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STATUS OF ADAPTIVE WALL TECHNOLOGY FOR MINIMIZATION OF WIND TUNNEL BOUNDARY INTERFERENCES

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Abstract

This paper reviews the status of adaptive wall technology to improve wind tunnel simulations. This technology relies on making the test section boundaries adjustable, with a tunnel/computer system to control the boundary shapes. This paper briefly considers the significant benefits of adaptive wall testing techniques. A brief historical overview covers the disjointed development of these testing techniques from 1938 to present. Currently operational Adaptive Wall Test Sections (AWTSs) are detailed. This review shows a preference for the simplest AWTS design with 2 solid flexible walls. A review of research experience with AWTSs shows the many advances in recent times. We find that quick wall adjustment procedures are available. Requirements for operating AWTSs on a production basis are discussed. Adaptive wall technology is mature enough for general use in 2-D testing, even in cryogenic wind tunnels. In 3-D testing, this technology is not so advanced because of low priority development and misconceptions.

Symbols

c	-	Chord
Cn	-	Normal force coefficient
h	-	Test section height
U_∞	-	Free stream velocity
Δu	-	Increment of local streamwise velocity
Δw	-	Increment of local upwash velocity

1. Introduction

The means to improve and gain more efficiency from our flight vehicles relies on better and better simulations of the "real" flow in our wind tunnel experiments. It is for this reason that improvements to wind tunnel data remain the subject of considerable research effort. Unfortunately, today's wind tunnel data still suffers from significant wall interference effects, particularly at transonic speeds. This is despite considerable efforts to remove this simulation problem over the last 44 years. Traditionally, the wind tunnel community uses 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 corrections, of varying sophistication, are applied to the model data in an effort to remove wall interferences. Usually, all three techniques are used together in transonic testing. Alas, these techniques still fail to achieve the high levels of accuracy we must now demand from wind tunnel simulations. In addition, these old techniques have led to expensive compromises for test section/model size.

A solution to this dilemma has existed, in a conceptual form, for about 52 years. It involves using testing techniques which minimize wall interferences at the very source of these disturbances. These techniques adapt the test section boundaries to streamline shapes so the test section walls become nearly invisible to the model. We know this concept as the **Principle of Wall Streamlining** which was first used in 1938 as a means of relieving transonic blockage.[1]

This paper briefly reviews the development of adaptive wall testing techniques as a background to the current status. We detail operational transonic AWTSs which are currently used for both conventional and turbomachinery research. This paper reviews 2- and 3-D research to illustrate the state of the art in adaptive wall testing techniques. Finally, we consider the operational aspects of AWTSs, since the practicalities of adaptive walls play a critical factor in the use of this technology. In conclusion, an assessment of the accumulated adaptive wall experience is presented and possible directions for future developments are indicated.

2. Adaptive Wall Benefits

Although the basic advantages of adaptive wall testing techniques have been reported many times, a brief overview is appropriate. Adaptive walls offer several important advantages other than the major benefit of minimizing wall interferences. With wall interferences minimized, we are free to increase the size of the model for a given test section. We can double the test Reynolds number and have a larger model to work with. Alternatively, we can shrink the test section and reduce the tunnel size and operating costs. Interestingly, the task of magnetically suspending models (to remove support interferences) becomes simpler in an AWTS because the supporting coils can be positioned closer to the model.

With solid adaptive walls (called flexible walls), the test section boundaries are simple and smooth compared to the complex boundaries with ventilated walls. This smoothness minimizes disturbances to the tunnel free stream significantly improving flow quality. (An advantage that is becoming more important in transonic boundary layer transition research.) In addition, smooth walls reduce the tunnel drive power required for a given test condition, with the model and test section size fixed. The elimination of the plenum volume, when a closed AWTS is used for transonic testing, reduces settling times and minimizes flow resonance, which is particularly important for blowdown tunnels.

Adaptive walls can provide the aerodynamicist with real-time "corrected" data, even in the transonic regime. This fact presents another significant advantage to the wind tunnel user. Since, the final results are know real-time, test programmes can be much more efficient. Use of adaptive walls should significantly reduce the number of data points and tunnel entries necessary to achieve the test objectives.

It should be noted that the simulation of free-air conditions is one of 6 flow field simulations[2] that adaptive wall technology can produce. It is possible to use multiple simulations with the same model and AWTS. This can and has been a useful advantage for CFD validation work and tunnel versatility.

3. Historical Overview of Adaptive Wall Research

The adaptive wall testing techniques we know today are a rediscovery of the first solution to severe transonic wall interferences (i.e. choking). The National Physical Laboratory (NPL), UK, built the first adaptive wall test section in 1938, under the direction of Dr. H. J. Gough.[1] Their pioneering research proved that streamlining the flexible walls of an AWTS was the first viable technique for achieving high speed (transonic) flows in a wind tunnel. They opted for minimum mechanical complexity in their AWTS and used only two flexible walls. The absence of computers made wall streamlining a slow and labour intensive process. Sir G. I. Taylor developed the first wall adjustment procedure.[3] NPL successfully used flexible walled AWTSs up until the early 1950s, generating a vast amount of 2- and 3-D transonic data.[4]

The arrival of ventilated test sections at NACA Langley in 1946, provided a "simpler" approach to high speed testing. The adjustments to the test section boundaries are passive in a ventilated test section and active in an AWTSs. The apparent simplicity of ventilated test sections led to the political obsolescence of NPL's AWTSs and the benefits of adaptive wall technology became forgotten.

After about 20 years, interest in AWTSs was rekindled. Around 1972, several researchers, in Europe and the USA, independently rediscovered the concept of adaptive wall testing techniques. These researchers sought better free air simulations in transonic wind tunnels. 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. Therefore, the adaptive wall concept* allows us to simplify the "correction codes" at the expense of increasing the complexity of the test section hardware.

This renewed interest, helped greatly by the availability of computers, has spawned the various adaptive wall research groups now found around the world. We have seen a variety of AWTS designs for testing 2- and 3-D models. Some unusual designs have been built including a rubber tube AWTS[5] and a pilot multi-wall AWTS for automobile research.[6] AWTSs are now available for commercial use at NASA Langley (USA), ONERA/CERT (France), and TsAGI (USSR). A complete list of currently operational AWTSs is shown on Table 1 below.

