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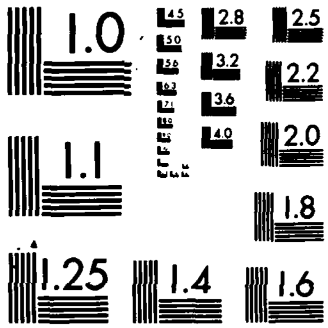

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A RAPID METHOD FOR ESTIMATING EQUIVALENT PARABOLIC POLARS FROM WIND-TUNNEL TESTS

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SUMMARY

A method for obtaining a 'best-fit' parabolic drag polar from measured force results is presented. The method is used in estimating the blockage correction due to separated flow that must be applied to wind-tunnel results.

An important part of the method is the use of computer graphics to identify the part of the measured drag polar that may best be described by a parabola, and thus used as the basis for a curve fit.

The method is fast, when compared to existing curve-fitting techniques, and suited to use with an 'online' data reduction system.

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1 INTRODUCTION

In the wind-tunnel testing of lifting models, it is often necessary to estimate the profile and induced drag components of the total drag, the remainder being referred to as the drag due to separated flow. A particular need for this form of drag decomposition arises in the application of constraint corrections to wind-tunnel results, in particular the correction for separated wake blockage (see, for example, Ref 1). The presence of a large amount of separated flow over the model, inferred from non-zero values of drag due to separated flow, leads to the generation of a separated flow wake. The constraining effect of the tunnel walls means that the separated flow wake can only be accommodated in the tunnel by an acceleration of the flow in the vicinity of the model. This acceleration of the flow is regarded as a change in freestream reference kinetic pressure (Δq) which must be found if the aerodynamic coefficients are to be calculated correctly.

To make the drag decomposition a more concrete process, it is assumed that in attached flow the drag of a general wing (or wing-body combination) may be written as

$$C_{D_A} = C_{D_0} + \frac{k}{\pi AR}(C_L - C_{L_0})^2 \quad , \qquad (1)$$

where C_{D_A} is the 'attached flow drag coefficient',
k is the induced drag factor,
AR is the aspect ratio of the model wing
and C_{L_0}, C_{D_0} are constants.

The parabolic drag polar given by equation (1) is an idealisation, having a rigorous foundation only in linear finite-wing theory, but it has been found to be a useful approximation for the drag of a model without extensive separation. However, in these cases, the lift-dependent drag term includes the variation of profile drag with sectional lift coefficient. This profile drag variation should, in principle, be extracted so that the blockage correction due to the 'attached flow wake' may be estimated, leaving the remaining lift-dependent drag as the induced drag alone.

At large lifts (high C_L's) the measured drag (C_D) will generally exceed the 'attached flow' drag given by C_{D_A}, and this difference is attributed to the separated flow drag, which is assigned a coefficient value of $C_{D_S} = C_D - C_{D_A}$ (see Fig 1).

Maskell[2] has given an expression relating the separated flow drag coefficient and the blockage it induces, via:

$$\frac{\Delta q}{q} = \frac{5}{2}\frac{S}{C}C_{D_S} \quad ,$$

where $\Delta q/q$ is the wake blockage factor used to correct the tunnel reference kinetic pressure, S is the reference area of the model, and C is the cross-sectional area of the tunnel working section.

The problem addressed in this paper is the estimation of C_{D_A}, or, more precisely, the estimation of the constants C_{D_0}, C_{L_0} and k in equation (1), from experimental data, so that the separated flow drag coefficient may be found. It must be emphasised, in view of the remarks above concerning the variation of profile drag coefficient with lift, that the resulting values for k do not represent the induced drag factor. The results from this analysis should not, therefore, be regarded as indicating the lifting efficiency of a particular wing.

2 PREVIOUS METHODS

Inspection of equation (1) reveals that the minimum value of C_{D_A} is C_{D_0}, and it thus appears that to determine C_{D_0} all that is required is to determine the minimum drag measured in the experiment. However, this assumes that the observed minimum drag lies in the range of lift for which equation (1) is an adequate description of the observed drag polar. This is not generally the case, as for some highly-cambered wings - such as a high-lift wing - minimum drag can occur at relatively high lift coefficients, as separations appear on the lower surface of a slat, leading to a drag rise as the lift decreases. An example of such behaviour will be given later. This highlights a particular difficulty with the problem of estimating an 'equivalent' parabolic drag polar - it does not apply to all of the observed drag polar, and the region where it is applicable must be estimated in some way. Early attempts at fitting a parabolic polar to part of the measured polar relied on a trial and error procedure of the following type. First, an estimate is made of C_{L_0}, and a curve of C_D against $(C_L - C_{L_0})^2$ is drawn. If the guessed value of C_{L_0} is close to the actual value, then the curve should be a substantially straight line. A rather arbitrary decision is made on what constitutes a satisfactory 'degree of straightness', and the process repeated with a new guess for C_{L_0} until a satisfactory fit is obtained. From the slope and intercept of this curve, values for k and C_{D_0} may be obtained.

Smith[3] attempts to rationalise the process by means of a sequence of least-squares curve fits. Again, a range of C_{L_0} values is estimated, and for each C_{L_0} a least-squares fit is taken over a defined range of lift coefficients on the observed polar. A correlation coefficient is then calculated which gives a measure of the goodness of fit of the curve to the specified part of the polar. C_{L_0} is then varied over the range specified in an attempt to find a maximum value for the correlation coefficient.

