

NON-DIMENSIONAL METHODS FOR THE MEASUREMENT OF LEVEL-FLIGHT PERFORMANCE OF TURBINE-ENGINED HELICOPTERS

1. NOTATION AND UNITS*

		SI	British
a	speed of sound	km/h, kn	kn
C_P	power coefficient, $\frac{P \times 550}{\rho \left(2\pi \frac{\Omega}{60} R \right)^3 \pi R^2}$ in British units $\frac{P \times 10^3}{\rho \left(2\pi \frac{\Omega}{60} R \right)^3 \pi R^2}$ in SI units,		
C_W	weight coefficient, $\frac{W}{\rho \left(2\pi \frac{\Omega}{60} R \right)^2 \pi R^2}$		
$f_3, f'_3,$ $f_6, f'_6,$ $f_7, f'_7,$ f_{10}, f_{11}	$\left. \begin{array}{l} \\ \\ \\ \end{array} \right\}$ functions used in Equations in Table 7.1		
G	fuel flow $\left\{ \begin{array}{l} \text{volume flow basis} \\ \text{weight flow basis} \\ \text{mass flow basis} \end{array} \right.$	1/h N/h kg/h	gal/h lbf/h slug/h
g	acceleration due to gravity	m/s ²	ft/s ²
H_p	pressure height	m	ft
$M_{tip, \psi = 90}$	rotor tip Mach number at $\psi = 90$, equal to $\frac{1}{a} \left(V + \frac{120\pi}{r} \Omega R \right)$		
m	helicopter mass	kg	slug
P	shaft power output from engine	kW	hp

* The units quoted here are those most commonly used in practice. They do not, however, constitute coherent sets (hence, for normal analytical purposes, the use of conversion factors would be necessary). Such units are permissible here since the object of the Item is the presentation, in parametric form, of flight-measured data and it is only necessary that the same units be applied throughout any given piece of work.

p	atmospheric pressure*	N/m ²	lbf/ft ²
R	rotor radius	m	ft
R_a	air range	km	n.mile
r	conversion factor (6 076.12 ft/n.mile, 1 000 m/km, 1 852 m/n.mile)	m/km, m/n.mile	ft/n.mile
T	ambient temperature	K	°C
t	endurance	h	h
V	true airspeed*	km/h, kn	kn
W	helicopter weight, mg	N	lbf
W_F	weight of fuel	N	lbf
δ	relative pressure, p/p_0		
Θ	collective pitch angle	deg	deg
θ	relative temperature, T/T_0		
μ	advance ratio, $V/\left(\frac{120\pi}{r}\Omega R\right)$		
ρ	density of air	kg/m ³	slug/ft ³
σ	relative density, ρ/ρ_0		
ψ	rotor azimuth measured in direction of rotation from line $\psi = 0$ parallel to helicopter fore-and-aft axis, facing rearwards	deg	deg
Ω	rotor speed*	rev/min	rev/min
Ω_s	standard rotor speed*	rev/min	rev/min
ω	relative rotor speed, Ω/Ω_s		

Suffixes

f	final
i	initial
max	maximum
min	minimum
0	denotes value at sea level in International Standard Atmosphere (Item No. 68046 gives numerical values).

* Units other than those quoted may also be in use.

2. INTRODUCTION

This Item describes methods for measuring and presenting the steady level-flight performance of turbine-engined helicopters in terms of “non-dimensional” parameters. A general introduction to such methods is given in Item No. 73026 where it is shown that alternative sets of non-dimensional parameters and corresponding test procedures and data presentations are possible depending, for example, on the particular atmospheric parameters chosen and whether rotor compressibility effects are to be investigated. The same Item also sets out general principles governing the conduct of test programmes using these methods and briefly considers such practical details as are common to most performance flight tests.

3. TEST METHODS FOR LEVEL FLIGHT PERFORMANCE

Table 7.1 sets out details of three non-dimensional test methods for level flight based on the measurement of engine shaft power output. The equations in Table 7.1 which are derived from Equations (3.2), (3.3), (3.5), (3.6), (3.7), (3.10) and (3.11) of Item No. 73026 are also applicable if measurements of power are made at other locations (see Item No. 73026, Section 5.1). The three test methods are distinguished by the atmospheric parameters used: density alone in method 1, density and temperature in method 2 and pressure and temperature in method 3. Reference to the footnotes to Table 7.1 shows how the methods may be adapted:

- (i) to cases where helicopter mass is used instead of weight,
- (ii) to cases where collective pitch is used instead of power,
- (iii) to the presentation of helicopter fuel flow data.