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_e (millions)	Walls	Adaptation Control	Remarks
Aachen, Aero. Institute[2]	TST	0.4 Square	1.414	4.0	2.8	2 Flexible 2 Solid	24 Jacks/Wall	Issue 10
Arizona University[3]	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
CAE[2] Harbin, China	FL-7	0.52 x 0.64 Rectangular	1.75	>0.8	...	2 Porous 2 Solid	11 PCCs/Wall	Issue 10
DLR[3]	HKG	0.67 x 0.725 Rectangular	4.0	>1.2	...	2 Flexible 2 Solid	17 Jacks/Wall	Issue 7
Genova University[2]	Low Defl. Cascade	0.2 x 0.05 Rectangular	1.58	2.0	1	2 Flexible 2 Soild	36 Jacks/Wall	Issue 7
Genova University[2]	High Defl. Cascade	0.2 x 0.05 Rectangular	1.6	>1.18	1	2 Flexible 2 Solid	13 Jacks-Ceiling 26 Jacks-Floor	Issue 7
NASA Ames[2+3]	HRC-2 AWTS1	0.61 x 0.41 Rectangular	2.79	>0.8	30	2 Flexible 2 Solid	7 Jacks/Wall	
NASA Ames[2]	HRC-2 AWTS2	0.61 x 0.41 Rectangular	2.79	>0.8	30	2 Flexible 2 Solid	11 Jacks/Wall	Issue 10
NASA Langley[2+3]	0.3-m TCT	0.33 Square	1.417	>1.3	120	2 Flexible 2 Solid	18 Jacks/Wall	Issues 1-5,7,8
N P Univ.[2+3] Xian, China	Low Speed	0.256 x 0.238 Rectangular	1.3	0.12	0.50	2 Flexible 2 Solid	19 Jacks/Wall	Issues 2,5,9
ONERA/CERT[2+3]	T2	0.37 x 0.39 Rectangular	1.32	>1.0	30	2 Flexible 2 Solid	16 Jacks/Wall	Issue 2
ONERA[2+3]	S5Ch	0.22 x 0.18 Rectangular	0.3	1.2	...	2 Multiplate 2 Solid	302 Transverse Sliding Plates	Issue 9
RPI[2] Troy, NY	3 x 8	0.20 x 0.07 Rectangular	0.6	0.86	...	1 Flexible 3 Solid	6 Jacks	
RPI[2] Troy, NY	3 x 15	0.39 x 0.07 Rectangular	0.6	0.8	...	4 Solid	Multiple Top Wall Inserts	
Southampton University[2+3]	SSWT	0.152 x 0.305 Rectangular	0.914	0.1	0.38	2 Flexible 2 Solid	17 Jacks/Wall	Variable T.S. Height
Southampton University[2+3]	TSWT	0.15 Square	1.12	>1.0	2.5	2 Flexible 2 Solid	19 Jacks/Wall	Issue 1
Sverdrup Technology[3]	AWAT	0.305 x 0.61 Rectangular	2.438	0.2	...	3 Multi-Flexible Slats 1 Solid	102 Jacks-Ceiling 15 Jacks/Sidewall	Issue 4
Tech. University Berlin[3]	III	0.15 x 0.18 Octagonal	0.83	>1.0	...	8 Flexible	78 Jacks Total	Issue 6
TsAGI[2+3] U.S.S.R.	T-128	2.75 Square	8.0	1.7	9	4 Porous	32 Control Panels per Wall	Issue 11
Umberto Nobile[2]	FWWT	*0.2* Square	1.0	0.6	3.5	2 Flexible 2 Solid	18 Jacks/Wall	

[2] - 2D Testing Capability
[2+3] -2D and 3D Testing Capability
April 1990
[3] - 3D Testing Capability
PCC - Plenum Chamber Compartments

Note: The Remarks column refers to **Adaptive Wall Newsletter** issues (published roughly quarterly by NASA researchers) which contain related articles.

4. Transonic AWTSs Currently Operational

(In alphabetical order by organization)

4.1 Aerodynamic Institute, RWTH Aachen, West Germany

The test section of the Transonic- and Supersonic Tunnel (TST) at RWTH Aachen was equipped with flexible walls in 1985/6. The AWTS is 40 cm (15.75 inches) square and 1.414 m (4.64 feet) long. The top and bottom walls are flexible and mounted between two parallel sidewalls. The flexible walls are made from 1.3 mm (0.051 inch) thick spring steel. Each wall is supported by 24 motorized jacks (See Figure 1).

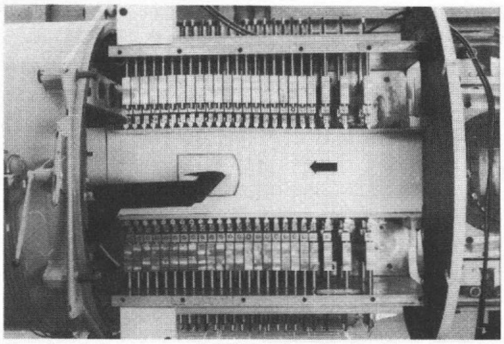


Fig. 1 - The exposed TST adaptive wall test section.

The TST is an intermittent tunnel capable of operation at Mach numbers between 0.2 and 4, with run times between 3 to 10 seconds. The AWTS has only been used for 2-D testing up to about Mach 0.8. Usually 3 or 4 tunnel runs are required for each data point at low transonic Mach numbers. Boundary measurements are static pressures measured along the flexible walls. Wall adaptation calculations and automatic wall adjustments are made between tunnel runs.

Empty test section calibrations reveal Mach number discrepancies less than 2%, where the model is usually mounted, at Mach 0.82. Lower Mach numbers produce lower discrepancies. Mach number is controlled, up to low transonic Mach numbers, by a downstream sonic throat. The average accuracy of the wall contours, measured by potentiometers at each wall jack, is ±0.1 mm (±0.004 inch).

4.2 CAE, Harbin, China

The Chinese Aeronautical Establishment, within the Harbin Aerodynamics Research Institute, installed adaptive walls in the FL-7 transonic tunnel during 1989. The AWTS measures 0.64 m (25.2 inches) wide, 0.52 m (20.47 inches) high and 1.75 m (5.74 feet) long. The AWTS is equipped with 2 uniform but variable porosity walls, with holes slanted 60° from the vertical, and 2 solid sidewalls. Each perforated wall is split into 11 equal length segments. The porosity of each segment can be independently varied between 0% and 11%, using some manual adjustments.

Researchers have made preliminary 2-D tests at Mach numbers up to 0.8 at zero lift conditions. The wall adaptation procedure is experimental at this stage. Boundary measurements were made at two control surfaces/lines near one of the porous walls, probably using Calspan pipes.

4.3 DLR - Institute of Experimental Fluid Mechanics, Goettingen, West Germany

During 1987/8, researchers at DLR modified the 2-D supersonic nozzle of the DLR High Speed Wind Tunnel (HKG) into an AWTS. The top and bottom nozzle walls are made of highly flexible 4 mm (0.157 inch) thick steel plates. The shape of each wall is set by 17 pairs of equally spaced hydraulic jacks (See Figure 2).

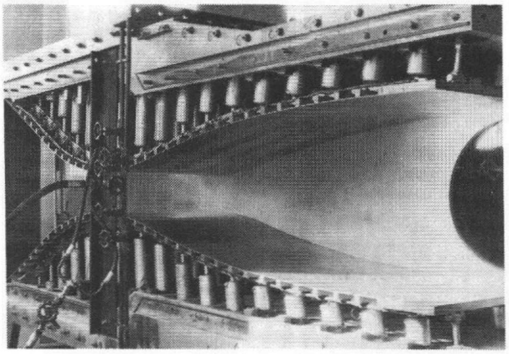


Fig. 2 - The HKG adaptive wall test section with the left sidewall removed.

The AWTS consists of an initial contraction followed by a 2.2 m (7.22 foot) straight section. This straight portion, in which the model is mounted, is nominally 0.67 m (2.2 feet) high and 0.725 m (2.38 feet) wide. Each wall of the test section is equipped with 3 rows of pressure taps for boundary measurements. The wall adjustment procedure of Wedemeyer/Lamarche[7] is used to minimize interferences along the tunnel centerline.

