31st Congress of the International Council of the Aeronautical Sciences

Belo Horizonte, Brazil; September 09-14, 2018

# HURRICANE-CS: CONTROL SURFACES AND HIGH LIFT DEVICES MODELING AND SIZING PROGRAM

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**Keywords:** *Conceptual Design, High Lift Devices, Control Surfaces, Sizing*

## Abstract

*Aircraft conceptual design is an iterative process that needs several design changes to narrow it down to the final design. To help the design process, this work presents automatic sizing of the control surfaces and high-lift devices for the conceptually designed aircraft, henceforth referred as HURRICANE-CS (CS stands for control surfaces). HURRICANE-CS uses MATLAB® programming language and allows automatic sizing of the high lift devices and control surfaces of civil aircraft from a number of known parameters of the aircraft (A/C). Initial hypotheses have been put together from various sources to size the control surfaces. Finally, the results found for an input geometry equivalent to that of an A320 are compared to the aircraft's real parameters.*

## Nomenclature

| | |
|---|---|
| A/C | Aircraft |
| AOA | Angle of attack |
| AEO | All Engines Operating |
| b | Span |
| c | Chord |
| $C_l$ | Airfoil lift coefficient |
| $C_L$ | Lift coefficient |
| $C_{lmax}$ | Maximum airfoil lift coefficient |
| $C_{Lmax}$ | Maximum lift coefficient |
| CS | Control surfaces |
| CS | Certification Specification |
| F | Forces along body axes |
| HLD | High Lift Devices |
| HTP | Horizontal Tail Plane |
| I | Moments of inertia |
| L, M, N | Moments along body axes |
| m | mass of the Aircraft |
| MLG | Main Landing Gear |
| MLW | Maximum Landing Weight |
| MTOW | Maximum Take-off Weight |
| OEI | One Engine Inoperative |
| p, q, r | Angular rates along body axes |
| S | Surface |
| TO | Take-off |
| u, v, w | Airspeed along body axes |
| $V_{cr}$ | Cruise speed |
| $V_{mo}$ | Maximum operating speed |
| $V_s$ | Stall speed |
| VTP | Vertical Tail Plane |
| $\phi$, $\theta$, $\psi$ | Euler angles |

### Subscripts

| | |
|---|---|
| A | Aero |
| a | Aileron |
| e | Elevator |
| f | Flap |
| h | HTP |
| L | Landing |
| r | Ruder |
| T | Thrust |
| wf | wing-fuselage |
| x, y, z | Component along body axes |

## 1 Introduction

On the one hand, the control surfaces of an aircraft (ailerons, elevator, and rudder) are in charge of controlling the attitude of the aircraft and their actuation affects both longitudinal and lateral-directional dynamics. Nevertheless, the equations that describe the longitudinal movement of the A/C are decoupled from the lateral-directional. Therefore, elevators sizing is not affected by the sizing of ailerons and rudder or vice-versa.

On the other hand, high lift devices, such as flaps and slats, enable the A/C to fly at very low speeds by increasing the chord and camber of the airfoil or controlling the boundary layer and therefore acting on the amount of $C_L$ that the wing can generate at a given AOA, while penalizing drag. Their sizing is therefore aimed to enable the A/C to operate safely in take-off and landing operations.

As the nature of both sizing problems is different, HURRICANE-CS treats both sizing problems separately. In addition, CS-25 and FAR-25 standards ([1] and [2]) have been taking into account to ensure that the final design enables the A/C to perform as established by FAA and EASA's regulation.

Finally, the aim behind HURRICANE-CS is to offer the user an automatic conceptual design tool that provides the sizing of all these surfaces from a set of basic known parameters of an A/C. These input parameters are the following:

- **Speeds**: $V_s$, $V_{cr}$ and $V_{mo}$.
- **Weights**: MTOW and MLW.
- **Aircraft geometry for the wing, HTP and VTP**: span ($b$), root chord ($c_r$), taper ratio ($\lambda$), sweep ($\Lambda_{c/4}$), dihedral angle ($\Gamma$), the twist angle and 4-digit NACA airfoil.

## 2 Methodology

HURRICANE-CS, developed in Matlab®, uses some of the functionalities of TORNADO VLM[1] including modified scripts inside TORNADO VLM, to calculate the aerodynamic coefficients needed to solve the dynamic equations in the CS sizing, see [3], while for the HLD sizing semi-empirical methods are used, see [4, 5, 6, 7]. Both methods will be explained hereafter. From a schematic point of view, the program follows the sequence shown in the flowchart of Fig.1 to achieve the sizing of HLD and CS.

