NASA Contractor Report 181680

EMPTY TEST SECTION STREAMLINING OF THE TRANSONIC SELF-STREAMLINING WIND TUNNEL FITTED WITH NEW WALLS

M. C. Lewis

UNIVERSITY OF SOUTHAMPTON
Southampton, England

Grant NSG-7172
July 1988

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

SUMMARY

The original flexible top and bottom walls of the Transonic Self Streamlining Wind Tunnel (TSWT), at the University of Southampton, have been replaced with new walls featuring a larger number of static pressure tappings and detailed mechanical improvements. This report outlines the streamlining method, results, and conclusions of a series of tests aimed at defining sets of *"aerodynamically straight"* wall contours for the new flexible walls. This procedure is a necessary prelude to model testing. The quality of data* obtained compares favourably with the *"aerodynamically straight"* data obtained with the old walls. No operational difficulties were experienced with the new walls.

* Quality of data is measured in terms of residual variations in the Mach number distributions along the centreline of the flexible walls.

This Page Intentionally Left Blank

CONTENTS

1. Introduction

Validation data[1,2,3] from the Transonic Self-Streamlining Wind Tunnel (TSWT), at the University of Southampton, has proved the notion that adjusting the top and bottom flexible impervious walls to unloaded streamlines allows the simulation of infinite flow around two-dimensional models. The iterative process of contouring the walls towards streamlines depends on the magnitude of the flow disturbances caused by the model within the test section, and also on computations of imaginary flowfields extending from the flexible walls to infinity. Both quantities depend upon the displacements of the walls from straight. Therefore a prerequisite of TSWT model tests is the determination of straight wall contours. The aim of straight wall contours is to diverge the two flexible walls from geometrically straight, in order to absorb the growth of the displacement thickness of the boundary layers on all four walls of the empty test section. The divergence results in a constant centreline Mach number along the walls of the empty test section equal to the reference value. Wall contours derived in this way are described as *"aerodynamically straight"*. In the streamlining of the walls around a model it has become practice that wall displacements be referenced to the appropriate *"aerodynamically straight"* wall contours. The TSWT has approximately constant stagnation conditions close to atmospheric and in these circumstances the contours are weak functions of air speed. The practice is to regard the contours as functions of reference Mach number.

This report outlines the streamlining method used, results, and conclusions of a series of tests aimed at defining sets of *"aerodynamically straight"* wall contours over a range of Mach number for the recently installed new flexible walls of the TSWT. Initial results from wind-on wall deflection tests are also reported.

2. Experimental Method

The TSWT test section is a nominal 6 inches square in cross section and has impervious flexible top and bottom walls 44 inches in length, each fitted with 20 motorised screw-jacks. The sidewalls are rigid and non porous. Static pressures are measured at each jack position on each flexible wall (except at Jack 20), allowing the local Mach number to be calculated and adjusted by means of jack movement. The tunnel has a closed circuit with induced drive, using dried air at atmospheric stagnation conditions in the test section (see Figure 1 for diagram of test section). The tunnel reference Mach number (M_{∞}) is derived from the settling chamber stagnation pressure and the centre-sidewall reference static orifice positioned level with the anchor point of the flexible walls.

The original flexible walls were in operational use for over 6 years, by which time signs of wear had become obvious. The new flexible walls, which have recently been installed, have an improved jack/wall swinging link mechanism to eliminate some weaknesses which had become apparent in the flexures hitherto used to join the jack pushrods to the wall stiffeners. The weaknesses included occasional flexure cracking and limited slipping of flexure end-fixings. Wall position is measured by monitoring pushrod movement, therefore uncontrolled free play between the pushrods and wall is most undesirable. Figure 2 shows the design of the jack/wall link mechanism now in use. The opportunity was taken to provide an increased number of static pressure orifices on the new walls (5 per jack position) to improve the three-dimensional research capability of the tunnel.

A prerequisite of all tests is the determination of "*aerodynamically straight*" wall contours. As a starting point the top and bottom flexible walls were manually set to geometrically straight contours, parallel to each other and to a pair of test section backbones. When run in this condition the centreline Mach number distribution along the flexible walls are, of course, non uniform due to growth of wall boundary layers. Figure 3 shows an example of the magnitude of the effect at a reference Mach number of 0.63. Towards the downstream end of the test section the centreline Mach number has risen to just over 0.7.

"*Aerodynamically straight*" streamlining diverges the two flexible walls in order to absorb the growth of the displacement thickness of the boundary layer on all four walls of the empty test section. The divergence is a function of Reynolds number and Mach number. In the TSWT the two vary together because of the atmospheric stagnation conditions. The determination of *"aerodynamically straight"* wall contours in tunnels which have the provision for variable stagnation conditions would be a more complex procedure.

The variation of *"aerodynamically straight"* wall contours is, in principle, a continuous function of (in the case of the TSWT) reference Mach number. In past tests[2,3,4], however, it was found that the variations of wall contours were a rather weak function of reference Mach number and it is adequate to determine only a few *"aerodynamically straight"* wall contours and to designate each to a band of reference Mach number.

