



Example of similarity methods applied to aircraft drag data from flight test

Endorsed by
The Royal Aeronautical Society

ESDU DATA ITEMS

Data Items provide validated information in engineering design and analysis for use by, or under the supervision of, professionally qualified engineers. The data are founded on an evaluation of all the relevant information, both published and unpublished, and are invariably supported by original work of ESDU staff engineers or consultants. The whole process is subject to independent review for which crucial support is provided by industrial companies, government research laboratories, universities and others from around the world through the participation of some of their leading experts on ESDU Technical Committees. This process ensures that the results of much valuable work (theoretical, experimental and operational), which may not be widely available or in a readily usable form, can be communicated concisely and accurately to the engineering community.

We are constantly striving to develop new work and review data already issued. Any comments arising out of your use of our data, or any suggestions for new topics or information that might lead to improvements, will help us to provide a better service.

THE PREPARATION OF THIS DATA ITEM

The work on this particular Data Item was monitored and guided by the Performance Committee. This Committee first met in 1946 and now has the following membership:

Chairman	
Mr G.J.R. Skillen	— Independent, UK
Vice-Chairman	
Mr K.J. Balkwill	— Independent, UK
Members	
Mr P.V. Aidala*	— Northrop Grumman ESID, Bethpage, New York, USA
Dr J.D. Avery	— MoD Boscombe Down, UK
Mr T.G.R. Bos*	— Dutch Airline Pilots Association, The Netherlands
Mr M. Broad	— Independent, UK
Dr G. van Es	— National Aerospace Laboratory NLR, The Netherlands
Mr N.J. Herniman	— Airbus Industrie, Toulouse, France
Mr M. Holcomb*	— Eclipse Aviation Corporation, Albuquerque, New Mexico, USA
Mr R.G. Humpston	— Rolls-Royce plc, Aero Division, Derby, UK
Mr D. Law	— Civil Aviation Authority, Safety Regulation Group, Gatwick
Mr D.J. Mitchell	— Independent, UK
Mr R.J. Orlowski*	— Boeing Commercial Airplane Company, Seattle, Washington, USA
Dr P. Render	— University of Loughborough, UK
Dr A. Smith	— Air Systems Test & Evaluation, QinetiQ, MOD Boscombe Down, UK
Mr G.E. Smith	— Independent, UK
Mr R. Storey	— BAE SYSTEMS, Brough, UK
Mr J. Tempest	— de Havilland Support Ltd, UK
Mr S. Tsach*	— Israel Aircraft Industries, Jerusalem, Israel
Mr C.J. Turner*	— Boeing Commercial Airplane Company, Seattle, Washington, USA

* Corresponding Member

The technical work involved in the assesment of the available information and the construction and subsequent development of the Data Item was carried out under contract to ESDU by

Mr K.J. Balkwill — Consultant to ESDU

The person with overall responsibility for the work in this subject area is C.J. Loughton, Head of Performance, Mechanical Motion and System Dynamics Groups.

EXAMPLE OF SIMILARITY METHODS APPLIED TO AIRCRAFT DRAG DATA FROM FLIGHT TEST

CONTENTS

	Page
1. NOTATION AND DEFINITIONS	1
1.1 Notation	1
1.2 Definitions	2
2. INTRODUCTION	2
3. SIMILARITY RULES FOR THREE-DIMENSIONAL FLOW	3
4. FLIGHT TEST DATA	3
5. CORRELATION PROCESS	4
6. STATISTICS	5
7. DISCUSSION	6
8. CONCLUDING REMARKS	7
9. REFERENCES	7
FIGURES 1 to 14	8 to 14

ESDU Copyright material. For current status contact ESDU.

EXAMPLE OF SIMILARITY METHODS APPLIED TO AIRCRAFT DRAG DATA FROM FLIGHT TEST

1. NOTATION AND DEFINITIONS

1.1 Notation

		<i>SI</i>	<i>British</i>
A	aspect ratio	—	—
a_0, a_1, a_2	coefficients defined by Equation (5.3)	—	—
C_D	drag coefficient ($= D/(qS)$)	—	—
C_{D_1}	minimum drag coefficient for given Mach number	—	—
C_L	lift coefficient ($= L/(qS)$)	—	—
C_{L_1}	lift coefficient at which drag coefficient is a minimum for given Mach number	—	—
D	drag	N	lbf
$E[\]$	expected value of quantity in $[\]$	—	—
f_D	pressure drag function	—	—
k	coefficient in modelling equation for drag coefficient	—	—
L	lift	N	lbf
M	Mach number in free stream	—	—
$\text{Pr}[\]$	probability of occurrence of event in $[\]$	—	—
p	ambient pressure	N/m ²	lbf/ft ²
q	kinetic pressure ($= \gamma p M^2/2$)	N/m ²	lbf/ft ²
S	reference area	m ²	ft ²
$U[\]$	uncertainty of quantity in $[\]$ at 95% level of probability	—	—
γ	ratio of specific heats for air	—	—
$\Delta[\]$	deviation of quantity in $[\]$ from $E[\]$	—	—
$\sigma[\]$	standard error (deviation) of quantity in $[\]$	—	—
τ	mean value of thickness to chord ratio for exposed wing	—	—
Φ	similarity parameter defined in Equation (3.2)	—	—
χ^2	“chi-squared” test statistic (see Reference 1)	—	—

1.2 Definitions

Drag and *Lift* forces are the result of solution of the force balance equations parallel with and normal to the air path velocity vector (in the plane of symmetry). Forces accounted include both direct and indirect effects of the power units and those arising from the presence of the (horizontal) tailplane in the downwash field behind the wing. In the particular case considered, drag data were adjusted for skin friction to a constant value of Reynolds number.

