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APPLICATION OF A FLEXIBLE WALL TESTING TECHNIQUE TO THE NASA LANGLEY 0.3-m TRANSONIC CRYOGENIC TUNNEL

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Abstract

The use of a flexible wall testing technique is a modern approach to minimising wall interference in 2- and 3-D transonic wind tunnel testing. The application of this testing technique relies on the test section boundaries being adaptable. In the Langley 0.3-m Transonic Cryogenic Tunnel (TCT), we have installed a test section with four solid walls where only the floor and ceiling are adaptable. The flexible walls are computer controlled to shorten the time attributed to wall adaptation. Our adaptive wall test section has unique capabilities. It can operate at continuous cryogenic temperatures and high pressures. In addition, our test section is capable of large wall deflections. These capabilities have allowed us to perform 2-D validation testing at flight Reynolds numbers and high lift. This successful validation is discussed in the paper together with other 2- and 3-D data highlights from over two and a half years of operation. The paper also describes various aspects of the testing technique including a discussion of the general operational characteristics of our adaptive wall test section. We conclude that the flexible wall testing technique can be successfully used by non-experts for 2-D transonic testing with a known operating envelope. In 3-D testing, we are encouraged by the data obtained so far but we still need to optimize our testing technique. We conclude that the 0.3-m TCT with an adaptive wall test section is the most capable 2-D wind tunnel anywhere.

Symbols

α	Angle of attack
c	Model chord
Cd	Drag coefficient
Cd_{min}	Minimum drag coefficient
C_L	Lift coefficient
Cn	Normal force coefficient
Cn_{max}	Maximum normal force coefficient
Cp	Pressure coefficient
h	Test section height
M	Mach number
Rc	Chord Reynolds number, per foot
x	Streamwise location downstream of model leading edge

1. Introduction

The problem of wall interference in wind tunnel testing remains despite considerable effort to eradicate it. Over the years, the wind tunnel community has used several well-known techniques to minimise wall interference. Models are kept small compared with the test section size. Ventilated test sections are used to relieve transonic blockage. Linearised corrections are applied to the model data. Usually, all three techniques are used together in transonic testing. Unfortunately, we find these techniques are inadequate for the high levels of accuracy we now demand from wind tunnel testing.

A solution to this dilemma exists. It involves using modern testing techniques which minimise the wall interference at its source. (Actually, these modern techniques are a re-discovery of one of the first solutions to transonic wall interference developed in the 1930s.) These techniques adapt the test section boundaries to streamline shapes that would exist around the model if it were in free air. (We referred to this as streamlining the adaptive walls.) In effect, we make the presence of the walls invisible to the model which then performs as if it were in an infinite flow field. This is the **principle of wall streamlining.** Figure 1 shows the general case for a 3-D model. The test section boundaries follow an arbitrary free air streamtube round the model. (For simplicity we ignore the boundary layer growth on the test section boundaries.) Therefore, the free air flow field is split into a *real part* within the test section and an *imaginary part* round the test section. The imaginary flow field extends to infinity in all directions. The principle is simple but applying the principle is complex. The complexity arises from the need to adjust the test section boundaries for each test condition.

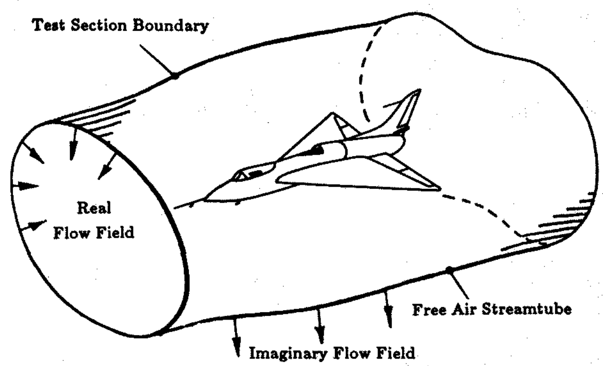

Fig. 1 Principle of wall streamlining for free air simulations.

The application of this testing technique relies on making the test section boundaries adaptable. The resulting test section is referred to as an Adaptive Wall Test Section (AWTS). In the Langley 0.3-m Transonic Cryogenic Tunnel (TCT) we installed an AWTS with two flexible walls and two rigid sidewalls. We describe why we chose flexible walls and the historical prospective to our choice. Our AWTS has unique capabilities. It can operate at continuous cryogenic temperatures and high pressures. In addition, our test section is capable of large wall deflections. These capabilities have allowed us to test at flight Reynolds numbers and high lift. Highlights of the 2- and 3-D validation results are discussed to illustrate the quality of our AWTS data. We also describe the operational characteristics of AWTSs. We include lessons learnt by us to help others benefit from our experiences.

1.1 Why Adaptive Walls ?

Other than the major benefit of minimising wall interference for free air simulations, AWTSs offer other significant advantages. With wall interference minimised, we are free to increase the size of the model relative to a given test section. Typically, we can double the model size and hence the chord Reynolds number, perhaps allowing testing at full scale Reynolds numbers. Larger models are also important for high dynamic pressure tests and provide increased dimensions for more detailing and more volume for instrumentation. We can also expect simpler magnetic suspension of a model using an AWTS because we can place the supporting coils closer to the model.

With solid adaptive walls (called flexible walls), the test section boundaries are much smoother than with perforated walls. This smoothness reduces the tunnel drive power required for a given test condition with the model and test section size fixed. In addition, the removal of slots and holes reduces tunnel noise and turbulence levels improving flow quality. For intermittently operating tunnels, the removal of the plenum volume from the tunnel circuit reduces settling times and minimises flow resonance.

Surprisingly, many wind tunnel users still consider that the complexity associated with operating an AWTS outweigh these advantages. But is using an AWTS more complex than using a conventional test section? Generally, we acquire force and pressure data from a relatively simple ventilated test section. Then post-test, we "correct" the real-time data for wall interference. Unfortunately, the necessary "correction" algorithms must consider the complicated model and wall flows and are therefore very complex. With an AWTS on the other hand, we acquire "corrected" data in real-time from a relatively complicated test section. Furthermore, we find that the AWTS wall adaptation ("correction") algorithms need only consider the flow field away from the model and are therefore relatively simple. So in an AWTS, the overall software complexity is reduced. In effect, AWTS users trade off software complexity with hardware complexity. Consequently, the overall level of system complexity remains roughly the same regardless of the test section used. However, the AWTS exhibits important advantages over a ventilated test section: the real-time data is "corrected"; these "corrections" are in some instances better; the model size can be significantly larger relative to the test section size; and the flow quality is superior with solid walls.

1.2 Historical Perspective

The modern adaptive wall testing techniques are a re-discovery of one of the first solutions to the problem of transonic wall interference. The National Physical Laboratory (NPL), UK built the first adaptive wall test section in 1938, under the direction of Dr. H. J. Gough.[1] They sought a solution to the problem of transonic blockage. Their research proved streamlining the flexible walls of an AWTS was a viable testing technique for high speed tunnels. They opted for minimum mechanical complexity in their AWTS by using only two flexible walls. Unfortunately, the absence of computers made wall streamlining a slow and labour intensive process. Sir G. I. Taylor developed the first wall adjustment procedure. His procedure was necessarily approximate to remove the need for any calculations during the streamlining process. (Subsequently, his procedure has been proved effective in a modern AWTS.[2]) Despite the impractical operation of their AWTSs, NPL generated a large amount of 2- and 3-D transonic data,[3] which we are still uncovering in the literature. NPL actually used flexible walled AWTSs into the early 1950s.

The advent of ventilated test sections in 1946 provided a "simpler" approach to high speed testing, since the adjustments to the test section boundaries are passive. Consequently, the labour intensive use of adaptive walls (to actively control the test section boundaries) was superseded, for practical reasons, by use of ventilated walls. The AWTSs of NPL eventually became obsolete and disappeared.

After a 20-year lull, interest in AWTSs was rekindled in the early 1970s. Several researchers independently re-discovered the adaptive wall testing technique in the quest for improved data accuracy at transonic speeds.[4,5,6] Several of these researchers were drawn to adaptive walls by the potential of reducing the sophistication of the tunnel interference corrections in favour of increasing the complexity of the test section hardware. Some advocated modifications of conventional ventilated test sections (the so-called variable porosity test section), while others opted for the NPL approach using flexible walled test sections. By this time, computer automation had arrived to remove the initial obstacle to AWTS development, namely impractical operation.

This renewed interest has led to the establishing of various adaptive wall research groups around the world. Researchers have built many AWTSs of various designs for testing 2- and 3-D models. This development has even led to production type AWTSs as described in this paper.

1.3 Overview of AWTS Design

The renewed interest in AWTSs has encompassed two approaches using ventilated or solid walls. We have observed many interesting designs during the modern era of AWTS development. In 2-D testing, only two walls need to be adaptable and researchers have tested both flexible wall and ventilated wall designs. In 3-D testing, the complexity of controlling the test section boundaries in 3 dimensions has led to a variety of AWTS designs. Moreover, some approximation in the shape of the test section boundaries is inevitable. The magnitude of this approximation has been the subject of much research. However, the number of adaptive walls necessary in a 3-D AWTS remains unclear. From practical considerations, the design of a 3-D AWTS must be a compromise between magnitude of residual interferences (remaining after wall streamlining), hardware complexity, model accessibility and the existence of a rapid wall adjustment procedure. We find that there is growing support for simplified AWTS designs for 3-D testing using just two adaptive walls, as describe in this paper.

The vast research experience reported on 2- and 3-D testing with AWTSs[7] shows flexible wall designs to have distinct advantages over ventilated wall designs. These advantages are as follows:

a) Flexible walls can be rapidly streamlined.
b) Flexible walls provide more powerful adaptation control of the test section boundaries.
c) Flexible walls provide simple test section boundaries for adaptation measurements and residual interference assessment.
d) Flexible walls improve flow quality providing reduced tunnel interferences and reduced tunnel operating costs.
e) No plenum required around the test section.

It is because of these advantages that the AWTS designed for the 0.3-m TCT has flexible walls. Additionally in 2-D testing, flexible walled test sections have operated successfully with test section height to chord ratios of unity and high model lift. No ventilated AWTS, past or present, can match these conditions. There is no evidence to indicate that this situation will change for 3-D testing either. Interestingly of the 18 AWTSs known to be in use to-day, 14 have flexible walls.

The old claim that ventilated AWTSs could be simply made from modified conventional ventilated test sections is no longer relevant. From Calspan, AEDC and NASA Ames research,[7] we now know that substantial changes to a conventional ventilated test section are necessary to make it adaptive. Therefore, any update of an existing wind tunnel to adaptive wall status will involve the design of an AWTS insert. Any attempt to modify an existing test section would probably be much more difficult and involve too many compromises.

2. Facility Description

Our description of the 0.3-m TCT is brief; more information is available in the literature.[8,9] Basically the 0.3-m TCT is a continuously operating cryogenic pressure tunnel. We show a sketch of the closed tunnel circuit in figure 2.

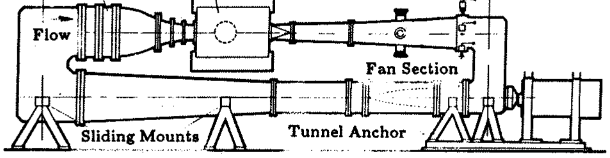

Fig. 2 Sketch of the 0.3-m TCT tunnel circuit with the AWTS.

A variable speed, 2.24 MW electric motor drives the fan. Test section Mach number is continuously variable between 0.2 and about 1.3, with suitable flexible wall shapes. We can vary the stagnation pressure from slightly over 1 bar up to 6 bars and the stagnation temperature from 340K down to about 77K. The test gas is nitrogen. The wide ranges of pressure and temperature allow us to investigate almost a 30 to 1 range in Reynolds number effects. A maximum Reynolds number of over 328 million per meter (100 million per foot) is possible. In addition, we can independently vary either pressure or temperature to achieve the desired Reynolds number. The 0.3-m TCT uses sophisticated systems for Mach number, pressure, and temperature control.

The AWTS[10] is nominally 33cm (13 inches) square and has an effective length of 1.42m (55.8 inches). The four walls are solid with only the floor and ceiling flexible. We enclose the complete test section in a pressure shell which forms a 1.86m (73.2 inches) long insert into the 0.3-m TCT tunnel circuit (see figure 3).

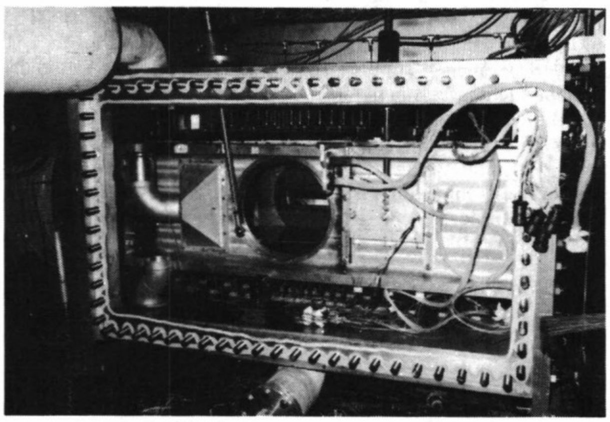

Fig. 3 View of the flexible walled AWTS with the left side of the surrounding pressure shell removed.

A system of 21 jacks supports each flexible wall as shown on the schematic diagram in figure 4. The length of the flexible walls is 1.82cm (71.7 inches) with the downstream 40cm (15.9 inches) providing a smooth transition from the adaptive portion of the test section to the fixed diffuser. The flexible walls are made of 308 stainless steel. The wall thickness varies along the length of each wall to optimize flexibility and resistance to bending due to pressure load. The volume surrounding the entire test section is vented to the test section downstream of the model to minimise pressure loading on the flexible walls.

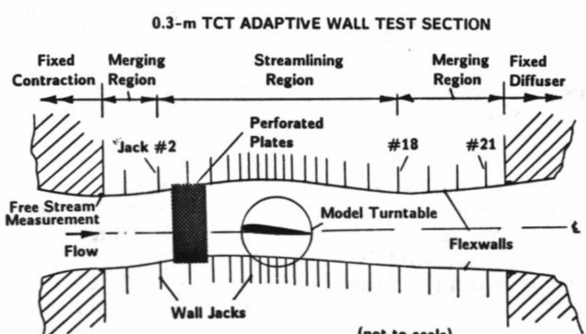

Fig. 4 Schematic diagram of the flexible walled AWTS.

Individual stepper motors power each wall jack giving a slow wall movement speed of 0.24mm (.009 inch) per second. A dedicated Modcomp Classic computer controls the displacement of each jack and measures the current position of each jack with an individual Linear Variable Displacement Transducer (LVDT). The LVDTs have an accuracy of 0.127mm (.005 inch) over a travel range of 10.16cm (4 inches). Both the stepper motors and the LVDTs are mounted outside the pressure shell. The jack mechanisms are therefore isolated from the severe cryogenic environment in the test section. Nevertheless during cryogenic operations, there are significant ambient temperature changes around the LVDTs which can cause electrical drift in the instruments. This drift can cause up to 1mm (.040 inch) of false jack displacement. The jack mechanisms connect to each jacking point on the flexible walls by a pair of push/pull rods. The associated 84 rods penetrate the pressure shell to attach to the flexible walls. We use two rods per jacking point to minimise unwanted spanwise wall movements.

For 2-D wall adaptation, we need only measure wall pressures on the tunnel centerline. For simplicity, we measure wall pressures at only the 17 jacking points per wall within the streamlining portion of the AWTS (see figure 4). For 3-D wall adaptation, we need more wall pressures, ideally both on and off the centerline of the flexible walls and also on the sidewalls. Due to hardware constraints, we currently operate with three sidewall pressure rows as well as the two centerline pressure rows on the flexible walls as shown in figure 5. We measure free stream static pressure at the entrance of the test section as shown in figure 4.