This AWTS is used for evaluation of 2-D wall adaptation in 3-D testing. Researchers have tested sting mounted 3-D models, both lifting and non-lifting, up to about Mach 0.8.[8]

4.4 Genoa University, Italy

The Department of Energy Engineering at the University of Genoa operates two adaptive wall cascade tunnels. Both tunnels have a cross-section of 0.2 m (7.87 inches) high and 5 cm (1.97 inches) wide. One is the Low Deflection Blade Cascade Tunnel (LDBCT), which became operational in 1982. The other is the High Deflection Blade Cascade Tunnel (HDBCT) which became operational in about 1985.

The LDBCT can test up to 12 blades, at Mach numbers up to 2.0, with flow deflections up to about 35°. The AWTS has 2 flexible walls and 2 solid transparent sidewalls. The flexible walls are 1.58 m (5.18 feet) long and each is shaped by 36 manual jacks (see Figure 3). Wall streamlining is performed upstream and downstream of the cascade.

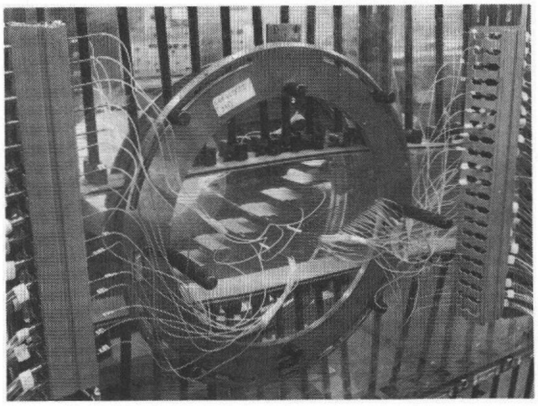


Fig. 3 - A side view of the Genoa University LDBCT.

The HDBCT has a similar configuration except the AWTS is 1.6 m (5.25 feet) long and wall adaptation is performed only downstream of the cascade. The top flexible wall is supported by 13 manual jacks and the bottom flexible wall by 26 manual jacks. The AWTS can accommodate flow deflections up to 140°. Up to 13 blades can be fitted in the cascade, with test Mach numbers up to 1.18 reported.

Both AWTS need only approximate wall adaptation procedures due to the large number of blades used in the cascade. The smooth flexible walls have provided remarkably good flow quality for cascade research. The LDBCT is also used for probe calibration.[9]

4.5 NASA Ames Research Center, California, USA

The Thermo-Physics Facilities Branch at NASA Ames has 2 AWTS for use in their intermittent High Reynolds Number Channel-2 (HRC-2) facility. AWTS (#1) was constructed in 1981 and AWTS (#2) followed in 1988. Both AWTS are fitted with 2 flexible walls and 2 parallel solid sidewalls. Both AWTSs have a rectangular cross-section which is 0.61 m (24 inches) high and 0.41 m (16 inches) wide. The AWTSs are 2.79 m (9.15 feet) long.

AWTS (#1) has 7 manually adjusted jacks supporting each flexible wall, while AWTS (#2) has 11 jacks powered by stepper motors (See Figure 4). This is the major difference between the two AWTSs. AWTS (#2) is intended as an automated replacement of AWTS (#1) with improved control of the flexible wall shapes. The wall jacks on AWTS #2 are fast moving because of the short duration tunnel runs. (Wall movement is at about 5 mm (0.2 inch) per second.)

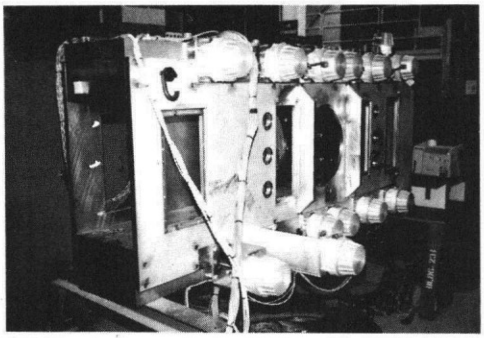


Fig. 4 - A view of the NASA Ames AWTS (#2) showing the many sidewall apertures.

The flexible walls are made of 17-4 PH stainless steel plates and are 2.53 m (8.32 feet) long. In AWTS (#1), the flexible walls are 15.9 mm (0.625 inch) at the ends tapering to 3.17 mm (0.125 inch) in the middle. In AWTS (#2), the flexible walls taper down to 2.39 mm (.094 inch) in the middle for increased flexibility. The downstream ends of the flexible walls each house a pivot joint which attaches to a variable sonic throat for Mach number control. Sidewall Boundary Layer Control (BLC) is available by installing porous plates in the sidewall, upstream of the model location. Mach number variations along the test section due to BLC suction are removed by suitable wall adaptation based on simple influence coefficients.[10]

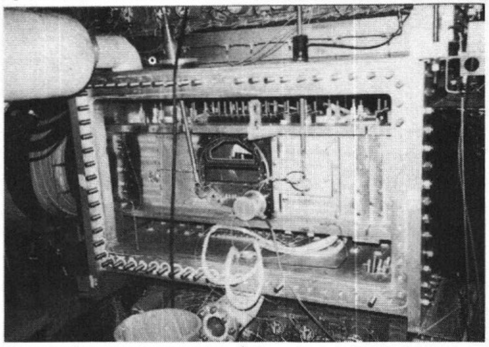
AWTS #1 has been used for 2-D and 3-D CFD code validation. No wall adjustment procedure is used. The flexible walls are simply set to predetermined shapes depending on the investigation underway. Studies of LDA wake measurements behind 2-D aerofoils have also been carried out. Preliminary 3-D tests with a sidewall mounted half model were performed with straight walls. The AWTS (#2) has yet to be installed in HRC-2.

4.6 NASA Langley Research Center, Virginia, USA

The NASA Langley 0.3-m Transonic Cryogenic Tunnel (TCT) was fitted with an AWTS during 1985. The AWTS has 2 flexible walls mounted between 2 parallel sidewalls. The flexible walls are made of 304 stainless steel, 3.17 mm (0.125 inch) thick at the ends and thin down to 1.57 mm (0.062 inch) thick in the middle.

The cross-section of the AWTS is 0.33 m (13 inches) square and the AWTS is 1.417 m (55.8 inches) long. The flexible walls are 1.417 m (55.8 inches) long and are shaped by 18 motorized jacks per wall. The downstream ends of the flexible walls are attached, by sliding joints, to a 2-D variable diffuser (formed by flexible wall extensions) between the AWTS and the rigid tunnel circuit. The shape of the variable diffuser is controlled by 6 motorized jacks. The wall jacks are designed with insufficient stepper motor power to permanently damage the flexible walls.

The AWTS functions over the complete operating envelope of the continuous running cryogenic tunnel (TCT).[11] The test gas is nitrogen. The AWTS can operate continuously over an 8 hour work shift at temperatures below 120 K. In addition, the AWTS is contained in a pressure vessel for operation up to stagnation pressures of 90 psia (6 bars). The jack motors and position sensors are located outside the pressure shell in a near ambient environment (see Figure 5). Sidewall boundary layer control is available by fitting porous plates in the sidewalls, upstream of the model position. Boundary layer suction has been successfully used in 2-D testing with normal wall adaptation. We take 2-D wake measurements using a traversing pitot/static probe mounted in one of 3 positions downstream of the aerofoil location.



