# DEVELOPMENT OF A LOW-CORRECTION WIND TUNNEL WALL CONFIGURATION FOR TESTING HIGH LIFT AIRFOILS

G.V. Parkinson
Professor,
Department of Mechanical Engineering
University of British Columbia
Vancouver, B.C. Canada

C.D. Williams
Research Officer
National Aeronautical Est.,
National Research Council
of Canada
Ottawa, Canada

A. Malek
Graduate Student
Department of Mechanical Engineering
University of British Columbia
Vancouver, B.C. Canada

## Abstract

A recent innovation in wind tunnel test section design intended to reduce wall corrections in high-lift airfoil testing to negligible values is described. The test-section wall opposite the pressure side of the test airfoil is solid as in conventional tunnels, but the wall opposite the suction side consists of uniformly spaced transverse slats of symmetrical airfoil profile. This configuration permits the streamline pattern near the test airfoil to approach free-air conditions, so that the loading on the airfoil approaches its free-air values. Parameters for the wall configuration are chosen on the basis of potential-flow modelling, and some of the theoretical predictions and experimental comparisons are presented in the paper. The results are encouraging.

## 1. Introduction

The problem of wind tunnel wall corrections for low-speed airfoil testing has been studied for several years in the Aerodynamics Laboratory of the Department of Mechanical Engineering at the University of British Columbia. A paper[1] at the seventh ICAS Congress described the unsatisfactory performance for high-lift airfoil testing of longitudinally-slotted and porous walls which are successfully used in transonic testing. One of the unsatisfactory features of the use of these walls is the dependence of the theory on an empirical factor which varies not only with the wall configuration but with the test model.

The first step in seeking a new type of wall was to consider what characteristics were desirable. Clearly, the ultimate objective would be to recreate the free-air streamline pattern about the test airfoil, which would then experience the corresponding free-air loading. Self-correcting wind tunnel test sections, such as the type in which wall porosity is adjusted through a feedback system to make the flow conform to the desired streamline pattern[2], represent one interesting approach to this objective. However, the complexity of such systems seems likely to rule them out for other than major wind tunnels. For smaller tunnels, including those in University Laboratories, where considerable airfoil research is conducted, a simpler passive wall arrangement would be preferable, but a single configuration should produce adequately low corrections to test data for a wide range of sizes, shapes, and angles of attack of test airfoil. For many purposes 'adequately low' would mean corrections of the order of 1% to pressure, force, and moment coefficients, and it should be possible to maintain such low corrections for relatively large models developing high lift coefficients.

Since closed and open jet test sections produce corrections of opposite sign, the possibilities of obtaining low corrections through cancelling effects by employing partly-open, partly-closed boundaries are obvious. The unsatisfactory empiricism of the longitudinally-slotted and porous wall methods is a result of the partly-separated flows through the walls. If, on the other hand, transverse slats of airfoil profile are used to create the partly-open wall, the flow through the wall will remain attached to the slats since they will operate within their unstalled incidence range. Further, only the wall opposite the suction side of the test airfoil needs to be slotted, since the pressure distribution on the other side of the test airfoil is dominated by the presence of a stagnation point near the leading edge, and a near stagnation condition at the trailing edge, and should undergo negligible change from free-air to tunnel conditions.

Thus, the proposed test-section configuration for two-dimensional lowspeed airfoil testing has the test airfoil mounted midway between a solid plane wall opposite the pressure side and a wall containing a row of transverse symmetrical airfoil slats at zero incidence opposite the suction side, extending some distance upstream and downstream of the test airfoil. A plenum receives the air passing through the slotted wall, as in Fig. 1. An advantage of the single slotted wall is that the shear layer produced in the plenum at the interface between the tunnel airflow and the stagnant plenum air only re-enters the tunnel downstream of the test model. If the other wall were slotted as well, a shear layer would be produced inside the tunnel near the test airfoil, degrading the flow locally.

In the remainder of the paper, the use of potential-flow modelling to arrive at an efficient wall configuration is described, and results of calculations and wind tunnel experiments are presented and compared.

