



Propeller/body interaction for thrust and drag

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PROPELLER/BODY INTERACTION FOR THRUST AND DRAG

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PROPELLER/BODY INTERACTION FOR THRUST AND DRAG

1. NOTATION AND UNITS

		SI	British
A	propeller disc area, $\pi d^2/4$	m^2	ft^2
C_{Dnp0}	drag coefficient of body in absence of propeller flow, $D_{np0}/(\frac{1}{2}\rho V_0^2 S_n)$		
C_P	power coefficient, $P/\rho n^3 d^5$		
D_{np0}	body drag in absence of propeller flow	N	lbf
ΔD_{ng}	component of ΔD_{ns} arising from pressure gradient in propeller flow ("buoyancy force")	N	lbf
ΔD_{ns}	increment in body drag due to propeller flow-induced effects	N	lbf
ΔD_{nv}	component of ΔD_{ns} arising from increased local velocities due to propeller flow	N	lbf
d	propeller disc diameter	m	ft
d_n	maximum diameter of axisymmetric body or maximum diameter of equivalent axisymmetric body, $(4S_n/\pi)^{1/2}$	m	ft
d_{sp}	spinner diameter in propeller disc plane	m	ft
F	coefficient of thrust-independent drag interaction, see Equation (3.4)		
G	coefficient of thrust-dependent drag interaction, see Equations (3.4) and (4.2)		
G_1	coefficient associated with ΔD_{nv} , see Equation (4.2)		
G_2	coefficient associated with ΔD_{ng} , see Equation (4.2)		
h	fractional reduction in mass flow through propeller due to body blockage		
J	propeller advance ratio, V_0/nd		
J_{eff}	effective free-air value of J allowing for body blockage, $J(1-h)$		
n	propeller rotational speed	rev/s	rev/s
P	power input to propeller	N m/s	ft lbf/s

S_n	maximum cross-sectional area of body	m^2	ft^2
T'_{cSn}	shaft thrust coefficient based on propeller disc area, $T_{Sn}/\rho V_0^2 A$		
T_{FA}	free-air thrust; axial force exerted by propeller blades in uniform flow field undisturbed by body	N	lbf
T_P	propulsive thrust; shaft thrust diminished by extra zero-lift drag due to propeller flow of those parts of aircraft immersed in it	N	lbf
T_{Pn}	propulsive thrust for propeller/body combination, see Equation (3.1)	N	lbf
T_S	shaft thrust; axial force exerted by propeller blades in flow field in which they are situated on aircraft	N	lbf
T_{Sn}	shaft thrust for propeller/body combination	N	lbf
V_0	free-stream velocity	m/s	ft/s
V_{eff}	effective free-stream velocity for propeller operating in combination with body, $V_0(1 - h)$	m/s	ft/s
η_{eff}	shaft efficiency corresponding to V_{eff} , $T_{Sn}V_{eff}/P$		
η_{FA}	free-air efficiency, $T_{FA}V_0/P$		
η_P	propulsive efficiency for aircraft, T_PV_0/P		
η_{Pn}	propulsive efficiency for propeller/body combination, $T_{Pn}V_0/P$		
η_S	shaft efficiency for aircraft, T_SV_0/P		
η_{Sn}	shaft efficiency for propeller/body combination, $T_{Sn}V_0/P$		
ρ	air density	kg/m^3	slug/ft^3

2. INTRODUCTION

This Item provides a simple means of estimating the interaction effects in terms of thrust and drag between a propeller and the body (or nacelle) on which it is mounted in either tractor or pusher configuration at zero angle of attack. In practice it is usually assumed that the interaction effects are invariant with angle of attack, for moderate angles (up to 10 degrees, say). Estimation of the interaction effects is a necessary part of the determination of propulsive thrust, which has traditionally been used in the UK in the evaluation of excess thrust for the aircraft, *i.e.* (total installed thrust for the aircraft) – (aircraft drag with propellers operating), see Section 4.3 of Item No. 85017 (Reference 17). This Item is therefore based on the assumption that propulsive thrust will be required. The other commonly used approach to the evaluation of excess thrust, particularly in the USA, involves the separate estimation of thrust and drag, and makes use of net thrust, see Section 4.4 of Item No. 85017.

Section 3 provides a development of a general expression for the propulsive thrust of a propeller/body combination and includes a detailed discussion of the factors affecting the interaction effects on propeller thrust and body drag. Section 4 provides a practical means of estimating the interaction effects involved in the evaluation of propulsive thrust and shaft thrust for either single- or counter-rotation propellers in tractor- or pusher-mounted configurations. The physical model implied in the method for estimating the interaction effects is a simple one based on the assumption of a mean flow velocity at any cross-section in the propeller streamtube. It is therefore an axisymmetric model which does not consider the pulsating flow effects at a point on the body due to individual blade wakes.

