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Development of a Self-Streamlining Flexible Walled Transonic Test Section

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This design eliminates the uncertainties found in data from conventional ventilated transonic test sections. The sidewalls are rigid, and the flexible floor and ceiling are positioned by motorized jacks controlled by an on-line computer to minimize tunnel setting times. The tunnel-computer combination is self-streamlining without reference to the model. Data are taken from the model only when the walls are good streamlines, and can be corrected for the small known but inevitable residual interferences. Two-dimensional validation testing in the Mach range up to about 0.85 where the walls are just supercritical shows good agreement with reference data using a height-chord ratio of 1.5. The work has demonstrated the feasibility of almost eliminating wall interferences, allowing advantage to be taken of the improved flow quality and reduced power requirements or increased Reynolds number inherent with a shallow unventilated test section.

Nomenclature

c	= model chord
C_L	= lift coefficient
C_N	= normal force coefficient
C_P	= pressure coefficient
C_P^*	= sonic pressure coefficient
M_∞	= freestream Mach number
R_c	= chord Reynolds number
u	= local horizontal velocity perturbation
U	= measured local real wall velocity
U_∞	= freestream velocity
v	= local vertical velocity perturbation
V	= calculated local imaginary wall velocity
x	= chordwise position relative to leading edge
X	= horizontal wall coordinate
Y,y	= vertical wall coordinates
α	= angle of attack
ξ	= dummy length variable
γ	= local strength of vorticity

I. Introduction

THE desire to reduce wall interference effects in wind tunnel testing led to the introduction in the United States[1] and Japan[2] of the partially open test section for low-speed testing during the early 1930s. The notion arose from the opposite signs of corrections applicable to completely open and closed test sections. The design of the test section, later given the familiar generic term "ventilated," found particular application in transonic testing where wall interferences were otherwise severe in the extreme. There was however an interim period in the 1940s when other solutions were used for the avoidance of blockage interference. Among them was a transonic flexible walled two-dimensional test section at the National Physical Laboratory[3] (NPL). The object was to shape the floor and ceiling of the test section with screw jacks so that they adopted streamline contours, thus eliminating boundary interference. Since the streamlining methods were time consuming and only approximate, the technique was not developed further at that time (presumably due to the lack of computational support).

The conventional ventilated test section, while relieving blockage interference and allowing transonic testing, unfortunately does not always provide interference corrections which can be confidently applied to the test data. In recent years there have emerged two alternatives to these test sections which attempt to remove this uncertainty.

One is a development of the NPL approach using impervious flexible walls, the subject of this paper, but now involving a new test for correct two-dimensional streamlining and also utilizing the advantages of the computer. The test for streamlined walls is simply that the pressure distribution measured along a flexible wall is compared with that computed for a flowfield imagined passing over the outside of the same wall shape. The distributions are matched when the wall follows an unloaded streamline.‡ A low-speed Self-Streamlining Wind Tunnel (SSWT) was commissioned[4,5] in 1973 to explore the new technique. The study and development of this type of test section has continued principally for transonic testing.[6-9] The linking of flexible walled test section technology with cryogenic tunnels is underway; a ⅓ m transonic test section is being developed in the United States, while an intermittent tunnel is being adapted in France.[10]

The second recent alternative is a modification of the ventilated test section proposed independently by Ferri and Baronti,[11] and Sears[12] and now under study in other establishments.[13,14] In these two-dimensional test sections, top and bottom wall interference is eliminated not by wall curvature but by providing a controlled flow of air through the wall perforations. Flow control is by means of segmented plenum chambers, each with its own air regulator valve. Measurements of velocity vectors near to the walls, just inside the test section, provide information on the flow adjustments required to minimize wall interferences.

Any claim for interference-free flow requires some qualification. It relates only to the effects of the top and

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‡This approach was proposed, placed on record, and witnessed in the invention declarations "Transonic Test-Section Design" and "Self Adapted Flexible Test Section Walls" by M. J. Goodyer in July 1972, retained for reference at NASA Langley Research Center, Hampton, Va.

bottom walls, and here one has to recognize that because of normal experimental and theoretical errors there will be residual interferences present, although they will normally be small. Further, in all wind tunnels there is an interference induced by the finite length of the test section, and in two-dimensional testing there may also be sidewall effects.

The two approaches outlined above have much in common: they both provide control over the flow adjacent to two test section boundaries and also require measurements to be taken along these boundaries. Both techniques can be used either to eliminate boundary interference in principle, or to reduce boundary interferences while providing information which allows corrections to be made for residual interferences. Further, they require for their practical implementation the on-line use of, at least, a minicomputer.

In addition to the elimination of boundary interferences in two-dimensional testing, the flexible walled test section offers the following advantages over conventional ventilated test sections:

1) Higher Reynolds number from a given size of wind tunnel, arising from a larger model in a different shape of test section.

2) Lower turbulence level with impervious walls.

3) Reduced drive power following elimination of ventilation, especially at transonic speeds.

4) Ability to simulate model environments other than steady motion in an infinite flowfield.

The work summarized in this paper provides information on points 1 and 4. It will be seen that interference-free two-dimensional testing may be routinely carried out at Mach numbers up to about 0.85 at moderate angles of attack, using an airfoil model relatively large in relation to the test section.

