



ESDU TECHNICAL MEMORANDUM

Aircraft performance from flight test: An example of the use of manoeuvring flight

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AIRCRAFT PERFORMANCE FROM FLIGHT TEST: AN EXAMPLE OF THE USE OF MANOEUVRING FLIGHT

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1. NOTATION, DIMENSIONS AND ABBREVIATIONS

1.1 Notation and Dimensions

		Dimensions
C_D	drag coefficient	–
C_L	lift coefficient	–
C_m	pitching moment coefficient	–
g	acceleration due to gravity	LT^{-2}
g_0	acceleration due to gravity at sea level in ISA	LT^{-2}
n	aeroplane normal acceleration, in lift direction, expressed in units of g_0	–
p	roll rate	T^{-1}
q	pitch rate	T^{-1}
r	yaw rate	T^{-1}
t	time	T
w	component of aircraft velocity along the Oz axis	LT^{-1}
α	angle of attack	–
ϕ	angle of bank	–
θ	angle of pitch	–

One dot above a quantity indicates the first derivative of that quantity with respect to time, t .

1.2 Abbreviations

AoA	Angle of Attack
AoS	Angle of Sideslip
RPM	Revolutions Per Minute (referring to engine fan)

2. INTRODUCTION

In constructing an aircraft performance model, it is sometimes necessary to make use of flight data that have not been expressly generated for that purpose. Such is the case in the example shown in this document. It is also shown that, if treated appropriately, the use of data from manoeuvring flight can be an efficient way of generating a performance model.

The example given demonstrates how quite severe manoeuvring flight can be used to derive aerodynamic data for a performance model. This example is a single-engined jet aircraft that was flown through a series of manoeuvres for the purpose of gathering fin loading data throughout the flight envelope. The manoeuvres were primarily wind-up turns flown over a range of Mach numbers of which one is shown in this example. These wind-up turns were supplemented with level flight acceleration/decelerations and steady-heading sideslips.

3. THE MANOEUVRE

The manoeuvre considered is a wind-up turn flown at a Mach number of 0.5 and an altitude of approximately 6000 feet and is representative of those flown on the trial. The pilot's brief was to maintain Mach number in the turn at the expense of altitude, to fly to some pre-determined handling limit and then recover with the use of full-forward stick. The entire manoeuvre lasted for 26 seconds.

Time histories of measured normal acceleration, n , and angular displacements, rates and accelerations through the manoeuvre are shown in Figures 1 to 8. The turn is not well coordinated; the 80 degrees of bank recorded is equivalent to approximately 6g in a coordinated turn whereas only 2.8g was achieved. Lateral accelerations of up to 0.2g and sideslip excursions of up to 5 degrees were noted.

High nose-down pitch rates, q , of $17^\circ/\text{s}^2$ and pitch accelerations, $\dot{q}$, of $70^\circ/\text{s}^2$ develop as the aircraft is recovered from the turn in response to the use of full-forward stick. This rapid motion in the pitch plane is accompanied by rapid motion in the rolling plane, with roll rates of -25 to $+50^\circ/\text{s}$ and roll accelerations of -50 to $+90^\circ/\text{s}^2$.

The manoeuvre also contains an aggressive throttle movement resulting in engine RPM increasing from 62 per cent to 89 per cent within 2 seconds.

The extreme motions of the manoeuvre can produce what appear to be contradictory results. For example, examination of the flight data between $t = 1547$ seconds and $t = 1552$ seconds shows that the time rate of change of pitch angle, $\dot{\phi}$, is negative (see Figure 5 and 6 respectively) though pitch rate, q , is positive. A combination of yaw rate and a large bank angle produces a greater component of $\dot{\theta}$ than that produced by q . The following relationship, obtained by inverting the matrix of Equation (B.7) in Reference 1, demonstrates the point.

$$\dot{\theta} = q \cos \phi - r \sin \phi \quad (3.1)$$

Inspection of Figures 2 and 8 shows that $\phi = -85^\circ$ and $r = -4^\circ/\text{s}$ at $t = 1150 \text{ s}$, resulting in $\dot{\theta} = -3.3^\circ/\text{s}$. Whereas in Figure 6, $q = +8^\circ/\text{s}$ is measured at the same time in the manoeuvre.

4. ANALYSIS OF THE MANOEUVRE

The manoeuvres of this flight trial were analysed to develop a performance model of the aircraft using the method described in Reference 1. Tailplane aerodynamics were available from wind-tunnel testing and a downwash model was constructed based on the method of Reference 2. This modelling of the tailplane environment enabled tail-off aerodynamic coefficients to be derived. Level flight manoeuvres were used to deduce calibrations for the angle of attack, angle of sideslip and air data pressure sensors.

