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The influence of propeller slipstream on aircraft rolling moment due to sideslip

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Mr J. Tweedie	— Short Brothers plc, Belfast
Mr S.F. Wood	— BAE SYSTEMS, Woodford

* Corresponding Member

The construction and subsequent development of the Data Item was undertaken under contract to ESDU by Mr M.J. Green.

The person with overall responsibility for the work in this subject area is Mr R.W. Gilbey, Head of Aircraft Aerodynamics Group.

THE INFLUENCE OF PROPELLER SLIPSTREAM ON AIRCRAFT ROLLING MOMENT DUE TO SIDESLIP

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THE INFLUENCE OF PROPELLER SLIPSTREAM ON AIRCRAFT ROLLING MOMENT DUE TO SIDESLIP

1. NOTATION AND UNITS

		SI	British
B	number of blades per propeller		
b	wing span	m	ft
C_L	lift coefficient based on $q_0 S$		
$(\Delta C_L)_{power}$	total increment in lift coefficient due to power		
$(\Delta C_L)_s$	total increment in lift coefficient due to slipstream		
$C_{Lth}(\alpha_z, \delta)$	thin-aerofoil theory value of lift coefficient increment due to slipstream incidence α_z and flap deflection δ , see Section 5.4		
C_l	rolling moment coefficient, $\mathcal{L}/q_0 S b$		
ΔC_l	increment in C_l due to propellers		
$(\Delta C_l)_s$	total increment in rolling moment coefficient due to slipstream, see Section 4.3		
$(\Delta C_l)_{s \text{ port}}$	increment in rolling moment coefficient due to slipstream from propeller on port wing		
$(\Delta C_l)_{s \text{ starboard}}$	increment in rolling moment coefficient due to slipstream from propeller on starboard wing		
C_{Mth}	thin-aerofoil theory value of pitching moment coefficient about leading edge at zero incidence		
C_T	propeller thrust coefficient, (thrust per propeller)/ $q_s S_P$, see Section 3		
C_T'	propeller thrust coefficient, (thrust per propeller)/ $\rho n^2 D^4$, $C_T' \equiv C_T \pi J^2 / [8(1 - C_T)]$, Equation (5.4)		
C_Y	propeller sideforce coefficient, (sideforce per propeller)/ $q_s S_P$		
C_{Yref}	propeller sideforce coefficient, (sideforce per propeller)/ $q_0 S$		
C_Y'	propeller sideforce coefficient, (sideforce per propeller)/ $\rho n^2 D^4$, (used in Item No. 89047, Reference 10)		

c	local wing chord at propeller station	m	ft
c'	local wing chord at propeller station, including any extension due to flap deployment, see Figures 1 and 2 and Section 5.4	m	ft
c_t	flap chord at propeller station, see Figures 1 to 3 and Section 5.4	m	ft
c_{t1}, c_{t2}	flap chords of double-element flap, see Figure 2	m	ft
D	propeller disc diameter	m	ft
E	ratio of flap chord to extended chord, c_t/c'		
f	double-element flap chord factor, see Figure 3		
G	sideforce derivative function ($\equiv dC_Y'/d\psi_e$ in Item No. 89047, Reference 10)	rad ⁻¹	rad ⁻¹
H_{flap}	centre of incremental lift due to flap, aft of local leading edge, see Section 5.4 and Equation (5.21)	m	ft
H_s	centre of incremental lift due to slipstream, aft of local leading edge, see Section 5.4 and Sketch 5.3a	m	ft
h_p	height in body axes [†] of centre of propeller disc above moment reference centre (negative if below), see Sketch 4.1	m	ft
h_s	height in stability axes [†] of centre of propeller disc above moment reference centre, see Sketch 4.1 and Equation (4.1)	m	ft
i_w	angle between local wing chord and propeller thrust axis, $\alpha_w - \alpha_p$, see Sketch 5.3	deg	deg
J	propeller advance ratio, V/nD		
$\mathcal{L}$	rolling moment in stability axes [†]	N m	lbf ft
L_v	aero-normalised rolling moment derivative due to sideslip, $(\partial \mathcal{L}/\partial v)/\frac{1}{2}\rho V_0 S b$, written as $dC_l/d\beta$ or $C_{l\beta}$ in some systems [†]		
ΔL_v	increment in L_v due to all propellers, $(L_v)_Y + (L_v)_s$		
$(L_v)_Y$	increment in L_v due to sideforce on all propellers		
$(L_v)_s$	increment in L_v due to slipstream from all propellers		
N_p	number of propellers		
n	propeller rotational speed	rev/s	rev/s
q_0	freestream kinetic pressure, $\frac{1}{2}\rho V_0^2$	N/m ²	lbf/ft ²