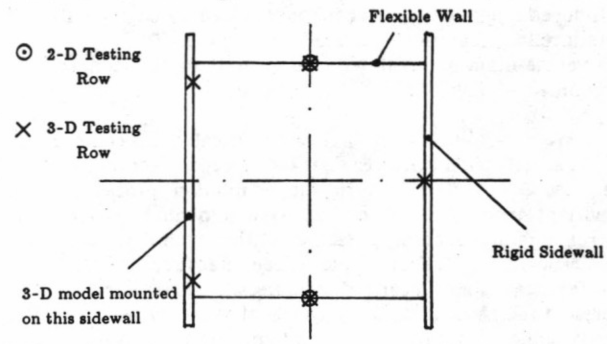

Fig. 5 A sketch of the AWTS cross-section showing the position of wall pressure rows for 2-D and 3-D testing.

We can mount a vertical sweep wake rake on the left sidewall at one of three downstream locations.[9] The rake supports six total head probes positioned along its span between the tunnel centerline and the sidewall. The vertical position of the rake is computer controlled.

The AWTS has provision for sidewall Boundary Layer Control (BLC) as shown in figures 3 and 4. We can fit porous plates in the rigid sidewalls just upstream of the model location as shown in figure 4. Both active and passive BLC is possible with this advanced system although we only discuss passive BLC data in this paper.

3. Wall Adaptation

The wall adaptation process is necessarily iterative[11] and generates real-time "corrected" data as shown by the event diagram in figure 6.

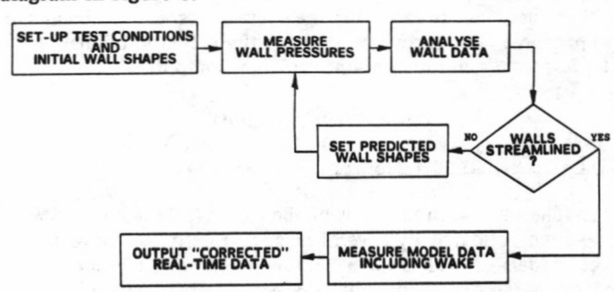

Fig. 6 Sequence of events in the wall adaptation process.

The *Analyse Wall Data* event refers to the prediction of new wall shapes for streamlining and the calculation of residual wall interference. The term *streamlining* requires some explanation. We achieve the elimination of top and bottom wall interference in 2-D testing by making the flexible floor and ceiling of the test section follow free air streamline shapes. The term streamlining therefore refers to the driving of the flexible walls to streamline shapes. In 3-D testing, we cannot eliminate wall interference because of our limited control of the test section boundaries. So streamlining in 3-D testing refers to driving the flexible walls to shapes which minimise the wall interference to a correctable level.

In 2-D testing, we use a rapid wall adjustment strategy developed by Judd, Goodyer, and Wolf[12,13] at the University of Southampton, UK, to predict wall shapes for streamlining. The method uses linearised compressible flow theory, without reference to the model, to compute new wall shapes. Strategy computations take less than 1 second per iteration on a Modcomp Classic computer. We consider the condition *Walls Streamlined* to exist when the modulus of measures of the residual wall interference reduce below fixed maxima. In the 0.3-m TCT these maxima are as follows:

1) Average Cp error (between streamline and actual values) along each wall - 0.01
2) Induced angle of attack at the model leading edge - 0.015°
3) Induced camber along the model chordline - 0.07°
4) Average induced streamwise Cp error along the model chordline - 0.007

We determine these maxima empirically as a compromise between perfection (zero residual interference) and minimising the number of iterations in the adaptation process. The important factor here is overall system quality in terms of instrumentation accuracy, test condition stability, and wall imperfections. We compute these measures of residual interference using linearised compressible flow theory. We represent the flexible walls by panels of vorticity placed on the aerodynamic contours (wall contours plus boundary layer displacement thicknesses) in an undisturbed potential flow field. The local strength of the wall vorticity is proportional to the local wall Cp error between the computed streamline value and the actual measured value.

In 3-D testing, we use a wall adjustment strategy developed by Rebstock.[14] This powerful method performs real-time assessment of wall interference at the model location using only wall data. The method does not require a mathematical representation of the model under test. If the gradients of the interference are small (say a change in induced α of about 0.1°) then it is sufficient to correct for the wall interference without moving the flexible walls. However, if the gradients are not small, the method predicts new wall shapes to minimise the gradients. The method achieves this by attempting to cancel the interference gradients on a single *Target Line*. Normally we choose this *Target Line* to coincide with the location of maximum wall interference on the model. The necessary computations simply extend the previously calculated wall interference, at the selected location on the wing, throughout the test section. This computed information is then used to predict the new wall shapes. Linearised compressible flow theory is used for these computations which take less than a minute on a MicroVAX computer.

4. Validation Results

4.1 Two-Dimensional Testing

The unique capabilities of the 0.3-m TCT with an AWTS have been validated by several means. Firstly, we have tested large models of well known 2-D aerofoils of different chords and compared our results with the best available "interference-free" data over a wide range of Reynolds number and model lift. Secondly, we have allowed our data to be analysed for residual wall interference by methods totally independent of the wall adjustment strategy. Thirdly, we have examined experimentally the tolerance of the adaptive wall testing technique to practical restrictions such as wall setting accuracy, test section length and wall flexibility. Finally, we have examined the effects of removing the sidewall boundary layer on the wall adaptation process.

The largest model we tested had a chord of 33cm (13 inches) equal to the test section height. The smallest model had a chord of 16.5cm (6.5 inches). Even the smallest model is more than double the permissible model size in an equivalent size ventilated test section. We initially tested aerofoil models with a symmetrical NACA 0012 section. We show sets of lift data from two different chord models in Figure 7 for Mach 0.5 and 0.7. The data for the two models agree remarkably well. Unfortunately, problems with our AWTS hardware restrict the angle of attack and Mach number for the larger of the two models. Nevertheless, this limited comparison shows that model size is not important. This finding is also true in terms of pressure distributions[10] and drag measurements.[15] This result supports the fact that top and bottom wall interference is eliminated. Further support for these findings was found in an independent assessment of the residual wall interference[15] and detailed comparisons with other experimental data and free air theoretical results.[16] In addition, the use of large models with the test section boundaries close to the model, seems to cause some intrinsic correction of sidewall boundary layer interferences. A finding supported by the minimal spanwise variation observed in the model wakes.

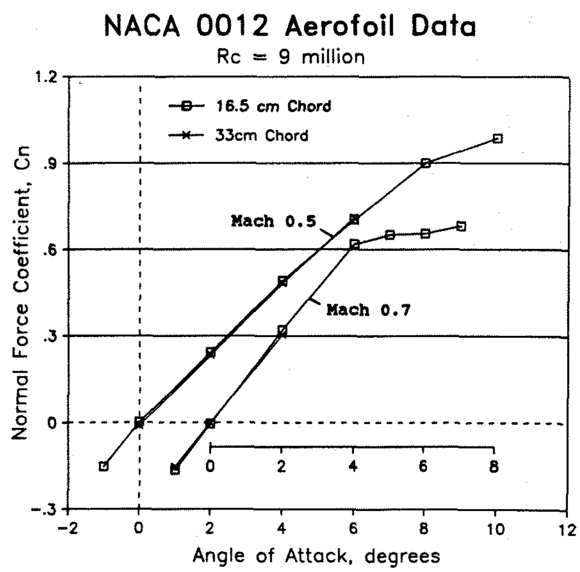

Fig. 7 Comparison of lift data from two NACA 0012 models at Mach 0.5 and Mach 0.7.

The NACA 0012 validation tests serve only as a classical evaluation of the AWTS, since the NACA 0012 does not perform like a modern aerofoil. So for a realistic evaluation of the AWTS, we have carried out further validation tests with a modern transonic aerofoil section. These tests are part of co-operative agreements between NASA, NAE, ONERA, and DFVLR. Researchers chose the CAST 10-2/DOA-2 section because it is a cambered supercritical aerofoil, tested worldwide. The CAST 10 performance is known to exhibit the extreme sensitivity to Reynolds number and Mach number we have come to expect with modern aerofoil sections. However in the past, researchers have experienced great difficulty in evaluating Reynolds number effects on the aerofoil data, when significant tunnel interferences are present. Now the modern AWTS provides a sophisticated method for real-time minimisation of tunnel interferences which should improve the researcher's plight. However, it is beyond the scope of this paper for us to discuss Reynolds number effects on the aerofoil.

