Report 4191

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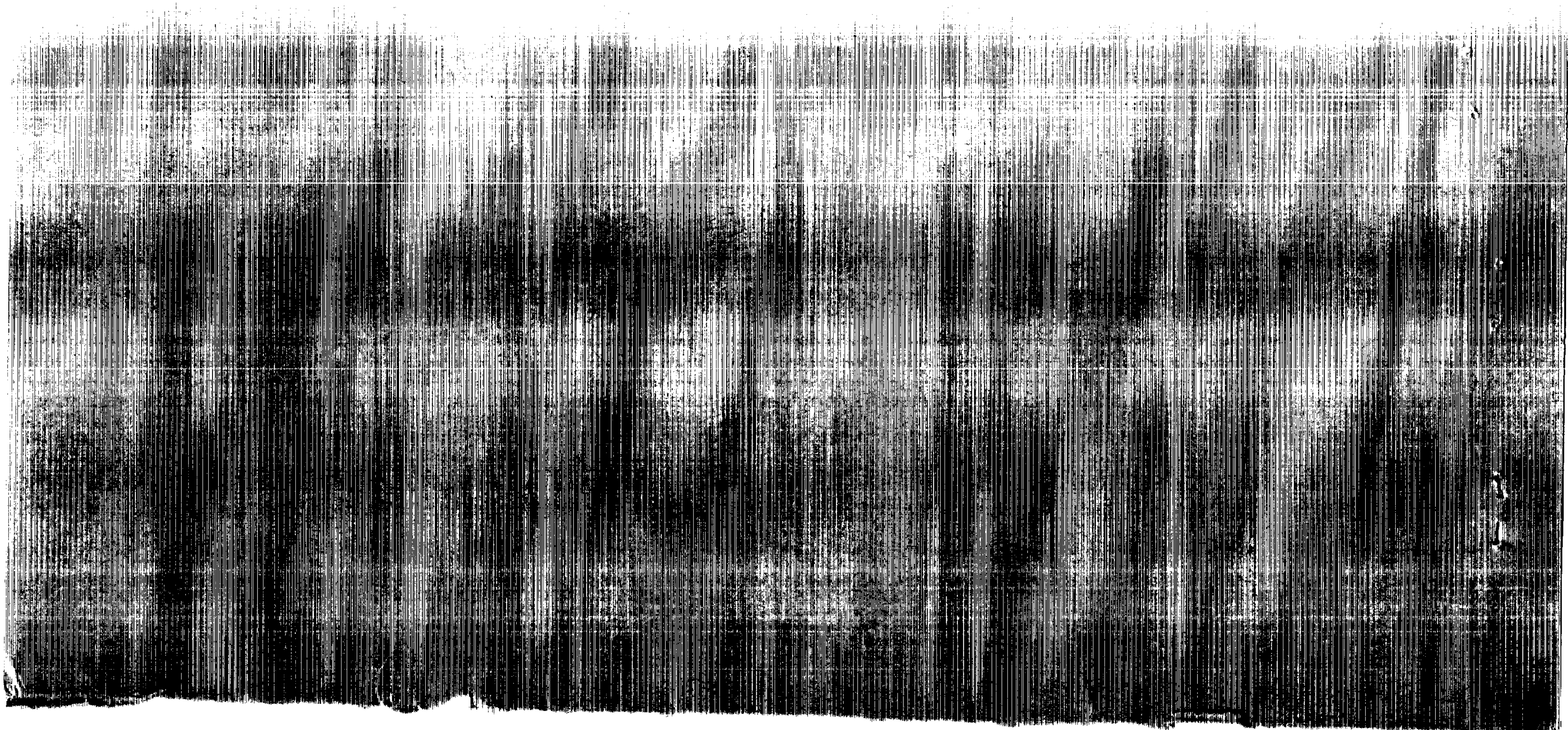

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Adaptive Wall Technology for Minimization of Wall Interferences in Transonic Wind Tunnels

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ADAPTIVE WALL TECHNOLOGY FOR MINIMIZATION OF WALL INTERFERENCES IN TRANSONIC WIND TUNNELS

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Abstract

This paper contains a review of modern experimental techniques to improve free air simulations in transonic wind tunnels by use of adaptive wall technology. The review considers the significant advantages of adaptive wall testing techniques with respect to wall interferences, Reynolds number, tunnel drive power, and flow quality. The application of these testing techniques relies on making the test section boundaries adjustable and using a rapid wall adjustment procedure. An historical overview shows how the disjointed development of these testing techniques, since 1938, is closely linked to available computer support. An overview of Adaptive Wall Test Section (AWTS) designs shows a preference for use of relatively simple designs with solid adaptive walls in 2- and 3-D testing. Operational aspects of AWTSs are discussed with regard to production type operation where adaptive wall adjustments need to be quick. Both 2- and 3-D data are presented to illustrate the quality of AWTS data over the transonic speed range. Adaptive wall technology is available for general use in 2-D testing, even in cryogenic wind tunnels. In 3-D testing, more refinement of the adaptive wall testing techniques is required before more widespread use can be envisaged.

Symbols

α	Angle of attack
c	Chord of model
d	Body diameter of model
C_D	Drag coefficient
C_L	Lift coefficient
C_n	Normal force coefficient
C_p	Pressure coefficient
h	Height of test section
L	Length of model
M_∞	Free stream Mach number
P	Local static pressure
P_0	Reference static pressure
Rc	Chord Reynolds number, per foot
x	Position relative to model leading edge or nose
Y	Wall deflection
ΔY	Change in wall deflection

1. Introduction

If we are to achieve more and more efficiency from flight vehicles, we must have better and better free air simulations in our wind tunnel experiments. It is for this reason that the quality of wind tunnel data remains the subject of considerable research effort. Unfortunately, significant wall interference effects still exist in transonic wind tunnels despite large efforts to eradicate this simulation problem. Traditionally, the wind tunnel community has used several well-known techniques to minimize wall interferences. Models are kept small compared with the test section size (sacrificing the test Reynolds number available). Ventilated test sections are used to relieve transonic blockage and prevent choking (introducing other complex boundary interferences). Post-test linearised corrections are applied to the model data to take some account of residual wall interferences. Usually, all three techniques are used together in transonic testing. However, we find these techniques fall short of the high levels of accuracy we now demand from wind tunnel simulations.

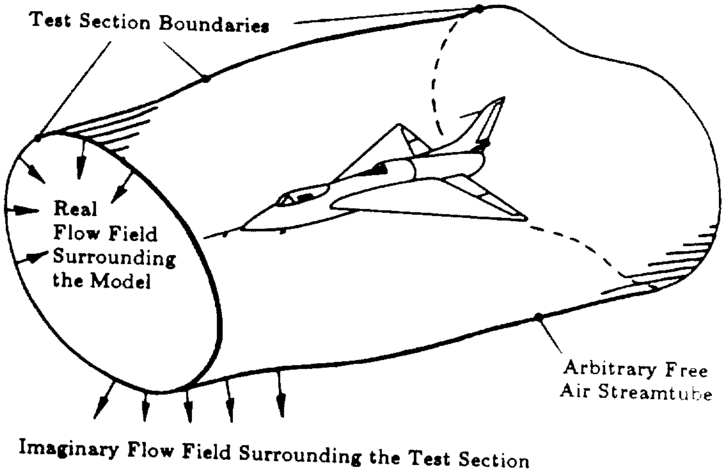


Fig. 1 - Principle of wall streamlining for free air simulations with any wind tunnel model.

A solution to this dilemma exists. It involves using modern testing techniques which minimize wall interferences at source. (Actually, these modern techniques are a re-discovery of one of the first solutions to transonic wall interferences developed in the 1930s.) These techniques adapt the test section boundaries to free air streamline shapes so the test section walls become invisible to the model. This is known as 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* surrounding the test section. The imaginary flow field extends to infinity in all directions. The principle is simple but the application of the principle is complex. This complexity arises from the need to adjust the test section boundaries for each test condition.

The application of adaptive wall testing techniques relies on making the test section boundaries adjustable and using a rapid wall adjustment procedure. Both these aspects are addressed in this paper highlighting the advantages of solid wall test section designs. An historical overview of Adaptive Wall Test Section (AWTS) development shows how disjointed progress has been over the last 50 years. Operational aspects of AWTSs are considered to address the practicalities of using adaptive walls over the transonic speed range. Both 2- and 3-D data are presented to show the quality of AWTS data with real-time minimization of wall interferences. In conclusion, I review the accumulated experience with adaptive wall technology for 2- and 3-D testing to indicate the possible direction of future developments.

2. Advantages of Adaptive Walls

AWTSs offer several important advantages other than the major benefit of minimizing wall interferences for free air simulations. With wall interferences minimized, we are free to increase the size of the model for a given test section. Typically, we can double the test Reynolds number. This perhaps allows testing at full scale Reynolds numbers to remove another free air simulation problem. Larger models are also important for high dynamic pressure tests and provide increased dimensions for more detailing and more volume for instrumentation. We also expect simpler magnetic suspension of models in an AWTS because the supporting coils can be closer to the model.

With solid adaptive walls (called flexible walls), the test section boundaries are much smoother than with ventilated 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 (giving better free air simulations). Also the elimination of the plenum volume from the tunnel circuit reduces settling times and minimizes flow resonance, which is particularly important for blowdown tunnels.

3. Historical Overview of Adaptive Wall Research

The adaptive wall testing techniques we know today are a re-discovery of one of the first solutions to the problem of transonic wall interferences. 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 and choking. 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.[2] NPL successfully used flexible walled AWTSs into the early 1950s, generating a vast amount of 2- and 3-D transonic data[3] which we are still uncovering in the literature.

The advent of ventilated test sections at NACA in 1946, provided a "simpler" approach to high speed testing, since the adjustments to the test section boundaries are passive. In contrast, AWTSs actively adjust the test section boundaries. The apparent simplicity of ventilated test sections eventually made the AWTSs at NPL obsolete and all AWTSs disappeared.