II. Principles of Flexible Wall Streamlining

The interference created by a wall depends on its loading which, in flexible walled test sections, is determined locally by the differences in velocities between the real flow over the wall inside the test section and an imaginary flow over the outside of the wall. The latter is computed from the shape of the wall, currently by using linearized compressible inviscid flow theory. Wall loading is brought to zero by adjustments of wall shapes toward streamline contours in iterative steps using methods described in Sec. IV. The only information needed for streamlining in two-dimensional testing is therefore the wall geometries, tunnel reference flow conditions, and flexible wall longitudinal static pressure distributions. These "wall data" are inherently easy to obtain for each iteration (one iteration comprises setting the walls to known shapes, measuring the wall pressures, and computing new wall contours). The "model data" are taken after a streamlining cycle is complete. (A streamlining cycle consists of a series of iterations bringing the walls to satisfactory streamlines).

It can be seen that the tunnel itself, influenced by disturbances created by the model, provides the information for streamlining, hence the use of the phrase "self-streamlining." So, in operating the tunnel, nothing need be assumed about the shape or position of the model. The walls may also be streamlined with no model present; this merely gives nominally straight walls and a constant Mach number along the test section.

The operating procedure is summarized in the flow diagram of Fig. 1. In this description it is assumed that the walls are to be restreamlined after a small change in the test conditions such as model attitude or Mach number. Tunnel pressures are scanned to complete the "wall data." From these measurements a new pair of wall contours are computed together with their imaginary-side or "external" velocity distributions. An assessment is made of the quality of streamlining as indicated by the levels of residual wall interferences. If the walls are unsatisfactory streamlines, they are driven to new contours, the wall pressures rescanned, and the interferences reassessed. The procedure is repeated until the interferences are acceptably small.

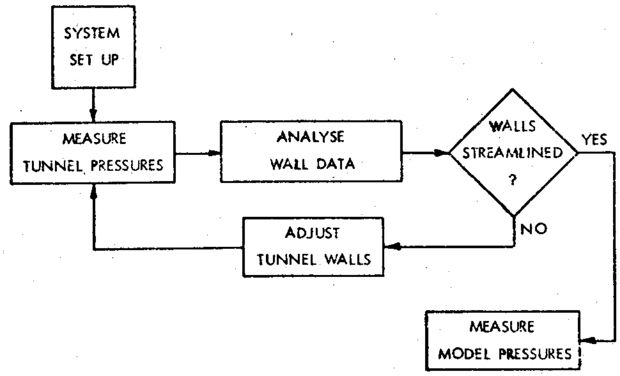

Fig. 1 Self-Streamlining Wind Tunnel operating procedure.

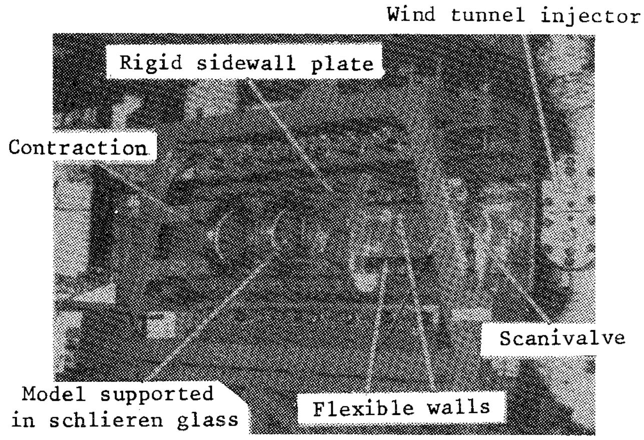

Fig. 2 Transonic Self-Streamlining Wind Tunnel.

The iterative nature of the streamlining cycle coupled with numerous measurements and involved calculations make mandatory the use of a computer for a rapid execution of the cycle. The self-streamlining procedure is ideally suited to on-line computer control because of the continual exchange of information between tunnel and computer. The impracticality of working without a computer perhaps explains the delay in flexible wall research until recently.

Aside from the simulation of an infinite flowfield, flexible walled test sections may be used in modes simulating other two-dimensional flows.[4,7,15] Among the most interesting are:

1) Ground effect: one wall is held straight, while the other is streamlined.

2) Cascade: walls are adjusted for equal pressures on opposite sides of the test section, parallel to the plane of the cascade, with one cascade element apart.

3) Steady pitching: walls are curved to produce a curved centerline to show the effects of the pitch rate.

It has already been demonstrated that it is relatively easy to use these modes at low speeds with a flexible walled test section. This paper is devoted to the mode of infinite flowfield simulation up to transonic speeds.

III. Transonic Self-Streamlining Wind Tunnel (TSWT)

The goal of a practical transonic facility has led to the development of a sophisticated flexible walled test section as seen in Fig. 2. The TSWT project, taking advantage of on-line computer control, has allowed extensive investigations of the flexible wall testing technique at high speeds.

