

GRAPHICAL METHOD FOR THE ANALYSIS OF MEASURED PERFORMANCE DATA USING DRAG DETERMINATION: AIRCRAFT WITH TURBO-JET AND TURBO-FAN ENGINES

1. NOTATION AND UNITS*

		SI	British
a	speed of sound	m/s, kn	ft/s, kn
C_L	lift coefficient, $\frac{L}{\gamma p_0 \delta M^2 S/2}$		
D	airframe drag	N	lbf
D_M	momentum drag (see Item No. 69006)	N	lbf
F_G, F_N	gross thrust, net thrust (see Item No. 69006 for thrust definitions)	N	lbf
g	acceleration due to gravity	m/s ²	ft/s ²
H	geopotential altitude	m	ft
H_p	pressure altitude	m	ft
h_e	energy height, $H + (V^2/2g_0)$	m	ft
L	lift	N	lbf
M	Mach number, V/a		
m	aircraft mass	kg	slug
N	engine speed	rev/s	rev/s
p	static pressure	N/m ²	lbf/ft ²
Q	engine fuel consumption	kg/s	lbf/s
S	wing area	m ²	ft ²
T	ambient temperature	K	K
t	time	s	s
V	true airspeed	m/s, kn	ft/s, kn

* As in previous Items, British units make use of a weight breakdown for the aircraft, but it should be noted that the SI units make use of a mass breakdown. The equations are written in British units but are equally applicable in SI units provided that the substitution $W = mg$ is made. The SI units chosen have not necessarily received universal acceptance for the particular applications, i.e. other multiples or sub-multiples may be used.

W	aircraft weight, mg	N	lbf
W_f	weight of fuel consumed	N	lbf
γ	ratio of specific heat capacities, taken as 1.4		
γ_c	angle of climb	rad	rad
α	incidence of datum line	deg	deg
Δn	normal acceleration due to flight path curvature, expressed as a fraction of g		
δ	relative pressure, p/p_0		
ε	angle between gross thrust vector per engine and aircraft plane of symmetry	deg	deg
θ	relative temperature, T/T_0		
τ	angle between projection of gross thrust vector on to aircraft plane of symmetry and datum line (positive when F_G contributes to lift)	deg	deg
Suffix			
0	denotes value at sea level in International Standard Atmosphere (Item No. 68046 gives numerical values)		

2. INTRODUCTION

This Item outlines the method of performance analysis used when drag is determined from a knowledge of thrust. The thrust may be obtained from flight measurements or it may be estimated. It involves more computational work than the methods discussed in Item No. 70022 and Data Sheets RJ 2/0 and RJ 2/1, but it enables greater use to be made of the flight time and is less demanding on pilot technique (see Section 3). It is applicable in the subsonic and supersonic flight regimes.

The theory is outlined in Item No. 70020 which indicates the limitations of the non-dimensional approach. Various additional factors (Reynolds number, thrust angle, centre of gravity variation, power plant operation, gravity variation, flight path length, buoyancy) which affect the analysis of measured performance are discussed in that Item, and methods by which they may be taken into account in applying the approach of this Item are indicated there.

3. FLIGHT TEST PROCEDURE AND ANALYSIS OF RESULTS

The airframe drag follows directly from a knowledge of thrust in steady level flight. In practice, although the major proportion of any engine operating condition change will occur within a few seconds of the throttle movement, it is possible that several minutes may elapse before the engine completely attains its new operating condition and it would therefore take an even longer time for the aircraft to settle down to steady conditions. Thus, to reduce flight test time, data may have to be measured during decelerated or accelerated level flight tests although this should be avoided because of the possible time dependence of measurements and because of the possible effect of engine operating condition on drag. However, one common technique is to stabilise the aircraft at a nominally constant altitude and at the highest Mach number for that altitude and then to reduce engine speed by a fixed amount. During the subsequent deceleration continuous measurements are made of pressure altitude, ambient temperature, airspeed, incidence, fuel flow, and, if possible, gross thrust. When stabilised conditions are reached again, the procedure is repeated until the required speed range at this test altitude has been covered. The tests are then repeated over the required range of altitudes. It is also possible to obtain results by flying an accelerated level followed by a decelerated turn and this technique is particularly useful when flight time is limited. It also enables results to be obtained at higher values of C_L than can be easily obtained in level flight.

