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Tecnología e Innovación

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Estudio de las cualidades de vuelo y manejo de una aeronave tipo planeador para instrucción*

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Resumen

El objetivo de este artículo es hacer un estudio de las cualidades de vuelo y manejo de una aeronave tipo planeador para propósitos de instrucción. Para el desarrollo, un modelo dinámico es propuesto en pequeñas perturbaciones a fin de calcular el estado de equilibrio longitudinal en condiciones de vuelo subsónico. Con los datos del equilibrio longitudinal, fueron mostradas las ecuaciones de movimiento linealizadas para hallar los valores numéricos dimensionales y adimensionales de las derivadas de estabilidad y control aerodinámico a lo largo de los ejes longitudinal y lateral-direccional. Seguido, las funciones de transferencia características por perturbaciones y aceleraciones para la velocidad de mejor relación de planeo, son encontradas para calcular las respuestas de la aeronave en controles aerodinámicos. Finalmente, las respuestas de estabilidad estática y dinámica fueron obtenidas, y así, las cualidades de vuelo y manejo fueron analizadas de acuerdo a los requerimientos estandarizados. Los resultados obtenidos son presentados a partir de coeficientes aerodinámicos, gráficas de Matlab® (Paso, impulso, rampa, diagrama de Bode y lugar de raíces), modos de estabilidad, curva de pendiente de sustentación de Rudder, punto neutro de controles fijos y el margen máximo de estabilidad permitido. De esta forma, el cálculo de estabilidad, los factores de influencia y sus efectos en las cualidades de vuelo y manejo de una aeronave tipo planeador fueron demostradas.

Palabras clave:

cualidades de vuelo y manejo, dinámica, estabilidad, estática, modos de estabilidad.

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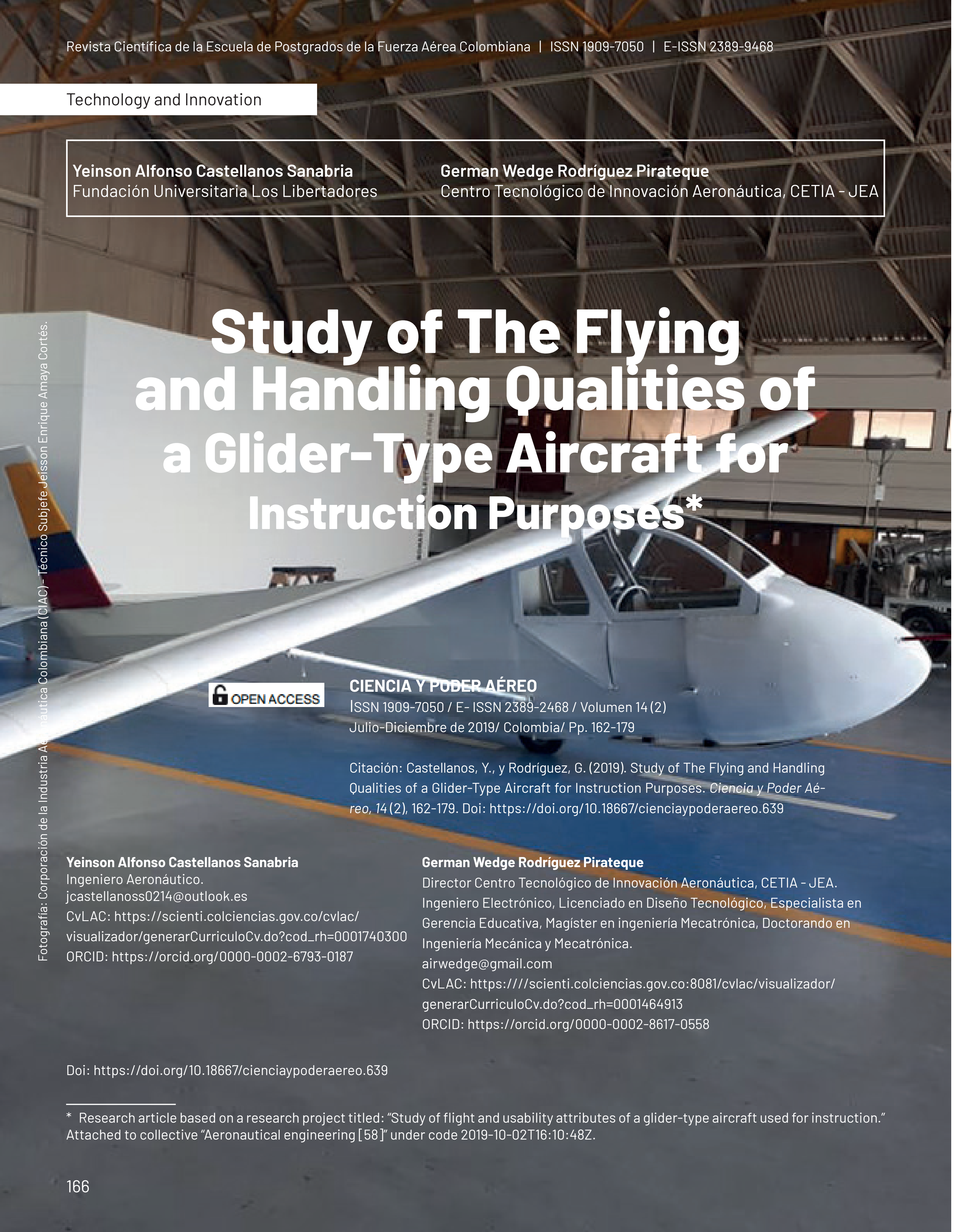
Resumo

O objetivo deste trabalho é fazer um estudo das qualidades de voo e manejo de um avião tipo planador para a instrução. Para o desenvolvimento, propomos um modelo dinâmico com pequenas perturbações para calcular o estado de compensação longitudinal em condições de voo subsônico. Com os dados de recorte longitudinal, mostramos as equações de movimento alinhadas para encontrar os valores numéricos adimensionais e dimensionais da estabilidade aerodinâmica e as derivadas de controle ao longo dos eixos direcionais longitudinal e lateral. A seguir, encontramos as características das funções de transferência por perturbações e acelerações à melhor velocidade de relação de planar para calcular as respostas da aeronave nos controles aerodinâmicos. Finalmente, obtivemos as respostas de estabilidade estática e dinâmica; e assim, analisamos as qualidades de voo e manejo de acordo com os requisitos padronizados. Os resultados obtidos se apresentam a partir de coeficientes aerodinâmicos, gráficos da MatLab® (passo, impulso, rampa, diagrama de Bode e lugar da raiz), os modos de estabilidade, a pendente da curva de elevação do volante, o ponto neutro fixo de controle e a margem de estabilidade máxima permitida. Desta forma, mostramos o cálculo da estabilidade, os fatores que influem e seus efeitos sobre as qualidades de voo e manejo de um avião tipo planador.