The maximum nominal reference Mach number at which *"aerodynamically straight"* wall contours were achieved, during the tests under discussion in this report, was 0.8. Streamlining at higher reference Mach numbers was not possible due to a temporary reduction in the pressure of the dried air supply (from 300 to 150 p.s.i.). Past TSWT tests[4], using the original flexible walls, have achieved satisfactory *"aerodynamically straight"* wall contours for reference Mach numbers up to 0.94. The sensitivity of Mach number to flow area, coupled with consequences of the weaknesses in the flexure design, prevented streamlining at Mach numbers higher than 0.94. It is possible that the new flexible walls of the TSWT with their modified jack/wall link mechanism may allow *"aerodynamically straight"* streamlining at higher speeds. *"Aerodynamically straight"* streamlining of the new flexible walls, at reference Mach numbers above 0.8, will commence once the dried air supply pressure has been returned to its original value (timetabled for the latter half of this year).

3. *"Aerodynamically Straight"* Wall Adjustment Strategy

The normal streamlining of the flexible walls around a two dimensional model is achieved by using Judd's predictive wall adjustment strategy[5,6]. However for *"aerodynamically straight"* streamlining the old *"imbalance"* wall adjustment strategy was used. This strategy uses the simple rule that, in subsonic flow, the Mach number at a point on the wall will be reduced by moving the wall locally away from the test section centreline, and vice-versa. The movement of a jack is made proportioinal to the difference between the local (centreline) and reference Mach numbers. Employment of this *"imbalance"* strategy resulted in satisfactory *"aerodynamically straight"* wall contours from geometrically straight contours after not more than 10 streamlining iterations.* Once the first set of *"aerodynamically straight"* wall contours was found the number of iterations required to produce the next set at another Mach number was significantly reduced if streamlining was initiated from the previous *"aerodynamically straight"* wall contour (as opposed to the geometrically straight contour). The relationship between the wall movement (δ_y inches) and the desired change of local Mach number (δM) which was used with this test section varied from

$$\frac{\delta_y}{\delta M} = 0.8 \quad to \quad \frac{\delta_y}{\delta M} = 0.1$$

the value being reduced with Mach number error. In an attempt to reduce the number of iterations required to produce a satisfactory contour, the value of $\delta_y/\delta M$ was chosen by the tunnel operator at the start of each streamlining iteration. However if one value of $\delta_y/\delta M$ is to be used, then 0.4 inches is recommended as this leads to satisfactory wall contours within an acceptable number of streamlining iterations.

4. Discussion of Results

4.1 *"Aerodynamically Straight"* Tests

4.1.1 Summary of Results

"Aerodynamically straight" wall contours for the new flexible walls were determined at reference Mach numbers of 0.3, 0.4, 0.5, 0.6, 0.7 and 0.8

* One streamlining iteration comprises of measuring the local Mach numbers at all jack positions on both walls, then moving all jacks in response to the local errors.

(contours A, B, C, D, E and F respectively). The quality of streamlining is summarised by the standard deviation (σ) of the wall centreline Mach number errors existing at the first 18 measuring points (first 18 jacks) on each wall. Wall adjustments were continued until the standard deviation values of the two walls were small and approximately equal, typically lying in the band of 0.0005 to 0.0035. The standard deviations are weighted by the reference Mach number, and the quality of the streamlining of a pair of walls is then summarised by the average weighted standard deviation (σ_{av}) given by:-

$$\sigma_{av} = \frac{\sigma_T + \sigma_B}{2M_{\infty}}$$

where σ_T, σ_B are respectively the top and bottom wall standard deviations.

Table 1 summarises the *"aerodynamically straight"* performance of the new flexible walls, whilst the Mach number distributions along the walls for each of the contours is shown in Figure 4. Typical *"aerodynamically straight"* wall displacements from the geometrically straight contours are illustrated in Figure 5.

4.1.2 Comparison of *"Aerodynamically Straight"* Performance of Original and New Flexible Walls

Table 2 compares *"aerodynamically straight"* data for reference Mach numbers of 0.7 and 0.8 obtained by:-

1) Wolf - using the original flexible walls early in their operational life (December 1981).

2) Lewis (A) - using the original flexible walls towards the end of their operational life (August 1984).

3) Lewis (B) - using the new flexible walls (December 1985).

Comparison of Wolf with Lewis (A) data indicates the extent of deterioration in performance of the original walls during their operational life. The Lewis (B) data indicates that the *"aerodynamically straight"* performance of the new flexible walls compares favourably with the initial performance of the original walls. The improved jack/wall link mechanism now in use should significantly increase the operational life of the new walls in terms of the rate of deterioration of the standard deviation in wall centreline Mach number.

4.1.3 The Consequence of using Contours Outside their Designated Mach Number Band

The data in Figure 6 demonstrates that the *"aerodynamically straight"* wall contours are a weak function of reference Mach number. Therefore the consequence of using one of the contours at a reference Mach number outside its designated band of validity is not serious. For example the A contour (derived for Mach 0.3) when run at Mach 0.7 showed an average weighted standard deviation value (σ_{av}) of 0.0048, which compares quite well with the value of 0.0037 obtained with contour E (derived for Mach 0.7).

4.1.4 Experimental and Predicted *"Aerodynamically Straight"* Wall Contours

The *"aerodynamically straight"* wall divergence absorbs the growth of displacement thickness of the boundary layer on all four walls of the empty test section. This is demonstrated in Figure 7, where discrepancies between total wall movement from geometrically straight and predicted values are small; the predicted values are 4 times the boundary layer displacement thickness for one wall. The displacement thickness was computed by the following 2 methods:-

1) a numerical solution of the Von Karman momentum integral equation for a turbulent boundary layer (TSWT BL Program).

