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Research paper

Employing control surface model in preliminary aircraft design software

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Abstract

Many aircraft design software packages are available in the market. Some of them are intended for preliminary design phase. These packages investigate the aircraft stability and controllability through the stability model to get the dimensional and non-dimensional derivatives. For students and fresh engineers, these derivatives are ambiguous and do not give a well-defined consideration about the influence of the control surface sizing on them.Therefore, adding the control surface model to preliminary software will assist, enhance, and improve students' knowledge, sympathy, and investigating studies. This paper presents the control surface model for use in preliminary aircraft design software. The model consists of three sub-models. Each sub-model is involved to perform the sizing of one of the primary conventional control surfaces. The aileron represents the first sub-model. The elevator represents the second sub-model, while the rudder represents the third sub-model. A flowchart for each sub-model is provided.

Keywords: *Aircraft Design Software, Control Surfaces, Aircraft Sizing Algorithms, Aircraft Stability And Control.*

1. Introduction

Stability and controllability are the most significant requirements for safe flight. These two purposes will affect the sizing of the control surfaces and generate a diversity of design restrictions. Control surfaces can roughly be categorized into two classes: conventional and non-conventional. Conventional control surfaces can also be classified into two categories: primary and secondary surfaces. The primary surfaces include aileron, elevator, and rudder. These are employed for lateral, longitudinal, and directional control, respectively, and also have a high impact on lateral, longitudinal, and directional trim of the aircraft [1].
As a general rule, Dave Wyatt from Lockheed-Ft. Worth said that: "*Having a Process to properly size the control power is essential to, optimize the configuration*" [2]. Therefore, the designer's aim at sizing the control surfaces is to offer enough control power to satisfy the military manoeuvre prerequisites, MIL-STD [3] [4] or civil certification rules, FAR 23 & 25 [5] [6]. In the design development, a set of parameters called control derivatives are extensively employed in the sizing of the control surfaces. Basically, these derivatives represent the rate of change of moments due to a control surface deflection. As the superior the control derivative, the extra influence is the related control surface. For instance, the most significant non-dimensional control derivatives are; the pitching moment due to elevator deflection derivative ($Cm_{\delta e}$), the rolling moment due to aileron deflection derivative ($Cl_{\delta a}$), and the yawing moment due to rudder deflection derivative ($Cn_{\delta n}$). Their unit is (*1/rad*) [7]. Achieving a successful design, it is significant to consider the controllability of the candidate designs early through the preliminary design phase. This paper presents the control surface model for use in preliminary aircraft design software. This model consists of three sub-models. Each sub-model is involved to perform the sizing of one of the primary control surfaces. The aileron represents the first sub-model. The elevator represents the second sub-model, while the rudder represents the third sub-model.

2. Related works

Looking inside the existing aircraft design packages, all of them include models such as: geometry, weight, cg locations, aerodynamics, performance, cost, and stability. Unfortunately, none of them had investigated the control surfaces sizing in detail. For instance, they presented the control surfaces in the conceptual design phase only as an input variables such as their chords, inboard and outboard spans, and the maximum deflections. However, passing quickly over the most popular software, we start with Roskam's software (AAA) [8]. The software is a programmed translation of his textbook [9]. The second one is released by Raymer in 1996 called (ADS) [10] which is established also as in his book [11]. Furthermore, the broad package entitled CEASIOM [12] was first released in 2008 and up to now in continuous development. Lastly, Nicolosi announced his software package called (ADAS) [13] in 2011.
All these packages investigate the aircraft stability and controllability through the stability model to get the dimensional and non-dimensional derivatives. For expert engineers, these derivatives are well representation to draw a clear picture of the aircraft stability and controllability. But for students and fresh engineers, these derivatives are ambiguous and do not give a well-defined consideration about the influence of the control surface sizing on them. Therefore, adding the control surface model to preliminary software will assist, enhance, and improve students' knowledge, sympathy, and investigating studies. Classically, the control surface sizing is performed in the detail phase of the aircraft design process.