The virtue of this method is that once a range of likely C_{L_0} values has been supplied, and the part of the measured drag polar thought to be near-parabolic has been estimated, the process is well defined and may be automated. However, some skill is required in estimating the parabolic part of the observed drag polar, for which the method gives no guidance. A similar problem arises in estimating a range of C_{L_0} values to be tried. Furthermore, in searching for a maximum value of the correlation coefficient, a number of curve fits has to be taken, which may lead to unacceptable computation times if a large number of runs has to be processed.

It was therefore felt desirable to develop a method which relied less on inspired guesswork by the user, and less on trial and error curve fitting.

3 NEW METHOD

Referring to equation (1), consider two adjacent datapoints (C_{L_i}, C_{D_i}) and $(C_{L_{i+1}}, C_{D_{i+1}})$. If these datapoints lie on a parabolic part of the observed drag polar, we may write:

$$C_{D_{i+1}} - C_{D_i} = \frac{k}{\pi AR}\left(C_{L_{i+1}} - C_{L_0}\right)^2 - \frac{k}{\pi AR}\left(C_{L_i} - C_{L_0}\right)^2$$

$$= \frac{k}{\pi AR}\left(C_{L_{i+1}}^2 - C_{L_i}^2 - 2C_{L_0}\left(C_{L_{i+1}} - C_{L_i}\right)\right)$$

$$= \frac{2k}{\pi AR}\left(C_{L_{i+1}} - C_{L_i}\right)\left(\frac{C_{L_{i+1}} + C_{L_i}}{2} - C_{L_0}\right) ,$$

therefore

$$\frac{C_{D_{i+1}} - C_{D_i}}{C_{L_{i+1}} - C_{L_i}} = \frac{2k}{\pi AR}\left(\frac{C_{L_{i+1}} + C_{L_i}}{2} - C_{L_0}\right) . \qquad (2)$$

Therefore, if we plot $(C_{D_{i+1}} - C_{D_i})/(C_{L_{i+1}} - C_{L_i})$ against $(C_{L_{i+1}} + C_{L_i})/2$, we will obtain a straight line. Note that because a parabolic drag polar is assumed, the 'finite-difference' expression $(C_{D_{i+1}} - C_{D_i})/(C_{L_{i+1}} - C_{L_i})$ is in fact the derivative of the drag polar at a lift coefficient of $(C_{L_{i+1}} + C_{L_i})/2$, and is thus written as dC_D/dC_L. In practice, we expect only part of the measured drag polar to be adequately represented by a parabola, so only part of the plot obtained in this way will consist of a straight line. However, with the naked eye, it is easier to identify a straight line than a parabola, and so the plot quickly indicates that part of the measured drag polar which is parabolic, and thus the part of the polar that may be used in a curve-fit to obtain C_{L_0}, etc.

Furthermore, the plot like that described by equation (2) may be used directly to determine k and C_{L_0}, as the straight-line portion of the plot has a slope of $2k/\pi AR$, and an intercept at C_{L_0}. Thus one straight-line curve fit (least-squares if necessary) over a range of datapoints that are (hopefully) obvious from the plot is sufficient to determine C_{L_0} and k. To determine C_{D_0}, the value of C_{L_0} found from the plot described above is used to obtain a plot of C_D against $(C_L - C_{L_0})^2$. A straight-line curve fit to this plot, over the same range of C_Ls used in the first fit, will determine C_{D_0} from the intercept of the fitted curve with the C_D axis.

The new method is regarded as having two distinct advantages over the previous methods:

(i) the range of measured datapoints over which the parabolic drag polar should be fitted is obvious from inspection of the first plot;

(ii) no iterative curve fitting is required. Only two curve fits are required per case.

An internal consistency check is possible, as two independent estimates of k are available from the slopes of the first and second plots.

4 RESULTS

Results are presented here using data obtained from tests on a civil transport model in the RAE 5 metre Tunnel. Four configurations of the model are considered, corresponding to cruise, take-off with two flap settings, and a landing case.

The associated graphical results obtained by using the present method are shown in Figs 2 to 5. Each Figure has three parts. The upper part shows the plot of dC_D/dC_L against C_L that is used to identify that parabolic part of the polar, *ie* the part of this plot that is straight, or very nearly so. This is easily seen for the cruise case (Fig 2), while the take-off and landing cases (Figs 3 to 5) show varying degrees of 'straightness' for this curve. However, they all show a characteristic feature, and that is a straight region in the middle of the curve which has the lowest slope of any part of the curve. This is the part of the polar where drag changes least rapidly with lift, and is identified with the 'attached flow' part of the polar. Either side of this part of the polar, the drag rises rapidly with increasing lift (on the right-hand side) or decreasing lift (on the left-hand side). A straight-line fit is taken through the points lying on this middle portion of the curve, between the region delimited by the vertical bars. From the slope and intercept of the straight line, an estimate is obtained for k and C_{L_0}. The value of C_{L_0} is then used to produce the second curve, of C_D against $(C_L - C_{L_0})^2$. This produces another straight line for part of the curve, and a least-squares straight line fit is taken through the same range of lift coefficients used for the straight-line fit in the first plot. The intercept of the second straight line determines a value for C_{D_0}. The parabolic polar is thus determined. The lower part of the Figure shows a plot of the original data with the fitted polar also drawn. Note that Figs 3 to 5 have C_{L_0} outside the range of the parabolic part of the curve. This is because of the drag rise with decreasing lift associated with separated flow on the slat, as described earlier.