Test Section Design

The new test section inserts into an existing induced-flow, closed-circuit atmospheric wind tunnel, with stagnation conditions of ambient pressure and temperature. Mach

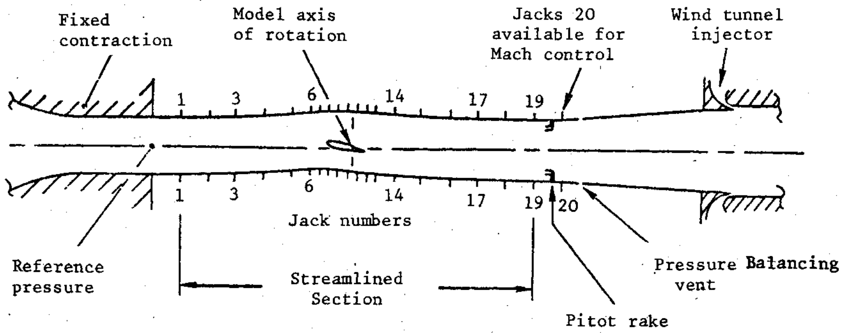

Fig. 3 Transonic flexible walled test section layout.

number in the tunnel is continuously variable from low subsonic to low supersonic by adjustment of inducing air pressure and test section wall contours.

A schematic layout of the test section is shown in Fig. 3, which represents what is currently regarded as a near-optimum design of a flexible walled test section. The test section is 15.24 cm (6 in.) wide and is shown at a nominal depth of 15.24 cm (6 in.) equal to 1.5 model chords for the data presented here. Each flexible wall, 11 chords (1.12 m, 44 in.) long is anchored to the fixed contraction and is controlled by a system of 20 jacks. Each jack except No. 20 is attached to a transverse wall rib by two thin metal flexures. Each rib supports three surface static pressure tappings spanning the wall but only the centerline tap is used for two-dimensional testing, the others are for use in future three-dimensional work. The last downstream jacks (No. 20) control the free ends of the flexible walls in sliding joints coupled to a variable diffuser.

The two-dimensional airfoil model is mounted on schlieren windows integral with the rigid sidewalls as shown in Fig. 2. There is no provision for sidewall boundary-layer control. The quarter-chord point of the model translates vertically with angle of attack to minimize wall curvature and to help centralize the model between the walls in the presence of changing up- and downwash.

The flexible walls are made from woven man-made fiber laminate, and deform between jacks to contours dictated by structural properties rather than to streamlines. Analysis[16] has substantiated a largely intuitive feeling of a requirement for the close grouping of jacks near the model to insure adequate control of wall shape. There are therefore eight jacks per wall with a spacing of ¼ model chord (2.54 cm, 1 in.) close to the model, while upstream and downstream the jack spacing increases to ¾ chord.

Jacks are housed in test section "backbones" and the volume formed between the backbone and the wall is vented to the test section to minimize wall pressure loading. Various wall thicknesses (depending on jack spacing) insure that the walls are rigid to pressure bending while remaining flexible enough for streamlining. Total jack travel has been set at 2.54 cm (1 in.) from considerations of theoretical streamline shapes. However, the test section design is versatile and can adapt in terms of travel to accommodate future research requirements.

Low-speed experience[15] showed the need for rakes of pitot tubes downstream of the model to prove the existence of potential flow cores between the model wake and wall boundary layers. The rakes are mounted between jacks 19 and 20 and extend a maximum of 2.54 cm (1 in.) from the walls (see Fig. 3). Provision is made on the sidewall for a wake traverse and the support of three-dimensional models.

Control System

The control system concept outlined in Sec. II has been applied to TSWT. The basis of the control system is shown in Fig. 4. The indicated interaction between the wind tunnel, operator, and computer generates the required test data.

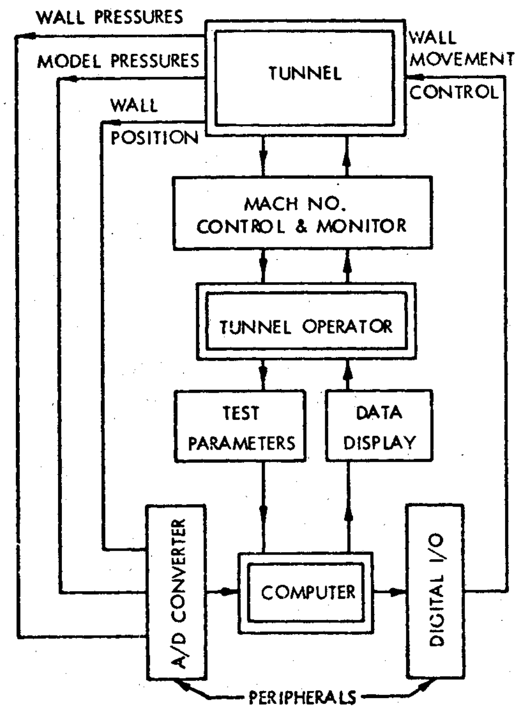

Fig. 4 Transonic Self-Streamlining Wind Tunnel control system outline.

The jacks are driven by stepper motors and controlled by an on-line computer by using a feedback of jack position from linear potentiometers. Setting accuracies of better than 0.127 mm (0.005 in.) are possible. Wall and model pressures are measured by a Scanivalve module system allowing 192 tappings to be sampled in about 6 s.

