteristics

3.2.2.1 Short-period response. The short-period response of angle of attack which occurs at approximately constant speed, and which may be produced by abrupt pitch control inputs, shall meet the requirements of 3.2.2.1.1 and 3.2.2.1.2. These requirements apply, with the cockpit control free and with it fixed, for responses of any magnitude that might be experienced in service use. If oscillations are nonlinear with amplitude, the requirements shall apply to each cycle of the oscillation. In addition to meeting the numerical requirements of 3.2.2.1.1 and 3.2.2.1.2, the contractor shall show that the airplane has suitable response characteristics in atmospheric disturbances (3.7 and 3.8).

3.2.2.1.1 Short-period frequency and acceleration sensitivity. The equivalent short-period undamped natural frequency, $\omega_{nsp}$, shall be within the limits shown on figures 1, 2 and 3. If suitable means of directly controlling normal force are provided, the lower bounds on $\omega_{nsp}$ and $n/\alpha$ of figure 3 may be relaxed if approved by the procuring activity.

3.2.2.1.2 Short-period damping. The equivalent short-period damping ratio, $\zeta_{sp}$, shall be within the limits of table IV.

TABLE IV. Short-period damping ratio limits.

| Level | Category A and C Flight Phases | | Category B Flight Phases | |
|---|---|---|---|---|
| | Minimum | Maximum | Minimum | Maximum |
| 1 | 0.35 | 1.30 | 0.30 | 2.00 |
| 2 | 0.25 | 2.00 | 0.20 | 2.00 |
| 3 | 0.15* | - | 0.15* | - |

*May be reduced at altitudes above 20,000 feet if approved by the procuring activity.

3.2.2.1.3 Residual oscillations. Any sustained residual oscillations in calm air shall not interfere with the pilot's ability to perform the tasks required in service use of the airplane. For Levels 1 and 2, oscillations in normal acceleration at the pilot's station greater than ±0.05g will be considered excessive for any Flight Phase, as will pitch attitude oscillations greater than ±3 mils for Category A Flight Phases requiring precise control of attitude. These requirements shall apply with the pitch control fixed and with it free.

3.2.2.2 Control feel and stability in maneuvering flight at constant speed. In steady turning flight and in pullups at constant speed, there shall be no tendency for the airplane pitch attitude or angle of attack to diverge aperiodically with controls fixed or with controls free. For the above conditions, the incremental control force and control deflection required to maintain a change in normal load factor and pitch rate shall be in the same sense (aft-more positive, forward-more negative) as those required to initiate the change. These requirements apply for all local gradients throughout the range of service load factors defined in 3.1.8.4.