After about 20-years, interest in AWTSs was rekindled. Around 1972, several researchers, in Europe and the USA, independently re-discovered the concept of adaptive wall testing techniques in the quest for better free air simulations in transonic wind tunnels. The complexity of correction codes, necessary to reduce significant wall interferences, encouraged researchers to look for alternative ways to improve data quality. The adaptive wall approach offered them an elegant way to simplify the wall interference problem. Adaptive wall adjustment procedures need only consider the flow at the test section boundaries (in the farfield), the complex flow field round the model need never be considered. So by using adaptive walls, we can simplify the "correction codes" by increasing the complexity of the test section hardware. Some researchers 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.

This renewed interest, helped by the availability of computers, has spawned various adaptive wall research groups around the world. We have seen a variety AWTS designs for testing 2- and 3-D models. Production type AWTSs are now in operation at NASA Langley, USA, and ONERA/CERT, France. Meanwhile in Russia, we only know that Fonarev,[4] Tretyakova, Sayadyan, Neiland, and Semenov have all proposed the use of variable porosity transonic AWTSs.

4. Adaptive Wall Fallacies

During the development of any new technology, mistaken beliefs will arise. Adaptive wall technology has not escaped. A selection of mistaken beliefs follows:

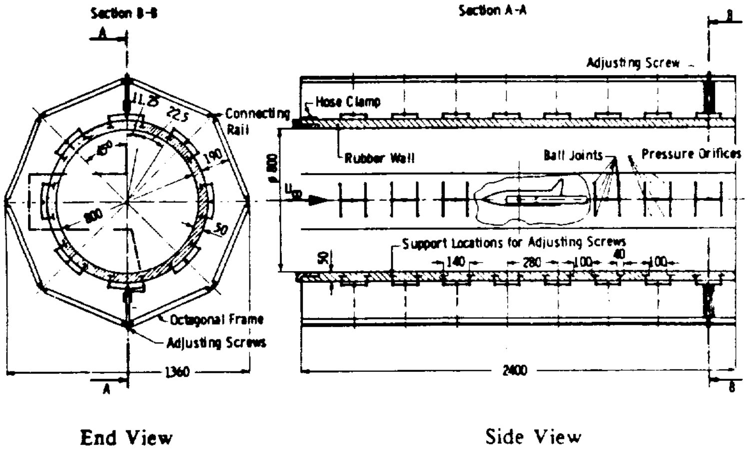
The idea of AWTSs originated in 1972.
AWTSs will not work in large wind tunnels.
AWTSs will not work at transonic speeds.
AWTSs cannot streamline with sonic flow at the test section boundaries.
The testing technique is too complex to be practical.
The testing technique requires more computer power than conventional test sections.
Knowledge of the flow round the model is a prerequisite for wall streamlining.
Wall streamlining for each data point wastes too much tunnel time.
Operation of an AWTS requires expert knowledge.
2-D testing is trivial and the effects of the walls are not important.

We hope you will agree that these statements are indeed fallacies, after studying this paper.

5. An Overview of AWTS Designs

The modern interest in AWTSs encompasses 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. The complexity of controlling a 3-D boundary 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. The number of adaptive walls necessary in a 3-D AWTS is not simple to answer and must ultimately be a compromise. From practical considerations, the design of a 3-D AWTS must be a compromise between magnitude of residual wall interferences (after streamlining), hardware complexity, model accessibility, and the existence of a rapid wall adjustment procedure. Table 1 shows a list of AWTSs currently in use around the world (as far as we are aware), highlighting the variety of designs operational.

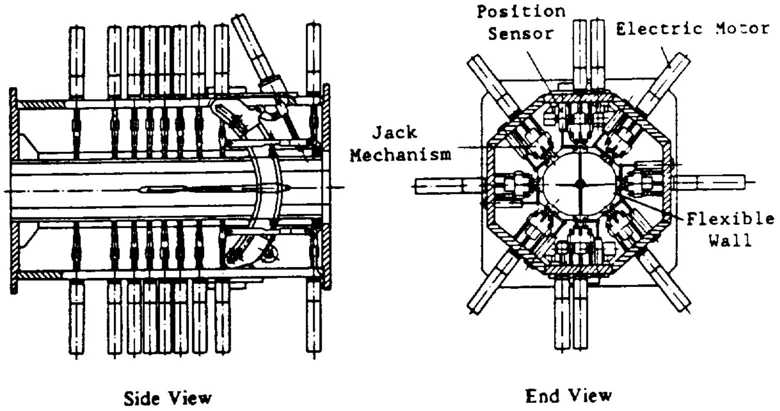
DFVLR at Göttingen tried perhaps the most adventurous 3-D AWTS design which is now mothballed. They put a nominally circular (0.8m diameter) thick walled rubber tube in their DAM test section.[5] The tube shape is controlled by eight circumferential positioning jacks at each of eight equally spaced streamwise stations (see Figure 2). With similar boundary control, Technical University of Berlin (TU-Berlin) built an octagonal AWTS[6] with eight flexible walls sealed to one another by spring steel leaves (see Figure 3). In contrast, the only (we believe) transonic 3-D variable porosity AWTS[7] (now mothballed at AEDC) has four adaptive walls and a square cross-section. Here, boundary control is by adjustment of the local porosity along each of the four



End View

Side View

Fig. 2 - DFVLR Göttingen DAM rubber tube AWTS.



Side View

End View

Fig. 3 - TU-Berlin octagonal AWTS with flexible walls.

Table 1 - Adaptive wall test sections currently in use

Organization	Tunnel	X–Section (h x w) m	Length m	Approx. Max. Mach No.	Approx. Max R_c millions	Walls	Adaptation Control	Remarks
Arizona University •••	HLAT	0.51 Square	0.914	0.2		2 Arrays of Venetian Blinds 2 Solid	16 Panels of Vanes and a Variable Angle Nozzle	Issue 3
DFVLR •••	HKG	0.75 Square	2.40	>1.2		2 Flexible 2 Solid	? Jacks/Wall	Issue 7
Genova University ••	Low Defl. Cascade	0.2x0.05 Rectangular	1.58	>.9	1	2 Flexible 2 Solid	33 Jacks/Wall	Issue 7
Genova University ••	High Defl. Cascade	0.2x0.05 Rectangular	1.6	>.9	1	2 Flexible 2 Solid	13 Jacks–Ceiling 26 Jacks–Floor	Issue 7
NASA Ames ••	2x2 ft	0.61 Square	1.53	>.85	2	2 Slotted 2 Solid	32 PCCs/Wall	Issue 4
NASA Ames •	HRC–2	0.61x0.41 Rectangular	2.79	>.8	30	2 Flexible 2 Solid	7 Jacks/Wall	
NASA Langley •	0.3–m TCT	0.33 Square	1.417	>1.1	120	2 Flexible 2 Solid	18 Jacks/Wall	Issues 1/2/3/4/5/7
N P Univ. •• Xian, China	Low Speed	0.256x0.15 Rectangular	1.3	0.12	0.50	2 Flexible 2 Solid	19 Jacks/Wall	Issues 2/5
ONERA/CERT •	T.2	0.37x0.39 Rectangular	1.32	>1.0	30	2 Flexible 2 Solid	16 Jacks/Wall	Issue 2
ONERA •	S5Ch	0.3 Square	?	1.2		1 Multiplate 3 Solid	Transverse Sliding Plates	
RPI ••	3x8	0.20x0.07 Rectangular	0.6	0.86		1 Flexible 3 Solid	6 Jacks	
RPI ••	3x15	0.39x0.07 Rectangular	?	0.8		2 Flexible 2 Solid	?? Jacks/Wall	
Southampton University •	SSWT	0.152x0.305 Rectangular	0.697	0.1	0.38	2 Flexible 2 Solid	15 Jacks/Wall	40 ° Swept Wing Panel
Southampton University •	TSWT	0.15 Square	1.12	>1.0	2.5	2 Flexible 2 Solid	19 Jacks/Wall	Issue 1/3
Sverdrup ••• Technology	AWAT	0.305x0.61 Rectangular	2.438	0.2		3 Multi–Flexible Slats 1 Solid	102 Jacks–Ceiling 51 Jacks/Sidewall	Issue 4
Tech. Univ. Berlin •	I/II	0.15 Square	0.99	>1.0	2	2 Flexible 2 Solid	13 Jacks/Wall	
Tech. Univ. Berlin •••	III	0.15x0.18 Octagonal	0.83	>1.0		8 Flexible	78 Jacks Total	Issue 6
Umberto Nobile ••	FWWT	0.2 Square	1.0	0.6	3.5	2 Flexible 2 Solid	18 Jacks/Wall	

•• – 2D Capability
••• – 3D Capability
• – 2D and 3D Capability
PCC – Plenum Chamber Compartments

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Note - The **Remarks** refer to issues of the **Adaptive Wall Newsletter** (published quarterly by the Experimental Techniques Branch, LaRC) in which we have published related articles.

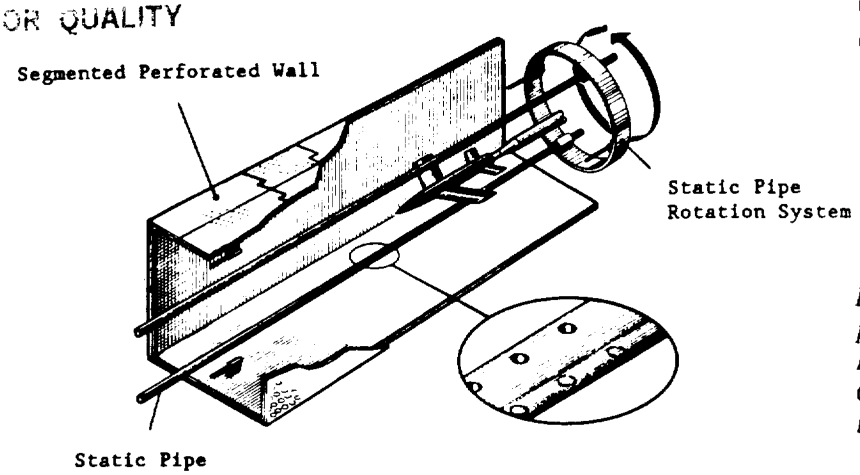

Fig. 4 (Left) - The variable porosity AWTS in the Arnold Engineering Development Center (AEDC) 1T transonic tunnel.