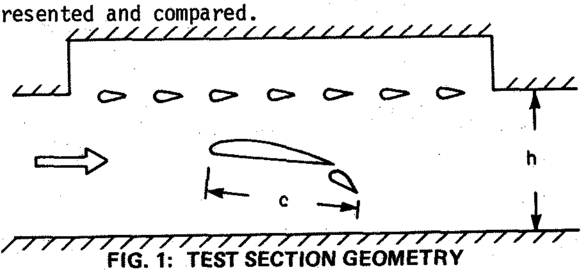

FIG. 1: TEST SECTION GEOMETRY

## 2. Theory

The criterion for re-creating free-air conditions in the wind tunnel is the pressure distribution on the test airfoil. If the pressure distribution is correct for the test Reynolds number Re, so will be the boundary layer characteristics, and therefore so will be the complete loading. Two-dimensional potential-flow theory is capable of providing good estimates of airfoil pressure distribution, even without interaction with boundary-layer theory, so it is the natural choice for a mathematical tool for studying the effects of different wall configurations.

The boundary conditions to be satisfied are uniform flow far upstream in the wind tunnel, tangent flow on the tunnel walls, the airfoil wall slats, and the test airfoil, Kutta conditions at the trailing edges of all airfoil elements, and a free-streamline pressure condition on the simulation of the shear layer generated in the plenum. The last condition is the most difficult to satisfy, and in the initial flow models used it has been ignored. Instead, the tunnel flow has been treated as the fraction originating between the walls of an infinite stream. The streamline that leaves the end of the upstream solid portion of the slotted wall and passes outside the slats is allowed to experience the pressure variation imposed by the streaming flow on its outside rather than that of the actual shear layer in the plenum. The justification for this might be called the 'intervening barrier hypothesis' that since the streamline in question is on the other side of the slotted wall from the test airfoil, its incorrect pressure distribution and shape will have a negligible effect on the test airfoil loading.

Since the boundary geometry, including an arbitrary test airfoil profile, is complex, and since an exact potential-flow pressure distribution is required, the obvious choice for modelling the flow is one of the surface-singularity methods. At first the source method of Hess and Smith[3] was used in which the boundary contours are replaced by polygons whose vertices are points of the original contours. On each polygonal element there is a uniform source sheet of unknown strength, and these strengths are determined by satisfying the tangent-flow boundary condition at control points at the mid-point of each element. Each lifting body in a system has a circulation supplied by a uniform vortex sheet over all elements of the body. The vortex sheets contribute to the tangent-flow boundary condition, and their strengths are determined by an additional Kutta condition for each lifting body. In the Hess-Smith method, this condition is equal velocity magnitude at the control points of the upper and lower trailing-edge elements. This can be called the 'no-load' Kutta condition since it eliminates any lift from the airfoil near the trailing edge. The application of this method to the present problem is described in more detail in an earlier paper[4].

Recently a different surface-singularity method, developed by Kennedy[5], has been applied to the problem. In this method the same polygonal elements are used, but the source sheets are replaced by vortex sheets of unknown strength which not only provide the circulation for any lifting bodies but are required to satisfy the tangent-flow and Kutta conditions as well. The stream function is the fundamental flow variable, and is required to be constant for all the control points of each body or component of the multi-body system. The Kutta condition for each lifting body is satisfied by choosing a point downstream of, but very close, to the trailing edge, lying on the bisector of the trailing-edge angle, and requiring this point to have the same constant value of the stream function. When the vortex sheet strengths have been evaluated by satisfying the tangent-flow and Kutta conditions, they are used directly to give the pressure distributions, since it can be shown that the vortex sheet strengths are equal to the tangential velocities at the corresponding control point. Lift coefficients are obtained by numerical integration of the pressure distribution. This method is computationally more efficient than the Hess-Smith method, and gives more accurate pressure distributions, since its form of Kutta condition is less restrictive.

