

ESTIMATION OF WINDMILLING DRAG AND AIRFLOW OF TURBO-JET AND TURBO-FAN ENGINES

1. NOTATION AND UNITS^{*†}

		SI	British
A	cross-sectional area [*]	m ²	ft ²
$\mathcal{A}$	airflow function defined in Section 3.2		
$C_{D_{wm}}$	windmilling drag coefficient, $D_{wm}/(\gamma p M^2 A_2/2)$		
$C_{D_{theory}}$	theoretical internal drag coefficient of inoperative engine defined in Equation (A4.13)		
$\Delta C_{D_{wm}}$	incremental windmilling drag coefficient, $\Delta C_{D_{wm}} = C_{D_{theory}} - C_{D_{wm}}$		
D_{wm}	windmilling drag	N	lbf
D_{theory}	theoretical internal drag of inoperative engine defined in Equation (A4.10)	N	lbf
$f(M)$	Mach number function defined in Equation (3.3)		
$f_{N_{s,0}}$	uninstalled net thrust of engine at maximum rating at ISA sea-level static conditions	N	lbf
g_0	standard sea-level value of acceleration due to gravity (see Table in Section 3.2 for numerical values)	m/s ²	ft/s ²
H_p	pressure height	m	ft
M	Mach number [*]		
$\dot{m}$	mass airflow through inoperative engine [†]	kg/s	slug/s
p	static pressure [*]	N/m ²	lbf/ft ²
p_t	total pressure [*]	N/m ²	lbf/ft ²
R	gas constant for air (see Table in Section 3.2 for numerical values)	N m/kg K	lbf ft/slug K
T	static temperature [*]	K	K

^{*} No subscript is used when considering ambient, free-stream or upstream infinity conditions.

[†] The equations and figures in this Item are presented in forms that allow the airflow of an *inoperative* (or windmilling) engine to be estimated in either mass or weight terms in both SI and British units. However, for the purpose of defining engine specific thrust, airflow is considered as a *weight* flow so that the specific thrust is expressed in the same units (seconds) in both SI and British units. This follows the practice adopted in Item No. 76034 and is justified by the resulting simplification of the figures.

Issued June 1981
With Amendment A, April 1984

T_t	total temperature [*]	K	K
$\dot{w}$	weight airflow through inoperative engine [†]	N/s	lbf/s
$\dot{w}_{s,0}$	weight airflow through engine at maximum rating [†] at ISA sea-level static conditions	N/s	lbf/s
γ	ratio of specific heat capacity at constant pressure to that at constant volume (taken as 1.4 for air)		
ρ	density	kg/m ³	slug/ft ³

Subscripts

<i>theory</i>	denotes value derived from one-dimensional flow analysis (see Appendix A)
<i>zst</i>	denotes value at zero specific thrust
1	denotes value at intake lip (see Item No. 76034)
2	denotes value at engine face (see Item No. 76034)
9	denotes value at nozzle exit (see Item No. 76034)

* No subscript is used when considering ambient, free-stream or upstream infinity conditions.

† The equations and figures in this Item are presented in forms that allow the airflow of an *inoperative* (or windmilling) engine to be estimated in either mass or weight terms in both SI and British units. However, for the purpose of defining engine specific thrust, airflow is considered as a *weight* flow so that the specific thrust is expressed in the same units (seconds) in both SI and British units. This follows the practice adopted in Item No. 76034 and is justified by the resulting simplification of the figures.

2. INTRODUCTION

This Item presents a method for estimating the internal[‡] drag and airflow of turbo-jet and turbo-fan engines in windmilling and, to a lesser extent, locked-rotor conditions. It is intended for use in the assessment of aircraft performance with one or more engines inoperative. Although the Item can be used for any flight conditions, those of greatest interest are likely to be during take-off, climb, and landing. However, it can also be used for cruise conditions, for example, ferry flights or “drift-down” with one or more engines inoperative. No intake or other “installation” effects have been considered in this Item.

For a more complete assessment of the installed performance of an inoperative engine, other factors must be taken into consideration, for example, spillage drag and the conditions downstream of the nozzle exit into which the flow exhausts. A suitable method for estimating spillage drag at $M < 1$ for a wide range of axisymmetric intakes is given in Item No. 84004. The combined usage of the spillage drag data of Item No. 84004 and the internal drag and airflow data of the present Item to estimate the total drag of an inoperative turbo-jet or turbo-fan engine is described in Item No. 84005. Note that the second of the examples in Section 6 herein is for the engine whose associated intake is the subject of the first example in Item No. 84004.

