TRANSONIC TESTS IN A WIND TUNNEL WITH ADAPTED WALLS[x)]

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Abstract

Flexible walls are used for wind tunnel working sections to control the flow condition around the model. The wall shape is adjusted to provide streamline-curvature equivalent to that occuring under free flight condition. If such an adjustment can be achieved the flow around the model will be free of wall interference and transonic blockage of the test section is avoided.

Test results for the supercritical CAST 7 aerofoil were obtained in a test section with two flexible walls. Comparison with reference data obtained in a much larger tunnel demonstrate the ability of the adaptive wall technique for 2-D model tests.

First results for a test section with eight flexible walls using a body of revolution as the model are presented. The results allow some conclusions about the general applicability of the adaptive wall technique for 3-D model testing.

1. Introduction

In order to avoid transonic blockage and to reduce wall interference effects, most transonic wind tunnels currently in use have ventilated walls. The correction of test results for wall interference of such tunnels is difficult because of uncertain boundary condition. An alternative concept is the control of wall boundary condition as applied in the adaptive wall technique. The possibility of using adaptive walls with differential adjustment of the wall boundary condition was contemplated in the earlier days of transonic testing, e.g. (1). However, the exploitation of this idea was delayed by three main problems: The differential adjustment of the wall boundary increased the mechanical complexity of the working section, calculation and control of the boundary condition was time-consuming and expensive, and finally a practical scheme for determing the correct boundary condition was missing.

In 1973 Sears (2) and Ferri and Baronti (3) suggested a simple procedure for achieving the correct boundary condition. At the same time, great advances were being made in computer techniques and electronics. Thus the prospects of a feasible solution to the adaptive-wall method had improved considerably. At various research institutions in Europe and the USA activities were aimed firstly at the two-dimensional flow problem. Two different concepts were used for adjusting the wall boundary-condition: Porous walls with variable suction (4,5,6) and adjustable flexible walls (7,8,9).

For aerofoil testing the adaptive wall technique proved successful fairly quickly, but further detailed work was necessary. This was aimed at establishing a detailed and complete picture of the capability and the limitations of the adaptive-wall technique. On the other hand, calculation and automatic control of the wall shape had to be developed, aiming at an economic on-line adaption.

Although the extension of the principle to 3D-model testing is natural, the problem is more complex and demanding in this case. It requires a compromise between the mechanical complexity of the test section, a good approximation of a three-dimensional wall configuration and acceptable corrections for residual wall interference.

In the following, test results for the 2-D case will be presented demonstrating the state of the art. For the 3-D case, a concept for a solution will be outlined and first test results will be shown. Some principal problems encountered in the course of this initial test period will be discussed.

2. Aerofoil tests

2.1 The test section with two adaptive walls

The 2-D test section of the TU Berlin adaptive wall tunnel is shown in Figure 1. It has a cross-section of 15 x 15 cm and a length of 69 cm.

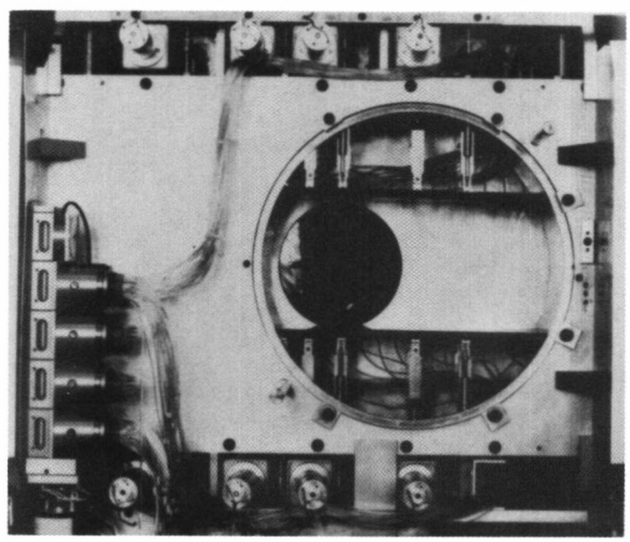

Figure 1: The 2-D test section

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The models used in this tunnel have a chord of 10 cm. The flexible walls extend over 65 cm. They are made of fibreglass, 1 mm thick. Eight jacks are attached to each of the flexible walls allowing wall displacement up to ± 25 mm. The jacks are driven by DC electro-motors. Wall positions can be measured by potentiometers with an accuracy of 7/100 mm. The entire wall adaption can be carried out with fully automatic control. The automatic control is described in more detail in (10).

There are three time-consuming procedures during the adaptation process: wall pressure measurement, wall shape calculation and wall setting.

For the wall-pressure measurements we use at present two Scanivalve blocks with Druck pressure transducer. The 24 pressure taps of each wall take 12 seconds to read (Scanner frequency 2 taps per second). This time can be reduced to a negligible amount by using the PSI pressure measurement system, which is currently being implemented.

The crucial problem for the wall adaptation is the wall shape calculation. Linear small perturbation theory is used for the calculation, which, for two-dimensional flow, yields a simple integral relation between pressure and wall curvature. The calculation of one wall shape requires 4 seconds computing time. By introducing a different numerical procedure reduction in computing time is considered to be possible.