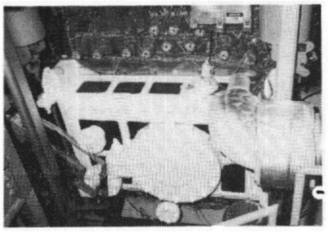


Fig. 5 - NASA Langley 0.3-m TCT adaptive wall test section: view above shows AWTS with the left side of the pressure shell removed; and insert left shows the AWTS covered in ice during cryogenic operation.

We have used the wall adjustment procedure of Judd et al[11] for 2-D testing. The 2-D test envelope includes normal force coefficients up to 1.54 and Mach numbers up to 0.82 with a model blockage of 12%. Boundary measurements are static pressures measured along the centerline of the flexible walls at the jack locations. Wall streamlining takes on average less than 2 minutes and is paced by slow wall movements. A generalized and documented non-expert system[12] is used for AWTS operation within known 2-D test envelopes. We have demonstrated the taking of up to 50 data points (each with wall streamlining) during a 6 hour period.

Researchers have carried out tests at Mach numbers up to 1.3, using sidewall mounted 3-D wings. For 3-D testing at Mach numbers below 0.8, we have used the wall adjustment procedure of Rebstock[13] to minimize interferences along a pre-set target line anywhere in the test section. Boundary measurements are static pressures from 3 rows of pressure taps on each flexible wall and a row of taps on the centerline of one sidewall. Downstream flexible wall curvature is automatically minimized by rotation of the tunnel centerline. For low supersonic tests, the adapted wall shapes are based on wave theory and form a 2-D supersonic nozzle ahead of the model.

The flexible walls are set to a nominal accuracy of ±0.127 mm (±0.005 inch). No aerodynamic effect of AWTS shrinkage, due to cryogenic operation, has been reported. Mach number is controlled by a closed loop fan drive system (designed around a PC computer) to better than 0.002 during each wall adaptation process (streamlining).

4.7 ONERA/CERT, Toulouse, France

The AWTS fitted in the intermittent ONERA/CERT T2 transonic cryogenic tunnel became operational in 1978. This AWTS became the first cryogenic AWTS in 1981, when the T2 tunnel was modified to operate cryogenically for 1 to 2 minutes at a time. This French AWTS is 0.37 m (14.57 inches) high, 0.39 m (15.35 inches) wide and 1.32 m (51.97 inches) long. The AWTS has 2 flexible walls and 2 parallel solid sidewalls. The flexible walls are made of 1.5 mm (0.059 inch) thick Invar steel plates. The shape of each flexible wall is controlled by 16 hydraulic jacks attached to wall ribs (See Figure 6). These ribs are electron beam welded to the outside of the flexible walls. The hydraulic jacks move the flexible walls very rapidly at about 6 mm (0.24 inch) per second. The wall jacks have enough power to damage the flexible walls. During a cryogenic run, the flexible walls rapidly reach the low test temperatures, while the jack mechanisms remain at near ambient temperatures. Sidewall BLC is available for 2-D testing by placing porous plates around the aerofoil/sidewall junctions. BLC suction is routinely used with wall adaptation. In 2-D tests, a pitot/static rake, mounted on a sting support downstream of the wing, is used for wake measurements.

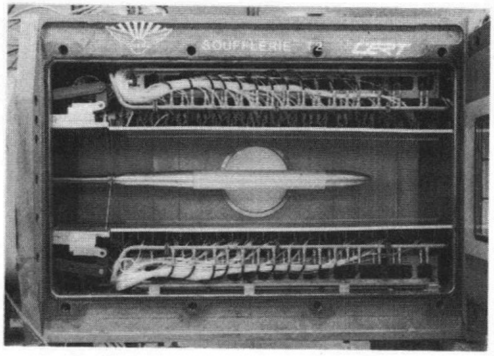


Fig. 6 - ONERA/CERT T2 AWTS with a C5 model installed for 3-D riblet tests.

A wall adjustment procedure developed by Chevallier et al is used for 2-D testing. This procedure is tunnel dependent and has no documented test envelope for non-expert use. Computer controlled wall streamlining in about 10 seconds is possible. However, 2 short tunnel runs are normally required per data point for 2-D tests at about Mach 0.8. Boundary measurements are static pressures measured equidistant along the centerline of the flexible walls.

For 3-D testing, the Wedemeyer/Lamarche wall adjustment procedure is used. Both lifting and non-lifting models have been tested up to Mach 0.97.[14] The T2 AWTS is the closest we have come to a production-type 3-D AWTS. Researchers have carried out several production-type studies of riblets with 3-D models (See Figure 6). Boundary measurements are static pressures measured along 3 rows on each flexible wall and a single row on one sidewall.

The shape of the flexible walls can be measured to 0.05 mm (0.002 inch). The wall curvature is checked before any wall movement is initiated. Mach number is control by a downstream sonic throat which acts as a fairing between the AWTS and the fixed diffuser. In general, the Mach number is not held constant during each wall adaptation process.

4.8 ONERA, Chalais-Meudon, France

The ONERA S5Ch wind tunnel was fitted with an AWTS about 1984, primarily to investigate shock wave cancellation with adaptable but solid test section boundaries. The AWTS is 22 cm (8.66 inches) high, 18 cm (7.09 inches) wide and 30 cm (11.8 inches) long. The impervious and adjustable floor and ceiling are mounted between solid parallel sidewalls (See Figure 7). The floor and ceiling are made up of 151 transverse sliding plates. Each of the 302 plates is 18 cm (7.09 inches) wide and 1.5 mm (.059 inch) thick. The plates are manually adjusted to match specially machined profiles for each test condition. Upstream of the AWTS is a fixed supersonic nozzle which produces a Mach 1.2 stream at the test section entrance.

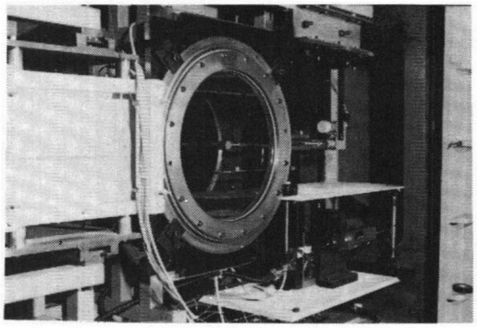


Fig. 7 - The ONERA S5Ch adaptive wall test section with a 2-D cylinder installed.

Both 2-D and 3-D models have been tested where strong shock waves reach the floor and ceiling. The model's streamwise position is adjusted to where the bow shock impinges on the floor and ceiling at the junction between the fixed nozzle and the AWTS. Suitable wall curvature is then used to cancel the shock wave reflection or deflect the reflection harmlessly downstream of the model. Boundary measurements are made along streamwise lines using a five hole probe. No special problems were reported during tests at low supersonic Mach numbers.[15]

4.9 Rensselaer Polytechnic Institute, New York, USA

Since the mid-1980s, the Rensselaer Polytechnic Institute has operated two AWTSs for rotorcraft research in particular the study of 2-D aerofoils with passive boundary layer control. The RPI 3 x 8 transonic wind tunnel is fitted with a rectangular AWTS, 20.3 cm (8 inches) high, 7.6 cm (3 inches) wide, and 0.6 m (23.62 inches) long. The top wall is flexible and supported by 6 jacks. The other three walls are solid. The 2-D aerofoil is mounted in the bottom wall with a boundary layer removal slot ahead of the leading edge. A relatively large aerofoil with a 10.16 cm (4 inch) chord has been tested in this AWTS at Mach numbers up to 0.86.