## 3. Experiments

The experiments were performed in a two-dimensional test-section insert designed and built for an existing low-speed closed-circuit wind tunnel. This insert is 915-mm wide by 388-mm deep in cross-section, and 2.59-m long. Test airfoils were mounted at the midpoint of the test section and spanned the 388-mm depth. One side-wall was surrounded by a 0.39 by 0.30 by 2.44-m plenum, and could be fitted with airfoil-shaped slats of NACA-0015 section and chords of 46 or 92-mm, at zero incidence. A full range of wall open-area ratios (OAR) could be tested.

Modifications to the existing wind tunnel consisted of an inserted nozzle and diffuser section in addition to the 388 by 915-mm test section. The test section walls are parallel and solid; no provision for compensation for boundary layer growth is attempted. Pitot-static tube traverses indicate that the test section wind speed is spatially uniform to within 0.3% in the central "core" flow outside the wall boundary layers. Boundary layer pitot-static tube measurements in the empty test section (over a range of wind speeds covering the range of Reynolds numbers for all airfoil tests) indicated a displacement thickness of the order of 8-mm, where the test airfoils would be mounted. The test airfoils were mounted vertically on the turntable of a 6-component balance.

Altogether nine different airfoils have been tested, with lift, drag and pitching moment data taken for each one. In addition, surface pressure measurements were made on two of the airfoils. The airfoils for which results are reported here are four airfoils of NACA-0015 section, 383-mm span and 153, 307, 462 and 616-mm chord, which were machined from solid aluminum billets to close tolerances. Each airfoil was mounted on a circular spar which passed through a circular hole in the test section floor with 3-mm clearance all around. The floor and ceiling tip-clearances were less than 2.5-mm on all tests.

The largest NACA-0015 airfoil was fitted with 65 center-span pressure taps. All pressure taps are flush-mounted and have 0.5-mm diameter orifices. Plastic tubes of 1.6-mm inside diameter and approximately 1-m length transmit the surface pressures through the mounting spar to a location external to the test section. Pressures were measured via a 48 port "Scanivalve" manual-scan pressure transducer. The tubes were disconnected during balance measurements to eliminate any effect of tension in the tubes.

The test section wind speed was deduced from a pitot-static tube mounted on the flow centerline in the tunnel nozzle midway between the settling-chamber exit and test section entrance. This pitot-static tube was calibrated against a second pitot-static tube mounted in the empty test section, on the flow centerline, where the test airfoils would be located. The pitot-static tubes were connected to "Barocel" pressure transducers and calibrations were performed for all wall OAR's. During tests, the nozzle pitot reading is simultaneously monitored on a "Betz" micromanometer. During pressure tests, the total head in the nozzle is measured, and used as a calibration pressure for the "Scanivalve" transducer. Since this total head is essentially the same as the total head in the test section, the equivalent empty test section undisturbed reference static pressure can be determined from the empty test section wind speed calibrations.

## 4. Results and Comparisons

The theoretical curves presented here were calculated by the method of Ref. 5. Figure 2 shows a comparison of theoretical pressure distributions for an NACA-0015 airfoil of chord c at angle of attack $\alpha = 10°$ in free air and between the solid walls of a conventional wind tunnel test section of height h, with $c/h = 0.8$. The tunnel lift coefficient $C_{LT}$ is 1.687, 37.6% higher than the free-air lift coefficient $C_{LF}$ of 1.226. It can be seen that nearly all of the incerase is due to the greater suction over the top of the airfoil, and that the pressure coefficient $C_p$ on the underside experiences very little change from the free-air values, supporting the motivation for the single-slotted-wall test section of Fig.1.

Figure 3 shows comparisons of the effect on theoretical lift coefficients of the ratio c/h for different airfoils and test-section configurations. The airfoils are a NACA-0015 at $\alpha = 10°$, a 14% Clark Y at $\alpha = 10°$, and a NACA 23012 at $\alpha = 8°$ with a 25.66% slotted flap at 20°. The test section walls are solid or single slotted as in Fig. 1, with suitable OAR. It can be seen that with solid walls, for the calculated range of c/h, the corrections can exceed 50% of the free-air values, while with a suitable OAR of slotted test section with the predicted corrections can be kept within 2% for all 3 airfoils, and for $c/h < 0.8$.