$n = \frac{L}{W}$

$\alpha$ = ANGLE OF ATTACK

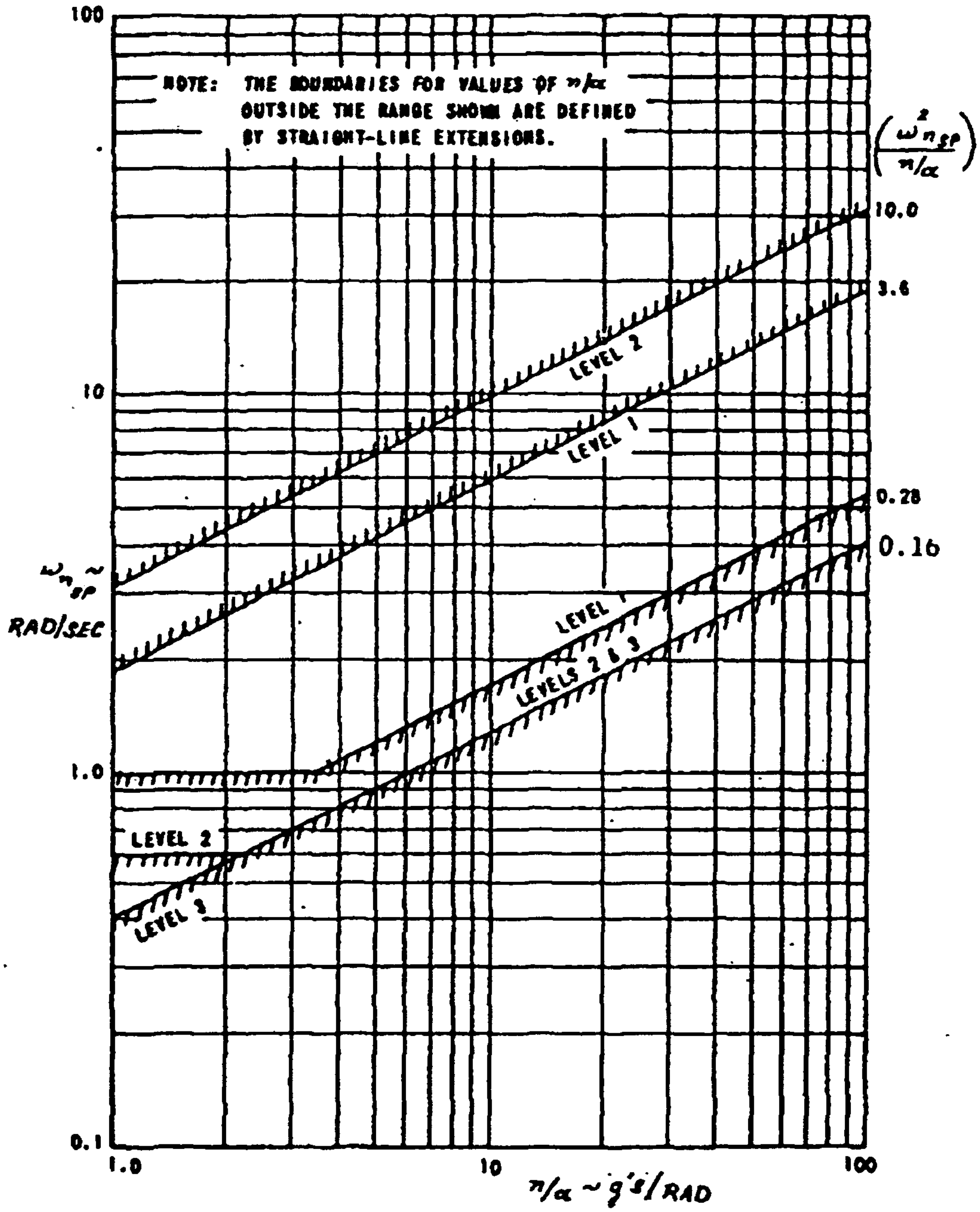



FIGURE 1. Short-period frequency requirements - Category A Flight Phases.