The heart of the control system is a dedicated DEC PDP 11/34 which communicates with the wind tunnel through its peripheral devices using digital and analog signals. The system hardware is designed for four functions: wall movement, wall pressure measurements and model data acquisition, wall position sensing, and system monitoring. Software has been developed using a versatile modular architecture and is written in FORTRAN IV language. This software will handle the exchange of information between the wind tunnel and computer and perform data reduction functions. The control system is complex and safety checks are included in the software to allow for possible failure.[16] There is capacity available for other tunnel functions. At present these include the automatic control of Mach number with jacks 20 and the control of a wake traverse.

The time to complete a streamlining cycle varies from about 1½ to 5 min, depending on the severity of changes to the test conditions between cycles. A cycle for the manual SSWT could take up to two working weeks!

IV. Wall-Setting Strategies

A good wall-setting strategy is a necessary basis for the rapid convergence of wall contours through successive approximations to streamline contours. The function of the adopted strategy is twofold: 1) to compute a set of imaginary wall pressures (or velocities) for given wall contours and 2) to predict from the wall loading the wall movements required for streamlining.

In general, the viscous effects of the model are contained within the test section boundaries and therefore the imaginary flowfields are irrotational when free from shocks. At low speeds, the irrotational imaginary flowfields can be solved exactly using potential flow theory, while linearized compressible theory appears adequate for transonic speeds to where the walls become critical. The imaginary flowfield is less severely perturbed than the flowfield close to the model, hence the accuracy of the imaginary flowfield computations can be expected to be better than theoretical estimates of model performance.

The current wall setting strategy is the product of gradual development involving innovation with continual theoretical and experimental checks. Initial work with SSWT used a nonpredictive wall setting strategy[4,7,18,19] but a new predictive rapid convergence method was developed by Judd[5,18] which reduced the streamlining cycle to about two iterations from eight[16,17] at low speeds.

This method considers each wall separately in the presence of the model. The wall is represented by a vortex sheet where the local vorticity $\gamma(\xi)$ is derived from the local wall loading at position ξ. The sheet is always assumed flat. Changes in wall boundary displacement thickness and velocity perturbations are assumed small. The object in moving a wall is to eliminate its loading. The local normal velocity component induced by the vorticity has therefore to be replaced by a change in the component of the freestream. To adjust this component, the wall slope is modified locally by the amount

$$\frac{dy_n(X)}{dX} = \frac{1}{2\pi U_\infty}\int\frac{\gamma_n(\xi)d\xi}{(\xi - X)} \tag{1}$$

at jack location X for the nth iteration.

The predicted position of one isolated wall for the next test is then

$$Y_{n+1}(X) = Y_n(X) + y_n(X) \tag{2}$$

by numerical integration of Eq. (1). The local external imaginary wall velocity $V_{n+1}(X)$ for this new wall shape is immediately found[5,18] using

$$V_{n+1}(X) \simeq \tfrac{1}{2}[U_n(X) + V_n(X)] \tag{3}$$

where $U_n(X)$ is the measured local real wall velocity. So, the imaginary wall velocity for the next wall shape is available from known velocity components, if the walls are set using this strategy.

The analytical prediction of the required wall movement is complicated by the strong aerodynamic coupling between the two flexible walls which introduces the iterative nature of the wall streamlining process. Experimental experience has led to satisfactory methods for coping with the coupling.[16,17]

The need for testing at transonic speeds led to the modification of the predictive method for compressibility effects, using linearized theory.[15] Experiment has shown that this method is reliable up to about Mach 0.85, with typically three iterations required for streamlining at the higher Mach numbers.

Tests have been conducted up to Mach 0.89 where the supercritical flow extends "through" the walls, invalidating the linearized approach. At this high Mach number a reduction in the effectiveness of the strategy was evident in that convergence was neither as rapid nor as stable, and the wall streamlining criterion of small interferences was not completely satisfied. To extend the Mach number further it is now necessary to develop rapid numerical techniques to solve the mixed flows in the imaginary flowfields. The method of predicting wall movement will probably be based on the present method using the improved estimate of wall loading.

V. Test Section Boundary Interference and Information from the Walls

Assessments have been made of interferences from the following sources: 1) approximations in the theoretical basis of the wall-setting strategy[5,18]; 2) finite length of the test section[5,18]; 3) differences between streamlines and the structural shapes of the walls[16]; 4) resolution of pressure and position measurements[4,5,16,18]; 5) computational accuracy.

The wind tunnel system has been designed to limit to acceptably small values the magnitude of errors which can arise from these sources. This policy was adopted partly because the errors would sometimes be of unknown magnitude, but also because we believe it to be undesirable to apply anything but small corrections to model data in two-dimensional transonic testing.

During streamlining the walls provide continuous information on the magnitudes of the remaining wall-induced errors, called "residual interferences." Since wall loading is already represented by distributed vorticity for streamlining purposes, its effect can be assessed in the region of the model. The option exists of terminating the streamlining process before the walls appear perfect and applying corrections to the model data, or proceeding until the walls are streamlined.

Typical effects of streamlining on the wall-induced velocity perturbations along the centerline of the test section are shown in Fig. 5, for a NACA 0012-64 section at $M_\infty = 0.7$ and $\alpha = 4$ deg. Gross interference exists with the walls straight: the horizontal perturbation u/U_∞ shows the blockage effect of the model and its wake; the vertical perturbation v/U_∞ shows the lift interference centered about the model ¼ chord. Both velocity perturbations are reduced to less than ¼% by streamlining.