Palavras-chave:

dinâmica, qualidades de voo e manejo, estabilidade, modos de estabilidade, estática.



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Abstract

The goal of this paper is to conduct a study on the flying and handling qualities of a glider-type aircraft used for instruction purposes. To develop this project, we propose a dynamic model where we introduce small disturbances to calculate the longitudinal trim state in subsonic flight conditions. Using longitudinal trim data, we showed the linearized equations of motion to find the dimensionless and dimensional numerical values for aerodynamic stability and control derivatives along the longitudinal and lateral-directional axes. After that, we found the characteristic transfer functions using disturbances and accelerations for the sake of the best glide ratio speed, in order to calculate the aircraft responses in aerodynamic controls. Finally, we got the static and dynamic stability responses; and so, we analyzed the flying and handling qualities according to the standardized requirements. The results obtained are shown using aerodynamics coefficients, MatLab® graphs (step, impulse, ramp, Bode diagram and Root place), the stability modes, the rudder lift curve slope, the control fixed neutral point and the maximum permissible stability margin. In this way, we showed the calculation of stability, influencing factors and its effects on the flying and handling qualities of a glider-type aircraft.

Key Words:

Dynamics, Flying and Handling Qualities, Stability, Stability Modes, Static.

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Introduction

The dynamic and static stability characterize the flight behavior of aircraft. Although each one is usually studied separately, they must be studied together, where static stability is the description of the tendency to orient itself to its initial equilibrium condition due to a disturbance; and the dynamic stability is the description of the transcendence of a movement involved in the recovery of equilibrium due to a disturbance (Cook, 2012). For aircraft, is important to have both types of stability in order to be safe in a flight mission. However, the stability degree is determined by the controls effectiveness and the mission for which the aircraft was designed, allowing to qualify them by the flying and handling qualities standards.

The flying and handling qualities standards are technical requirements promulgated by the authorities for aircraft and their operation, encompassing airworthiness, operations, maintenance and crew requirements, providing a safety level in the limitations of the aircraft capabilities. Its content is consigned in MIL-STD-1797A (Standard, 1990), MIL-F-8785C (Holmberg J, Leonard J, King D, Cotting M, 2008) and Av.P.970 (Reeves, 1970) standards, which collect the knowledge obtained during decades of theoretical study and experimentation on land, flight and simulators (Tierno M, Cortés M, Márquez C, 2012).

The effectiveness of an aerial maneuver is given by the structural and aerodynamic configuration with the performance and power parameters, which are reduced by external and internal factors inducing high pressures to the pilot and the aircraft with negative responses in psychology, physiology and ergonomics, impairing the attitude to maintain a flight path.

Through engineering, flying and handling qualities allow the certification of any aircraft, therefore, knowing and interpreting them is useful in each of the design phases. With this article, progress can be made on the aircraft stability studies on linear behaviors with inputs and outputs by aerodynamic controls, as a support to advance in future studies with non-linear responses allowing developments in the design, manufacture and certification to the aeronautical sector.

This study was made for the glider-type aircraft *Schweizer SGU 2-22*, an American two-seater aircraft. Since the acquisition of the technical and geometric data, with the permissible speeds range, an aerodynamic analysis in *XFLR5*® was made to create a database with geometrical and aerodynamic information, and so, exemplification of a dynamic model in *MatLab*® was possible to calculate the trim conditions, aerodynamic stability and control derivatives, transfer functions, responses to controls by perturbation and acceleration variables, and the longitudinal and lateral-directional oscillation modes from a straight and level flight state were found.

In this order, the results and conclusions are supported by the *step*, *impulse* and *ramp* graphs in disturbance inputs, *Bode* diagrams and root place diagrams by disturbance variables. Through this, we want to publish a study model, under minimum flight conditions, to understand how the stability characteristics are determined and how they influence the flying and handling qualities, exposing them as a regulatory technical standard with its direct application to make policies aimed at models and methodologies to analyze the characteristics of stability and maneuverability in flying objects, seeking to contribute to the development of the national and international aerospace and the aeronautic industry.

After this introduction section concerning the dynamic and static concept, its regulatory standard and justification, the methodology section presents the type of methodology used and its application in the work phases chosen, such as trim conditions calculation, responses to aerodynamic controls and stability responses. Next, the results section displays the trim condition, the responses to controls by perturbations and accelerations variables, and the static and dynamic stability responses; all this, along the longitudinal and lateral-directional axes. Finally, the discussion and conclusion sections are presented with the main considerations regarding the execution of the general objective "to do a study of the flying and handling qualities of a glider-type aircraft for instruction purposes" and their specific objectives regarding a proposal of a dynamic model to calculate the trim condition in subsonic flight conditions; determine the aerodynamic stability and control derivatives along the longitudinal and lateral-directional axes to calculate the responses to aerodynamic controls; and finding the characteristic oscillation modes along the longitudinal and lateral-directional axes to make an analysis according to the flying and handling qualities requirements.

