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Introduction to installation effects on thrust and drag for propeller-driven aircraft

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INTRODUCTION TO INSTALLATION EFFECTS ON THRUST AND DRAG FOR PROPELLER-DRIVEN AIRCRAFT

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. INTRODUCTION	3
3. DIMENSIONLESS COEFFICIENTS	4
4. PROPELLER THRUST AND EFFICIENCY IN FREE AIR	4
4.1 Losses Involved in Free-air Thrust and Efficiency	5
4.1.1 Propeller flow field	5
4.1.2 Sources of energy loss	6
4.1.3 Determination of η_i	6
4.2 Effect of Propeller Design on Free-air Efficiency	7
5. EFFECTS OF PROPELLER INSTALLATION	8
5.1 Propeller-body Interference	9
5.1.1 Tractor propeller	9
5.1.2 Pusher propeller	11
5.1.3 Intermediate arrangement	12
5.2 Propeller-nacelle-wing Interference	12
5.2.1 Nacelle-wing interference	12
5.2.2 Propeller-wing interference for a tractor propeller	12
5.2.3 Propeller-wing interference for a pusher propeller	13
5.3 Other Interference Effects	14
5.3.1 Cooling air inlets	14
5.3.2 Intakes for turbine engines	14
5.3.3 Jet exhausts	15
5.3.4 Undercarriage	15
6. REFERENCES	15
APPENDIX A PROPELLER INFLOW AND SLIPSTREAM CHARACTERISTICS USING SIMPLE AXIAL MOMENTUM THEORY ¹⁸	
A1. ADDITIONAL NOTATION AND UNITS	18
A2. INTRODUCTION	20
A3. SIMPLE AXIAL MOMENTUM THEORY	20
A4. ADDITIONAL REFERENCES	23

INTRODUCTION TO INSTALLATION EFFECTS ON THRUST AND DRAG FOR PROPELLER-DRIVEN AIRCRAFT

1. NOTATION AND UNITS

		SI	British
AF	activity factor, per blade, $\frac{10^5}{d^5} \int_{r_{root}}^{r_{tip}} cr^3 dr$		
C_P	power coefficient, $P/\rho n^3 d^5$ (P in N m/s or ft lbf/s)		
C_Q	torque coefficient, $Q/\rho n^2 d^5$		
C_T	thrust coefficient, $T/\rho n^2 d^4$		
c	propeller blade chord at distance r from axis of rotation	m	ft
d	propeller disc diameter	m	ft
ΔD_g	component of ΔD_s arising from pressure gradient in slipstream ("buoyancy force")	N	lbf
ΔD_s	increment in body drag due to slipstream	N	lbf
ΔD_v	component of ΔD_s arising from increased local velocities due to slipstream	N	lbf
J	advance ratio, V_0/nd		
n	propeller rotational speed	rev/s	rev/s
n_b	number of blades per propeller		
P	power input to propeller	kW, N m/s	hp, ft lbf/s
ΔP_i	power loss arising from inviscid flow effects, <i>i.e.</i> loss associated with kinetic energy of slipstream ("induced loss"), see Equation (4.1)	kW, N m/s	hp, ft lbf/s
ΔP_p	power loss arising from effects of viscous flow, <i>i.e.</i> loss associated with profile drag of propeller blades ("profile loss"), see Equation (4.1)	kW, N m/s	hp, ft lbf/s
Q	propeller shaft torque	N m	lbf ft
r	radial distance along blade	m	ft
r_{root}	radial distance to blade root (spinner radius)	m	ft

Issued June 1985
With Amendments A and B, August 2006 - 24 pages
This page Amendment B