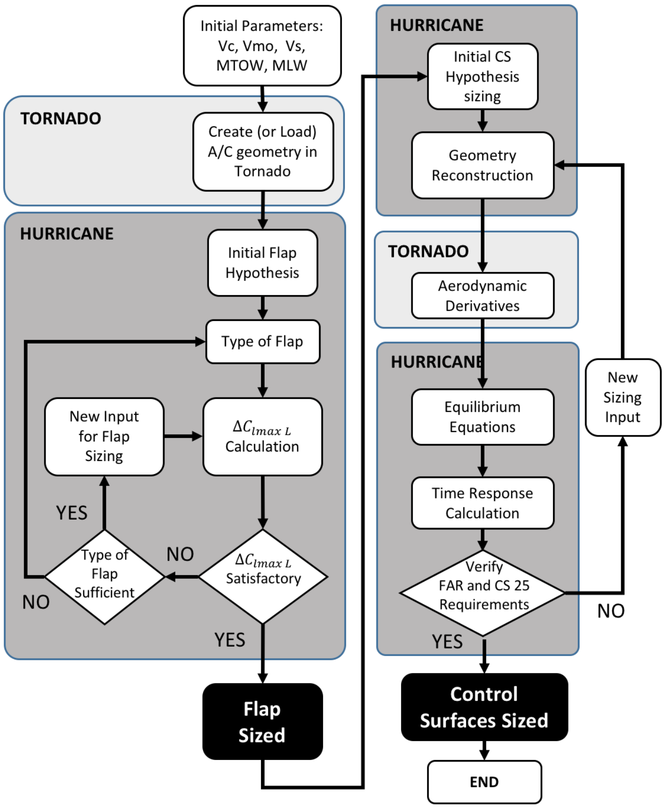



Fig. 1 : HURRICANE-CS process flow [8]

Once the user has introduced the input parameters, the flap sizing is carried out first. As the program is intended for commercial A/C, requirements for take-off and landing performance entail a higher priority than the controllability of the A/C[2]. Thus, a higher percentage of the span (up to a 70%, as per [6]) is left available for the sizing of the HLD.

In addition, the goal behind the design of the wings of commercial A/C is to optimize its geometry aiming for the best possible cruise performance, which translates in a smaller Wing Sur-

[1]TORNADO VLM is a vortex lattice program developed in MATLAB by Tomas Melin at KTH under GNU-Open license protocol that calculates linear aerodynamics of 2-Dimensional wings

[2]This principle may not be valid when designing fighter A/Cs as high rolling maneuverability is vital for fighters

face than the needed to perform adequately in take-off and landing operations. A drawback that is successfully overcome with a large area of the wingspan covered with HLD. Nevertheless, even if the space left for ailerons is not more than a 30%, when needed, commercial A/C also make use of the spoilers to achieve the desired rolling capability.

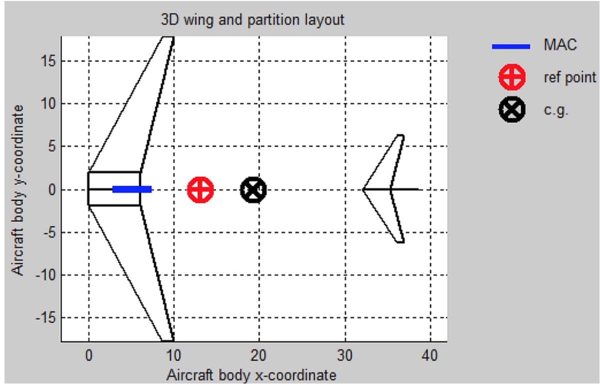
Once the flap sizing is achieved, the clean geometry that had been previously introduced by the user (wing, HTP, and VTP) is modified in TORNADO VLM taking into account the dimensions of the HLD as well as some initial dimensions for the CS. One part of TORNADO VLM code was drastically modified in order to implement this function as the original TORNADO VLM only enables the implementation of flapped surfaces into partitions in a hole. This presents a great limitation for the sizing of the HLD and CS, as for a wing shown in Fig.2 only the whole span could be flapped.

Consequently, in each iteration the modification implemented in HURRICANE-CS takes the geometrical parameters of the control surfaces ($S_x/S$, $b_x/b$, $c_x/c$, $b_{xi}/b$ where $x$ equals $A$ for Aileron, $E$ for Elevator and $R$ for Rudder), identifies which partition of the wing, HTP or VTP the implementation of each control surface affects and reconstructs the wing keeping the global parameters of the wing untouched. Then, in each loop the aerodynamic derivatives are calculated with the Vortex Lattice Method implemented in TORNADO VLM and the equations of motion are solved. The program then iterates in the geometric parameters of the control surfaces until the CS/FAR - 25 requirements (see [1] and [2]) are fulfilled.

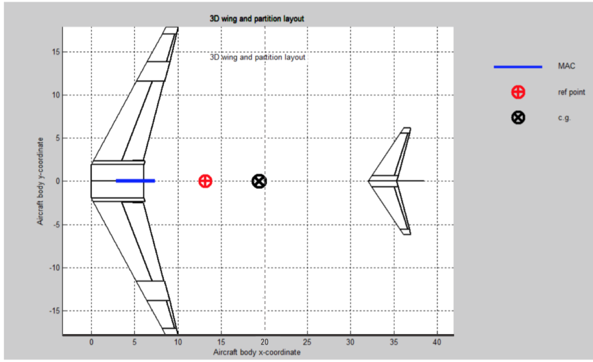
## 2.1 Flap sizing

The purpose of the flap sizing is to obtain a preliminary value for the parameters: $(b_f/b)$, $(b_{fi}/b)$ and $(c_f/c)$, as well as select the flap type so that the lift requirements at take-off and landing operations are fulfilled.