2) RAE Lag Entrainment turbulent boundary layer program (RAE BL Program).

As expected similar boundary layer displacement thickness distributions are computed by either method for this simple case.

4.1.5 Future Tests

The errors revealed in Table 1 are thought to be quite acceptable for use with TSWT. The *"aerodynamically straight"* wall contours will be used when necessary as a starting point for streamlining with a model present. Table 3 shows the designated band of reference Mach number for each contour. At present it is thought that three-dimensional model testing demands a finer definition of *"aerodynamically straight"* wall contours than two-dimensional testing. Therefore all 6 contours may be required for three-dimensional model tests, whilst only 3 contours (D, E, F) will be used during two dimensional model tests.

Once the tunnel's dried air supply has been returned to its original value of 300 p.s.i. *"aerodynamically straight"* streamlining will commence for reference Mach numbers greater than 0.8.

4.2 Wind-On Wall Deflection Tests

Conventional TSWT control software relies on the position of the flexible walls remaining unchanged between the wind-on and wind-off stages of streamlining. However during some high subsonic two-dimensional model tests[4] using the original flexible walls, wind-on wall deflections (at jack positions) of up to 0.015 inch were experienced compared with their wind-off positions. The wall deflection was almost always towards the tunnel axis indicating a greater plenum chamber pressure than test section pressure. If ignored, wind-on wall deflections of such a magnitude are likely to have a significant effect on the quality of streamlining. Therefore the wind-on wall deflections of the new walls were measured. The test procedure was to continuously monitor wall position at the 20 jack positions on each wall during the wind-on stage of a streamlining iteration. Empty test section results were highly encouraging as no wind-on wall deflections were recorded. Wall deflection tests with a model installed in the test section provide a much more severe test case. However initial low speed (M_∞ not greater than 0.8) two-dimensional model tests indicate no significant wind-on wall movement. Therefore it can be concluded that the new flexible walls have improved the wind-on wall deflection performance of the tunnel.

4.3 Some Cautionary Notes

4.3.1 Repeatability of *"Aerodynamically Straight"* Performance

It has been found that the quality of the results shown in Table 1 cannot always be repeated if for any reason the walls have been moved by their jacks a substantial distance away from straight and are then returned to one of the straight contour sets. However, if the wall setting procedure is repeated or the necessary wall movements are small then reasonable repeatability can be achieved. At present the reason for this is not fully understood.

4.3.2 *"Aerodynamically Straight"* Wall Contours with Centreline Curvature

By changing the streamlining procedure it is possible to derive *"aerodynamically straight"* wall contours that fulfill the standard deviation criteria but do not diverge symmetrically from geometrically straight. Figure 8 shows a wall contour derived by Neal* that produces centreline Mach number standard deviation values for the top and bottom walls of 0.0016 and 0.0012 respectively at a reference Mach number of 0.6, despite top wall displacements between jacks 2 and 9 being negative (that is, towards the tunnel centreline) with respect to geometrically straight. The contour was produced by using a larger $\delta_y/\delta M$ value for the bottom wall than for the top wall during initial streamlining iterations and then using equal values during the final iterations. While this contour does absorb the test section boundary layer displacement thickness (see Figure 9), it should not be used as *"aerodynamically straight"* since the tunnel centreline is curved. The data on Figure 8 suggests a curvature of about 0.1 inches over a 20 inch length of test section. Approximating this to an arc it is easy to show that the curvature of the centreline will induce a camber angle of just

* G. Neal - Research Assistant, Department of Aeronautics and Astronautics, University of Southampton, U.K. (NASA Grant NSG-7172)

over 0.1 degrees over the chord of a typical aerofoil model. Therefore during *"aerodynamically straight"* streamlining it is recommended that wall displacements be carefully monitored to minimise the effect, otherwise there could be questions on the validity of later claims for the quality of streamlining around a model because of uncertainty in the effects of induced camber and on angle of attack.

4.3.3 Off-Centre *"Aerodynamically Straight"* Performance of the New Flexible Walls

The indications of the row of pressure orifices along the centreline of each wall were used in setting the walls, and the performance figures so far presented are for these orifices. The flexible walls have a total of 5 rows of orifices (95 tappings per wall in total - jacks 20 do not have pressure tappings) and it is found that the standard deviations in wall Mach number along off centre rows is higher than along the centreline (see Table 4 and Figure 10*). The most likely reason is waviness in the walls and a monitoring device, designed to be bolted onto the side of the test section in place of the usual sidewall to show defects in wall shape, is presently being manufactured. When completed, investigations will commence aimed at identifying the reason for large variations in wall Mach number across the width of the test section.

5. Conclusions

1) The new flexible walls exhibit no operational difficulties of a mechanical nature.

2) For reference Mach numbers up to 0.8, *"aerodynamically straight"* wall contours have been determined which will be suitable for two dimensional testing.

* See Figure 2 for relative positions of pressure orifices (1), (2) and (3)

3) Care must be taken to ensure that a straight test section centreline exists after setting the walls *"aerodynamically straight"*.

