Control Reversal

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1 Control reversal - Definition

Control reversal is a steady state phenomenon in which at a certain speed and height, control surfaces (ailerons) activation will not produce extra lift, so the pilot will not have any control over the aircraft. It was first discovered during World War II, where high roll velocities along with high flight speeds were essential for combat performance, and control reversal was a major disadvantage for the pilot.

2 Theoretical Formulation of the Problem

There are two possible ways of explaining this phenomenon: considering the reference as the plane on the ground before flight or considering the reference as the plane on a cruise flight with constant speed. We will focus on the second one since it's the most typical one the difference between them will be explained in the subsequent section.

2.1 Simplification of the Wing

Theodorsen and Garrick [1] defined a characteristic section, which is the profile situated at 0.7 times the semi-span of the wing from the root. This two-dimensional model simplifies the behavior of the whole wing accurately.

The wing-box (which consists of the spars, ribs, stringer and skin) provides the torional resistance to the wing. To represent it we will use a torsion spring whose coefficient depends on the material properties and construction of the structure.

2.2 Condition for Control Reversal

The elastic axis (EA) is the line where all the elastic capacity of the wing is concentrated. The aerodynamic center *ac* is the point on the airfoil about which the aerodynamic moment is independent from the angle of attack (AoA). These two are separated by a distance e, which is considered a constant. For a typical airfoil, the *ac* is one-quarter of the chord away from the leading edge. We also assume a constant flight level and flight speed.

Consider an airplane cruising at an AoA α_0. The forces experienced by the section defined in section 2.1 are shown in Fig. 1a. Since the airplane is in equilibrium, the net moment around the EA is zero.

$$\sum M_{\mathrm{EA}} = 0 \tag{1}$$

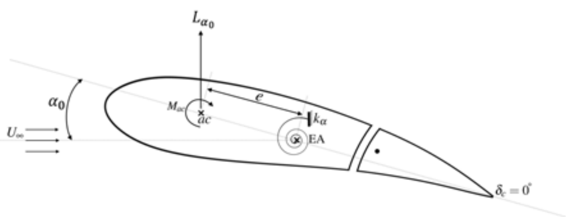
Substituting, we get

$$k_\alpha \alpha_0 = L_{\alpha_0} e + M_{ac} \tag{2}$$

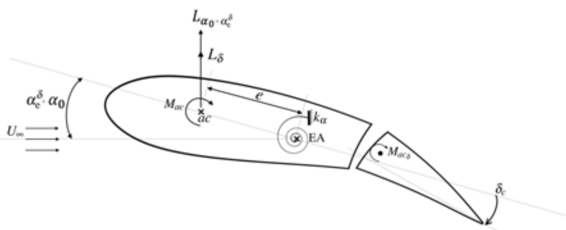
where:

k_α = Torisonal stiffness of the wing.
L_{α_0} = Lift at AoA α_0.
M_{ac} = Moment about the *ac*.

When the control surface is deflected by δ_c, it will generate and extra lift L_δ, and a moment about the *ac* (M_{ac}) due to the deflection of the control surface. Additionally, it will create torsion about the EA, and effectively changes the AoA by α_e^δ. This will generate an extra lift $L_{\alpha_e^\delta}$.



(a) Force diagram with control surface undeflected.



(b) Force diagram with control surface deflected.

Fig. 1 . Forces and moments on the lifting surface with undeflected and deflected control surfaces.

Figure 1b shows the new forces and moments created due to the control surface activation. Here lies the main difference between the two methods described in section 2. If the reference is the plane in the ground, M_{ac} will not appear in the original equilibrium equation, but it will in the incremental moment equilibrium due to deflection. However, since we used the second approach, the equations of equilibrium about the EA can be expressed as:

$$k_\alpha \alpha_e^\delta = (L_{\alpha_e^\delta} + L_\delta)e + M_{ac_\delta} \tag{3}$$

where:

L_δ = Lift increment at control deflection. δ_c
$L_{\alpha_e^\delta}$ = Lift increment at torsional angle. α_e
M_{ac_δ} = Moment about ac at control deflection. δ_c