These results are compared to those obtained by using Smith's method[3] in Table 1. It is seen that there is quite good agreement for the values of C_{D_0}, but that there are marked differences in the values of C_{L_0} and k for some cases. However, it is misleading just to compare the values of C_{L_0}, C_{D_0} and k - we are concerned with the differences that this implies in the final wake blockage correction. Table 1 therefore shows the implied value of the 'separated flow' drag coefficient, and the corresponding blockage correction. The final values of wake blockage correction at $C_{L_{max}}$ obtained by each method are in good agreement, despite the differences in k and C_{L_0} used in each case. This is because a 'low' value of C_{L_0} is offset by a 'low' value of k. A similar result was noted by Lovell[4]. This indicates that the problem of determining k and C_{L_0} is to some degree ill-conditioned, in that appreciable differences in k and C_{L_0} do not affect the 'goodness of fit' very strongly. However, the converse of this argument is that the final parabolic polar fit is not very sensitive to the actual values of k and C_{L_0} obtained by the curve fit.

Therefore, while the estimation of accurate values of k and C_{L_0} from experimental data is difficult, the estimation of the corresponding parabolic polar is easier.

Two further applications of the present method are shown in Figs 6 and 7. Fig 6 shows the analysis of some results from testing a trainer model, while Fig 7 is based on results obtained from tests on a canard-delta combat aircraft model. Both Figures show an easily identifiable linear portion of the top curve (dC_D/dC_L vs C_L), although they represent configurations markedly different to the civil transport, the results from which are shown in Figs 2 to 5.

5 CONCLUSIONS

A rapid and reliable method for estimating equivalent parabolic drag polars from wind-tunnel data has been described, and compared with an alternative technique described in Ref 3. The new method has some advantages over that in Ref 3, in that the part of the measured drag polar that may be represented accurately by a parabola is identified at the outset. An important part of the current method is the use of an interactive computer graphics system, where linear portions of the polar slopes may be selected from the keyboard for processing by the computer.

If such a graphics system is available in the wind-tunnel control room, then the possibility arises of performing the separated-flow wake blockage correction 'online', *ie* as data is acquired. For example, in a typical test to determine the maximum lift coefficient of a model, the test proceeds by measuring forces over a range of incidences, increasing incidence between successive datapoints. If dC_D/dC_L is plotted against C_L as the test proceeds, the test controller can observe when a linear portion of the curve appears, and signal the computer to use this linear portion to fit a parabolic drag polar. The test results can then be corrected for wake blockage effects due to separated flow.

Table 1

COMPARISON OF RESULTS FROM PRESENT METHOD (1) AND METHOD OF REFERENCE 3 (2)

Figure	Method	C_{L_0}	C_{D_0}	k	C_{D_S}	$\Delta q/q$
2	1	0.146	0.029	1.58	0.0855	0.0075
	2	0.092	0.028	1.41	0.0875	0.0077
3	1	0.097	0.037	1.41	0.1175	0.0103
	2	0.086	0.037	1.40	0.1167	0.0102
4	1	0.224	0.057	1.30	0.1343	0.0118
	2	0.277	0.060	1.38	0.1290	0.0113
5	1	0.427	0.105	1.49	0.0804	0.0070
	2	0.426	0.105	1.49	0.0802	0.0070

LIST OF SYMBOLS

AR	aspect ratio
C_D	drag coefficient
C_L	lift coefficient
k	coefficient in lift-dependent drag term
q	kinetic pressure
Δq	increment in kinetic pressure due to wake blockage

Subscripts

i, i + 1	datapoint numbers
A	attached flow
S	separated flow

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No.	Author	Title, etc
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2	E.C. Maskell	A theory of the blockage effects on bluff bodies and stalled wings in a closed wind tunnel. ARC R&M 3400 (1963)
3	J.S. Smith	A curve-fitting method for the analysis of data obeying an assumed analytic relationship. RAE Technical Memorandum Aero 1961 (1963)
4	D.A. Lovell	A wind-tunnel investigation of the effects of flap span and deflection angle, wing planform and a body on the high-lift performance of a 28° swept wing. RAE Technical Report 76030 (1976)

