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DEVELOPMENTS IN AIRFOIL TESTING TECHNIQUES AT UNIVERSITY OF SOUTHAMPTON*

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SUMMARY

The evolution in Europe of the flexible walled test section, as applied to two dimensional testing at low and transonic speeds, is traced from its beginnings at NPL, London, in the early 1940's, and is shown to lead logically to the latest version now nearing completion at Southampton University. The principal changes that have taken place are improvements in the methods of choosing wall contours such that they rapidly follow appropriate streamlines, and reductions in the depth of test sections.

Most effort is directed to the simulation of an infinite two dimensional flowfield around a single isolated airfoil. Test data illustrates the large reductions of wall interference obtained as the wall contours are moved from the straight to streamlines in an infinitely deep flowfield.

The latest transonic test section presently under assembly at Southampton is described, the design drawing on the accumulated past experience. It has as its principal new feature the facility for the automation of wall streamlining with the aid of an on-line computer.

The versatility of the flexible walled test section is emphasised by reference to the simulation of alternative flows including cascade, steady pitching in an infinite flowfield, and ground effect. Finally, sources of error in streamlining are identified, with methods for their alleviation.

INTRODUCTION

The notion of providing a test section with walls curved in the streamwise direction is probably nearly as old as wind tunnel testing itself. The stimulus is the desire to reduce, ideally to eliminate, wall interference with the model such that it behaves as though in an infinite flowfield. For this purpose the walls are required to follow a streamtube encompassing the model. Obvious barriers to the implementation of the notion in three-dimensional testing include the difficulties of providing walls which will take double curvature, and the complication of the associated jacking system. Furthermore, as the flowfield and hence wall contours would be a function of model attitude, and the flow Mach and Reynolds numbers, changes of contour would be required with almost every change of test condition.

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The flowfield cannot be calculated with certainty; otherwise, presumably the model would not be under test. Therefore, the shape of a suitable encompassing streamtube is not known in advance.

The question would arise of the correctness of the wall contours which are imposing boundaries on the streamtube. The question can, in principle, be answered by flowfield calculations applied to the wall regions, calculations which can be made with reasonable confidence if the streamtube lies in potential flow. However, without the aid of a computer such calculations are a practical impossibility.

The situation is eased somewhat in two-dimensional flow. At least the mechanical design of walls and jacks is relatively simple. During World War Two the pressure to introduce a flexible walled test section increased with the discovery of severe wall interference effects at transonic speeds. NPL in London responded in 1941 by constructing a transonic two-dimensional test section, with two opposite flexible walls adjusted manually through jacks distributed along their lengths. The test section was conventional in terms of depth and length in relation to the airfoil chord, and is sketched to scale with other test sections on Figure 1. The walls were set to approximate streamline shapes by invoking some trends seen in two-dimensional potential flows calculated around simple bluff and lifting bodies: the infinite flowfield streamline and therefore wall contour lay roughly midway between the straight and the contour giving constant static pressure. The streamlining operation established an experimental procedure that is followed invariably today, namely that the contours are based on measurements made only at the wall. The measurements are of local wall position and static pressure.

The quality of the aerodynamic data taken from airfoil models in this tunnel was quite satisfactory, but eventually the emergence of the ventilated designs of test section superceded it because they did not require the slow, manual wall setting procedure. However, in moving to the ventilated design at least two features of testing were worsened: tunnel drive power rose, and flow unsteadiness increased.

There followed a lengthy lapse in interest in the use of flexible walls for reduced interference at low and transonic speeds, but then in the early 1970's at several different research establishments and perhaps responding to different stimuli, researchers re-examined test techniques and postulated new solutions. The following sections of this report summarise the features of the newer flexible walled tunnels in Europe, show typical test data obtained at Southampton, and underline the need and means for automation in the operation of such tunnels.

Reference citations are denoted herein by superscripts.

LOW SPEED TEST SECTIONS

The work at Southampton sprang from discussions held at Langley Research Center[1] in 1971, where attempts were made to identify reasons for the magnetic suspension and balance system failing to satisfy the needs of mainstream aerodynamic testing. Among the possible solutions to the problem were the cryogenic wind tunnel to raise Reynolds number without increase in tunnel size, and therefore without increase in the cost and power demands of the magnetic suspension system, and the use of a flexible walled test section to eliminate the need for ventilation with its bulky plenum chamber.