3. Control surfaces sizing principles

In general, two methodologies are usually employed to perform the control surfaces sizing. The first methodology is so called "semi-empirical" method, which is based on a chart to achieve all the necessary contributions for the calculation [9]. The second methodology is called one strip integration. It is originated on the fundamentals of aerodynamic analysis [14]. It is more accurate than the first methodology because of its assumptions [15]. Hence, it is applied here to implement the control surface sizing sub-models. Fig. 1 is extensively employed in the sizing of flaps and control surfaces. It represents the surface angle of attack effectiveness with respect to its chord ratio. The surface effectiveness (τ_s) can mathematically be evaluated using the following formula:

$$\tau_s = 1.129 \times \left(\frac{C_s}{C}\right)^{0.4044} - 0.1772$$

Where: $\frac{C_s}{C}$ is the ratio of the surface chord to the lifting chord.

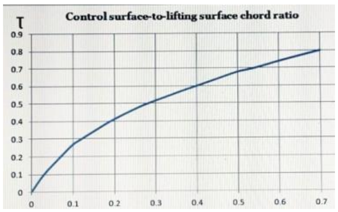

Fig. 1: A general representation of the control surface effectiveness [21]

However, the process of the control surfaces sizing starts generally with the trade-off study and terminates with optimisation, to create a well-defined line between stability and controllability prerequisites. The sizing process begins by selecting the configuration of the control surfaces in the conceptual design phase. This first step is actually performed as a part of aircraft configuration (such as wing, tail,and engine), performance, cost, controllability, and operational prerequisites. The output of the first stage is to establish the forward and the aft locations of the aircraft centre of gravity. Note that the surfaces related to pitch, roll, and yaw control, are sizing in parallel. Next, the probability of cross-coupling occurrence between any two of the control surfaces is investigated to certify that there is not any reversal of the control characteristics in other areas of the aircraft. If the investigation of the cross-coupling shows an unacceptable influence of one of the control surfaces, then, resizing one or more control surfaces to answer the problem.

Aileron sizing sub-model

Aircraft aileron is defined as a clear-cut flap, positioned in the back of the outboard of the wing. Right aileron and left aileron are working together up/down simultaneously and differentially to create the required rolling moment. The amount of this moment relies on aileron's: size, deflection, and distance from the center line of the fuselage. Therefore, the fundamental task of the aileron is primarily in the roll control, but it has an effect in the yaw control, as well [16]. The roll control is directed basically all through the roll rate (*P*). Hence, in aileron sizing, a careful consideration must be taken in a way to minimize the control forces as possible to minimize the actuating size and cost.
On the other hand, there are a number of constraints that limit any engineering design problem. For aileron sizing, six constraints should take into consideration; aileron reversal, adverse yaw, flap, wing rear spar, aileron stall, and wing tip. For instance, aileron reversal, harmfully has some bearing on the effectiveness of the aileron. This phenomenon happened usually when the aircraft flies near its maximum speed. In general, there is no actual structure is perfectly unbending and has static and dynamic elasticity. Therefore, the process of wing structural design should investigate the effect of this aero-elasticity of the aileron deflection. Adverse yaw occurs when the aircraft yaws in the opposite direction to the direction of the wanted turn. This makes the aircraft to slip or skid due to the uncoordinated aircraft turn. To avoid the adverse yaw, one solution is to employ concurrent aileron and rudder deflection, or on the one side aileron up-deflection is greater than the other side aileron down-deflection. Another solution is by employing a spoiler or a Frise aileron. Fig. 2 shows the flowchart of the aileron sizing algorithm. Primarily, four input variables related to aileron are chosen or estimated based on the configuration of the wing in the conceptual design phase, which are; area, span, chord, and maximum deflection. In general, the typical values of these variables for transport aircraft are: area (Sa/S) = 0.05-0.1, span (b_a/b) = 0.2-0.3, chord (Ca/C) = 0.15-0.25, and maximum deflection (±*30 deg.*). Also, it is necessary to establish the time required to bank the aircraft based on landing flight phase as the speed is the lowest [7]. This time is extracted from FAR regulations [5] [6] for transport aircraft or from MIL-STD [3] [4] for military aircraft.