4) Variations of wall Mach numbers across the width of the test section seem higher than necessary. Action is needed to identify the reason.

5) Further work is necessary to define *"aerodynamically straight"* wall contours for reference Mach numbers above 0.8.

6. References

1. M.J. Goodyer, S.W.D. Wolf. *"The Development of a Self-Streamlining Flexible Walled Transonic Test Section"*. AIAA Paper 80-0440 (March 1980).

2. S.W.D. Wolf, I.D. Cook, M.J. Goodyer. *"The Status of Two and Three-Dimensional Testing in the University of Southampton Transonic Self-Streamlining Wind Tunnel"*. AGARD Conference Proceedings No.335 (May 1982).

3. S.W.D. Wolf. *"The Design and Operational Development of Self-Streamlining Two-Dimensional Flexible Walled Test Sections"*. NASA Contractor Report 172328 (March 1984).

4. M. C. Lewis. *"The Status of Two-Dimensional Testing at High Transonic Speeds in the University of Southampton Transonic Self-Streamlining Wind Tunnel"*. NASA Contractor Report 3919 (October 1985).

5. M. Judd, S.W.D. Wolf, M.J. Goodyer. *"Analytical Work in Support of the Design and Operation of Two-Dimensional Self-Streamlining Test Sections"*. NASA Contractor Report 145019 (July 1976).

6. S.W.D. Wolf, M.J. Goodyer. *"Predictive Wall Adjustment Strategy for Two-Dimensional Flexible Walled Adaptive Wind tunnel. A Detailed Description of the First One-Step Method"*. NASA Contractor Report 181635 (January 1988).

Table 1: *"Aerodynamically Straight"* Performance of New Flexible Walls

Contour	Reference Mach Number (M_∞)	Standard Deviation of Local Mach Number (Wall Centreline)		Average Weighted Standard Deviation (σ_{av})
		Top Wall (σ_T)	Bottom Wall (σ_B)	
A	0.3	0.0007	0.0017	0.0040
B	0.4	0.0014	0.0015	0.0036
C	0.5	0.0012	0.0020	0.0032
D	0.6	0.0014	0.0024	0.0032
E	0.7	0.0023	0.0029	0.0037
F	0.8	0.0029	0.0031	0.0037

Table 2: Comparison of *"Aerodynamically Straight"* Performance of Original and New Flexible Walls

Reference Mach Number (M_∞)	Flexible Wall	Author of Data	Standard Deviation of Local Mach Number (Wall Centreline)		Average Weighted Standard Deviation (σ_{av})
			Top Wall (σ_T)	Bottom Wall (σ_B)	
0.7	Original	Wolf	0.0021	0.0023	0.0031
		Lewis (A)	0.0030	0.0036	0.0047
	New	Lewis (B)	0.0023	0.0029	0.0037
0.8	Original	Wolf	0.0023	0.0027	0.0031
		Lewis (A)	0.0031	0.0048	0.0049
	New	Lewis (B)	0.0029	0.0031	0.0037

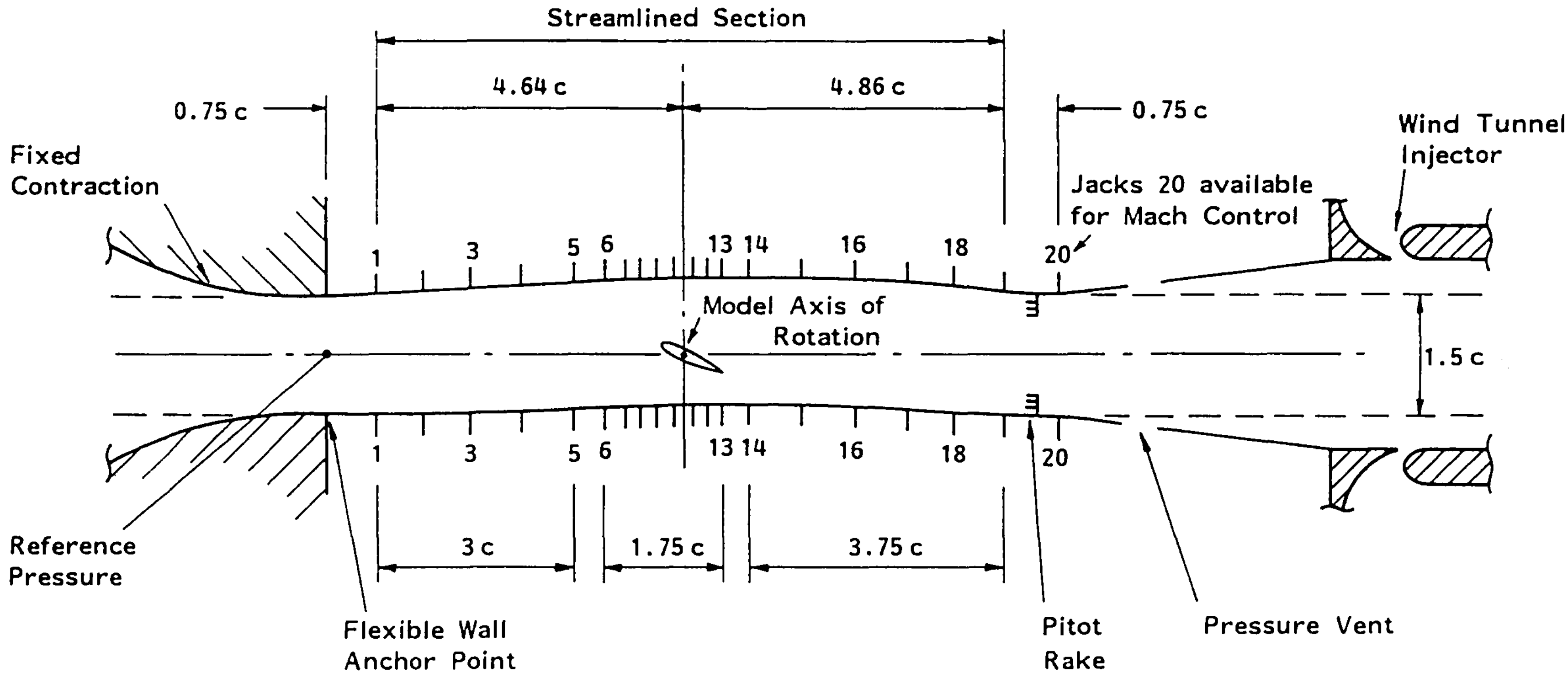
Table 3: Designated Mach Number Band for *"Aerodynamically Straight"* Wall Contours