Because of the obvious cost, technical risk and complexity of such a three-dimensionally deformable test section, it was decided, in 1972, to proceed with a two-dimensional design. A computer would allow the rapid execution of the necessary wall-based calculations. A low speed wind tunnel was modified by the incorporation of flexible walls with 14 jacks on each wall. The tunnel began tests in May 1973. This design began a trend towards reduced depth which has since been followed, the depth:chord ratio being about 1.4 compared with about 3.4 in the NPL tunnel. The argument for reduced depth (or increased chord) is based on the achievement of low interference. In subsequent years the test section was progressively modified as it became clear that a greater length of streamlined wall was required, also that symmetry[2] was desirable. The evolution is illustrated on Figure 1. The latest version of the low speed test section is 1.1 chords deep (the wing chord used is 13.72 cm), has eighteen jacks per wall, a total length of 9.4 chords, but a "streamlined" length of only about five chords centered about the quarter-chord point. The studies paralleling this work have shown the need for close jack spacing near to the model in order to adequately define wall shape. In fact, in the light of what we now know we would judge the old NPL tunnel to have had well chosen jack spacings. The sketches on Figure 1 show in most cases the point where the flexible walls are anchored to the contractions.

The wall measurements of contour and static pressure are particularly simple, and the subsequent computations should in principle be based[3] on the boundary layer displacement thickness contour. In practice, this requires estimates only of the small changes in thickness between model present and absent. The estimates can be based on boundary layer measurements, or on boundary layer theory using model-induced wall pressure gradients. The latter has been chosen. However, we find that the changes in thickness on the flexible walls are so small that whether or not they are taken into account has no measurable effect on the model in low speed testing. There seem to be much more serious effects from the sidewall boundary layers.

The setting of the walls to streamlines is necessarily iterative, with, in our early experience, several steps being required to take the walls from "straight" to "acceptable streamlines". One development in technique which has taken place in recent years, the importance of which must be emphasised, is Judds[2] predictive method for wall adjustment. The adoption of this method has reduced the average number of iterations from about eight[3] to about two[4] for each model attitude. There are proportional reductions in the time for streamlining, which of course is time not available for taking model data.

The reductions in wall interference by streamlining are illustrated on Figure 2 which shows the normal force coefficient C_N for an NACA 0012-64 airfoil tested in the latest (1976) version of the low speed test section and in Langley's LTPT as baseline data. It is seen that streamlining the walls largely corrects the data except at the highest angle of attack investigated, 12 degrees. Some considerable effort has been expended in searching for reason(s) for this disparity, so far without positive conclusions. However, there is a strong indication that sidewall boundary layer effects might be responsible since the addition of small disk-shaped leading edge fences about 1 cm from the sidewalls went some way towards reducing the error in force coefficient. Despite the residual disparity at this angle of attack, with wing fences the streamlining of the walls had eliminated 82% of the "straight walls" interference.

It should be noted that data taken in any non-automated self streamlining test section is hard-won because of the slowness of the streamlining procedure. The data shown on Figure 2 is the most extensive so far published from any similar contemporary wind tunnel.

Besides the simulation of a single model in an infinite flowfield, the self streamlining wind tunnel can simulate a variety of other flowfields around a single model including[3] ground-effect and open-jet testing. More recently* the low speed tunnel has been used for simulating steady pitching of the same NACA airfoil, in the manner of the old Dynamic Stability tunnel at Langley. The photograph on Figure 3 shows the walls curved around an arc chosen to give negative rates of pitch. Note that in these tests the airfoil is mounted inverted. The curvature introduces a rate of pitch q of the airfoil which depends on the radius of curvature and airspeed v. There is as yet no rational method available for streamlining with a curved axis, therefore, in these tests the walls were deformed from arcs by the same amount that they had been deformed in streamlining from the straight in earlier non-pitching tests. The streamlining can therefore have been only approximate, but despite this the resultant data is encouraging. This is shown on Figure 4 as ΔC_N the change of normal force coefficient due to pitching, and ΔC_M the change of pitching moment about the leading edge due to pitching, each as functions of the ratio of rate pitch to airspeed q/v. The ΔC_N test data compares well with thin airfoil theory.

