7th Australasian Hydraulics and
Fluid Mechanics Conference,
Brisbane, 18-22 August, 1980

Self Streamlining Wind Tunnels Without Computers

N. POLLOCK
Research Scientist, Aeronautical Research Laboratories, Victoria

SUMMARY A brief review of wind tunnel wall interference is presented with particular emphasis on "self correcting" and "correctable interference" tunnels. Two simple methods of modifying tunnel walls to approximate unconstrained flow streamlines are presented. One method, which requires only very limited computation, involves the use of an analytic expression for the far field flow, and the other, which requires no computation, uses a purely mechanical wall arrangement which deflects appropriately under the applied pressure field.

1 INTRODUCTION

Due to the presence of the tunnel test section boundaries, the flow about a model in a subsonic wind tunnel is not in general identical to that which would exist in an unbounded stream. The magnitude of this wall interference, for a particular test condition, depends on the relative size of the model and tunnel and the nature of the tunnel boundaries. Since the 1930's it has been common practice for theoretical and empirical corrections to be applied to tunnel data to account for the effects of wall interference. When the interference is small, corrections to the tunnel stream velocity and angle are sufficient. For larger interference, streamwise gradients of flow velocity and downwash angle cannot be neglected. When these gradients become significant the flow over a model becomes basically different from the free flight flow and simple corrections to tunnel data cease to be satisfactory.

Low speed tunnels have for many years successfully used solid wall or open jet test sections with corrections derived from linear potential flow theory. Since the early 1950's most transonic wind tunnels have used ventilated, porous or slotted, test sections and linear interference theory has been extended to include these types of walls. Unfortunately, due to uncertainties concerning the wall boundary conditions, this has not been as satisfactory as the equivalent theory applied to solid wall and open jet tunnels. Despite the use of ventilated walls and theoretical corrections the maximum permissible model blockage ratio for transonic tunnel testing is only of the order of 1%. Since Reynolds number is a vitally important parameter in many tests, this low usable blockage ratio has led to the use of very large and expensive transonic wind tunnels. It is evident that any significant reduction in interference would lead to a reduction in tunnel size for a given test Reynolds number capability. Recently the main impetus for tunnel interference reduction has come from the transonic speed range , but it is recognised that any developments will also benefit low speed testing.

In this paper a brief review of the recently developed "self correcting" tunnels is presented along with two original suggestions for simplifying this type of tunnel.

2 SELF CORRECTING WIND TUNNELS

Ferri (1973) and Sears (1974) independently proposed a new type of wind tunnel where the test section walls are modified during tunnel operation to make a streamline of the tunnel flow near the wall identical to an equivalent streamline in an unconfined flow. This type of tunnel, which is theoretically free of wall interference, has been called: "self streamlining","adaptive wall","interactive wall" and "interference free". The philosophy of operation of these tunnels will be described by reference to a test section with flexible solid walls although it is recognised that identical results can be obtained in other ways; eg. walls of variable local porosity and walls of fixed porosity with multiple plenum chambers with controlled suction rates.

Consider a model in an unconfined stream. If a test section is introduced which lies along the unconfined flow streamlines the model will not experience any interference (assuming in practice that appropriate allowance is made for tunnel wall boundary layer growth). In a self streamlining tunnel the walls lie on streamlines of the flow in the test section and on streamlines of an imaginary infinite flow outside the test section. The flow inside the test section is in general complex, involving strong viscous effects and the presence of shock waves in transonic flows. The imaginary flow outside the test section is relatively simple and adequately described by small disturbance compressible inviscid flow theory. Given a flexible wall tunnel with a known wall shape and pressure distribution it is possible to determine whether it is a legitimate unconfined streamline (ie. whether the perterbations die out at infinity) using only computations of the simple outer flow without reference to the complex inner flow. If it proves not to lie along legitimate streamlines it is possible to approach the desired shape using a logical iterative system of wall pressure and shape measurement, computation and wall reshaping. The obvious questions regarding the convergence and uniqueness of this procedure have been satisfactorily answered.