The measures of the quality of wall streamlining are:

1) E for each wall, the average of the modulus of the imbalance in pressure coefficient between real and imaginary flows.

2) Angle-of-attack error induced by both walls at the airfoil leading edge.

3) Camber induced by both walls.

4) Streamwise velocity error at the ¼ chord point.

The last three effects are converted to estimated errors in C_L. Experience has shown that for good streamlines E should be less than 0.01 on both walls. Typically this limit results in

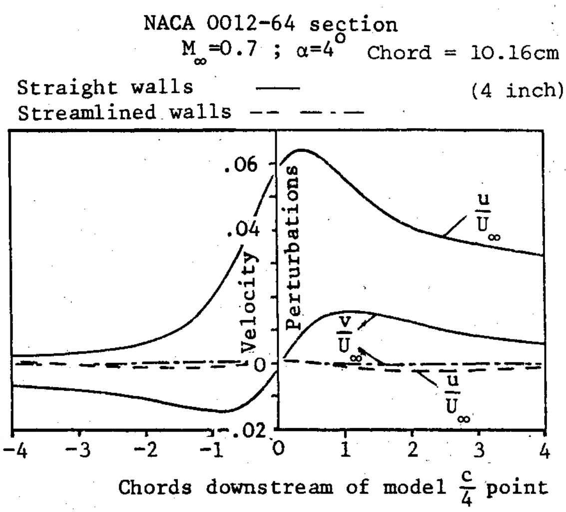

Fig. 5 Wall-induced velocity perturbations along TSWT centerline.

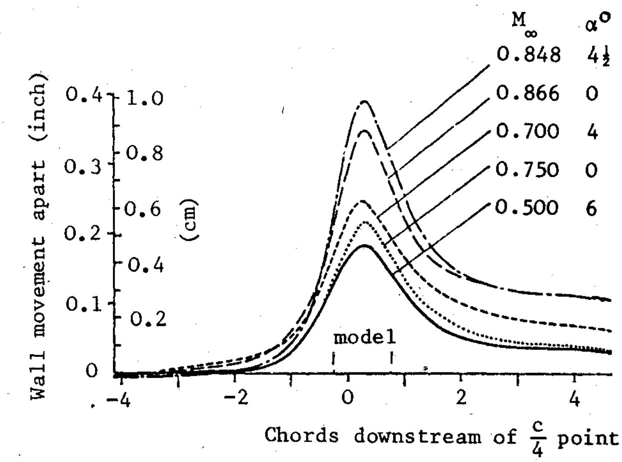

Fig. 6 Relative separation of streamlined walls for various model attitudes and Mach numbers.

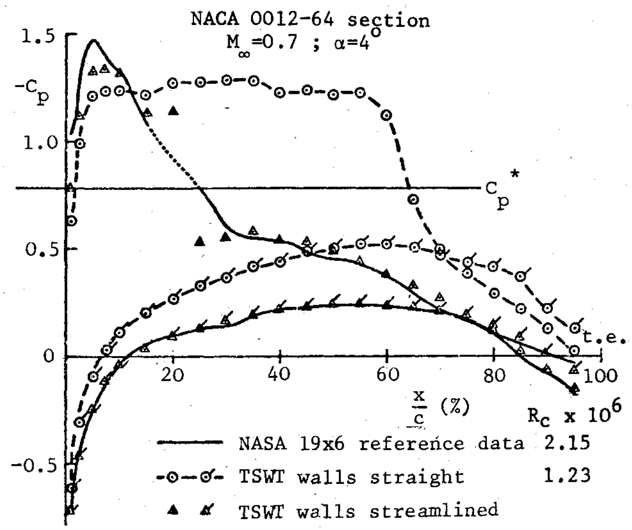

Fig. 7 Model pressure distributions with walls straight and streamlined compared with reference data, $M_\infty = 0.7$.

the following maximum wall-induced errors at the model: α, 0.015 deg; chamber, 0.07 deg; and C_P, 0.007. With wall-induced errors larger than these there is a risk in transonic testing of inducing position errors in the model shocks.

In principle, the "wall data" also contains information on lift, pitching moment, wake displacement thickness,[15] model aerodynamic shape, and pressure distribution throughout the test section. In practice, only lift and wake displacement thickness have so far been satisfactorily estimated from the wall data. Inadequate resolution of the wall measurements currently prevents a satisfactory assessment of the others.

The displacement thickness of the model wake is immediately available from the movement apart of the flexible walls downstream of the model after wall streamlining. Examples of this are given in Fig. 6, showing the relative separation of the walls compared with straight walls for various model attitudes and Mach numbers. Markedly different wake thicknesses are produced by the effects of change of lift and shock-induced separations on the model. Interestingly, the wall shapes show the increase of model blockage with Mach number. Lift can be extracted from the measured pressure distributions along the flexible walls together with vertical components of momentum at the test section ends. The average difference between C_L derived from "wall" and "model" pressure data for all cases analyzed (representative of all TSWT tests) is 0.011.