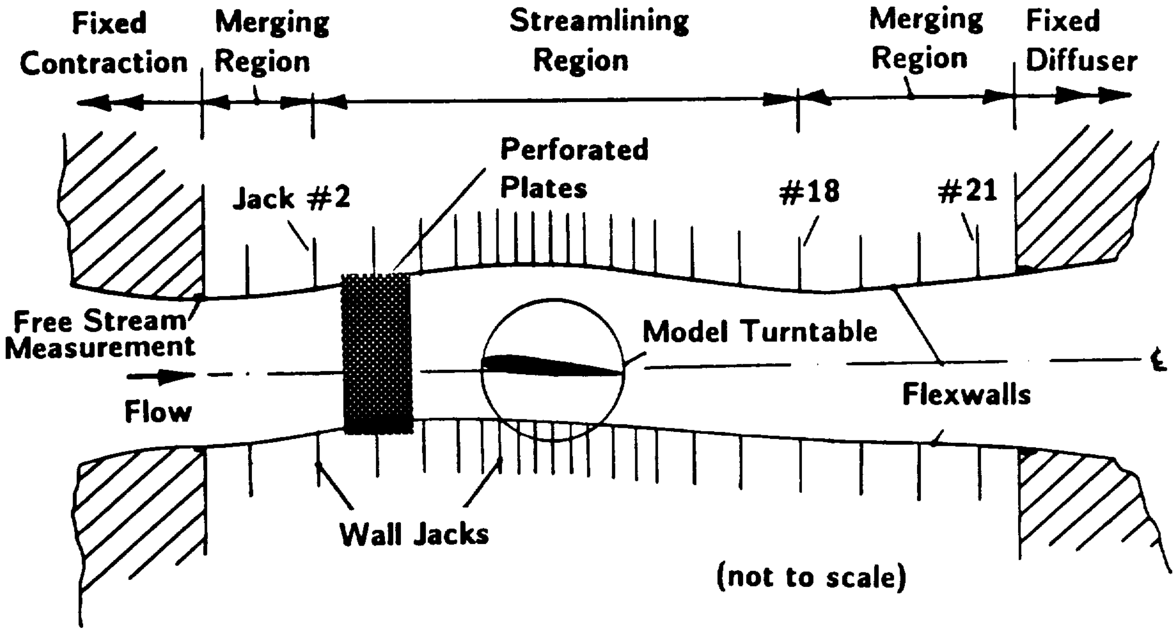

Fig. 5 - NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) flexible walled AWTS.

perforated walls as shown in Figure 4. In addition, researchers have made 3-D tests in 2-D AWTSs at NASA Langley[8] (see Figure 5), University of Southampton,[9] ONERA,[10] TU-Berlin,[6] and DFVLR. These 2-D AWTSs have two flexible walls supported between two rigid sidewalls with roughly square cross-sections. This is the preferred design for 2-D AWTSs.

Unfortunately, we find that experience with AWTSs in 3-D testing is limited. Nevertheless, there are strong indications that the simpler the AWTS the better the system. Simplicity reduces hardware complexity, gives better model access, and simplifies the assessment of residual wall interferences. These are major benefits and we see no major disadvantages, but we need more research to confirm this. The development of 3-D adaptive wall testing techniques will continue to emphasize a trade-off between the complexity of the boundary adjustments and residual wall interference corrections. The outcome of this trade-off will significantly affect the AWTS design.

The vast research experience reported on validation testing with AWTSs[11] indicates that flexible walls have more capability than variable porosity walls. Researchers have successfully operated flexible walled AWTSs with test section height to chord ratios as low as 1.0. Also, we have recorded model normal force coefficients up to 1.537 with the walls streamlined (see subsection 7.1.1). No variable porosity AWTS, past or present, at Calspan, AEDC, or NASA Ames can streamline at these conditions. In fact, the demonstrated 2-D capability of flexible walled AWTSs is considered by many to be adequate for the needs of production type testing.

The effectiveness of solid adaptive walls clearly makes flexible walled designs the preferred designs for transonic testing. We can summarize this effectiveness as follows:

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

Interestingly, of the 13 high speed AWTSs operational worldwide, only one AWTS does not have flexible walls (see Table 1). The claim that a variable porosity AWTS is simply a modified ventilated test section, is no longer relevant. We now know that substantial changes to a ventilated test section are necessary to make it adaptive.[7,12] It seems best to insert a new test section when upgrading any existing wind tunnel to adaptive wall status. This approach avoids the more difficult task of modifying an existing test section with inevitably too many compromises.

6. Operational Experience with AWTSs

We continue to direct operational experience with AWTSs towards the following goals:

1) Minimization of time attributed to wall streamlining.
2) Examination of the operating envelope and measurement tolerances.
3) Establishment of an operating system for production type testing.

The wall streamlining procedure for any type AWTS is necessarily iterative. The procedure involves an interaction between the tunnel hardware and the control software as shown in Figure 6. The hardware provides wall pressures and wall adjustments when requested by the control

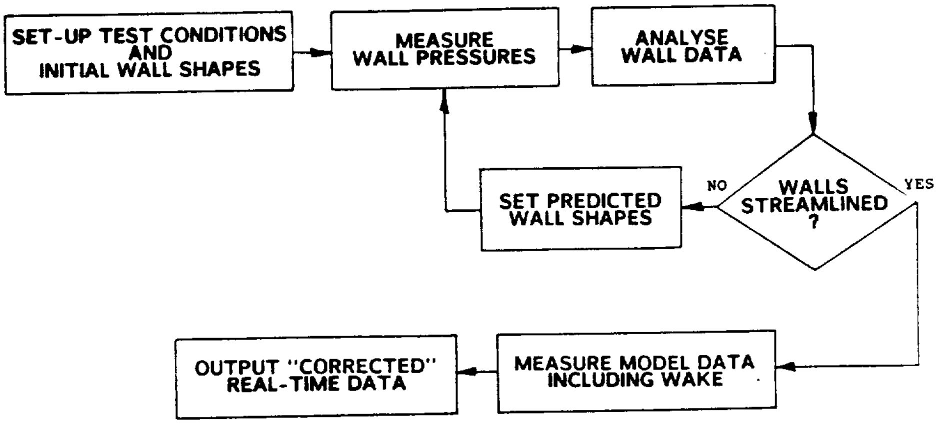

Fig. 6 - Flow diagram of the wall streamlining procedure.

software. The analyses of the wall data, within the control software, involves calculating the wall adjustments and an assessment of the wall streamlining quality. We use this quality to decide if the walls are streamlined. When the walls are streamlined, we acquire "corrected" model data.

Since 1975, researchers have made significant reductions to the time associated with the streamlining process, particularly with flexible walled AWTSs. A major part of this progress has been the development of rapid wall adjustment procedures for flexible walled AWTSs. (The term *rapid* refers to minimization of the number of necessary iterations in the streamlining process.) For 2-D testing, the linear method of Judd, Goodyer, and Wolf[13,14] (University of Southampton, UK) is now well established for reasons of speed, accuracy, simplicity (we can easily use the method on any mini-computer), and adaptability for general use with any flexible walled AWTS. For 3-D testing, the linear methods of Wedemeyer/Lamarche[15] (Von Karman Institute, Belgium/DFVLR) and Rebstock[16] (TU-Berlin/NASA) show promise in speed and accuracy. Nevertheless, we require more evaluation of these 3-D methods before we can regard them as well established. We know these linear methods are effective to where the flexible walls are just sonic.

Other time-saving features of modern AWTSs are computer controlled movement of the adaptive walls and automated acquisition of wall data. However, for the tunnel user to benefit from the full potential of these time-saving features, we require a good practical definition of the situation when the walls are streamlined. We call this definition a *free air streamlining criterion*. We optimize the streamlining process by adjusting the streamlining criterion to allow for tunnel measurement accuracies. For 2-D testing, AWTSs at ONERA/CERT and TU-Berlin use the condition of insignificant wall adjustments and model flow changes. We prefer the condition of residual wall interferences reduced below acceptable maxima used at the University of Southampton[17] and NASA Langley.[18] The acceptable maxima are: induced $\alpha < 0.015°$; induced camber $< 0.07°$; and induced velocity C_P error < 0.007. Unfortunately, we do not yet have sufficient testing experience to be able to define a streamlining criterion for 3-D testing.

We find that the nett result of these time-saving features is an acceptable time attributed to 2-D wall streamlining. The pacing item in the streamlining process is usually the speed of wall movement. The AWTS at ONERA/CERT has particularly fast wall movement capability and wall streamlining is performed in about ten seconds.[10]

After wall streamlining, we have an important operational advantage over conventional test sections, namely that the real-time data is "corrected." The advantage is demonstrated by comparing two sets of real-time CAST 10 aerofoil data from the 0.3-m TCT, as shown on Figure 7. One data set is from a deep slotted wall test section (h/c = 7.87) and the other set from a shallow AWTS (h/c = 1.83). There is considerable difference in the lift curve slope and the level of maximum lift. Of course, we can apply post-test corrections to the slotted wall data to minimize interference effects. However, we believe that the real-time AWTS data is close to the "interference free" result. (I hope you will agree with this observation after reading this paper.) So with an AWTS, a real-time investigation of specific aspects of an aerofoil's performance is now possible. This capability is a considerable bonus leading to more efficient use of tunnel run time.

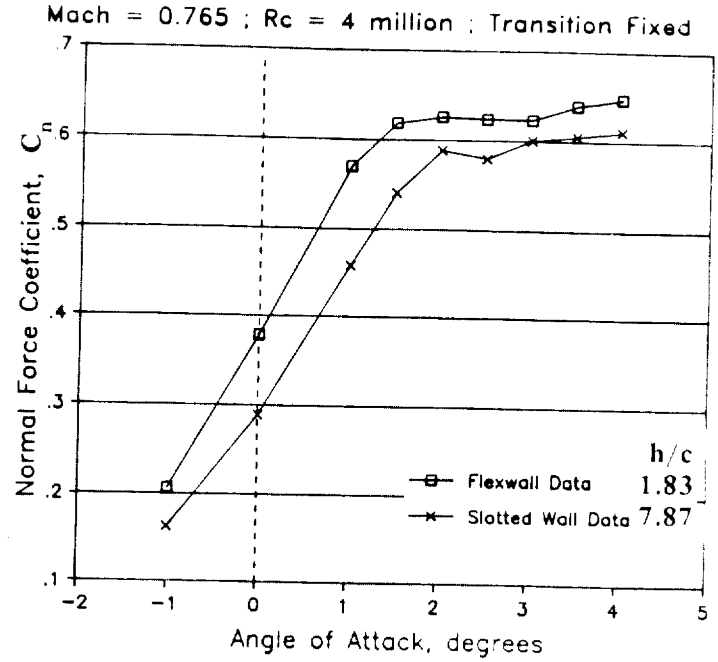

Fig. 7 - Comparison of real-time CAST 10 aerofoil lift.