The concept described above is applicable to the general three - dimensional case, but, due to the physical and computational difficulties involved, all of the practical demonstrations of self streamlining tunnels have been two - dimensional.

It has now been demonstrated by a number of investigators that wall interference can be considerably reduced by this method. However the final converged "interference free" results have not agreed with large wind tunnel and flight results as well as would be desired. One possible cause of these discrepancies is the finite length of the contoured test section walls. Current work suggests that the computational and mechanical complexity of a three dimensional self correcting tunnel would be very large and that some residual corrections would still be necessary. This raises the question of how best to proportion the available computing power between wall modification and residual interference correction.

Kemp (1976&1979) has proposed what he terms a "correctable - interference" wind tunnel, where the walls are set to approximate the streamlined shape and the measured flow conditions near the wall are used to determine whether the results are correctable and if so to compute the corrections. The correctable interference concept has not yet been fully developed but it appears to be an attractive approach to the use of large tunnel blockage ratios without requiring prohibitively complex adjustable walls.

At present the optimum method of setting tunnel walls to approximate the interference free condition has not been established. The most obvious (and most complex) approach is to use closed loop computer control as for a self correcting tunnel. In the remainder of this paper two simple alternative approaches to wall shaping, which have not been described previously, will be presented.

3 ANALYTIC CALCULATION OF WALL SHAPES

Workers in wind tunnel testing and in numerical flow computation have one major problem in common; namely that they require to model an infinite flow field. For two dimensional flows the numerical worker has a powerful tool not available to the experimenter in that he can use a conformal transformation to map the entire flow into the interior of a circle and satisfy the conditions at infinity at a single point. However if the computation is to be done in the physical plane rather than in a transformed plane the computational grid must be terminated in just the same way that the tunnel flow must be limited in its extent. The same trade off applies in both fields; as the tunnel or computational grid are made larger with respect to the model size the results become more accurate but tunnel cost and computing time become prohibitively large.

Murman & Cole (1971) developed a method of limiting the size of the computational grid while still satisfying the far field boundary conditions. Their approach was to match the numerical solution of the near field to an analytic representation of the far field, at the grid boundaries, to satisfy in effect the far field boundary conditions. Two dimensional calculations using this method have shown excellent agreement with exact solutions for a number of test cases. Analytic expressions for the far field flow about three dimensional lifting wings at transonic speeds are available (Klunker,1971) so the procedure is not limited to two dimensional or wholy subsonic flows.

It would appear that an identical procedure could be applied to wind tunnel wall modifications. Based on the model geometry, measured lift and possibly measured drag it should be possible to compute the wall shape which satisfies the conditions at infinity, using the appropriate analytic expression for the far field flow. The wall modifications will alter the model lift and drag, so the wall reshaping would require to be an iterative process. However, since the computation required for each iteration is limited to the substitution of values into an expression, the computing power required would be minimal.

In the following section an alternative method of wall shaping which requires no computation will be described.

4 AERODYNAMICALLY ACTUATED WALLS

The simplest and most elegant method of producing a self streamlining tunnel would be to devise a set of walls which, under the action of the model pressure field, deform in the same way as a streamline in an infinite flow field. The use of a simple tensioned membrane has been suggested for this purpose but, unfortunately, elementary considerations indicate that such a wall would collapse towards a model rather than bulge to follow streamlines.

The basic requirement for an aerodynamically actuated self streamlining wall for subsonic flow is that it should have a radius of curvature approximately proportional to the local pressure coefficient and to β (where $\beta=\sqrt{1-M^2}$ and M is the free stream Mach number). The wall curvature should be concave towards regions of low pressure. A proposal for a two dimensional wall arrangement meeting these requirements is described below.

