ICAS PAPER
No. 72 – 13

POTENTIAL FLOW CALCULATIONS TO
SUPPORT TWO-DIMENSIONAL WIND TUNNEL
TESTS ON HIGH-LIFT DEVICES

by
Th. E. Labrujere, Senior Research Engineer,
G. J. Schipholt and O. de Vries, Research Engineers,
National Aerospace Laboratory (NLR)
Amsterdam, The Netherlands

The Eighth Congress of the International Council of the Aeronautical Sciences

INTERNATIONAAL CONGRESCENTRUM RAI-AMSTERDAM, THE NETHERLANDS
AUGUST 28 TO SEPTEMBER 2, 1972

Price: 3. Dfl.

POTENTIAL FLOW CALCULATIONS TO SUPPORT TWO-DIMENSIONAL WIND TUNNEL TESTS ON HIGH-LIFT DEVICES.*)

Th.E. Labrujere, G.J. Schipholt, O. de Vries
National Aerospace Laboratory NLR, Amsterdam, The Netherlands.

Abstract

The applicability of potential flow calculations for developing high-lift devices, is evaluated by comparing calculated pressure distributions over wing sections with trailing and leading edge high-lift devices, and experimental results, obtained during routine wind tunnel tests.

From these comparisons it was found, that the results of the calculations can be used for a number of purposes, viz.:
- The load estimation on an element of a multiple aerofoil.
- The interpretation of wind tunnel test results.
- The modification of a configuration, already tested.

It turned out to be impossible to optimize a given configuration by potential flow calculations only, the viscous effects being too important. In such a case boundary layer calculations must be included. It seems possible to refine the calculations by including boundary layer effects, but it is open to discussion, whether the maximum lift and the drag, which are vital in the optimization procedure, can be predicted with sufficient accuracy at the present state-of-the-art of boundary layer calculations.

1. Introduction

High-lift research very often involved two-dimensional investigations, to the effect that the optimization is performed in two-dimensional tests and the optimal configuration thus established, is checked in a test on a three-dimensional model.

This procedure is adopted, because of the relative simplicity of optimization tests in two dimensions, compared with three dimensions.

A standard testing technique has been developed, involving pressure measurements at the mid-span section of a two-dimensional model and a control of the tunnel wall boundary layer at the wing-wall junctions by blowing (1). Since the feasibility of calculating the potential flow pressure distribution around a multiple aerofoil by means of singularity methods, was already shown by a number of investigators (2,3,4), the question was put forward, whether such potential flow calculations can support the development of high-lift devices.

These calculations might be used for several purposes, viz.:
- Load estimation.
- Interpretation of wind tunnel test results.
- Modification of a configuration already tested.
- Pre-selection of a configuration out of a number of proposed configurations.
- Optimization of a chosen configuration.

The usefulness of the potential flow calculations in the above mentioned cases is evaluated by comparing the calculated pressure distribution on some configurations, with the results of earlier routine optimization tests (6).

The calculations were carried out with a two-dimensional version of a singularity method, developed in the first place for three-dimensional problems. The method uses a source distribution on the contour and a vortex distribution on the mean line (5).

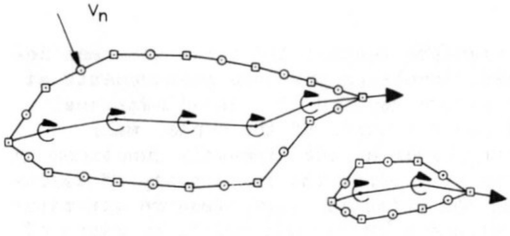
2. The singularity method

2.1 Short description

The programme for calculating the pressure distribution around a multiple aerofoil, is a limiting case in two dimensions of a method for calculating wing-body combinations, the NLR panel method (5).

*) This investigation was performed under contract with the Netherlands Agency for Aerospace Programs (NIVR).

The NLR panel method is a singularity method, with a source distribution on the contour and a vortex distribution on the mean line (see figure 1). The profile contours are approximated by straight line segments, connecting the given contour points. The mean line is defined by the points midway between pairs of points opposite to each other at the upper and lower side of the profiles. Vortices are located at these points of the mean line. As a consequence, the number of contour points on the upper and lower surface of the contour, must be equal.