r_{tip}	radial distance to blade tip ($d/2$)	m	ft
T	propeller thrust	N	lbf
T_{FA}	“free-air” thrust, <i>i.e.</i> axial aerodynamic force exerted by propeller blades in uniform flow field undisturbed by nacelle or other structure, see Section 4	N	lbf
T_N	net thrust, see Section 5.1.1 and Equation (5.4)	N	lbf
T_P	propulsive thrust, <i>i.e.</i> shaft thrust diminished by extra zero-lift drag due to slipstream of those parts of aircraft immersed in it, see Section 5.1.1	N	lbf
T_S	shaft (or “apparent”) thrust, <i>i.e.</i> axial aerodynamic force exerted by propeller blades in flow field in which they are situated as installed on aircraft, see Section 5.1.1	N	lbf
TAF	total activity factor for propeller, $n_b AF$		
V_0	free-stream velocity	m/s	ft/s
V_{tip}	propeller blade tip speed, πnd	m/s	ft/s
η	propeller efficiency; ratio of useful work done by propeller to total work input to propeller, see Equations (3.4) and (3.8)		
η_{FA}	free-air, or uninstalled, propeller efficiency, see Equations (4.2) and (4.4)		
η_i	ideal induced efficiency, see Equation (4.5)		
η_N	net efficiency, see Section 5.1.1		
η_P	propulsive efficiency, see Section 5.1.1		
η_S	shaft (or “apparent”) efficiency, see Section 5.1.1		
$\Delta\eta_{axial}$	loss in propeller efficiency due to kinetic energy of slipstream axial flow component		
$\Delta\eta_i$	loss in propeller efficiency in inviscid flow, being loss associated with kinetic energy of slipstream (“induced loss”), see Equation (4.3)		
$\Delta\eta_p$	loss in propeller efficiency due to blade profile drag		
$\Delta\eta_{swirl}$	loss in propeller efficiency due to kinetic energy of slipstream rotational flow component (swirl)		

ρ	air density	kg/m^3	slug/ft^3
ρ_0	air density at sea level in International Standard Atmosphere	kg/m^3	slug/ft^3
σ	density ratio, ρ/ρ_0		

2. INTRODUCTION

The main aims of this Item are to present the various definitions of thrust in common use for propeller-driven aircraft, to describe the ways in which the thrust of a propeller is modified by its installation in an aircraft and to discuss some of the effects of the installation on drag.

As an aid to the discussions in the Item the various dimensionless parameters used in propeller performance work are introduced in Section 3.

Traditionally, the first step in predicting what the thrust of an aircraft propeller would be in its intended installation has been to acquire a knowledge of its “free-air” thrust. This is discussed in Section 4.

Installing the propeller on an aircraft results in mutual interference with the engine nacelle and other parts of the airframe. The types and relative magnitudes of the various interferences will depend very considerably on the installation; for example on whether the propeller is tractor-mounted or pusher-mounted and on whether the powerplant is fuselage- or wing-mounted. Section 5 deals with the numerous installation effects on propeller thrust and efficiency together with some of the associated effects on drag.

Different qualifying adjectives are used to describe the various thrusts, particularly in relation to the mutual interference effects, and it is essential that they are carefully defined in order to avoid ambiguity. The importance of this is illustrated by the fact that, whereas the manufacturer of smaller propellers for the light aircraft section of the industry will normally quote free-air thrust values, the manufacturer serving the large transport aircraft section of the industry will usually take some account of the particular installation when predicting propeller performance. Indeed, in the case of the propeller designed for operation at high subsonic speeds, it is necessary to allow for the presence of the nacelle in order to produce an optimum design.

The foregoing discussion points to the wider need for a framework for thrust/drag accounting (commonly, and appropriately, called “book-keeping”) to be used in aircraft performance estimation and in the evaluation of flight and wind-tunnel test data. Such a framework for the various components of thrust and drag ensures that no component is overlooked and that none is counted twice. Chapter 2 of Reference 15 and Appendix A of Reference 28 provide detailed thrust and drag book-keeping schemes for turbo-jet and turbo-fan propulsion systems. Item No. 85017 (Reference 27) provides a scheme to account for propeller/airframe interference.

In the preparation of the present Item a number of references, listed in Section 6, have been used. Considerable background material was obtained from References 6, 9, 16, 20 and 21 in particular.

3. DIMENSIONLESS COEFFICIENTS

Before discussing propeller free-air thrust and efficiency and the effects of installation it is helpful to introduce a number of dimensionless coefficients used in propeller performance work.

$$\text{Thrust coefficient, } C_T = \frac{T}{\rho n^2 d^4}. \quad (3.1)$$

$$\text{Power coefficient, } C_P = \frac{P}{\rho n^3 d^5}. \quad (3.2)$$

$$\text{Advance ratio, } J = \frac{V_0}{nd}. \quad (3.3)$$

In the above equations P is the power input to the propeller (in N m/s or ft lbf/s) and n is the propeller rotational speed (in revolutions per second).