The operating envelope of an AWTS relies on the design criterion applied to the AWTS itself. Sufficient design guidelines are reported to allow any new AWTS design to be good enough to eliminate all wall adjustment problems so far encountered.[8,17] (But, this idyllic situation has yet to be realized with any existing AWTS.) With good design, only software limitations will restrict the operating envelope. We can experience software limitations to free stream Mach number, because we use linearised theory in the wall adjustment procedure. Since sonic flow at the flexible walls invalidates the linearised theory, we must restrict the free stream Mach number depending on the blockage of the model in the test section. However, we can simply overcome this restriction in 2-D testing by using a more sophisticated high speed wall adjustment procedure derived from Judd's method. This high speed procedure can be use successfully up to Mach 0.95 (see sub-section 7.1.3).[19] Supersonic 2- and 3-D testing is also feasible using wave theory to predict the wall shapes (see sub-section 7.2.3).[20] However, the adaptive wall testing techniques require us to develop a proven residual interference assessment method for use at supersonic speeds.

We have examined the effects of measurement accuracy on AWTS operation, particularly for flexible wall designs.[8,17] With flexible walls, we can only measure the position of each wall at a finite number of points. The position of these measurement points, along each wall, is optimized for 2-D flexible walled AWTS designs (as shown in Figure 5). Notice how the wall jacks are more closely spaced in the vicinity of the model. Operationally, flexible walled AWTSs are tolerant to jacks being disconnected due to hardware failures[18], but restrictions to the operating envelope may apply in some situations. Interestingly, because the wall position accuracy requirements are proportional to (1/h), we can benefit from reduced accuracy requirements for a large AWTS.

The adaptive wall testing techniques are also tolerant to uncertainties in the wall pressures. This important feature is due to the adaptive walls being in the far field relative to the model. However, at high Reynolds numbers (when the wall boundary layers are thin) or with near sonic flow at the adaptive walls, this tolerance to measurement imperfections reduces. The uncertainties in the wall pressures arise from wall imperfections and the stability of the tunnel test conditions which is not easily quantified. However, we do know that if the model perturbations at the adaptive walls are small (as found in 3-D testing), the accuracy of the wall data needs to be better than when the model perturbations are large (as found in 2-D testing).

The establishment of an AWTS operating system for straightforward production .type testing is a prerequisite for general use of adaptive wall technology. If only experts can use this technology, then only a few specialist facilities will be able to benefit from the advantage of adaptive wall testing techniques. Research at NASA Langley, using the 0.3-m TCT,[8,18] involves the first attempts to develop a transparent operating system. This means, we are attempting to make the complexities of the AWTS invisible to the tunnel operators. We have developed a *user friendly* AWTS operating interface.[8] Unfortunately, this difficult task is hampered (in the case of the 0.3-m TCT) by a lack of flexibility in the adaptive walls and use of inappropriate computer systems. Nevertheless, we have established regions within the overall 2-D test envelopes for expert and non-expert users, as shown in Figure 8. These envelopes are closely

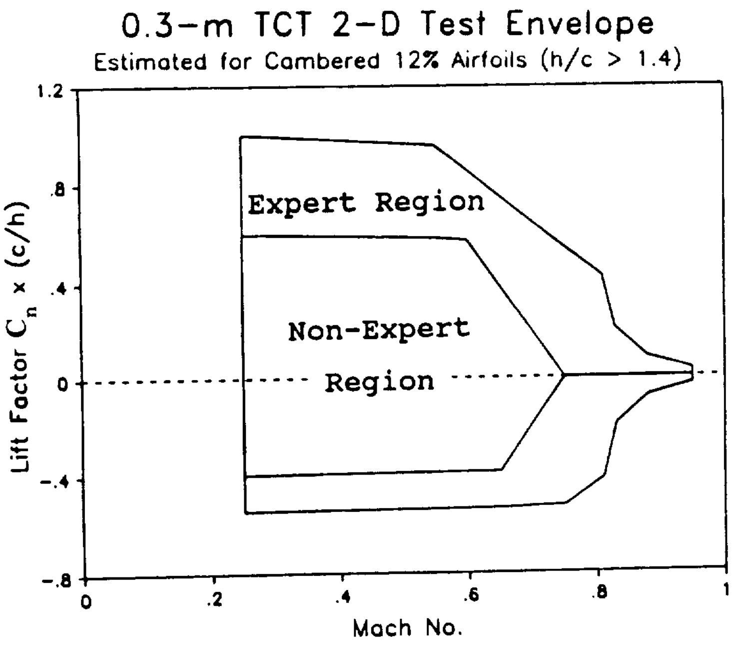

Fig. 8 - A model dependent test envelope for AWTS 2-D testing.

associated with the model size and performance. At present, the operating envelope for non-experts is generally restrictive. The operating envelope for experts restricts the testing of very large models. With hardware improvements,[8] we hope that the expert and non-expert envelopes will become almost the same and both operating envelopes will be expanded.

7. Testing Experience with AWTSs

There is a wealth of testing experience with AWTSs reported in the literature.[11] Validation testing forms a major part of this experience to determine data quality and limits to the operating envelope of AWTSs. In presenting some testing results, I highlight important observations to show what can be expected of an AWTS in terms of model data and wall streamlining. I discuss 2-D and 3-D testing separately. Data from various tunnels is presented and, where possible, I include references to allow more detailed study of the results than possible here. I have tried to present these data without prejudice. The data come exclusively from flexible walled test sections because this design of AWTS happens to pace the State of the Art.

7.1 Some 2-D Testing Results from AWTSs

7.1.1 Effects of Wall Streamlining in 2-D Testing

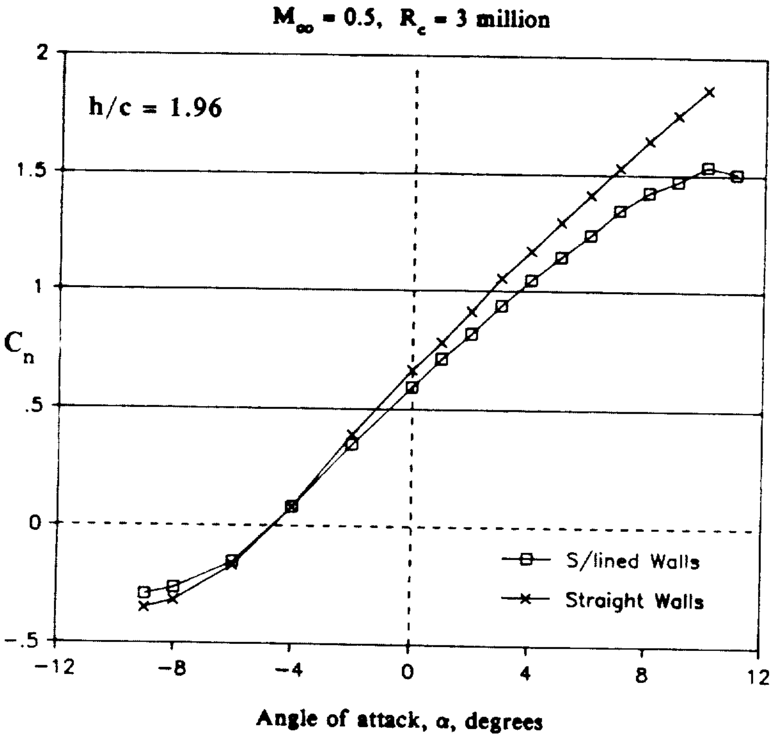

Fig. 9 - Effects of wall streamlining at subsonic speeds.

We can see the effects of adjusting the flexible walls of a 2-D AWTS on aerofoil lift in Figure 9. With the flexible walls straight (simulating a conventional closed tunnel), the aerofoil normal force coefficients, C_ns, are typical of data affected by large wall interferences. The streamlined wall data are essentially free of top and bottom wall interferences. So, the considerable differences between the straight wall and streamlined wall results are due to what can be called *classical lift interference* induced by the test section boundaries. At the zero lift angle (near -4.6°), notice the flexible wall shapes have no

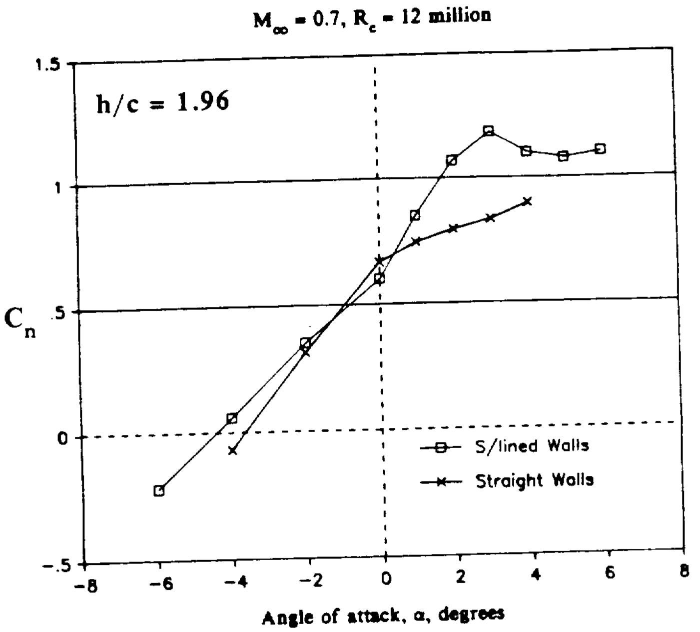

Fig. 10 - Effects of wall streamlining at transonic speeds.

influence on the model C_n. This shows the model blockage is small at zero lift. We took these data at a subsonic Mach number of 0.5. Notice the model experiences stall with the flexible wall streamlined. But, with the flexible walls straight, the model C_n shows no stall up to the structural load limit of the model.

