Piecewise Polynomial Model of the Aerodynamic Coefficients of the Cumulus One Unmanned Aircraft

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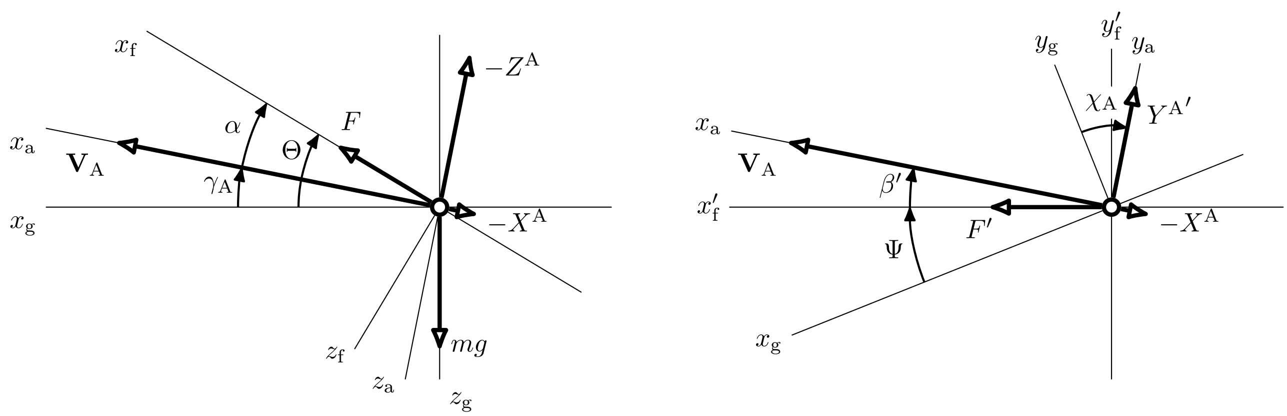
Abstract

This document illustrates a piecewise polynomial model for Cumulus One, based on continuous fluid dynamics simulation, derived using the `pwpfit` toolbox. The model has been developed in a joint project of Sky-Watch and the University of Aalborg.

Preliminaries

If not stated otherwise, all variables are in SI units. We will refer to the following axis systems of ISO 1151-1: the *body axis system* $(x_\mathrm{f}, y_\mathrm{f}, z_\mathrm{f})$ aligned with the aircraft's fuselage; the *air-path axis system* $(x_\mathrm{a}, y_\mathrm{a}, z_\mathrm{a})$ defined by the velocity vector $\mathbf{V}_\mathrm{A}$; and the *normal earth-fixed axis system* $(x_\mathrm{g}, y_\mathrm{g}, z_\mathrm{g})$. The orientation of the body axes with respect to the normal earth-fixed system is given by the attitude angles Φ, Θ, Ψ and to the air-path system by angle of attack α and side-slip β; the orientation of the air-path axes to the normal earth-fixed system is given by azimuth χ_A, inclination γ_A, and bank-angle μ_A. (Fig. **??**.)



(a) Longitudinal axes ($\beta = \mu_\mathrm{A} = 0$).

(b) Horizontal axes ($\gamma_\mathrm{A} = 0$).

Fig. 1: Axis systems with angles and vectors. Projections into the plane are marked by $'$.

I. Aerodynamic Coefficients

The piece-wise polynomial models of the aerodynamic coefficients are given

$$C_\odot(\alpha, \beta, \xi, \eta, \zeta) = \begin{cases} C_\odot^{pre}(\alpha, \beta, \dots) & \text{if } \alpha \leq \alpha_0, \\ C_\odot^{post}(\alpha, \beta, \dots) & \text{else,} \end{cases} \tag{1}$$

where $C_\odot \in \{C_\mathrm{X}, C_\mathrm{Y}, C_\mathrm{Z}, C_\mathrm{l}, C_\mathrm{m}, C_\mathrm{n}\}$ are polynomials in angle of attack, side-slip, and surface deflections; and the boundary is found at