The RPI 3 x 15 transonic tunnel has a similar AWTS arrangement except the test section height is increased to 38 cm (15 inches). Also the top wall is not flexible and different wall shapes are set in the AWTS by using interchangeable wooden wall inserts. Tests of 14% thick aerofoils at Mach numbers up to 0.9 are reported.[16]

Researchers use a simple wall adjustment procedure in these AWTSs. One-dimensional wall influence coefficients are used to remove the blockage effects associated with testing a large aerofoil in these small test sections. Boundary measurements are static pressures measured along the test section walls.

4.10 Southampton University, Hampshire, England

The Transonic Self-Streamlining Tunnel (TSWT) at the University of Southampton is one of the first fully automated AWTSs. Built in 1976/7, TSWT has a 15 cm (6 inch) square test section which is 1.12 m (3.67 feet) long. The floor and ceiling are flexible and made from woven man-made fibre (Terylene). The flexible walls are 5 mm (0.2 inch) thick at the ends tapering to 2.5 mm (0.1 inch) thick in the middle. Each flexible wall is supported by 19 motorized jacks (See Figure 8). A sliding joint attaches the downstream ends of the flexible walls to a 2-D variable diffuser (which is 2 plates, each controlled by a single motorized jack). The wall jacks are designed with insufficient stepper motor power to permanently damage the flexible walls. The 2 sidewalls are solid and parallel.

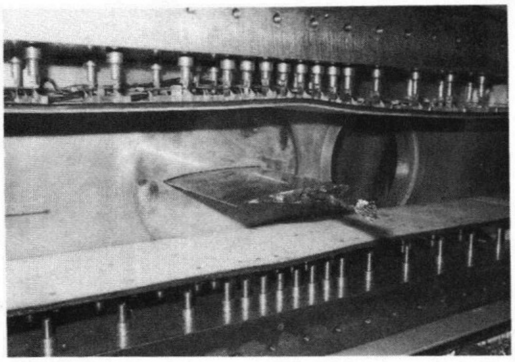


Fig. 8 - The Southampton TSWT with the flexible walls set in streamline shapes round a large chord NPL 9510 2-D aerofoil.

The wall adjustment procedure of Judd et al[17] for 2-D testing was developed in TSWT, and is used routinely for all 2-D tests where the flow at the flexible walls is up to just sonic. Wall streamlining is generally achieved in less than 2 minutes. If the walls become sonic, a Transonic Small Perturbation code is included in the Judd procedure and 2-D testing has been successfully carried out up to Mach 0.96.[18] For low supersonic 2-D testing at up to Mach 1.2, a wall adjustment procedure based on wave theory is used to generate a simple 2-D supersonic nozzle in the AWTS, upstream of the model. Since 1978, researchers have used TSWT to build up a substantial database on 2-D testing in AWTS with blockage ratios up to 12% and test section height to model chord ratios down to unity.

In addition, TSWT has been used for 3-D tests with sidewall and sting mounted models with blockage ratios up to 4%. A wall adjustment procedure developed by Goodyer et al is used for 3-D test up to about Mach 0.9.[19] 3-D tests have been performed at transonic speeds up to Mach 1.2 using wall adjustment procedures still under development. Boundary measurements are static pressures measured along 5 rows on each flexible wall and a single row on one sidewall.

The wall shapes are measured by potentiometers at each wall jack to an accuracy of ±0.127 mm (±0.005 inch). Free stream Mach number is controlled by automatic throttling of the inducing air pressure. Mach number variation up to .002 is typical during a test at Mach 0.8. Calibration of TSWT with an empty test section reveals a standard deviation in Mach number variation of about 0.003 at Mach 0.8.

4.11 Technical University of Berlin, West Germany

During 1980, an octagonal AWTS was built at the Technical University of Berlin to study the use of adaptive walls in 3-D testing. This unusual test section is 15 cm (5.9 inches) high, 18 cm (7.09 inches) wide and 83 cm (32.68 inches) long.[20] The test section is formed by 8 flexible walls supported by a total of 78 jacks powered by individual DC motors (See Figure 9). The flexible walls are made of thin steel plates. The corners are sealed by spring steel lamellas so the test section boundary is impermeable and continuous.

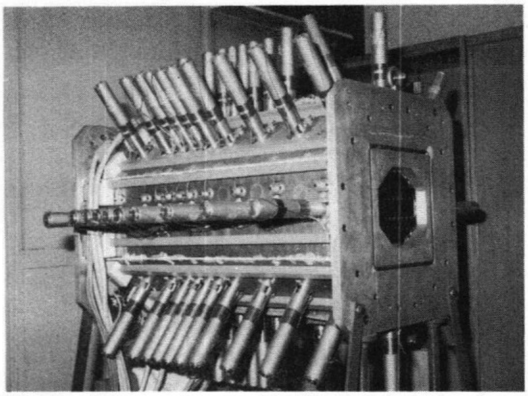


Fig. 9 - The octagonal AWTS of TU-Berlin has a strange appearance due to the inline motor drive systems fitted to each wall jack.

This 3-D AWTS uses a wall adjustment procedure developed by Rebstock et al. Wall adaptation is possible in 2 iterations at Mach numbers up to 0.95. Model blockage ratios up to 1.3% have been successfully tested, both with lifting and non-lifting sting mounted models. Boundary measurements are static pressures measured along the centerline of each flexible wall. Low supersonic tests of non-lifting bodies indicate that bow shock reflections from the flexible walls can be deflected away from the model.[21]

4.12 TsAGI (Central Aero-Hydrodynamic Institute), Zhukovsky, USSR

The Experimental Techniques Branch at TsAGI currently operates the largest AWTS anywhere. The new Russian T-128 tunnel is fitted with a 2.75 m (9 foot) square AWTS which is 8 m (26.25 feet) long. All four walls are perforated. Each wall is made up of 32 segments. The porosity of each segment can be varied between 0 and 18%. Each segment is made up of 2 porous plates (one on top of the other). These 2 plates are moved relative to one another (manually) to achieve a desired porosity over the segment.

Apparently wall adjustment procedures have been developed by Neyland for 2- and 3-D testing at transonic speeds.[22] Boundary measurements are 5 static pressures measured on each of the 128 quadrilateral wall segments, then an average pressure is found for each segment. The T-128 has 5 interchangeable test sections which are probably configured for either 2- or 3-D testing. The maximum blockage ratios for 2-D testing are 6% and for 3-D testing about 3%. These high blockage ratios are beyond the capabilities of other reported variable porosity AWTS. Unfortunately, no data has been published to substantiate these claims. Nevertheless, the T-128 tunnel is supposed to have been used for production-type testing. Automation of the AWTS is planned in the near future.

5. An Overview of AWTS Designs

In 2-D testing, only two walls need to be adaptable and a simple AWTS is sufficient. 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 best number of adaptive walls for a 3-D AWTS is still unknown and must ultimately be a compromise. From practical considerations, this design compromise is between size/correctability of residual wall interferences (after streamlining), hardware complexity, model accessibility, and the existence of rapid wall adjustment procedures.