Two CAST 10 models were built, one in France with a 18cm (7.09 inch) chord and the other in Canada with a 22.86cm (9.0 inch) chord. We discuss data on both models from facilities other than the 0.3-m TCT, the smaller model in the ONERA/CERT T2 tunnel which has a 2-D flexible walled AWTS[17], and the larger model in the NAE 5-ft x 5-ft Blowdown Wind Tunnel fitted with a deep 38.1cm (15 inch) wide 2-D test section with perforated top and bottom walls.[18]

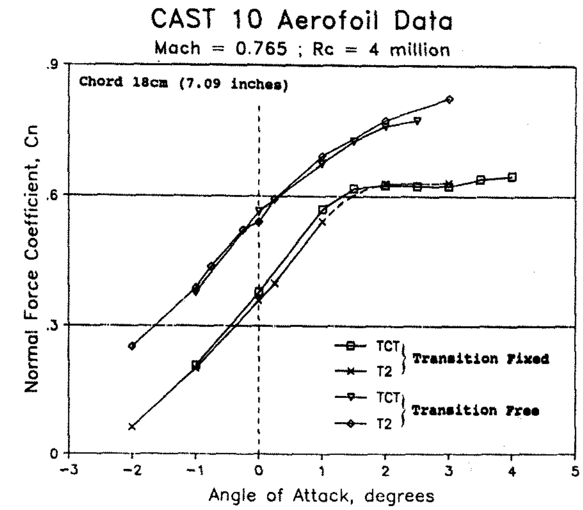

Fig. 8 Comparison of lift data from the 0.3-m TCT and T2 tests at Mach 0.765 and 4 million Reynolds number.

We tested the smaller French model in the 0.3-m TCT over the Mach number range 0.7 to 0.8 with chord Reynolds numbers from 4 million to 45 million. However we concentrate our comparison of data around the aerofoil design conditions at Mach 0.765. We consider these conditions to be a severe and realistic test of AWTS aerodynamic performance with this aerofoil We show a comparison of lift data from T2[19] and the 0.3-m TCT in figure 8, for the design Mach number of 0.765 at 4 million Reynolds numbers with transition fixed and free. The comparisons are good particularly in the matching of Cn_{max}. Transition was fixed at 5% chord in the T2 tunnel and 6% chord in the 0.3-m TCT. The severe effect of transition fixing at low Reynolds number is perfectly matched in both data sets. This is quite remarkable

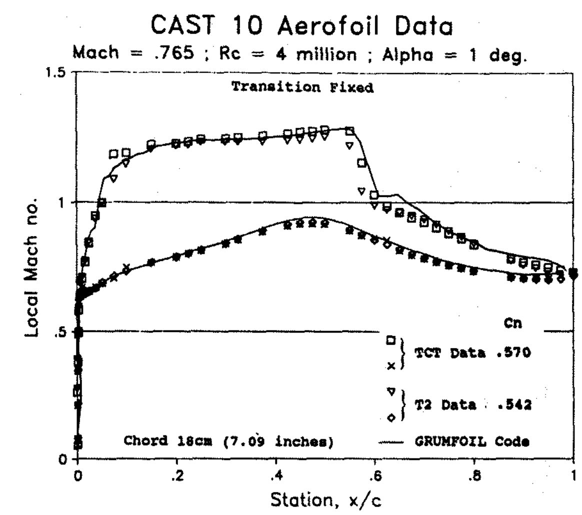

Fig. 9 TCT and T2 experimental pressure distributions for a demanding lifting case compared with a free air theoretical prediction.

considering the sensitivity of the aerofoil to changes in tunnel turbulence and test conditions. In fact, the operation of the T2 tunnel makes it difficult to maintain the same Mach number for an α sweep. For example, in the 0.3-m TCT the Mach number variation between the data points at Mach 0.765 was about .002. In the T2, this variation was about .008. The test section height to model chord ratios are 1.83 in the 0.3-m TCT and 2.05 in the T2 tunnel. Different but similar wall adaptation procedures were used in each test. No sidewall boundary layer treatment was used in either of these tests. An associated comparison of aerofoil pressure distributions is also good as shown in figure 9, for the demanding case of Mach 0.765; $\alpha = 1.0°$; Rc = 4 million. We include in this comparison a theoretical free air pressure distribution obtained using the GRUMFOIL code. The agreement is encouraging and gives support to the claim that the AWTS data is essentially free of wall interference.

The drag data from the two tunnels is also in good agreement when the slight differences in lift curve slope are removed from the comparison, as shown in figure 10. The comparison of lift and drag data together is very good, particularly in the matching of Cd_{min}. Unfortunately, we can only make useful comparisons with the T2 data at low Reynolds number due to a sparsity of T2 data.

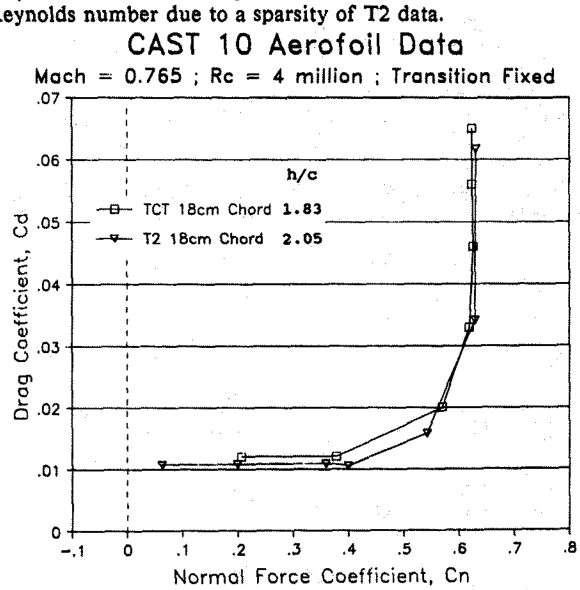

Fig. 10 Comparison of lift and drag data from 0.3-m TCT and T2 tests with the same model at Mach 0.765 and 4 million chord Reynolds number.

However we are able to make high Reynolds number comparisons with the NAE data. NAE tested the large Canadian model with sidewall boundary layer treatment. They then applied post-test wall interference corrections to the real-time data using the subsonic method of Mokry and Ohman.[18] The NAE tests had a test section height to chord ratio of 6.67 (which is very large compared with a ratio of 1.44 in the 0.3-m TCT). The use of a small model in the NAE tunnel minimises the top and bottom wall interference at its source, so this corrected 2-D data is probably the best available from a ventilated transonic test section. We carried out the 0.3-m TCT (NASA) tests over a Mach number range of 0.3 to 0.8 and chord Reynolds numbers from 6 million up to a record-breaking 72.4 million.[20] We show a comparison of NASA and NAE lift data in figure 11 at Mach 0.765 and 20 million Reynolds number.

We fixed transition at 5% chord to minimise the effects of tunnel turbulence on both data sets. The comparison is very good, except for a small uncertainty in Cn_{max}. We have also seen that there is good agreement in the pressure distributions and drag measurements.[21,22]

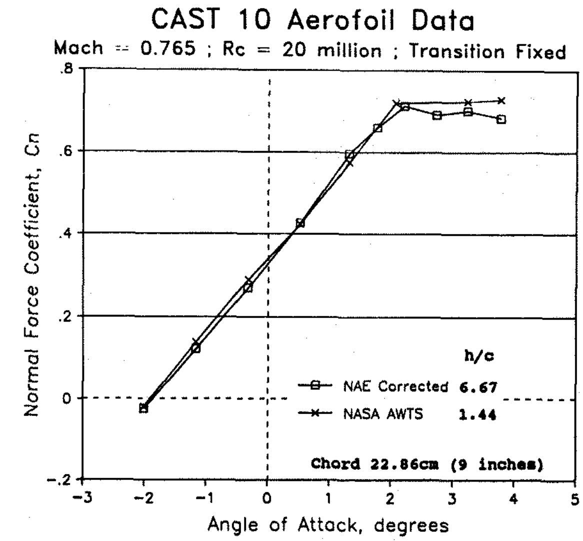

Fig. 11 Comparison of NAE and NASA lift data from the same model at Mach 0.765 and 20 million chord Reynolds number.