$$\alpha_0 = 17.949°. \tag{2}$$

The polynomials in low and high angle of attack, $C_\odot^{pre}$, $C_\odot^{post}$, are sums

$$C_\odot^{pre} = C_{\odot\alpha}^{pre}(\alpha) + C_{\odot\xi}(\beta, \xi) + C_{\odot\eta}^{pre}(\alpha, \eta) + C_{\odot\zeta}(\beta, \zeta)\,; \tag{3}$$

$$C_\odot^{post} = C_{\odot\alpha}^{post}(\alpha) + C_{\odot\xi}(\beta, \xi) + C_{\odot\eta}^{post}(\alpha, \eta) + C_{\odot\zeta}(\beta, \zeta)\,. \tag{4}$$

In the following subsections, we present the polynomial terms obtained using the `pwpfit` toolbox. Coefficients of absolute value lower than 10^{-2} have been omitted for readability.

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A. Domain of low angle of attack

Polynomials in angle of attack:

$$C_{\mathrm{X}\alpha}^{pre} = -2.566 \times 10^{-2} + 5.722 \times 10^{-1}\alpha + 1.496\alpha^2 - 1.148 \times 10^1\alpha^3; \quad (5)$$

$$C_{\mathrm{Y}\alpha}^{pre} = 5.402 \times 10^{-2} - 2.345 \times 10^{-1}\alpha - 2.001\alpha^2 + 7.054\alpha^3; \quad (6)$$

$$C_{\mathrm{Z}\alpha}^{pre} = -3.475 \times 10^{-1} - 5.467\alpha + 1.853\alpha^2 + 2.663 \times 10^1\alpha^3; \quad (7)$$

$$C_{\mathrm{l}\alpha}^{pre} = 4.875 \times 10^{-2} - 2.190 \times 10^{-1}\alpha - 2.004\alpha^2 + 7.146\alpha^3; \quad (8)$$

$$C_{\mathrm{m}\alpha}^{pre} = 6.214 \times 10^{-2} - 1.755\alpha - 3.427\alpha^2 + 1.256 \times 10^1\alpha^3; \quad (9)$$

$$C_{\mathrm{n}\alpha}^{pre} = 4.748 \times 10^{-2} - 2.097 \times 10^{-1}\alpha - 2.016\alpha^2 + 7.171\alpha^3; \quad (10)$$

Polynomials in angle of attack and elevator deflections:

$$C_{\mathrm{X}\eta}^{pre} = 4.327 \times 10^{-2}\eta - 4.458 \times 10^{-1}\alpha\eta + 3.370 \times 10^{-1}\alpha^2\eta - 4.567 \times 10^{-1}\alpha\eta^2 + 7.331 \times 10^{-2}\eta^3; \quad (11)$$

$$C_{\mathrm{Y}\eta}^{pre} = 1.832 \times 10^{-2}\eta + 7.484 \times 10^{-2}\alpha\eta - 4.384 \times 10^{-1}\alpha^2\eta; \quad (12)$$

$$C_{\mathrm{Z}\eta}^{pre} = -2.567 \times 10^{-1}\eta + 3.085 \times 10^{-1}\alpha\eta - 5.105 \times 10^{-2}\eta^2 - 7.394 \times 10^{-1}\alpha^2\eta + 6.936 \times 10^{-1}\alpha\eta^2 + 1.337 \times 10^{-1}\eta^3; \quad (13)$$

$$C_{\mathrm{l}\eta}^{pre} = 1.699 \times 10^{-2}\eta + 8.936 \times 10^{-2}\alpha\eta - 4.564 \times 10^{-1}\alpha^2\eta + 1.571 \times 10^{-2}\alpha\eta^2; \quad (14)$$

$$C_{\mathrm{m}\eta}^{pre} = -9.028 \times 10^{-1}\eta + 7.437 \times 10^{-1}\alpha\eta - 4.924 \times 10^{-2}\eta^2 - 8.415 \times 10^{-1}\alpha^2\eta + 2.210\alpha\eta^2 + 5.251 \times 10^{-1}\eta^3; \quad (15)$$

$$C_{\mathrm{n}\eta}^{pre} = 1.532 \times 10^{-2}\eta + 8.758 \times 10^{-2}\alpha\eta - 4.513 \times 10^{-1}\alpha^2\eta + 1.487 \times 10^{-2}\alpha\eta^2. \quad (16)$$