Test results should be obtained in steady level flight in relatively calm conditions. If the helicopter is controlled manually then, for each test run, a rotor collective pitch setting is selected and a period allowed for flight at steady speed and altitude to become established. This flight condition is held for a further period (typically three minutes) during which several sets of measurements can be taken. (Note, however, that the greater the duration of the test run the greater the tendency to gain height and/or speed as the helicopter becomes lighter). If automatic height and/or speed holds are available the required steady state can probably be achieved more quickly and held more precisely. To obtain reliable measurements at speeds near and below the minimum power speed, the use of, for example, a pace vehicle or doppler speed measuring equipment and a radio altimeter is desirable.

The tests are made throughout the required forward flight envelope at a number of values of the relevant weight parameter ($W/\sigma\omega^2$, C_W or W/δ). If the effects of compressibility are to be investigated, several values of $\omega/\theta^{1/2}$ must be used at each value of the weight parameter.

3.1 Test Method 1

The required value of $W/\sigma\omega^2$ or C_W is maintained between successive test runs by increasing altitude or by decreasing rotor speed or by changing both altitude and rotor speed in combination. The last of these possibilities requires the provision of a greater amount of information for in-flight use but does mean that once a test height has been reached where $W/\sigma\omega^2$ is near to the required value, the exact value can be obtained quickly by making a small change in rotor speed. In addition, by varying both test altitude and rotor speed, the widest possible range of values of $W/\sigma\omega^2$ can be investigated.

Since test method 1 involves one less non-dimensional parameter than either of test methods 2 or 3, it requires fewer test runs and provides a more compact presentation of the helicopter's level-flight performance. The omission of $\omega/\theta^{1/2}$ as a parameter means, however, that no account is taken of rotor Mach number effects.

3.2 Test Method 2

In Table 7.1, Equations (3.6), (3.6'), (3.7) and (3.7'), the rotor speed occurs in both the weight and rotor speed parameters and therefore it is not possible to make independent adjustments to these parameters by changes in H_p and Ω . Consequently it is necessary either to conduct tests at non-constant values of $\omega/\theta^{1/2}$ and subsequently to deduce results for constant values of $\omega/\theta^{1/2}$ or to modify the equations in such a manner as to permit constant values of both the weight and rotor speed parameters to be maintained. The latter approach usually results in fewer tests to complete the required programme but does require additional effort at the planning stage.

Test method 2 is the only one in which rotor compressibility effects may be systematically investigated and still retain the C_p , C_w form of presentation. In addition, the parameter $\omega/\theta^{1/2}$ is in this case a direct measurement of the rotor compressibility effects (in contrast to method 3 where all rotor speed effects are included in this parameter). The method also provides a means of making a brief assessment of the significance of ignoring rotor compressibility effects during a series of tests using test method 1 by, for example, carrying out tests at the extreme values of the weight and rotor speed parameters (see Sketch 5.2).

3.3 Test Method 3

The weight parameter, W/δ , is held constant by increasing altitude between test runs and the required value of $\omega/\theta^{1/2}$ is re-established at each test altitude by changing the rotor speed to match changes in outside air temperature.

Provided that the form of the non-dimensional parameters is acceptable, this method provides the simplest means of investigating helicopter level-flight performance when compressibility effects are to be considered (although these effects are not as clearly separated out as in the presentation available with method 2).

3.4 Fuel Flow Measurements

Where practicable the mean fuel flow should be measured during each test run. Such measurements are in some cases essential for the estimation of engine shaft power output (see Item No. 73026, Section 5.1.2) and in most cases they can provide a check on possible engine deterioration due to wear. Fuel flow measurements may also be required for the derivation of range and endurance data (see Sections 5.1 and 5.2).

4. PLANNING

Ranges of values of dimensional and non-dimensional parameters are determined in the manner described in Item No. 73026, Section 6.1 and illustrated in Section (a) of the Example in the present Item. Such details as the take-off weight and initial test altitude are chosen to make best use of the expected atmospheric conditions. The data required in flight to assist in the selection of appropriate test altitudes and rotor speeds depend on the particular test method and the presentation of such data is considered in Sections 4.1 to 4.3.

4.1 Weight Parameter Alone

For test method 1, if both altitude and rotor speed are to be varied to maintain constant $W/\sigma\omega^2$ or C_W , then the information required for in-flight use consists of

- (i) a presentation of the values of W , σ and Ω which give the required value of $W/\sigma\omega^2$,
- (ii) a presentation of values of σ as a function of H_p and T .