Methodology

This experimental study was made with a hypothetical-deductive model in a descriptive research, divided in three phases of work:

First phase: Trim conditions calculation

Data Base

From the *Schweizer SGU 2-22* glider, data collection was performed through the approved technical documentation such as: certificate type G-18 approved by FAA (Department of Transportation FAA, 2007), maintenance manual approved by Schweizer Aircraft Corporation (S. A. Corporation,1946) and the specialist magazine *Sailplanes by Schweizer History* written by *Ernest Schweizer* (Simons & Schweizer, 1998). Following this, the weight estimation, balance, inertial and load factor calculations were done according to the book *Aircraft design: A systems engineering approach* by *Mohammad H. Sadraey* (Sadraey, 2012) which is a reference to *Airplane design* by *Jan Roskam* (Roskam, 1985) book. With the permissible speeds margin calculated in the *v-n* diagram (Figure 1), an aerodynamic analysis was done in *XFLR5*® to make a geometric and aerodynamic database (Table 1) switching Reynolds and Mach numbers, where the incidence was in the range of -20º < α < 20º by the main wing airfoil section, tail plane airfoil section and fin airfoil section (UIUC Department of Aerospace Engineering, 2019).

Table 1. Aerodynamic database items (Cook, 2012)

α_{w_0}	Zero lift incidence of wing
a_w	Wing or wing–body lift curve slope
d_α	Downwash
C_{D_0}	Wing zero lift drag coefficient
K_w	Wing induced drag factor
e_w	Wing Oswald efficiency factor
C_{m_0}	Pitching moment coefficient about wing
$C_{D_{0_T}}$	Tail plane zero lift drag coefficient
a_0	Tail plane zero incidence lift coefficient
a_{1_T}	Tail plane lift curve slope
a_{2_η}	Elevator lift curve slope
e_T	Tail plane Oswald efficiency factor
K_T	Tail plane induced drag factor
a_{1_F}	Fin lift curve slope
$\frac{dC_{D_T}}{d\alpha_T}$	Tail plane drag curve slope
$\frac{dC_D}{d\alpha}$	Wing or wing–body drag curve slope
a_{2_ξ}	Aileron lift curve slope
$\frac{dC_D}{d\xi}$	Aileron drag curve slope
a_{2_ζ}	Rudder lift curve slope

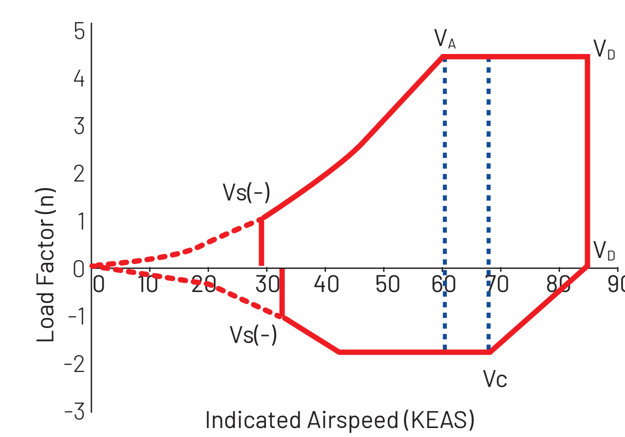

Figure 1. *Schweizer SGU 2-22* Load factor

Trim conditions calculation

The trim state defined the initial condition on which the glider dynamics was studied from the primary control surfaces (ailerons, elevator and rudder). The object of trimming was to bring the forces and moments acting into a state of equilibrium where the axial, normal and side forces, and the roll, pitch and yaw moments are all zero expressed as the requirement for the lift to equal the weight and the thrust to equal the drag (Roskam, 1998). The lateral-directional forces and moments were assumed to remain in equilibrium, and the problem was reduced to the establishment of longitudinal equilibrium because the glider is symmetric on the *OY* axis. Thus, the reference axis system was body axes which defined the plane of symmetry on the *OXZ* axis, with the origin *O* located at the gravity center under the contributions for the wing-tail aerodynamic ratio including the angle of incidence of the wing (α_{w_r}) and the downwash at zero lift (ε_0), Figure 2.

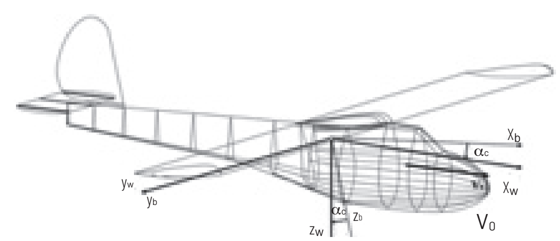

Figure 2. Body axes system

In order to calculate the trim condition for each maneuver velocity, it was convenient to assume a straight flight. For a glider, mass, a gravity center position, an altitude and an airspeed, symmetric trim was described by the aerodynamic operating condition, namely, angle of attack, thrust, pitch attitude, elevator angle and flight path angle, Table 2.

Table 2. Flight condition

Weight	3916.53	N
Mass	399.24	Kg
Altitude	1080 3543	m ft
γ	0	
α_e	0	
$X_{c.g}$	2.203	m
K_n	0.188	
h_n	0.444	

Using a set of equations found in chapter 3 "Static equilibrium and trim" from the bibliographic source (Cook, 2012), we provided the trim condition, where it was assumed that the elevator trim tab angle is zero and that glider trim was determined by the elevator angle to trim η_e. It is assumed that $a_0 = 0$, where the tail plane airfoil section is symmetrical.

Thus, there was a variation from the stall speed and maximum permissible speed, at around 15.1994 *m/s*, to 40.2336 *m/s* in 1 *m/s* increments.

Mathematical model

With the body axes system fixed (Figure 2), through to linear quantities transformation (Euler angles) the linear velocities and accelerations values were resolved as from an initial condition to the perturbed state, where roll was (ϕ) pitch was (ψ) and yaw was (ψ). Thus, equilibrium velocities, components and the angular rates transformations from an airspeed input were calculated (V0) with equations (2.15) and (2.21) from the bibliographic source (Cook, 2012).

With these items, our mathematical model is about maneuvering angles and airspeed inputs to define the initial condition analysis from MatLab®.