There are strong theoretical[7] and experimental[19] indications that the simpler the AWTS design the better the testing technique (see sub-section 6.2). A simple design reduces both the complexity of calculating the residual wall interferences and the complexity of the tunnel hardware, and gives better model access as a bonus. A major factor in the design of new AWTSs will undoubtedly be the trade-off between the complexity of the boundary adjustments and the quality/cost of the residual wall interference corrections. Researchers have made preliminary 3-D tests in 2-D flexible walled AWTSs at NASA Langley[13], University of Southampton[19], ONERA/CERT[14], TU-Berlin[20], DLR Goettingen[8], and China.[23]

Published data clearly shows that flexible walled AWTSs provide testing capabilities superior to that of variable porosity AWTS designs. We can summarize the effectiveness of flexible walls thus:

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 disturbances which lower operating costs.
e) No plenum is required around the test section.

Interestingly, of the 16 transonic AWTSs now operational worldwide, only 2 AWTSs do not have flexible walls (see Table 1).

The optimum 2-D AWTS has two flexible walls supported by jacks closely grouped in the vicinity of the model. A good example is the AWTS in the 0.3-m TCT shown on Figure 10. The flexible walls (made of thin metal) are anchored at the upstream ends and the downstream ends are attached by a sliding joint to a variable 2-D diffuser. The AWTS requires a square cross-section for optimum 2-D testing (i.e. maximizing Reynolds number capability). For 3-D testing, a rectangular cross-section, which is wider than it is tall, seems better for minimizing 3-D wall interferences with 2-D wall adaptation.

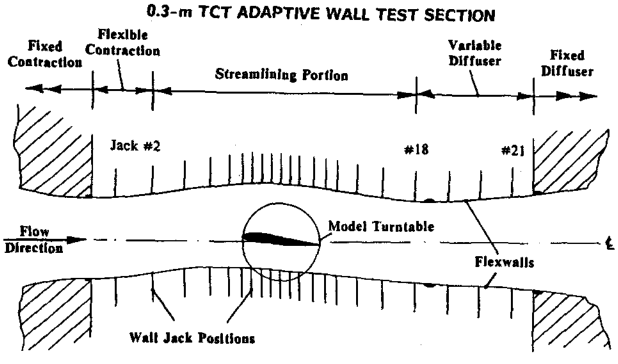


Fig. 10 - The optimum 2-D AWTS with flexible walls.

6. Review of AWTS Research

Research into adaptive wall testing techniques, with both variable porosity and flexible wall AWTS designs, has concentrated on the following goals:

1) Shortening of time attributed to wall streamlining.
2) Detailed examination of AWTS operating envelopes and measurement tolerances for 2- and 3-D testing.
3) Study of different applications.

However, we now know that the variable porosity AWTS is much less effective than the flexible walled AWTS. So, we will only consider the flexible wall research from here on.

Since 1938, researchers have made significant reductions to the time associated with wall streamlining. A major factor in 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 iterations necessary in any wall adaptation procedure.) Early empirical type methods (requiring 8 iterations) have given way to analytical methods (requiring 1 or 2 iterations) as computer support has improved. These analytical methods now use both linear and non-linear theory. Nevertheless, simple empirical methods are still appropriate where the use of large models is not important, as found in some of the AWTSs (particularly the cascade AWTSs) described in this paper.

For 2-D free air simulations, the linear method of Judd, Goodyer, and Wolf[17] (University of Southampton, UK) is now well established for reasons of speed, accuracy, simplicity (Non-experts can easily use the method on any mini-computer), and adaptability for general use with any flexible walled AWTS. A non-linear version is also available for use in 2-D testing where the flow at the walls is sonic.[18] For free air simulations in 3-D testing, researchers use the linear methods of Wedemeyer/Lamarche[7] (DLR), Rebstock[13] (NASA), and Goodyer et al[19] (Southampton). However, all these 3-D methods are still under development. Supersonic 2- and 3-D testing is possible using the method of characteristics (wave theory) to predict the wall shapes necessary to generate supersonic flow.[21]

Another time-saving feature of modern AWTSs is the automation of the wall streamlining. Researchers have shown that computer controlled movement of the adaptive walls and automatic acquisition of wall data dramatically reduce the time attributed to wall streamlining from a week to seconds. In addition, researchers have found that fast wall streamlining requires a good practical definition of when the walls are streamlined. We call this definition the *streamlining criterion* (the point at which we stop wall adaptation). The criterion is directly related to the accuracy of the tunnel/wall measurements (discussed later). For 2-D free air simulations, the best approach appears to be a quantitative approach which is to set, as the streamlining criterion, an acceptable maxima for the residual wall interferences. This approach is used at the University of Southampton and NASA Langley. At present there are only qualitative streamlining criterions in 3-D testing, whereby the walls are streamlined when the model data is unaffected by subsequent iterations of the wall adjustment procedure. On-line residual wall interference codes are available but require development for 3-D testing techniques in AWTSs.[19,24]

Researchers have probed the limits of 2-D adaptive wall testing techniques. These limits are related to aerodynamic, theoretical basis and mechanical aspects of the wind tunnel tests. The use of sidewall BLC is only a factor in altering the wall curvature requirements. In 2-D testing, the operating envelope of an AWTS can be assessed from the test section geometry, the wall adjustment procedure and the instrumentation. These are the same factors defined in the design phase of a new AWTS. Researchers have provided many design guidelines to eliminate wall hardware problems, so far encountered, from future AWTS designs. With good design, only theoretical assumptions should restrict the operating envelope for 2-D testing. In 3-D testing, the situation is far from clear, as no AWTS operating envelopes are well defined. Research has been spread thinly over many AWTS designs and numerous model configurations. The result is that the favoured AWTS design for 3-D testing has gradually become the simplest design (as described earlier).

Researchers have examined the effects of measurement accuracy on AWTS operation, particularly for flexible wall designs.[2] With flexible walls, we can only measure the position of each wall at a finite number of points. The measurement accuracy at each of these points is of the order ±0.127 mm (±0.005 inch) in current AWTSs. The relative position of these measurement points, along each wall, can be optimized for 2-D flexible walled AWTS designs (as shown on Figure 10). Operationally, flexible walled AWTSs have proved tolerant to wall jacks being disconnected due to hardware failures.[11] Interestingly, because the wall position accuracy requirements are proportional to (1/h), the measurement accuracy requirements reduce significantly for a large AWTS. This should be an encouraging factor for potential large AWTS operators. A factor that is already proven in large supersonic nozzle systems operational to-day.

We have found the flexible wall adaptation procedures to be tolerant to uncertainties in the wall pressures. This important feature is due to the smearing effect of the wall boundary layers. 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 uncertainties reduces. The uncertainties in the wall pressures can be caused by wall imperfections or fluctuations in the tunnel test conditions. Again, large AWTS should provide more tolerance to these uncertainties. 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 pressures needs to be better than when the model perturbations are large (as found in 2-D testing).

Furthermore,the allowance necessary for the boundary layer growth on the test section flexible walls is dependent on the accuracy of the wall pressures. In theory, each test condition should require a different boundary layer allowance (i.e. a change in test section cross-sectional area). In practice, researchers have shown that a series of say 4 *Aerodynamically Straight* wall contours are sufficient to provide uniform Mach number distributions, through an empty AWTS, for Mach numbers up to 0.9.[2] In addition, we do not need to make an allowance for the wall boundary layer thinning due to the presence of the model itself, until the flow on the flexible walls is sonic. Most AWTS operators monitor this boundary layer thinning real-time. Researchers have demonstrated that the adaptive wall testing techniques are tolerant to simple boundary layer allowances. In the 0.3-m TCT, for example, we use approximate *Aerodynamically Straight* contours which are simply linear divergence contours. This situation is a result of unacceptable wall waviness in the experimentally determined wall contours. The quality of TCT data does not show any problems due to this approximate wall boundary layer allowance.