Information relating to the empirical development of the methods using a one-dimensional flow theory as a basis is given in Appendix A. “Curve-fit” equations to Figures 1 to 3 are given in Appendix B.

[‡] A definition of internal drag arising from windmilling or locked-rotor conditions is given in Section A3 of Appendix A.

3. METHOD FOR FREELY WINDMILLING ENGINE

This section contains details of a method for estimating the windmilling drag and airflow of turbo-jet and turbo-fan engines, based on the correlation of engine manufacturers' test and brochure data. The windmilling drag coefficient, $C_{D_{wm}}$, and airflow function, $\mathcal{A}$, are based on the cross-sectional area of the engine face, A_2 , i.e. the total of the fan or low pressure compressor annulus area and the centre-body area at engine inlet (station 2 in Sketch 1.1, Item No. 76034). Sections 3.1 and 3.2 give procedures for estimating windmilling drag coefficient and windmilling airflow respectively.

The method requires a knowledge of the design specific thrust, $[f_N/\dot{w}]_{s,0}$, at maximum rating at ISA sea-level static conditions and engine face area, A_2 , for the specified engine. If specific thrust data are not available but the bypass ratio is known, reference should be made to Figure 9 in Item No. 76034 for an estimate of $[f_N/\dot{w}]_{s,0}$. If the nozzle exit area, A_9 , is known instead of the engine face area, reference should be made to Figure A1 in Appendix A which provides a means of estimating A_2 from A_9 .

3.1 Estimation of Windmilling Drag Coefficient

For known values of $[f_N/\dot{w}]_{s,0}$ and M , the estimation procedure is as follows:

- (i) Obtain the value of $C_{D_{theory}}$ from Figure 1 using the curve labelled "Free windmilling".
- (ii) Obtain the value of $\Delta C_{D_{wm}}$ from Figure 2.
- (iii) Calculate $C_{D_{wm}}$ using,

$$C_{D_{wm}} = C_{D_{theory}} - \Delta C_{D_{wm}}. \quad (3.1)$$

Note: A single graph can be obtained by combining the curve labelled "Free windmilling" of Figure 1 with Figure 2 to give the relationship between $C_{D_{wm}}$, $[f_N/\dot{w}]_{s,0}$, and M directly, but its shape results in a loss of clarity.

3.2 Estimation of Windmilling Airflow

Figure 3 shows the airflow function, $\mathcal{A}$, plotted against design specific thrust, $[f_N/\dot{w}]_{s,0}$, at maximum rating at ISA sea-level static conditions and freestream Mach number, M , where

$$\mathcal{A} = \frac{\dot{m} \sqrt{RT_t}}{A_2 p_t f(M)} = \frac{\dot{w} \sqrt{RT_t}}{g_0 A_2 p_t f(M)} \quad (3.2)$$

and

$$f(M) = \frac{\sqrt{\gamma} M}{\left[1 + \frac{\gamma-1}{2} M^2\right]^{\frac{\gamma+1}{2(\gamma-1)}}}. \quad (3.3)$$

The effect of using $f(M)$ in the definition of $\mathcal{A}$ is that any further influence of freestream Mach number could be neglected in Figure 1 and is relatively small in Figure 3 (see Appendix A, Sections A4). The following Table gives values of g_0 and R in SI and British units.

	SI	British
g_0	9.806 65 m/s ²	32.1740 ft/s ²
R	287.052 87 N m/kg K	3089.8114 lbf ft/slug K

For known values of $[f_N/\dot{w}]_{s,0}$ and M , the estimation procedure is as follows:

- (i) Obtain the value of $\mathcal{A}$ from Figure 3 using the curves labelled “Free windmilling”.
- (ii) Evaluate $f(M)$ using Equation (3.3).
- (iii) Using values of p and T corresponding to ambient flight conditions evaluate p_t and T_t from the expressions

$$p_t = p \left[1 + \frac{\gamma - 1}{2} M^2 \right]^{\gamma/(\gamma - 1)} \quad (3.4)$$

and

$$T_t = T \left[1 + \frac{\gamma - 1}{2} M^2 \right]. \quad (3.5)$$

- (iv) Evaluate the airflow $\dot{m}$ or $\dot{w}$ using,

$$\dot{m} = \mathcal{A} f(M) A_2 \frac{p_t}{\sqrt{RT_t}} \quad (3.6)$$

$$\text{or} \quad \dot{w} = \mathcal{A} f(M) g_0 A_2 \frac{p_t}{\sqrt{RT_t}}. \quad (3.7)$$

4. NOTES ON CORRELATION OF WINDMILLING DATA

The following Table presents a summary of engines for which windmilling drag and airflow data were available from engine manufacturers' tests and/or brochures. Test data were available for 12 of the 39 engines. Curves drawn through both airflow and drag data are biased towards actual test data. The scatter of the drag data is significantly greater than that of the airflow data. Approximately 80 percent of the windmilling drag data lie within ± 25 percent of the mean curve values presented in Figure 2, and about 80 percent of the windmilling airflow data lie within ± 15 percent of the mean curve values given in Figure 3. It is anticipated that estimates of $C_{D_{wm}}$ obtained using the method of this Item should lie within ± 30 percent of actual values.

Type of engine		Bypass ratio	Design specific thrust at maximum rating at ISA sea-level static conditions, $[f_N/\dot{w}]_{s,0}$ s	Maximum thrust, $f_{N,s,0}$		Number of engines
				SI kN	British lbf	
TURBO-JET	axial compressor	0	54 to 73	31 to 138	7000 to 31 000	15
	centrifugal compressor	0	50	17	3750	1
TURBO-FAN	mixed-stream exhaust	0.3 to 1.0	45 to 65	22 to 80	5000 to 18 000	8
	separate-stream exhaust	1.3 to 6	26 to 45	22 to 222	5000 to 50 000	15

5. THE EFFECT OF POWER OFFTAKE AND LOCKED-ROTOR PERFORMANCE

The effect of taking shaft power from a windmilling engine is to decrease rotational speed and airflow. The airflow reaches a minimum at locked-rotor conditions, *i.e.* when engine rotational speed is zero. The curve labelled “Locked-rotor” in Figure 3 presents values of the airflow function $\mathcal{A}$ plotted against $[f_N/\dot{w}]_{s,0}$ for the locked-rotor condition. Due to paucity of airflow data for this condition (data available for six engines only) the variation of $\mathcal{A}$ with $[f_N/\dot{w}]_{s,0}$ is presented simply as two straight-line segments. The curve labelled “Locked-rotor” in Figure 1 gives values of $C_{D_{theory}}$ plotted against $[f_N/\dot{w}]_{s,0}$ for this condition. No equivalent to Figure 2 for the locked-rotor case is presented, as drag data were only available for two high bypass ratio turbo-fans. These data show that, despite the reduction in $C_{D_{theory}}$ for locked-rotor conditions (see Figure 1) the effect of the locked-rotor, for engines of low specific thrust, is to increase the internal drag by 30 to 50 percent of that which occurs under free-windmilling conditions.

The spillage drag is likely to increase with increasing power offtake due to the reduction in airflow through the engine. Spillage drag will be a maximum at locked-rotor conditions, *i.e.* when the airflow through the engine is a minimum, see Item No. 84004.

6. EXAMPLES

6.1 Low Bypass Ratio Engine – Windmilling Drag Only

A single-engined fighter-type aeroplane is powered by a turbo-fan engine having a design specific thrust at maximum rating, at ISA sea-level static conditions, of 61.3s. Assuming that following engine failure the engine continues to windmill freely, estimate the variation of windmilling drag coefficient with flight Mach number over the range $0 \leq M \leq 0.8$.