□ GIVEN CONTOUR POINTS

○ CONTROL POINTS (V_n=0)

VORTEX POINTS (MEAN LINE)

▶ KUTTA CONTROL POINT

Fig.1 Representation of multiple aerofoil contour by straight line segments with a source distribution on the segments and discrete vortices on the mean line.

The boundary condition (zero normal velocity) is imposed on the control points in the centre of each contour panel. In the lifting case, the requirement for circulation leads to the condition of smooth flow at the trailing edge of each of the profiles. This Kutta-condition is applied to each of the profiles of the configuration, by requiring the velocity at a short distance behind the trailing edge, to have the direction of the bisector of the tail angle.

The Kutta-condition only determines the total vortex strength within a profile, not the distribution over the different points of the mean line. This must be chosen a priori. Most cases treated with the present method, appeared to be very little sensitive to the shape of the chosen vorticity distribution, as long as the distribution was sufficiently smooth, and the vorticity is zero in a region near the leading and trailing edge of the profile. The forces and moments on the constituting parts are calculated by integrating the calculated pressures. All coefficients are non-dimensionalized by the same reference length, viz. the basic (flap up) chord of the wing. The total lift and the pitching moment are calculated from the forces and moments on the separate parts.

The NLR panel method contains a compressibility correction, which has been developed for small incidences and high subsonic Mach numbers and which gives reliable results in those cases. It has not been verified yet, whether the same compressibility correction may be applied, when low subsonic Mach numbers are considered with high angles of attack, as encountered with high-lift devices.

2.2 The accuracy of the singularity method

The accuracy of the singularity method depends on the number and the distribution of the contour points used in the calculations. Up to now, a proper mathematical error analysis for the singularity method considered, has not been carried out. However, it was found from applications to isolated profiles, for which exact analytical solutions are available, that the distribution of contour points has to satisfy a number of general rules (for a comparison with exact solutions, see the Refs. 8 and 9).

The most important of these general rules is, that the distribution of the contour points has to be smooth. In addition, the local panel length should be small with respect to a local characteristic dimension of the aerofoil. The latter implies an increase in contour point density in the leading and trailing edge regions of the aerofoil. It was found, however, that this condition could be weakened in the trailing edge region, if the contour points on the upper and lower surface were chosen opposite to one another.

When the general rules, just mentioned, are followed, the experience at NLR is, that 60 to 80 contour points are sufficient to obtain a $1^o/o$ accurate solution for a single aerofoil. For a smaller number of contour points, the potential flow lift is generally underestimated.

Satisfying the rules for multiple aerofoils implies that special attention must be paid to the slot regions, where the local characteristic dimension is generally small.

2.3 The choice of the number of contour points

The purpose of the calculation method was to use it on a routine basis and therefore, the method had to be fast and cheap.
Because no boundary layer calculations are included in this routine method, the general characteristics of the potential flow pressure distribution are of interest only, and a high accuracy is not needed.
For that reason, only a limited number of contour points is used, which are normally readily available.
Only in those cases, where the potential flow lift and pressure distribution have to be known accurately, an increased number of contour points must be applied.

An impression of the influence of the number of contour points on the calculated lift of a single slotted flap (deflected 30 degrees), is given in the table below.

number of contour points	calculated lift	
	$\alpha=0^o$	$\alpha=6^o$
66	2.023	2.736
88	2.160	2.921
116	2.164	2.928

The time required, to calculate a single configuration with 110 contour points at one angle of attack on a CDC 6600 computer, is about 40 system seconds (central processor time about 30 seconds).

3. The application of potential flow calculations

3.1 General remarks

As already mentioned in the Introduction, potential flow calculations might be used e.g. for:

- Load estimation.
- Interpretation of wind tunnel test results.
- Modification of a configuration already tested.
- Pre-selection of a configuration out of a number of proposed configurations.
- Optimization of a chosen configuration.