The time required for wall setting is determined by the maximum jack movement of 1mm/sec and depends on the required displacement (initial shape) of the wall.

On average, 2÷3 iterations are necessary to arrive at the adapted wall shape. In Figure 2 the final wall configuration is sketched for the CAST 7 aerofoil close to its design condition. Wall displacement at the 16 jacks position is indicated. During the entire test series the maximum wall displacement was 15 mm. The maximum local Mach number reached at the wall was M = 1.oo5. Thus the use of subsonic small pertubation theory for calculating the wall shape seems to be justified.

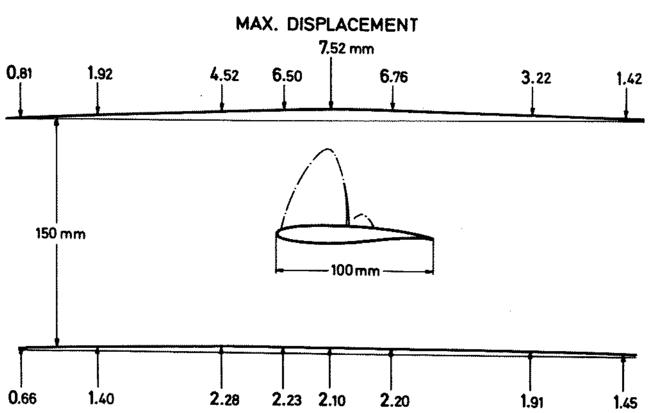

Figure 2: The adapted wall configuration for CAST 7 aerofoil at M_∞ = o.76 and α = 1°

2.2 Test results for the CAST 7/Do A2 aerofoil

The CAST 7 aerofoil was designed by Dornier with a thickness of 11.8 % and nearly shock-free flow at a Mach number of M_∞ = o.76 and a lift coefficient of C_L = 0.579 (11). The aerofoil has moderate adverse pressure gradients on the upper surface. The latter makes it relatively insensitive to Reynolds number effects - a reason why it was chosen as a test case for comparison with results from other wind tunnels. On the other hand, near the design point the flow around the aerofoil is very sensitive to changes in freestream conditions. Thus it is a good example for demonstrating the capability of the compliant wall concept.

Figure 3 demonstrates the sensitivity of the aerofoil to changes in angle of attack near the design condition (the lift coefficient of C_L = o.52 at M_∞ = o.76 was obtained for an angle of attack of α = o.81°).

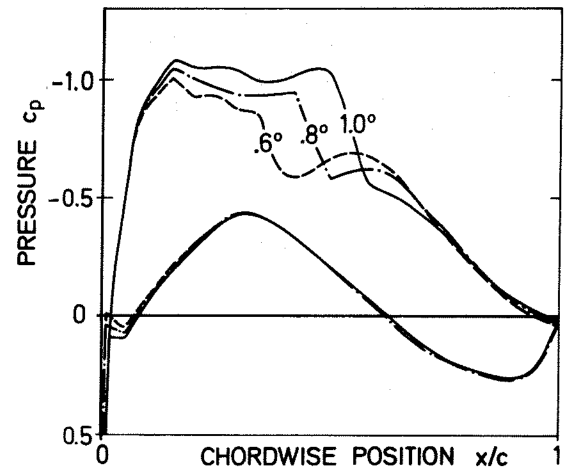

Figure 3: Pressure distribution CAST 7 aerofoil
Sensitivity to angle of attack
M_∞ = o.76 Re = 1.4 × 10^6

The test program was that agreed by the GARTEur Action Group 02 (Two-dimensional transonic testing methods). It included angle of attack sweeps at the three main stream Mach numbers M_∞ = o.60, o.70 and o.76 and two Mach number sweeps at angles of attack providing lift coefficients of C_L = o.52 and C_L = o.73 at M_∞ = o.76. For all tests transition was fixed with 107μ Ballotini roughness extending from x/l = o.o65 to x/l = o.o75.

Figure 4 shows representative results of the test program. They include the most difficult flow condition, i.e. the extremes in angle of attack, the highest Mach number and the sensitive condition near the design point. Comparison is made between test results obtained in the TU-Berlin tunnel with adapted walls (full points) and those obtained in the DFVLR Transonic 1 x 1 m tunnel (open triangles). While in the TU-Berlin tunnel the tunnel height to model chord ratio was as small as H/c = 1.5 that ratio became H/c = 10 using the same model in the DFVLR Göttingen tunnel.

One of the important results of the tests in the TU Berlin tunnel is that wall adaptation was demonstrated to be feasable throughout the entire test regime with no particular problems. Thus the adaptive wall technique is applicable in a flow

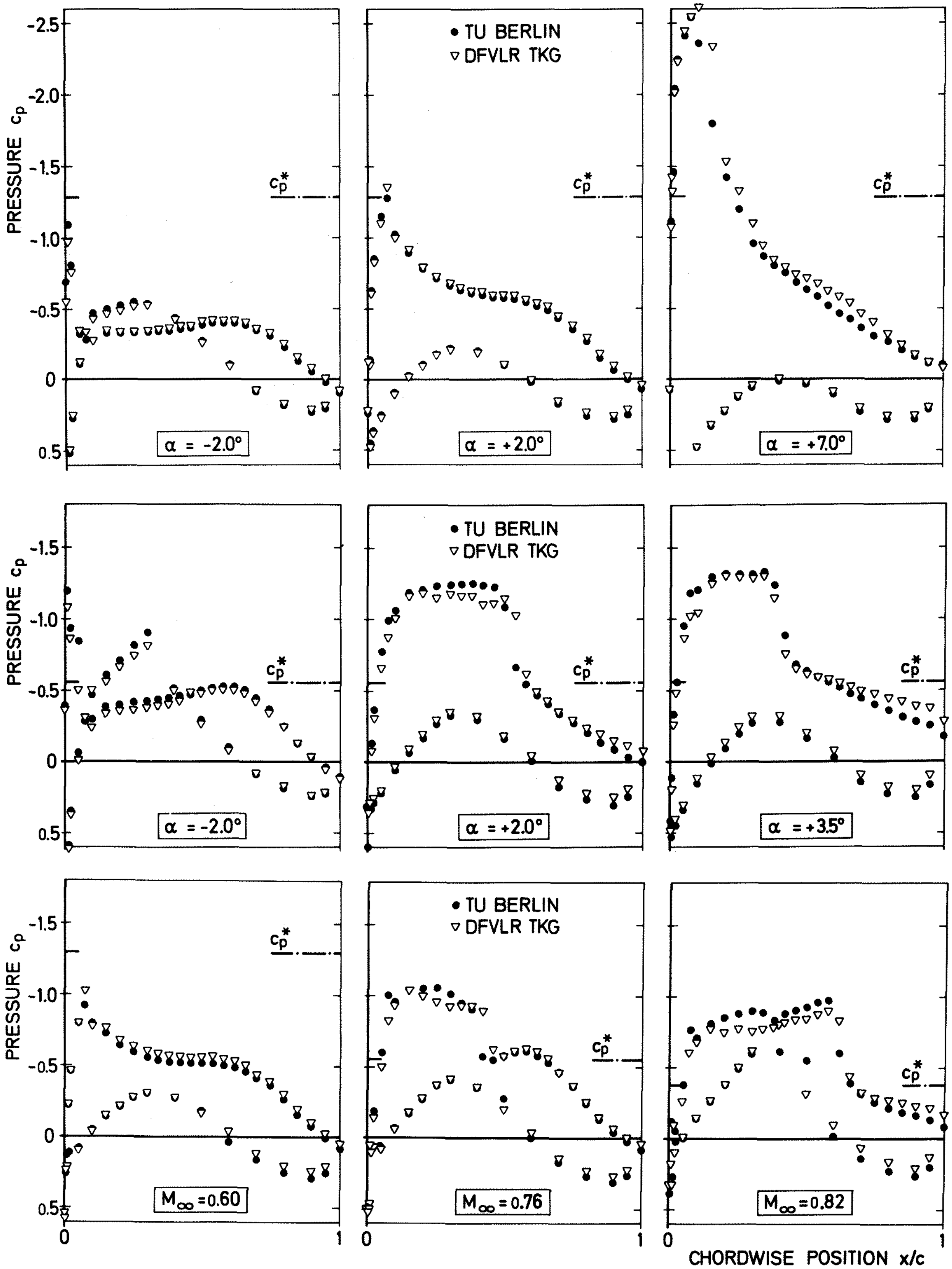

Figure 4: Pressure distributions for CAST 7 aerofoil. Comparison between results obtained in the TU Berlin o.15m tunnel with adapted walls and in the DFVLR Göttingen 1m transonic tunnel.

upper row:	M = o.60	Re = $1.2 \cdot 10^6$	α - variation
middle row:	M = o.76	Re = $1.4 \cdot 10^6$	α - variation
lower row:	α = o.8°	Re = $1.2 \div 1.4 \cdot 10^6$	M - variation

regime representative of modern aerofoil testing even in a test section with very small tunnel height to aerofoil chord ratio.

As far as the residual discrepancies between TU Berlin and DFVLR TKG data are concerned, it has to be said, that the test conditions in the two tunnels were somewhat different. Apart from errors due to different flow quality and uncertainties in determining the main stream condition, the installation of endplates to obtain a model aspect ratio of $\Lambda = 1.5$ led to flow conditions somewhat different to those in the TU Berlin tunnel. The endplates were parallel which led to a Mach number gradient in streamwise direction amounting to $\Delta M = 0.013$ at $M_\infty = 0.760$ over the aerofoil chord, Figure 5.

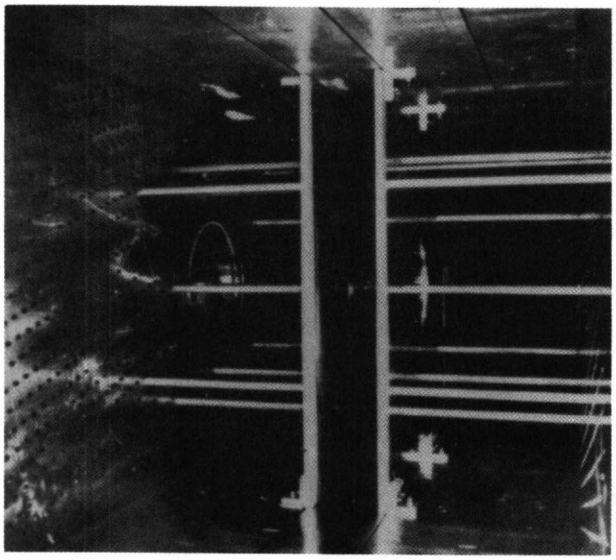

Figure 5: DFVLR 1x1m transonic tunnel with endplates for low aspect ratio aerofoil tests

The side-walls were supposed to produce a similar side-wall boundary layer as in the TU Berlin tunnel. Only a rough estimate of boundary layer thickness was used when designing the plates as at that time the importance of a correct reproduction of side-wall flow condition was not yet recognized.

2.3 Side-wall interferences

The installation of endplates in the DFVLR 1x1m transonic tunnel provided a chance to make airfoil tests at different aspect ratios. For such tests a CAST 7 model of 1m span and 15cm chord was available. The endplates were set at distances of 15, 30 and 60cm so as to provide model aspect ratio of $\Lambda = 1, 2$ and 4. A representative example of the test results obtained for the model at different aspect ratios is shown in Figure 6.

The example refers to the design condition of the CAST 7 where the aerofoil is very sensitive to changes in flow condition. However, a large number of tests have been made at a variety of test conditions including higher Reynolds number ($Re = 2.4 \cdot 10^6$) showing, in principle, very similar influences of the aspect ratio on the test results (12). This may be demonstrated by Figure 7, which shows lift coefficients for various angles of attack at the three different aspect ratios.

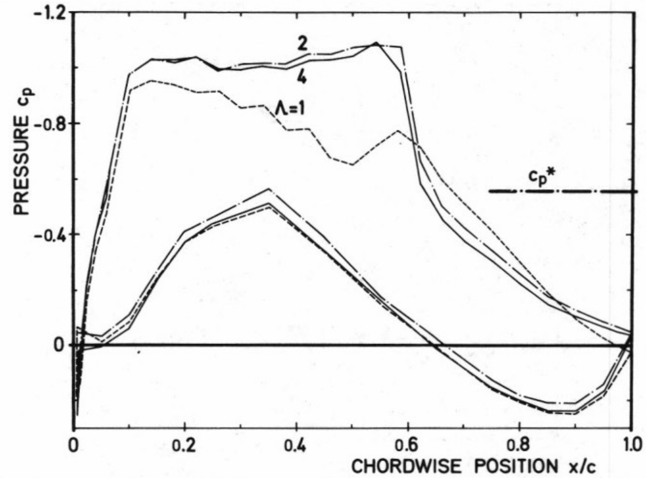

Figure 6: Pressure distribution CAST 7 aerofoil Various aspect ratios $M_\infty = 0.76$ $\alpha = 1$ $Re = 1.4 \cdot 10^6$

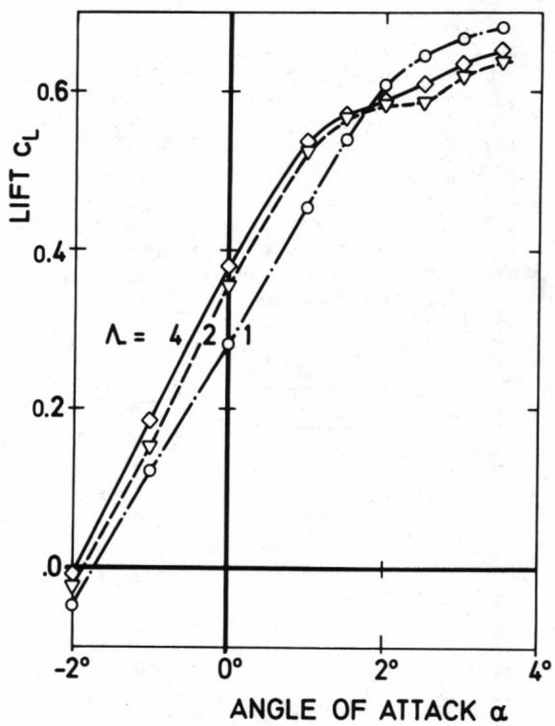

Figure 7: Lift vs angle of attack for CAST 7 Various aspect ratios $M_\infty = 0.76$ $Re = 1.4 \cdot 10^6$

The test results obtained with the 15cm chord CAST 7 aerofoil in the DFVLR transonic wind tunnel in Göttingen are also shown in Figure 8. They are marked 'Gö' and compared with data measured in various other European tunnels as part of a GARTEur Action Group activity (13). The Reynolds number for these tests varied between $Re = 1.2 \div 6 \cdot 10^6$. These results suggest that there is a systematic error in the use of small aspect ratio models.