The propeller efficiency, which is defined as $\eta = TV_0/P$, can also be expressed in terms of C_T , C_P and J through Equations (3.1) to (3.3), i.e.

$$\eta = \frac{C_T}{C_P} J. \quad (3.4)$$

The advance ratio is a measure of the local flow angle at the blade tip, since J/π is the tangent of the angle made by the resultant of the blade tip speed (πnd) and the forward speed with the propeller disc plane.

In some presentations of propeller performance use is made of a torque coefficient, C_Q , instead of power coefficient.

$$C_Q = \frac{Q}{\rho n^2 d^5} \quad (3.5)$$

in which Q is the propeller shaft torque. Since

$$P = 2\pi nQ, \quad (3.6)$$

$$\text{then } C_P = 2\pi C_Q, \quad (3.7)$$

which leads to the alternative expression for propeller efficiency,

$$\eta = \frac{C_T}{2\pi C_Q} J. \quad (3.8)$$

4. PROPELLER THRUST AND EFFICIENCY IN FREE AIR

The **free-air thrust**, T_{FA} , of a propeller is the axial aerodynamic force that would be generated by the propeller blades in isolation. The assumptions are that the propeller is operating in a uniform flow with an undistorted inflow and a slipstream free of disturbance caused by the proximity of any engine nacelle or other airframe surface. It is obtained from theoretical calculations which usually ignore the spinner. The closest that it can be realised in practice is via wind-tunnel tests to obtain **minimum-body thrust**.

This page Amendment B

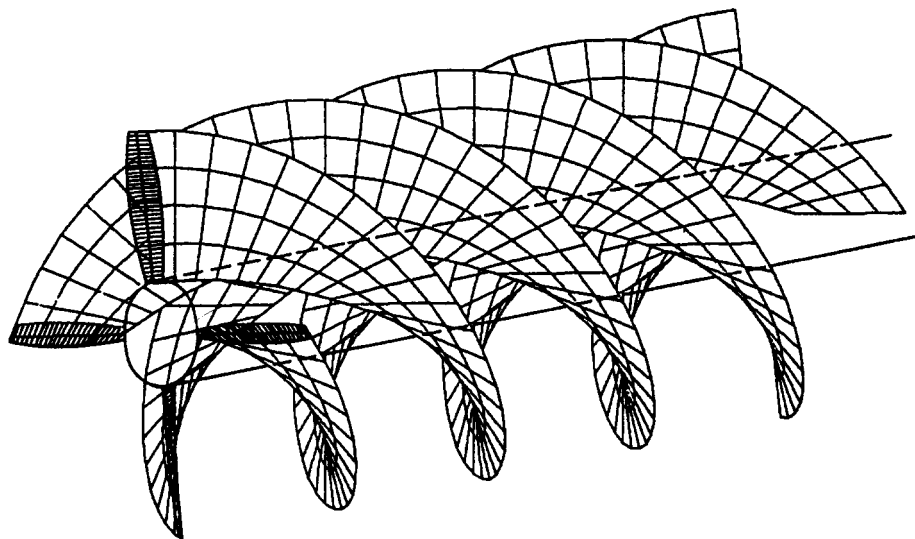
Minimum-body thrust is a common form of wind-tunnel data obtained from tests of a propeller/body combination in which the body (necessary to house the propeller drive shaft) is chosen to present the minimum of disturbance to the uniform flow field in the absence of the propeller blades. The ideal set-up, offering no significant interference, would be one in which the propeller is mounted in the middle of a long, non-rotating, cylinder of diameter equal to that of a spinner base for aircraft application. However, for practical reasons the upstream half of the cylinder is most commonly replaced by a rotating spinner, which, if it is sufficiently slender, will introduce little disturbance to the flow into the propeller. In such tests the measured thrust of the propeller/spinner combination is sometimes taken as the minimum-body thrust. However, in order to obtain a closer approximation to free-air thrust, the usually small drag of the spinner, blades off, is often added to the measured thrust.