Contour	Designated Reference Mach Number Band	
	Two-Dimensional Model Tests	Three-Dimensional Model Tests
A	–	up to 0.35
B	–	0.35 to 0.45
C	–	0.45 to 0.55
D	below 0.65	0.55 to 0.65
E	0.65 to 0.75	0.65 to 0.75
F	above 0.75	above 0.75

Table 4: Off-Centre *"Aerodynamically Straight"* Performance of the New Flexible Walls

Contour	Reference Mach Number (M_∞)	Average Weighted Standard Deviation (σ_{av})		
		Off-Centre		Centreline
		Orifice (1)	Orifice (2)	Orifice (3)
A	0.3	0.0155	0.0115	0.0040
B	0.4	0.0135	0.0095	0.0036
C	0.5	0.0141	0.0102	0.0032
D	0.6	0.0195	0.0134	0.0032
E	0.7	0.0183	0.0125	0.0037
F	0.8	0.0166	0.0114	0.0037

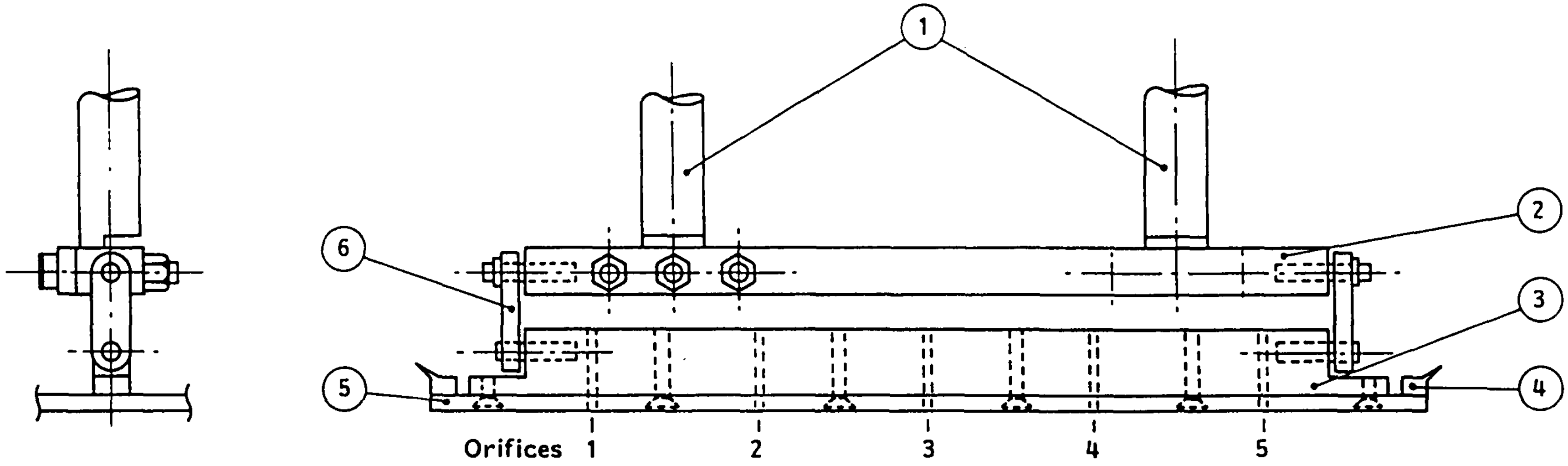
Note:- See Figure 2 for relative positions of pressure orifices (1), (2) and (3)



c = Aerofoil chord (= 4.0 inches)

Scale 1:10 approx.

FIG. 1:- SCHEMATIC LAYOUT OF TRANSONIC SELF - STREAMLINING WIND TUNNEL



Key ① Jack Push Rods ② Lifting Bar ③ Wall Stiffener Rib
④ Rubber Seal ⑤ Flexible Wall ⑥ Swinging Link

Scale 1:1 approx.