Wind-up turn manoeuvres were then used to obtain the aerodynamic force and moment coefficients required for performance modelling, that is, drag, lift and pitching moment coefficients. (C_D , C_L and C_m respectively.) In line with convention for this aircraft all pitching moments are referred to 10 per cent standard mean chord. These derived coefficients have been adjusted to datum conditions; that is, intake drag coefficient has been adjusted to a mass flow ratio of unity and afterbody drag coefficient to a nozzle pressure ratio of unity. An observed throttle effect on the pitching moment balance has been accounted as a power effect on downwash.

To demonstrate how the dynamics of the manoeuvre influence the derived coefficients the manoeuvre is presented with different levels of analysis. Aerodynamic coefficients are Mach number (M) dependent; it is therefore necessary to apply a tolerance when selecting data at a nominally constant Mach number. For aircraft of this type it has been found that selecting $M = 0.5 \pm 0.005$ is satisfactory for the manoeuvre considered here. For manoeuvres at higher Mach numbers a smaller tolerance is required.

The first set of coefficients, Figures 9 to 11, represent the entire manoeuvre and the data have not been adjusted for dynamic effects due to angular motion of the aircraft. The charts show significant scatter. A study of the manoeuvre revealed that there was a rapid throttle movement so that engine RPM increased from 62 per cent to 89 per cent in 2 seconds. During such conditions engine performance will be unknown; the thrust-RPM characteristics of the steady state engine performance model will not be valid and consequently the derived aerodynamic forces and moment will be in error. For this reason throttle movement during manoeuvres must be avoided if there is any intention to use the data for constructing a performance model.

In the second set of coefficients, Figures 12 to 14, the data containing the power transient, due to rapid throttle movement, have been removed. Scatter is significantly reduced, particularly in drag coefficient where an error in assumed thrust has the largest effect.

In the third case, Figures 15 to 17, power transient data have been removed; in addition, the data have been adjusted for the following dynamic effects.

- Transfer of measured accelerations to the centre of gravity (see Equations 5.7 to 5.9 of Reference 1).
- Changes in effective flow angle at AoA, AoS and pressure probes due to aircraft motion. (See Section 4.3 of Reference 3.)
- Changes in effective flow angle at AoA, AoS and pressure probes due to structural distortion. (See Section 4.5 of Reference 3.)
- Lag on AoA measurements due to time rate of change of AoA, ($\dot{\alpha}$). (See Section 4.4 of Reference 3.)
- Pressure lag in air data system.
- Downwash lag at tailplane due to acceleration in heave $\dot{\alpha}$ and induced flow angle due to pitch rate. (See Section 4.2 of Reference 1.)
- Inertia components in pitching moment balances. (See Equation 3.11 of Reference 1.)

Figures 15 to 17 show much improved correlations. As well as reducing scatter some detailed changes to the shape of the correlations has occurred.

The large displacements of the accelerometers and flow sensors from the centre of gravity, which are 11 feet for the accelerometers and 17 feet for the AoA probe, in combination with high pitch rates resulted in significant adjustments. The largest adjustments occurred at the peak of the turn, where the pilot applied full-forward stick and 7° of aileron to recover from the manoeuvre. This resulted in very high angular rates and angular accelerations requiring adjustments in normal acceleration, n , of up to 0.45g and in angle of attack of up to 0.65° in referring these parameters to the centre of gravity.

Some of the residual scatter in pitching moment coefficient is due to a very high rate of tailplane input (up to $25^\circ/\text{s}$), which is faster than the aircraft's response in pitch under these conditions. As the tail angle is the dominant term in the derivation of pitching moment, these rapid changes show up as excessive scatter.

5. DISCUSSION

The use of data from wind-up turn manoeuvres for the generation of a performance model is very efficient in terms of flight time. In this example the full AoA range for positive normal acceleration, n , at one Mach number is covered in less than half a minute. It is essential that dynamic effects are properly accounted for as these can entail significant adjustments to the data. The greatest adjustments occur at the extremes of the manoeuvre; that is, at high angle of attack. It is here that the aircraft is approaching a handling limit and the pilot initiates a rapid recovery with high rates of angular motion.

The data sampling rate was dictated by the requirements of the structural trial; each parameter being recorded 256 times per second. For the purpose of performance modelling a full analysis was performed on every 60th record, that is, at just over 4 times per second. Even for dynamic manoeuvres of the type shown here the highest oscillatory rate noted in the data is approximately 2 Hertz on roll acceleration. This response rate is considerably lower than the sampling rate, hence the generation of artefacts, for example aliasing, is not a concern.

Some typical curve fits to the data are shown in Figures 18 to 21. The repeating of manoeuvres such as these across the aircraft Mach number envelope will enable a full performance model to be constructed. The example presented here shows that flight trials not intended for performance modelling can be successfully utilised for this purpose. However, if dedicated testing is available it is recommended that manoeuvre progression is carried out more smoothly and turns are better coordinated to minimise motion normal to the plane of symmetry. Whatever the source of the data it is essential that the manoeuvres are flown at constant engine throttle setting.

6. REFERENCES

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