We compare NAE and NASA lift data at different chord Reynolds numbers in figure 12, for the test conditions of α approximately equal to 0.45° and 2.15° at Mach 0.765. There is remarkably good agreement between the two data sets over the Reynolds number range *10 to 20 million* for both the moderate and high lift cases considered. Figure 12 also shows that Reynolds number effects are still present at Reynolds numbers of about 70 million.

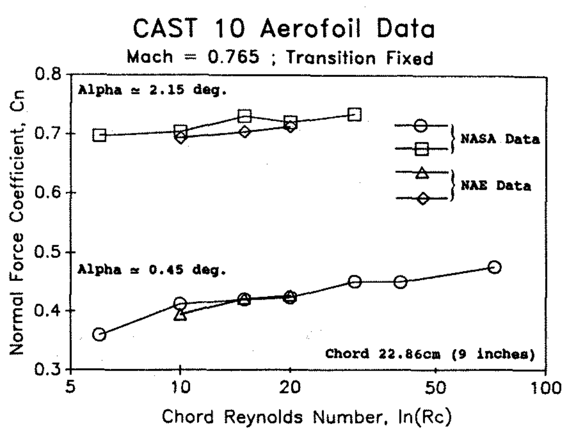

Fig. 12 Effect of Reynolds number on the lift data from the NAE and NASA tests at Mach 0.765.

So, we see that there is good overall agreement between various combinations of CAST 10 data, despite the sensitivity of the CAST 10 to variations in tunnel conditions. This is quite remarkable when one considers the normal difficulty of comparing sets of data between different tunnels, even when using the same model. Unfortunately, a comparison between data from the different chord CAST 10 models is not straightforward for two reasons. Firstly, the model angle of attack datum line is different for each model.[22] Secondly, we have some reservations about the repeatability of Cn_{max} with the larger of the two models. The reason for this problem with Cn_{max} (and the associated drag) is probably related to the performance of the aerofoil. The CAST 10 aerofoil seems to be capable of exchanging lift for drag at high Reynolds numbers and high lift. Nevertheless, we have been able to get good data comparisons between the two models, as shown on figure 13. In this instance, we tested the two models one after the other which may be significant. We think it is realistic to *assume that both sets of* NASA CAST 10 data are close to the true free air result aside from the uncertainties in Cn_{max} and the associated drag. As found with the NACA 0012 data, the NASA CAST 10 data validates the adaptive wall testing technique.

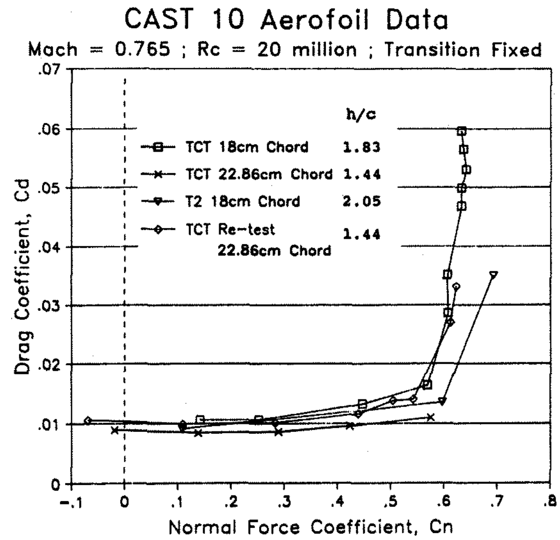

Fig 13 Comparison of lift and drag data for the two CAST 10 models tested in the 0.3-m TCT.

During the course of these validation tests, we were able *to investigate the effect of some practical restrictions in the* test section. For example, we examined the effects of the wall setting tolerance which is nominally 0.127mm (.005 inch). We repeated tests with the walls fixed in previously found *streamline shapes for the same test conditions.* We saw good repeatability in the model data even when the operating temperature of the tunnel was changed. However, we have yet to examine repeatability close to Mach 1.0, when flow sensitivity to the local wall positions is greatest. It is encouraging to know that in production type 2-D tests, we can achieve good data repeatability of the order .001 in Cn and .0005 in Cd even with extensive laminar flow on the aerofoil. This repeatability was noticed even after the model had been removed and re-installed in the test section. Unfortunately, our repeatability after a long time delay is not so good and is probably due to instrumentation deterioration. This is a problem we are endeavouring to remove from the facility and is not related to the AWTS alone.

The length of our AWTS was particularly short when we tested our largest validation model. With a 33cm (13 inch) chord model, the effective test section length is only 4.3 chords. This is considerably less than the normal 7 chords. Theory predicts significant truncation effects but the data did not support this prediction. We performed some special tests with the smaller of the two NACA 0012 models whereby we reduced the effective test section length artificially.[10] In addition, we simulated different model positions relative to the test section entrance and exit. Only when we greatly reduced the test section length, down to a mere 3.07 chords, could we see small changes in the model data.[10] Looking at the wall Mach numbers for a Mach 0.76 case (shown on figure 14), we can see that the only real warning of truncation effects is a higher Mach number at the test section exit. Without truncation, the wall Mach numbers are near free stream at the *upstream and downstream ends of the test section* with streamlined walls. This is a good indication that the wall adaptation process is working correctly. We conclude that we probably cannot measure the truncation effects in our tests with the 33cm (*13 inch*) chord model. However, the shorter the length of the test section relative to the model chord, the more severe is the curvature requirement for the flexible walls, as shown later.

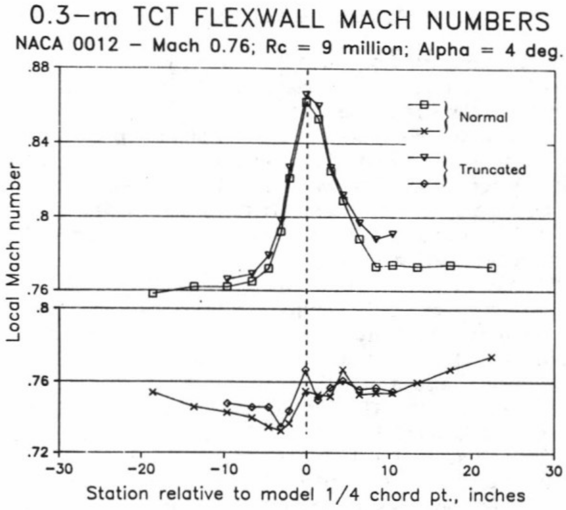

Fig. 14 Local Mach number distribution along each flexible wall with and without simulation of test section truncation.

A lack of wall flexibility in our AWTS has been a problem. Unfortunately, the design criterion for our flexible walls was wrong.[10] However, we have found ways to minimise the effect of this problem. Firstly, we can limit the size of the model to less than 22.86cm (9 inches) if we are to avoid jack overload and wall curvature problems. Secondly, we can favourably alter the streamlined wall shape for a given test condition by effectively rotating the test section centerline.[22] The angle of rotation becomes an angle of attack correction to be applied to the model data after wall streamlining. It is our experience that the final result is unaffected by the use of centerline rotation. This demonstrates that the wall adaptation process is again working correctly.