These data are for an advanced cambered aerofoil tested in the NASA Langley 0.3-m TCT.[8] Notice the high C_n obtained during this test with the flexible walls streamlined. The maximum C_n of 1.537 is the highest ever achieved in any AWTS with the walls streamlined. The test section height to model chord ratio was a low 1.96 for this test.

At transonic speeds the effects of adjusting the flexible walls are significantly different from the subsonic case. We show this difference in Figure 10. The onset of compressibility is an important factor in this difference. Notice how the lift interference changes sign at an angle of attack of about 0.5°. This is because of the phenomena of test section choking caused by an increase in model blockage. As we increase angle of attack, so the model blockage increases due to the growth of shocks on the model surface.

If we increase the angle of attack high enough with straight walls, the flow channel above the model chokes causing significant wall interferences. We show this in Figure 11 with a schlieren picture from the Transonic Self-Streamlining Wind

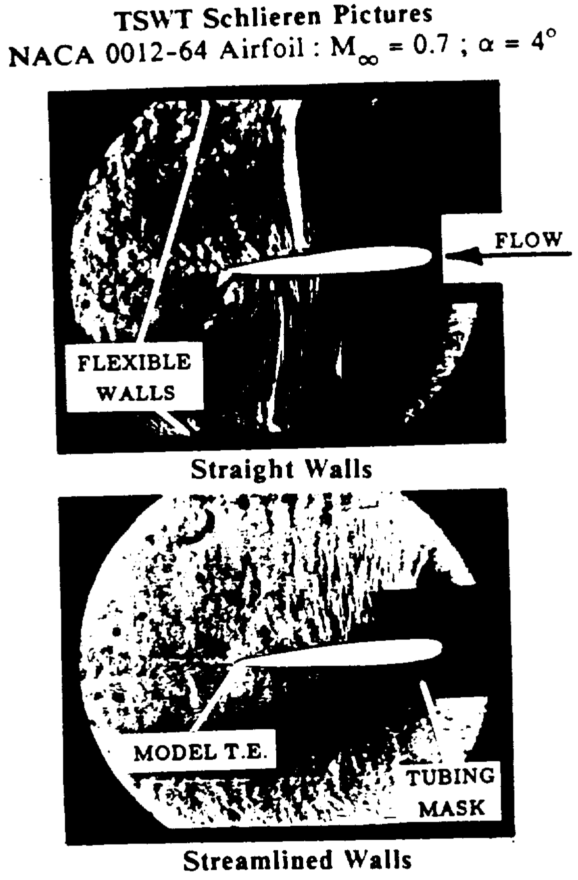

Fig. 11 - Model flow changes with wall adaptation.

Tunnel (TSWT) at the University of Southampton, UK.[17] By streamlining the flexible walls, we can remove this choking and simulate an interference free flow field around the model. Sometimes, as shown here, the model shock changes position and reduces in strength. This causes a reduction in lift as for the subsonic case. However, the data in Figure 10 show that C_n increases at, for example, an angle of attack of 4°. This sign change is due to the use of different aerofoils. (In the schlieren pictures the aerofoil is symmetrical; the lift data are from a cambered aerofoil.)

I highlight this point to show how unpredictable boundary interferences can be in transonic wind tunnel testing. This unpredictability is because of the existence of non-linear flow field patches in the test section. Of course, this is the reason why the prediction of accurate wall interference corrections is so very difficult at transonic speeds.

Notice in Figure 10 that the C_n data with straight and streamlined walls agree at two lifting angles of attack. While the values of C_n match, the detailed pressure distributions do not agree for these two angles of attack. Interestingly, the zero lift angles are not the same for the two data sets. This shows that the model blockage is not small with the walls straight. Indeed, at some higher Mach number the test section flow (with straight walls) will completely choke, preventing any increase in Mach number. However, as NPL found back in 1938, wall streamlining can remove test section choking and allow us to test at the higher Mach numbers we desire.[19]

7.1.2 2-D Validation Testing

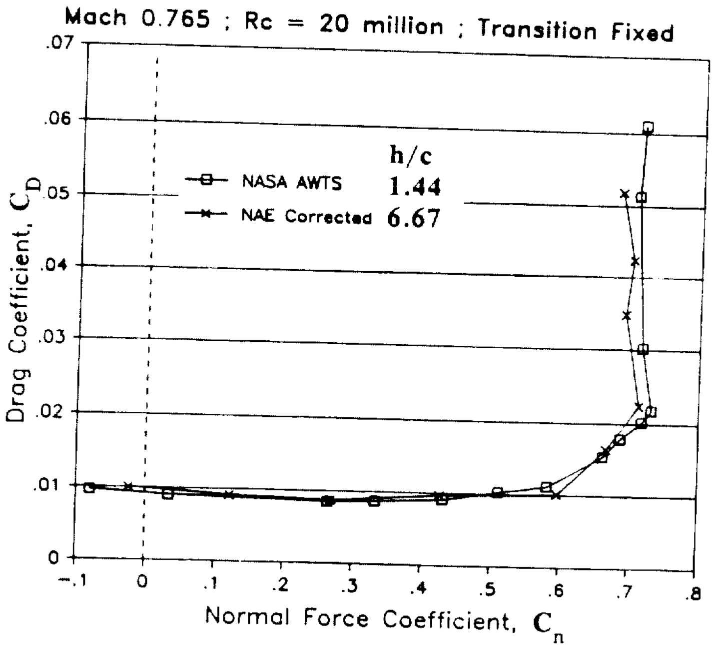

Fig. 12 - Comparison of CAST 10 aerofoil data from an AWTS with "interference free" results.

The claim that 2-D AWTS data are free of wall interferences requires some qualification. Researchers have made many validation tests on well known aerofoils to assess the quality of free air simulations in AWTSs. Many published data comparisons show AWTS data matching "interference free" data.[11] An example is given in Figure 12 for lift and drag data on a supercritical CAST 10 aerofoil at Mach 0.765 and a chord Reynolds number of 20 million.[18] The NAE, Canada, data were obtained in a deep ventilated test section (height/chord ratio is 6.67) with post test corrections applied. The NAE data is regarded as "interference free" data. The NASA data from a relatively small AWTS (height/chord ratio is 1.44) with no post test corrections, compares very well.

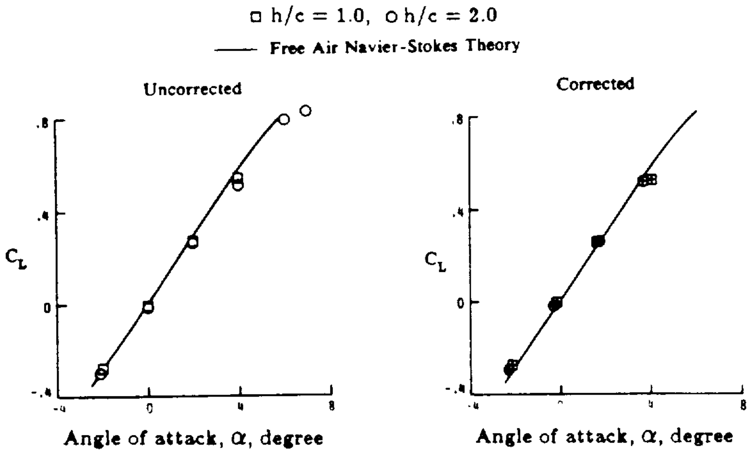

Fig. 13 - Comparison of NACA 0012 aerofoil lift for two model chords at Mach 0.6, with and without corrections according to the WIAC procedure.

An alternative validation approach is to make an independent assessment of the residual wall interferences (a real time assessment is made to determine if the walls are streamlined). We used this approach with 0.3-m TCT data using a NASA Langley Wall Interference Assessment/Correction (WIAC) procedure.[21] Figure 13 shows a plot of model lift versus angle of attack which is an extract from this work. This plot shows how well AWTS data for two different size NACA 0012 aerofoils compare to a theoretical prediction of the free air result, before and after correction for residual interferences. The corrections to the AWTS data are small and appear unnecessary for this case at Mach 0.6.

Also of significance here is the agreement between AWTS data using different size models, one has a chord twice the other. The larger model has a test section height to chord ratio of only 1.0. The comparison of model pressure distributions for the different chord aerofoils is equally good.[8] These and other observations that the AWTS data are independent of model size further support the claim that 2-D AWTS data are free of wall interferences.

7.1.3 Testing with Sonic Flow at the Test Section Walls

Figure 14 shows wall streamlining for a 2-D aerofoil in a fully choked test section is possible. The montage of real and imaginary flow fields comprises a schlieren picture of the real flow around the aerofoil inside the test section and outlines of the supercritical patches in the imaginary flow field outside the test section. Notice that in the test section flow both aerofoil shocks reach the flexible walls. The montage shows how well the real and imaginary flow fields match at the flexible wall interfaces to satisfy the free air streamlining criterion. This good match, particularly about the shock locations and sonic points, is an indication of good wall streamlining.