B. Domain of high angle of attack

Polynomials in angle of attack:

$$C_{\mathrm{X}\alpha}^{post} = 1.266 \times 10^{-2} - 3.159 \times 10^{-1}\alpha + 3.832 \times 10^{-1}\alpha^2 - 1.226 \times 10^{-1}\alpha^3; \quad (17)$$

$$C_{\mathrm{Y}\alpha}^{post} = -2.297 \times 10^{-2}\alpha^2 + 1.337 \times 10^{-2}\alpha^3; \quad (18)$$

$$C_{\mathrm{Z}\alpha}^{post} = -4.179 \times 10^{-1} - 2.345\alpha + 9.586 \times 10^{-1}\alpha^2 - 3.665 \times 10^{-2}\alpha^3; \quad (19)$$

$$C_{\mathrm{l}\alpha}^{post} = 2.006 \times 10^{-2} - 8.200 \times 10^{-2}\alpha + 1.012 \times 10^{-1}\alpha^2 - 3.515 \times 10^{-2}\alpha^3; \quad (20)$$

$$C_{\mathrm{m}\alpha}^{post} = -2.552 \times 10^{-1} - 5.131 \times 10^{-1}\alpha - 2.677 \times 10^{-1}\alpha^2 + 1.332 \times 10^{-1}\alpha^3; \quad (21)$$

$$C_{\mathrm{n}\alpha}^{post} = 1.159 \times 10^{-2} - 3.062 \times 10^{-2}\alpha + 2.727 \times 10^{-2}\alpha^2; \quad (22)$$

Polynomials in angle of attack and elevator deflections:

$$C_{\mathrm{X}\eta}^{post} = -1.342 \times 10^{-2}\eta - 1.663 \times 10^{-1}\alpha\eta - 1.796 \times 10^{-1}\eta^2 + 2.254 \times 10^{-2}\alpha^2\eta + 9.274 \times 10^{-2}\alpha\eta^2 + 7.331 \times 10^{-2}\eta^3; \quad (23)$$

$$C_{\mathrm{Z}\eta}^{post} = -2.922 \times 10^{-1}\eta + 1.829 \times 10^{-1}\alpha\eta + 1.277 \times 10^{-1}\eta^2 + 2.284 \times 10^{-2}\alpha^2\eta + 1.229 \times 10^{-1}\alpha\eta^2 + 1.337 \times 10^{-1}\eta^3; \quad (24)$$

$$C_{\mathrm{m}\eta}^{post} = -9.498 \times 10^{-1}\eta + 6.099 \times 10^{-1}\alpha\eta + 5.093 \times 10^{-1}\eta^2 + 6.456 \times 10^{-2}\alpha^2\eta + 4.264 \times 10^{-1}\alpha\eta^2 + 5.251 \times 10^{-1}\eta^3; \quad (25)$$

$C_{\mathrm{Y}\eta}^{post}$, $C_{\mathrm{l}\eta}^{post}$, $C_{\mathrm{n}\eta}^{post}$ are approximately zero. (26)

C. Full-envelope polynomials

Polynomials in side-slip and aileron deflections:

$$C_{\mathrm{X}\xi} = 6.557 \times 10^{-2}\beta^2 + 4.214 \times 10^{-2}\beta\xi - 1.493\xi^2 + 4.264 \times 10^{-2}\xi^3 - 1.647 \times 10^{-2}\beta^4 - 2.321 \times 10^{-2}\beta^3\xi + 9.649 \times 10^{-2}\beta^2\xi^2 + 2.859 \times 10^{-2}\beta\xi^3 + 3.084 \times 10^{1}\xi^4; \tag{27}$$