Second phase: Responses to aerodynamic controls

Aerodynamic stability and control derivatives

The aerodynamic stability and control derivatives were calculated in Dimensional, Dimensionless and Concise format on the longitudinal and lateral-directional axes with the help of the aerodynamic and geometric database, trim condition and mathematical model. Hence, a solution and linearization for the equations of motion to determine the transfer functions for each axis were necessary. The equations of motion were in terms of aerodynamic stability and control derivatives, equations (4.42) and (4.47) from the bibliographic source (Cook, 2012), those terms were solved to subsonic conditions in chapter 13 "Aerodynamic stability and control derivatives" from the bibliographic source (Cook, 2012).

Next, with the stall speed and the maximum permissible speed range, the derivatives calculation was made for straight and level flight in zero degrees in roll, pitch and yaw angles. Next, the results are shown at the best glide ratio speed 21.0109 *m/s* in British notation and North American notation.

Table 3. Dimensionless longitudinal aerodynamic stability and control derivatives

$C_{x_u} \equiv X_u = -0.0378$	$C_{z_u} \equiv Z_u = -1.034$
$C_{x_\alpha} \equiv X_w = 0.488$	$C_{z_\alpha} \equiv Z_w = -5.8117$
$C_{x_q} \equiv 2X_q = -0.0474$	$C_{z_q} \equiv 2Z_q = -1.9504$
$C_{x_\alpha} \equiv 2X_{\dot{w}} = -0.0201$	$C_{z_\alpha} \equiv 2Z_{\dot{w}} = -0.8267$
$C_{x_{\delta_e}} \equiv X_\eta = -0.0106$	$C_{z_{\delta_e}} \equiv Z_\eta = -0.4351$
$C_{m_u} \equiv M_u = 0.00097$	$C_{m_q} \doteq 2M_q = -6.53$
$C_{m_\alpha} \equiv M_w = -1.089$	$C_{m_\alpha} \equiv 2M_w = -2.769$
$C_{m_{\delta_e}} \equiv M_\eta = -1.4575$	

Table 4. Dimensionless lateral-directional aerodynamic stability and control derivatives

$C_{y_v} \equiv Y_v = -0.3713$	$C_{l_v} \equiv L_v = -0.1195$
$C_{y_p} \equiv 2Y_p = -0.0535$	$C_{l_p} \equiv 2L_p = -0.4958$
$C_{y_r} \equiv 2Y_r = 0.1303$	$C_{l_r} \equiv 2L_r = 0.1027$
$C_{y_{\delta_A}} \equiv Y_\xi = 0$	$C_{l_{\delta_A}} \equiv L_\xi = -0.4056$
$C_{y_{\delta_R}} \equiv Y_\zeta = 0.2386$	$C_{l_{\delta_R}} \equiv L_\zeta = 0.0269$
$C_{n_v} \equiv N_v = 0.1303$	$C_{n_p} \equiv 2N_p = -0.0417$
$C_{n_{\delta_A}} \equiv Y_\xi = -0.0061$	$C_{n_r} \equiv 2N_r = -0.0417$
$C_{n_{\delta_R}} \equiv Y_\zeta = -0.0837$	

Table 5. Dimensional concise longitudinal aerodynamic stability derivatives

$x_u = -0.021\ ^1/_s$	$z_u = -0.57\ ^1/_s$
$m_u = -0.032\ ^1/_s$	$x_w = -0.281\ ^1/_s$
$z_w = -3.201\ ^1/_s$	$m_w = -0.126\ ^1/_s$
$x_q = -0.0567\ ^m/_s$	$z_q = 18.679\ ^m/_s$
$m_q = -3.877\ ^1/_s$	$x_\theta = -9.81\ ^m/_{s^2}$
$z_\theta = 0\ ^m/_{s^2}$	$m_\theta = 0\ ^1/_{s^2}$
$x_\eta = -0.122\ ^m/_{s^2}$	$z_\eta = -5.036\ ^m/_{s^2}$
$m_\eta = -8.374\ ^1/_{s^2}$	

Table 6. Dimensional concise lateral-directional aerodynamic stability derivatives

$y_v = -0.2115\ ^1/_s$	$l_v = -0.2111\ ^1/_{ms}$
$n_v = -0.1504\ ^1/_{ms}$	$y_p = -0.3996\ ^m/_s$
$l_p = -10.9801\ ^1/_s$	$n_v = -0.1768\ ^1/_s$
$y_r = -20.0383\ ^m/_s$	$l_r = -2.3234\ ^1/_s$
$n_r = -0.7905\ ^1/_s$	$y_\phi = 9.81\ ^m/_{s^2}$
$l_\phi = 0\ ^1/_{s^2}$	$n_\phi = 0\ ^1/_{s^2}$
$y_\psi = 0\ ^m/_{s^2}$	$l_\psi = 0\ ^1/_{s^2}$
$n_\psi = 0\ ^1/_{s^2}$	$y_\xi = 0\ ^m/_{s^2}$
$l_\xi = 14.438\ ^1/_{s^2}$	$n_\xi = 0.4113\ ^1/_{s^2}$
$y_\zeta = 2.8559\ ^m/_{s^2}$	$l_\zeta = 1.0732\ ^1/_{s^2}$
$n_\zeta = -1.9621\ ^1/_{s^2}$	

Transfers functions

To give solutions to the equations of motion, Laplace transform was applied to obtain a description in the mathematical and graphical form of all the responses of aerodynamic controls with respect to the input data in angles and maneuver speeds. The solution of the equations of motion was governed by Cramer's rule. Thus, replacing the mathematical solutions of the aerodynamic stability and control derivatives, Cramer's rule was applied to the matrix format of the equations of motion (Kuo & Golnaraghi, 1995). Consequently, we obtained transfers functions in aerodynamic controls given by a common denominator polynomial and the numerator polynomials by each disturbance variable.