FIG. 2:- SCHEMATIC OF JACK/WALL LINK MECHANISM OF THE NEW FLEXIBLE WALLS

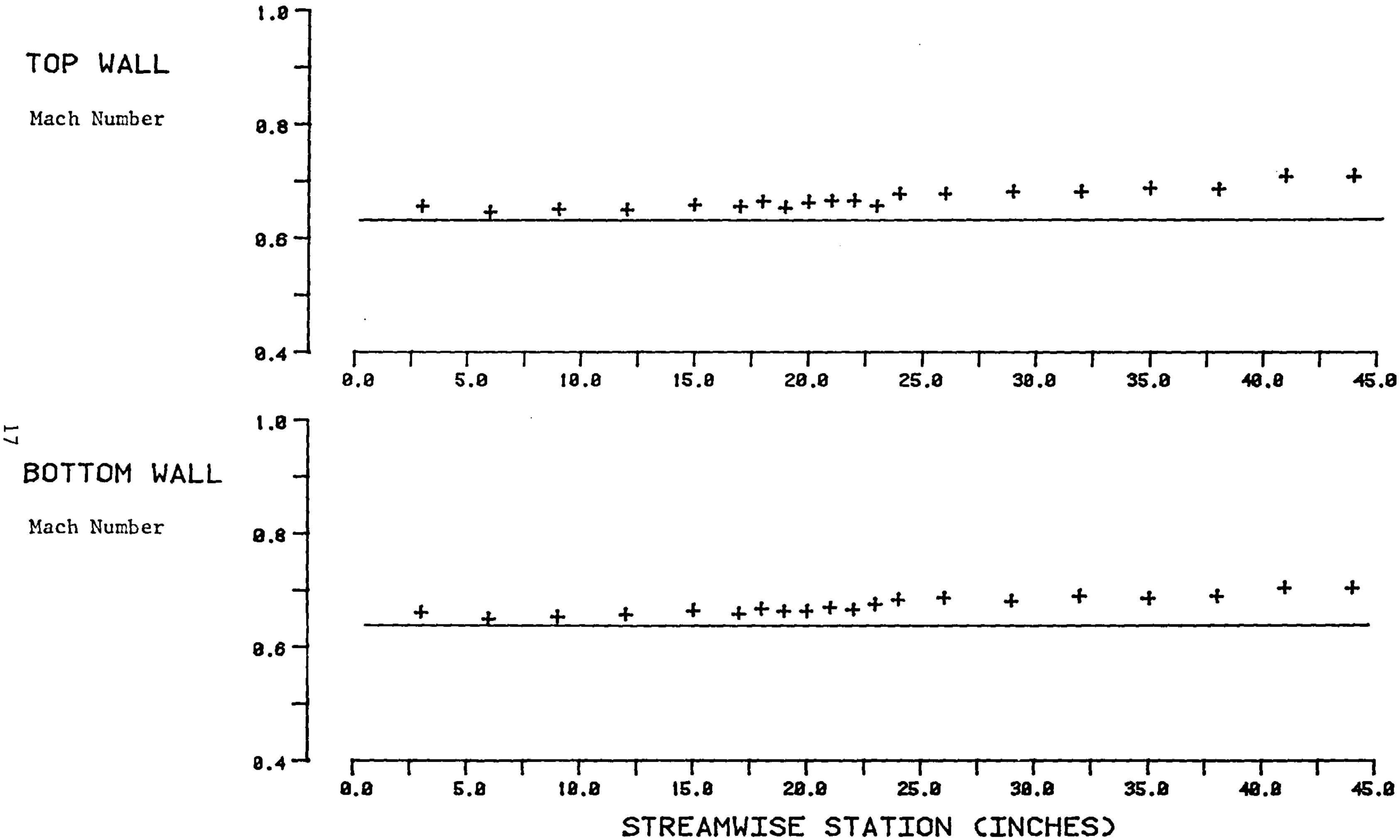


Figure 3:- Mach Number Distributions Along Flexible Walls Set to Geometrically Straight ($M_\infty = 0.63$)