In summary: 1) it has been shown that the "wall data" provides essential information for wall streamlining, some estimate of model performance, and a method of assessing residual interferences; and 2) it seems likely that flexible walled test sections can provide more reliable boundary information than conventional transonic designs. The notion of the correctable interference wind tunnel postulated by Kemp[20] has been validated in some of this testing.

VI. Validation Model Data and Tunnel Operating Experience

Transonic Model Aerodynamic Data from TSWT

The validation airfoil is NACA 0012-64 of 10.16 cm (4 in.) chord. This model had previously been tested in the NASA Langley Research Center 19×6 in. blowdown transonic tunnel fitted with a slotted test section, our source of reference data. The comparison here is between this reference data taken at a height-chord ratio of 4.75, with TSWT data taken at a height-chord ratio of 1.5. In the following discussions of representative results two general points should be noted:

1) Streamlined wall airfoil pressure distributions are compared with the reference data at near equal values of C_N. The reference data are uncorrected for any interference.

2) The Reynolds number of the reference data was approximately 85% higher than in TSWT.

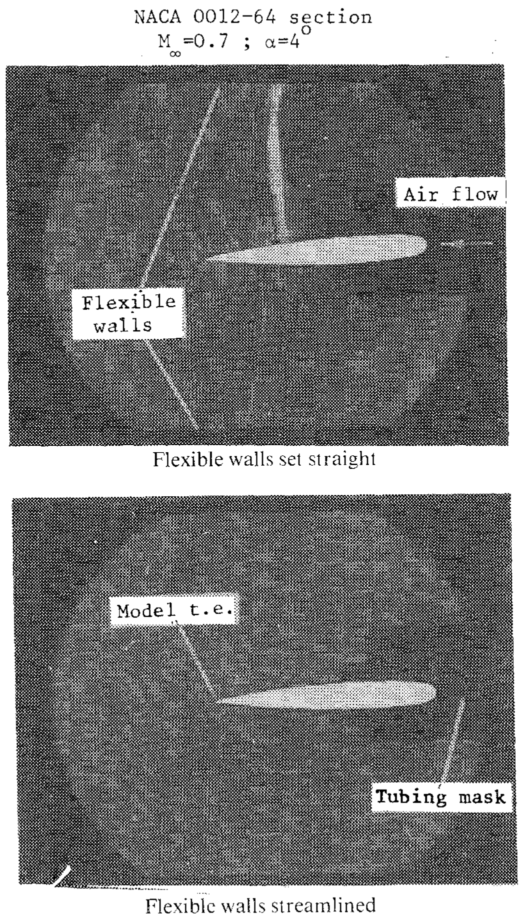

Fig. 8 Spark schlieren pictures show the effects of wall streamlining.

Much experience has now been gained during over 300 tunnel runs, most at Mach numbers up to 0.85. At subsonic and low transonic speeds it is possible to run with the walls straight as well as streamlined. Representative of the body of data taken at these conditions is the test case $M_\infty = 0.7$, $\alpha = 4$ deg. Airfoil pressure distributions are given on Fig. 7. Gross interference is evident with the walls straight, a high value of lift arising from the upper surface shock lying too far aft at about 65% chord and incidentally extending to the top wall. After streamlining the shock moved to about 22% chord and away from the wall, giving a pressure distribution which is in

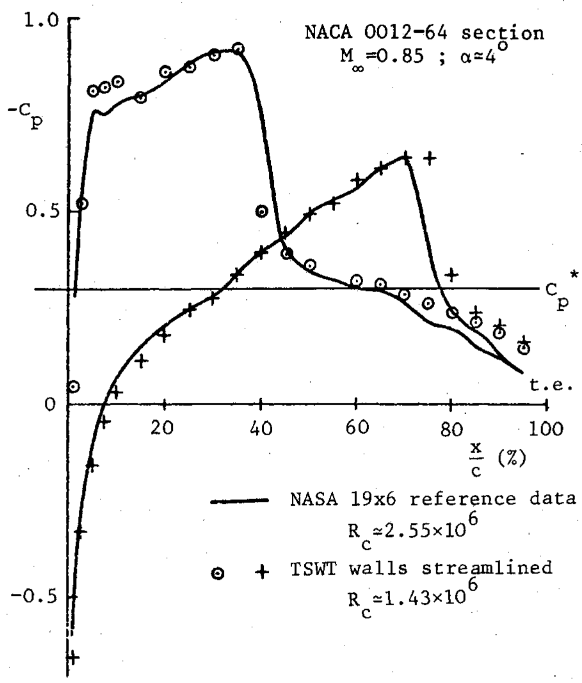

Fig. 9 Comparison of model pressure distribution with reference data, $M_\infty = 0.85$.