Figure 4 shows a comparison of theoretical pressure distributions for the airfoil and angle of attack of Fig. 2 in free air and in a single slotted test section of OAR 55%, again with $c/h = 0.8$. It is seen that the distortion of the pressure distribution in the slotted-wall test section is quite small although the lift coefficients differ by 7.0%, with $C_{LT} = 1.312$, and $C_{LF} = 1.226$, largely because of the more positive pressure on the underside for the slotted-wall curve. This is commented on in the Discussion.

However, the potential-flow calculations serve merely as a guide to a suitable configuration, and the success of the single slotted wall system will depend on its experimental results. Figure 5 shows experimental values of lift curve slope, m (per degree) for four sizes of NACA-0015 airfoil in the presence of walls of different OAR, 0, 60%, 70% and 80% using the large slats. The m-values were obtained by least-squares fitting of straight lines to the $C_L$ - $\alpha$ data, taken on 1° increments, for $-2° < \alpha + 8°$. All tests for the three larger airfoils were run at a Re of $0.5(10^6)$. This Re could not be reached for the smallest (153-mm chord) airfoil, which was tested at a Re of $0.3(10^6)$. The data for it were then adjusted to correspond to the $0.5(10^6)$ using published m-Re data for the NACA-0015[6]. The adjusted data are the flagged points in Fig. 5. The results show a convergence towards a free air (zero c/h) lift curve slope value of 0.093, in good agreement with the theoretical prediction of Fig. 3.

Figures 6 and 7 give comparisons of experimental pressure distributions for the NACA-1500 airfoil of 616-mm chord (giving $c/h = 0.67$), tested at $\alpha = 10°$ and $Re = 1.0(10^6)$ between solid walls and with a slotted wall of OAR 60%. In Fig. 6 the data are uncorrected, and the values of Cp are seen