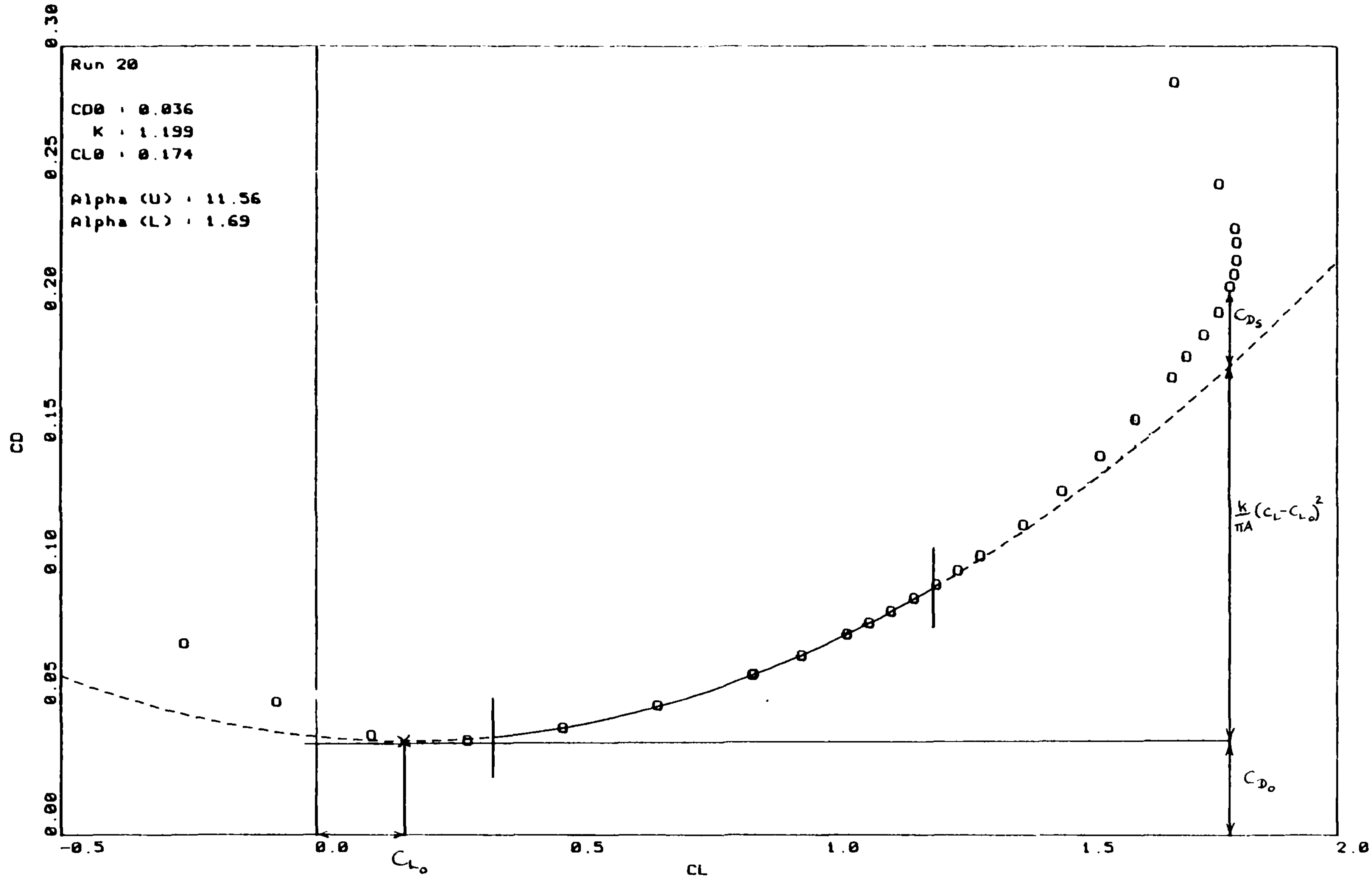
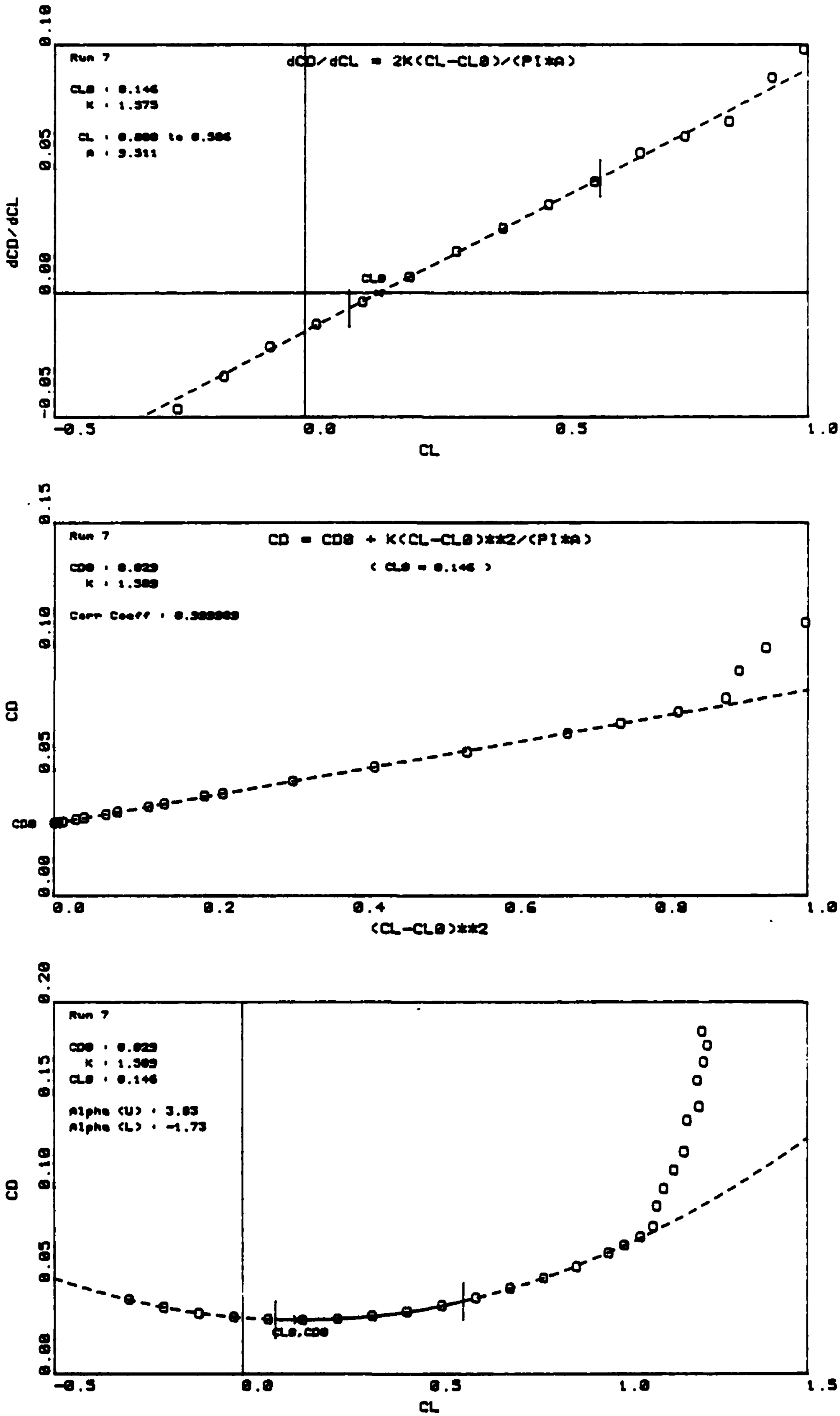