The pressure distributions over a number of configurations already tested in the wind tunnel, were calculated and compared with the experimental results. From this comparison, limited conclusions can be attained concerning the usefulness of the calculations. This will be discussed in the following sections.

3.2 Load estimation

The figures 2 and 3 show a comparison between the calculated and experimental load on a double slotted flap and on a slat. The

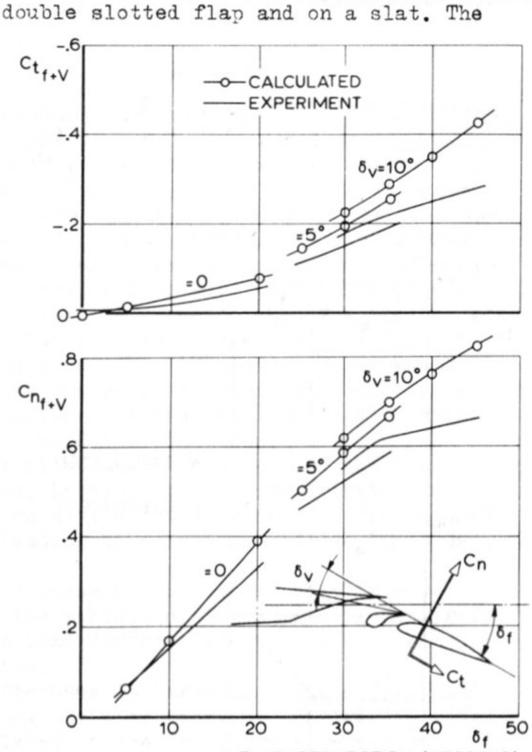


Fig.2 The calculated and experimental normal and tangential force on a double slotted flap, as a function of the flap deflection and at three values of the vane angle.
Note: the coefficients are referred to the basic wing chord instead of the flap chord.

agreement is reasonable, but the discrepancies in the tangential force c_t are larger than in the normal force c_n, especially for the slat.

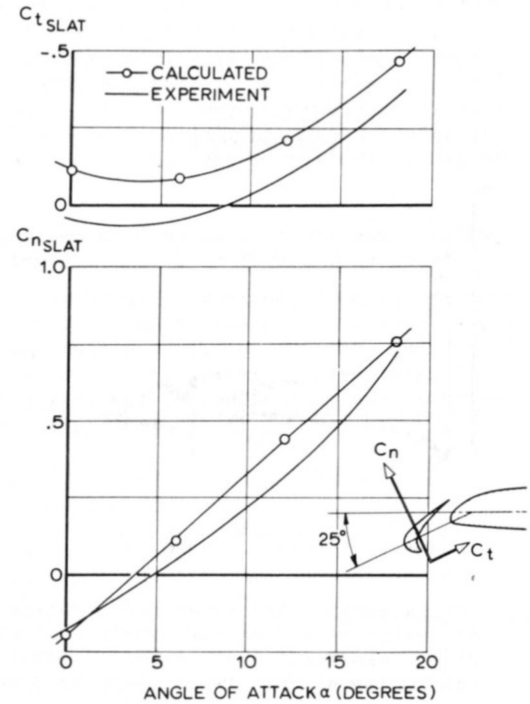


Fig.3 The calculated and experimental normal and tangential force on a slat, as a function of the angle of attack.
Note: the coefficients are referred to the basic wing chord instead of the flap chord.

It seems natural, that the flow separation at the slat lower surface (due to the sharp edge in the lower contour), has a large influence on the tangential force (drag). Fortunately, its influence on the normal force (lift) is less.

The forces on a flap or slat can be predicted accurately enough, to use them in a preliminary design study concerning the flap or slat drive mechanism. This may be important in estimating the disturbance in the flap or slat slot by this drive mechanism.
The load estimation can also be useful in designing the two-dimensional wind tunnel model.

3.3 The interpretation of wind tunnel test results

From the comparison between calculation and experiment, it is possible to give some examples, which illustrate the use that has been made of the calculations in interpreting experimental results.

3.3.1 Influence of separation bubble

In figure 4, the calculated pressure distribution on a single slotted flap is compared with the experimental result. Noticeable differences occur at the shroud lower surface and at the leading edge of the flap upper surface.