4.1 Losses Involved in Free-air Thrust and Efficiency

Although the treatment of propeller performance prediction is considered to be outside the scope of this Item, a brief look at some of the physical principles involved will help in the understanding of the thrust losses in free-air and their associated propeller efficiencies.

4.1.1 Propeller flow field

The flow field associated with each blade of a propeller rotating with its axis aligned to a uniform stream is similar in many respects to that associated with a wing. The local lift at any radial station on a blade is associated with the circulation around the blade. As with a wing the circulation around the blade (the bound vorticity) varies along the blade from root to tip resulting in the shedding of a sheet of vortex filaments from the blade trailing edge (trailing vorticity). The vortex sheet (wake) from each blade passes downstream in an approximately helicoidal path, and, in association with the wakes from the other blades, forms the slipstream, see Sketch 4.1.



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Sketch 4.1 Simplified blade helicoidal wakes

Because the blade trailing vorticity arises from a sheet of closely spaced vortex filaments, each of which is free to move under the influence of the other filaments and the bound vortex, the tendency is for the slipstream boundary to contract as the sheet moves downstream. The amount of slipstream contraction is very dependent on the propeller loading and forward speed, becoming greater as the disc loading increases and as the speed decreases. The blade wake is likely to become unstable as it progresses downstream, rolling up into discrete vortices corresponding to the root and tip.

This page Amendment B

The helicoidal vortex sheets springing from the trailing edges of the blades induce local velocity components at the blades, which are vectorially additive to the free-stream velocity and the local rotational velocity of the blades. The lift on the propeller blades, which is the major influence on the thrust and torque generated by the propeller, is therefore affected by a complicated system of vorticity associated with the propeller flow field.

4.1.2 Sources of energy loss

The input power to the propeller is here denoted P . In order to generate thrust the propeller blades have to impart an increase in momentum to the flow in the slipstream, and there is an energy loss associated with the total kinetic energy of the slipstream. This “induced loss”, which would be present even in inviscid flow, is here denoted ΔP_i . In real viscous flows an additional source of energy loss arises from the momentum deficit in the wake behind the propeller blades, *i.e.* a loss due to the profile drag of the blades, here denoted ΔP_p .

The useful work done by the propeller in free air, which is the product of the free-air thrust and the forward speed of the propeller, is equal to the useful work input to the propeller, *i.e.*

$$T_{FA}V_0 = P - \Delta P_i - \Delta P_p. \quad (4.1)$$

The **propeller efficiency** in free air, η_{FA} , is defined as the ratio of the useful work done by the propeller in free air to the total work input, *i.e.*

$$\begin{aligned} \eta_{FA} &= \frac{T_{FA}V_0}{P} = 1 - \frac{\Delta P_i}{P} - \frac{\Delta P_p}{P} \\ &= 1 - \Delta\eta_i - \Delta\eta_p. \end{aligned} \quad (4.2)$$

In Equation (4.2) $\Delta\eta_p$ is the total loss in efficiency arising from blade profile drag, commonly called the “profile loss”, and the “induced loss” $\Delta\eta_i$ is the total loss in efficiency arising from inviscid flow effects, induced by the helicoidal vortex sheets shed from the blades. The loss $\Delta\eta_i$ can be further split into components due to axial and rotational (or swirl) velocities, *i.e.*

$$\Delta\eta_i = \Delta\eta_{axial} + \Delta\eta_{swirl}, \quad (4.3)$$

so that Equation (4.2) becomes

$$\eta_{FA} = 1 - \Delta\eta_{axial} - \Delta\eta_{swirl} - \Delta\eta_p. \quad (4.4)$$

For propellers designed to operate at high subsonic speeds, local compressibility effects can also cause loss of efficiency and these are considered as part of the profile loss.

4.1.3 Determination of η_i

The exact theoretical determination of even the induced loss in η_{FA} using the realistic vortex model described in Section 4.1.1 has not yet been achieved for the wide ranges of propeller loadings and operating conditions of practical interest. Current work is proceeding along the lines of the lifting-surface treatment of wings, see for example References 11, 22 and 26.