Fig 1 Measured and fitted drag polars, showing drag due to separated flow

Fig 1

Fig 2


Run 7
dCD/dCL = 2K(CL-CL0)/(PI*A)
CL0 : 0.146
K : 1.373
dCD/dCL
CL
CL0
-0.5
0.0
0.5
1.0
-0.05
0.00
0.05
0.10
Run 7
CD = CD0 + K(CL-CL0)**2/(PI*A)
(CL0 = 0.146)
CD0 : 0.029
K : 1.389
CD
CD0
(CL-CL0)**2
0.0
0.2
0.4
0.6
0.8
1.0
0.00
0.05
0.10
0.15
Run 7
CD0 : 0.029
K : 1.389
CL0 : 0.146
Alpha (U) : 3.83
Alpha (L) : -1.73
CD
CL
CL0,CD0
-0.5
0.0
0.5
1.0
1.5
0.00
0.05
0.10
0.15
0.20

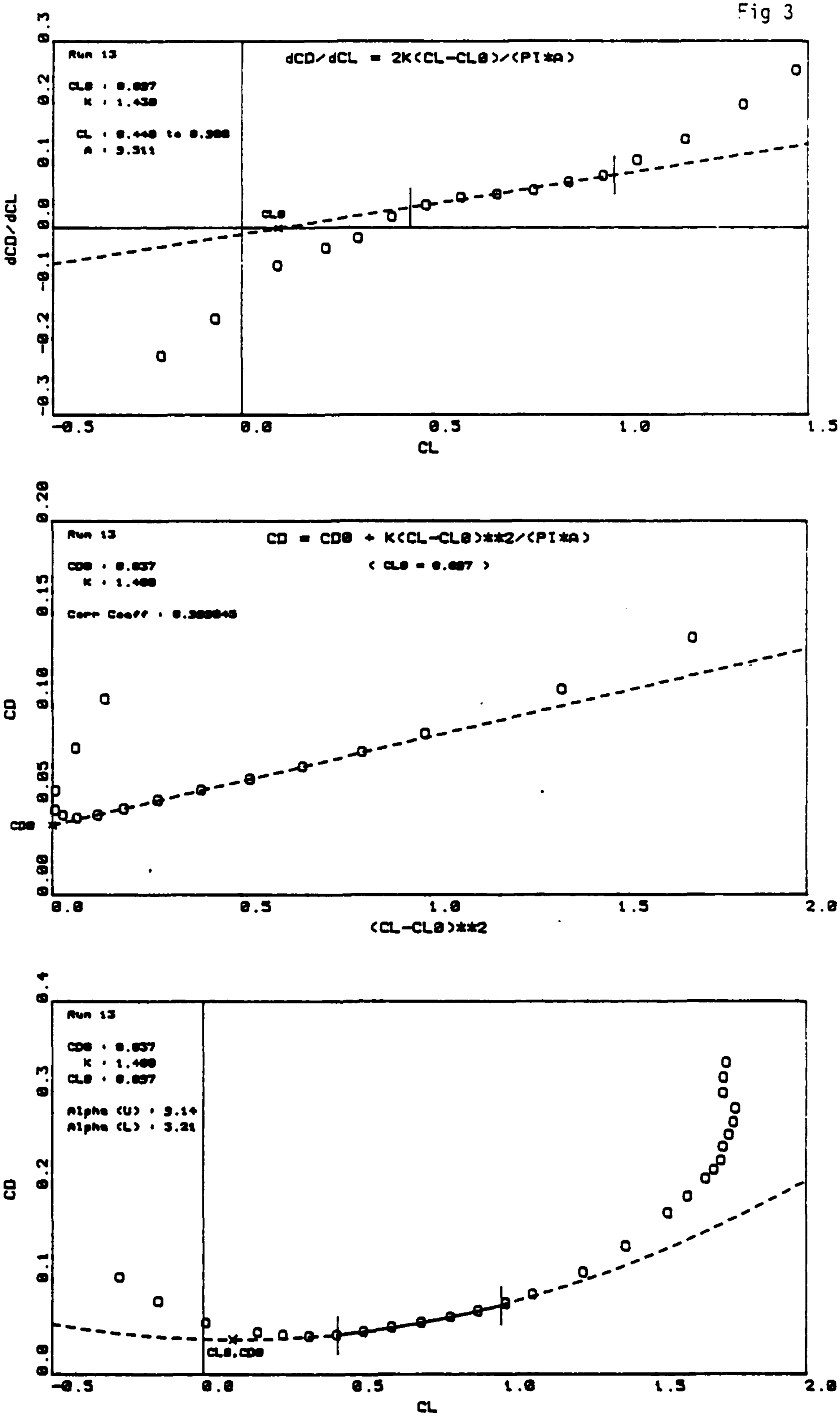


Fig 3 Results from civil transport tests - take-off configuration 1

Fig 4

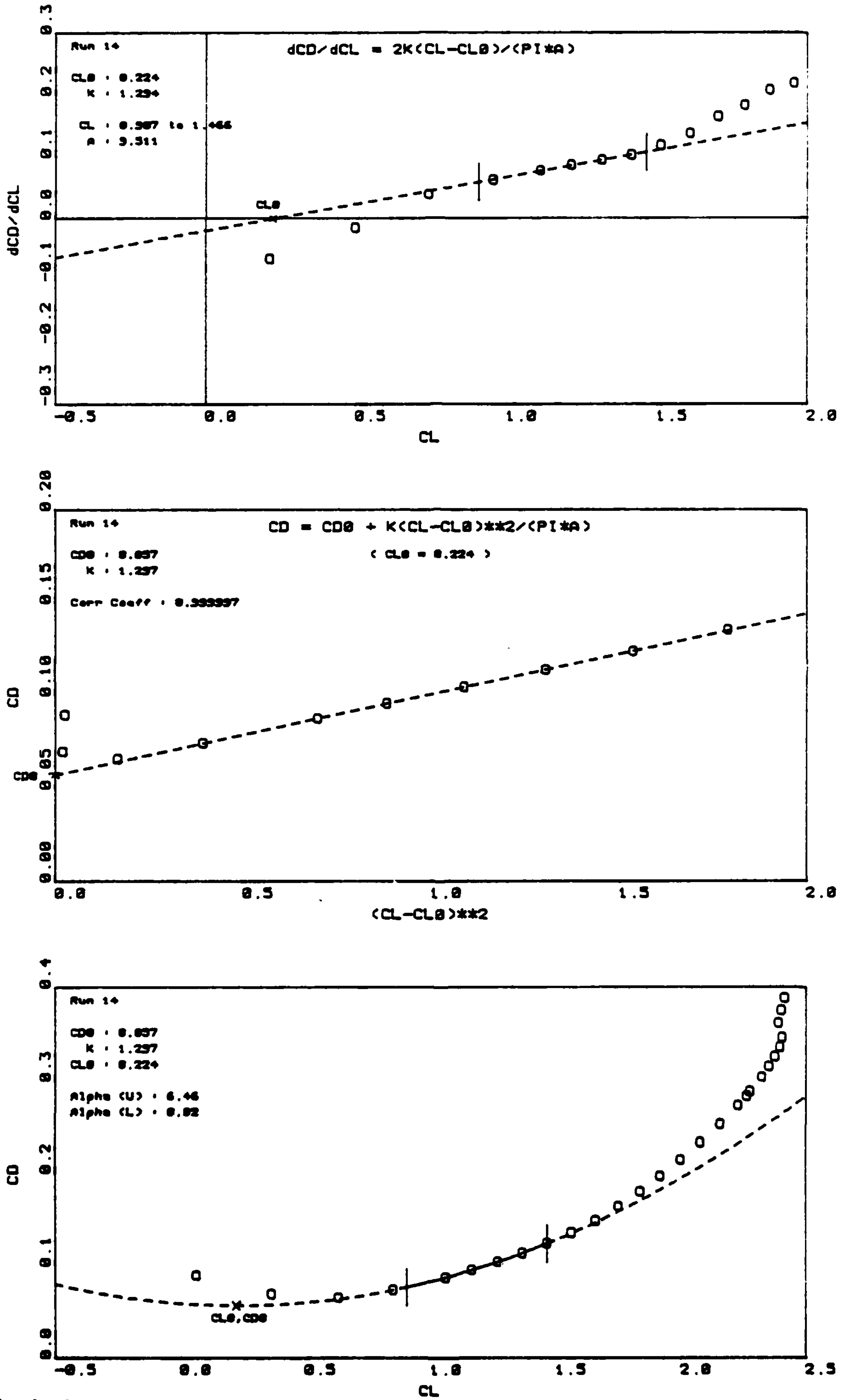


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Fig 4 Results from civil transport tests - take-off configuration 2