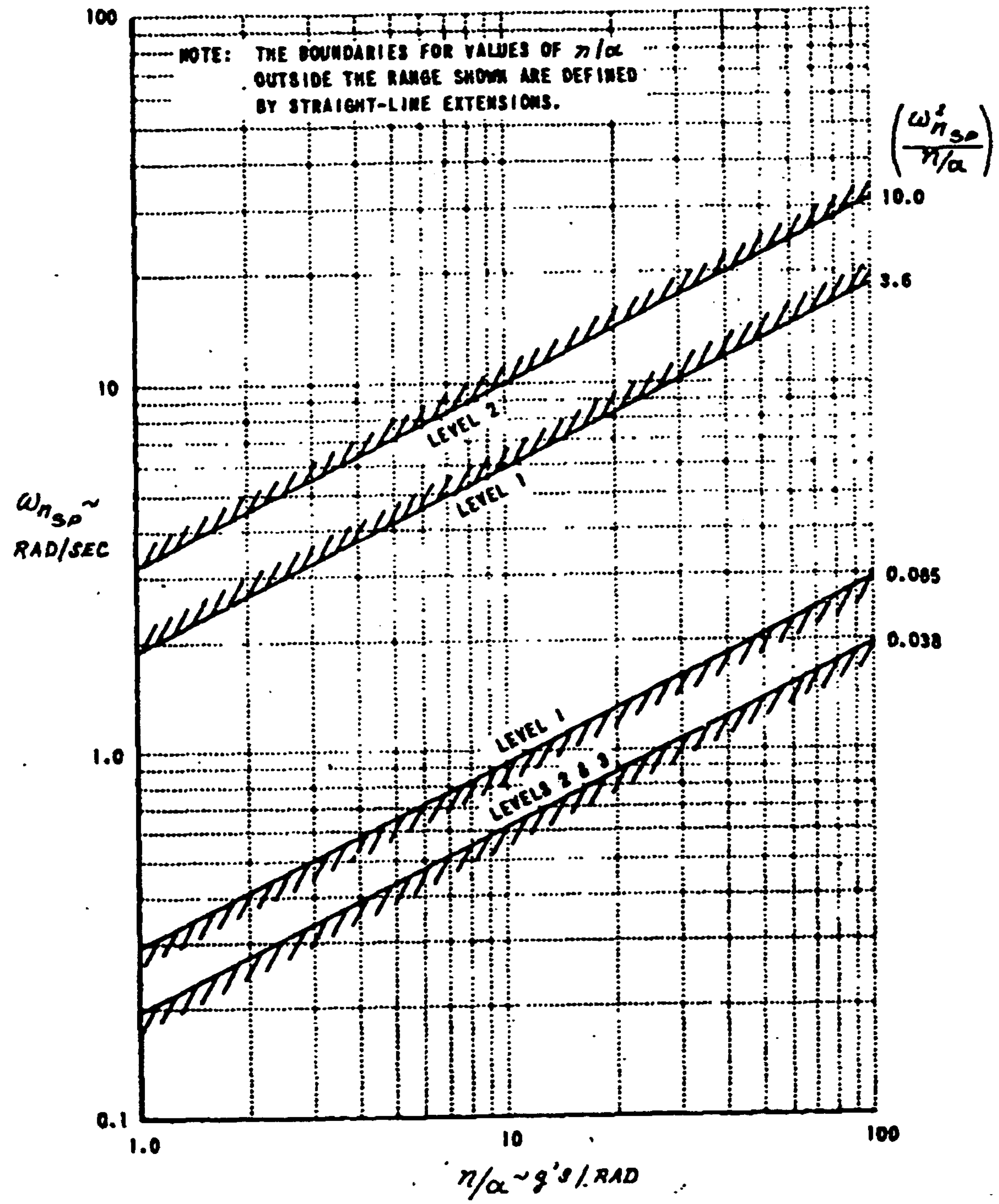



FIGURE 2. Short-period frequency requirements - Category B Flight Phases.

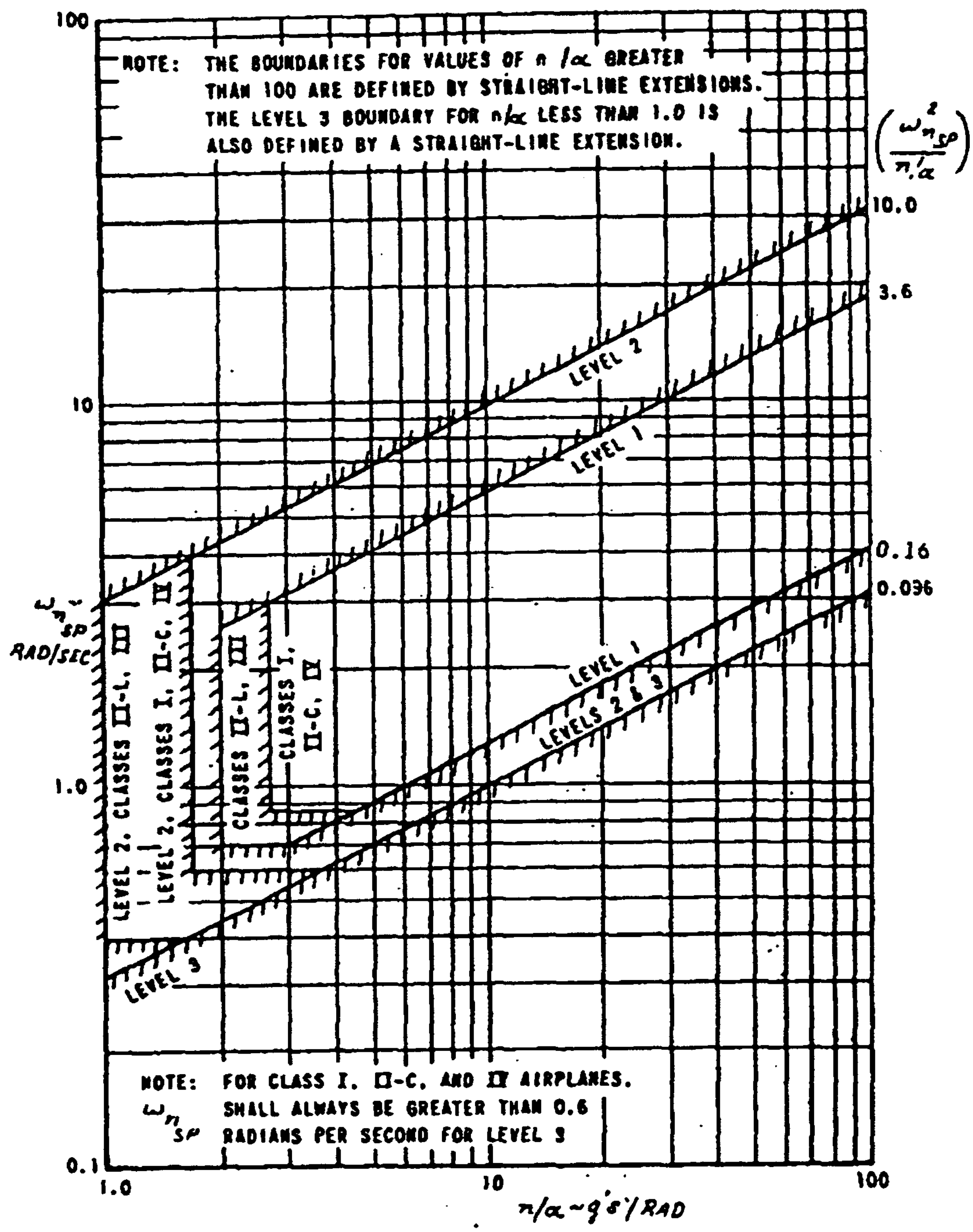



FIGURE 3. Short-period frequency requirements - Category C Flight Phases.

controls fixed and with them free, in oscillations of any magnitude that might be experienced in operational use. If the oscillation is nonlinear with amplitude, the requirement shall apply to each cycle of the oscillation. In calm air residual oscillations may be tolerated only if the amplitude is sufficiently small that the motions are not objectionable and do not impair mission performance. For Category A Flight Phases, angular deviations shall be less than ±3 mils.

