

The Seven Parameters of Highly Effective Cable Control Systems

Takashi S. Maeda
Cessna Aircraft Company

Copyright © 2008 SAE International

ABSTRACT

Despite the recent trend toward increased use of Fly-By-Wire systems, conventional cable control systems remain a popular option for most general aviation aircraft, as they provide a reliable and economical way of controlling aircraft. Cables, however, elongate under load due to the nature of their braided construction and impose unique system characteristics which will affect an airplane's handling qualities and aeroelastic stability. But those characteristics can be effectively controlled by carefully laying out kinematics of individual cable loops and linkages within the system. This paper identifies major design parameters of the cable control system and discusses how those parameters determine the mechanical characteristics of the system, focusing mainly on the aileron controls. A major objective of this paper is to provide useful guides for flight controls designers to lay out effective system geometries that will fulfill intended performance and characteristics of the cable control systems.

1. INTRODUCTION

While Fly-By-Wire flight control systems are a growing trend for modern faster and larger aircraft, conventional manually-controlled systems, which consist of cables, pulleys, and linkages, are still a popular option for most general aviation aircraft. The cable flight control systems have been providing a low-tech, yet reliable and inexpensive way to control the aircraft from day one of aviation history, and their design and fabrication methods seem to be well established.

However, in the nature of their braided construction, the cables elongate under load to no small extent, and impose unique system characteristics, which are sometimes not intuitive. The effects of the cable elasticity become more significant as the speed and size of the aircraft approach the limitations of manually-powered control systems. The effects of the system elasticity, however, could be positively utilized to achieve optimum system performance and characteristics by carefully laying out kinematic geometries of individual cable loops and mechanical linkages within the system.

For example, it had been believed that control systems should be designed as rigid as possible for effective controllability, but Dr. Jiro Horikoshi, the chief designer of Zero, a legendary Japanese WWII fighter, deliberately reduced the elevator system stiffness to successfully improve his airplane's sensitive pitch response. The Zero's relaxed control stiffness increased the control stick motion for the same amount of g, and effectively eased its control sensitivity at high speed as shown in Figure 1.1 [1]. Figure 1.1 also includes the effect of the reduced system gearing ratio for comparison. As shown in Figure 1.2, the increased stick motion reduced the gradient of control force per stick motion as well, to resolve the unfavorable stiff control feel. The final value of the system stiffness selected for the production was only 23 percent of the minimum allowable limit specified in the then Japanese Navy's Technical Standards, yet the Zero demonstrated its outstanding handling qualities over wide range of airspeed. Figure 1.3 illustrates the Zero's maneuverability in terms of the loop recovery performance evaluated by Corwin Meyer, a Grumman test pilot [2].

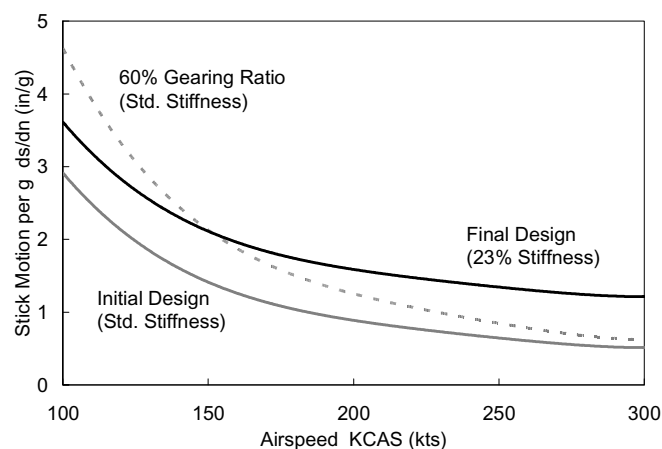


Fig. 1.1 Effect of system stiffness on stick motion per g [1]

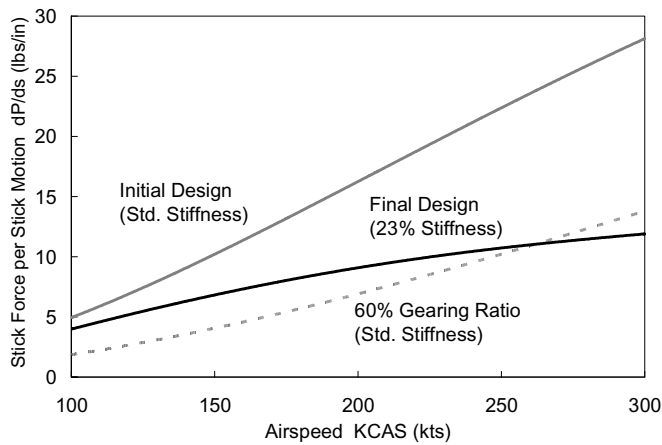


Fig. 1.2 Effect of system stiffness on stick force per stick motion gradient [1]