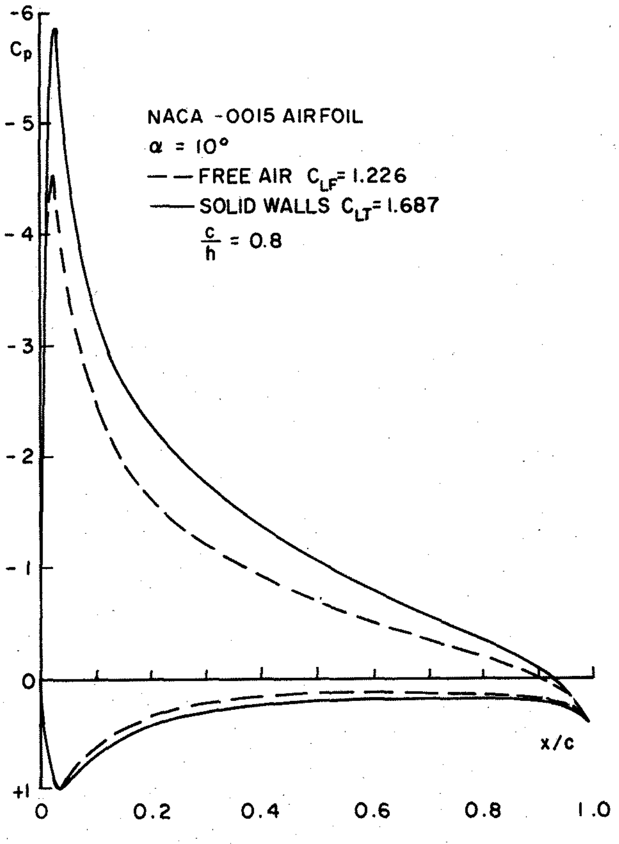

FIG. 2: EFFECT OF SOLID WALLS ON PRESSURE DISTRIBUTION: THEORY

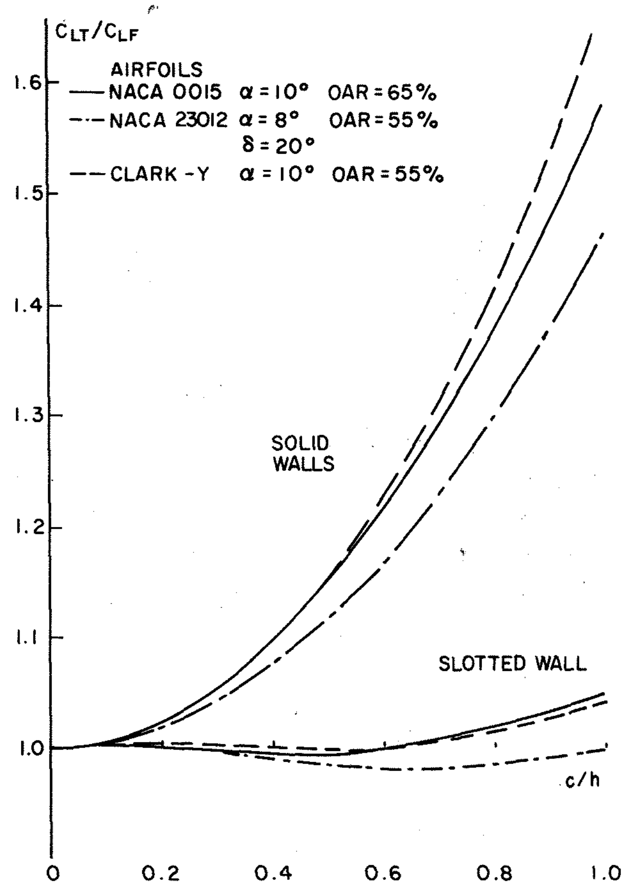

FIG. 3: EFFECT OF TEST MODEL SIZE ON LIFT: THEORY

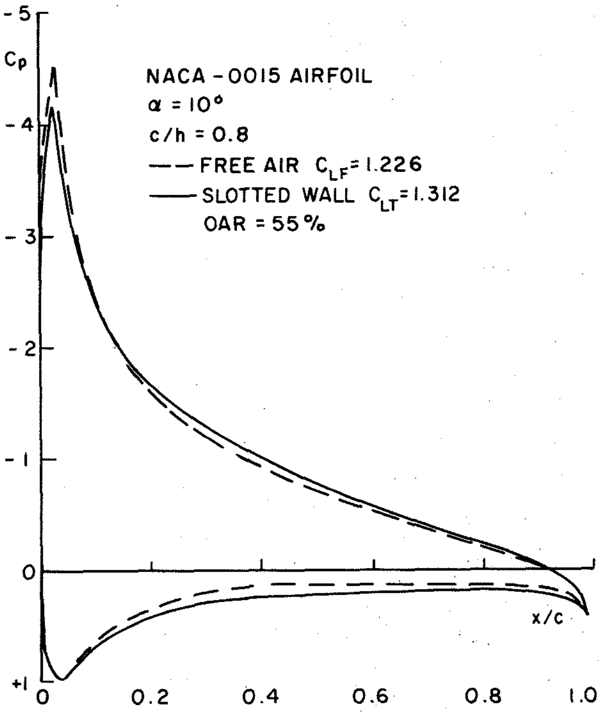

FIG. 4: COMPARISON OF PRESSURE DISTRIBUTIONS: THEORY

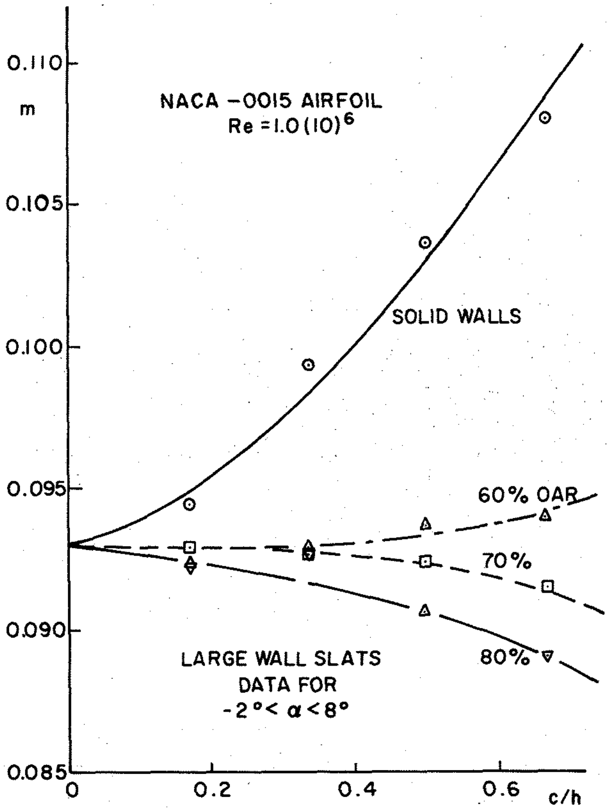

FIG. 5: EFFECT OF AIRFOIL SIZE ON LIFT-CURVE SLOPE: EXPERIMENT

to be much more negative over the upper surface of airfoil in the presence of solid walls than in the presence of the slotted wall, whereas the two distributions nearly coincide over the lower surface. This confirms the trends predicted in the theoretical curves of Fig. 2, but in order to check how closely the data from the slotted-wall test reproduces free-air values, the only means at hand is to make conventional wind tunnel wall corrections to the data from the solid-walls test. This has been done in Fig. 7, using the equation

$$\frac{1 - C_{p_F}}{1 - C_{p_T}} = \frac{C_{L_F}}{C_{L_T}}$$

where the subscripts refer to free-air and tunnel values, and $C_{L_F}$ is obtained from the data of Ref. 6, also used below in Fig. 9. The corrected values of $C_p$ for the solid-walls test, now supposedly representing free-air values, are seen to be in quite good agreement with the slotted-wall values although the corrected values are consistently slightly more positive. This is commented on in the Discussion.

Figure 8 gives comparisons of the experimental variations of $C_L$ with α for the airfoil, c/h,