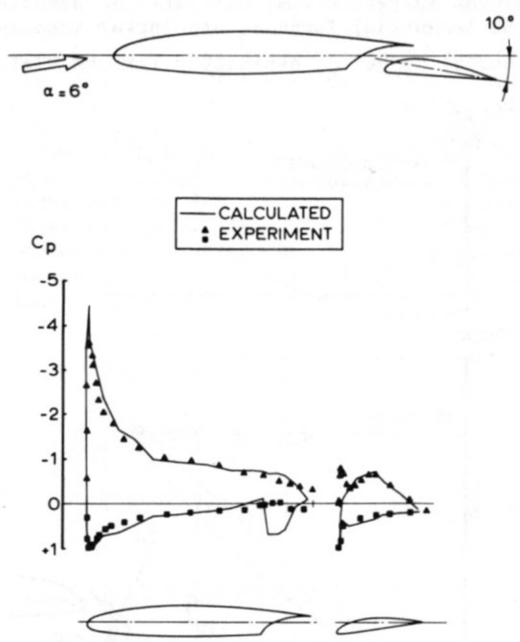


Fig.4 The calculated and experimental pressure distribution around the single slotted flap. Take special notice of the discrepancies at the shroud lower surface and the flap upper surface.

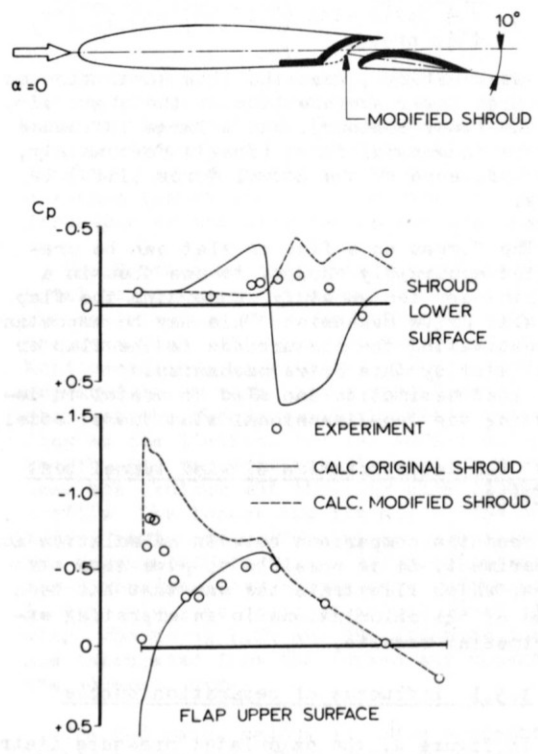


Fig.5 The simulation in potential flow of the "free streamline" of the separation bubble at the shroud lower surface by a modification of the shroud contour.

This is probably due to a separation bubble at the shroud, caused by the sharp edge in the lower contour. This separation bubble modifies the flow through the flap slot in such a way, that a suction peak appears on the flap. This conjecture was investigated somewhat further, by assuming a shape of the "free streamline" of the separation bubble and calculating the potential flow pressure distribution with this modified shroud (Fig.5). It appears from figure 5, that it is possible to induce a suction peak on the flap by simulating a separation bubble, which confirms the conjecture, that the suction peak was due to the separation bubble. By trial and error a closer agreement with the experimental results might be realized, but that was not the purpose of this calculation.

3.3.2 Interaction between wing and flap

Optimizing the position of a flap relative to the main wing, often gives results, which cannot be interpreted unequivocally. It is possible to get a deeper insight into the mutual interference between wing and flap, by using potential flow calculations (10).

Figure 6 shows the calculated and experimental influence on the total lift and on the flap load, of a rearward displacement of the flap and figure 7 shows the influence of a vertical displacement.