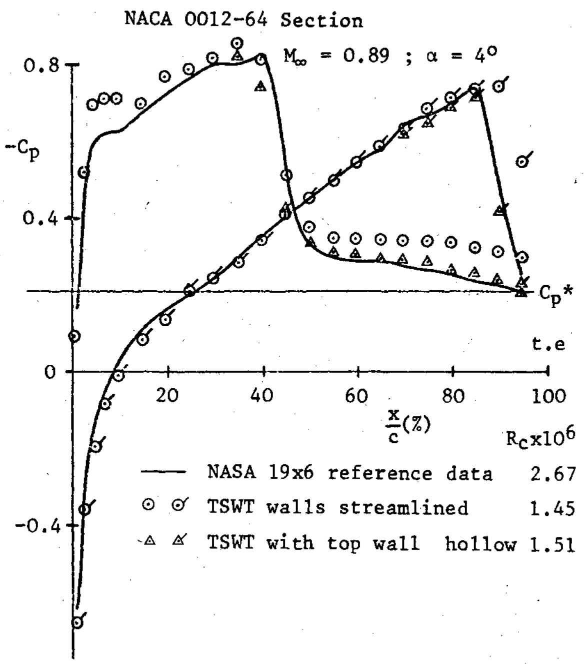

Fig. 10 Effects of allowance for shock/wall boundary-layer interaction on model pressure distributions compared with reference data, $M_\infty = 0.89$.

good agreement with the reference data. The schlieren photographs in Fig. 8 also illustrate the powerful effects of streamlining. The small differences in the wall positions can be discerned.

Figure 8 serves to illustrate a point which became apparent as the testing proceeded. The airfoil shock is normal in its outer reaches and therefore is not reflected from the flexible wall. The wall itself supports the pressure rise and prevents the flow direction change downstream of the shock which might otherwise occur with a shallow ventilated test section.

A series of data was taken at $M_\infty = 0.85$ where it was found that upper and lower shock locations and shapes were sen-

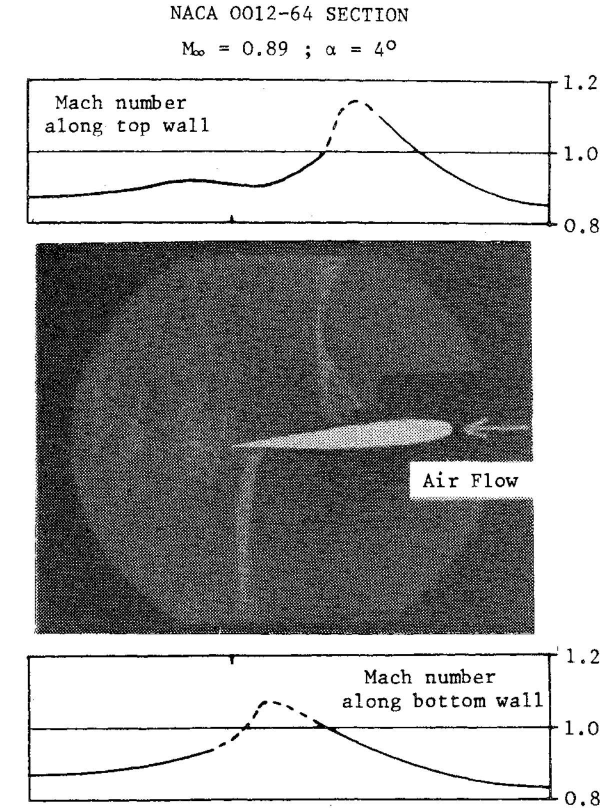

Fig. 11 Spark schlieren picture with wall Mach number distribution, $M_\infty = 0.89$.

sitive to transition fixing on the airfoil. Since the reference data show characteristics of a turbulent boundary layer at the upper surface shock with and without fixing, the comparisons of TSWT data with the reference data are made with the transition fixed at this Mach number, as shown on Fig. 9. There is excellent agreement in general shape and in detail between the two sets of data. The upper and lower surface shock positions coincide to within about 2 and 3% of chord, respectively, and with pressure orifices spaced at 5% chord it is difficult to be more precise. It should be noted that these good results were obtained despite the upper shock extending to the top wall where a maximum Mach number of 1.047 was recorded. The linearized theories should not cope precisely with this flow.

At higher Mach numbers the model shock/wall boundary-layer interaction is strong and it is necessary to account for the change in wall boundary-layer displacement thickness. This is illustrated by data from tests at $M_\infty = 0.89$ and $\alpha = 4$ deg. The local Mach number on the top wall reached about 1.1 ahead of the shock and the boundary-layer displacement thickness increased by about 80% through the shock.§ With the walls streamlined, there is a noticeable effect on model pressures due to the introduction of a localized hollow in the top wall, to accommodate the thickening. Figure 10 shows the two airfoil pressure distributions with and without the hollow, compared with reference data. It can be seen that introducing the hollow changed the pressure distribution and moved the airfoil lower shock significantly, to give good agreement with the reference data. The presence of boundary-layer interactions at model and wall is shown by the spark schlieren photograph in Fig. 11 for the above test case, with a top wall hollow introduced. Reproduced to scale are the distributions

§This work formed part of a Bachelor degree dissertation by B. Mason who received advice on shock displacement thickness effects from Dr. J. Green, Royal Aircraft Establishment, Farnborough, England.