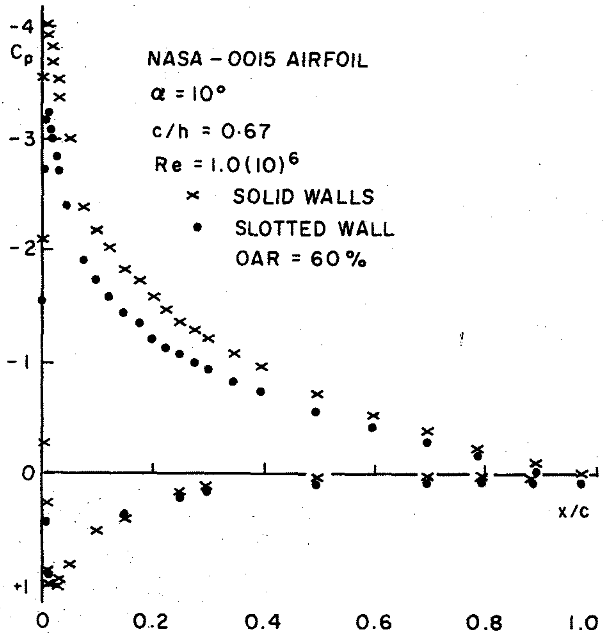

FIG. 6: EFFECT OF SLOTTED WALL ON PRESSURE DISTRIBUTIONS: EXPERIMENT

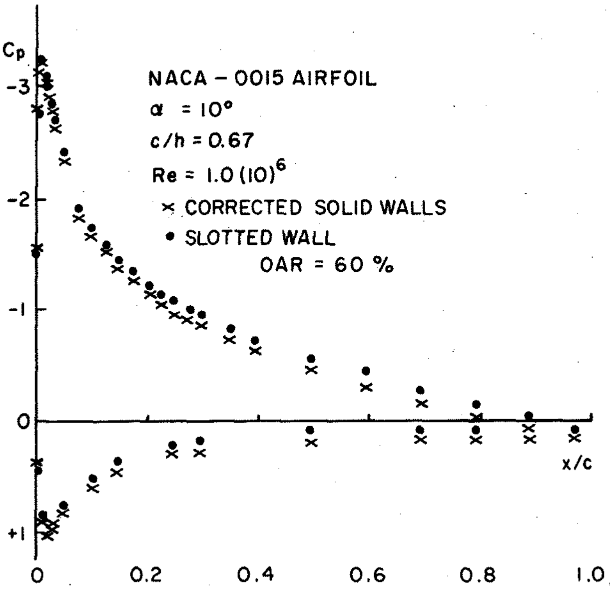

FIG. 7: COMPARISON OF PRESSURE DISTRIBUTIONS: EXPERIMENT

Re, and tunnel configurations of Figs. 6 and 7. The solid-wall values are more than 20% higher than the slotted-wall values. In Fig. 9 the slotted-wall values are compared with free-air values from Ref. 6, and are seen to be in excellent agreement.

## 5. Discussion

The quest for great accuracy in the measurement of the aerodynamic properties of airfoil sections is ultimately frustrating, because apart from the problems of tunnel wall constraints which have been studied in this paper, boundary layers and geometric imperfections prevent real flows from being two-dimensional, and the accuracy of measurement of the raw data is limited by the instrumentation available. Thus, in the present experiments the errors in $C_L$ measurement are of the order of 1%, the same order to which it was desired to limit the wall corrections.

Despite this, the results of the present investigation of the performance of a tunnel test section with a single slotted wall appear promising. The theory predicts, and the experiments confirm, that a test section with a slotted wall of OAR in the 55% - 65% range will produce lift data within 2% of free-air values, and pressure distributions of lower, but still quite good, accuracy. It is interesting that the present method of potential-flow calculation, based on Ref. 5, predicts lower values of OAR for best results than did the previously-used method of Ref. 3.

Some aspects of the $C_p$ - distribution results require further comment. In the theoretical curves of Figs. 2 and 4, there are larger differences in the lower-surface distributions than had been expected. In Fig. 2, the difference appears small, but would amount to between 1% and 2% of $C_{LF}$ and in Fig. 4 the difference accounts for most of the 7% difference in $C_L$. It is not yet clear whether these differences are real effects of airfoil and tunnel geometry, or whether they are at least partly effects of the numerical calculation procedure. In the experimental results of Figs. 6 and 7, on the other hand, the lower-surface distributions are nearly coincident in Fig. 6, but are separated by the correction procedure in Fig. 7. As a result, in Fig. 7, the corrected 'free-air' pressure distribution on the underside is more positive than the slotted-wall distribution, whereas in Fig. 4 the predicted free-air distribution is less positive than that for the slotted wall. It may be that the standard correction procedure applied to $C_p$ values needs re-examination.

Finally, as Fig. 4 shows, the upper-surface suctions in the presence of the slotted wall tend to be slightly low near the leading edge and slightly high further aft. These effects tend to cancel for lift but lead to appreciable errors in pitching moment. A solution to this problem would appear to be graded rather than uniform spacing of the wall slats, and work is in progress along these lines.

## Acknowledgement

The work described here was supported by Grant A586 of the National Research Council of Canada.