In reviewing research goals for adaptive walls, there are still many applications yet to be studied. The classical transonic free-air and cascade simulations have received attention in this paper. There is basic research going on with high lift 3-D tests at low speeds at the University of Arizona (see Table 1); swept wing studies and minimum test section height studies in a low speed 2-D AWTSs at the University of Southampton (See Table 1); and research at Sverdrup, Tennessee, USA is directed towards use of AWTSs in automotive testing.[6] The 6 simulations possible with AWTSs were first studied experimentally by Goodyer back in 1974/6.[25] However, the adaptive wall research effort has concentrated on free-air and cascade simulations. Although, we now find closed tunnel simulations are proving to be very useful for CFD code validation.

6.1 2-D Testing Experience in AWTSs

Validation data[26] shows 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 but, as with any wind tunnel measurements, calibration procedures affect long term repeatability.

We have observed that the model wake in an AWTS shows minimal spanwise variation. We can speculate that the use of large models (relative to the test section size) intrinsically minimizes secondary flows at the aerofoil-sidewall junction. This observation may explain why sidewall BLC does not significant effect wing performance in a relatively small AWTS. There are strong indications that the flow in an AWTS can be an excellent simulation of a 2-D flow field. If we ever need to use sidewall BLC in an AWTS, then researchers have found that no special testing procedures are necessary.

Researchers have found many limitations to the various 2-D adaptive wall testing techniques, none of which are fundamental. These limitations are associated with wall movement (hardware), model size (theoretical assumptions) and Mach number (theory sophistication). Researchers have made 2-D tests close to Mach 1.0[19], and some limited tests at Mach 1.2.[15] 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 is probably only academic, providing experience leading to production-type supersonic 3-D testing.

6.2 3-D Testing Experience in AWTSs

Limited 3-D validation tests[26] support the claim that wall interferences are minimized in AWTSs. However, the wall interferences present before any wall streamlining tend to be already small. So the effectiveness of AWTSs to minimize severe wall interferences in 3-D testing has not been studied.

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 found that they must use low aspect ratio models to increase the model blockage above the normally accepted value of 0.5 percent. (This is because the model span is limited to about 70 percent of the test section width by wind tunnel users.) Consequently, there is a need for new generation of 3-D AWTSs with a rectangular cross-sections, where the width is greater than the height.[7] We still do not know the maximum model blockage we can successfully test in a 3-D AWTS.

Numerous 3-D AWTS designs have been studied (as discussed earlier). In fact, researchers have spent considerable time and effort to develop 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.) An example of the promise of simple AWTSs in 3-D testing is shown on Figure 11. Data from residual interference codes are presented as contour plots of blockage and upwash wall interferences on a simple cropped delta wing, mounted on a sidewall of the 2-D Southampton TSWT. Notice on Figure 11a how the blockage interference patterns, with straight walls, are normal to the flow and 2-D in nature. We can see 2-D wall streamlining significantly reduces the blockage interference. On Figure 11b, the upwash interference pattern with the walls straight still exhibits some two-dimensionality and again 2-D wall streamlining significantly reduces the upwash.

University of Southampton TSWT 3-D Data
Cropped Delta Wing - Mach 0.7; Alpha = 8°
Span/Width = 57%; Nominal Blockage = 2%

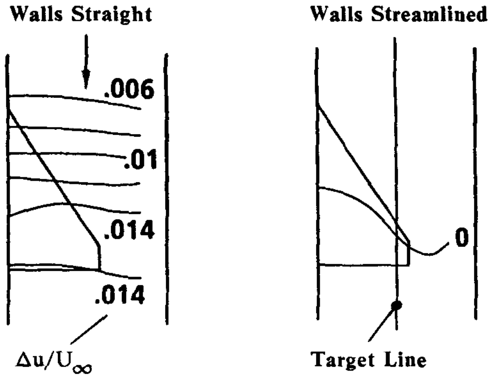


Fig. 11a - Effect of 2-D wall streamlining on blockage interference in a 3-D test.

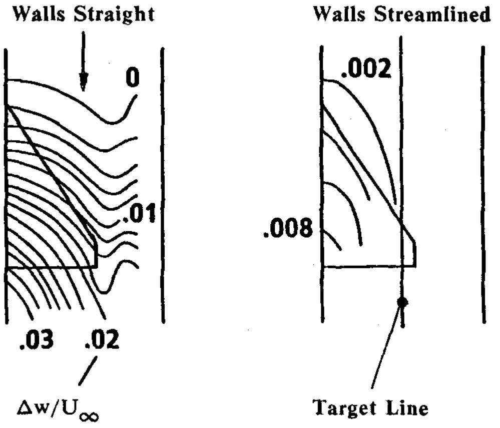


Fig. 11b - Effect of 2-D wall streamlining on upwash interference in a 3-D test.

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 eliminate oblique shock reflections onto the model, as found in 2-D testing. The smearing of the shock/wall interaction does much to ease the curvature requirements on the flexible walls. However, in supersonic testing, there is no clear indication of the quality of the model data after wall streamlining, nor is there yet a proven wall adjustment procedure.

The wall adjustment procedures for 3-D testing have taken advantage of the fast and large capacity mini-computers available for real-time 3-D flow computations. Research continues to identify the amount and type of wall interferences that can be successfully "corrected" by 3-D adaptive wall testing techniques. The different wall adjustment procedures minimize the 3-D wall interferences differently. For example, the Rebstock method[13] minimizes interferences along a pre-set streamwise line anywhere in the test section. In addition, the Rebstock method minimizes wall curvature by introducing a uniform angle of attack error throughout the test section. We do not know where best to minimize the wall interferences for different model configurations nor do we know where the concept of a uniform angle of attack error will break down.

The type of wall pressure measurements necessary to adequately assess the residual wall interferences is also an unknown. The exploitation of real-time residual interference assessment codes is now critical to progress in 3-D adaptive wall testing techniques. This has come about because we now realize that 3-D wall interferences cannot be eliminated with even the most sophisticated AWTS.

Hardware limitations currently restrict AWTS test envelopes (in particular model lift) for reported 3-D tests. These hardware limitations arose from inappropriate AWTS design criteria and the use of AWTSs originally designed for only 2-D testing. Unfortunately, these limitations have hampered 3-D adaptive wall research. This situation would appear to be one of the outcomes of low priority funding.

7. Production Requirements

The production requirements for an adaptive wall testing technique is the same as for any modern testing technique. Firstly, the technique must be easy to use. Consequently, we need to make the complexities of the AWTS invisible to the tunnel operators (similar to operating large flexible supersonic nozzles). Secondly, the technique must not require excessive tunnel time. So we require the AWTS wall movements to be quick. Thirdly, the technique must have a known test envelope for successful use. Therefore, we must ensure the testing technique is well researched, so that we know the limitations and restrictions and can avoid them during normal operations. Fourthly, the technique must, of course, be financially viable.