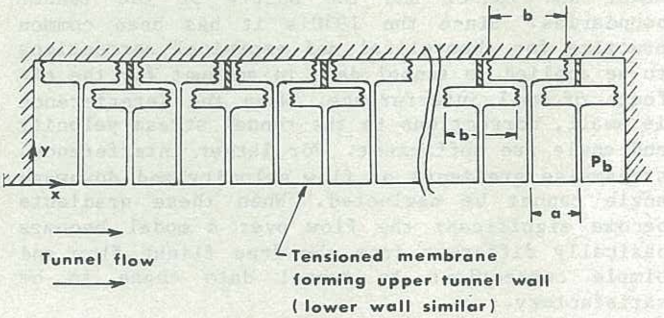

Figure 1 Arrangement of Proposed Wall

4.1 Description of Concept

The physical arrangement of the proposed self adaptive wall is shown in Figure 1. A flexible membrane forming the actual flow boundary is subject to a streamwise tension (T) which is made inversely proportional to β. In the two dimensional configuration considered here the edges of the top and bottom membrane walls are assumed to slide without friction on the rigid sidewalls. The membrane wall is equipped with a number of equally spaced pressure tappings which communicate with flexible bellows via rigid connecting tubes. The total bellows area to wall area ratio (b/a in Figure 1) must exceed 1.0 and the highest possible value should be used to maximise the wall tension and thus minimise bulging between pressure tappings. With the two layer bellows arrangement shown in Figure 1 b/a ratios approaching 2 can be achieved. With more complex bellows arrangements more desirable higher values of b/a can be obtained. The volume behind the wall membrane and containing the flexible bellows is subject to a backing pressure (Pb) which is adjusted so that the sum of the wall force components in the y direction at the two ends of the wall is equal to zero. From Figure 1 it is evident that this condition can be met using two angle transducers and adjusting Pb until the wall slopes at the two ends are equal.

The arrangement described above has equally spaced pressure tappings and a constant bellows size along the entire length of the wall. This was done for simplicity of exposition. In practice, to minimise manufacturing difficulties, the tappings and bellows would probably be spaced more closely in the critical region near the model and more widely elsewhere.