[†] See Item No. 86021, Reference 8, for an introduction to aircraft body axes, stability axes and aero-normalised derivatives.

q_s	mean kinetic pressure in fully-developed slipstream, $\frac{1}{2}\rho V_s^2$	N/m ²	lbf/ft ²
R	propeller disc radius, $D/2$	m	ft
S	reference wing area	m ²	ft ²
S_P	propeller disc area, $\pi D^2/4$	m ²	ft ²
T	thrust of one propeller	N	lbf
T_C	alternative symbol for thrust coefficient, see Section 3		
V_a	velocity of slipstream at propeller disc	m/s	ft/s
V_s	velocity of air in fully-developed slipstream	m/s	ft/s
V_0	freestream velocity	m/s	ft/s
v	sideslip velocity in stability axes [†]	m/s	ft/s
$OXYZ$	stability axes system [†] with origin at moment reference centre		
$Oxyz$	body axes system [†] with origin at moment reference centre and Ox axis parallel to aircraft horizontal datum		
x_{le}	distance in body axes [†] from centre of propeller disc to leading edge of wing at propeller station, see Sketch 5.3a	m	ft
x_P	distance in body axes [†] of centre of propeller disc ahead of moment reference centre, see Sketch 4.1	m	ft
x_s	distance in stability axes [†] from centre of propeller disc to centre of lift increment due to slipstream, see Sketches 4.3 and 5.3a, and Equation (5.23)	m	ft
Y_P	sideforce from one propeller in Y direction, see Sketch 4.1a	N	lbf
y_P	distance in stability axes [†] of centre of propeller disc from centre line of aircraft (always positive as used), see Sketch 4.3	m	ft
α	angle of attack of Ox body axis [†] (and aircraft horizontal datum), see Sketch 4.1	deg	deg
α_P	angle of attack of propeller thrust axis, see Sketch 5.3	deg	deg
α_s	angle of fully-developed slipstream to propeller thrust axis, see Sketch 5.3	deg	deg
α_W	angle of attack of wing section chord line at propeller station, see Sketch 5.3	deg	deg

[†] See Item No. 86021, Reference 8, for an introduction to aircraft body axes, stability axes and aero-normalised derivatives.

α_z	angle of attack of slipstream to zero-lift line of wing section at propeller station, see Sketch 5.3b	deg, rad	deg, rad
α_0	angle of attack of zero-lift line of wing section at propeller station, see Sketch 5.3b	deg	deg
β	sideslip angle [†] , $\sin^{-1}(v/V_0)$, (as β_P in Item No. 06013, Derivation 2)	deg, rad	deg, rad
β_s	sideslip angle of fully-developed slipstream to propeller thrust axis, see Sketch 5.2	deg, rad	deg, rad
β_0	blade pitch angle referred to zero-lift line of blade section at 75% of propeller blade radius, see Item No. 89047, Reference 10	deg	deg
δ	flap deflection angle, measured in streamwise plane, see Figures 1 and 2	deg, rad	deg, rad
δ_1, δ_2	flap deflection angles for double-element flap, see Figure 2	deg, rad	deg, rad
ρ	density of air	kg/m ³	slug/ft ³
σ_e	propeller effective solidity, ratio of average blade element area to annulus area at 75% of propeller blade radius, see Item No. 89047, Reference 10		
σ_P	lateral angle of fully-developed slipstream relative to freestream, Equation (5.10)	deg, rad	deg, rad
ϕ	angular measure of flap chord ratio, $\cos(\phi) = 2E - 1$	rad	rad
ψ	yaw angle (also as ψ_e in Item No. 89047, Reference 10, and ψ_P in Item No. 06013, Derivation 2)	rad	rad

[†] See Item No. 86021, Reference 8, for an introduction to aircraft body axes, stability axes and aero-normalised derivatives.

2. INTRODUCTION

Multi-engined propeller driven aircraft are known to suffer from a reduction in lateral stability due to sideslip (the “dihedral effect”, L_v), particularly at a combination of high power and large flap angle. An example which arises during certification is the baulked-landing case.

The origins of this effect are discussed in Section 4, which shows it to be dominated by the propeller slipstream passing over the wing. A method of estimating its magnitude in the linear range is presented in Section 5. Non-linearities due to flap end effects are illustrated in Section 6, and further general limitations are discussed in Section 7. The Derivation and References are given in Section 8. A worked example is provided in Section 9.

3. THRUST COEFFICIENT

There are many forms of the definition of “thrust coefficient” currently in use, usually denoted by either C_T or T_C . These are variously defined as either “thrust per propeller” or “total thrust”, normalised by either aircraft parameters (wing area, freestream velocity, *etc*) or propeller parameters (disc diameter, rotational speed). Each definition is useful in different circumstances, but care must be taken to establish which is being used in a particular application.