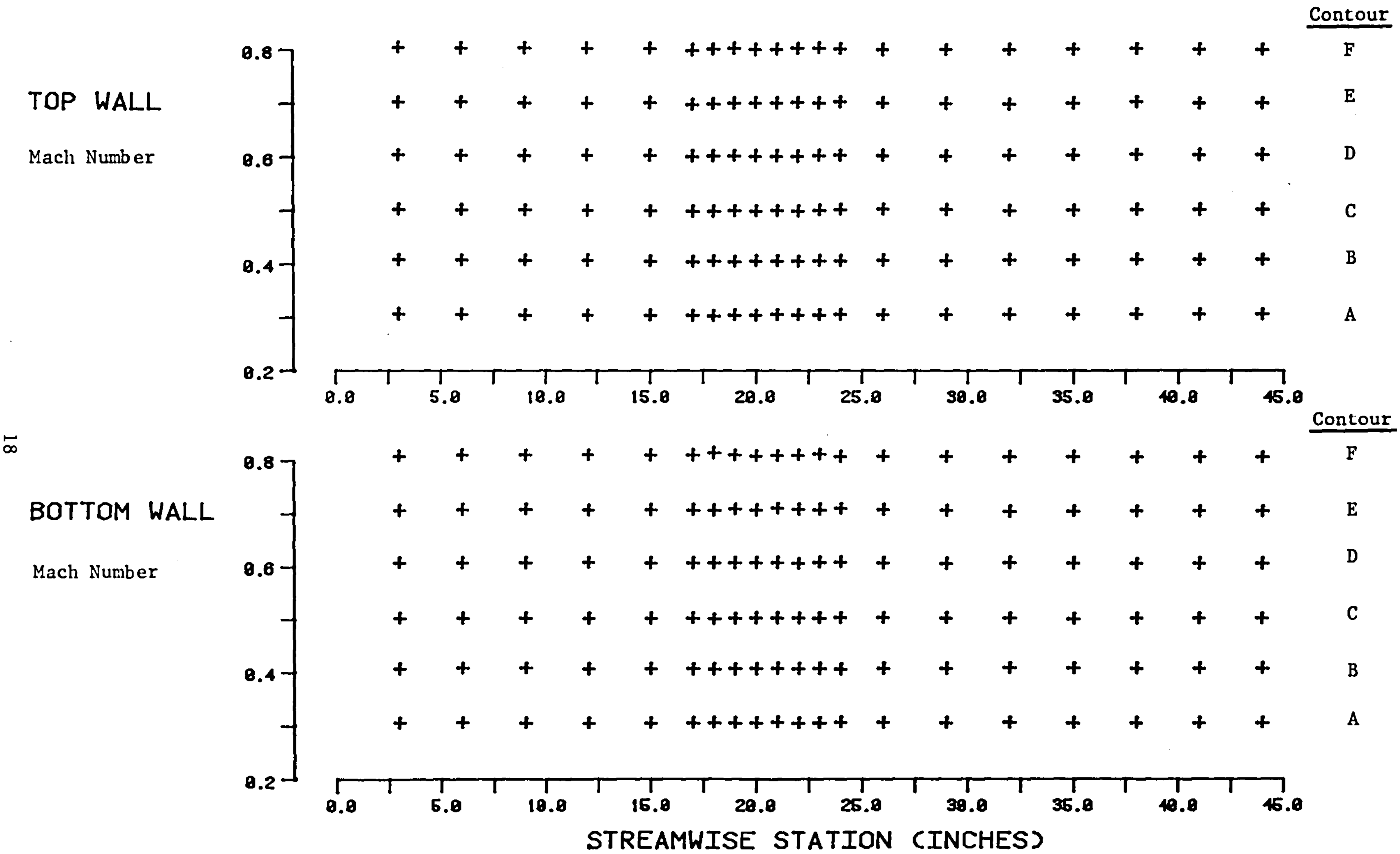


Figure 4:- Mach Number Distributions Along Flexible Walls Set to "Aerodynamically Straight" Contours