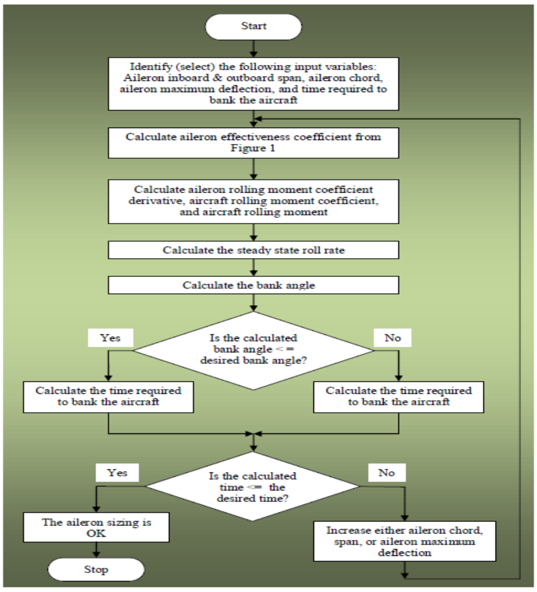

Fig. 2: The flowchart of the aileron sizing algorithm

Elevator sizing sub-model

For conventional aircraft, the classical approach to achieve the longitudinal control is by providing an extra force on the horizontal tail [18]. Basically, this is managed by the deflection of the elevator and also by the engine throttle. It is directed through the pitch rate and in turn, the angular acceleration, along the aircraft y-axis. Therefore, the elevator can be classified as a pitch control tool. It should be noted that the lateral directional control is not coupled with the longitudinal control, and hence, the process of the elevator sizing is not associated with the process of the rudder sizing [16]. So, the design process of the elevator is easier. However, three major issues must be in consideration during the elevator sizing process. These issues are related to elevator; effectiveness, hinge moment, and aerodynamic and mass balancing [19]. In contrast, the longitudinal control prerequisites at the rotation of the takeoff stage are distinguished as: the period of the takeoff rotation at a predefined pitch rate must be lower than a predefined period of time. Based on the second law of Newton, this period is carried out in terms of the aircraft angular acceleration at the point of the rotation of the main gear [7]. For instance, the takeoff period of the transport aircraft is in the range of 3-5 seconds with angular acceleration of 4-6 deg/s^2 and the aircraft centre of gravity is located at the most forward position.

Fig. 3 (part 1 & 2) shows the flowchart of the elevator sizing algorithm. Similar to aileron sizing algorithm, four input variables related to elevator are chosen or estimated initially based on the configuration of the horizontal tail in the conceptual design phase, which are; area, span, chord, and maximum deflection. In general, the typical values of these variables for transport aircraft are: area (S_e/S_h) = 0.15-0.4, span (b_e/b_h) = 0.8-1.0, chord (C_e/C_h) = 0.26-0.34, and maximum deflection (±*25 deg.*) [20].