How can the adaptive wall testing technique meet the production requirements shown above? First, lets consider the complexity of an adaptive wall testing technique. We must design the associated test section hardware so the wall shapes can be continually changed. We also need an interaction between the AWTS and a computer system to set the wall to streamline shapes. If we make the AWTS of simple design then access to the model is unaffected. Furthermore, if we make the wall adjustments automatic via a user-friendly computer system, the operator need only issue *Go/Stop* commands (See Figure 12). Consequently, the complexity of the testing technique is invisible to the operator. The tunnel operator's contact with the AWTS becomes simply to setup the model and acquire test data.

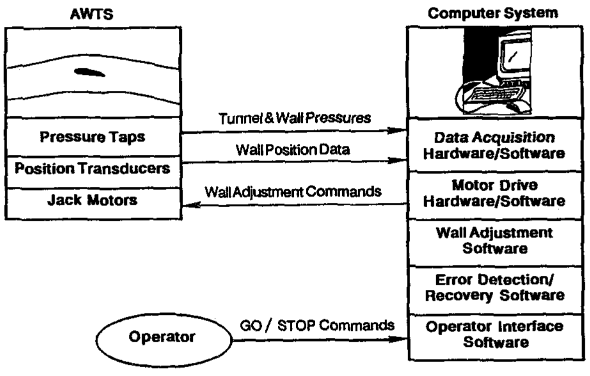


Fig. 12 - A schematic diagram of the interaction between AWTS, operator, and computer system for automatic control of an AWTS.

Second, lets consider the time factor. Adjusting walls in the test section takes time. How much time depends on the AWTS hardware (jack type) and the wall adjustment procedure. We can design the wall jacks to be very responsive. The wall adjustment procedure can find the streamline shapes in one or two iterations. The result is that wall streamlining can be quick. The French have already demonstrated wall streamlining in 10 seconds for 2-D testing. Computer advances will make this possible for 3-D testing in the future. Another time factor is the elimination of post-test corrections and lengthy test programmes, because real-time AWTS data is the final data. We show the importance of this fact on Figure 13. In this example, we compare real-time transonic 2-D lift data from a deep slotted walled test section with equivalent real-time data from a shallow flexible walled AWTS, at the same test conditions. The differences are alarming. With the final data known during the tunnel run, AWTSs can and should save overall tunnel run time.

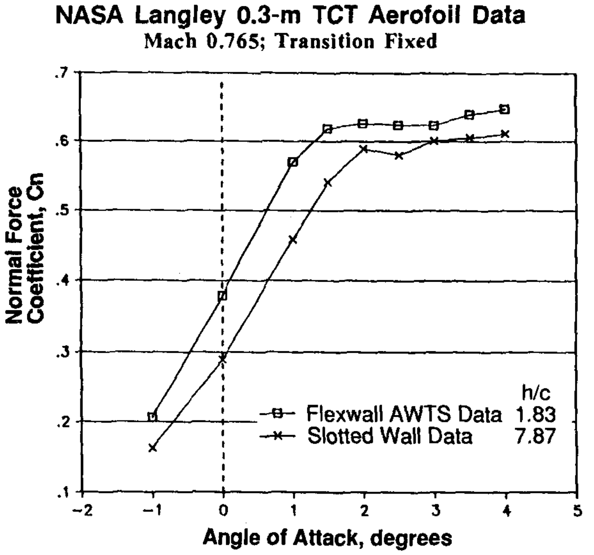


Fig. 13 - The importance of corrected real-time transonic 2-D aerofoil data from a shallow flexible walled AWTS.

Third, lets consider the test envelopes for AWTSs. Researchers have defined the test envelope for various 2-D adaptive wall testing techniques (described earlier). So we can direct non-expert users away from these known limitations. Alas, in 3-D testing, we are still learning what limitations exist.

Fourth, consider the cost factor. The simple AWTS design can be incorporated in existing test sections by the replacement of only two walls. Also, the plenum, which surrounds ventilated transonic test sections, can provide adequate volume, within the pressure vessel, for the jack mechanisms. These factors will reduce the overall hardware costs. In addition, the AWTS control system requires the same computer/tunnel interface found with other tunnel features such as a motorized sting or speed controls. The era of cheap data acquisition systems based around powerful PC type computers means that the AWTS control system should be relatively inexpensive. In addition, an AWTS control system can be integrated with other tunnel systems, which do not need to operate at the same time as wall streamlining. Other favourable cost factors are the reduction of tunnel operating costs possible by using a smaller AWTS (as much as 75% smaller than the original) and having smooth walls.

Interestingly of the three wind tunnels with AWTSs which come closest to being production-type tunnels, non-experts can only use one. The Langley 0.3-m TCT has the only *User Friendly* AWTS control system that allows non-expert 2-D testing within defined test envelopes.[11]

8. The Future of AWTSs?

The status of adaptive wall technology is ongoing and positive. The vast 2-D testing experience will continue to be very important to the development of 3-D adaptive wall testing techniques. Six research groups around the world are carefully pursuing the development of 3-D adaptive wall testing techniques. Work to find the best techniques to achieve specific test objectives at transonic speeds will also demonstrate all the AWTS advantages in 3-D testing. I speculate that only after this action will misconceptions, in the wind tunnel community, be dispelled leaving the way clear for adaptive wall technology to be properly utilized.

At the time of writing, a 30 cm (11.8 inches) square high speed tunnel in the Northwestern Polytechnical University, Xian, China is being fitted with a flexible walled AWTSs. Also, a flexible walled AWTS is being built at DLR Goettingen, West Germany for transonic cascade testing with as few as a single blade installed. Another transonic cascade tunnel with a flexible walled test section is planned at the University of Genoa, Italy. This AWTS will have a 3 blade cascade. There is also a strong possibility of unreported adaptive wall activity in Russia where transonic boundary layer transition is receiving much attention.

This news shows there is still interest in improving our testing techniques. If production testing is the ultimate goal, then we have finished developing 2-D adaptive wall testing techniques for free-air simulations. However, work must continue to dispel the inevitable misconceptions about AWTS complexity. In 3-D testing, we still have test envelopes to define and testing techniques to optimize.

We can summarize the current status as the development of a "new" technology to a point where this technology could be made very useful to the aerodynamicist (both theoretician and experimentalist) given the right priority. I am certain that if adaptive wall research had been given similar priority to the development of transonic "correction codes", we would have a production 3-D adaptive wall testing technique available right now. Today, most, if not all, wind tunnel designers make allowances in their designs for that AWTS which will be fitted into their new wind tunnel someday! This situation demonstrates again that wind tunnel users agree there is a need for better testing techniques.

Now that the expectations of CFD have become more realistic, the relationship between wind tunnel and computer has become much stronger. In my opinion, the AWTS provides the near perfect combination of experimental and theoretical aerodynamics (wind tunnel and computer) to improve our understanding of aerodynamics in the future. Perfection can only be achieved by making full use of all advanced technologies available to us.

9. Conclusions

1. Adaptive wall testing techniques, particularly those which utilize flexible walls, offer major advantages over conventional techniques in transonic testing.
2. We can significantly improve data quality by using adaptive wall technology available to us now.
3. Computer advances have removed any impractical aspects of adaptive wall technology.
4. Non-expert use of AWTSs for routine 2-D testing has been demonstrated.
5. We can now design an AWTS so there are no hardware restrictions to 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. Adaptive wall technology offers significant potential in 3-D testing which has yet to be fully demonstrated.

8. General acceptance of adaptive wall technology now relies on the development of testing techniques for general 3-D transonic testing.

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