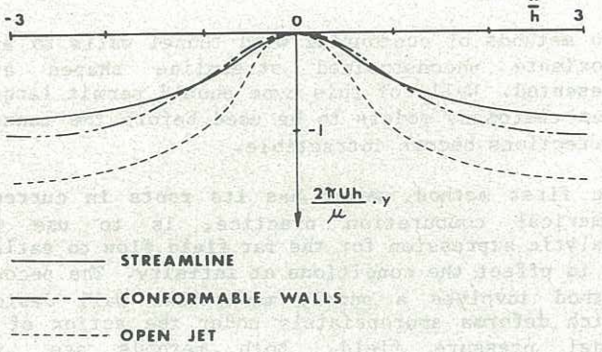

Figure 2 Wall Shapes. Doublet M = 0

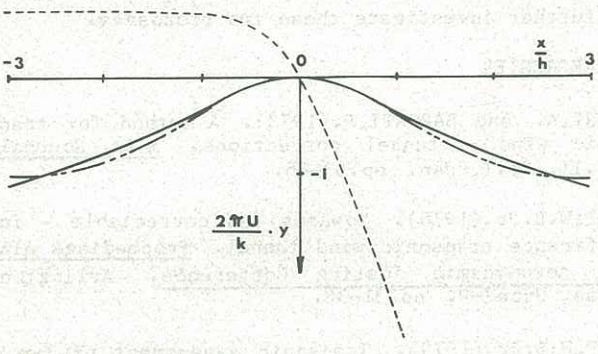

Figure 3 Wall Shapes, Vortex M = 0

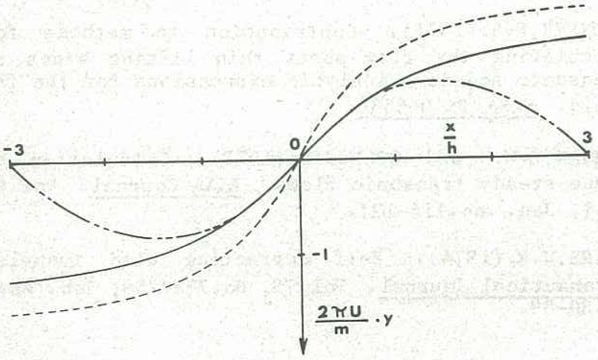

Figure 4 Wall Shapes, Source M = 0

4.2 Calculated Wall Shapes.

Numerical calculations were carried out of the shape assumed by the proposed walls when subject to the pressure field of two - dimensional doublet, vortex and source singularities in a subsonic compressible free stream. The walls were three tunnel heigts long with the singularity located at mid height and length of the test section. There were 30 pressure tappings in each wall and the b/a ratio was set at 1.95. For comparison purposes the free jet and

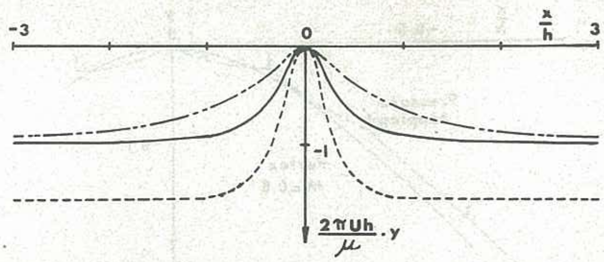

Figure 5 Wall Shapes, Doublet M = 0.95

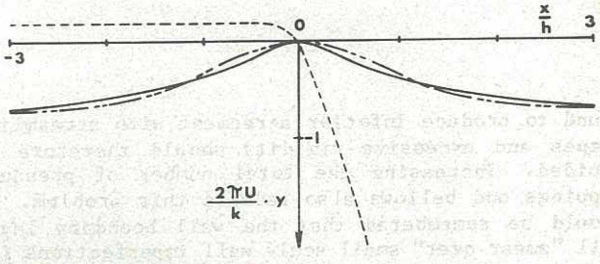

Figure 6 Wall Shapes, Vortex M = 0.95

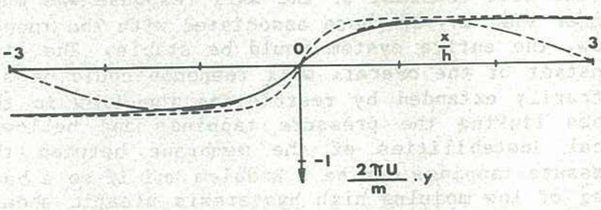

Figure 7 Wall Shapes, Source M = 0.95

unconstrained streamline shapes were also calculated.

A single value of T/β was found which gave good agreement near the model location between calculated wall shapes and unconstrained streamline shapes for doublet, vortex and source singularities at Mach numbers from 0 to 0.95. A number of the computed wall shapes are plotted in Figures 2 to 7. To simplify comparisons the wall and streamline shapes have been shifted to coincide at x=0. This is legitimate since it is equivalent to only a small change in tunnel height. The definition of the curves on all of these Figures is given in Figure 2. In the axis scales U=free stream velocity, h=tunnel semi height, μ=doublet strength, k=vortex strength, and m=source strength.

4.3 Further Developments

One of the basic problems with the proposed conformable walls is that the membrane tends to bulge between the pressure tappings under the action of the pressures acting on either side. A typical example demonstrating this, using the walls discussed in the previous section, is shown in Figure 8. This bulging can be reduced by increasing the b/a ratio with a consequent increase in wall tension. Alternatively the membrane could be arranged to have some bending stiffness with a consequent reduction in the maximum curvature. However wall stiffness has been