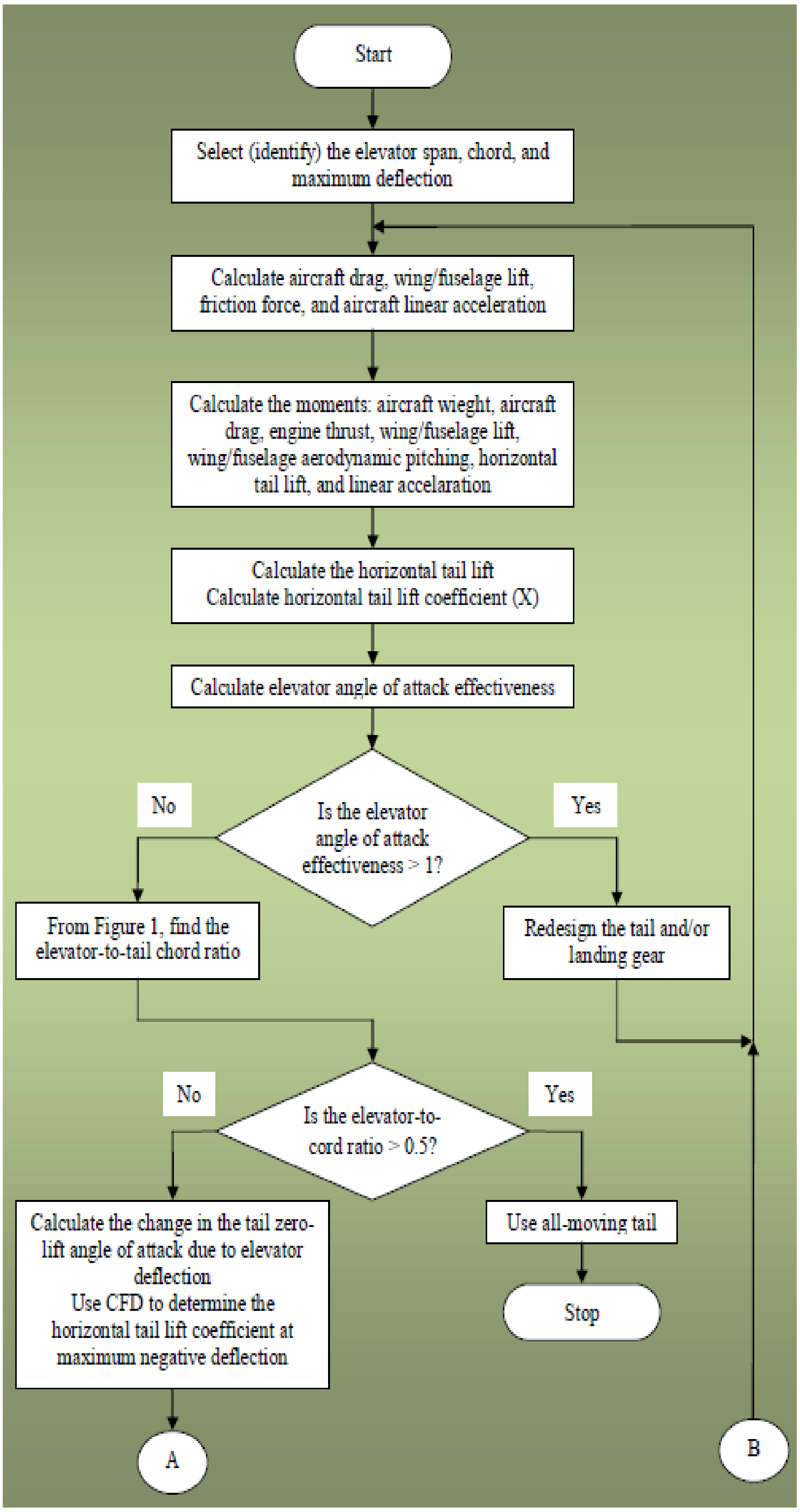

Fig. 3: (part 1 of 2) The flowchart of the elevator sizing algorithm

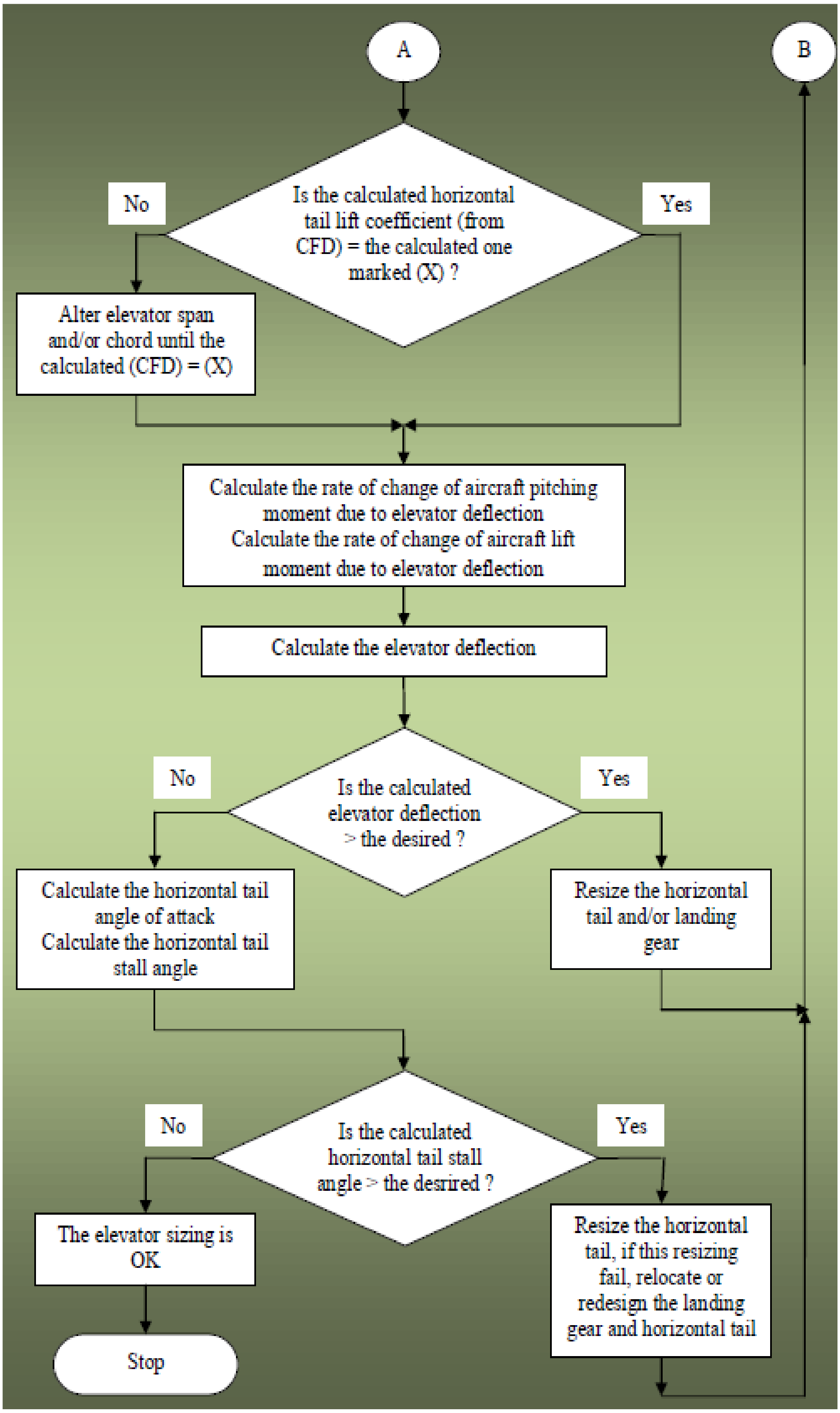

Fig. 3: (part 2 of 2) The flowchart of the elevator sizing algorithm

Rudder sizing sub-model

As mentioned before, the aircraft rudder is sorted as a primary control surface. It is employed to provide a directional control. A yawing moment is generated due to the side force created by the rudder deflection. This moment is along the z-axis of the aircraft and around the aircraft cg. Directional control and trim are the two rudder's essential tasks. Both are managed via the yaw rate and the maximum deflection of the rudder. In the rudder sizing process, FAA [20] and MIL-STD [3] [4] regulations, for civil and military aircraft consequently, must be satisfied. Also, it is better to note that there is an interference between rudder and aileron and commonly working concurrently, and in turn, there is a coupled between directional dynamics and lateral dynamics. Therefore, it is recommended to size both rudder and aileron simultaneously.