If only one parameter is to be varied then the information required is reduced accordingly.

For test method 3 the information required consists of a single plot of W against H_p for each required value of W/δ .

4.2 Rotor Speed Parameter Alone

In test method 3, to maintain constant $\omega/\theta^{1/2}$ during tests at different altitudes, a presentation is required of values of Ω and T which correspond to the required value of $\omega/\theta^{1/2}$. In addition, since the range of temperatures for tests at a particular value of $\omega/\theta^{1/2}$ is fixed by the range of permissible rotor speeds and since the helicopter gains height during the course of a test flight, a guide to the altitudes at which a particular test should be flown can be obtained from measurement of temperature at ground level and by assuming a realistic lapse rate.

4.3 Tests at Constant $\omega/\theta^{1/2}$ and $W/\sigma\omega^2$ (or C_W)

In test method 2, if tests are to be carried out at fixed values of $W/\sigma\omega^2$ and $\omega/\theta^{1/2}$ a modification must be made to the non-dimensional parameters in Equations (3.6), (3.6'), (3.7) and (3.7') in Table 7.1. In the case of Equations (3.6) and (3.7) the modification is to express the weight parameter in the form

$$\frac{W}{\sigma\omega^2} = \frac{W}{\delta} \frac{\theta}{\omega^2} = \frac{W}{\delta} \left(\frac{\omega}{\theta^{1/2}} \right)^{-2}.$$

Thus, if test results are required for the values $W/\sigma\omega^2 = A$ and $\omega/\theta^{1/2} = B$ where A and B are constants then, from the above relationship,

$$A = \frac{W}{\delta} B^{-2}.$$

It follows that the required test results can be obtained by flying in such a way as to maintain

$$\frac{W}{\delta} = AB^2 \text{ and } \frac{\omega}{\theta^{1/2}} = B.$$

By this means the test method effectively becomes that of test method 3 in Table 7.1 but the results are plotted in the manner required by test method 2 and planning charts are constructed as described in Section 4.1 for W/δ and Section 4.2 for $\omega/\theta^{1/2}$.

A similar modification can be derived for Equations (3.6') and (3.7') of Table 7.1: if test results are required for the values $C_W = A_1$ and $\omega/\theta^{1/2} = B_1$, where A_1 and B_1 are constants, then the tests should be flown with

$$\frac{W}{\delta} = A_1 B_1^2 \rho_0 \left(\frac{2\pi R}{60} \right)^2 \pi R^2 \text{ and } \frac{\omega}{\theta^{1/2}} = B_1 .$$

5. PRESENTATION OF RESULTS

Level flight power-required performance measurements may be presented in carpet form such as that shown in Sketch 5.1 for the parameters of test method 3. When this form is used a separate Figure is necessary for each value of $\omega/\theta^{1/2}$ at which tests are carried out.

Sketch 5.2 illustrates a form of presentation that is widely used (both for dimensional and non-dimensional data) particularly when the data are insufficient to construct a carpet, see also Sketch 6.4. The curves in Sketch show the relative magnitudes of the effects on the power required of changes in both the weight and rotor speed parameters.

The results of tests in which the parameter $\omega/\theta^{1/2}$ is used can be presented in terms of a rotor Mach number and the value usually chosen is the tip Mach number at the 90 degree azimuth position, i.e. $M_{tip, \psi = 90}$. Conversions between the parameters used in Sketch 5.2 and $M_{tip, \psi = 90}$ may be made by using

$$\begin{aligned} M_{tip, \psi = 90} &= \frac{1}{a_0} \left(\frac{\omega}{\theta^{1/2}} \right) \left[\frac{V}{\omega} + \frac{120\pi\Omega_s R}{r} \right] \\ &= \frac{1}{a_0} \left(\frac{\omega}{\theta^{1/2}} \right) \left(\frac{V}{\omega} \right) \left(1 + \frac{1}{\mu} \right) . \end{aligned}$$

When rotor collective pitch is used as a parameter in the measurement of level-flight performance, the usual form of presentation of results is that shown in Sketch 5.3 for test method 1 with constant rotor speed. Sketch 5.3a defines the helicopter's forward-speed capability and may be used without any additional information. Sketch 5.3b is presented in addition to Sketch 5.3a since it permits the information of Sketch 5.3a to be related, for example, to engine fuel flow characteristics and torque limits.

Typically, this presentation is used where the production helicopter has a collective pitch gauge but where suitable power or torque measurements are only available on the test helicopter.