We cannot expect the 2-D wall adaptation process to remove all the 3-D interferences induced by the sidewall boundary layers. Consequently, we need to consider either applying corrections to the 2-D aerofoil data for residual sidewall interferences (remaining after wall streamlining) or use sidewall BLC to remove the interferences. To investigate the sensitivity of the model data to different amounts of sidewall boundary layer removal, we decided to integrate an existing sidewall BLC system (briefly described earlier) into our AWTS. This combination has allowed us to examine the effects of BLC on both the model and the wall adaptation process. Preliminary results with the large CAST 10 aerofoil indicate that passive BLC has no significant effects on the measured lift curve slope. However, the BLC can affect Cn_{max} if shock induced separations are likely. With the CAST 10, it seems that Mach numbers of 0.78 and above fall into this category, i.e. after shock stall of the model. The effect of BLC at Mach 0.765 is not significant and so sidewall interferences are unlikely to cause the uncertainty in Cn_{max} we have observed experimentally. The CAST 10 data comparisons do not strongly advocate the need to apply corrections for residual sidewall boundary layer interferences, but we realize this may not always be the case. The use of the BLC system with the 2-D wall adaptation process is routine. The successful use of the BLC system gives the 0.3-m TCT an extremely useful capability for future 2-D studies of Reynolds number and sidewall boundary layer effects and interactions.

4.2 Three-Dimensional Testing

We have carried out preliminary tests on a semi-span wing in the 0.3-m TCT as part of the validation process for our 3-D wall adaptation scheme. We mounted a simple unswept wing on the right sidewall of our AWTS as shown in figure 15. This force model has an aspect ratio of 4.0 with a mean aerodynamic chord of 8.66cm (3.41 inches). The wing section is a NACA 65A006. We chose this model because it has an "interference free" database. The model is small in our AWTS. The solid blockage is 0.79% and the semi-span/tunnel width ratio is 0.51.

We tested the model at low Reynolds numbers and non-cryogenic temperatures over the Mach number range 0.7 to 0.9 and an α range from 0° to +7° (as limited by balance loads). We also tested the model at two vertical positions in the test section. A normal position on the centerline of the sidewall and a high position midway between the centerline of the sidewall and the nominal position of the top wall. These two positions allowed us to change the model perturbations at the walls for any given test condition.

As expected, the wall interference present with the model in the normal position was small and correctable. However, with the wing mounted in the high position we did encounter some significant wall interference at the highest angle of attack. Figure 16a shows the calculated lift and blockage interference at the wing root with the walls straight. The induced Mach number is small and almost constant over the chord. However, there is a significant gradient in the induced angle of attack of 1.35° over the chord. The wall interference at other spanwise locations are similar, although the upwash become more uniform towards the wing tip.

After one movement of the flexible walls according to our 3-D wall adaptation scheme, the wall interference at the wing root is reduced, as shown on figure 16b. The induced Mach number becomes negligible and the upwash gradient is greatly reduced to 0.32°. A similar interference reduction occurs over the span of the wing.[14]

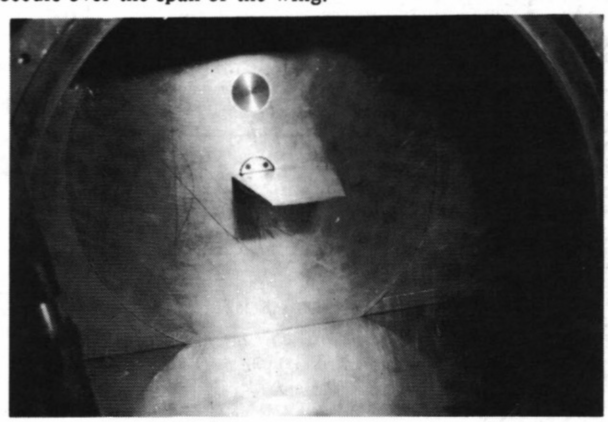

Fig. 15 Semi-span wing model mounted on the right sidewall of the 0.3-m TCT AWTS in the normal position.

We show a summary of the lift data at Mach 0.7 in figure 17. Reference data obtained in the NASA Langley 7x10 wind tunnel is shown for comparison. Linear corrections, based on the wall interference assessment, are adequate in most cases. Only for the highest angle of attack, do we actually need to adapt the flexible walls and then only for one iteration. The results are very encouraging although our "correction technique" has only small levels of wall interference to correct in this test.

At higher Mach numbers, the comparison of our AWTS data with the reference data is similar but not as good. We attribute this reduction in data quality to the restricted location and amount of pressure data available on the test section boundaries (see figure 5).[14]

These preliminary tests indicate the potential of using a 2-D AWTS for 3-D testing as found by others.[7] We observed that the residual interference in the spanwise direction had no effect on the measured model data in this test. However, this may not always be the case with different 3-D model configurations. Further tests are required to assess the potential of our 3-D wall adaptation scheme with a range of useful 3-D model configurations.

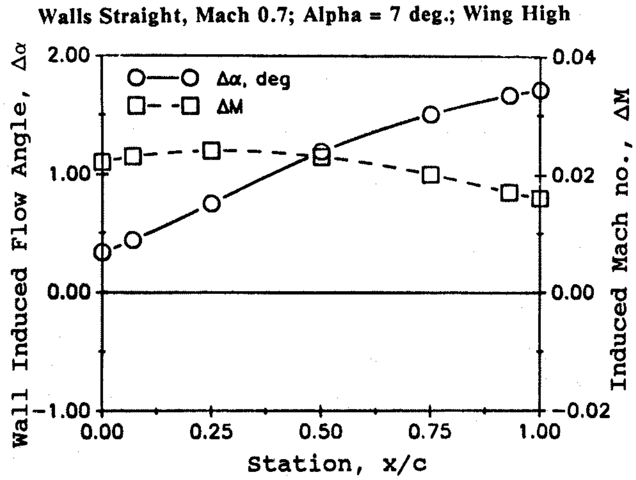

Fig. 16a Chordwise variation of wall interference at the wing root with walls straight.

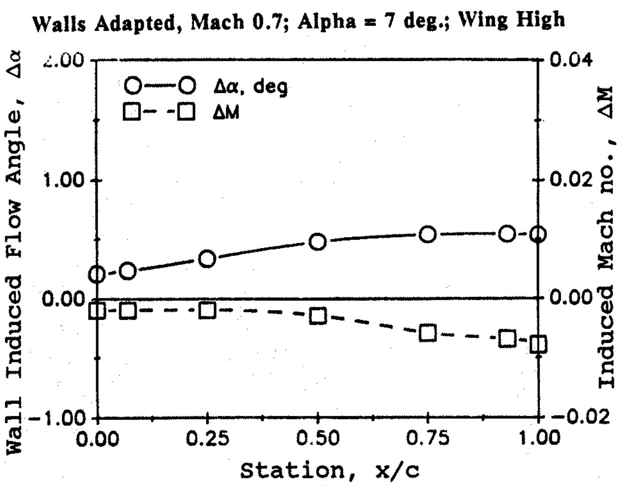

Fig. 16b Chordwise variation of wall interference at the wing root after one iteration of the 3-D wall adaptation scheme with walls shaped.

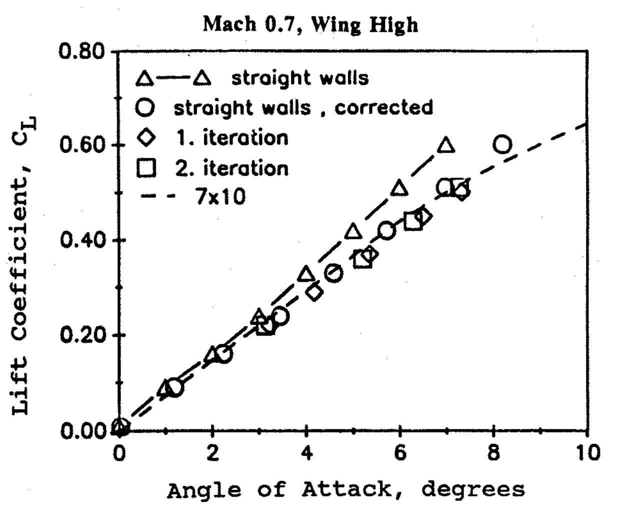

Fig. 17 Measured and corrected wing lift data from the 0.3-m TCT compared with 7x10 reference data at Mach 0.7.