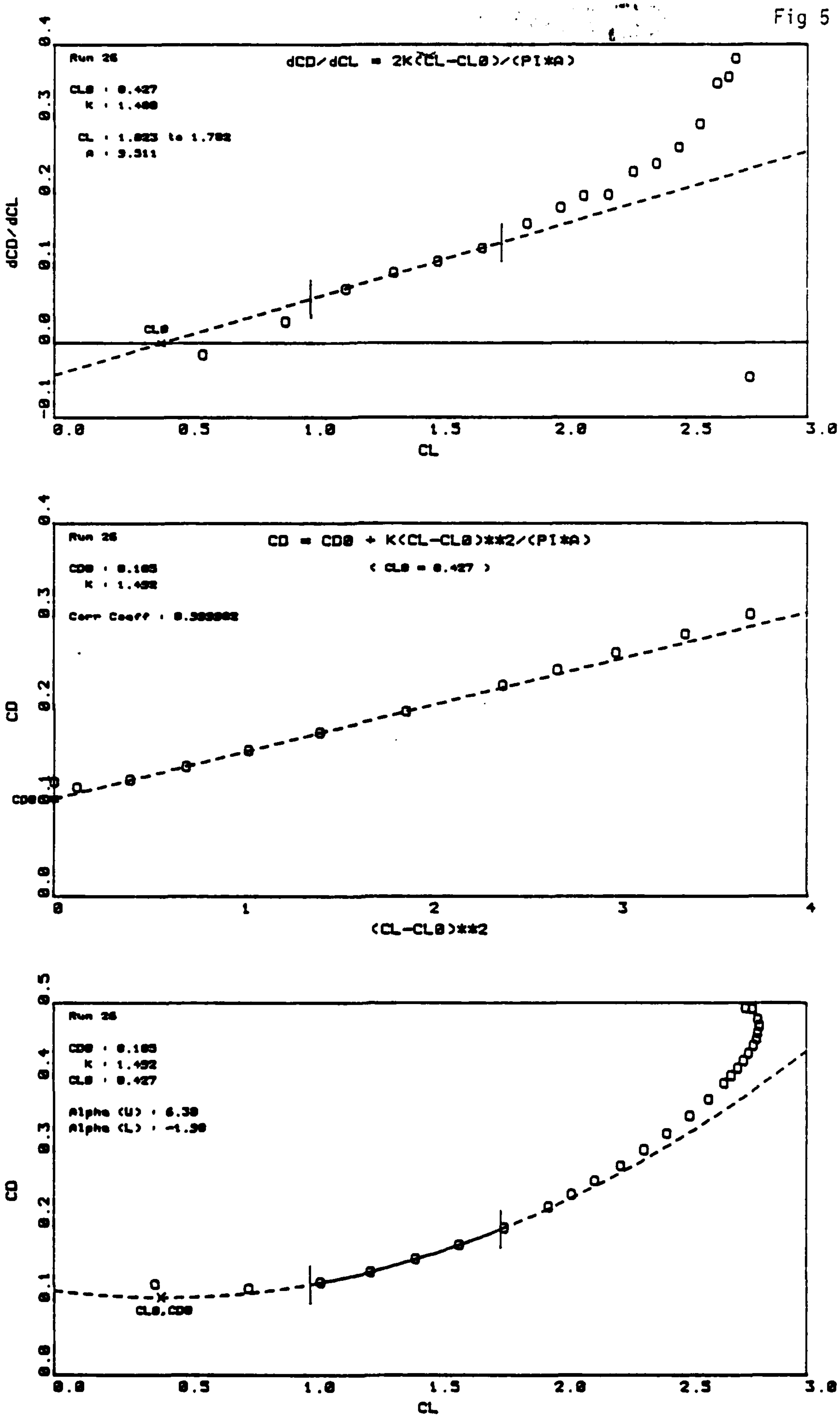

Fig 5 Results from civil transport tests - landing configuration

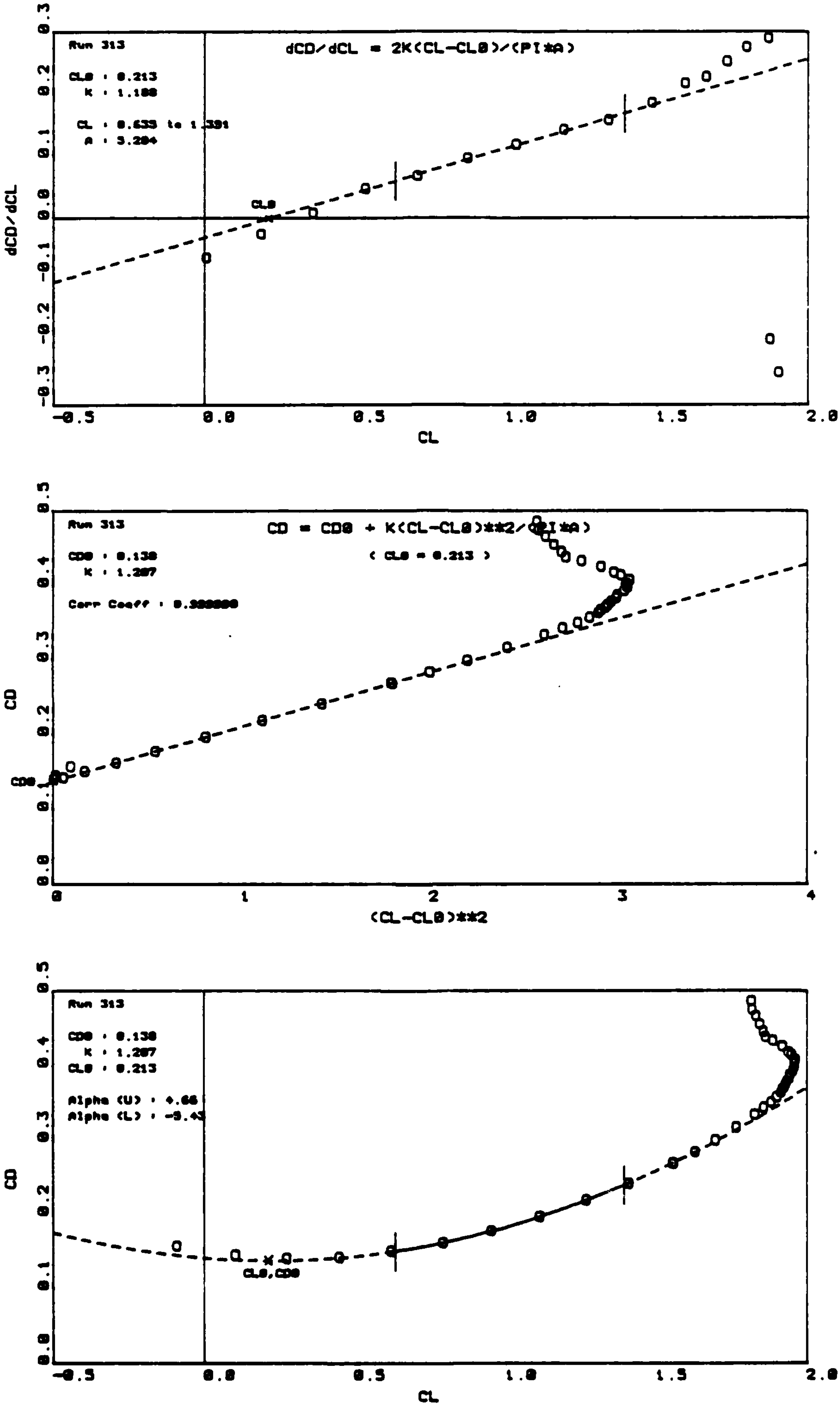

Fig 6 Results from trainer aircraft tests

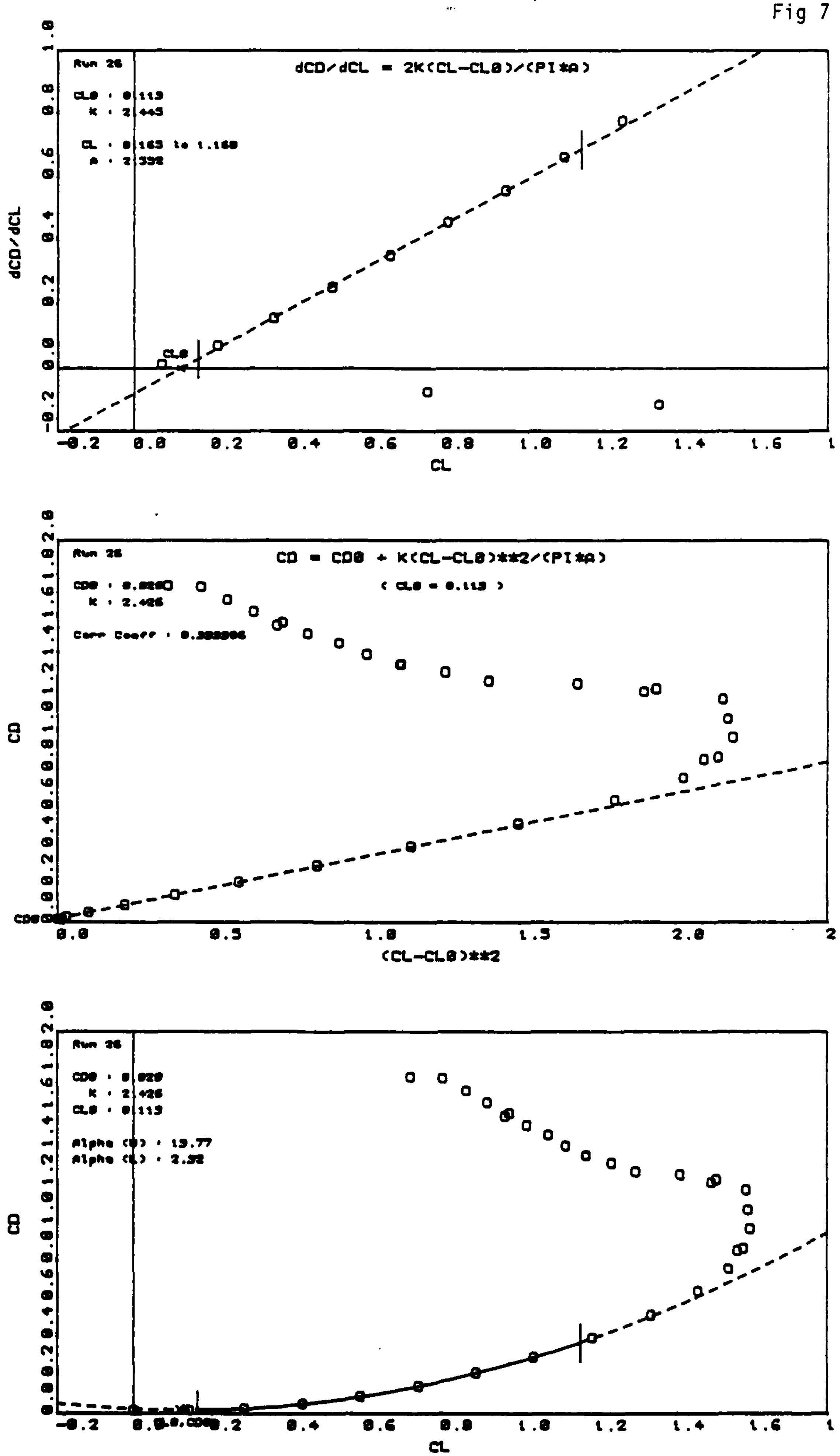

Fig 7 Results from combat aircraft tests

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17. Abstract

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An important part of the method is the use of computer graphics to identify the part of the measured drag polar that may best be described by a parabola, and thus used as the basis for a curve fit.

The method is fast, when compared to existing curve-fitting techniques, and suited to use with an "online" data reduction system.

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