Researchers made this demonstration in TSWT at the University of Southampton during 1986.[19] The test section height to chord ratio for this test is 1.5. They used a modern Transonic Small Perturbation (TSP) code to calculate the imaginary flows. They found an uncomplicated

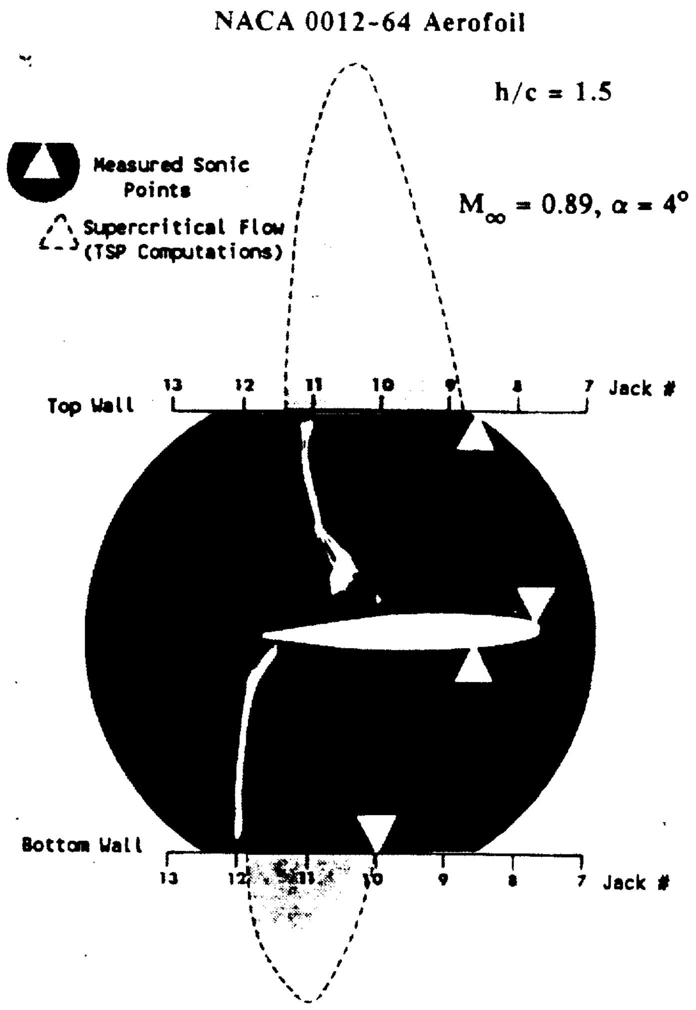

Fig. 14 - Montage of real and imaginary flow fields with sonic flow on the AWTS flexible walls.

procedure for wall streamlining. The wall adjustment procedure used here is a more sophisticated version of Judd's method, previously mentioned, which includes TSP and wall boundary layer calculations.[19]

An important observation from these tests is the non-existence of shock reflections from the flexible walls. For some time skeptics considered the potential of shock reflections as a serious limit to free stream Mach number in AWTSs. We have now demonstrated that this is not the case. Until the oblique bow shock appears ahead of the model near Mach 1.0, there cannot be any reflection problems. Even then, with an oblique shock present, we can at least direct any reflections away from the model, by suitable wall curvature. This procedure is illustrated later in an example of 3-D testing at supersonic speeds.[20]

7.1.4 Effect of Compressibility on Streamlined Wall Contours in 2-D Testing

So far, I have only considered the aerofoil data. It is also important to look at the wall contours required for streamlining. This is because we determine the wall adaptation contours without reference to the model. These wall contours should follow expected aerodynamic trends if the wall adjustment procedure is working properly.

A clear example of aerodynamic trends is the effect of compressibility on the wall contours. The plot in Figure 15 shows TSWT wall contours for two Mach numbers, one subsonic and one transonic.[17] The model, a NACA 0012-64 aerofoil, was at a fixed angle of attack of about 4°. The subsonic contours show lift induced upwash ahead of the model and a small model wake shown by the small movement apart of the walls downstream of the model. The transonic contours

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show minimal upwash ahead of the model because the aerofoil has lost lift due to shock stall. In the region of the model, the walls move apart an amount equal to the aerofoil thickness. Downstream of the model streams a large wake, shown by the large movement apart of the flexible walls. This large wake is due to shock induced flow separations on the model. The exaggerated wall deflection scale helps to amplify the effects of compressibility on the wall contours. We expected these contour changes. This finding adds to our confidence in the wall adjustment procedure of Judd et al.[14]

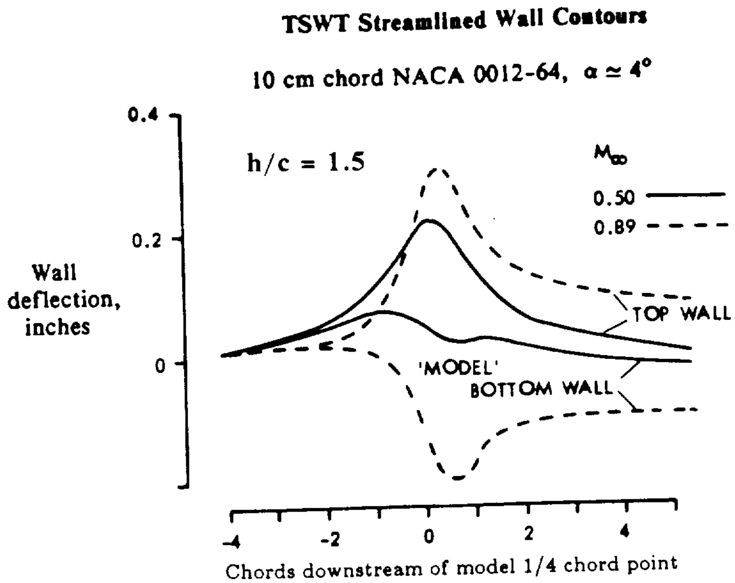


Fig. 15 - Streamlined wall shapes at subsonic and transonic Mach numbers.

In addition, these wall contours demonstrate the poor performance of the symmetrical NACA 0012-64 aerofoil at transonic speeds. This poor performance requires more severe flexible wall curvature for streamlining which can limit the AWTS operating envelope. Better performing supercritical cambered aerofoils demand less wall curvature at the same test conditions. So, the flexibility requirements of the adaptive walls are model dependent. I raise this point because it does mean that the types of models to be tested must be considered in the AWTS design process.

7.1.5 Effect of Model Lift on Flexible Wall Contours in 2-D Testing

The effect of model lift on streamlined wall contours is shown in Figure 16. In this plot, the model C_n is increased from near zero to 1.537. As C_n increases, we can see an increase in the the wall deflections of the ceiling (top wall) required for streamlining. This increasing deflection is due to increasing upwash ahead of the model and a growing wake associated with drag rise.

I again emphasize that we determine these contours experimentally without reference to the model. We show in Figure 16, data for a subsonic case to avoid complication of the wall contours associated with the onset of compressibility, shown previously. Interestingly, each streamlined wall contour fits into the family of shapes as one would expect.

This family of contours shows the usefulness of using streamlined wall contours for a lower angle of attack as initial contours for a higher angle of attack. The closer the initial wall contours

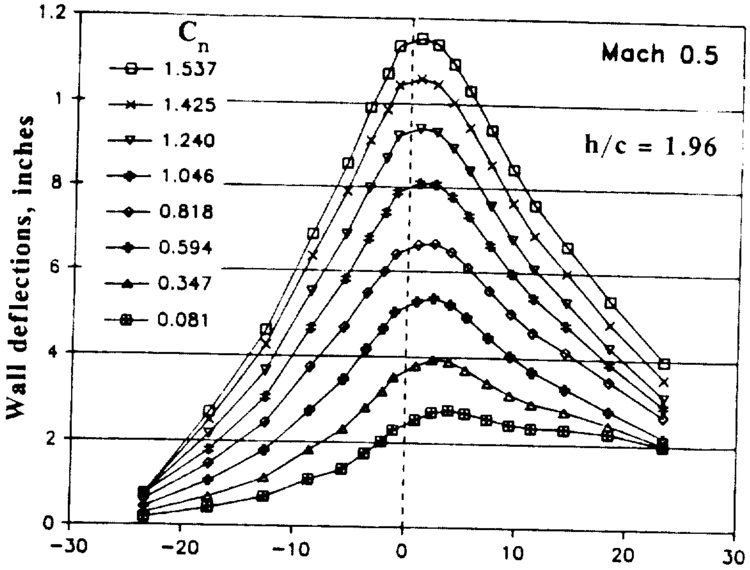


Fig. 16 - Family of top wall streamline shapes in the presence of increasing model lift.

are to the streamline shape, the quicker the streamlining procedure. This is because of reduced physical movement and reduced iterations within the streamlining procedure. In an angle of attack sweep, the change in angle of attack between successive data points is usually less than 2°. The α interval between the wall contours shown here is 2° (see Figure 9). In this case, the choice of the streamlined contours for the last data point as the initial contours for the next data point is ideal.

Unfortunately, the effects of compressibility and operational requirements complicate this selection of initial contours. At transonic speeds, it is better to select streamline contours for a lower Mach number at the same angle of attack. We can achieve operational flexibility by building a library of wall contours and, when necessary, calculating theoretical wall contours for a required set of test conditions.[8,22] In this manner, optimal initial wall shapes are available for any sequence of test conditions that may be required by the test engineer.

7.1.6 Overview of 2-D Testing in AWTSs

We can see that real-time 2-D data from AWTSs is essentially free of top and bottom wall interferences. We have found no problems with testing an aerofoil through stall (no wall shape induced model hysteresis present). Data repeatability from day to day is excellent. However, instrument calibration schedules may significantly affect long term repeatability.

We have observed that the model wake in an AWTS shows minimal spanwise variation.[18] We speculate that the secondary flows at the aerofoil-sidewall junction are intrinsically minimized by use of large models relative to the test section size. There are strong indications that the flow in an AWTS is an excellent simulation of a 2-D free air flow field. We appreciate that this desirable situation may not always exist for every type of model and all test conditions. So, sidewall boundary layer control systems have been successfully integrated with AWTSs for subsequent use.[18]

Aerodynamic limits to free stream Mach number are not fundamental but due to particular hardware or software restrictions. Researchers have made 2-D tests close to Mach 1.0[19] and some limited tests at Mach 1.2.[23] In the supersonic tests, researchers used local wall curvature to remove shock reflections on to the model. However, the usefulness of 2-D testing in the supersonic regime may be only academic, providing experience leading to production supersonic 3-D testing.

The time attributed to wall streamlining is less than 2 minutes for a good operating system. Rapid wall adjustment procedures are well established. ONERA has achieved very fast wall movements.[10] Up to 50 data points in a 6-hour test shift is the State of the Art. 2-D testing experience indicates that transparent use of AWTSs for production type testing is now possible.

The vast testing experience with AWTS designs using two flexible walls, clearly indicates that solid adaptive walls are the best design. Researchers have successfully used only flexible walled AWTSs in the realms of full scale Reynolds numbers and high lift.[18] Unfortunately, hardware limitations in current AWTSs restrict the test envelope for large aerofoils (chords larger than 75 percent of the test section height). However, we now have adequate AWTS design guidelines to remove any hardware limitations by careful design or modification.