Longitudinal transfers functions:

Elevator

$$\frac{N_\eta^u}{\Delta_{(s)}} = \frac{-0.122s^3 - 1.807s^2 + 32.3s + 256.8}{s^4 + 7.1s^3 + 15.08s^2 + 1.091s + 1.73}\ ^m/_s$$

$$\frac{N_\eta^w(s)}{\Delta_{(s)}} = \frac{-5.036s^3 - 167s^2 - 3.788s - 48.44}{s^4 + 7.1s^3 + 15.08s^2 + 1.091s + 1.73}\ ^m/_s \tag{1}$$

$$\frac{N_\eta^\theta(s)}{\Delta_{(s)}} = \frac{-8.375s^2 - 26.36s - 196}{s^4 + 7.1s^3 + 15.08s^2 + 1.091s + 1.73}\ ^\circ$$

$$\frac{N_\eta^\theta(s)}{\Delta_{(s)}} = \frac{-8.375s^3 - 26.36s^2 - 196s}{s^4 + 7.1s^3 + 15.08s^2 + 1.091s + 1.73}\ ^\circ/_s$$

Lateral-directional transfers functions:

Aileron

$$\frac{N_{\xi}^{v}(s)}{\Delta_{(s)}}=\frac{-2.471s^3-279.1s^2-102.6s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7}\,{}^{m}\!/_{s}$$

$$\frac{N_{\zeta}^{\phi}(s)}{\Delta_{(s)}}=\frac{-14.44s^3-13.51s^2-43.97s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7}\,{}^{\circ}$$

$$\frac{N_{\xi}^{p}(s)}{\Delta_{(s)}}=\frac{-14.44s^4-13.51s^3-43.97s^2}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7}\,{}^{\circ}\!/_{s} \qquad (2)$$

$$\frac{N_{\xi}^{\psi}(s)}{\Delta_{(s)}}=\frac{0.4113s^3+7.156s^2+2.328s^2-20.45}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7}\,{}^{\circ}$$

$$\frac{N_{\xi}^{r}(s)}{\Delta_{(s)}}=\frac{0.4113s^4+7.156s^3+2.328s^2-20.45s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{\circ}\!/_{s}$$

Rudder

$$\frac{N_{\xi}^{v}(s)}{\Delta_{(s)}}=\frac{2.856s^4+72.51s^3+473.5s^2-36.4s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{m}\!/_{s}$$

$$\frac{N_{\xi}^{\phi}(s)}{\Delta_{(s)}}=\frac{1.073s^3-4.086s^2-5.329s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{\circ}$$

$$\frac{N_{\xi}^{p}(s)}{\Delta_{(s)}}=\frac{1.073s^4-4.086s^3-5.329s^2}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{\circ}\!/_{s} \qquad (3)$$

$$\frac{N_{\xi}^{\psi}(s)}{\Delta_{(s)}}=\frac{-1.962s^3-21.72s^2+0.325s-2.48}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{\circ}$$

$$\frac{N_{\xi}^{r}(s)}{\Delta_{(s)}}=\frac{-1.962s^4-21.72s^3+0.325s^2-2.48s}{s^5+11.9s^4+14.51s^3+37.9s^2-1.7s}\,{}^{\circ}\!/_{s}$$

Response to controls

By each transfer function, the responses to controls by disturbances and accelerations were calculated, the initial value theorem and final value theorem was used allowing what the initial starting condition is to be known, and the steady state value of the dynamic system by each transfer function, equation (4)(Kuo & Golnaraghi, 1995).

$$f(t)_{t\to\infty}=\lim_{s\to 0}\left(sf(s)\right)$$
$$f(t)_{t\to\infty}=\lim_{s\to\infty}\left(sf(s)\right) \qquad (4)$$

With the responses to controls it was possible to determine the total linear velocity components, equation (2.1), and the rate of change of height due to the perturbation in motion, equation (2.17) in the chapter 2 "Systems of axes notation" from the bibliographic source (Cook, 2012), describing the final state of glider disturbance in a better way.

Third phase: Stability responses

Static stability

The lateral-directional static stability was determined assuming that lift component acts above the *OX* axis on the fin aerodynamic center, mathematically expressed:

$$\frac{dC_L}{d\beta}<0$$
$$\frac{dC_L}{d\beta}=\bar{V}_F\frac{h_F}{l_F}a_{1_F} \qquad (5)$$

In the longitudinal static stability, the range of gravity center position determined the acceptable margins of stability. The aft limit often corresponds with the controls fixed neutral point h_n, whereas the forward limit is determined by the maximum permissible stability margin K_n. Where too much stability can be as hazardous as too little stability, and thus, for each permissible speed by the *v-n* diagram, h_n and K_n had a different value, where those values ensured the glider's and pilot's integrity (Cook, 2012), therefore:

$$K_n=-\left(\left(h-h_0\right)-\bar{V}_T\frac{a_1}{a}\left(1-\frac{d\varepsilon}{d\alpha}\right)\right) \qquad (6)$$

$$h_n=h_0+\bar{V}_T\frac{a_1}{a}\left(1-\frac{d\varepsilon}{d\alpha}\right) \qquad (7)$$

Dynamic stability

Once all the transfer functions were determined, these completely describe the linear dynamic response to a control input identified with the oscillation modes. With the help of the *damp( )* command in *MatLab*® software and chapter 6 and 7 from the bibliographic source (Cook, 2012) for subsonic conditions, the dynamic properties were determined given by the equations 6.2, 6.3, 6.4, 6.5, 7.2, 7.3, 7.4, 7.5, 7.6, 7.7, 7.8 and 7.9:

Flying and handling qualities analysis

From the characteristic oscillation modes on the longitudinal and lateral-directional axes an analysis was performed through the Control Anticipation Parameter (CAP), Routh-Hurwitz stability criterion and the longitudinal and lateral-directional flying qualities requirements.

The control anticipation parameter was determined to know the precise adjustments for the flight path, using the angular pitching acceleration. The system's stability condition was tested with the Routh-Hurwitz criterion, and the stability from the type of airplane and the flight phase (Nelson, 1998) was studied through the flying qualities requirements.