$$C_{\mathrm{Y}\xi} = -3.697 \times 10^{-1}\beta - 1.570 \times 10^{-1}\xi - 3.231 \times 10^{-2}\beta^2 - 6.137\xi^2 + 7.416 \times 10^{-2}\beta^3 + 1.611 \times 10^{-2}\beta\xi^2 + 2.214\xi^3 + 6.487 \times 10^{-1}\beta^2\xi^2 + 5.323 \times 10^{-2}\beta\xi^3 + 1.456 \times 10^{2}\xi^4; \tag{28}$$

$$C_{\mathrm{Z}\xi} = 3.411 \times 10^{-1}\beta^2 + 4.141 \times 10^{-1}\beta\xi - 3.717\xi^2 + 4.234 \times 10^{-2}\xi^3 - 9.915 \times 10^{-2}\beta^4 - 1.922 \times 10^{-1}\beta^3\xi + 1.945 \times 10^{-1}\beta^2\xi^2 + 9.909 \times 10^{-1}\beta\xi^3 + 9.856 \times 10^{1}\xi^4; \tag{29}$$

$$C_{\mathrm{l}\xi} = -5.798 \times 10^{-2}\beta - 3.929 \times 10^{-1}\xi - 2.906 \times 10^{-2}\beta^2 - 5.551\xi^2 + 1.763 \times 10^{-2}\beta^3 + 1.722 \times 10^{-1}\beta^2\xi + 4.557 \times 10^{-1}\xi^3 + 5.835 \times 10^{-1}\beta^2\xi^2 + 5.332 \times 10^{-2}\beta\xi^3 + 1.319 \times 10^{2}\xi^4; \tag{30}$$

$$C_{\mathrm{m}\xi} = -3.978 \times 10^{-2}\beta^2 + 5.554 \times 10^{-1}\beta\xi - 4.689\xi^2 + 4.229 \times 10^{-2}\xi^3 + 2.585 \times 10^{-2}\beta^4 - 2.309 \times 10^{-1}\beta^3\xi + 4.077 \times 10^{-1}\beta^2\xi^2 - 5.068 \times 10^{-1}\beta\xi^3 + 1.160 \times 10^{2}\xi^4; \tag{31}$$

$$C_{\mathrm{n}\xi} = 3.686 \times 10^{-2}\beta + 1.392 \times 10^{-2}\xi - 2.828 \times 10^{-2}\beta^2 - 5.410\xi^2 - 1.160 \times 10^{-1}\xi^3 + 5.678 \times 10^{-1}\beta^2\xi^2 + 5.334 \times 10^{-2}\beta\xi^3 + 1.286 \times 10^{2}\xi^4. \tag{32}$$

Polynomials in side-slip and rudder deflections:

$$C_{\mathrm{X}\zeta} = -1.031 \times 10^{-2}\beta\zeta - 7.986 \times 10^{-2}\zeta^2 + 1.086 \times 10^{-2}\beta\zeta^3 + 9.739 \times 10^{-2}\zeta^4; \tag{33}$$

$$C_{\mathrm{Y}\zeta} = -8.526 \times 10^{-2}\zeta - 2.128 \times 10^{-2}\beta^2 - 3.569 \times 10^{-1}\zeta^2 + 1.049 \times 10^{-2}\beta^2\zeta + 1.924 \times 10^{-2}\beta\zeta^2 + 7.679 \times 10^{-2}\zeta^3 + 5.663 \times 10^{-2}\beta^2\zeta^2 + 5.247 \times 10^{-1}\zeta^4; \tag{34}$$

$$C_{\mathrm{Z}\zeta} = -2.036 \times 10^{-2}\beta^2 - 1.332 \times 10^{-2}\beta\zeta - 1.743 \times 10^{-1}\zeta^2 + 1.834 \times 10^{-2}\beta^2\zeta^2 + 3.683 \times 10^{-2}\beta\zeta^3 + 2.631 \times 10^{-1}\zeta^4; \tag{35}$$

