HISTORY OF DRAG ESTIMATE ON THE ARROW

Introduction

The following is a summary of the methods used to estimate the drag of the Arrow from the first estimates made in 1951, up to the limited verification obtained from Flight testing in 1958.

The Avro reports in which the original estimates were made are quoted here, and whenever possible the sources of the original data are given. The Avro reports are in most cases unpublished, but copies could be obtained from the micro film records.

This report will restrict itself to the external aerodynamic drag, i.e. profile drag, elevator or trim drag, and drag due to lift. For information on spillage and internal drag see Report No. 71/Aero Data/12, prepared by Mr. W.B. McCarter, November 1958. Sheet 68 of 71/Aero Data/12 gives the results of estimates prepared in 1951, 1952, 1954 and 1956, this present report will amplify these results by giving the method and source.

Estimate No.1 - September 1951

This estimate was made by J. Lucas and is reported on in P/Aero Data/4. This was a very preliminary estimate and as such ignored the drag due to trim.

That is $C_D = C_{D_o} + \frac{C_L^2}{\pi e A}$ was used. The value of C_{D_o} was obtained from free flight tests on rocket powered delta wing models from NACA Reports RM L50D26; RM L50I22 and RM L50F01 which provided good data covering the range M=0.85 to 1.6. The value of 'e' was obtained from wind tunnel tests and are to be found in the following NACA reports, RM A50K20; RM A50K21; RM A50K24a and RM A50K24. The value of 'e' against M is as shown on sheet 14, and C_{D_o} against M as sheet 22 of P/Aero Data/4. This first estimate is of little practical value but has been reported on here for the sake of completeness.

Estimate No.2 - May 1952

This estimate was made by R. Warren and is reported on in P/Perf/43. This was the first estimate to include the drag due to trim. The drag equation therefore became,

$$C_D = C_{D_{MIN}\,\delta=0} + \frac{\Delta C_{D_{MIN}}}{\Delta \delta^2}\delta^2 + \left(\frac{1}{e + \frac{\Delta e}{\Delta \delta}\delta}\right)\frac{C_L^2}{\pi A}$$

The variation of $\frac{\Delta C_{D_{MIN}}}{\Delta \delta^2}$ and $\frac{\Delta e}{\Delta \delta}$ with M.N. is given on sheet 13 of P/Perf/43, this data was extracted from NACA Report No. RM L51I04, wind tunnel tests on a Convair Delta.

Estimate No.2 - May 1952 (continued)

This work based on RM L51I04 assumed linearity of the functions ΔC_D versus δ^2, and Δe versus δ. Subsequent work in P/Perf/43 done by J. Hodge based on data extracted from NACA Report No. RM A52D01c, showed that ΔC_D vs δ^2 is reasonably linear up to $\delta = -20^\circ$, but that Δe vs δ are certainly not linear. However as the component due to Δe is very small a large inaccuracy in this quantity can be tolerated in the overall drag estimate.

Fig.9D of P/Perf/43 shows the variation of $\frac{\Delta C_{D_0}}{\Delta \delta^2}$ with M.N. as obtained from NACA reports RM A52D01c; A52L04 and L51I04 for various t/c ratios and aspect ratio, all corrected to an elevator to wing area ratio of 8.7%. The variation $\frac{\Delta e}{\Delta \delta}$, (or $\frac{\Delta \frac{dC_D}{dC_L^2}}{\Delta \delta}$), with M.N. from the same NACA reports is shown in Fig.21. This second drag estimate was then based on the value of 'e' given in P/Aero Data/4, and a slightly modified C_{D_0}. The revised C_{D_0} estimate is as in Report P/Aero Data 17, sheet 14. The values of elevator angle used were calculated by D. Procter-Gregg in P/Control/38, and R. Warren in P/Control/32.

Estimate No.3 - January 1956

The third estimate was based partly on experimental data and partly on theoretical data.

C_{D_0} was based on Free Flight Model tests and the analysis is covered in Report No. P/Aero Data/66, by J. Stein. This is covered in a more concise manner in Report No. 71/Aero Data/12, by W.B. McCarter.

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Estimate No.3 - January 1956 (continued)

The trim drag was based on theory and experiment, using a method prepared by J. Morris in Report No. P/Perf/114, and is covered in Periodic Performance Report No.4.

The expression used was,

$$C_D = C_{D_{MIN}} + \frac{(C_L - C_{L_{CD_{MIN}}})^2}{\pi eA} + \left(\frac{K_2}{a_2} - \frac{2K_2}{a_1} + \frac{1}{\pi eA}\right)\left(\frac{C_{M_\delta}}{h_o - h_\delta}\right)^2$$

$$+ \left(\frac{K_2}{a_1} - \frac{1}{\pi eA}\right) C_{M_\delta}\, 2 \left(\frac{C_L - C_{L_{D_{MIN}}}}{h_o - h_\delta}\right)$$

$$K_2 = \frac{\text{lift increment on control}}{\text{lift increment on wing}}$$

The variation with M.N. of $C_{D_{MIN}}$, e, $C_{L_{D_{MIN}}}$ and K_2 are given in Periodic Performance Report No. 4. These values are based on W/Tunnel tests up to 1.23 M.N., and theory from 1.23 to M=2.0, except for $C_{D_{MIN}}$ which was bassed on FFMT as already stated. The ratio of experimental K_2 to theoretical K_2 as tested by NACA, see RM A52L04, on delta Planforms shows the theoretical value to be within = 5% of experiment over most of the Mach No. range.

Estimate No. 4 - December 1956

This drag estimate was based entirely on experimental data. The wind tunnel data used was as follows,

NAE	Dec. 1955	M=0.21
CAL	May 1955	M=0.5 to 1.23
Langley	March 1956	M=1.41
Langley	June 1956	M=1.6 to 2.0

Thus for the first time test data was available covering up to M=2.0.

Estimate No.4 - December 1956 (continued)

Analysis of this data, see P/Aero Data/74, by S. Singer showed that because of the non linearity of the derivatives it was preferable to use the actual values measured for drag due to lift and elevator deflection. An attempt was made in P/Aero Data/74 to obtain values of K_2, a_1, and a_2 vs Mach No., such that the method as outlined in Estimate No. 3 could be used, but was found to be impractical.

Periodic Performance Report No. 9 shows the result of this analysis. The curve of $C_{D_{MIN}}$ vs M.N. was based on FFMT, see P/Aero Data/66, and was .009 subsonic and approx. .023 const supersonic. The tunnel tests for zero elevator were then corrected to this $C_{D_{MIN}}$, and drag polars plotted for each test Mach No. The ΔC_D due to elevator angle was found to be independent of C_L and thus a curve of C_D vs M.N. and elevator angle was prepared.

Hence the drag was given by,

$$C_{D_{Total}} = C_{D_{\delta_e=0}} + \Delta C_{D_{\delta_{e_{Trim}}}}$$

In conclusion it can be said that the final drag estimate on the Arrow is composed as follows:

$C_{D_{MIN}}$ - Free Flight Model Test - Report P/Aero Data/66

$C_{D_{\delta_e=0}}$, $\Delta C_{D_{\delta_{e_{Trim}}}}$ - Wind tunnel test - Report P/Aero Data/74

These results were first used in Periodic Performance Report No. 9, and the appropriate curves are to be found in Report No. 9.

Area rule showed that an improvement in drag should be realised with the larger ejector. This was not used in performance work, for a discussion of this effect see Report No. 71/Aero Data/12 by W.B. McCarter.

For a comparison of estimated drag with limited F/Test data see note prepared by R. Waechter.