The applicability and accuracy of the methods of Section 4 are discussed in Section 5 and a detailed worked example illustrating the use of the Item is given in Section 7.

3. PROPULSIVE THRUST FOR A PROPELLER/BODY COMBINATION

As noted in the Introduction, Section 4.3 of Item No. 85017 (Reference 17) deals with the current approach to the evaluation of aircraft excess thrust in the UK using propulsive thrust. In the determination of propulsive thrust for this purpose it is common practice to assume that the body (or nacelle) interference is the most significant. Further approximations are made in assuming that body blockage has the most significant effect on free-air thrust, while body lift is negligibly small so that any induced effects on thrust and drag are also negligible. These assumptions lead to Equation (4.9b) of Item No. 85017 for propulsive thrust, which, for an individual powerplant, becomes

$$T_{Pn} = T_{Sn} - \Delta D_{ns}, \quad (3.1)$$

which can be rewritten as,

$$\frac{T_{Pn}}{T_{Sn}} = 1 - \frac{\Delta D_{ns}}{T_{Sn}}. \quad (3.2)$$

Here T_{Pn} is the propulsive thrust, T_{Sn} is the shaft thrust and ΔD_{ns} is the increment in body drag due to the propeller flow, given by

$$\Delta D_{ns} = \Delta D_{nv} + \Delta D_{ng} \quad (3.3)$$

in which ΔD_{nv} is the component arising from the increased local velocities, both axial and rotational, due to the propeller flow and ΔD_{ng} is the so-called "buoyancy force" arising from the pressure gradient in the slipstream.

Analysis of test data shows (see Reference 8, for example) that, to a good approximation, the effect of propeller flow on body drag is a linear function of propeller shaft thrust, *i.e.*

$$\frac{D_{np0} + \Delta D_{ns}}{D_{np0}} = F + GT'_{cSn} \quad (3.4)$$

where D_{np0} is the body drag with propeller-off and T'_{cSn} is a shaft thrust coefficient defined as

$$T'_{cSn} = T_{Sn} / \rho V_0^2 A. \quad (3.5)$$

The coefficients F and G would be expected to depend on the body geometry, the position of the propeller on the body and, to some extent, on the propeller design. With regard to this last possibility it should be noted that, depending on the propeller characteristics, putting $T'_{cSn} = 0$ in Equation (3.4) does not necessarily imply that there is no effect on body drag. For this and other reasons F is not necessarily unity, although for most practical cases it can be assumed so (see Section 3.1).

Equation (3.4) can be rearranged, and use made of Equation (3.5), to give

$$\frac{\Delta D_{ns}}{T_{Sn}} = \frac{D_{np0}}{T_{Sn}}(F-1) + \frac{D_{np0}}{\rho V_0^2 A} G, \quad (3.6)$$

which can be further modified, again using Equation (3.5), and a drag coefficient defined by

$$C_{Dnp0} = D_{np0} / \frac{1}{2} \rho V_0^2 S_n \quad (3.7)$$

to give

$$\frac{\Delta D_{ns}}{T_{Sn}} = \frac{1}{2} \frac{S_n}{A} \frac{C_{Dnp0}}{T'_{cSn}} (F-1) + \frac{1}{2} \frac{S_n}{A} C_{Dnp0} G. \quad (3.8)$$

Substitution of Equation (3.8) in Equation (3.2) then gives

$$\frac{T_{Pn}}{T_{Sn}} = 1 - \frac{1}{2} \frac{S_n}{A} \frac{C_{Dnp0}}{T'_{cSn}} (F-1) - \frac{1}{2} \frac{S_n}{A} C_{Dnp0} G. \quad (3.9)$$

It is possible to rewrite T'_{cSn} in terms of the corresponding efficiency, η_{Sn} , i.e.

$$T'_{cSn} = \frac{d^2}{A} \frac{C_P}{J^3} \eta_{Sn} \quad (3.10)$$

where $J (= V_0/nd)$ is the advance ratio and $C_P (= P/\rho n^3 d^5)$ is the propeller power coefficient.

Equation (3.9) therefore becomes

$$\boxed{\frac{T_{Pn}}{T_{Sn}} = 1 - \frac{1}{2} \frac{S_n}{A} \frac{J^3}{C_P} \frac{C_{Dnp0}}{\eta_{Sn}} (F-1) - \frac{1}{2} \frac{S_n}{A} C_{Dnp0} G.} \quad (3.11)$$

3.1 The Factors Affecting F and G

As noted earlier in Section 3, although the value of F might be expected to be unity from an inspection of Equation (3.4) when $T'_{cSn} = 0$, it is not necessarily so. In addition to the possible effects of the propeller characteristics at zero thrust already mentioned, other factors can affect the value of F . It can be significantly greater than unity, particularly for a tractor propeller configuration, if the body were of a smoothly-contoured low-drag form. For such a body the immersion in a highly turbulent propeller flow would be expected to: