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Programmable Aileron Sizing Algorithm for use in Preliminary Aircraft Design Software

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Abstract: All aircraft, military and commercial, must satisfy controllability and in turn, maneuverability prerequisites to be espoused by the military or certified for transport aircraft. So, it is imperative for the designers to assess the control authority of candidate configurations early in the preliminary design phase. This early assessment formulates the design process very proficient and cost-effective. Aileron sizing is one of the controllability concepts that should be involved in the preliminary design process. Adding aileron sizing module as a helpful tool for aeronautical students enhance their knowledge, understanding and analyzing studies. This study presents a programmable algorithm for aileron sizing to be employed in any preliminary aircraft design software. The study introduced the necessary formulae as a guide to size the aileron to achieve the prerequisites of the roll control. A solved example has been added to explain the application of the algorithm.

Key words: Aileron sizing software, educational software, control surface design, preliminary aircraft design software

INTRODUCTION

Ailerons are similar to simple flaps located at the outside of the wing. Both (left and right) ailerons move up/down simultaneously and differentially to generate the desired rolling moment. This moment depends on aileron deflection, aileron size and the distance from the center line of the fuselage. Although, the essential task of the aileron is in the roll control but it also affects the yaw control (Etkin and Reid, 1996). This roll control is managed mainly throughout a roll rate (P). Changing the aileron deflection or geometry will change the roll rate. Therefore, sizing the ailerons should be done in a way that minimizes the control forces as possible to reduce the actuating system size and cost.

On the other hand, all aircraft, military and commercial, must satisfy controllability and in turn, maneuverability prerequisites to be espoused by the military or certified for transport aircraft. So, it is imperative for the designers to assess the control authority of candidate configurations early in the preliminary design phase. This early assessment formulates the design process very proficient and cost-effective. Aileron sizing is one of the controllability concepts that should be involved in the preliminary design process. Adding aileron sizing module as a helpful tool for aeronautical students enhance their knowledge, understanding and analyzing studies.

A quick pass of the available developed software for preliminary aircraft design is shown here. Starting with Roskam's Software (AAA) (Roskam and Malaek, 989) as a coded version of his textbook (Roskam, 1985). Raymer (1996) released his software package (ADS) (Raymer, 1996) based also on his book (Raymer, 2006). Then, the comprehensive software CEASIOM (Kaenel *et al.*, 2008) was developed in 2008 and still in the stage of improvement. Finally, Nicolosi released his software (ADAS) (Nicolosi and Paduano, 2011). Unfortunately, all these software packages present the aileron sizing indirectly by offering just the stability and controllability derivatives, dimensional and non-dimensional. These derivatives are not so clear for students and many practices must be exercised to be familiar with. Typically, the aileron sizing process is done in the detail phase.

From the research side view, the current researches are investigating aileron sizing for the aircraft industry and not for teaching which are out of the scope of the paper. For example, Elham and Tooren (2015) concluded that the required value for the aileron effectiveness is changed quadratically with the wing box weight. Amendola *et al.* (2016) suggested a design of an adaptive aileron with details of its structure to reduce the total wing trailing edge drag by 6%.

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MATERIALS AND METHODS

Aileron sizing principles: As mentioned above, the fundamental principal behind ailerons is to adapt the spanwise lift distribution to generate a moment about the aircraft longitudinal axis. The estimation of aileron roll control power can be evaluated by two methodologies: a-semi-empirical which depends on a chart that obtain all the required contributions for the calculation (Roskam, 1985) and b-one strip integration which is founded on basic aerodynamic analysis (Howe, 2000). The second methodology is more accurate than the first one due to its assumptions Esercitazioni. Thus, it is used here to implement the algorithm.

Initially, four parameters must be determined in the aileron sizing process. They are: aileron area (S_a), aileron chord to aileron span ratio (C_a/b_a), maximum aileron deflection ($\pm Aa_{max}$) and aileron inboard location on the length of the wingspan (b_{ai}). These parameters in general, have the typical values: S_a/S = 0.05-0.1, b_a/b = 0.2-0.3, C_a/C = 0.15-0.25 and $Aa_{max} = \pm 30°$. Table 1 shows considerable criteria for aileron sizing of military aircraft (Anonymous, 1980, 1997). It provides the time needed to bank an aircraft at a particular bank angle. Mostly, sizing the aileron is based on take-off or landing flight phase where the speed should be the lowest (Nelson, 1989). The roll control derivative ($C_{l_{\delta_a}}$) is calculated using the following equation:

$$C_{l_{\delta_a}} = \frac{C_{L_{\alpha_w}} \tau_a C_r}{Sb}\left[\frac{y^2}{2}+\frac{2}{3}\left(\frac{\lambda-1}{b}\right)y^3\right]_{y_i}^{y_0} \quad (1)$$

Where:

y_i and y_o = The aileron inboard and outboard locations, respectively

τ_a = Obtained from Fig. 1 (Roskam, 2007; Sadraey, 2013)

The following Eq. 2 represents the mathematical model of Fig. 1 using MATLAB, CF tool:

$$\tau_a = -6.624\times\left(\frac{S_a}{S}\right)^4+12.07\times\left(\frac{S_a}{S}\right)^2-8.292\times\left(\frac{S_a}{S}\right)^2+3.295\times\left(\frac{S_a}{S}\right)+0.004942 \quad (2)$$

The rolling moment Coefficient (C_l) is obtained as:

$$C_l = C_{l_{\delta_A}}\delta_A \quad (3)$$

Table 1: The time required to bank the aircraft based on its weight and class phase

Aircraft class (kg)	B (climb, cruise, descent) bank angle of 40° (sec)	C (take-off, landing) bank angle of 30° (sec)
<6000	1.7	1.3
6000-30000	1.9	1.8
Over 30000	2.3	2.5

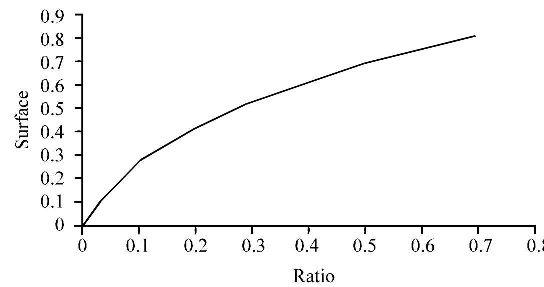

Fig. 1: A general representation of the control surface effectiveness (Roskam, 2007; Sadraey, 2013)

The ailerons moved up/down generates an incremental lift force which in turn creates a rolling moment and can be determined as:

$$L_a = \bar{q}SC_l b = \frac{1}{2}pV_T^2SC_l b \quad (4)$$

On the other hand, the generated aerodynamic rolling moment at a constant roll rate is equal to the drag of the aircraft, i.e.:

$$L_a = \frac{1}{2}p(P\times y_D)^2(S_w+S_h+S_v)C_{D_R}\times y_D \quad (5)$$

where, y_D is the distance between the aircraft center of gravity and the rolling drag center. Solving Eq. 4 for P_{ss} yields:

$$P_{ss} = \sqrt{\frac{2\times L_A}{p(S_w+S_h+S_v)C_{D_R}\times y_D^3}} \quad (6)$$

Now, determination of the bank angle (φ_1) at steady state roll rate can be obtained as:

$$\varphi_1 = \frac{I_{xx}}{py_D^3(S_w+S_h+S_v)C_{D_R}}\ln(P_{ss}^2) \quad (7)$$

By comparing φ_1 with the required bank angle in Table 1, if φ_1 is smaller than desired, then calculate the required time (t_2) using the following Eq. 8:

$$t_2 = t_{ss} + \Delta t_R \tag{8}$$

Where:

$$\Delta t_R = \frac{\varphi_2 - \varphi_1}{P_{ss}} \tag{9}$$

Δt_R the time required to roll linearly from φ_{ss}-φ_2. If φ_1 is greater than the desired bank angle, then calculate the required time (t_2) by calculating the angular acceleration first:

$$P^{\cdot} = \frac{P_{ss}^2}{2\varphi_1} \tag{10}$$

Finally, the time required (t_{req}) to satisfy the designed bank angle (φ_{des}) is obtained as:

$$t_2 = \sqrt{\frac{2\varphi_{des}}{P^{\cdot}}} \tag{11}$$

This study introduced the necessary formulae as a guide to size the aileron to fulfill the requirements of the roll control. It is important to note that the greatest roll control by an aileron can be achieved by considering the conventional configuration, i.e., the flap at the inboard of the wing and the aileron at the outboard of the wing (Anonymous, 1980). The final results of this configuration are light, small and less cost aileron surfaces. The aileron sizing algorithm will be presented in the next section.

Aileron sizing algorithm: For a conventional aircraft, the aileron sizing algorithm steps are as follows: Assigning the basic inputs of the program. This step includes: identifying the aircraft class based on its mass (Table 1), selection of the flight phase based on the lowest speed (mostly Phase C), assigning the time required to achieve a specific bank angle (Table 1) and identifying the parameters b_{ai}/b, b_{ao}/b and C_a/C.

Determine the aileron effectiveness parameter (τ_a) using Eq. 2. Calculating the aileron rolling moment coefficient derivative ($C_{l\delta a}$) from Eq. 1. Selecting the maximum aileron deflection (δa_{max}), typically about ±25°. Using Eq. 3, the aircraft rolling moment Coefficient (C_l) is calculated. Using Eq. 4, the aircraft rolling moment (La) is calculated. Calculating the steady-state roll rate (P_{ss}) using Eq. 6. Calculating the bank angle (Φ_1) using Eq. 7.

Comparing the calculated bank angle in step 8 with the required bank angle in Table 1. If the calculated angle smaller than the desired bank angle, then, calculate the required time (t_2) using Eq. 8 and 9.

If the calculated angle greater than desired, calculate the required time (t_2) using Eq. 10 and 11. Comparing the calculated roll time (step 9 or 10) with the required roll time (step 1). If the calculated time is equal or shorter, the aileron design prerequisite has been satisfied. If the calculated time is greater, then, the aileron design has not satisfied the prerequisite. So, either the aileron chord or span is expanded or the maximum aileron deflection is increased. Return to the first step and begin over again.