The longitudinal force equation is

$$F_G \cos \epsilon \cos (\alpha + \tau) - D_M - D = \frac{W g_0}{V} \frac{d}{dt} \left(H + \frac{V^2}{2g_0} \right) \quad (3.1)$$

which may be simplified when $(\alpha + \tau)$ and ϵ are small to give

$$F_N - D = \frac{W g_0}{V} \frac{d}{dt} \left(H + \frac{V^2}{2g_0} \right), \quad (3.2)$$

where V is measured in ft/s or m/s as appropriate. The normal force equation is

$$L = W(\cos \gamma_c + \Delta n) - F_G \cos \epsilon \sin (\alpha + \tau) \quad (3.3)$$

which may be simplified when $(\alpha + \tau)$ is small to give

$$L = W(\cos \gamma_c + \Delta n). \quad (3.4)$$

From Equations (3.1) and (3.2), if $H + (V^2/2g_0)$ is plotted against time from the measured results the difference between the thrust component and drag may be determined from the slope of the curve at any time. Care must be taken to ensure that compatible definitions of thrust and drag are used in deducing the drag from this force value (see Item No. 69006).

Gross thrust may be measured in flight by any of the techniques discussed in Item No. 69007. In the absence of such measurements, thrust may be estimated using data from the manufacturer's brochure, making allowance for the effect of installing the engine in the aircraft (including making allowance for the actual intake recovery and for any engine-airframe force component interaction).

From the measured data, the airframe characteristics may be plotted as illustrated in Figure 1 and the engine characteristics may be plotted on a transparent overlay for each engine condition (*i.e.* for one intake and nozzle geometry, one reheat setting, and one non-dimensional value of air bleeds and shaft power offtakes,

see Item No. 70020) as illustrated in Figures 2 and 3. Putting the engine overlay on the airframe graph yields the complete representation of the aircraft performance in non-dimensional terms for one engine condition as illustrated in Figure 4. From this final graph the aircraft performance in terms of level speed, range, rate of climb and time to height, and fuel flow can be deduced for any specified atmospheric conditions. The details of the calculation procedure are illustrated in the Example. It should be noted that, while Figure 4 is useful to indicate trends, when the detail of the Example is considered separate carpet plots of airframe and engine data are more convenient for interpolation. Frequently, as an alternative to the graphical representation and use of the data, the characteristics of the airframe and the engine will be stored in a computer so that any performance data required may be calculated with a suitable program.