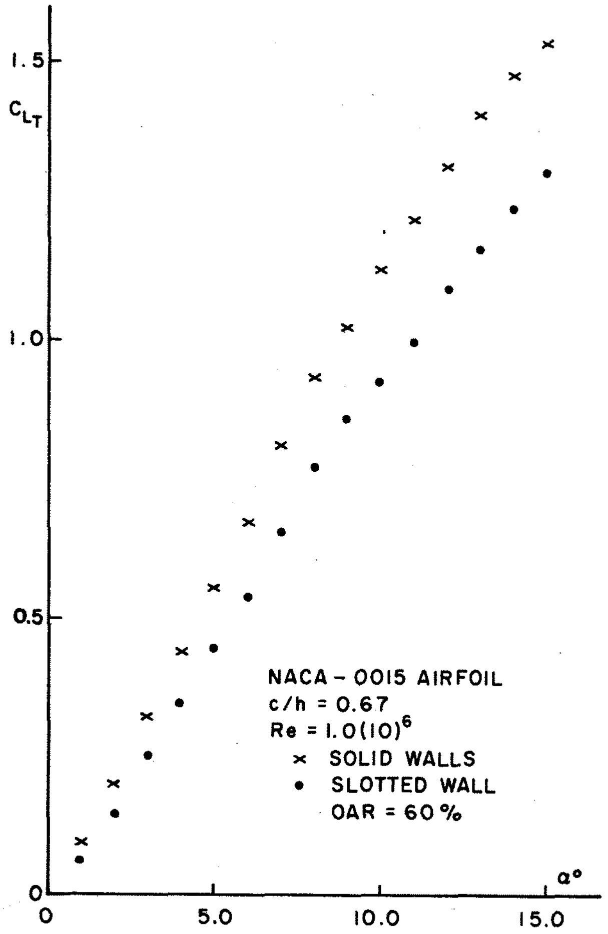

FIG. 8: EFFECT OF SLOTTED WALL ON LIFT: EXPERIMENT

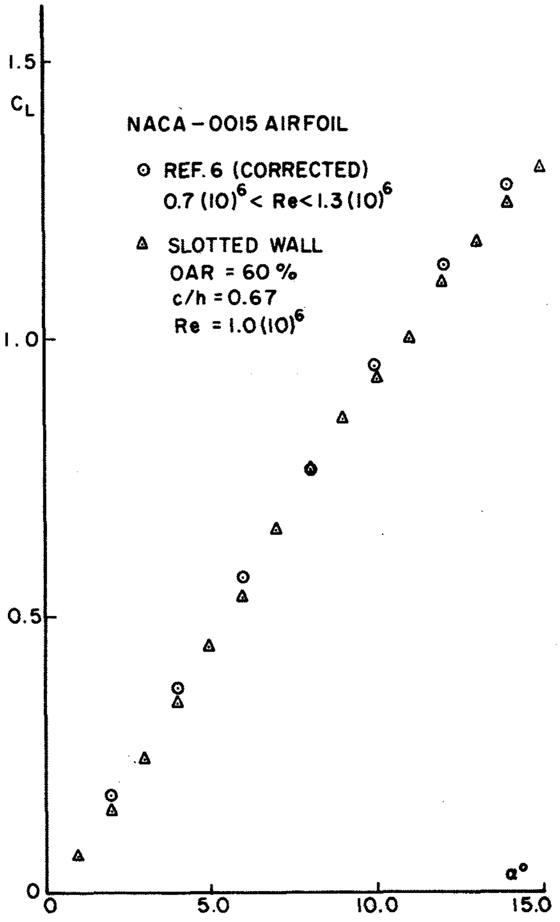

FIG. 9: LIFT COMPARISON: EXPERIMENT

## REFERENCES

1. Parkinson, G.V., and Lim, A.K.; 'On the Use of Slotted Walls in Two-Dimensional Testing of Low Speed Airfoils', Seventh ICAS Congress, Rome, 1970; Trans. C.A.S.I., 4, 2, September, 1971, pp. 81-87.

2. Sears, W.R.; 'Self-Correcting Wind Tunnels', Aeronautical Journal, 78, February-March, 1974, pp. 80-89.

3. Hess, J.L., and Smith, A.M.O.; 'Calculation of Potential Flow about Arbitrary Bodies', Prog. in Aero. Sci., 8, Pergamon, 1966.

4. Williams, C.D., and Parkinson, G.V.; 'A Low-Correction Wall Configuration for Airfoil Testing', Proc. AGARD Symposium on Windtunnel Design and Testing Techniques, London, October, 1975, pp. 21-1 to 21-7.

5. Kennedy, J.L.; 'The Design and Analysis of Airfoil Sections', Ph.D. Thesis, University of Alberta, Spring, 1977.

6. Jacobs, E.N., and Sherman, A.; 'Airfoil Section Characteristics as Affected by Variations of the Reynolds Number', NACA TR586, 1937.