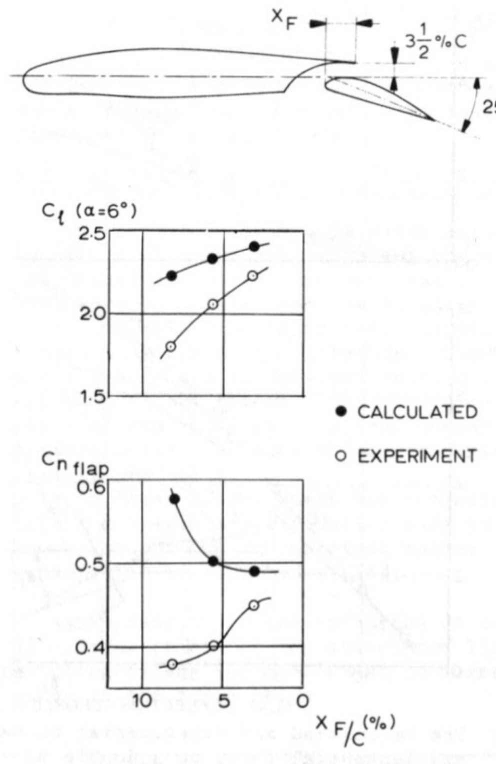


Fig.6 The influence of a rearward displacement of the flap at a constant gap width, on the total lift and on the flap load.
C_n is referred to the wing chord instead of the flap chord.

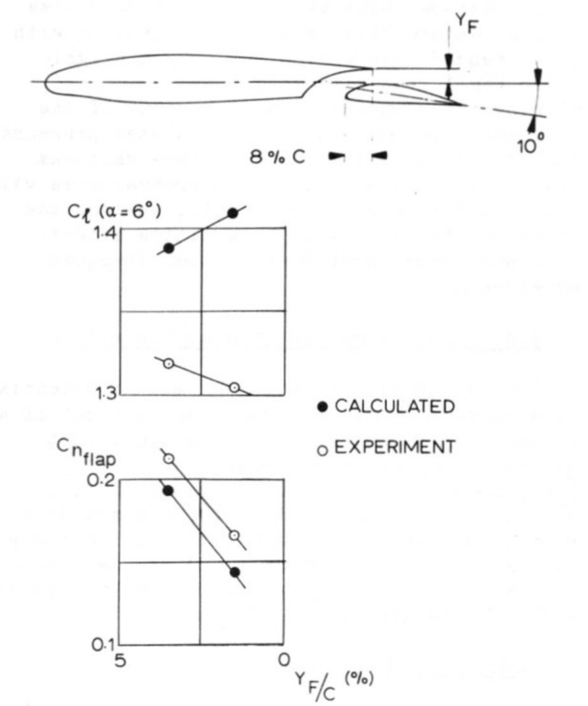


Fig.7 The influence of a variation of the gap width at a fixed rearward position, on the total lift and on the flap load. C_n is referred to the wing chord instead of the flap chord.

The calculated results in both figures show an increase in total lift and a decrease of the flap load by moving the flap rearward or by diminishing the gap width, thus in those cases, where the leading edge of the flap approaches the trailing edge of the main wing. This can be explained as follows:
Close to the leading edge of the flap, a strong upflow is present. When the leading edge of the flap approaches the trailing edge of the main wing, the circulation about the main wing must increase to compensate this cross-flow component at the trailing edge in order to satisfy the Kutta-condition.
The effective angle of attack of the flap diminishes, however, by the prescribed flow direction at the trailing edge of the main wing, leading to a decrease of the flap load.

The figures 6 and 7 show, that in some cases, the variation of the experimental lift or flap load differs from the calculated variation.
The difference in variation of the flap load by moving the flap rearward (Fig.6), is possibly related to the separated flow region on the shroud lower surface (cf. Sect. 3.3.1). With the flap in the forward position, the lift on the flap is disturbed by the separated flow of the shroud. Moving the flap rearward, the flap comes out of this separated flow region and the load increases in such a way, that it overcompensates the load decrease, found by the potential flow calculations.