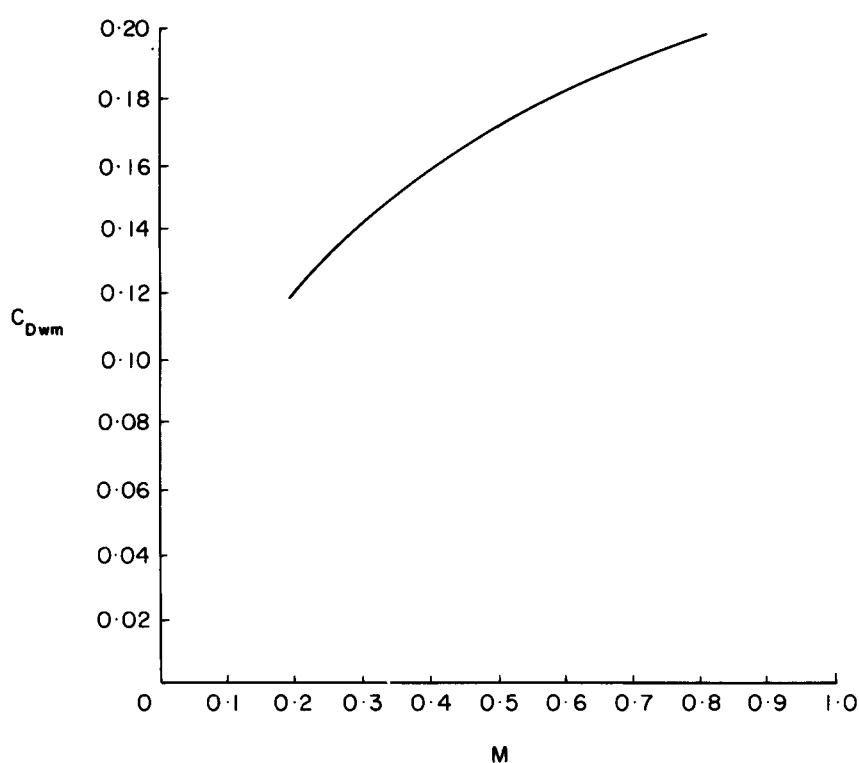
From Figure 1, for an engine having $[f_N/\dot{w}]_{s,0} = 61.3s$ and free windmilling

$$C_{D_{theory}} = 0.178.$$

The calculations of the variation of windmilling drag coefficient with flight Mach number are made in Table 6.1 using the procedure described in Section 3, and illustrated in Sketch 6.1.

TABLE 6.1

Flight Mach Number, M	0.2	0.3	0.4	0.5	0.6	0.7	0.8
From Figure 2, for $\left[\frac{f_N}{\dot{W}}\right]_{s,0} = 61.3s, \Delta C_{D_{wm}} =$	0.061	0.038	0.022	0.008	-0.003	-0.015	-0.023
Using Equation (3.1), $C_{D_{wm}} = 0.178 - \Delta C_{D_{wm}} =$	0.117	0.140	0.156	0.170	0.181	0.193	0.201



Sketch 6.1

6.2 High Bypass Ratio Engine – Windmilling Drag and Airflow

A transport aeroplane operating at $H_p = 1500$ m, ISA + 20 K conditions is powered by two wing-pylon-mounted turbo-fan engines each having a design specific thrust at maximum rating at ISA sea-level static conditions of 35.4 s and an engine face area of 1.85 m^2 . Assuming that one engine fails and that after failure it continues to windmill freely, estimate:

- The variation of windmilling drag with flight Mach number over the range $0.2 \leq M \leq 0.9$.
- The windmilling mass flow at $M = 0.2$.

Using Table 8.3 of Item No. 68046 at $H_p = 1500$ m, gives $p = 84\,556 \text{ N/m}^2$ and, for ISA + 20 K, $T = 298.4 \text{ K}$. Therefore, using Equation (3.4), $p_t = 86\,947 \text{ N/m}^2$ and from Equation (3.5), $T_t = 300.8 \text{ K}$.