The question is, how far some global corrections, such as suggested in (14) and (15), might be appropriate to account for the sidewall interferences on the aerofoil measurements. In the

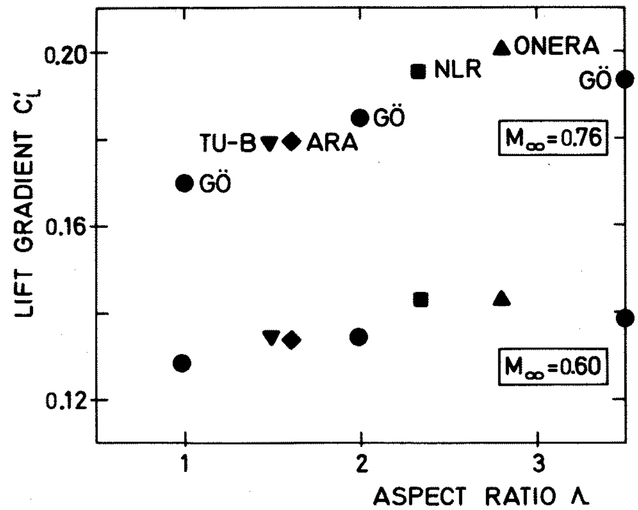

Figure 8: Influence of aspect ratio on lift gradient of CAST 7 aerofoil Re = 1.2 ÷ 6·10⁶

TU Berlin tunnel with adaptive walls Laser measurements have been made in the flow field around the CAST 7 aerofoil which provide some information about the nature of the sidewall interference effects (16). A Laser Two-Spot velocimeter was used for traversing the model span slightly above the aerofoil surface at three different chordwise positions. In addition two traverses were made just downstream of the trailing edge, slightly above and below the wake. The traversing lines are indicated in Figure 9, which also shows the aerofoil contour and the surface pressure distribution as measured by the pressure taps.

Figure 10 shows the corresponding Laser velocimeter readings across the span for the various chordwise stations. A substantial variation of pressure across the span is seen. Obviously, the aerofoil shock causes a separation or at least a thickening of the sidewall boundary layer which spreads upstream and produces compression waves that run toward the centre line. The arrows in Figure 10 indicate the spanwise position of the pressure taps which were located off the centre line. It is obvious that for the x/c = o.43 pressure tap the pressure measured is different from that at the centre line and small changes in sidewall flow condition might lead to noticeable changes in the pressure readings.

These results for the sidewall influence indicate, that careful reproduction of sidewall flow condition is required, when comparison of test results from different tunnels is intended. On the other hand, it broaches the question of flow control along the sidewalls. It is believed that not only sidewall boundary layer/shock interaction is deteriorating the two-dimensional flow around the aerofoil but the entire pressure signature of the aerofoil flow will influence the sidewall boundary layer. In particular the high pressure at the stagnation point and the subsequent strong expansion around the leading edge will lead to steep changes in boundary layer displacement thickness (16). This in turn will influence the expansion and thus the development of the supersonic region. Sidewall flow control using perforated walls and a control scheme in some way deduced from the adaptive wall concept might provide a solution to this problem. The pressure measured on the aerofoil surface might directly be used to control the flow on the side walls.

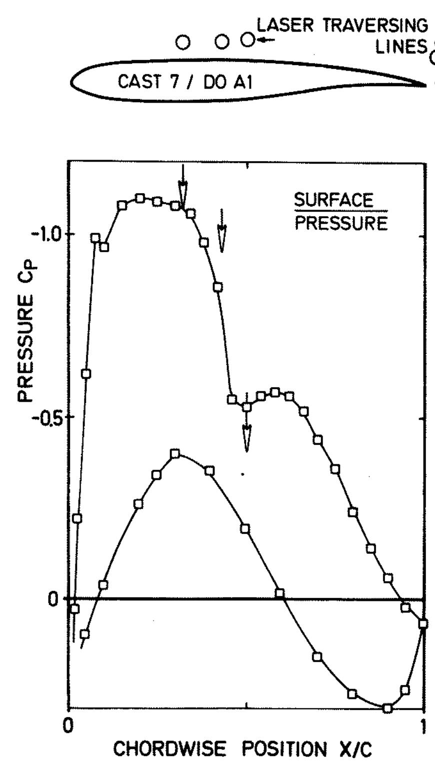

Figure 9: CAST 7 aerofoil contour with Laser traversing position and surface pressure for M_∞ = o.76 α = 1°