Flap sizing process implemented on HURRICANE-CS is based on an automation of Roskam's semi-empirical methods for different flap types as per [7]. Under this approach, landing is taken as the critical condition (the highest $\Delta C_L$ is required).




(a) Geometry plotted by original TORNADO




(b) Geometry plotted by HURRICANE-CS

Fig. 2 : Comparison between geometry plotted by TORNADO VLM (Top) and geometry with the flaps and the CS plotted by HURRICANE-CS (Bottom) [8].

The HLD included in HURRICANE-CS to perform the conceptual design of flaps are: Plain flap, Slotted flap, Fowler flap, Double-slotted flap and Triple-slotted flap.

### 2.1.1 *Initial assumptions*

As a starting point of the iterative flap sizing process described henceforth, the initial hypotheses gathered in Table 1 are given for the geometrical flap parameters.

The flap sizing process iterates within the acceptable range of values for each parameter defined in Table 2.

As landing is the operational condition used to sizing the HLD, Table 3 shows the typical flap deflections ($\delta_f$) at landing for each flap type implemented in HURRICANE-CS.

| Flap Parameter | Initial Value |
|---|---|
| Span ratio, $\frac{b_f}{b}$ | 0.580 |
| Span-wise position ratio, $\frac{b_{if}}{b}$ | 0.025 |
| Chord ratio, $\frac{c_f}{c}$ | 0.150 |

**Table 1**: Initial values for the flap sizing process [6].

| Flap Parameter | Acceptable interval |
|---|---|
| Span ratio, $\frac{b_f}{b}$ | 0.55 - 0.70 |
| Chord ratio, $\frac{c_f}{c}$ | 0.15 - 0.45 |

**Table 2**: Flap acceptable range of values [6].

| Flap type | $\delta_f$ [°] |
|---|---|
| Plain flap | 60 |
| Slotted flap | 40 |
| Fowler flap | 40 |
| Double slotted flap | 50 |
| Triple slotted flap | 40 |

**Table 3**: Typical flap defection at landing operations for different flap types [9].

### *2.1.2 Method*

Flap type selection is the first step in the conceptual design process proposed in HURRICANE-CS since the flap sizing method depends on it. As shown in Table 4, maximum increment of airfoil lift required at landing ($\Delta C_{lmax_L}$) is the criteria used to select the flap type.

| Flap type | $\Delta C_{lmax_L}$ |
|---|---|
| Plain flap | up to 1.1 |
| Slotted flap | 1.1 - 1.7 |
| Fowler flap | 1.7 - 2.4 |
| Double-slotted flap | 2.4 - 2.9 |
| Tripe-slotted flap | from 2.9 |

**Table 4**: Typical range of $\Delta C_{lmax_L}$ as flap type [10].

For the set of initial parameters entered in HURRICANE-CS and according to [7], $\Delta C_{lmax_L}$ is calculated as:

$$\Delta C_{lmax_L} = \frac{\Delta C_{Lmax_L}}{K_\Lambda}\frac{S_w}{S_f} \tag{1}$$

Where $K_\Lambda$ is a function of the wing sweep angle (input of HURRICANE-CS) as per [7], the $\frac{S_f}{S_w}$ is a target value for the flap sizing and $\Delta C_{Lmax_L}$ is estimated as:

$$\Delta C_{Lmax_L} = 1.05(C_{Lmax_L} - C_{Lmax}) \tag{2}$$

A factor of 1.05 is taken into account for the trim penalty introduced for the use of flaps. $C_{Lmax}$ in clean configuration is established to 1.4, typical value for commercial A/C's according to [7]. $C_{Lmax_L}$ is modeled as a function of the HURRICANE-CS inputs, $MLW$ and $S_w$. Modeling of $C_{Lmax_L} = f(MLW, S_w)$ is based on the data extracted from [9] for several Airbus and Boeing commercial aircrafts.

Flap type is a function of the investigating flap surface ratio, which can be expressed as:

$$\frac{S_f}{S_w} = \frac{b_f(2-(1-\lambda)(2b_{if}+b_f))}{1+\lambda} \tag{3}$$

A first estimation of the flap surface ratio and consequently of the flap type selected is obtained by using the initial values gathered in Table 1.

Depending on the flap type selected in the previous step, one different equation for the required $\Delta C_{lmax_L}$ as a function of the flap chord ratio is extracted from [7]. Flap deflections ($\delta_f$) used in the following equations were shown in Table 3.

- **Plain Flap**

$$\Delta C_{lmax_L} = \Delta C_l \cdot K = C_{l_{\delta_f}} \cdot \delta_f \cdot K' \cdot K \tag{4}$$

$K'$ and $C_{l_{\delta_f}}$ have been modeled as a function of $\frac{c_f}{c}$ for the $\delta_f = 60°$, see [7].

- **Fowler Flap**

$$\Delta C_{lmax_L} = \Delta C_l \cdot K = C_{l_{a_f}} \cdot a_{\delta_f} \cdot \delta_f \cdot K =$$
$$= 1.8\pi(1+0.8\cdot\frac{t}{c})(1+\frac{c_f}{c}) \cdot a_{\delta_f} \cdot \delta_f \cdot K \tag{5}$$

Where, $a_{\delta_f}(\delta_f = 40°) = f(\frac{c_f}{c})$, see [7].