This Data Item follows the convention of Item No. 88031, Reference 9:-

$$C_T = T/(q_s S_p), \quad (3.1)$$

where T is the thrust per propeller, q_s is the mean kinetic pressure in the fully-developed slipstream and S_p is the propeller disc area. Using actuator theory this definition can be more conveniently written as

$$C_T = \frac{T/S_p}{(T/S_p) + q_0}, \quad (3.2)$$

which shows that $C_T = 1$ whenever $q_0 = 0$, *i.e.* the static condition.

An alternative form is

$$C_T = 1 - (V_0^2/V_s^2) = 1 - q_0/q_s, \quad (3.3)$$

from which the fully-developed slipstream velocity, V_s , can be obtained for a given C_T .

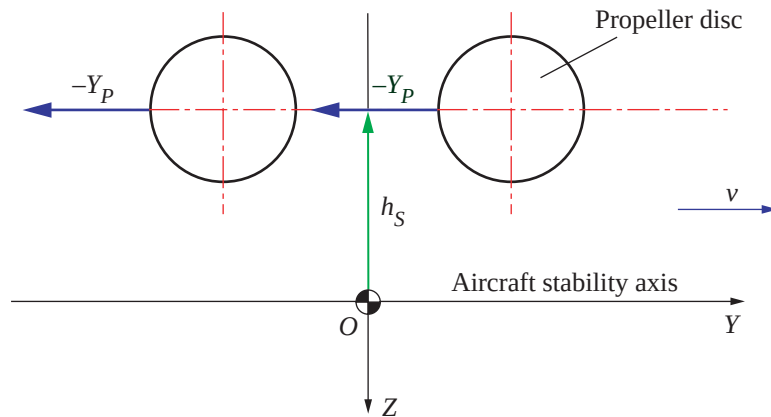
4. FORCES AND MOMENTS IN SIDESLIP

There are two main contributions to rolling moment arising from propellers in sideslip, that due to in-plane forces at the propeller, and that due to the slipstream effect on the wing in the wake of the propeller. The latter is the dominant effect and forms the main body of this Data Item. For illustrative purposes a conventional twin-engined configuration is used.

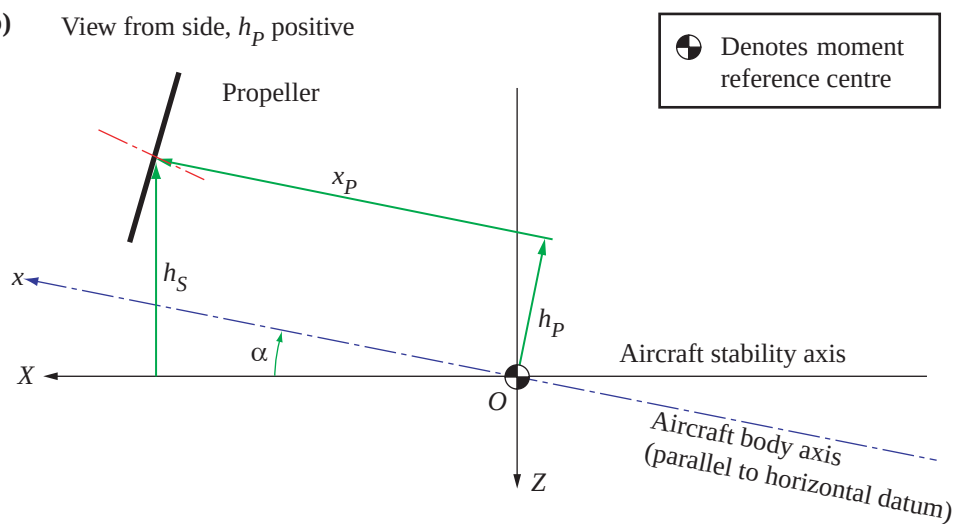
4.1 Propeller Sideforce Effect

A propeller in sideslip will develop a sideforce *in the plane of the disc* acting down-wind. This consists of two contributions, one of which is “power-off” while the other is a function of power (see Equation (4.1) of Item No. 89047, Reference 10, for example). The “power-off” (but propellers on) term may possibly be included in the stability characteristics of the basic aircraft. The sideforce will contribute to rolling moment, see Sketch 4.1a. Although the effect is small on conventional aircraft, it could be significant with a high thrust line and low vertical centre of gravity.