Results

Trim conditions calculation

Table 8. Trim condition data

$V_0\left(\frac{m}{s}\right)$	M_0	η_e	C_L	C_m	C_m	L/D
15.1994	0.044	8.96	0.510	0.019	-0.014	25.8
16.1994	0.047	8.83	0.513	0.019	-0.013	25.9
17.1994	0.050	9.1	0.516	0.019	-0.013	26.1
18.1994	0.053	9.1	0.516	0.019	-0.013	26.2
19.1994	0.056	8.99	0.516	0.019	-0.013	26.3
20.1994	0.059	8.68	0.487	0.018	-0.008	26.6
21.0109	0.061	8.92	0.515	0.019	-0.013	26.5
22.1994	0.065	9.04	0.516	0.019	-0.013	26.6
23.1994	0.068	8.74	0.492	0.018	-0.008	26.9
24.1994	0.071	9.04	0.515	0.019	-0.013	26.8
25.1994	0.074	9.02	0.514	0.019	-0.013	26.9
26.1994	0.076	9.05	0.514	0.019	-0.013	27
27.1994	0.079	9.08	0.515	0.019	-0.013	27.1
28.1994	0.082	9.14	0.515	0.018	-0.013	27.1
29.1994	0.085	9.07	0.515	0.018	-0.013	27.2
30.1994	0.088	9.09	0.516	0.018	-0.012	27.3
31.1994	0.091	8.94	0.516	0.018	-0.012	27.3
32.1994	0.094	9.09	0.517	0.018	-0.012	27.4
33.1994	0.097	9.1	0.519	0.018	-0.012	27.4
34.1994	0.100	9.1	0.521	0.018	-0.012	27.5
35.1994	0.103	9.11	0.518	0.018	-0.012	27.6
36.1994	0.106	9.12	0.516	0.018	-0.013	27.6
37.1994	0.109	9.14	0.517	0.018	-0.012	27.7
38.1994	0.112	9.16	0.518	0.018	-0.012	27.7
39.1994	0.115	9.20	0.517	0.018	-0.013	27.8
40.2336	0.118	8.88	0.491	0.017	-0.007	28.1

Responses to aerodynamic controls

To see the *MatLab*® graphs (*step, impulse and ramp*) about responses to aerodynamic controls, you are invited to read the bibliography source (Castellanos & Rodríguez, 2019) in section 9.2 "Respuestas en control aerodinámicos".

Table 9. Responses to aerodynamic controls by disturbance variables

	Elevator		
	Initial	**Final**	
$u_{(t)}$	$0.0\ {}^{m}/_{s}$	$148.3467\ {}^{m}/_{s}$	Axial velocity
$w_{(t)}$	$0.0\ {}^{m}/_{s}$	$-27.9841\ {}^{m}/_{s}$	Normal velocity
$\theta_{(t)}$	0.0 °	−1.1324 °	Pitch angle
$q_{(t)}$	$0.0\ {}^{\circ}/_{s}$	$0.0\ {}^{\circ}/_{s}$	Pitch rate
	Ailerons		
	Initial	**Final**	
$v_{(t)}$	$0.0\ {}^{m}/_{s}$	$57.3086\ {}^{m}/_{s}$	Lateral velocity
$\phi_{(t)}$	0.0 °	24.5638 °	Roll angle
$p_{(t)}$	$0.0\ {}^{\circ}/_{s}$	$0.0\ {}^{\circ}/_{s}$	Roll rate
$r_{(t)}$	$0.0\ {}^{\circ}/_{s}$	$11.4205\ {}^{\circ}/_{s}$	Yaw rate
	Rudder		
	Initial	**Final**	
$v_{(t)}$	$0.0\ {}^{m}/_{s}$	$20.3318\ {}^{m}/_{s}$	Lateral velocity
$\phi_{(t)}$	0.0 °	2.9767 °	Roll angle
$p_{(t)}$	$0.0\ {}^{\circ}/_{s}$	$0.0\ {}^{\circ}/_{s}$	Roll rate
$\psi_{(t)}$	0.0 °	0.0 °	Yaw angle
$r_{(t)}$	$0.0\ {}^{\circ}/_{s}$	$1.3852\ {}^{\circ}/_{s}$	Yaw rate

Table 10. Responses to aerodynamic controls by accelerations

	Initial	Final	
Elevator			
a_x	$-0.1224\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Axial acceleration
a_y	$0.0\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Lateral acceleration
a_z	$-5.036\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Normal acceleration
Aileron	**Initial**	**Final**	
a_x	$0.0\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Axial acceleration
a_y	$0.0\ ^{m}/_{s^2}$	$239.9556\ ^{m}/_{s^2}$	Lateral acceleration
a_z	$0.0\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Normal acceleration
Rudder	**Initial**	**Final**	
a_x	$0.0\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Axial acceleration
a_y	$2.8559\ ^{m}/_{s^2}$	$29.1039\ ^{m}/_{s^2}$	Lateral acceleration
a_z	$0.0\ ^{m}/_{s^2}$	$0.0\ ^{m}/_{s^2}$	Normal acceleration

		Longitudinal axis		Lateral axis
$V_0\left(\frac{m}{s}\right)$	M_0	K_n	h_n	$\frac{dC_l}{d\beta}$
15.1994	0.044	0.1930	0.4489	-0.0404
16.1994	0.047	0.1880	0.4440	-0.0406
17.1994	0.050	0.1914	0.4473	-0.0408
18.1994	0.053	0.1917	0.4477	-0.0405
19.1994	0.056	0.1890	0.4450	-0.0397
20.1994	0.059	0.1913	0.4473	-0.0408
21.0109	0.061	0.1880	0.4440	-0.0404
22.1994	0.062	0.1900	0.4460	-0.0406
23.1994	0.068	0.1888	0.4447	-0.0405
24.1994	0.071	0.1910	0.4469	-0.0404
25.1994	0.074	0.1909	0.4469	-0.0406
26.1994	0.076	0.1917	0.4476	-0.0409
27.1994	0.079	0.1916	0.4476	-0.0412
28.1994	0.082	0.1934	0.4494	-0.0406
29.1994	0.085	0.1917	0.4476	-0.0408
30.1994	0.088	0.1913	0.4473	-0.0406