5. Operational Experience

The operation of our AWTS in the 0.3-m TCT has been remarkably successful. We have taken over 2,000 data points with the walls streamlined since our AWTS was commissioned in March 1986. We can achieve up to 50 data points in one 6-hour testing shift. However, tunnel productivity is affected by many factors other than wall streamlining. We find that the pacing item in our test setup is the wake rake system. Wall adaptation typically takes less than 2 minutes for each data point in 2-D testing.

As with any new facility, we have attempted to explore all the operating features available. In this instance, the elimination of top and bottom wall interference in 2-D testing can actually be seen real-time. Figure 18 shows the effect on lift of setting the flexible walls straight when testing an advanced 2-D aerofoil at Mach 0.5. The difference in Cn with straight and streamlined walls is a good illustration of classical lift interference. The wall interference generated by straight wall shapes prevents stall up to the load limit of the model.

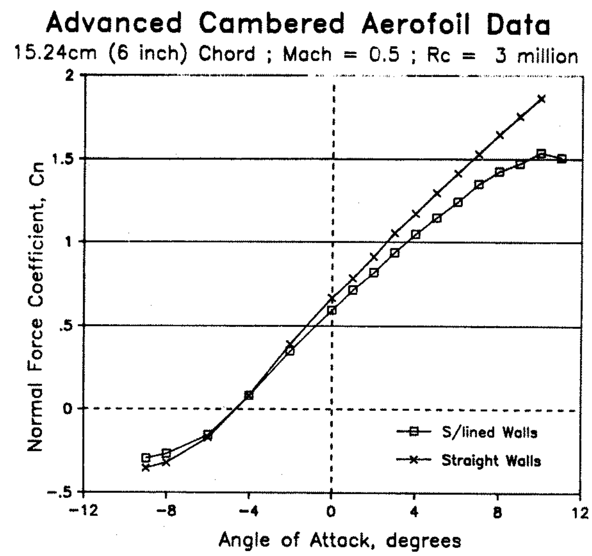

Fig. 18 Effect of wall streamlining on model lift at Mach 0.5.

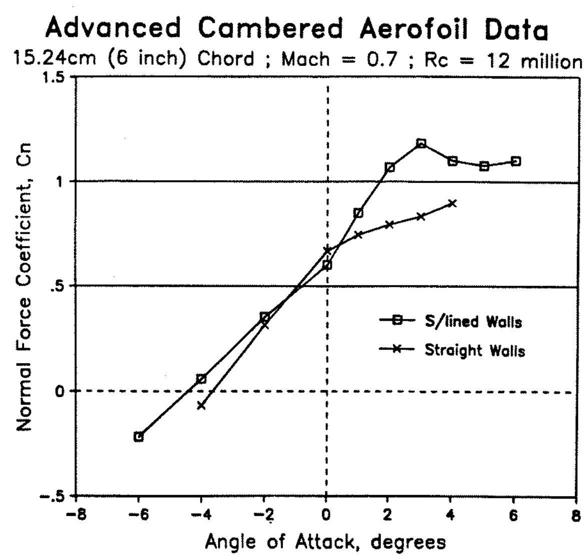

Fig. 19 Effects of wall streamlining on model lift at Mach 0.7.

At transonic speeds, the wall interference can be quite different as indicated by the lift data on the same advanced aerofoil at Mach 0.7 shown in figure 19. Notice how the difference in the Cns changes sign at an α of about 0.5°. This effect is caused by the phenomena of test section choking. As we increase the model blockage by changing α the flow channel adjacent to the suction surface of the model will choke. The significant wall interference that results is unpredictable and model dependent. This unpredictability is the main reason we seek better ways to correct our aerofoil data for wall interference at transonic speeds.

With an AWTS we have an important operational advantage over conventional test sections and that is the real-time data is "corrected." For example, in figure 20, we show the significant lift interference present in a slotted wall test section (previously fitted in the 0.3-m TCT) by comparing real-time data from the slotted wall test section[23] with the AWTS data. The big difference in the test section height to model chord ratios for the two data sets (7.87 in the slotted wall test section and 1.83 in the AWTS) does not minimise the data differences. Admittedly, we can apply post test corrections to the slotted wall data to improve the lift curve slope but what about Cn_{max}? The important point I make here is that there is a problem with trying to use the real-time data obtained in a conventional ventilated test section. Consequently, an engineer is unable to perform an efficient real-time investigation of some specific aspect of an aerofoil's performance at transonic speeds without using an AWTS.

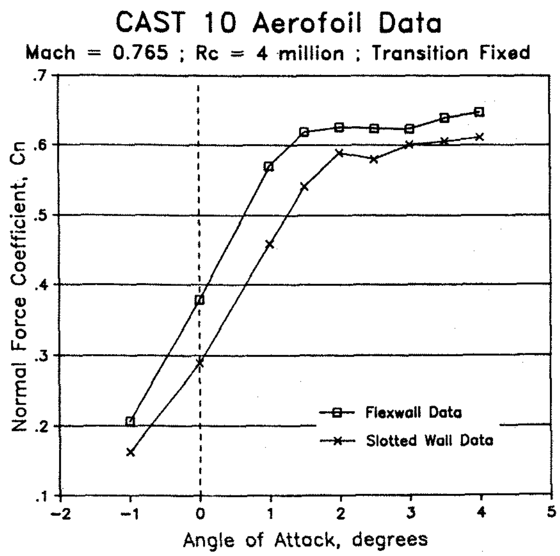

Fig. 20 Comparison of real-time 0.3-m TCT data using a slotted wall test section and a flexible walled AWTS.

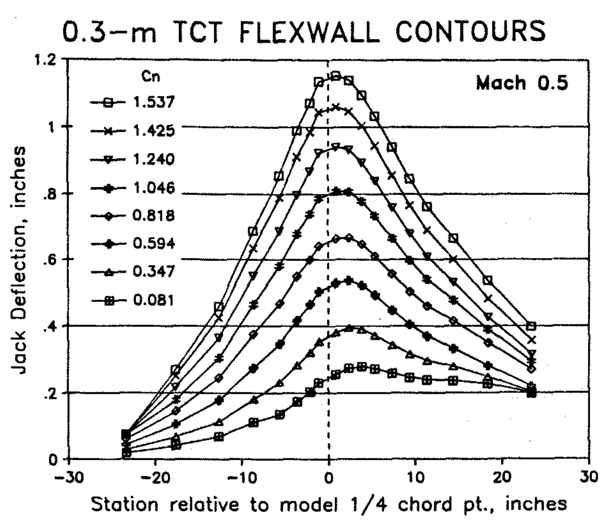

Fig. 21 Family of streamline wall shapes found experimentally by varying the lift of a 2-D model.

We have gained considerable operational experience with the wall shapes required for streamlining. Figure 21 shows how the streamline shapes of the top wall change with increasing lift in a 2-D test. As we increase lift so the upwash ahead of the model causes the walls to translate vertically. In addition, we see a vertical translation at the downstream end of the test section due to the growing wake. This family of wall shapes is similar to what we would expect theory to predict using some mathematical representation of the model. However, the streamline wall shapes are determined without any reference to the model.

Model size in 2-D testing has a significant effect on wall curvature requirements. The closer the streamlines followed by the walls are to the model, the more movement and curvature is required. We show this in figure 22, for the case of two different chord models at the same test conditions. The onset of compressibility has a similar effect on the streamline wall shapes. In this instance, the walls move apart to account for transonic blockage. Interestingly, the better the model performance at transonic speeds the less severe is the wall curvature required for streamlining. These observations are important considerations for an AWTS designer. In our AWTS, hardware limitations restrict the useful model chord and restrict high speed testing where the walls are near sonic.