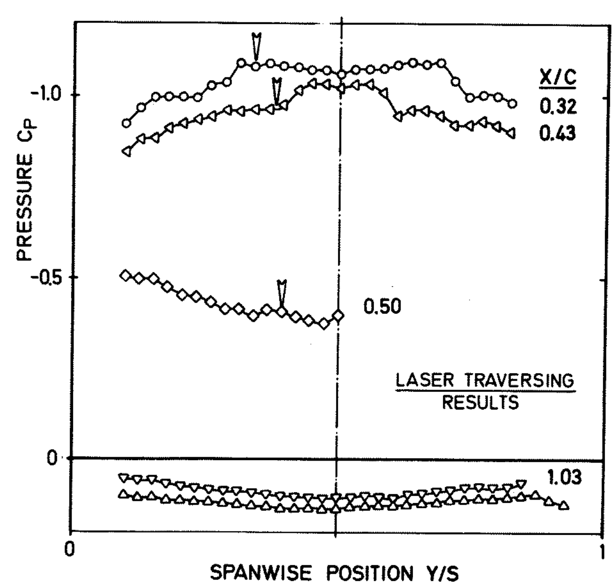

Figure 10: Spanwise pressure variation as measured with Laser velocimeter for CAST 7 M_∞ = o.76 α = 1°

3. Testing 3-D models

3.1 The test section with 8 adaptive walls

The development of adaptive wall test sections for three-dimensional model tests is underway both in Europe and the United States since 2 or 3 years, following extensive work with 2-D test sections. The various approaches differ in the type of boundary control mechanism used for the test section walls.

At NASA Ames slotted walls are used controlled by adjusting pressures in segmented plenums (18). This is similar to the approach Calspan had used for their 2-D test section. AEDC with Calspan Field Services apply now segmented perforated walls which allow local variation of porosity (19). NASA Langley intends to use two flexible solid walls also for 3-D model testing as suggested and investigated by Southampton University (20). At the TU Berlin an approximate three-dimensional solid wall configuration is achieved by using eight flexible walls (21). The DFVLR has proposed the use of a deformable rubber tube (21).

While the DFVLR rubber tube is still under construction, the other institutions have made their first tests. The most recent information about this work was presented at an AGARD Specialist Meeting on 'wall interference in wind tunnels' in London 19-20 May, 1982. At that date the AEDC just had started their tests. From NASA Ames and Southampton University some preliminary experimental information was available, while from the TU Berlin the first test result for a body of revolution was presented.

The test section used for the experiments at the TU Berlin is shown in Figure 11. It has an 18cm wide and 15 cm high octagonal cross-section formed by eight flexible walls. Typical model span will be 12cm. One of the major problems in this design was the sealing of the corners between the individual walls. The first suggestion was to have wedges fitted into the corners so that the flexible walls could slide along a perpendicular surface just as in the 2-D test section. This solution was ruled out, because the wedges may give too large disturbances to the flow when wall deflections is large. After that various rubber and plastic materials were tried on a test-rig. They produced circumferential forces on the flexible walls resulting into bumps. Finally springsteel lamellas were chosen as the solution. As much as 73 lamellas are spot-welded over a length of 80.5cm on one side of a flexible wall and then are arranged to slide on the adjacent wall. Thus circumferential forces are avoided. Another advantage of this solution is that it is may be used at cryogenic flow condition, too.

The exterior of the test section exhibits a large number of DC electromotors, Figure 12. Altogether 78 of them are used to move an equal number of jacks, which are inside the plenum chamber. The jacks are of very similar design to those used for the 2-D test section. They can be seen in Figure 13, which shows the interior of the plenum chamber and the working section with two of the walls removed. In the lower part of the picture potentiometric displacement feelers may be seen. They touch a tongue coming off the jack system to measure the wall position.

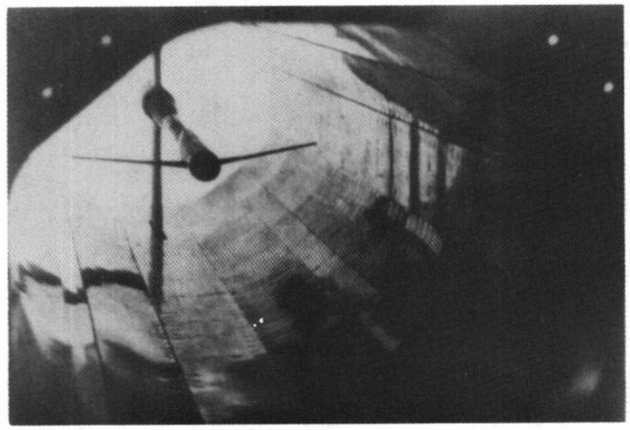

Figure 11: Test section with eight flexible walls, spring-steel lamella sealing in the corners