From the other side, the rudder is a distance control tool which is similar to the elevator, while the aileron is a speed control tool. Thus, the sizing elementals of elevator and rudder are the same, but usually, the elevator sizing is much easier [1].

However, the aircraft rudder is served to solve six major conditions which are: turn coordinate, crosswind landing, asymmetric thrust balancing, spin recovery, adverse yaw, and adjustment of a glide slope. According to the aircraft configuration and its flight, one or more of these conditions plays the most considerable and crucial task. More specifically, multi-engine aircraft frequently have asymmetric thrust balancing due to one engine fail, which defined as the most critical condition, in addition to the crosswind landing. In single-engine aircraft, the critical condition is the crosswind landing.

In this paper, the considerable and crucial conditions for the conventional aircraft are the crosswind landing and the asymmetric thrust balancing. Fig. 4 shows the flowchart of the rudder sizing algorithm for the crosswind landing prerequisites, whereas, Fig. 5 shows the flowchart of the rudder sizing algorithm for the asymmetric thrust balancing prerequisites. The first step in both Figures is to select/estimate the vertical tail geometry as well as the rudder input variables, which are; chord, span , area, and maximum deflection. Typical values for conventional aircraft are: chord (C_r/C_v) = 0.15-0.4, span (b_r/b_v) = 0.7-1.0, area (S_r/S_v) = 0.15-0.3, and maximum deflection (±*30 deg.*) [1].