Figure 7 shows, that a decrease of the gap width, leads to a decrease of the experimental total lift instead of an increase, as was expected from potential flow calculations. This is connected with the mixing of the boundary layers of the main wing and the flap (cf. Ref. 10). This merging of the boundary layers does not affect the variation of the flap load. It suggests that this merging must principally affect the conditions at the trailing edge of the main wing and not the conditions at the flap.
Note:
The experimental flap load at the small flap deflection ($\delta_f = 10^o$) in figure 7 is larger than the potential flow value. This is caused by the suction peak on the flap, induced by the separation bubble on the shroud (cf. Sect. 3.3.1), which is not present in the potential flow calculations. This effect is much smaller at larger flap deflections.

3.3.3 The "aerodynamic efficiency" of a configuration

Comparing the experimental lift curves with potential flow lift, an indication is obtained of the influence of viscosity on lift. In other words, the magnitude of the difference between the calculated and experimental lift, is a measure of the "aerodynamic efficiency" of the configuration.

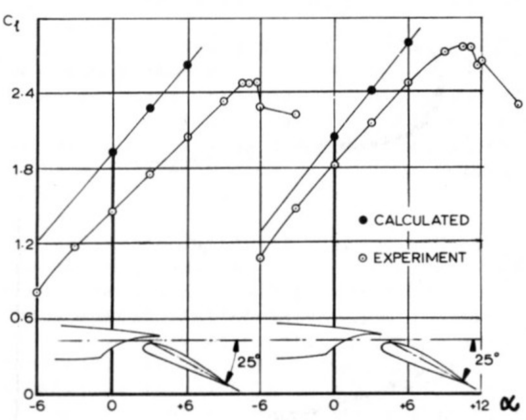


Fig.8 Comparison between the calculated and experimental lift, as a measure of the "aerodynamic efficiency" of a flap configuration.

In figure 8, the calculated and experimental lift curves are compared for two different positions of the single slotted flap behind a wing. The configuration with the flap in the forward position shows the largest deviation from the calculated lift, which is due to the interaction with the separated flow region of the shroud (cf. Sect. 3.3.2).

Because of the limited number of contour points used in the present calculations, the potential flow lift is underestimated, but the magnitude of the underestimation will be roughly equal in both cases and it will not seriously affect the comparison.

3.4 Modification, pre-selection and optimization

The pre-selection of a configuration out of a number of proposed configurations (choice of the type of device), the modification of a configuration already tested (shape variation) and the optimization of a chosen configuration (relative positions of the elements), with the help of potential flow calculations, all have one problem in common, viz. the translation of the shape of the pressure distribution into the boundary layer effect on maximum lift and also drag.
In the next sub-sections will be discussed, to what extent this can be accomplished, without incorporating boundary layer calculations.

3.4.1 Modification of a configuration

When a configuration has been tested in a wind tunnel and the results have been analysed, the over-all influence of the boundary layer is known. This greatly simplifies the task of choosing a particular shape out of several proposed modifications.

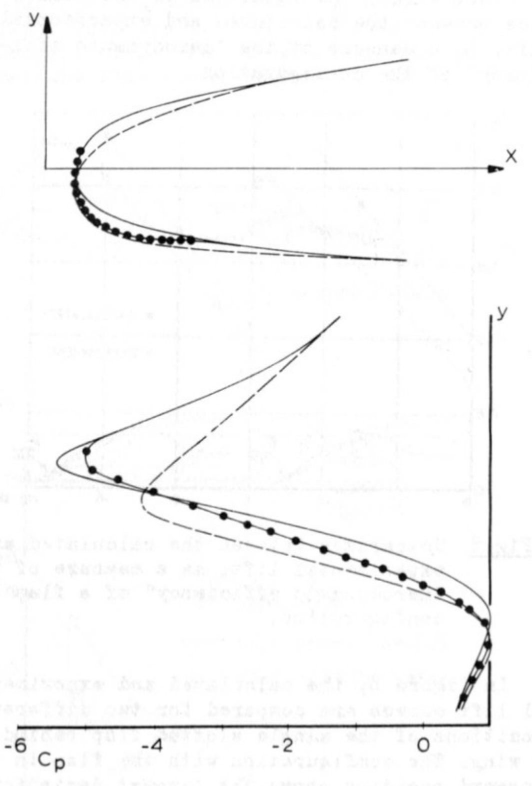


Fig.9 The calculated pressure distribution about three different nose sections, at a constant angle of attack.