TABLE VI. Minimum Dutch roll frequency and damping.

| Flight Phase Level | Category | Class | Min $\zeta_d$ * | Min $\zeta_d\omega_{n_d}$ * rad/sec. | Min $\omega_{n_d}$ rad/sec. |
|---|---|---|---|---|---|
| 1 | A (CO and GA) | IV | 0.4 | - | 1.0 |
| | A | I, IV | 0.19 | 0.35 | 1.0 |
| | | II, III | 0.19 | 0.35 | 0.4** |
| | B | All | 0.08 | 0.15 | 0.4** |
| | C | I, II-C, IV | 0.08 | 0.15 | 1.0 |
| | | II-L, III | 0.08 | 0.10 | 0.4** |
| 2 | All | All | 0.02 | 0.05 | 0.4** |
| 3 | All | All | 0 | - | 0.4** |

* The governing damping requirement is that yielding the larger value of $\zeta_d$, except that a $\zeta_d$ of 0.7 is the maximum required for Class III.

** Class III airplanes may be excepted from the minimum $\omega_{n_d}$ requirement, subject to approval by the procuring activity, if the requirements of 3.3.2 through 3.3.2.4.1, 3.3.5 and 3.3.9.4 are met.

When $\omega_{n_d}^2|\phi/\beta|_d$ is greater than 20 (rad/sec)$^2$, the minimum $\zeta_d\omega_{n_d}$ shall be increased above the $\zeta_d\omega_{n_d}$ minimums listed above by:

Level 1 - $\Delta\zeta_d\omega_{n_d} = .014(\omega_{n_d}^2|\phi/\beta|_d - 20)$

Level 2 - $\Delta\zeta_d\omega_{n_d} = .009(\omega_{n_d}^2|\phi/\beta|_d - 20)$

Level 3 - $\Delta\zeta_d\omega_{n_d} = .005(\omega_{n_d}^2|\phi/\beta|_d - 20)$

with $\omega_{n_d}$ in rad/sec.

3.3.1.2 Roll mode. The roll-mode time constant, $\tau_R$, shall be no greater than the appropriate value in table VII.

TABLE VII. Maximum roll-mode time constant, seconds.

| Flight Phase Category | Class | Level 1 | Level 2 | Level 3 |
|---|---|---|---|---|
| A | I, IV | 1.0 | 1.4 | |
| | II, III | 1.4 | 3.0 | |
| B | All | 1.4 | 3.0 | 10 |
| C | I, II-C, IV | 1.0 | 1.4 | |
| | II-L, III | 1.4 | 3.0 | |

3.3.1.3 Spiral stability. The combined effects of spiral stability, flight-control-system characteristics and rolling moment change with speed shall be such that following a disturbance in bank of up to 20 degrees, the time for the bank angle to double shall be greater than the values in table VIII. This requirement shall be met with the airplane trimmed for wings-level, zero-yaw-rate flight with the cockpit controls free.

TABLE VIII. Spiral stability - minimum time to double amplitude.

| Flight Phase Category | Level 1 | Level 2 | Level 3 |
|---|---|---|---|
| A & C | 12 sec | 8 sec | 4 sec |
| B | 20 sec | 8 sec | 4 sec |

3.3.1.4 Coupled roll-spiral oscillation. For Flight Phases which involve more than gentle maneuvering, such as CO and GA, the airplane characteristics shall not exhibit a coupled roll-spiral mode in response to the pilot roll control commands. A coupled roll-spiral mode will be permitted for Category B and C Flight Phases provided the product of frequency and damping ratio exceeds the following requirements:

| Level | $\zeta_{RS}\omega_{n_{RS}}$, rad/sec |
|---|---|
| 1 | 0.5 |
| 2 | 0.3 |
| 3 | 0.15 |

3.3.2 Lateral-directional dynamic response characteristics. Lateral-directional dynamic response characteristics are stated in terms of response to atmospheric disturbances and in terms of allowable roll rate and bank oscillations, sideslip excursions, roll control forces and yaw control forces that occur during specified rolling and turning maneuvers both to the right and to the left. The requirements of 3.3.2.2, 3.3.2.3 and 3.3.2.4 apply for roll commands of all magnitudes up to the magnitude required to meet the roll performance requirements of 3.3.4 and 3.3.4.1.