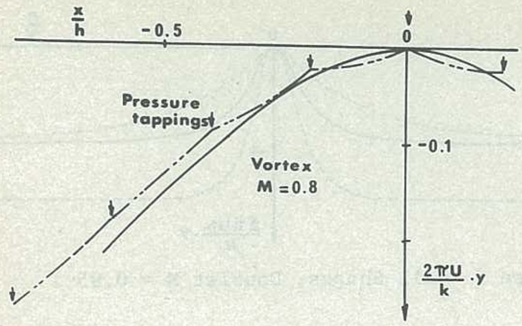

Figure 8 Wall Bulging Between Tappings

found to produce inferior agreement with streamline shapes and excessive rigidity should therefore be avoided. Increasing the total number of pressure tappings and bellows also reduces this problem. It should be remembered that the wall boundary layer will "smear over" small scale wall imperfections (as well as altering the effective wall shape to some extent).

The stability of a tunnel fitted with the proposed wall configuration has not been investigated in detail. However it seems reasonable to assume that if the time constant of the wall response was much longer than any of those associated with the tunnel flow, the entire system would be stable. The time constant of the overall wall response could be arbitrarily extended by restricting the flow in the tubes linking the pressure tappings and bellows. Local instabilities of the membrane between the pressure tappings may be a problem and if so a backing of low modulus high hysteresis plastic should effect a cure.

The basic wall design described has fixed test section entry and exit dimensions. For a model with a large wake the agreement between wall shape and streamline shape could be considerably improved if the test section entry or exit dimensions could be varied. It is tentatively suggested that either the entry or exit dimensions be varied until the sum of the wall slopes at the two ends is zero. This would only require one additional actuator since the wall slopes are already measured for the setting of the backing pressure.

To extend the present concept to a three dimensional test section the following suggestions are offered. The tunnel test section should consist of a continuous membrane in the form of a tube of suitable shape. The membrane should be of an anisotropic material with a high axial modulus of elasticity and a low circumferential modulus. The surface of the membrane should be covered with pressure tappings on a fixed grid spacing (the more tappings the better). The bellows connected to the pressure tappings should apply a force along the local normal to the undeflected wall. Wall slopes should be measured at a number of points in the test section entry and exit planes with mean values being used for the setting of wall backing pressure. A check on the validity of the above suggestions awaits the availability of suitable three - dimensional streamline data.

5 CONCLUSION.

Two methods of contouring wind tunnel walls to approximate unconstrained streamline shapes are presented. Walls of this type should permit larger than customary models to be used before the tunnel corrections become intractible.

The first method, which has its roots in current numerical computation practice, is to use an analytic expression for the far field flow to satisfy in effect the conditions at infinity. The second method involves a purely mechanical wall design which deforms appropriately under the action of a model pressure field. Both methods are, in principle, applicable to two and three dimensional flows.

A pair of flexible walls are currently being designed for the ARL 533mm by 813mm transonic wind tunnel to further investigate these two proposals.

6 REFERENCES

FERRI, A. and BARONTI, P. (1973). A method for transonic wind - tunnel corrections. AIAA Journal. Vol.11, No.1, Jan. pp.63-66.

KEMP, W.B. Jr. (1976). Towards the correctable - interference transonic wind tunnel. Proceedings AIAA 9th Aerodynamic Testing Conference. Arlington, Texas, June7-9. pp.31-38.

KEMP, W.B. Jr. (1979). Transonic assessment of two - dimensional wind tunnel wall interference using measured wall pressures. Advanced Technology Airfoil Research - Volume 1. NASA CP-2045 Part 2.

KLUNKER, E.B. (1971). Contribution to methods for calculating the flow about thin lifting wings at transonic speeds - Analytic expressions for the far field. NASA TN D-6530.

MURMAN, E.M. and COLE, J.D. (1971). Calculation of plane steady transonic flows. AIAA Journal. Vol.9, No.1, Jan. pp.114-121.

SEARS, W.R. (1974). Self correcting wind tunnels. Aeronautical Journal. Vol.78, No.758/759, Feb./Mar. pp.80-89.