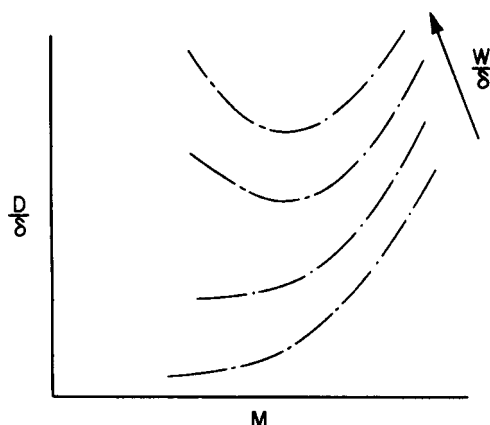


FIGURE 1

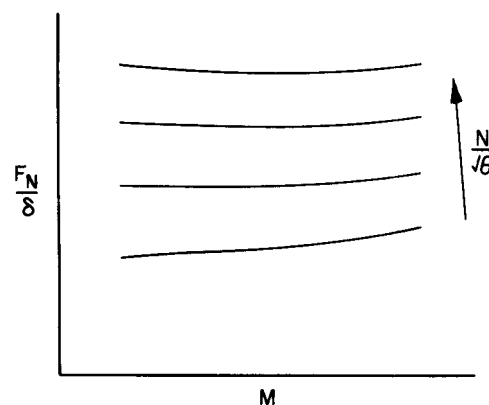


FIGURE 2

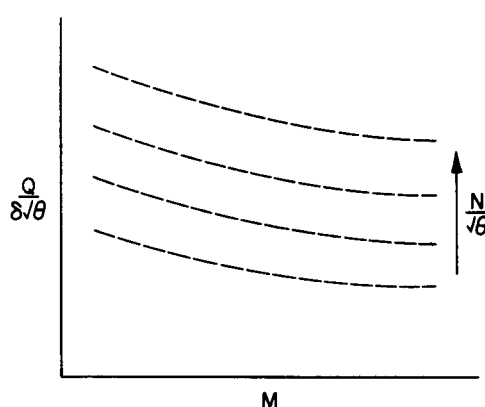


FIGURE 3

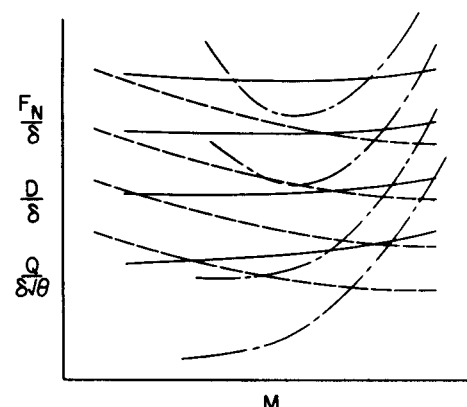


FIGURE 4

4. EXAMPLE

The performance characteristics of a subsonic interceptor having a fixed geometry engine without reheat were determined from flight test and are shown on Figure 5 as a carpet plot of D/δ against C_L and M , in Figure 6 as a carpet plot of F_N/δ against $N/\sqrt{\theta}$ and M and in Figure 7 as a carpet plot of $Q/(\delta\sqrt{\theta})$ against $N/\sqrt{\theta}$ and M . The wing area is 350 ft² and it can be assumed that the gross thrust is aligned with the flight path, i.e. $(\alpha + \tau) = \epsilon = 0^\circ$. At the altitudes and speeds appropriate to this aircraft the effects of gravity variation and buoyancy can be neglected. Also, weight variation is small enough for no Reynolds number effects to be evident in the test data and the centre of gravity does not change sufficiently for the data to require correction. Engine operation effects on drag were negligible for this configuration and the thrust data have been corrected to zero air bleeds and shaft power offtakes.

From the data of Figures 5, 6 and 7 determine

- (i) the level speed at 20 000 ft, (ISA + 10) K, at a weight of 18 000 lbf and a power setting of 7 000 rev/min,
- (ii) the fuel consumption under the conditions of (i),
- (iii) the minimum time to 40 000 ft, ISA, starting with a weight of 18 000 lbf at sea level and maintaining a power setting of 8 000 rev/min.

(i) Level Speed

From Item No. 68046 Table 8.4 at $H_p = 20\,000\text{ ft}$, (ISA + 10) K,

$$\delta = 0.459\,54 \text{ and } \sqrt{\theta} = 0.947\,20.$$

Thus for level flight where $\Delta n = 0$ and $\gamma_c = 0$,

$$\begin{aligned} C_L &= \frac{W}{\gamma p_0 \delta M^2 S/2} \\ &= \frac{18\,000}{0.5 \times 1.4 \times 2 \times 116.22 \times 0.459\,54 M^2 \times 350} \\ &= \frac{0.075\,5}{M^2}. \end{aligned}$$

In order to plot the D/δ curve on Figure 5, a range of values of M must be chosen and the corresponding values of C_L calculated. The results are shown as follows:

M	C_L
0.70	0.154
0.75	0.134
0.80	0.118
0.85	0.104

and from these values the example curve is drawn on Figure 5. Also,

$$N/\sqrt{\theta} = 7\,000/0.947\,20 = 7\,390 \text{ rev/min}$$

and the curve of F_N/δ can be plotted as shown on Figure 6 for this value of $N/\sqrt{\theta}$. Replotting these two curves on a single sheet gives an intersection at

$$M = 0.83$$

which is the level flight Mach number.

(ii) Fuel Consumption

From Figure 7, at $N/\sqrt{\theta} = 7\,390 \text{ rev/min}$ and $M = 0.83$,