An example is given in figure 9. It appeared from wind tunnel tests on a wing with a trailing edge flap, that the maximum lift of this configuration was determined by a leading edge stall. The nose section of the aerofoil involved was almost symmetrical (see full line in figure 9). Two modifications were proposed, viz. a drooped nose with about the same nose radius (dashed line) and a configuration with an increased nose radius but only a slight droop (full line with dots).
Knowing the boundary layer behaviour of the original nose section, the calculated pressure distributions of the modified nose sections leads one to expect, that the drooped nose will postpone the leading edge stall, whereas the other modification will have little effect.
This was indeed confirmed by the subsequent experiments.

3.4.2 Pre-selection of a configuration

The pre-selection, with the aid of potential flow calculations, of a configuration out of a number of proposed high-lift devices, must strongly rely on experience.
The pre-selection based on maximum lift, can only be accomplished, if a simple correlation exists between the maximum lift and the shape of the pressure distribution. A pre-selection on the basis of low drag, seems hardly possible without boundary layer calculations.

3.4.3 Optimization

In this case, the objective is to find that position of the flap or the slat, that gives the highest maximum lift (or the highest lift-drag ratio at a given lift).
At first sight, it seems not impossible to predict in some cases the variation in maximum lift with flap or slat position, from the calculated pressure distributions.

There are cases, however, where the inviscid pressure distribution is not correlated with the maximum lift. The discussion in section 3.3.2 is an example of a situation, where the potential flow calculations and the experimental results show opposite trends.

Another example, where the pressure distribution alone gives not enough information to predict the trend of the maximum lift variation, is the determination of the slat position in front of a wing, that gives the highest maximum lift.
Figure 10 shows the experimental pressure distribution on the slat upper surface and on the front part of the main wing at maximum lift (thus just before the stall), for two slat positions.
It appeared from experiment, that in both cases, the main wing stalled first. Therefore, the main wing determined the maximum lift.
The configuration with the narrow gap (broken line) shows the smallest maximum lift.
This is not evident from the pressure distribution on the main wing. The pressure distribution for the narrow gap looks more favourable with respect to the boundary layer behaviour, than the pressure distribution for the wide gap, but in both cases, the flow on the main wing is close to separation.
This contradiction can be explained by considering the mixing of the wake of the slat with the boundary layer of the main wing. This mixing affects the initial conditions of the boundary layer unfavourably.

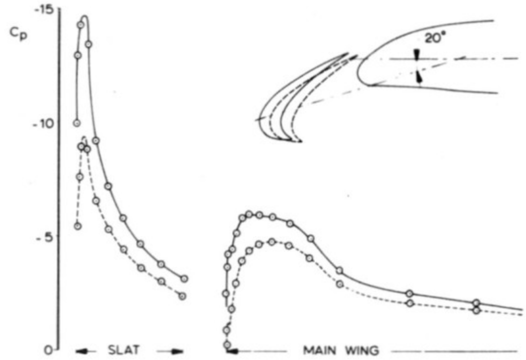


Fig.10 The experimental pressure distribution just before the stall, for two slat positions. The full line is the large gap and the broken line the small gap.

This effect can only be handled by boundary layer calculations incorporating mixing effects (confluent boundary layers, see Ref.7).

Summing up, the modification of a shape already tested in the wind tunnel, can be guided by potential flow calculations. The usefulness of potential flow calculations for preselection and optimization is limited, as long as no boundary layer calculations are included and must strongly rely on experience.

4. The feasibility of boundary layer calculations

In the foregoing discussion of the application of potential flow calculations, it appeared, that the range of problems, that could be handled by calculation, possibly can be extended by including boundary layer calculations.