Total velocities

$U = 21.0109\ ^{m}/_{s} + 148.3467\ ^{m}/_{s} = 169.357\ ^{m}/_{s}$

$V_\xi = 0\ ^{m}/_{s} + 57.3086\ ^{m}/_{s} = 57.3086\ ^{m}/_{s}$

$V_\zeta = 0\ ^{m}/_{s} + 20.3318\ ^{m}/_{s} = 20.3318\ ^{m}/_{s}$

$W = 0\ ^{m}/_{s} - 27.9841\ ^{m}/_{s} = -27.9841\ ^{m}/_{s}$

Z

$\dot{h}_\xi = 27.98\ ^{m}/_{s}$

$\dot{h}_\zeta = 27.98\ ^{m}/_{s}$

Stability responses

Table 11. Static stability response

		Longitudinal axis		Lateral axis
$V_0\left(\frac{m}{s}\right)$	M_0	K_n	h_n	$\frac{dC_l}{d\beta}$
31.1994	0.091	0.1883	0.4442	-0.0407
32.1994	0.094	0.1902	0.4461	-0.0406
33.1994	0.097	0.1889	0.4448	-0.0407
34.1994	0.100	0.1875	0.4434	-0.0408
35.1994	0.103	0.1904	0.4464	-0.0409
36.1994	0.106	0.1917	0.4477	-0.0411
37.1994	0.109	0.1915	0.4475	-0.0413
38.1994	0.112	0.1914	0.4474	-0.0414
39.1994	0.115	0.1928	0.4487	-0.0409
40.2336	0.118	0.1926	0.4486	-0.0408

To see the *MatLab*® graphs (*Bode diagram* and *Root place*), you are invited to read the bibliography source (Castellanos & Rodríguez, 2019) in section 9.3 "Respuestas de estabilidad estática y dinámica"

Table 12. Dynamic stability by elevator

u	k	q	θ
$k_u = -0.12$	$k_w = -5.03$	$k_q = -8.37$	$k_q = -8.37$
$T_u = -0.07$ s	$T_\alpha = 0.02$ s	$T_{\theta_1} = 13.12$ s	$T_{\theta_1} = 13.12$ s
$\zeta_u = 1.19$	$\zeta_u = 0.01$		
$\omega_u = 12.14\ ^{rad}/_{s}$	$\omega_\alpha = 0.52\ ^{rad}/_{s}$	$T_{\theta_2} = 0.32$ s	$T_{\theta_2} = 0.32$ s
Mode			
Phugoid		$\zeta_d = 0.0261$	
		$\omega_p = 0.341\ ^{rad}/_{s}$	
Short period		$\zeta_s = 0.919$	
		$\omega_p = 3.851\ ^{rad}/_{s}$	

Table 13. Dynamic stability by ailerons

v	p	r	ϕ
$k_v = -2.47$	$k_p = -14.44$	$k_r = -0.41$	$k_\phi = -14.44$
$T_{\beta_1} = -2.71$ s	$\zeta_\phi = 0.268$	$T_\psi = 0.675$ s	$\zeta_\phi = 0.268$
		$\zeta_\psi = 1.62$	
$T_{\beta_2} = 0.008$ s	$\omega_\phi = 1.74\ ^{rad}/_{s}$	$\omega_\psi = 5.79\ ^{rad}/_{s}$	$\omega_\phi = 1.74\ ^{rad}/_{s}$
Mode			
Dutch roll		$\zeta_d = 0.2806$	
		$\omega_d = 1.875\ ^{rad}/_{s}$	
Roll		$T_r = 0.0911$ s	
Spiral		$T_s = 21.563$ s	

Table 14. Dynamic stability by rudder

v	p	r	ϕ
$k_v = -2.47$	$k_p = 1.07$	$k_r = -1.96$	$k_\phi = 1.07$
$T_{\beta_1} = 13.16$ s	$T_{\phi_1} = 0.206$ s	$T_\psi = 0.0901$ s	$T_{\phi_1} = 0.206$ s
		$\zeta_\psi = 0.0373$	
$\zeta_v = 0.983$	$T_{\phi_2} = 0.973$ s	$\omega_\psi = 0.337\ ^{rad}/_{s}$	$T_{\phi_2} = 0.973$ s
Mode			
Dutch roll		$\zeta_d = 0.2806$	
		$\omega_d = 1.875\ ^{rad}/_{s}$	
Roll		$T_r = 0.0911$ s	
Spiral		$T_s = 21.563$ s	

Flying and handling qualities responses

Table 15. Flying and handling qualities glider data

Aeroplane type	Class I
Flight phase	Category C
Short period mode damping	$\zeta_s = 0.919$
Phugoid damping ratio	$\zeta_p = 0.0261$
CAP	2.1628
Roll mode time constant	$T_r = 0.0911$ s
Spiral mode time constant	$T_s = 21.563$ s
Dutch roll damping	$\zeta_d = 0.2806$
	$\zeta_d\omega_d = 0.5261\ ^{rad}/_{s}$
Dutch roll frequency	$\omega_d = 1.875\ ^{rad}/_{s}$

Longitudinal axis

Mode	Levels of flying qualities
CAP	Level 1
CAP = 2.1628	Level 2
	Level 3
Short period	Level 1
$\zeta_s = 0.919$	Level 2
	Level 3
Phugoid	Level 2
$\zeta_p = 0.0261$	Level 3

Lateral-directional axis

Mode	Levels of flying qualities
Roll	Level 1
$T_r = 0.0911$ s	Level 2
	Level 3
Spiral	Level 1
$T_s = 21.563$ s	Level 2
	Level 3
Dutch roll	
$\zeta_d = 0.2806$	Level 1
$\zeta_d\omega_d = 0.5261\ ^{rad}/_{s}$	Level 2
$\omega_d = 1.875\ ^{rad}/_{s}$	Level 3

Routh–Hurwitz criterion

Longitudinal axis

$\Delta_{(s)long} = s^4 + 7.1s^3 + 15.08s^2 + 1.091s + 1.73$

$-8.92e-03+3.41e-01i$

$-8.92e-03-3.41e-01i$

$-3.54e-00+1.52e-00i$

$-3.54e-00-1.52e+00i$

Lateral-directional axis

$\Delta_{(s)lat} = s^5 + 11.9s^4 + 14.51s^3 + 37.9s^2 - 1.7s$

$0.00e+00$

$4.64e-02$

$-5.26e-01+1.80e+00i$

$-5.26e-01-1.80e+00i$

$-1.10e+01$

Control Anticipation Parameter CAP

To know how to find the control anticipation parameter (*CAP*), you are invited to read the bibliography source (Castellanos & Rodríguez, 2019) in section 8.3.2, tittle "Control Anticipation Parameter CAP".