RESULTS AND DISCUSSION

Testing the algorithm: The algorithm can be coded in a high level language and encapsulated in any preliminary aircraft design software to aid students and fresh engineers to enhance their understanding and analyzing of the aileron sizing process. The following example illustrates the application of this algorithm as an instructional use Algorithm 1:

Algorithm 1; Example:

Example: Design a low cost aileron for a military transport aircraft that meets the MIL-STD roll control requirements. A conventional configuration is selected with the following data:

M_{TO} = 6500 kg, S = 21 m², AR = 8, λ = 0.7, S_h = 5.3 m², S_v = 4.2 m², V_s = 80 knot, $C_{L\alpha w}$ = 4.5 1/rad, I_{xx} = 28 000 kg m²; the outboard flap location = 60% of the wing span and the location of the wing rear spar = 75% of the wing chord.

Solution; step 1: Based on Table 1, the aircraft mass is classified to Class 2 and phase C is considered for the roll control at the lowest speed. Hence, the required time is 1.8 sec to satisfy a bank angle of 30°. Due to the outboard flap location, the aileron inboard and outboard locations are selected to be at 70 and 95% of the wing span, respectively. Due to the wing rear location, the ratio of 20% is selected for the aileron chord to wing chord.

Step 2: From Eq. 2, the aileron effectiveness parameter is 0.41 for aileron-to-wing chord ratio is 0.2.

Step 3: Pre-calculations needed before applying Eq. 1 to find aileron rolling moment coefficient derivative, i.e.,:

$$b = \sqrt{S \times AR} = \sqrt{21 \times 10} = 14.49 \text{ m}$$

$$\bar{C} = \frac{b}{AR} = \frac{14.49}{10} = 1.449 \text{ m}$$

$$\bar{C} = \frac{2}{3} C_r \left(\frac{1+\lambda+\lambda^2}{1+\lambda}\right) \Rightarrow 1.449 = \frac{2}{3} C_r \left(\frac{1+0.8+0.8^2}{1+0.8}\right)$$

Note that, these calculations are already implemented in any aircraft design software and presented here just for clarification.

Inboard position at 70%:

$$y_i = 0.7\frac{b}{2} = 0.7 \times \frac{14.49}{2} = 5.072 \text{ m}$$

Outboard position at 95%:

$$y_0 = 0.95\frac{b}{2} = 0.95 \times \frac{14.49}{2} = 6.883 \text{ m}$$

Now, applying Eq. 1 yields:

$$C_{l_{\delta_a}} = 0.176\frac{1}{\text{rad}}$$

Step 4: φ_{des} of ±20° is selected.

Step 5: Applying Eq. 3 yields: $C_l = 0.061$.

Step 6: Generally, the approach speed is considered to be $1.3V_s$ at the sea-level altitude. Therefore:

$$V_{app} = 1.3V_s = 1.3\times 80 = 104\text{knot} = 53.5\frac{\text{m}}{\text{sec}}$$

Applying Eq. 4 yields: La = 32692.6 Nm.

Step 7: Assuming $C_{DR} = 0.9$ and 40% of the wing span are selected for the drag moment arm:

$$y_D = 0.4\frac{b}{2} = 0.4\times\frac{14.49}{2} = \frac{2.898}{s}$$

Applying Eq. 6 yields: $P_{ss} = 8.937$ rad/sec.

Step 8: Applying Eq. 7 yields: $\varphi_1 = 149.32$ rad = 8584.14°.

Step 9: The calculated φ_1 is greater than the desired bank angle (i.e., 30°). So, applying Eq. 10 yields: $P^* = 0.267$ rad/sec^2 and applying Eq. 11 yields: $t_2 = 1.982$ sec.

Step 10: From the previous step, the calculated t_2 is longer than the required (1.8 sec). Therefore, the designed aileron does not match the requirements. To achieve the desired aileron requirements, either the aileron chord or span is enlarged or the maximum aileron deflection is increased. Since, the aileron chord to wing chord ratio and the maximum aileron deflection cannot changed because of the rear spar location and aileron stall concerns, so, it is better to enlarge the aileron span.

Step 11: Because the outboard location of the flap is at 60% of the wing span, so, it is suggested to set the aileron inboard location at 61%. Thus:

$$y_i = 0.61\frac{b}{2} = 0.61\times\frac{14.49}{2} = 4.42 \text{ m}$$

while, the aileron outboard location will not altered (i.e., $y_0 = 6.883$ m).

Hence:
$C_{l_{\delta_a}} = 0.08$, $L_a = 42429.6$ Nm, $P_{ss} = 10.18$ rad/sec, $\varphi_1 = 158.74$ rad $P^* = 0.327$ rad/s^2 and $t_2 = 1.791$ sec.

CONCLUSION

A programmable algorithm for aileron sizing has been presented for use in preliminary aircraft design software. For fresh engineers and aeronautical students, this algorithm is useful to enhance their knowledge, understanding and analyzing studies. The study introduced the necessary formulae as a guide to size the aileron to achieve the roll control requirements with a solved example as an instructional use, step by step to explain the application of the algorithm.

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