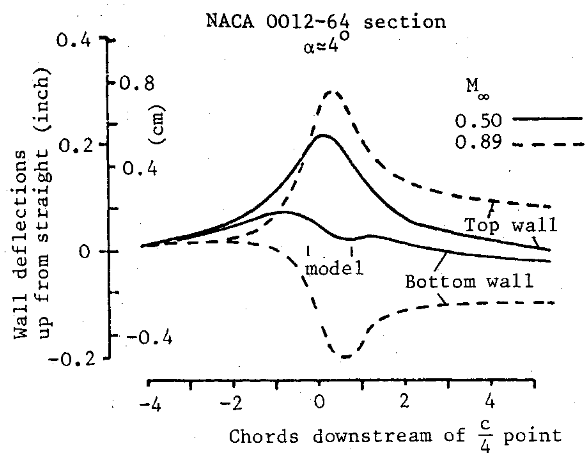

Fig. 12 Effect of Mach number on streamlined wall contours.

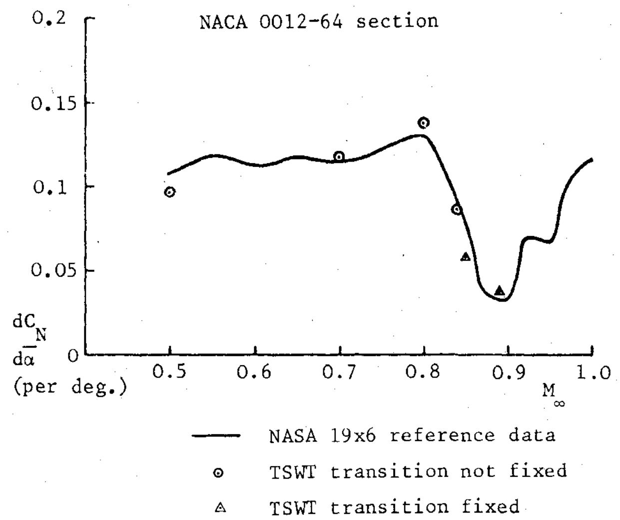

Fig. 13 Comparison of TSWT normal force slopes with reference data over M_∞ range.

of wall Mach number indicating the extent of the supercritical regions.

A comparison of streamlined wall contours is interesting. Figure 12 shows the contours for two markedly different cases, the principal variable being the Mach number. The effect of compressibility is seen to demand more pronounced wall movements with the increase in Mach number. At the higher Mach number the walls have moved apart a maximum distance roughly equal to the section thickness, while the inprint of the airfoil in the bottom wall is clear at the lower Mach number.

Accumulated airfoil data[21] are summarized in Fig. 13, which shows the normal force coefficient slope as a function of M_∞. Streamlined wall TSWT data are compared with reference data. There is very encouraging agreement, particularly in the reproduction of the shock stall. This evidence coupled with operating experience leads to a belief that two-dimensional validation is complete at Mach numbers up to about 0.85.

Operating Experience at Transonic Speeds

Two limits to freestream Mach number have been encountered. The first was test section choking with the walls set straight. This was overcome by the use of test sequences where the walls were moved apart to known contours for moderate M_∞ or α, resulting in subcritical walls and an unchoked test section; then the required M_∞ was achieved, followed by a streamlining cycle.

The second limit occurred at higher Mach numbers (>0.8) where supercritical flow extended to the flexible walls with the size of model shown under test in Fig. 11. The tunnel was then choked even with streamlined walls and the shock positions became sensitive to the inducing air pressure, while M_∞ was insensitive. Flow downstream of the shocks was controlled and stabilized with a secondary throat formed by jacks 20 at the downstream end of the test section.

The largest zone of near-sonic flow will occupy the test section with this model at $M_\infty \approx 0.9$, where the sensitivity of model pressures to wall movement will probably be a maximum. Observations at Mach 0.89 have shown that wall movements as small as 0.1 mm (0.004 in.) produce noticeable effects at the model in terms of shock movement. Model pressures are insensitive to such small wall movements at Mach numbers less than about 0.85.

By limiting the increments in the variables α and M_∞ to values typical of conventional aerodynamic tests, between streamlining cycles, it is normal to streamline in just one iteration. This is a good illustration of the power of the predictive streamlining strategy, which is about as efficient as it is possible to be. Since the computing time is short, any further reduction in streamlining time now depends mainly on improvements in the speed of the wall movement. Of course, no restreamlining is required with the change of M_∞ at low speeds. Above about Mach 0.85 with this model the streamlining process becomes less stable due to the inadequacies of the strategy, and more iterations become necessary.

VII. Conclusions

1) The concept of a practical self-streamlining wind tunnel requires the use of a computer for data manipulation and wall control.

2) Tunnel streamlining times as short as 1.5 min are achieved as a result of the adopted setting strategy coupled with automation of the facility using a dedicated mini computer.

3) The rapid wall-setting strategy is effective over the Mach number range up to where the walls are just supercritical. Extension of the test Mach number requires that account be taken of shock/wall boundary-layer interactions, and beyond that the development of a fast numerical technique to solve for mixed imaginary flowfields.

4) Supercritical flow reaching the flexible walls is not a major practical problem since the associated shocks so far observed are locally normal to the wall and do not reflect onto the model.

5) Some measurements of model performance, and also the residual wall-induced interferences, are given by information routinely provided by the flexible walls.

6) The application of the flexible wall technique to two-dimensional testing has been shown to be feasible at low speeds and up to transonic speeds where the flexible walls are just supercritical.

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