- **Slotted Flap**

$$\Delta C_{lmax_L} = \Delta C_l \cdot K = C_{l_{a_f}} \cdot a_{\delta_f} \cdot \delta_f \cdot K =$$
$$= C_{l_a}(1+2(\frac{z_{fh}}{c})\tan(\frac{\delta_f}{2})) \cdot a_{\delta_f} \cdot \delta_f \cdot K =$$
$$= 1.8\pi(1+0.8\cdot\frac{t}{c})(1+2(\frac{z_{fh}}{c})\tan(\frac{\delta_f}{2}))\cdot$$
$$\cdot a_{\delta_f} \cdot \delta_f \cdot K \quad (6)$$

$\frac{z_{hf}}{c}$ is a geometrical flap parameter which have been established to 0.4 according to [5] whereas $a_{\delta_f}(\delta_f = 40°) = f(\frac{c}{c_f})$ has been modeled as per [7].

- **Double Slotted Flap**
Flap sizing for double slotted flap has to determine the flap chord ratio for each partition. Subscripts "1" and "2" correspond respectively to the inward and outward partition.

$$\Delta C_{lmax_L} = \Delta C_l \cdot K = (\eta_1 \cdot C_{l_{\delta_{f_1}}} \cdot \delta_{f_1} \cdot$$
$$\cdot(\frac{c+c_1}{c}) + \eta_2 \cdot C_{l_{\delta_{f_2}}} \cdot (\delta_{f_1}+\delta_{f_2}) \cdot (\frac{c'}{c})) \cdot K \quad (7)$$

$\eta_1$ and $\eta_2$ are the lift efficiency factor and are a function of the corresponding effective flap partition deflection (see [7]). The effective flap partition deflection is defined as:

$$\phi_1 = \delta_{f_1} + \phi_{TEUPPER} \quad (8)$$
$$\phi_2 = \delta_{f_1} + \delta_{f_2} + \phi_{TEUPPER} \quad (9)$$

Where $\phi_{TEUPPER}$ is:

$$\phi_{TEUPPER} = \arctan(10\cdot(Y_{90} - Y_{100})) \quad (10)$$

$Y_{90}$ and $Y_{100}$ are the thickness for the 90% and the 100% of the chord airfoil respectively. They are known parameters for the entered 4 digit NACA airfoil.

The parameter $\frac{c'}{c}$ from 7 can be expressed as:

$$\frac{c'}{c} = 1 + \frac{\Delta c_w}{c_f} \cdot \frac{c_f}{c} \quad (11)$$

$\frac{\Delta c_w}{c_f}$ has been modeled as a function of the flap deflection according to [5] Thus, for double slotted flap sizing the following assumptions have been made using typical values as per [7] and [5]:

  - Flap partition deflection:
    * $\delta_{f_1} = 35\ °$
    * $\delta_{f_2} = 15\ °$
  - Flap partition chord ratio:
    * $\frac{c_1}{c_f} = 0.15$
    * $\frac{c_2}{c_f} = 0.85$

- **Triple Slotted flap**

$$\Delta C_{lmax_L} = \Delta C_l \cdot K = C_{l_{a_f}} \cdot a_{\delta_f} \cdot \eta_{\delta_f} \cdot K =$$
$$= 1.8\pi(1+0.8\cdot\frac{t}{c})(1-\frac{\theta_f - \sin\theta_f}{\pi}) \cdot \eta_{\delta_f} \cdot K (12)$$

$\eta_{\delta_f}$ is for the concerned flap deflection at landing ($\delta_f = 40°$) equal to 0.81 according to [5].

$\theta_f$ is defined as:

$$\theta_f = \arcsin(2\cdot\frac{c'_f}{c'} - 1) \quad (13)$$

And $\frac{c'_f}{c'}$ is:

$$\frac{c'_f}{c'} = \frac{1+\frac{\Delta c}{c_f}}{\frac{c}{cf}+\frac{\Delta c}{c_f}} \quad (14)$$

$\frac{\Delta c}{c_f}$ is set to 1.6, typical value according to [5].

Note that, the parameter $K$ (equations 4 to 12) is a semi-empirical parameter defined according to [7] as a function of the flap chord ratio and the flap type.

For the flap type selected, HURRICANE-CS calculates the corresponding $\Delta C_{l_{maxL}} = f(\frac{c_f}{c})$ for the initial flap chord ratio shown in Table 1. If the calculated $\Delta C_{l_{maxL}}$ satisfies the required $\Delta C_{l_{maxL}}$ obtained from equation 2, the flap is sized. If not, an iterative process is afterwards carried out in all three levels (Top to Bottom): flap chord ratio, flap span ratio and as corresponds, the flap type, until a final configuration with the parameters within the acceptable range defined in Table 2 is reached.