Finally, in connection with low speed testing mention should be made of the possibility of simulating cascade flows around one (or more) airfoils by imposing appropriate flow boundaries with flexible walls. A streamlining criterion has been laid down[3] and the test section built for a single airfoil is shown on Figure 1. Current effort is aimed at demonstrating the achievement of cascade flow, and at adapting the predictive method for rapid wall streamlining. This work will be reported separately by Wolf.

TRANSONIC TEST SECTIONS

In parallel with the low speed work at Southampton, Chevallier at ONERA constructed a transonic test section[5] of similar size, again with manually adjusted jacks. The proportions of the test section are conventional, but the number of jacks and their spacing we now believe to be rather inadequate for the satisfactory definition of wall shape in the presence of an airfoil model

* This work followed a suggestion by Mr. J. Pike of R.A.E. Farnborough

much larger than that shown and used. The test section has been used to demonstrate adequate streamlining of the wall at transonic speeds using the modern type of streamlining criteria.

Lastly on Figure 1 is sketched the transonic test section which has been manufactured for an existing induced flow atmospheric tunnel at Southampton. The test section has motorised jacks and provision for the rapid scanning of wall pressures and position transducers at each jack. The test section is intended for coupling to a PDP 11-34 computer for online streamlining[2], followed by the online acquisition of model data. The development program will include airfoil testing with comprehensive sidewall and wake instrumentation, followed by some testing of wing-body combinations with the aim of evolving streamlining methods which may alleviate wall interference in three dimensional flow. It is also planned to investigate the possibility of attenuating reflected shocks, to allow testing at high transonic speeds. The tunnel will begin running in mid 1978.

SOURCES OF ERROR

Length truncation

The test section can only reproduce a limited length of correctly contoured streamtube. The effects of truncation can be assessed as a correction to model data[2]. The correction is minimised by placing the model mid-way along the test section, and reduces with increase in the streamlined length of test section.

Boundary layers on flexible walls

The small effect of variation in displacement thickness has already been noted. At transonic speeds there could be a shock/boundary-layer interaction from the wing shock.

Sidewall boundary layers

The effects of unexpected or uncontrollable behaviour of these boundary layers can be profound. The problem is common to all two-dimensional testing and must be addressed if reliable data is to be obtained at all angles of attack.

Differences between the elastic structure and streamline

The flexible wall can only be constrained to pass through streamlines at discrete points coinciding with the jacks. Between jacks the wall departs from the streamline. The effect is minimised by closely spacing the jacks where the streamline curvature is strongest, that is adjacent to the model. A method for assessing the magnitude of the resultant wall errors has been developed by Wolf.[4]

Centreline Curvature

There seems to be the possibility of building into the test section some centreline curvature, when the tunnel is being set for "straight" walls with the test section empty, the curvature arising from the finite resolution of measuring instruments. The curvature will in turn induce flow errors at the position of the model. Assessments have been made of the required resolving power of the wall instrumentation.[2]

Wall pull-up

The unanchored end of the test section wall moves axially as curvature is built into the wall. Since wall geometry is known, simple corrections have been built into the data reduction software.

Imaginary flowfield calculations

This places on record the recognition of these computations as a possible source of error. The tunnel users are continually reviewing computational techniques to balance resolution with computing speed. An extensive series of computations has indicated that with one algorithm for the imaginary flowfields, reproduction of wall displacement in the algorithm accurate to about 0.03 mm is quite adequate.

CONCLUDING REMARKS

The combined European experience with wind tunnels with flexible walls leads to the conclusion that interference can be reduced and in many cases eliminated. Also, the tunnel appears to be usefully versatile in the flowfield types which can be produced. A predictive method for wall contouring has been successfully developed.

Once the newest transonic test section is commissioned in its automated form, we can expect to see not only further developments in streamlining techniques, but also the results of attempts to extend upwards the useful Mach number range of this type of test section, and attempts to alleviate interferences in three dimensional testing.

One final point which should be re-emphasised is the probable susceptibility of model behaviour to sidewall boundary layer effects when the sidewalls are not provided with appropriate treatment.