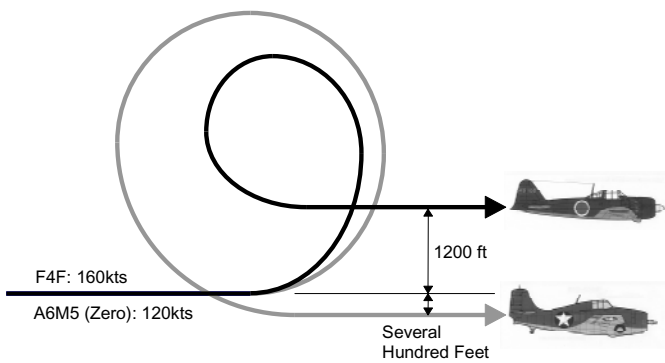


Fig. 1.3 Zero vs. F4F maneuverability comparison (constructed from statements in [2])

As the title suggests, this paper is intended to provide self-help information for flight control system designers to lay out effective system kinematics which will fulfill desirable system performance and characteristics. To this end, this paper identifies the seven major design parameters of the cable control systems and discusses how those parameters affect the mechanical characteristics of the system. The discussions will be focused mainly on the aileron control system, which is generally the most complex and has unique characteristics. The same design and analysis methods described herein can be applied to systems for the other control axes.

The design parameters to be discussed in this paper include; (1) aileron wing sector gearing, (2) system gearing ratio, (3) system installation stiffness factor, (4) cable primary modulus, (5) critical control force for cable slack, (6) overall system stiffness, and (7) frequency of symmetric aileron rotation. Among these parameters, the system gearing ratio and the overall system stiffness play major roles in determining an airplane's handling qualities in conjunction with the aerodynamic characteristics of the control surfaces. The frequency of symmetric aileron rotation is also an important parameter that affects the airplane's wing/aileron-related flutter characteristics, particularly for high speed aircraft.

2. SYSTEM SCHEMATIC

Figure 2.1 shows a schematic of the typical aileron control system using cables and linkages, on which the analyses for the rest of this paper will be based. Definitions and units of the symbols used in Figure 2.1 are summarized in the last section of this paper. It is assumed that the system is left-right symmetrical except for the aileron surface inertias ($I_{AL} \neq I_{AR}$), which are often not equal due to the asymmetric installation of the aileron trim tab. Sign conventions defined in Figure 2.1 apply to all the equations in this paper.

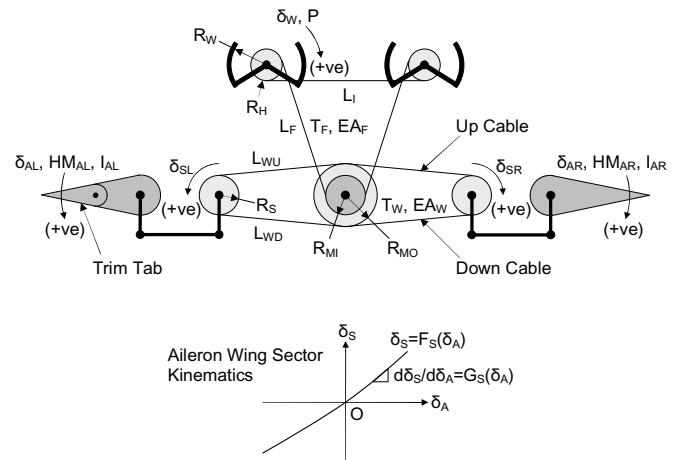


Fig. 2.1 Aileron system schematic diagram

Kinematic relationship between the wing sector and the aileron surface connected by a linkage can be expressed as a mathematical function, $\delta_S = F_S(\delta_A)$, as shown in Figure 2.1. A polynomial equation of the aileron wing sector kinematics can be obtained by curve-fitting the plot of the wing sector angle, δ_S , vs. aileron surface deflection, δ_A .

$$\delta_S = F_S(\delta_A) = C_4 \delta_A^4 + C_3 \delta_A^3 + C_2 \delta_A^2 + C_1 \delta_A \quad [\text{deg}] \quad (2.1)$$

where C_4 , C_3 , C_2 , and C_1 are polynomial coefficients. The polynomial should have reasonably high order for accuracy. A typical example of the aileron wing sector kinematics is presented in Figure 2.2.