$$C_{\mathrm{l}\zeta} = -1.930 \times 10^{-2}\beta^2 - 3.221 \times 10^{-1}\zeta^2 + 5.111 \times 10^{-2}\beta^2\zeta^2 + 4.735 \times 10^{-1}\zeta^4; \tag{36}$$

$$C_{\mathrm{m}\zeta} = -3.231 \times 10^{-2}\beta^2 - 1.436 \times 10^{-2}\beta\zeta - 2.672 \times 10^{-1}\zeta^2 + 1.241 \times 10^{-2}\beta^3\zeta + 1.472 \times 10^{-2}\beta^2\zeta^2 + 1.051 \times 10^{-2}\beta\zeta^3 + 4.193 \times 10^{-1}\zeta^4; \tag{37}$$

$$C_{\mathrm{n}\zeta} = 2.158 \times 10^{-2}\zeta - 1.882 \times 10^{-2}\beta^2 - 3.137 \times 10^{-1}\zeta^2 - 1.338 \times 10^{-2}\zeta^3 + 4.978 \times 10^{-2}\beta^2\zeta^2 + 4.611 \times 10^{-1}\zeta^4. \tag{38}$$

II. Equations of Motion

We have the aerodynamic forces and moments in body axis system

$$\begin{bmatrix} X^{\mathrm{A}} \\ Y^{\mathrm{A}} \\ Z^{\mathrm{A}} \end{bmatrix}_{\mathrm{f}} = \frac{1}{2}\varrho S V_{\mathrm{A}}^2 \begin{bmatrix} C_{\mathrm{X}} \\ C_{\mathrm{Y}} \\ C_{\mathrm{Z}} \end{bmatrix}; \qquad \begin{bmatrix} L^{\mathrm{A}} \\ M^{\mathrm{A}} \\ N^{\mathrm{A}} \end{bmatrix}_{\mathrm{f}} = \frac{1}{2}\varrho S V_{\mathrm{A}}^2 \begin{bmatrix} b\,C_{\mathrm{l}} \\ c_{\mathrm{A}} C_{\mathrm{m}} \\ b\,C_{\mathrm{n}} \end{bmatrix} + \begin{bmatrix} X^{\mathrm{A}} \\ Y^{\mathrm{A}} \\ Z^{\mathrm{A}} \end{bmatrix}_{\mathrm{f}} \times \left(\mathbf{x}_{\mathrm{cg}} - \mathbf{x}_{\mathrm{cg}}^{\mathrm{ref}}\right); \tag{39}$$

and the weight force by rotation into the body axis system

$$X_{\mathrm{g}}^{\mathrm{G}} = -g \sin\Theta; \tag{40}$$

$$Y_{\mathrm{g}}^{\mathrm{G}} = -g \sin\Phi \cos\Theta; \tag{41}$$

$$Z_{\mathrm{g}}^{\mathrm{G}} = -g \cos\Phi \cos\Theta; \tag{42}$$

The resulting forces lead to changes in the velocity vector, in body axis system, by

$$\dot{\mathbf{V}}_{\mathrm{A\,f}} = \frac{1}{m} \begin{bmatrix} X^{\mathrm{A}} + X^{\mathrm{G}} + X^{\mathrm{F}} \\ Y^{\mathrm{A}} + Y^{\mathrm{G}} \\ Z^{\mathrm{A}} + Z^{\mathrm{G}} \end{bmatrix}_{\mathrm{f}} + \begin{bmatrix} p \\ q \\ r \end{bmatrix} \times \mathbf{V}_{\mathrm{A\,f}}. \tag{43}$$

with the thrust $X_\mathrm{f}^\mathrm{F} = F$ (engines aligned with the x_f-axis). For a symmetric plane ($I_{xy} = I_{yz} = 0$), the resulting moments in body axis are given as

$$L_\mathrm{f} = L_\mathrm{f}^\mathrm{A} - q\,r\,(I_z - I_y) + p\,q\,I_{zx}; \tag{44}$$
$$M_\mathrm{f} = M_\mathrm{f}^\mathrm{A} - p\,r\,(I_x - I_z) - \left(p^2 - r^2\right) I_{zx}; \tag{45}$$
$$N_\mathrm{f} = N_\mathrm{f}^\mathrm{A} - p\,q\,(I_y - I_x) - q\,r\,I_{zx}; \tag{46}$$