7.2 Some 3-D Testing Results from AWTSs

7.2.1 Effects of Wall Streamlining in 3-D Validation Testing

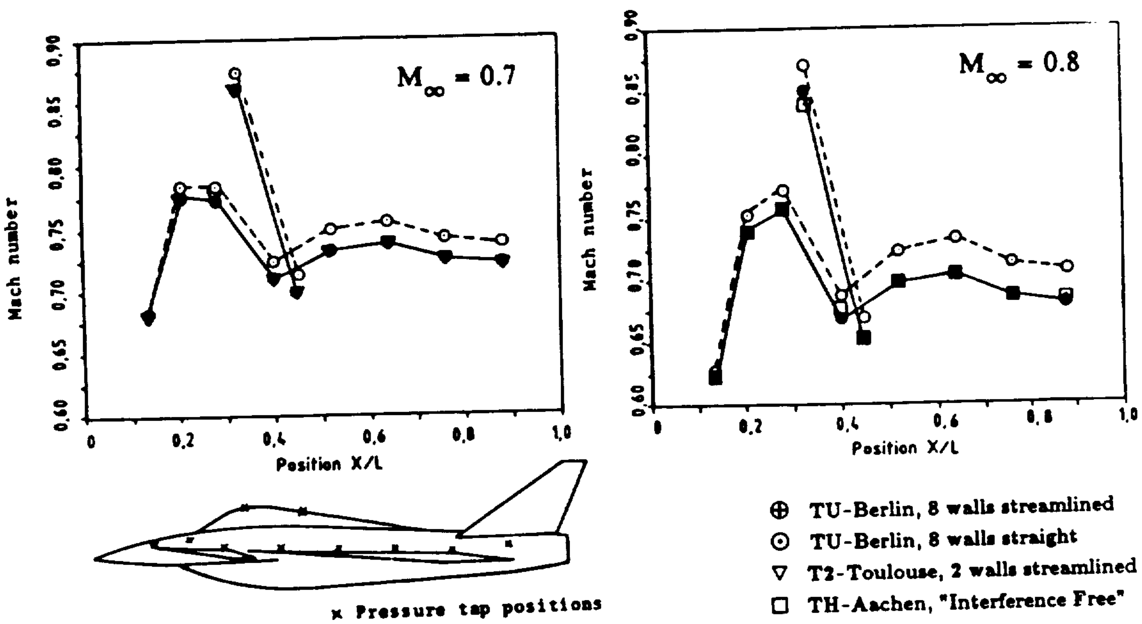


Fig. 17 - Mach number distributions on a 3-D canard model; $\alpha = 2^\circ$.

Figure 17 shows pressure data measured on a canard model of low aspect ratio (see Figure 18). Researchers have tested this model in several tunnels at Mach 0.7 and 0.8. Stagnation conditions were ambient. There are two data sets from the TU-Berlin octagonal AWTS.[6] One set is with the eight flexible walls streamlined and the other set is with the eight walls set straight. The two sets show the levels of interference removed by wall streamlining. Also shown is a data set from the ONERA/CERT T2 tunnel which has a larger AWTS with two flexible walls.[10] For this data set, researchers streamlined the two flexible walls according to a 3-D wall adjustment procedure of Wedemeyer and Lamarche.[15] We show the data from TH-Aachen as "interference free" data, since the model was very small in this tunnel. The comparison between the streamlined wall data and the "interference free" data is excellent.

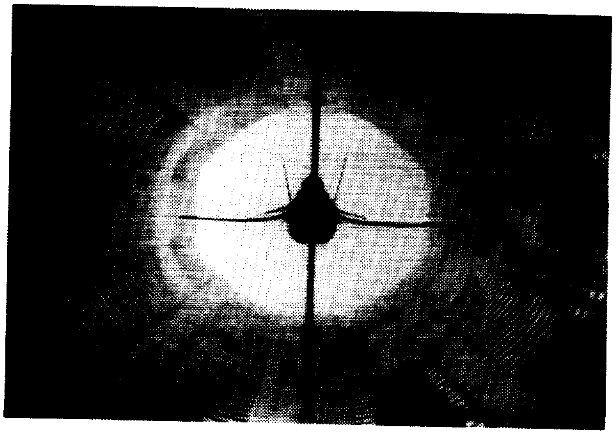


Fig. 18 - 3-D Canard model mounted in the TU-Berlin octagonal AWTS.

Figure 19 shows a comparison of lift and drag results for the same canard model. We compare data sets from the octagonal AWTS and the T2 AWTS with streamlined walls, together with reference data from TH-Aachen.

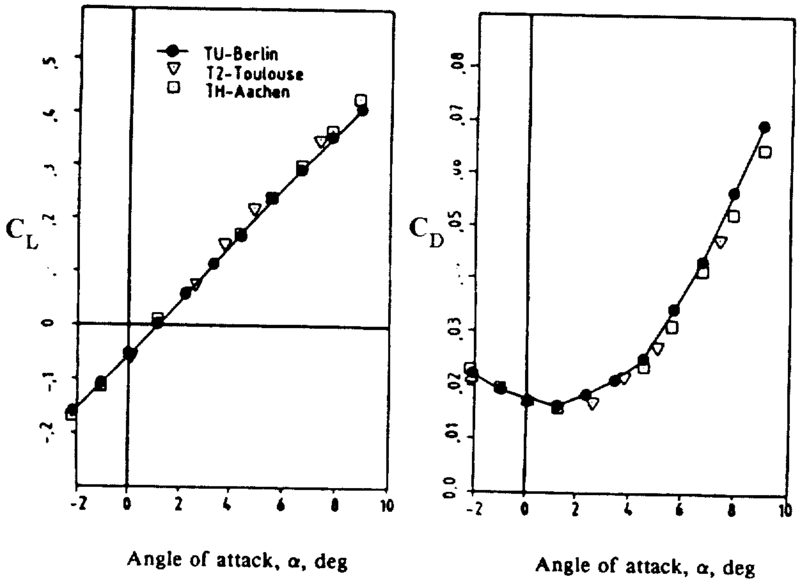


Fig. 19 - Comparison of force data on a canard model at Mach 0.7 from three different wind tunnels.

The comparison of lift coefficient is reasonable. The T2 lift data agrees slightly better with the reference data at the higher angles of attack. We find a similar comparison with the drag data. Again the T2 data agree slightly better with the reference data at the higher angles of attack. We can perhaps explain this weak tendency for the TU-Berlin data to differ at high α as a blockage effect. The nominal blockage of the canard model is 1.3 percent in the octagonal AWTS (the largest reported blockage in a 3-D AWTS test with a non-axisymmetric model) and only 0.18 percent in the T2 AWTS.

Nevertheless, the data differences are small and the data from the two AWTSs show minimal wall interferences. An interesting observation since neither AWTS is able to provide perfect control of its test section boundaries in three-dimensions. Model size and type are important factors in this finding, since real-time 3-D AWTS data should, in general, require some correction for inevitable residual wall interferences. Alas, researchers have so far avoided the situation of significant residual wall interferences in the model data, after wall streamlining.

7.2.2 Flexible Wall Contours for 3-D Tests

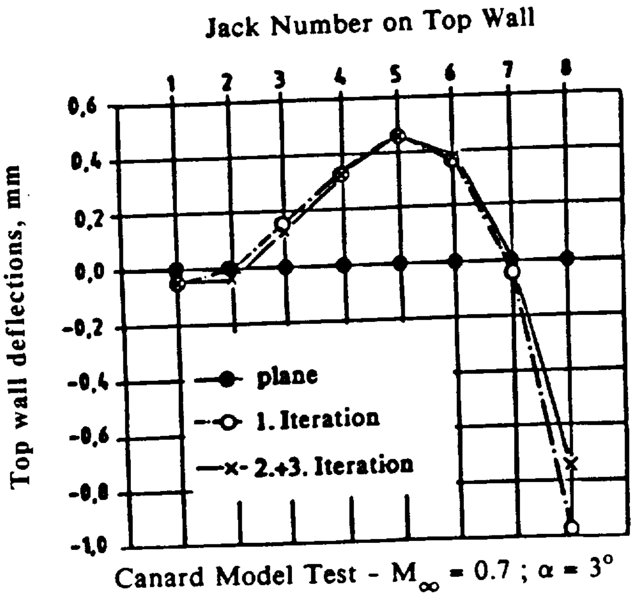


Fig. 20 - Convergence of the top wall contour during a typical 3-D test in the TU-Berlin octagonal AWTS.

The flexible walls of the TU-Berlin octagonal AWTS[6] are usually streamlined after two iterations starting from straight. We depict an example of the required wall shapes in Figure 20 for the top wall only. Notice the large wall deflections necessary downstream of the canard model. These deflections are necessary to accommodate the downwash generated by this high lift configuration.

Interestingly, researchers obtained similar streamlined wall shapes in the 0.3-m TCT AWTS with just two flexible walls, as shown in Figure 21. They obtained these wall contours during tests of a lifting half model mounted on one sidewall of the AWTS.[16] The free stream Mach number was 0.7. The aerodynamically straight wall contours generate a constant Mach number distribution along the empty test section at Mach 0.7. These contours were used as initial contours in the wall streamlining. The streamlined wall contours were found using the 3-D wall adjustment procedure of Rebstock[16] in just one iteration.