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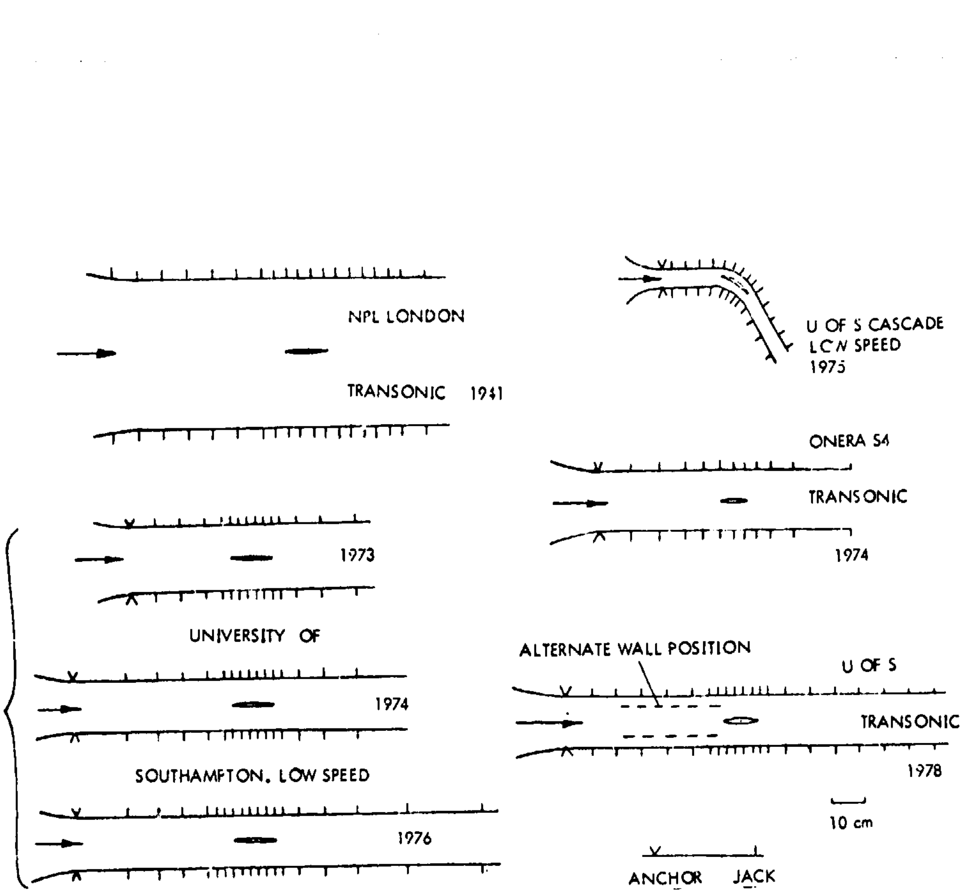

Figure 1.- European low-speed and transonic flexible-walled wind tunnels.

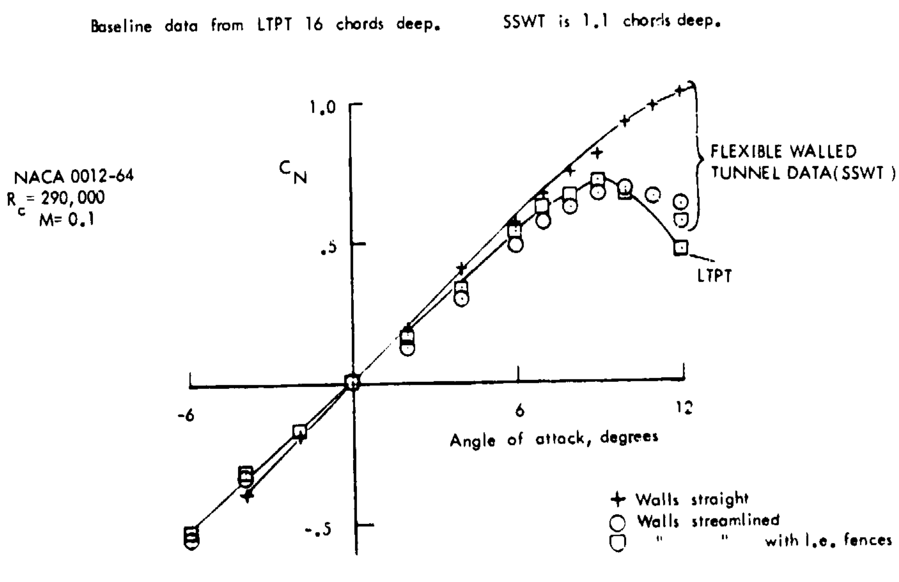

Figure 2.- Normal-force coefficient from integrated airfoil pressures where M denotes the Mach number and R_c denotes the chord Reynolds number.