with the inertias I_x, I_y, I_z, I_{zx}. The changes of angular body rates are then given as

$$\dot{p} = \frac{1}{I_x I_z - I_{zx}^2}\left(I_z L_\mathrm{f} + I_{zx} N_\mathrm{f}\right); \tag{47}$$
$$\dot{q} = \frac{1}{I_y} M_\mathrm{f}; \tag{48}$$
$$\dot{r} = \frac{1}{I_x I_z - I_{zx}^2}\left(I_{zx} L_\mathrm{f} + I_x N_\mathrm{f}\right). \tag{49}$$

Here, the normalized body rates have been used with

$$\begin{bmatrix}\hat{p}\\ \hat{q}\\ \hat{r}\end{bmatrix} = \frac{1}{2V_\mathrm{A}}\begin{bmatrix}b\,p\\ c_\mathrm{A}\,q\\ b\,r\end{bmatrix} \iff \begin{bmatrix}p\\ q\\ r\end{bmatrix} = 2V_\mathrm{A}\begin{bmatrix}b^{-1}\,\hat{p}\\ c_\mathrm{A}^{-1}\,\hat{q}\\ b^{-1}\,\hat{r}\end{bmatrix} \tag{50}$$

and

$$\begin{bmatrix}\dot{\hat{p}}\\ \dot{\hat{q}}\\ \dot{\hat{r}}\end{bmatrix} = \frac{1}{V_\mathrm{A}}\left(\frac{1}{2}\begin{bmatrix}b\,\dot{p}\\ c_\mathrm{A}\,\dot{q}\\ b\,\dot{r}\end{bmatrix} - \dot{V}_\mathrm{A}\begin{bmatrix}\hat{p}\\ \hat{q}\\ \hat{r}\end{bmatrix}\right). \tag{51}$$

The change of attitude is finally obtained by rotation into normal earth-fixed axis system:

$$\dot{\Phi} = p + q\sin\Phi\tan\Theta + r\cos\Phi\tan\Theta; \tag{52}$$
$$\dot{\Theta} = q\cos\Phi - r\sin\Phi; \tag{53}$$
$$\dot{\Psi} = q\sin\Phi\cos^{-1}\Theta + r\cos\Phi\cos^{-1}\Theta. \tag{54}$$

III. Longitudinal Model

The longitudinal model is restricted to the x_a-z_a-plane, assuming $\beta = \mu_\mathrm{A} = \chi_\mathrm{A} = 0$.

A. *Aerodynamic Coefficients*

The longitudinal aerodynamic coefficients, $C_\mathrm{L}, C_\mathrm{D}, C_\mathrm{m}$, are obtained as

$$\begin{bmatrix}C_\mathrm{L}\\ C_\mathrm{D}\end{bmatrix} = \begin{bmatrix}+\sin\alpha & -\cos\alpha\\ -\cos\alpha & -\sin\alpha\end{bmatrix}\begin{bmatrix}C_\mathrm{X}\\ C_\mathrm{Z}\end{bmatrix}. \tag{55}$$

B. *Equations of motion*

The longitudinal equations of motion are given as

$$\dot{V}_\mathrm{A} = \frac{1}{m}\left(T\cos\alpha - \frac{1}{2}\rho S V_\mathrm{A}^2 C_\mathrm{D}(\alpha,\eta,q) - mg\sin\gamma_\mathrm{A}\right), \tag{56}$$
$$\dot{\gamma}_\mathrm{A} = \frac{1}{mV_\mathrm{A}}\left(T\sin\alpha + \frac{1}{2}\rho S V_\mathrm{A}^2 C_\mathrm{L}(\alpha,\eta,q) - mg\cos\gamma_\mathrm{A}\right), \tag{57}$$
$$\dot{q} = \frac{1}{I_y}\frac{1}{2}\rho S c_\mathrm{A} V_\mathrm{A}^2 C_\mathrm{m}(\alpha,\eta,q); \tag{58}$$
$$\dot{\Theta} = q; \tag{59}$$