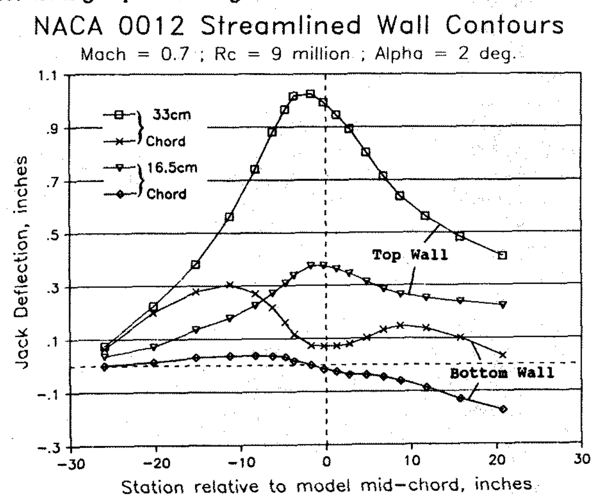

Fig. 22 Streamline wall shapes for different chord models at the same test conditions

During our limited 3-D testing, we have not encountered any wall movement limitations. This is probably due to an important addition to the 3-D wall adaptation scheme which minimises the downstream movement of the flexible walls.

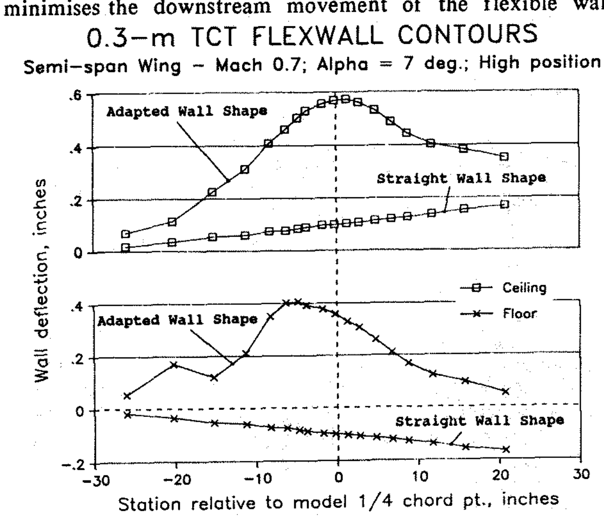

Fig. 23 Typical set of wall shapes required for streamlining in 3-D testing with a semi-span wing.

This feature is achieved by introducing an angle of attack correction previously referred to as *centerline rotation* in 2-D testing. A typical set of streamline wall shapes for 3-D testing is shown on figure 23 for the case discussed in sub-section 4.2. The wall curvature requirement is generally less for subsonic 3-D testing due to the smaller blockage and chord sizes associated with 3-D models. However, preliminary 0.3-m TCT tests at about Mach 1.3 indicate that the wall curvature requirements will probably increase at supersonic speeds.

We have found the effect of Reynolds number on the 2-D adaptive wall testing technique to be much less than the effect of Mach number. What small effects we have seen over the large Reynolds number range possible in the 0.3-m TCT is model dependent. If the model flow changes significantly with Reynolds number then the streamline wall shapes will also change significantly. As shown earlier, we can repeat data for two different chord models even though we test at different unit Reynolds numbers to match chord Reynolds numbers. Operationally, a change in Reynolds number typically requires one iteration of the 2-D wall adaptation process to streamline the walls. Changes to Mach number or angle of attack require 2 or 3 iterations to streamline the walls.

Our efforts to make the operation of the AWTS invisible to the operator have naturally centered around the operator interface with the control system and the selection of initial wall shapes for each data. This selection process can significantly affect the operating efficiency of an AWTS, particularly if the flexible walls are slow to move. We have software which makes intelligent choices of initial wall shapes that does not restrict the test programme.[24] Our AWTS system, while handicapped with inappropriate and unreliable computers, has performed well. Non-expert operators can use our AWTS within a defined test envelope (see figure 24) which is model size dependent. This feature has helped us perform numerous test programmes related to subjects other than the adaptive wall testing technique. Expert operators can expand the test envelope by careful manipulation of the flexible walls and strict monitoring of test conditions.

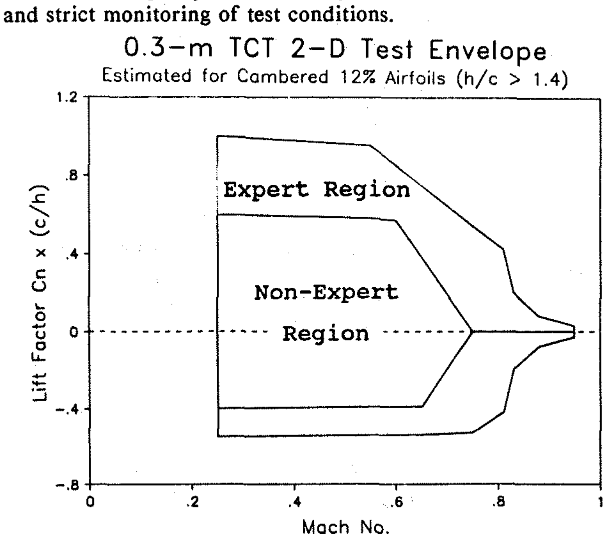

Fig. 24 Typical model dependent test envelope for the 0.3-m TCT AWTS.

At high speeds, we have problems with maintaining the test Mach number during a streamlining cycle. This is due to the short length of the 0.3-m TCT tunnel circuit which closely couples any aerodynamic changes in the test section with the drive fan performance. At transonic speeds, the model wake is very sensitive to changes in the wall shapes and these changes cause large free stream Mach number fluctuations. The movement of the rake during a wake survey has a similar undesirable effect. So the operation of our AWTS is not as routine as we would like at high speeds.

Operationally, we can and do accommodate the requirements of most 2-D tests. Despite hardware limitations, we have extended our knowledge of the 2-D adaptive wall testing technique into the realms of flight Reynolds numbers and high lift. We have tested successfully up to a very large chord Reynolds number of 72.4 million. Model normal force coefficients up to 1.53 have been achieved with the walls streamlined. These high lift conditions have demanded some large wall deflections and do not require any special operating procedures. We have observed maximum wall displacements up to 3.76cm (1.48 inches) in the vicinity of the model at subsonic speeds. These displacements exceed those possible with any other flexible walled test sections. We have, I think, proved that the 0.3-m TCT AWTS is the most capable AWTS ever built for 2-D testing.

Interesting, we have noticed a significant reduction in drive power requirements compared with the use of the slotted wall test section. However, this can not be attributed to the AWTS alone, since a new, more efficient diffuser was fitted along with the AWTS. Also we have measured about a 50% reduction in the levels of turbulence in the 0.3-m TCT due to the installation of the AWTS and its diffuser.

Our AWTS represents the first attempt to produce a production type system using adaptive wall technology. We have found the testing technique to be tolerant to inevitable imperfections in the hardware and operator errors. We feel that an AWTS could be successfully inserted into any transonic wind tunnel, large or small. Basically, the technology is proved in 2-D testing, more research is required in 3-D testing. Like so many of the correction codes, adaptive wall technology is treated with skepticism. However, adaptive walls have so much more to offer than just minimisation of wall interference. I think that eventually the usefulness of AWTSs will become accepted and AWTSs will become a requirement for certain transonic tests. However, this will probably only happen when the full potential of AWTSs has been realized in both 2- and 3-D wind tunnel testing.

6. Conclusions

1. A flexible wall testing technique has been successfully used at flight Reynolds numbers and high lift in 2-D testing. The 0.3-m TCT validation results from large 2-D aerofoils compare very favourably with other sources of "interference free" data.

2. Preliminary 3-D tests confirm that a simple AWTS design, with just two flexible walls, may be all that is necessary to minimise wall interference. More research is required to optimize the testing technique for different, more demanding, model configurations.

3. A flexible wall testing technique can be used with a continuous flow cryogenic wind tunnel.

4. We know more about the design of flexible walled AWTS and can now increase the 0.3-m TCT test envelope for very large 2-D aerofoils (where the test section height/chord ratio approaches unity) by improving wall flexibility.

5. We have demonstrated non-expert use of AWTSs within test envelopes which are bounded by wall movement restrictions.

6. An AWTS system generates real-time "interference free" data with no more overall complexity than usual found in conventional transonic wind tunnel testing.

7. We have realized real-time minimisation of wall interference, use of large models, reduction in drive power and tunnel turbulence by use of a flexible walled AWTS.

8. The 0.3-m TCT with an AWTS is the most capable 2-D wind tunnel anywhere.

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