### 2.2 Control surfaces sizing

The control surface sizing process presented has the purpose of obtaining the preliminary values for the span ratio $(b_x/b)$, span-wise position $(b_{xi}/b)$ and chord ratio $(c_x/c)$ (where $x$ equals $A$ for Aileron, $E$ for Elevator and $R$ for Rudder) which satisfy the most critical requirements for the sizing of control surfaces extracted from CS-25 [1] and FAR-25 [2].

#### *2.2.1 Requirements*

Under this approach, the following conditions are taken as critical requirements for the CS to fulfill:

- **Ailerons**: conditions described in paragraphs 25.147(d), 25.147 (f) and 25.149 (h)(3) of CS-25 Amendment 14 which cover respectively roll capability at $V_2$ in TO configuration with OEI, at a range of speeds in En-route and Approach configuration with AEO and at $V_{MCL}$ in landing configuration with OEI[3].
- **Rudder**: conditions described in paragraphs 25.147(a) and 25.237 of CS-25 Amendment 14 which cover respectively sufficient directional control in an asymmetric thrust condition at $1.3V_{SR}$, MLW and approach configuration and in a cross-wind case with a velocity component of wind that equals 46 km/h at both take-off and landing.
- **Elevator**: a rotation time of not more than 3 seconds and a pitch angular acceleration of not less than $8°/s^2$ during the take-off rotation phase (requirement extracted from [6]).

#### *2.2.2 Initial assumptions*

The hypotheses for the CS's geometrical parameters gathered in Table 5 are used as starting point of the iterative CS sizing process carried out by HURRICANE-CS. According to [6], the acceptable range of values for each parameter is shown in Table 6. The CS sizing process iterates with these three parameters keeping them within the defined ranges. The program iterates firstly on the chord ratio parameter until a superior limit is reached and then on the span ratio if needed.

[3]The specific conditions proposed for each of these paragraphs in the Accepted Means of Compliance (AMC) of CS-25 have been used to solve the equations of motion

| Parameters | Aileron | Elevator | Rudder |
|---|---|---|---|
| Span ratio | 0.200 | 0.800 | 0.700 |
| Chord ratio | 0.150 | 0.150 | 0.150 |
| Span-wise position ratio | 0.725 | 0.100 | 0.150 |

**Table 5**: Initial values for CS sizing process [6].

| Parameters | Aileron | Elevator | Rudder |
|---|---|---|---|
| Span ratio | 0.20-0.30 | 0.80-1.00 | 0.70-1.00 |
| Chord ratio | 0.15-0.25 | 0.20-0.40 | 0.15-0.40 |
| Span-wise position ratio | 0.60-0.80 | 0.00-0.20 | 0.00-0.30 |

**Table 6**: Acceptable range of values for CS sizing process as per [6].

It is important to remark that under the hypothesis that the rear spar will be used as common hinge for both the flaps and ailerons, a maximum chord ratio of that obtained for the flaps in the HLD sizing has been set inside the program as a higher limit in the ailerons sizing. Furthermore, for the maximum deflection angles permitted to the ailerons, elevator, and rudder an average of the maximum deflection angles for a range of significant commercial A/C is shown in Table 7 and has been calculated with data taken from [9].

| Parameters | Aileron | Elevator | Rudder |
|---|---|---|---|
| $\delta_{max}$ (up/left) | 20° | 20° | 30° |
| $\delta_{max}$ (down/right) | 25° | 25° | 30° |

**Table 7**: CS maximum and minimum deflections (average values for commercial A/Cs as per [9]).

#### *2.2.3 Method*

For each lateral or longitudinal case, the Euler equations of motion for a rigid body in 3D space (shown in Equations 15 and 16), which are derived from the linear momentum theorem or Newton's second law and the angular momentum theorem, are characterized.

$$\begin{cases} F_x = m\cdot(\dot{u}+q\cdot w - r\cdot v) \\ F_y = m\cdot(\dot{v}+r\cdot u - p\cdot w) \\ F_z = m\cdot(\dot{w}+p\cdot v - q\cdot u) \end{cases} \tag{15}$$

$$\begin{cases} L = I_x\cdot\dot{p} - I_{xz}\cdot\dot{r} + q\cdot r\cdot(I_z - I_y) - I_{xz}\cdot p\cdot q \\ M = I_y\cdot\dot{q} + r\cdot p\cdot(I_x - I_z) + I_{xz}\cdot(p^2 - q^2) \\ N = I_z\cdot\dot{r} - I_{xz}\cdot\dot{p} + p\cdot q\cdot(I_y - I_x) + I_{xz}\cdot q\cdot r \end{cases} \tag{16}$$

The following kinematic relationships are also taken into account to solve the system of equations.

$$\begin{cases} \dot{\theta} = \cos\phi\cdot q - \sin\phi\cdot r \\ \dot{\phi} = p + \tan\theta\cdot(\sin\phi\cdot q + \cos\phi\cdot r) \\ \dot{\psi} = \frac{1}{\cos\theta}\cdot(\sin\phi\cdot q + \cos\phi\cdot r) \end{cases} \tag{17}$$

Straightaway, a distinction between the resolution for lateral and longitudinal is performed as both cases can be studied separately due to the fact that their equations are decoupled.