CAP = 2.1628

Discussion

On the total trim conditions calculation, the aerodynamic and geometric configuration determine the increase or decrease of the aerodynamic coefficients values conditioning to ηe. In negative maneuvers, the elevator deflection is maximum at $-2.20° < \eta e < -2.74°$ approximately; and in positive maneuvers it is maximum at $2.14° < \eta e < -20.5°$, where in both cases, the elevator deflections are within the permissible margins by the type certificate, 25° up and 21° down (Department of Transportation FAA, 2007).

Considering an initial state of straight and level flight in the stall speed, the aerodynamic stability and control derivatives numerical quantity will be lower than in the maximum admissible speed, reflected in the transfer functions with greater or lesser amounts in their values. Under these considerations, at stall speed, the transfer functions will have smaller numerical quantities with high damping ratios and time response; at the maximum permissible speed, that effect will be different, there the transfer functions will have larger numerical quantities with low damping ratios and time response. These conditions are linearly reflected in the perturbation and acceleration responses, regardless of the maneuver, for low speed, the aerodynamic controls responses will be smaller the numerical amounts, and contrary to high speeds.

The stability will vary for each maneuver, where in negative maneuvers the stability and the recovery time to a stable condition decrease; and in positive maneuvers the stability and recovery time increase to a stable condition. Similarly, the aerodynamic configuration for angles of incidence, dihedral effect, sweep angle and primary control surfaces would vary the flight and handling qualities. As for the angles of attack and the primary control surfaces, their variation would generate longitudinal pitching moments, increasing the range of maneuver angles while maintaining the trim conditions.

Engines: The direction and magnitude of the power influences the airframe and the movement, and an aeroelastic analysis helps to take it into account. The fuel consumption is assumed as constant and very slow; therefore, the mass will always be the same in any phase of flight. Finally, in the two or more engines configuration, a different power magnitude for each engine would cause changes in direction not desired by the pilot, influencing not only the flight path, but also in the downwash or upwash.

Atmosphere and speed margins: Its influence is on the Reynolds and Mach number, by compressibility effects. In the low Mach numbers, there are no variations in the calculations, being zero or insignificant. In contrast, at high Mach numbers, it is important to consider as a factor of variation in the aerodynamic analysis and in the Aerodynamic stability and control derivatives calculations, especially at high disturbance angles where the aerodynamic effects are not linear. Likewise, a Viscous or non-viscous fluid would require more structural work, and the pilot, would have more physical workload to establish a flight path.

Aerodynamic: The flight mission for which the aircraft have been designed influences the aerodynamic. For acrobatic and heavy aircraft, very low stability levels are allowed to take advantage of this lack of stability to increase maneuverability. In this way, factors like a dihedral angle, sweep angle, incidences, airfoil type and location on the airframe, guarantee these design requirements. A negative dihedral angle allows maneuvers with very high angles tending to destabilize the aircraft, therefore, it is allowed for combat, acrobatics, cargo and passenger aircraft. In contrast, a positive dihedral angle allows better recoveries in stall speed maneuvers, increasing the stability; these same effects are reproduced at the sweep angle, where high sweep angles will be for acrobatic and large aircraft with no-linear maneuvers. In simple aircraft configurations with simple flight missions, it becomes zero. The angle of incidence, airfoil type and airframe location determine the pitch moment, and therefore, they are important in the trim longitudinal condition by the downwash and the upwash. An important topic not studied is the aircraft lateral drag, is that its influence is very difficult to calculate, but with great importance in lateral-directional stability being a stability factor recovery together with the main wing aerodynamic effects, make a specialist software necessary to obtain them.

Conclusions

The main wing and tail plane incidence are the most important geometric parameters to determine the trim conditions calculation. For this reason, it is understood that the aerodynamic and geometric effects will provide pitching moments; therefore, the elevator is the most important aerodynamic control surface to generate that trim condition, while its angular deflection is within the type certificate margins.

The Mach number regime and the reference axis system will allow being accurate with the aerodynamic stability and control derivatives responses. In the permissible speed ranges, the aerodynamic stability and control derivatives will have an infinity of results for any flight condition depending on trim conditions calculation.

The effects of the aerodynamic configuration with respect to the geometric configuration determine the static and dynamic stability, which at the same time will give a state of flight and handling qualities. This is important to make any modification in these two aspects from maintenance and engineering environments, or from a primary design phase.

For future works, there is the opportunity to study from direct calculations in a wind tunnel with prototypes to scale. This way, besides corroborating possible errors, we can take into account effects of profile thickness from changes in the angles of incidence, effects of air compressibility; and therefore, to improve the methodology in the development of studies of flight and handling qualities based on static and dynamic stability. In this way, we would allow more complex calculations with non-linear equations in maneuvers and aircraft of higher categories, creating a margin of work possibilities in the flight phases and in electronic control.

Finally, from the aerodynamics and geometrical configuration, the static and dynamic stability responses for the glider *Schweizer SGU 2-22*, referenced by flight and handling qualities standards, it can be concluded that each characteristic stability mode is within the allowed ranges. Therefore, we understand that the glider will provide optimum performance in any aerial maneuver that the pilot wants to execute, giving a high performance margin without any fault or failure occurring in airframe or systems that degrade the level of flying qualities with an acceptable pilot workload; where in all cases the glider met the maximum and minimum flight qualities levels. This allows us to conclude that the geometrical and aerodynamic configuration meets the requirements for the *Schweizer SGU 2-22* to be an aerial training aircraft with high work margins in flight, knowing that this study is done without taking into account an electronic control and automatic pilot, which in case of their implementation, would allow to increase the flight and handling qualities levels.

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