with

$$\Theta = \alpha + \gamma. \tag{60}$$

Nomenclature

α	=	Angle of attack (rad);
α_0	=	Low-angle of attack boundary (°);
β	=	Side-slip angle (rad);
γ_A	=	Flight-path angle relative to air (rad);
ζ	=	Rudder deflection (rad), negative if leading to positive yaw moment;
η	=	Elevator deflection (rad), negative if leading to positive pitch moment;
Θ	=	Pitch angle (rad);
μ_A	=	Air-path bank angle (rad);
ξ	=	Aileron deflection (rad), negative if leading to positive roll moment;
ϱ	=	Air density ($\varrho = 1.200\,\mathrm{kg\,m^{-3}}$);
χ_A	=	Air-path azimuth angle (rad);
Φ	=	Bank angle (rad);
Ψ	=	Azimuth angle (rad);
C_l	=	Aerodynamic coefficient moment body x_f-axis ($\cdot$);
C_m	=	Aerodynamic coefficient moment body y_f-axis ($\cdot$);
C_n	=	Aerodynamic coefficient moment body z_f-axis ($\cdot$);
C_D	=	Aerodynamic drag coefficient ($\cdot$), positive along negative air-path x_a-axis;
C_L	=	Aerodynamic lift coefficient ($\cdot$), positive along negative air-path z_a-axis;
C_X	=	Aerodynamic coefficient force body x_f-axis ($\cdot$);
C_Y	=	Aerodynamic coefficient force body y_f-axis ($\cdot$);
C_Z	=	Aerodynamic coefficient force body z_f-axis ($\cdot$);
D	=	Drag force (N), positive along negative air-path x_a-axis;
F	=	Thrust force (N), positive along body x_f-axis;
L	=	Lift force (N), positive along negative air-path z_a-axis;
q	=	Pitch rate ($\mathrm{rad\,s^{-1}}$);
b	=	Reference aerodynamic span ($b = 2.088\,\mathrm{m}$);
c_A	=	Aerodynamic mean chord ($c_\mathrm{A} = 2.800 \times 10^{-1}\,\mathrm{m}$);
g	=	Standard gravitational acceleration ($g \approx 9.810\,\mathrm{m\,s^{-2}}$);
m	=	Aircraft mass ($m = 2.619 \times 10^{1}\,\mathrm{kg}$);
p	=	Roll rate ($\mathrm{rad\,s^{-1}}$);
r	=	Yaw rate ($\mathrm{rad\,s^{-1}}$);
L_f	=	Roll moment ($\mathrm{N\,m}$), mathematically positive around x_f-axis;
M_f	=	Pitch moment ($\mathrm{N\,m}$), mathematically positive around y_f-axis;
N_f	=	Yaw moment ($\mathrm{N\,m}$), mathematically positive around z_f-axis;
S	=	Wing area ($S = 5.500 \times 10^{-1}\,\mathrm{m^2}$);
$V_\mathrm{A}, \mathbf{V}_\mathrm{A}$	=	Aircraft speed and velocity *relative to air* ($V_\mathrm{A} = \lVert\mathbf{V}_\mathrm{A}\rVert_2$, $\mathrm{m\,s^{-1}}$);
X_f^A	=	Aerodynamic force along body x_f-axis (N);
X_f^F	=	Thrust force along body x_f-axis (N);
Y_f^A	=	Aerodynamic force along body y_f-axis (N);
Z_f^A	=	Aerodynamic force along body z_f-axis (N);
$(\cdot)^{post}$	=	Domain of high angle of attack;
$(\cdot)^{pre}$	=	Domain of low angle of attack;
x_a, y_a, z_a	=	Air-path axis system;
x_f, y_f, z_f	=	Body axis system;
x_g, y_g, z_g	=	Normal earth-fixed axis system;