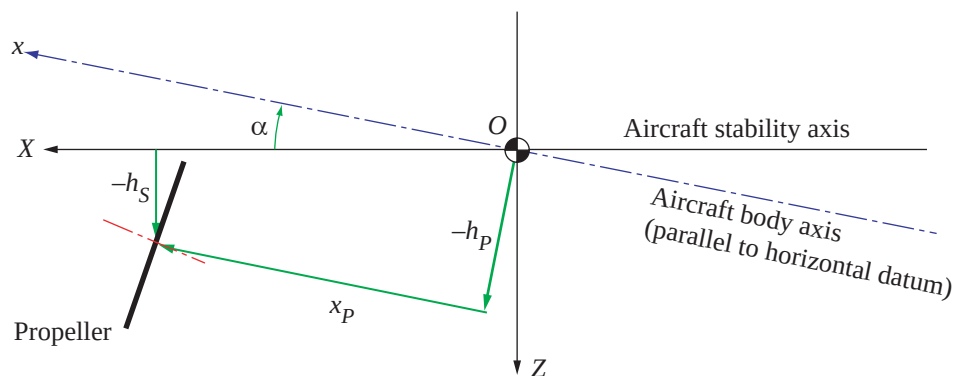
(a) View from rear, h_S positive



(b) View from side, h_P positive



(c) View from side, h_P negative



Sketch 4.1 Contribution of sideforce to rolling moment

For an individual propeller in aircraft body axes, let the height of the centre of the propeller disc be a distance h_P above the aircraft body axis Ox , and a distance x_P forward of the moment reference centre (stability axis origin) O as shown in Sketch 4.1b. Then at an angle of attack α , in stability axes the height of the propeller disc centre above the OX -axis is given by

$$h_S = h_P \cos(\alpha) + x_P \sin(\alpha). \quad (4.1)$$

The same equation holds, with h_P negative in value, if the centre of the propeller disc is below the Ox body axis, as in Sketch 4.1c.

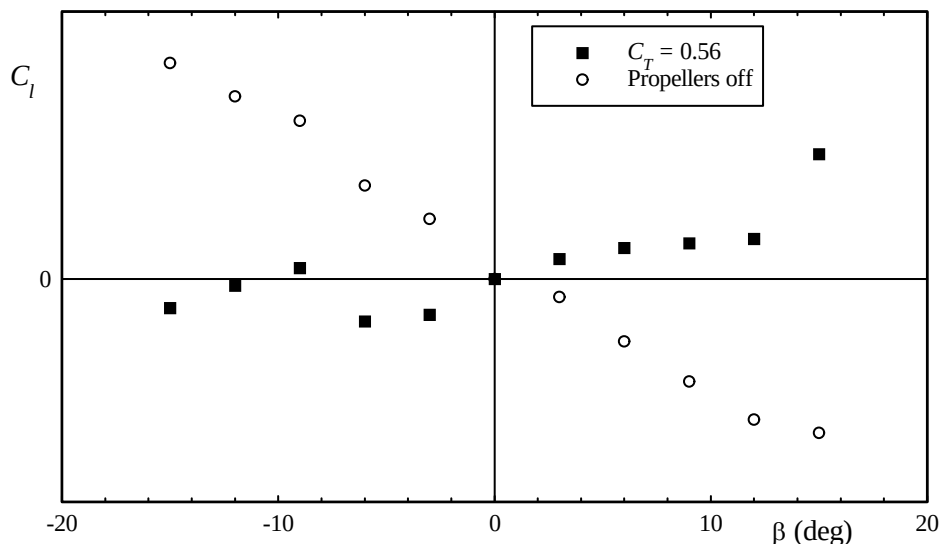
Now, using the sideforce derivative $dC_{Yref}/d\beta$, where C_{Yref} is the sideforce coefficient per propeller based on q_0 and reference wing area S , the aero-normalised rolling moment derivative due to sideslip is

$$(L_v)_Y = \sum_1^{N_P} [(dC_{Yref}/d\beta)h_S/b], \quad (4.2)$$

where N_P is the number of propellers (note that in the multi-engined case the geometry of each symmetric propeller pair may differ).

4.2 Slipstream Effect

For high-powered aircraft with powerful flaps (for example a twin turbo-prop transport type), the slipstream effect is by far the more dominant and can lead to a complete elimination of the conventional wing “dihedral effect”. To illustrate this, wind-tunnel results from Derivation 3 are presented in Sketch 4.2 for a typical twin-engined airliner in the landing configuration (large flap deflection and high power).



Sketch 4.2 Effect of power on rolling moment in sideslip

The open symbols depict the generally linear, stable (negative gradient) characteristic of the basic aircraft. However, at high power (solid symbols) the stability is at best neutral, tending to become unstable at high sideslip angles. This characteristic is confirmed qualitatively by flight test, and is typical of this class of aircraft. It should be noted that these results, in going from “propellers off” to the full power case embrace