#### *2.2.3.1. Lateral cases*

From Equations15 and 16, the equations of rolling and yawing moments ($L$ and $N$), the lateral force ($F_y$) and the second kinematic relation in Equation 17 are used. In addition, the following assumptions are applied:

- $I_{xz} = 0$
- $u, \alpha, \theta = cte$
- q = 0

Then, with the wind speed components expressed in terms of $\alpha$ and $\beta$ as shown below,

$$\begin{cases} u = V\cdot\cos(\alpha)\cdot\cos(\beta) \\ v = V\cdot\sin(\beta) \\ w = V\cdot\sin(\alpha)\cdot\cos(\beta) \end{cases} \xrightarrow[\dot{V}\approx 0]{\beta\approx 0} \begin{cases} u = V\cdot\cos(\alpha) \\ \dot{v} = V\cdot\dot{\beta} \\ w = V\cdot\sin(\alpha) \end{cases} \tag{18}$$

the equations of motion result in the following:

$$\begin{cases} L_A + L_T = I_x\cdot\dot{p} \\ N_A + N_T = I_z\cdot\dot{r} \\ F_{y_A} + F_{y_T} + F_{y_m} = m\cdot V(\dot{\beta} + r\cdot\cos(\alpha) - p\cdot\sin(\alpha)) \\ \dot{\phi} = p + \tan\theta\cdot + \cos\phi\cdot r \end{cases} \tag{19}$$

where:

$$\begin{cases} L_A = Q\cdot S\cdot b\cdot(Cl_\beta\cdot\beta + Cl_r\cdot\frac{r\cdot b}{2V} + Cl_p\cdot\frac{p\cdot b}{2V} + \\ \quad Cl_{\delta_a}\cdot\delta_a + Cl_{\delta_r}\cdot\delta_r) \\ N_A = Q\cdot S\cdot b\cdot(Cn_\beta\cdot\beta + Cn_r\cdot\frac{r\cdot b}{2V} + Cn_p\cdot\frac{p\cdot b}{2V} + \\ \quad Cn_{\delta_a}\cdot\delta_a + Cn_{\delta_r}\cdot\delta_r) \\ F_{y_A} = Q\cdot S\cdot(Cy_\beta\cdot\beta + Cy_r\cdot\frac{r\cdot b}{2V} + Cy_p\cdot\frac{p\cdot b}{2V} + \\ \quad Cy_{\delta_a}\cdot\delta_a + Cy_{\delta_r}\cdot\delta_r) \end{cases}$$

$$\begin{cases} F_{y_m} = m\cdot g\cdot cos(\theta)sin(\phi) \end{cases} \tag{20}$$

$$\begin{cases} L_T \approx 0 \\ F_{Y_T} \approx 0 \\ N_T = 0 \quad for \quad AEO \\ N_T = F_{x_{T_{1e}}}\cdot(y_T - y_{cg}) \quad for \quad OEI \end{cases} \tag{21}$$

All the aerodynamic derivatives shown above are calculated by TORNADO VLM using the vortex lattice method. For the resolution of the maneuvers two steps are needed when solving the equations. Firstly, the resolution of the equations is made for the equilibrated load state (with all time derivatives equal to zero) and then the time response is calculated.

With respect to the equilibrated loaded state, the possible unknown variables that appear in the equations are the following six: $r, p, \phi, \beta, \delta_a$ and $\delta_r$. However, depending on the maneuver to be solved some of these variables are known and others unknown, they differ from one case to another. Assumptions made for each case can be found in [8].

For the time response an explicit integration scheme is introduced, as per Equation 22. The moments of inertia that appear in these equations have been modeled as a function of the A/C mass following the data found in [11].

$$\begin{cases} p_{n+1} = p_n + dt\cdot\frac{L_A+L_T}{I_x} \\ r_{n+1} = r_n + dt\cdot\frac{N_A+N_T}{I_z} \\ \beta_{n+1} = \beta_n + dt\cdot\frac{F_{y_A}+F_{y_T}+F_{y_m}}{m\cdot V} + \\ \quad +dt\cdot(-r_n\cdot\cos(\alpha) + p_n\cdot\sin(\alpha)) \\ \phi_{n+1} = \phi_n + dt\cdot(p_n + \tan\theta\cdot\cos\phi_n\cdot r) \end{cases} \tag{22}$$

#### 2.2.3.2. Longitudinal cases

From Equations 15 and 16, only the equations of longitudinal and vertical forces ($F_x$ and $F_z$) as well as the pitching moment ($M$) and the first kinematic relation in Equation 17 are used. The pitch angle has been set to zero, $\theta = 0$, as the goal is to study the pitch acceleration at the moment where the A/C is finalizing the ground roll phase and starts the rotation phase. In addition, the following assumptions are applied:

- $p, r, \beta = 0$
- $I_{xz} = 0$
- $w \approx 0$

Thus, the wind speed components in Equation 18 are reduced to $u = V \cdot cos(\alpha) \approx V$. The equations of motion can be then reduced to the following[4]:

$$\begin{cases} F_{x_A} + F_{x_T} - F_{x_f} = m \cdot \dot{V} \\ F_{z_A} + N = m \cdot g \\ M_A + M_T - M_W + M_a = I_x \cdot \ddot{\theta} \end{cases} \tag{23}$$

where:

$$\begin{cases} F_{x_A} = Q \cdot S \cdot Cx_{\alpha} \cdot \alpha \\ F_{z_A} = Q \cdot S \cdot Cz_{\alpha_{wf}} \cdot \alpha_{wf} + Q \cdot S_h \cdot Cz_{\alpha_h} \cdot \alpha_h \\ F_{x_f} = \mu \cdot N \\ M_T = F_{x_T} \cdot (z_T - z_{MLG}) \\ M_W = MTOW \cdot g \cdot (x_{MLG} - x_{cg}) \\ M_a = m \cdot \dot{V} \cdot (z_{cg} - z_{MLG}) \\ M_A = Q \cdot S \cdot (C_{z_{wf}} \cdot (x_{MLG} - x_{ac_{wf}}) + \\ \quad + \frac{S_h}{S} \cdot C_{z_h} \cdot (x_{ac_h} - x_{MLG}) + \\ \quad + C_{x_{wf}} \cdot (z_{ac} - z_{MLG}) + \\ \quad + C_{m_{ac_{wf}}} \cdot c) \end{cases} \tag{24}$$

From the set of equations defined above the parameter sought in the longitudinal case resolution, the pitching angular acceleration $\ddot{\theta}$, may be easily obtained for a speed equal to the rotation speed $V = V_R = 1.1V_s$.

## 3 Results

With the purpose of validating the automatic sizing process performed in HURRICANE-CS, the conceptual design of HLD and CS resulting from HURRICANE-CS for an A320 geometry is hereafter evaluated. Table 8 shows the required input data to model the A320 and to start the HURRICANE-CS automatic sizing process.

| Parameters | Values |
|---|---|
| MTOW | 73500 kg |
| MLW | 64900 kg |
| $V_s$ | 61.7 $\frac{m}{s}$ |
| $V_{mo}$ | 0.82 (Mach) |
| $V_{cruise}$ | 251 $\frac{m}{s}$ |
| Altitude | 11278 m |
| Thrust | 111200 N |
| Y-coordinate (OEI to $cg_{A/C}$) | 5.75 m |
| Z-coordinate (AOE to ground) | 1.72 m |
| Mean L/G position | 1.01 m |

**Table 8**: Required input to model the A320 in HURRICANE-CS as per [9] and [12]

### 3.1 Flap sizing results

A comparison between the dimensions of the sized flap from HURRICANE-CS and the real A320's flap dimensions (extracted from [12]) are shown in Table 9. Taking into account that the aim of HURRICANE-CS is to provide an automatic conceptual design for flaps, the results provided in Table 9 can be considered as a good approach in the conceptual design phase. As is shown, HURRICANE-CS resulting dimensions are not far away from the final design A320.

| Parameters | HURRICANE-CS | A320 |
|---|---|---|
| $\Delta C_{Lmax_L}$ | 2.94 | 3.00 |
| Type | Double Slotted Flap | Fowler Double Slotted |
| Span ratio $\left(\frac{b_f}{b}\right)$ | 0.58 | 0.78 |
| Chord ratio $\left(\frac{c_f}{c}\right)$ | 0.25 | 0.20 |
| Area [$m^2$] | 23.87 | 21.10 |

**Table 9**: Comparison between the HURRICANE-CS flap sized proposal and the A320's flap dimensions [12].

### 3.2 Control surfaces sizing results

Thus, Table 10 shows the dimensions proposed by HURRICANE-CS for the conceptual design

[4] The MLG has been now taken as reference to define the equation of pitching moment, instead of using the cg

of the control surfaces of an equivalent A320 geometry compared to those of the real A/C.

| Parameters | HURRICANE-CS | A320 |
|---|---|---|
| AILERONS | | |
| Span ($b_A$) [m] | 3.58 | 2.01 |
| Chord ratio $(\frac{c_A}{c})$ | 0.15 | 0.23 |
| Area [$m^2$] | 2.31 | 2.74 |
| RUDDER | | |
| Span ($b_R$) [m] | 4.11 | 5.87 |
| Chord ratio $(\frac{c_R}{c})$ | 0.15 | 0.286 |
| Area [$m^2$] | 4.23 | 5.76 |
| ELEVATOR | | |
| Span ($b_E$ [m] | 9.96 | 10.88 |
| Chord ratio $(\frac{c_E}{c})$ | 0.15 | 0.37 |
| Area [$m^2$] | 6.22 | 8.37 |

**Table 10**: Comparison between the HURRICANE-CS CS sized proposal and the A320's CS dimensions [12].

As shown with the resulting CS area, the CS sized by HURRICANE-CS are slightly smaller than those of the real A320's. This result may be due to the fact that the CS sizing process implemented in HURRICANE-CS considers as a good approach for the conceptual design, finding the minimum CS dimensions which fulfill the critical operational requirements found in [1] and [2]. Therefore, a constant factor may be applied in the future to these dimensions in order to obtain more precise results.

As the critical operational requirements consist on the capability of the aircraft to perform different maneuvers within a maximum interval of time, Table 11 shows the time response obtained in HURRICANE-CS for each one of the requirements considered and for the CS dimensions presented in Table 10.