One *drag count* is an increment in drag coefficient of 1×10^{-4} .

2. INTRODUCTION

This Data Item provides an example of the application of the similarity methods introduced in Reference 2 to aid in the correlation of in-flight measurements of aircraft drag coefficient. Similarity rules are used only to identify the *form* of the variables to be used in the process of correlation. Once this form has been determined, the usual processes of modelling and correlation can continue.

The aircraft considered is a heavy, subsonic, low-level attack type, powered by two side-mounted low-bypass-ratio turbo-fan engines (fixed geometry intakes) and has a static sea-level thrust-to-weight ratio close to 0.4 in ISA conditions. Longitudinal control and trim are achieved with an “all-moving” tailplane (no elevator). Geometric characteristics are given in Table 2.1.

The relevant similarity rules are summarised in Section 3 and an outline of the flight-test procedure, from which data were drawn, is given in Section 4. In Section 5, the three stages of the modelling and correlation process are stated and the developed relationships are given. Statistics associated with the mathematical model are briefly considered in Section 6. A discussion of the model is given in Section 7 and the process is summarised in Section 8.

TABLE 2.1
Leading dimensions of heavy, subsonic, low-level attack type aircraft

Wing	
Reference area	508.5 ft ²
Span	44.1 ft
Aspect ratio	3.83
Standard mean chord	11.97 ft
Mean sweep of quarter-chord line	34 degree
Taper ratio	0.45
Rigging incidence, nose-up	2.5 degree
Twist	0
Dihedral	0
Mean thickness-to-chord ratio	7.5%
Horizontal tail	
Reference area	75.52 ft ²
Span	14.46 ft
Aspect ratio	2.69
Standard mean chord	5.3 ft
Mean sweep of quarter-chord line	25 degree
Taper ratio	0.58
Mean thickness-to-chord ratio	0.05
Moment arm (quarter chord to quarter chord)	23.3 ft
Height above datum (at quarter chord)	9 ft

3. SIMILARITY RULES FOR THREE-DIMENSIONAL FLOW

Reference 2 presents a selection of similarity rules that can be useful in the context of modelling aerodynamic data for performance estimation. In the particular case of the complete aircraft considered, it may be expected that a drag model to cover the level-flight envelope may need to incorporate the effects due to wing, body and the tailplane.

In order to simplify the task of modelling for performance purposes, the tailplane of the test aircraft was instrumented so that the forces and moments for the aircraft without tailplane could be determined. Furthermore, both primary and secondary effects due to the engines were identified either by calibration (for thrust and intake mass-flow) or by calculation (for intake spillage and afterbody pressure drag). The result of accounting for these effects is to leave only the (drag) forces generated on the wing and part of the body to be related to lift and Mach number. In principle, this implies the need to treat the body using three-dimensional axisymmetric flow. The wing would therefore be treated using the rules for three-dimensional planar flow. However, in the case considered, much of the body effect is eliminated in the process of determining spillage and afterbody forces. It is therefore feasible to treat the remaining drag forces as if the wing were in isolation.

It is shown in Reference 2 that the similarity rule for three-dimensional planar flow is, for $M \leq 1$,

$$C_D = \frac{\tau^{5/3}}{((\gamma + 1)M^2)^{1/3}} f_D \left[\frac{(1 - M^2)}{(\tau(\gamma + 1)M^2)^{2/3}}, A(|1 - M^2|)^{1/2} \right].$$

In this analysis the first parameter of the function f_D is replaced by parameter Φ to give

$$C_D = \frac{\tau^{5/3}}{((\gamma + 1)M^2)^{1/3}} f_D \left[\Phi, A(1 - M^2)^{1/2} \right], \quad (3.1)$$

in which Φ has been chosen as the following function

$$\Phi = \cos \left[\tan^{-1} \left[\frac{(1 - M^2)}{(\tau(\gamma + 1)M^2)^{2/3}} \right] \right]. \quad (3.2)$$

The flight data will be analysed in terms of the parameter Φ only, since the aspect ratio is fixed for the given sets of flight measurements.

4. FLIGHT TEST DATA

The flight test information from Reference 3, were collected as part of a programme to determine the changes in lift, drag, pitching moment and downwash induced by fitting a range of stores under the wing of the aircraft. The datum case was taken to be the aircraft with no stores fitted to the wing. Close attention was paid to establishing a precise force and moment model for the datum in order to minimise errors in deriving the effects of fitting stores.