The accurate calculation of the complete viscous flow about a multiple aerofoil, is a formidable task and seems still remote. Such a calculation must include:
- The potential flow about a given contour, including the correction for boundary layer displacement.
- The laminar boundary layer.
- A prediction of the transition region, or a prediction, whether a separated laminar boundary layer shows turbulent reattachment (laminar stall or laminar separation bubble).
- The turbulent boundary layer and a prediction of the turbulent separation point.
- A good representation of the singular behaviour at the trailing edge(s).
- Mixing of two boundary layers (confluent boundary layer).
- Viscous flow through strongly curved slots.
- Calculation of separated flows.

Reference 7 gives an example of a computer programme, which includes many of the above mentioned items, but which is not yet capable of calculating separated flows and of estimating the maximum lift and the drag with sufficient accuracy.

However, the above mentioned programme might be very useful in showing trends, by varying a certain configuration. To assess the range of applicability of such a programme, all the different theoretical and empirical elements, which constitute this programme, must be evaluated separately. It seems a big task indeed, to carry out such an evaluation and to gather the experience to work effectively and with confidence with such a complicated programme.

5. Concluding remarks

To further the development of high-lift devices by theoretical calculations, necessitates in many cases the prediction of drag and maximum lift of a multiple aerofoil system. Very much empirical data must be included to predict trends in drag and maximum lift from potential flow calculations only and therefore, the pre-selection of a configuration out of a number of proposed high-lift systems and the optimization of a chosen system with the help of potential flow calculations, seem not very appropriate.

By comparing potential flow pressure distributions with experimental results, it was found, that these calculations could be useful in the following cases:

- The load estimation for a preliminary design study.
- The interpretation of wind tunnel test results.
- The modification of a configuration, already tested.

In those cases, the over-all character of the pressure distribution was of interest only, and the calculations could be simplified by using a limited number of contour points (about 30 to 40 per profile).

The incorporation of viscous effects into the calculations, to predict maximum lift and drag, seems a formidable task in view of the large number of theoretical and empirical elements involved, which should all be evaluated separately as well as in combination.
A sensible approach is probably to incorporate in the computer programme the different aspects of viscosity (especially the prediction of separation points and the calculation of separated flows) in a step by step manner, with evaluation of the merits of the extension in each step.

References

1. De Vos, D.M.: Low Speed Wind Tunnel Measurements on a Two-Dimensional Flapped Wing Model, Using Wall Boundary Layer Control at the Wing-Wall Junctions. NLR TR 70050 U (to be published).

2. Giesing, J.P.: Potential Flow About Two-Dimensional Airfoils. Douglas Aircraft Co. Rept. No. LB31946, December 1966.

3. Foster, D.N. and Lawford, J.A.: Experimental Attempts to Obtain Uniform Loading over Two-Dimensional High-Lift Wings. R.A.E. TR 68283, 1968.

4. Mavriplis, F.: Aerodynamic Research on High-Lift Systems. AGARD Lecture Series No. 43, Paper No. 15, February 1971.

5. Labrujere, Th.E., Loeve, W. and Slooff,J.W.: An Approximate Method for the Calculation of the Pressure Distribution on Wing-Body Combinations at Subcritical Speeds. AGARD Conference Proceedings No. 71, Paper No.11, September 1970.

6. Labrujere, Th.E., Schipholt, G.J. and De Vries, O.: Evaluation of a Method for the Calculation of the Pressure Distribution on Two-Dimensional Wing-Flap Configurations in Subsonic Flow. NLR TR 72031 C, March 1972.

7. Stevens, W.A., Goradia, S.H. and Braden, J.A.: Mathematical Model for Two-Dimensional Multi-Component Airfoils in Viscous Flow. NASA Contractor Report CR-1843, July 1971.

8. Rubbert, P.E., et.al.: A General Method for Determining the Aerodynamic Characteristics of Fan-in-Wing Configurations. Boeing Cy., D6-15047-1, 1967.

9. Labrujere, Th.E. and Bleekrode, A.L.: A Survey of Current Collocation Methods in Inviscid Subsonic Lifting Surface Theory. Von Karman Institute for Fluid Dynamics, Lecture Series 44, February 1972.

10. Foster, D.N.: The Flow Around Wing Sections With High-Lift Devices. R.A.E. Tech.Memo Aero. 1269, November 1970.