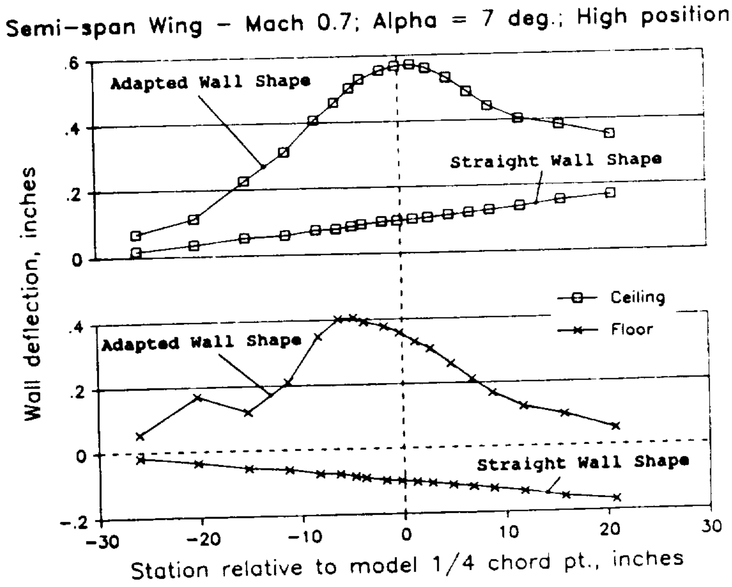
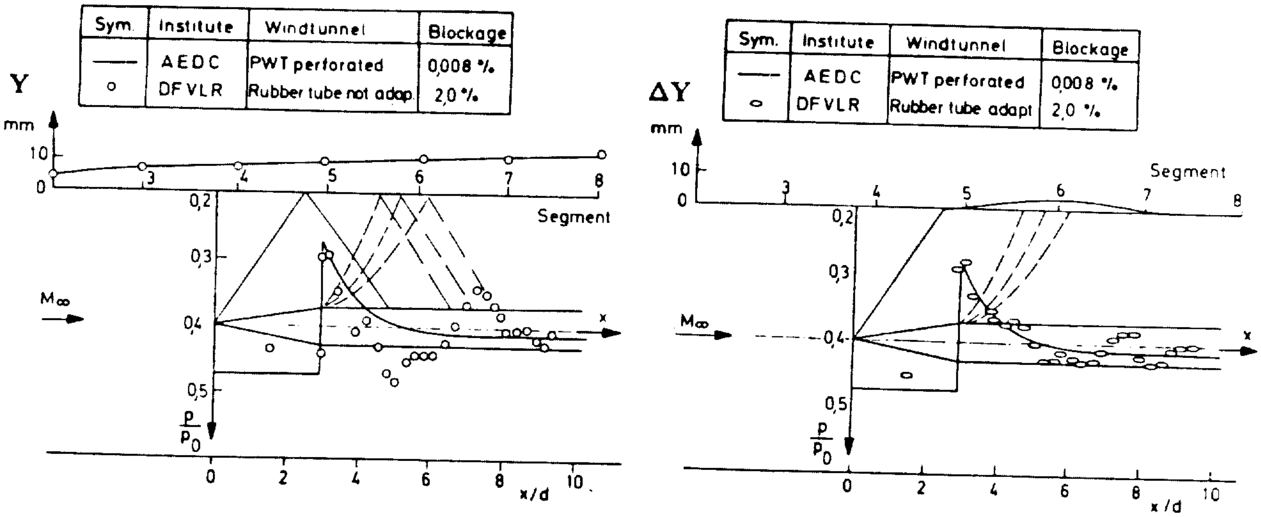


Fig. 21 - Typical wall contours found in 3-D tests using AWTSs with only two flexible walls.

From a designer's point of view, the general wall shapes required for streamlining in 3-D tests can pose some problems. Unfortunately, the downstream movements of the flexible walls tend to be large compared with movements encountered in 2-D testing. This movement requirement will make necessary a more complicated fairing arrangement between the downstream end of the test section and the rigid tunnel circuit, if we are not to restrict the test envelope or model size. Alternatively, the centerline of the test section can be rotated in the wall adaptation procedure to produce an angle of attack correction and generate more acceptable wall shapes for streamlining. A technique included in the Rebstock wall adjustment procedure.[16]

7.2.3 Supersonic 3-D Tests in AWTSs

Figure 22 shows pressure distributions on a cone-cylinder at Mach 1.2. DFVLR Göttingen made these tests in their rubber tube DAM AWTS.[5] We show two pressure distributions, one before wall adaptation and one after. This adaptation involved the calculation of adjustments to the rubber tube at one streamwise location to absorb expansion and compression waves.



C_p **distribution before adaptation**

C_p **distribution after adaptation**
Wall displacement, ΔY = 3.5 mm at 6th segment

Fig. 22 - 3-D supersonic test in the DFVLR DAM rubber tube AWTS.

Shown with the DFVLR data is reference data from the AEDC PWT tunnel with a very small model. Hence, we can consider this AEDC data as "interference free." With the rubber tube straight, there is a reflection of the model bow shock onto the model at x/d = 5.0. We see this interference as a local pressure rise on the model, which wall adaptation significantly reduces.

The researchers at DFVLR did not design their AWTS for supersonic testing. Therefore, finer wall adjustments would only be possible if the wall jacks were closer together. However, a remarkable reduction of wall interference is possible with coarse wall adaptation. This is due to the smearing effect of the wall boundary layer on the shock location. There would seem to be no fundamental limit to the use of impervious flexible walls at supersonic speeds.

With only two flexible walls in the 0.3-m TCT, we have achieved supersonic Mach numbers throughout the model region of the test section with a simple convergent/divergent nozzle ahead of a sidewall mounted wing. Mach number control in the test section was relatively straightforward based on one-dimensional isentropic flow considerations.

7.2.4 Overview of 3-D Testing in AWTSs

Limited validation tests[11] support the claim that wall interferences are minimized in 3-D AWTSs. However, the wall interferences present before any wall streamlining tend to be already small. Consequently, we do not know how effective the 3-D adaptive wall testing techniques will be when severe wall interferences occur.

This situation is due to the low blockage of the 3-D models so far tested in AWTSs. We can increase the model disturbances in the test section by using larger models or testing only at high speeds. Unfortunately, the roughly square cross-section of current AWTSs restricts the size of non-axisymmetric lifting models. Researchers have been forced to use low aspect ratio models to increase the model blockage above the normally accepted value of 0.5 percent. (Wind tunnel users usually limit the model span to about 65 percent of the test section width.) Consequently, there appears a need for new type 3-D AWTSs with a rectangular cross-section, where the width is greater than the height. This is a notion that has received support from theoretical work by Wedemeyer.[24] However, further research is necessary to determine just how large a model blockage we can successfully test in a 3-D AWTS.

We have not found any fundamental limits to Mach number when using AWTSs in 3-D testing. Preliminary tests at low supersonic speeds show we can bend the AWTS's flexible walls to remove oblique shock reflections onto the model. What we do lack in supersonic testing, is a clear indication of the data quality available after wall streamlining and also a proven wall adjustment procedure. This is another area requiring research.

The wall adjustment procedures for 3-D testing are still in a development stage. We now have available the fast and large capacity mini-computers necessary for real-time 3-D flow computations. But, we are unable to investigate the amount and type of wall interferences that can be successfully "corrected" by 3-D adaptive wall testing techniques. Other important questions about the 3-D testing technique remain unanswered. How many wall pressure measurements are necessary to adequately assess the very important residual wall interferences? Also, where on different configuration models is it best to minimize the wall interferences so we can apply residual corrections with confidence? We need further research to resolve these questions and allow us to optimize the 3-D wall adjustment procedures.

The simplest 3-D AWTS design, with just two flexible walls, seems to provide data of similar quality to that found in more complex AWTS designs. Consequently, this relatively simple design has gained favour amongst 3-D AWTS users. Hardware limitations restrict the test envelope (in particular model lift) for 3-D testing in AWTSs. However, these hardware limitations arise from inappropriate AWTS design criteria. There is now sufficient design experience to minimize any hardware limitations to the AWTS operating envelope.

Unfortunately, we see that experience with 3-D AWTS testing still trails behind 2-D work. I speculate that the availability of computers to carry out real-time 3-D flow computations may be a significant factor in the slow development of 3-D AWTSs. In addition, considerable time and effort has been spent in developing a wide range of complex 3-D AWTS designs, when it now appears the simpler 2-D design may well be adequate. (In hindsight, this effort appears unnecessary but the contribution to overall knowledge is nevertheless important.) At present, no one (except maybe ONERA) uses an AWTS in production type 3-D testing. The validation tests made over the years have not adequately defined the operating envelope for 3-D AWTSs. We are left with many questions about the benefits and limitations of 3-D testing in AWTSs.

8. The Future of AWTSs?

The development of AWTSs for 2-D testing has reached an important stage. Routine AWTS operation for production type 2-D testing is possible with suitable control system design. Use of AWTSs in cryogenic wind tunnels is not a problem. We can test large models successfully to obtain significant increases in chord Reynolds number. We can also benefit from improved flow quality and reduced tunnel drive power requirements due to the smooth walls of an AWTS. The adaptive wall technology available is mature enough to make routine 2-D testing a reality. Any limitations to 2-D testing in current AWTSs are due to lack of experience in the design phase. Computers have removed the impractical aspect of AWTS operation so the advantages of AWTSs are available to all wind tunnel users.

The vast 2-D testing experience is an important stepping stone to 3-D testing. Several research groups around the world are pursuing the development of 3-D adaptive wall testing techniques. Researchers need to find the best techniques to achieve specific test objectives and in doing so demonstrate <u>all</u> the AWTS advantages. I speculate that only after these actions will there be any hope of removing the apparent unwillingness of the wind tunnel community to accept adaptive wall technologies. (This unwillingness is presumably linked to a phobia about the increased test section complexity associated with an AWTS.) The importance of adaptive wall technology to transonic wind tunnel testing is a fact. To achieve perfection, we must make full use of all advanced technologies available to us.

9. Conclusions

1. Adaptive wall testing techniques, particularly those which utilize flexible walls, offer considerable advantages over conventional techniques in transonic testing.

2. Adaptive wall technology allows better data quality to be achieved in transonic testing.

3. Computer advances have removed any impractical aspects of adaptive wall technology.

4. Non-expert use of AWTSs for routine testing has been demonstrated with suitable system design.

5. We can now design an AWTS so there are no hardware restrictions on the operating envelope.

6. In 2-D testing, adaptive wall testing techniques are well proven and are already in use for production type transonic testing in cryogenic wind tunnels.

7. Use of AWTSs in 3-D testing has significant potential which has yet to be demonstrated.

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16. Abstract

This paper contains a review of modern experimental techniques to improve free air simulations in transonic wind tunnels by use of adaptive wall technology. The review considers the significant advantages of adaptive wall testing techniques with respect to wall interferences, Reynolds number, tunnel drive power, and flow quality. The application of these testing techniques relies on making the test section boundaries adjustable and using a rapid wall adjustment procedure. An historical overview shows how the disjointed development of these testing techniques, since 1938, is closely linked to available computer support. An overview of Adaptive Wall Test Section (AWTS) designs shows a preference for use of relatively simple designs with solid adaptive walls in 2- and 3-D testing. Operational aspects of AWTSs are discussed with regard to production type operation where adaptive wall adjustments need to be quick. Both 2- and 3-D data are presented to illustrate the quality of AWTS data over the transonic speed range. Adaptive wall technology is available for general use in 2-D testing, even in cryogenic wind tunnels. In 3-D testing, more refinement of the adaptive wall testing techniques is required before more widespread use can be envisaged.

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