Finally, Fig. 2 in section 2 shows a comparison between the geometry entered as input in HURRICANE-CS for the A320 and the final geometry with the flaps and the CS.

## 4 Conclusion

HURRICANE-CS, using functionalities of TORNADO VLM and taking some initial parameters such as $V_s, V_{cr}, V_{mo}$, MTOW, MLW and wing geometry is able to:

| Case | HURRICANE-CS | Requirements |
|---|---|---|
| Ailerons C.I | 4.4 s | < 11 s |
| Ailerons C.II | 3.0 s | < 5 s |
| Ailerons C.III | 2.7 s | < 7 s |
| Rudder C.I | 10.9 s | — |
| Rudder C.II | 3.9 s | — |
| Elevator | $\ddot{\theta} = 0.118 \frac{rad}{s^2}$ | $\ddot{\theta} < 0.175 \frac{rad}{s^2}$ |

**Table 11**: Time response for the A320 verification case.

- Estimate well enough the increment of lift required at landing (only 1% of error).
- Select the most similar flap type to the real one from those implemented in the sizing process.
- Present small differences between its estimation and the A320 flap surface (11% of error).
- Provide a flap chord ratio and a flap span ratio inside the acceptable range of values for civil aircrafts.
- Provide dimensions for ailerons, rudder an elevator inside the range of acceptable values for commercial aircraft which also accomplish the requirements established in [1] and [2].
- Plot the geometry with the flaps and the CS sized by reconstructing the initial wing geometry introduced on TORNADO VLM.

Therefore, the results provided by HURRICANE-CS can be considered as a good starting point to the preliminary design. Furthermore, the dimensions/parameters can be sent to RAPID [13, 14] to obtain the HLD and CS as presented in [15], the 3D geometry can later used for further analysis.

## 5 Future Work

Several points of improvement have been identified in order to make the method more robust and ensure that the results are as realistic as possible:

- Currently, HURRICANE-CS only accepts 4-digit NACA airfoils as an input, improvement may be done in order to let the user enter any type of airfoil geometry.

- For the sizing of the CS, a study of dynamic modes could be perform in order to assure that the selected CS sizing provides a dynamically stable design for all lateral and longitudinal modes (Roll Subsidence mode, Dutch Roll mode, Spiral Divergence, Phugoid oscillations and Short Period oscillations).
- In addition, the sizing of slats for the HLD could be added as well as the sizing of spoilers on the CS side.
- Furthermore, during the resolution of the equations of motion, a close control loop could be added (with a PID controller) to guarantee an stable response of the system, to the deflection of the control surfaces in each case of study.
- Finally, an adaptation of the equations for Four-Engined A/C may be done, as per now the method is limited to Twin-Engined A/Cs.

## References


[1] EASA. *Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes, CS-25*, 2013.

[2] FAA. *FAR Part-25, Airworthiness standards: Transport category airplanes*.

[3] Melin T. A vortex lattice matlab implementation for linear aerodynamic wing applications. *Master's Thesis, Department of Aeronautics, Royal Institute of Technology (KTH), Stockholm, Sweden*, 2000.

[4] Raymer D P. Aircraft design: A conceptual approach, american institute of aeronautics and astronautics. *Inc, Reston, VA*, 1999.

[5] Torenbeek E. *Synthesis of Subsonic Airplane Design*. Delft University Press, 1982.

[6] Sadraey M H. *Aircraft Design: A Systems Engineering Approach*. John Wiley & Sons, Chichester, West Sussex, 2012.

[7] Roskam J. *Airplane design*, vol. 2. Roskam Aviation and Engineering Corporation, 1985.

[8] Sánchez Franco D and López Sánchez C. Hurricane, a control surfaces and high lift devices sizing and modeling program. *Master's Thesis, Division of Fluid and Mechatronic Systems, Linköping University, Linköping, Sweden*, 2014.

[9] Ships J F. *Jane's All The World's Aircraft*. Jane's Information Group., 2013.

[10] *Aircraft Design compendium*. Polytechnic University of Madrid, 2014.

[11] Filipponne A. *Advanced Aircraft Flight Performance*. Cambridge University Press, 2012.

[12] AIRBUS. A320 family, A320neo aircraft. http://www.airbus.com/aircraft/passenger-aircraft/a320-family/a320neo.html.

[13] Munjulury R C, Staack I, Berry P and Krus P. A knowledge-based integrated aircraft conceptual design framework. *CEAS Aeronautical Journal*, vol. 7, no. 1, pp. 95–105, 2016.

[14] Munjulury R C. *Knowledge-Based Integrated Aircraft Design. An Applied Approach from Design to Concept Demonstration.* Linköping Studies in Science and Technology. Dissertations: 1853. Linköping Department of Management and Engineering, Linköping University, 2017, 2017.

[15] Munjulury R C, Escolano Andrés I, Diaz Puebla A and Krus P. Knowledge-based flight control system and control surfaces integration in rapid. *FT2016 - Aerospace Technology Congress*. FTF - Swedish Society Of Aeronautics and Astronautics, Solna, Stockholm, Sweden, 2016.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