(a) Variation of Windmilling Drag with Flight Mach Number

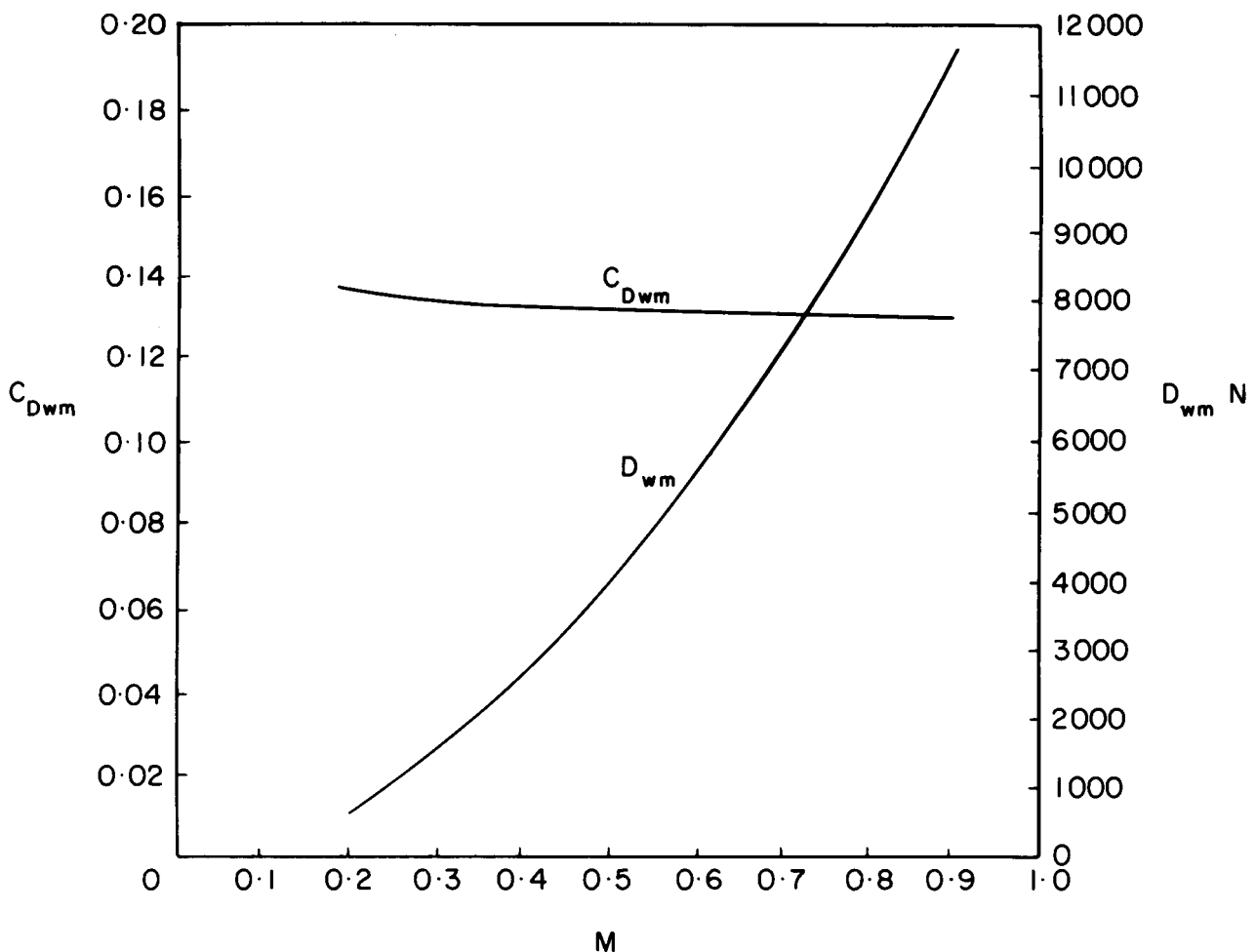
From Figure 1, for $[f_N/\dot{w}]_{s,0} = 35.4s$ and free windmilling

$$C_{D_{theory}} = 0.290.$$

Calculations of the variation of windmilling drag coefficient and windmilling drag with flight Mach number, using the procedure described in Section 3, are shown in Table 6.2 and illustrated in Sketch 6.2.

TABLE 6.2

Flight Mach Number, M	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
From Figure 2, for $[f_N/\dot{w}]_{s,0} = 35.4s$, $\Delta C_{D_{wm}} =$	0.149	0.150	0.152	0.153	0.154	0.155	0.156	0.157
Using Equation (3.1), $C_{D_{wm}} = 0.290 - \Delta C_{D_{wm}} =$	0.141	0.140	0.138	0.137	0.136	0.135	0.134	0.133
Using $p = 84\,556 \text{ N/m}^2$ and $A_2 = 1.85 \text{ m}^2$, $D_{wm} = \gamma p M^2 A_2 C_{D_{wm}} / 2 =$	620 N	1380 N	2420 N	3750 N	5360 N	7240 N	9390 N	11 800 N



Sketch 6.2