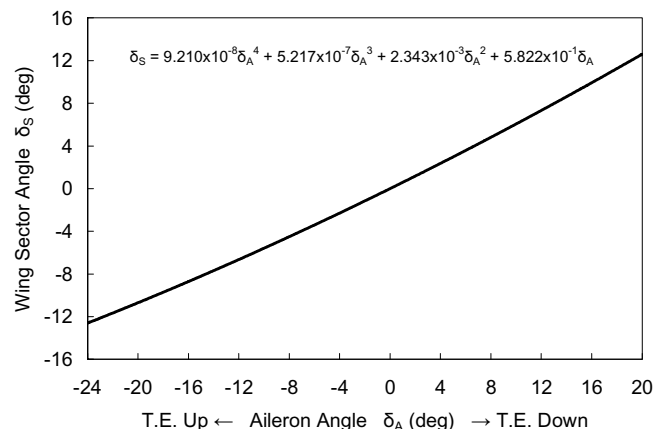


Fig. 2.2 Aileron wing sector kinematics

Note that the plotted curve should be slightly concave downward for the conventional differential aileron control. The equation should be identical for the left and right ailerons due to the symmetrical design. Differentiation of the equation (2.1) with respect to δ_A leads to the function, $G_S(\delta_A)$, which provides the δ_S vs. δ_A gradient, or *aileron wing sector gearing*, at any corresponding aileron position.

$$\frac{d\delta_S}{d\delta_A} = G_S(\delta_A) = 4C_4\delta_A^3 + 3C_3\delta_A^2 + 2C_2\delta_A + C_1 \quad (2.2)$$

This equation will be used to calculate the overall system gearing ratio in Section 4. With the aileron at neutral ($\delta_A=0^\circ$), the expression of Equation (2.2) is reduced to a constant as follows:

$$G_{S0} = G_S(0) = C_1 \quad (2.3)$$

Figure 2.3 displays a typical curve of the aileron wing sector gearing, $G_S(\delta_A)$, which corresponds to the aileron wing sector kinematics shown in Figure 2.2.

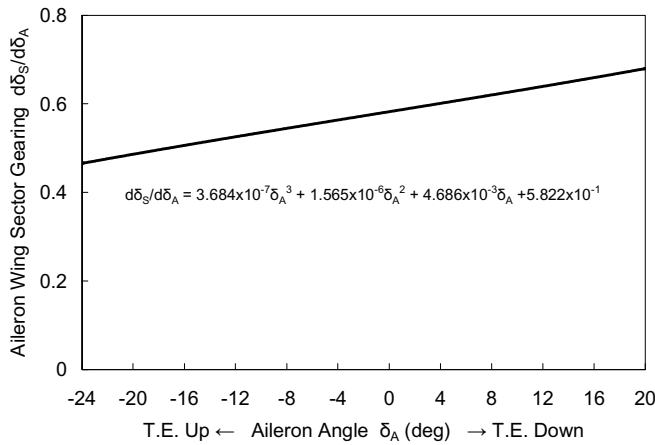


Fig. 2.3 Aileron wing sector gearing

3. CONTROL WHEEL ANGLE VS. AILERON DEFLECTION

The relationship between the control wheel angle, δ_W , and the wing sector angle, δ_S , for each aileron can be expressed as follows:

$$\delta_W(\delta_{AL}) = \frac{1}{R_H} \cdot \frac{R_{MI}}{R_{MO}} R_S \delta_S \quad [\text{deg}] \quad (\text{LH Aileron}) \quad (3.1)$$

$$\delta_W(\delta_{AR}) = -\frac{1}{R_H} \cdot \frac{R_{MI}}{R_{MO}} R_S \delta_S \quad [\text{deg}] \quad (\text{RH Aileron}) \quad (3.2)$$

where R_H , R_{MI} , R_{MO} , and R_S are pitch radii of the cable sectors in the system as shown in Figure 2.1. Substituting the expression of the aileron wing sector kinematics defined by Equation (2.1) into these equations, the relationship between the control wheel input angle, δ_W , and the left aileron deflection, δ_{AL} , can be derived as follows:

$$\delta_W(\delta_{AL}) = \frac{1}{R_H} \cdot \frac{R_{MI}}{R_{MO}} R_S F_S(\delta_{AL}) \quad [\text{deg}] \quad (3.3)$$

In the same manner, the equation based on the right aileron deflection, δ_{AR} , can be written as:

$$\delta_W(\delta_{AR}) = -\frac{1}{R_H} \cdot \frac{R_{MI}}{R_{MO}} R_S F_S(\delta_{AR}) \quad [\text{deg}] \quad (3.4)$$

Equation (3.3) or (3.4) is particularly useful for evaluating the desired control wheel deflection for the maximum aileron angles. It should be noted, however, that these equations are for the rigid systems or no load condition, since they do not account for the effects of the cable stretch nor structural deformations. Figure 3.1 shows a typical example of the control wheel vs. aileron deflection curves.