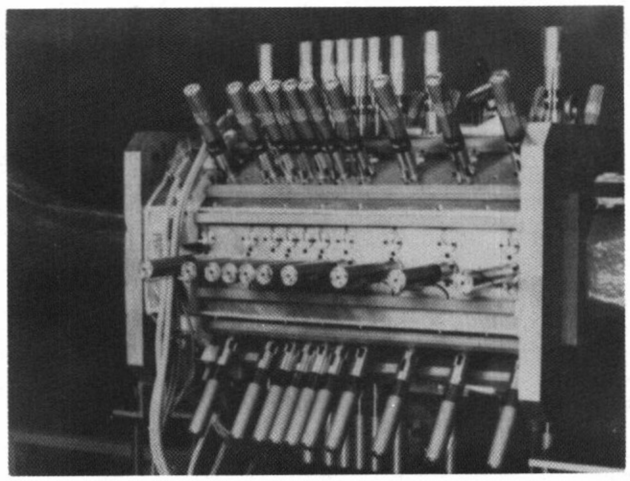

Figure 12: Exterior of the test section with eight adaptive walls

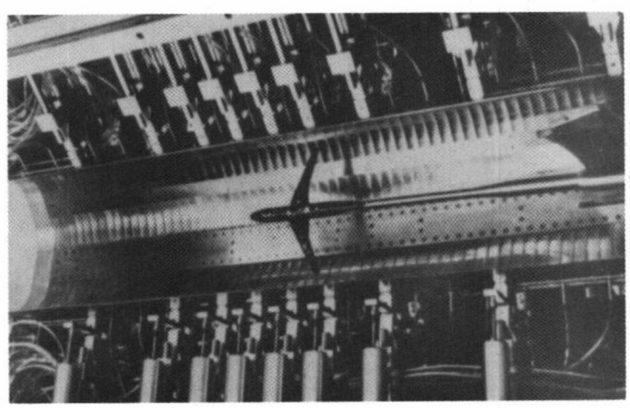

Figure 13: Interior of the test section for 3-D model tests showing details of lamella and jack fixing

DC motors, jacks and potentiometers are elements of the control loop which provides fully automatic control for the wall position. The control system has been developed during the past two years and differs somewhat from the one originally employed for the 2-D test section. Its main features are a 'Direct Digital Control' arranged by a microprosessor and the application of phase-gate-control through the thyristors, which provide power supply for the DC motors. More details are given in (10) and (21). The control system is believed to be optimised for fast wall adjustment and control, high precision, low hardware-costs and low energy consumption. Motor speeds are differentiated so that all jacks start moving at the same time and also stop at the same time, whereby the jack which has to make the largest displacement will move with maximum speed. A special endcontrol provided by the microprocessor and high precision potentiometers assure a wall setting accuracy of 1/100mm. Within an interval of 100msec up to 80 jacks can be controlled. Using the microprocessor as the key control-unit reduced hardware requirements substantially. It also contributed to the reduction of energy consumption as does the use of phase-gate controlled thyristors. This is not so much ment as energy saving but as avoiding heating problem for the electronics.

The procedure for determining the adapted wall shape is, in principle, the same as used for a 2-D test section, e.g. as explained in (9). It requires the measurement of wall pressure distributions. Each of the eight flexible walls is equiped with 23 pressure taps. On the other hand a method for calculating the exterior (fictitious) three-dimensional flow is needed. For this, a first order panel method is used. The test section is divided into a number of panels, 24 in lengthwise direction and 8 in circumferential direction. Due to flow symmetry for models without yaw, the number of panels necessary for the calculation is only 5*24 = 120. Computing time for one complete wall configuration is 12 sec on a HP 1000F process computer.

3.2 Test results for ONERA C5 body of revolution

The calibration model C5 was designed by ONERA to have a distribution of cross sectional area equivalent to that of some transport aircraft. Such a body is particularily suited to study blockage effects in transonic wind tunnels. Interference-free data for the surface pressure distribution are available from (22). The lowest Mach number case of $M_\infty = o.699$ was thought to be the most difficult one to study in the test section with adaptive walls as the pressure signature of the body on the wall was expected to be small and barely distinguished from the scatter band of the empty tunnel data.

For the tunnel without model but in presence of the quadrant it was hoped to arrive at a constant Mach number all along the wall with deviations less then $\Delta M = \pm\ o.001$ by careful wall adjustment. This aim was only achieved in the region of the model. Upstream and downstream of the model, were the jack spacing is larger, deviations from the nominal Mach number came up to $\Delta M = \pm\ o.012$, Figure 14. As one can expect, the situation gets worse at higher Mach numbers. Obviously, the spring-forces of the lamellas act on the flexible walls leading to an outward displacement. In the region of large jack spacing the wall must either be stiffend or additional bearing must be provided.

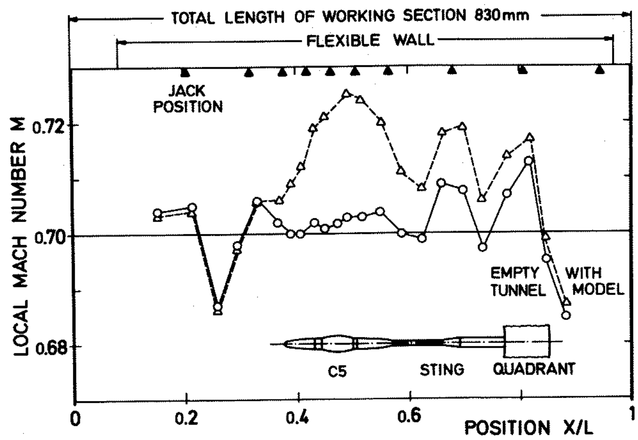

Figure 14: Mach number distribution along wall 2 with and without C5 model. Plane walls $M_\infty = o.70$