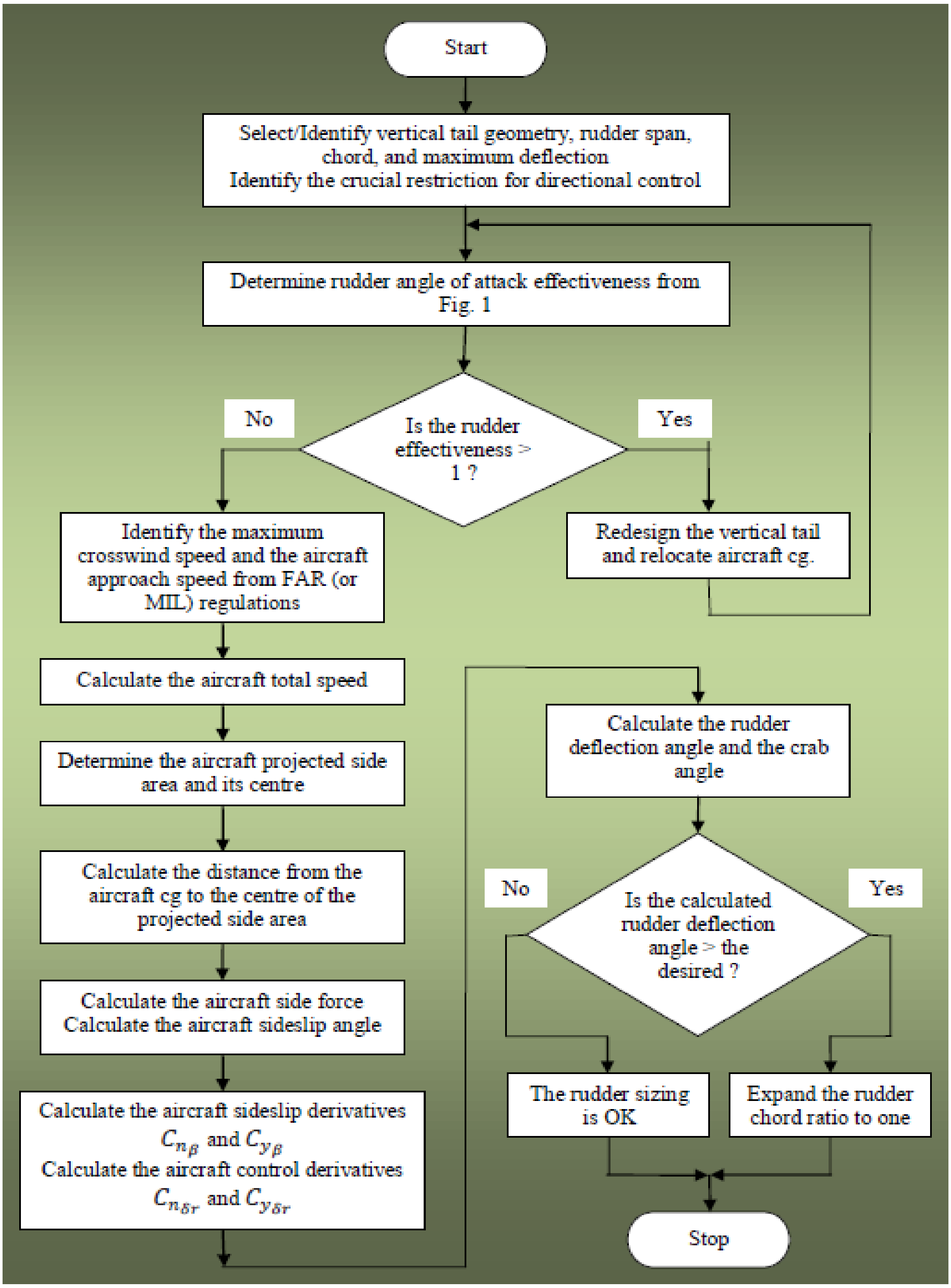

Fig. 4: The flowchart of the rudder sizing algorithm (the crosswind landing prerequisites)

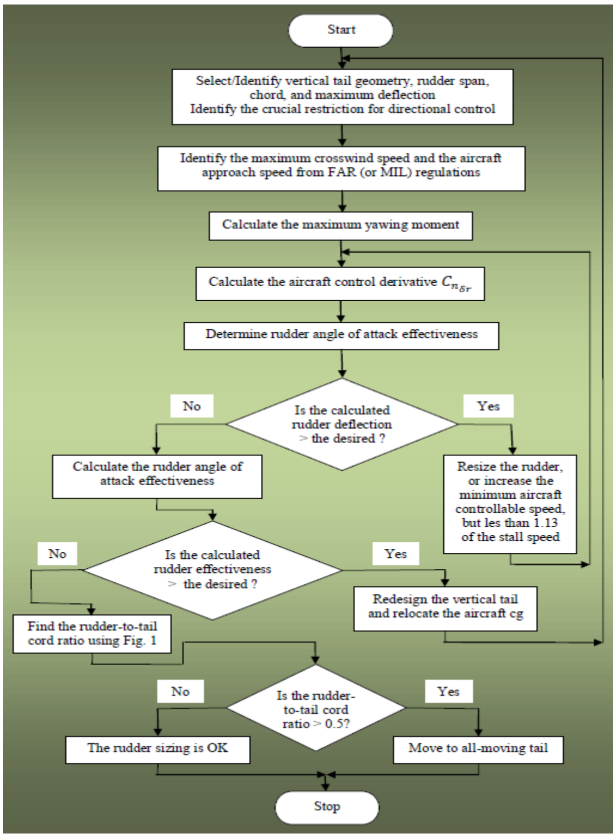

Fig. 5: The flowchart of the rudder sizing algorithm (the asymmetric thrust prerequisites)

4. Conclusion

The paper introduced the development of a control surface sizing model. It consists of three sub-models, which represent the primary control surfaces. The aileron represents the first sub-model. The elevator represents the second sub-model, while the rudder represents the third sub-model. The model, which is intended for aeronautical students and fresh engineers, is employed to assist, enhance, and improve their knowledge, sympathy, and investigating studies. A flowchart for each sub-model is developed.

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