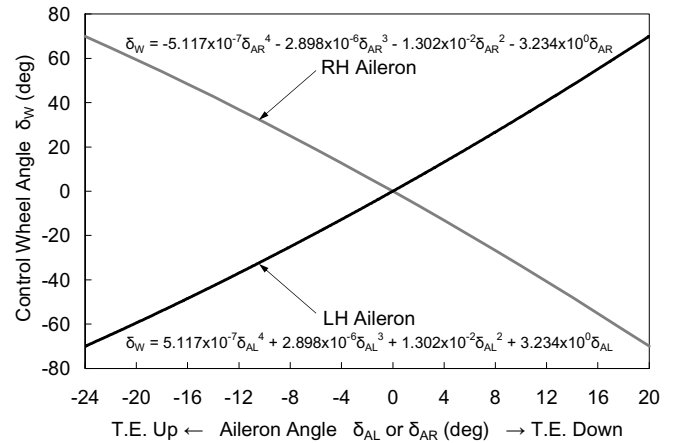


Fig. 3.1 Control wheel angle vs. aileron deflection (rigid system)

4. SYSTEM GEARING RATIO

The *system gearing ratio* of the flight control system is defined as a ratio of the applied pilot force, P , to the surface hinge moment, HM . It is also defined as a gradient of the surface angle, δ , to the pilot control deflection, s .

$$G = \frac{P}{HM} = -\frac{12}{57.3} \cdot \frac{d\delta}{ds} \quad [1/\text{ft}] \quad (4.1)$$

As Equation (4.1) indicates, the pilot force to counteract the same surface hinge moment decreases proportionally as the gearing ratio decreases at the cost of the maximum available surface angle. The gearing ratio is generally expressed in 1/ft to match the unit of the surface hinge moment, ft-lbs. For aileron control systems, the system gearing ratio can be written as follows:

$$G_A = \frac{P}{HM_A} = -\frac{12}{57.3} \cdot \frac{d\delta_A}{ds} = -\frac{12}{57.3} \cdot \frac{d\delta_A}{d\delta_S} \cdot \frac{d\delta_S}{ds} = -\frac{12}{R_W} \cdot \frac{d\delta_A}{d\delta_S} \cdot \frac{d\delta_S}{d\delta_W} \quad [1/\text{ft}] \quad (4.2)$$

Substituting Equations (2.2), (3.1), and (3.2) into the last expression of Equation (4.2), the system gearing ratio for the left and right ailerons can be derived as follows:

$$G_{AL}(\delta_{AL}) = -\frac{R_H R_{MO}}{R_W R_{MI} R_S} \cdot \frac{12}{G_S(\delta_{AL})} \quad [1/ft] \quad (4.3)$$

$$G_{AR}(\delta_{AR}) = \frac{R_H R_{MO}}{R_W R_{MI} R_S} \cdot \frac{12}{G_S(\delta_{AR})} \quad [1/ft] \quad (4.4)$$

Each equation is expressed as a function of the deflection of the corresponding aileron, δ_{AL} or δ_{AR} .

Figure 4.1 shows a typical example of the aileron system gearing ratios. Note that, for the conventional differential aileron design, the magnitude of the gearing ratio for each aileron decreases as the surface moves in positive direction (downward).

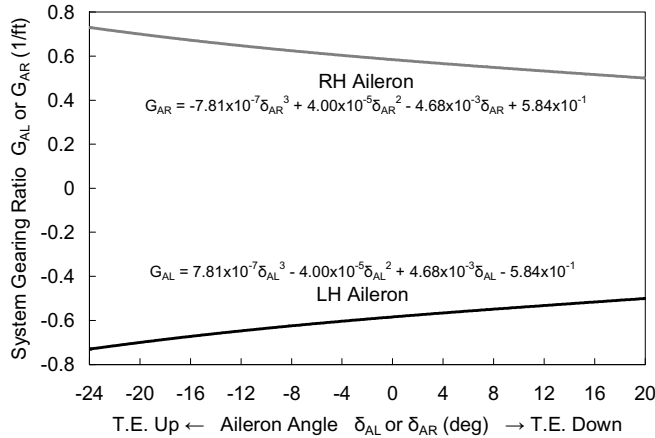


Fig. 4.1 Aileron system gearing ratio curves

With the data of the aileron hinge moment available, the pilot control effort to counteract the total aerodynamic loads can be calculated using the following equation:

$$P = G_{AL}(\delta_{AL})HM_{AL}(\delta_{AL}) + G_{AR}(\delta_{AR})HM_{AR}(\delta_{AR}) \quad [lbs] \quad (4.5)$$

where the hinge moment of each aileron, which is also a function of the surface position, is given by:

$$HM_A(\delta_A) = C_{ha}(\delta_A) \bar{q} S_A \bar{c}_A \quad [ft \cdot lbs] \quad (4.6)$$

Unlike Equations (3.3) and (3.4), Equation (4.5) is not affected by the elasticity of the cables and their support structures, provided that the wing sector/aileron linkages remain rigid.

5. CABLE AND SYSTEM INSTALLATION STIFFNESS

Cables in the flight control systems stretch under load to no small extent and affect the system characteristics. The cable stretch consists of the elasticity of the material itself and the constructional stretch due to its unique braided structure. The latter causes the cable's spring rate to vary with load until the effect of the braided construction dissipates at a higher load. Figure 5.1 shows elastic characteristics of the corrosion resistant steel cable of 1/8 inch diameter and 7x19 strand, which is typically used for the primary control systems. Curves in Figure 5.1 are mathematical approximations of the tested data, showing the relationships between the cable

tension, T , and deflection per unit cable length, d . The curve shape must be established from the test data, as the cable's elastic characteristics vary depending on its size, number of strands, material, and manufacturer.

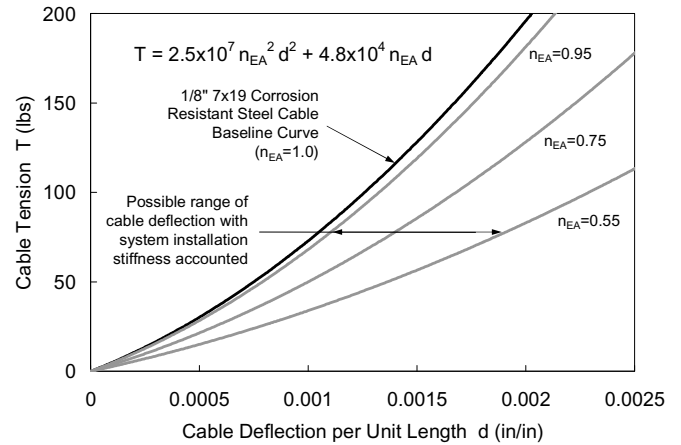


Fig. 5.1 Cable tension vs. deflection characteristics

The cable's tension vs. deflection curve can be approximated by the following second order polynomial:

$$T = a_{EA} n_{EA}^2 d^2 + b_{EA} n_{EA} d \quad [lbs] \quad (5.1)$$

where a_{EA} and b_{EA} are coefficients of the polynomial and n_{EA} is a *system installation stiffness factor* which accounts for elasticity of the cable system installations such as sector/pulley brackets and their support structures.

The system installation stiffness factor, n_{EA} , has a wide range of values depending on the individual system installation design, and possibly varies from 0.55 to 0.95. For a preliminary calculation, it is recommended to use a factor of 0.75. The actual system installation stiffness factor for a specific model and control axis should be determined by a control force/deflection test with the control surfaces restricted at their neutral positions.

EA is a cable's *primary modulus*, which is the product of the elastic modulus and the section area. The EA value represents the spring rate of a unit length cable under the corresponding tension load, and can be obtained from the slope of the cable's tension vs. deflection curve as shown in Figure 5.1. Using the same polynomial coefficients, a_{EA} and b_{EA} , and the system installation stiffness factor, n_{EA} , introduced in Equation (5.1), the mathematical expression of the cable EA value can be derived as follows:

$$EA = n_{EA} \sqrt{b_{EA}^2 + 4a_{EA}T} \quad [lbs] \quad (5.2)$$

The variation of the EA value along with the cable tension, T , for the 1/8" 7x19 corrosion resistant steel cable is shown in Figure 5.2 with the effects of the system installation stiffness factor, n_{EA} . The spring rate of an L inch length cable can then be calculated using the EA value as follows:

$$k = \frac{EA}{L} \quad [lbs/in] \quad (5.3)$$