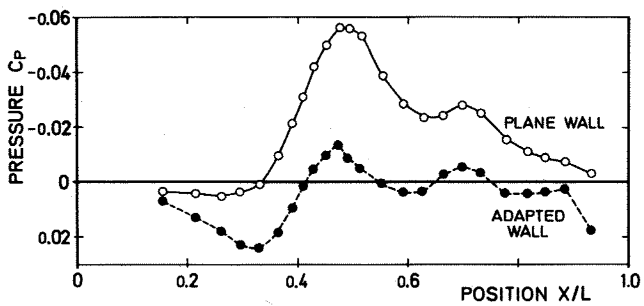

Figure 15: Pressure signature of C5 model on wall 2, plane & adapted (2nd iteration) $M_\infty = o.70$

Although the Mach number distribution in the empty tunnel was unsatisfactory, these data may be used to deduce the pressure signature of the model on the wall. The difference between the wall pressure distribution measured with and without model is plotted in Figure 15. The pressure signature thus obtained for the 'plane wall' configuration was then used to calculate an improved wall shape which finally led to the adapted wall configuration. (A quotation mark is assigned to the designation 'plane wall' because the walls were basicly divergent to account for the wall boundary layer and displaced in the region of the quadrant to achieve constant Mach number in the test section without model. However, for the exterior flow field calculation, this wall configuration was taken as plane).

The surface pressure distribution for the ONERA C5 body of revolution was measured with the wall 'plane' and adapted, and plottet as surface Mach number distribution in Figure 16. For subcritical flow condition at $M_\infty = o.70$ the improvement in the experimental results due to wall adaptation is not as spectacular as experienced in aerofoil testing. However, at the higher main stream Mach number $M_\infty = o.84$ the test section was choked with the 'plane wall' configuration. Wall adaptation (maximum displacement o.6mm) led to the elimination of the transonic blockage. For both cases it is encouraging to see that the measured values come fairly close to the interference free data.

These very first successful measurements for a 3-D model in a wind tunnel with adaptive walls have revealed a number of problems. It already was indicated that high accuracy in wall pressure measurements as well as in wall setting is required. The exterior flow field calculation reacts extremly sensitive to changes in the prescribed pressure distribution used as the input, as the flow reacts sensitive to changes in the wall configuration. The problem is that local changes will, in general, have far-reaching global effects. To illustrate this, it should be mentioned, that for determining the adapted wall configuration, a dummy model was used without pressure taps. This could more easily be removed for the repeated measurements of empty tunnel data. Finally the model with pressure taps was used to measure the model pressure distribution. The only difference in the test setup was then due to pressure tubes coming off the model-sting at the downstream end of the quadrant. Only for $M_\infty = 0.84$ the wall was readjusted in that region which led to an improved pressure distribution along the base-part of the model.

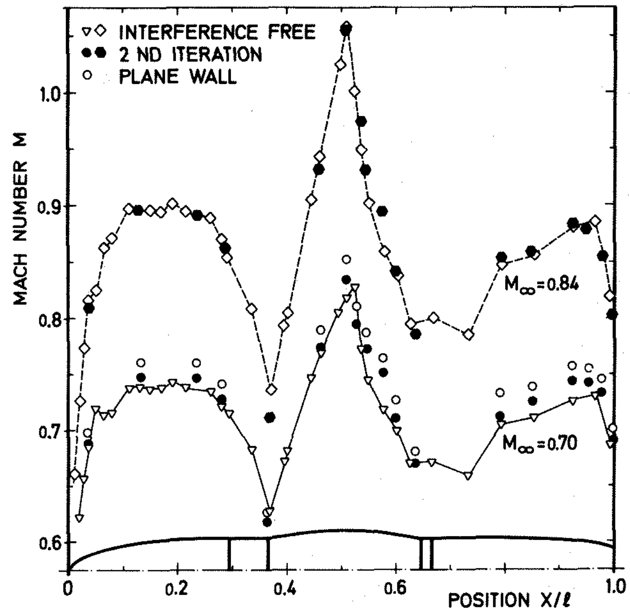

Figure 16: Mach number distribution for C5 body of revolution. $M_\infty = 0.70$ & $M_\infty = 0.84$

4. Conclusions

The comprehensive test serie carried out with the supercritical CAST 7 aerofoil in the TU Berlin wind tunnel with adaptive walls demonstrate that this test technique yields reliable results in a comparatively small tunnel. By now, the adaptive wall technique may be considered as well established for aerofoil testing and ready for general practical application.

Attention is drawn to the problem of sidewall interferences in aerofoil testing. Sidewall flow control by means of perforated walls and a control scheme deduced from the adaptive wall concept may be used in order to avoid large aspect ratio models.

The first results for a test section with eight flexible walls using a body of revolution as the model demonstrate, that, in principle, the adaptive wall technique is feasable for 3-D model tests. It leads to a substantial reduction in wall interference and eliminates blockage.

Acknowledgement

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Note: All references marked 'to be published in AGARD CP' refer to papers presented to the 50th AGARD FDP Specialist Meeting on 'Wall Interference in Wind Tunnels' held in London UK 19-20 May, 1982.