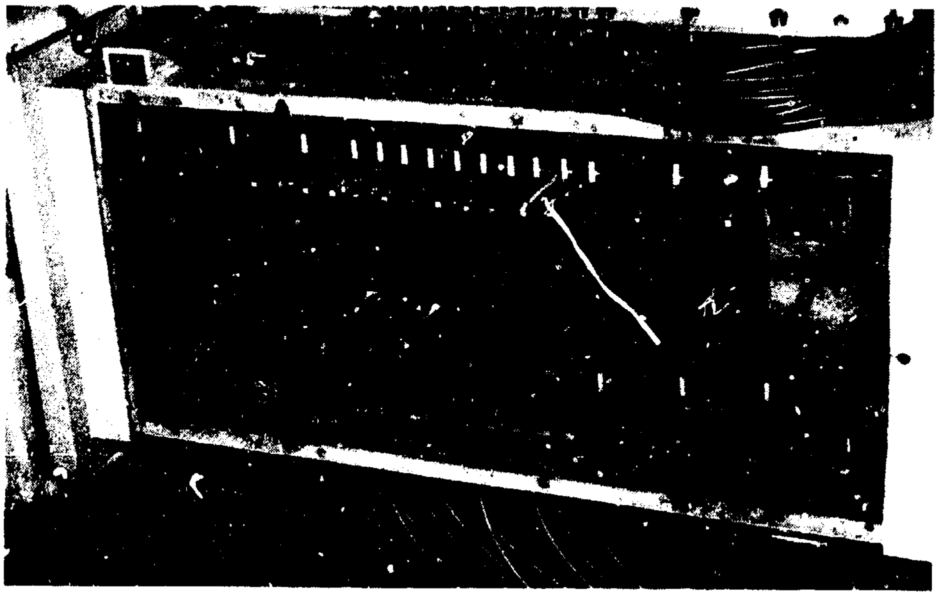

Figure 3.- View of low-speed test section. Axis curved for pitch-derivative measurement.

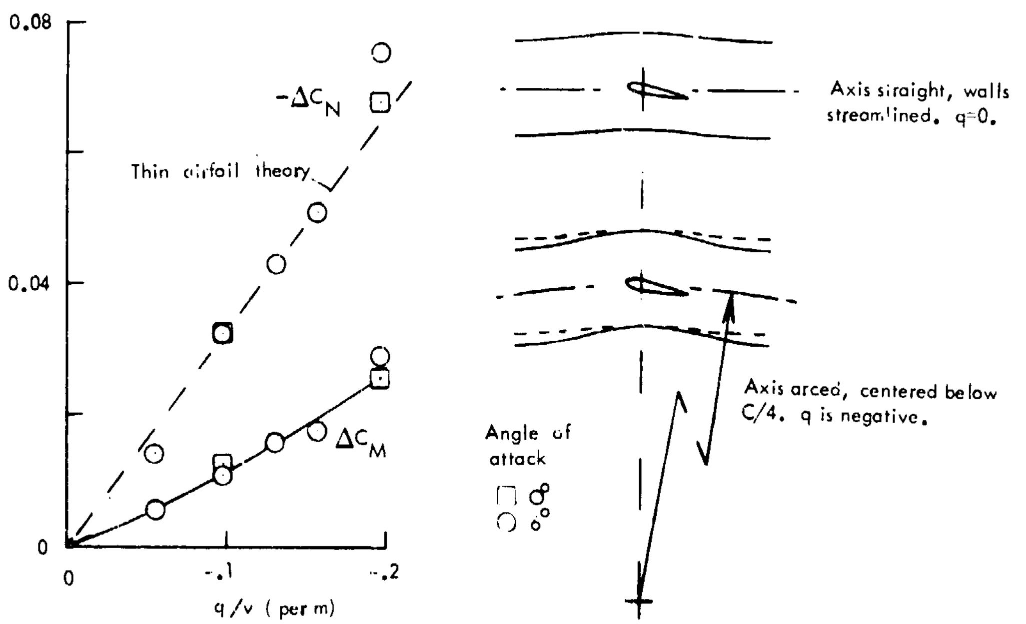

Figure 4.- Rate-of-pitch derivative data where c denotes the chord. Axis curved.