The original forces and moments (corresponding to undeflected control surfaces) are not considered here since they already sum to zero. Expressing the lifts and moments in coeffficient form, we get:

$$k_\alpha \alpha_e^\delta = ((C_{L_\alpha} \alpha_e^\delta + C_{L_\delta} \delta_c)e + C_{M_{ac_\delta}} c) q_\infty S \tag{4}$$

where:

$C_{L_\alpha}, C_{L_\delta}, C_{M_{ac_\delta}}$ = Lift and moment coefficients.
q_∞ = Freestream dynamic pressure.
c = Chord of the wing section.
S = Reference area of wing.

Rearranging, we get:

$$\frac{\alpha_e^\delta}{\delta_c} = \frac{q_\infty S e}{k_\alpha - q_\infty S e C_{L_\alpha}} \left(C_{L_\delta} + \frac{c}{e} C_{M_{ac_\delta}} \right) \tag{5}$$

The net extra lift generated by the control surface can be expressed as control efficiency:

$$\begin{aligned} \frac{\Delta L}{L} &= \frac{L_\delta + L_{\alpha_e^\delta}}{L_\delta} \\ &= \frac{q_\infty S (C_{L_\alpha} \alpha_e^\delta + C_{L_\delta} \delta_c)}{q_\infty S C_{L_\delta} \delta_c} \\ &= 1 + \frac{C_{L_\alpha}}{C_{L_\delta}} . \frac{\alpha_e^\delta}{\delta_c} \end{aligned} \tag{6}$$

Substituting the value of $\frac{\alpha_e^\delta}{\delta_c}$ from (5), we get:

$$\frac{\Delta L}{L} = 1 + q_\infty \frac{Sc}{k_\alpha} . \frac{C_{L_\alpha} C_{M_{ac_\delta}}}{C_{L_\delta}} \tag{7}$$

According to the definition in section 1, control reversal occurs when $\frac{\Delta L}{L}$ becomes zero. The corresponding value of freestream dynamic pressure is q_R.

$$q_R = -\frac{k_\alpha}{Sc} . \frac{C_{L_\delta}}{C_{L_\alpha} C_{M_{ac_\delta}}} \tag{8}$$

We also know the dynamic pressure depends on the speed and altitude (density). So, therefore, for a concrete height we can calculate the speed at which control reversal occurs. Lift and momentum coefficients in the expression above are considered constant as well.

3 Graphical representation

We conclude the report by presenting Fig. 2, which is a graph of the extra lift generated by control surfaces over dynamic pressure dimensionless (with divergence pressure).

If control efficiency remains at 100 percent until the wing fails due to divergence (Induced torsion higher than the wing can withstand), the aircraft will break and crash. Therefore, it is desirable to first lose control before divergence is reached. This is why wings are designed so that they progressively lose control before reaching divergence, in order to warn the pilot that the limit of the structure is close (with values of $q\mathrm{R}/q\mathrm{D}$ lower than 1, where the extra lift is zero before the divergence appears).

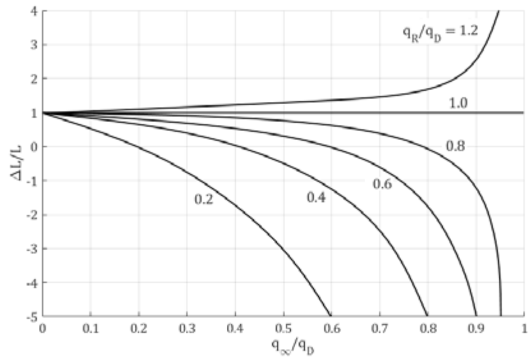


Fig. 2 . Graph of extra lift against dimensionless dynamic pressure with divergence pressure. Figure adapted from Pablo [2]

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REFERENCES

[1] Theodorsen T. General theory of aerodynamic instability and the mechanism of flutter. Tech. Rep. No. 496, 1935.

[2] Garcia P and Lozano F. *Introduccion a la Aeroelasticidad*. Garceta, 2015.