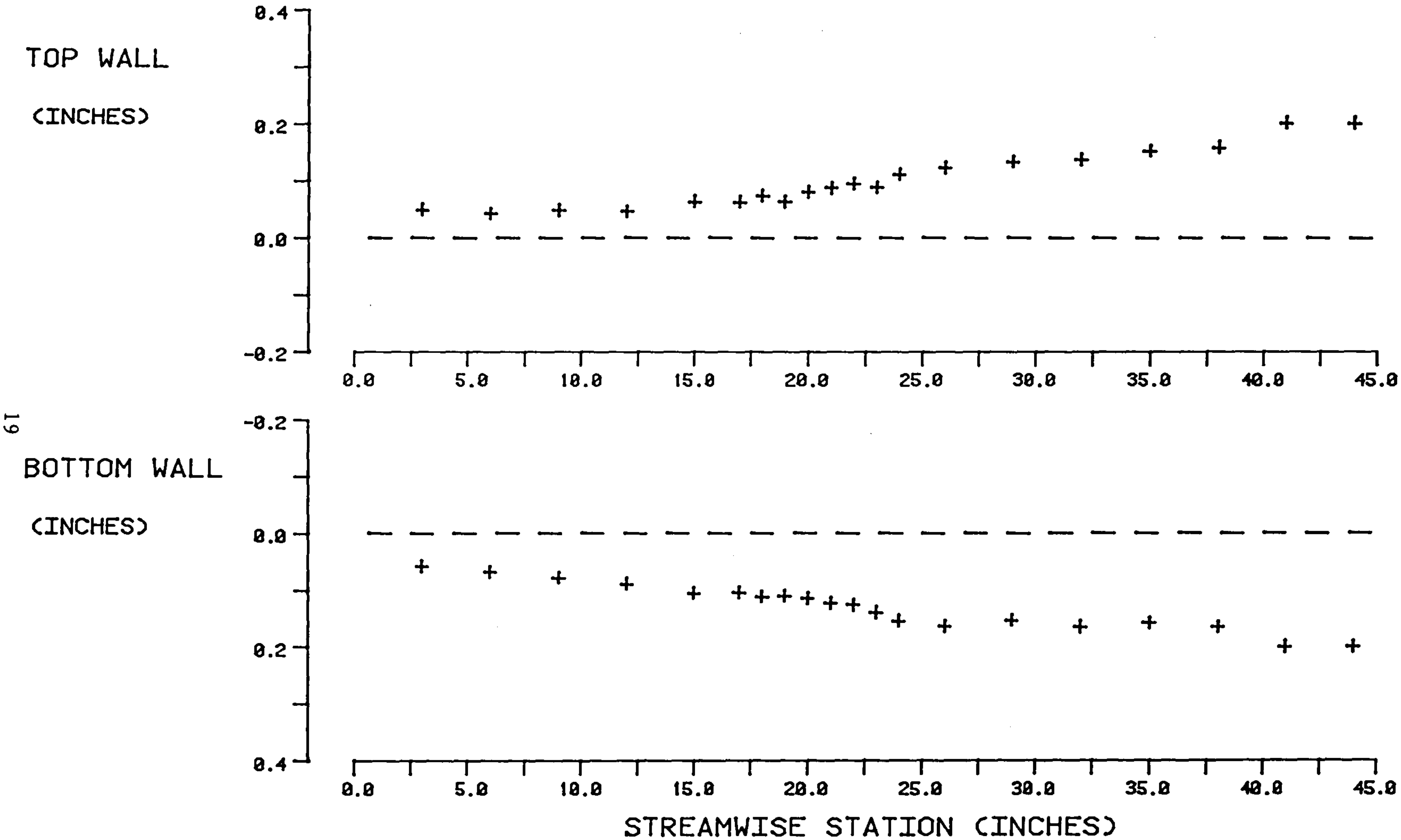


Figure 5:- Flexible Wall Displacements of "Aerodynamically Straight" Contour D

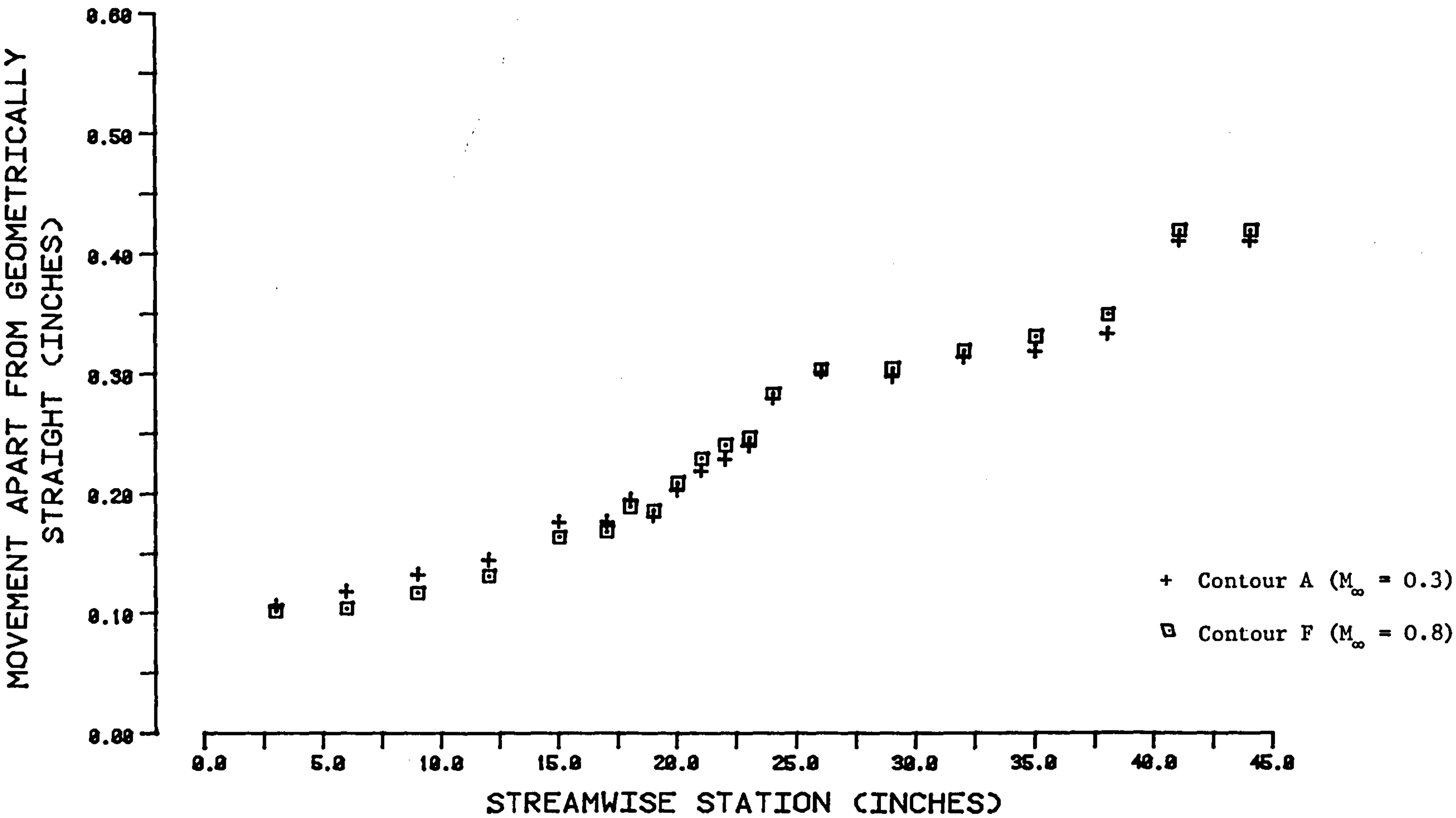


Figure 6:- Total Wall Movement of "Aerodynamically Straight" Contours A and F

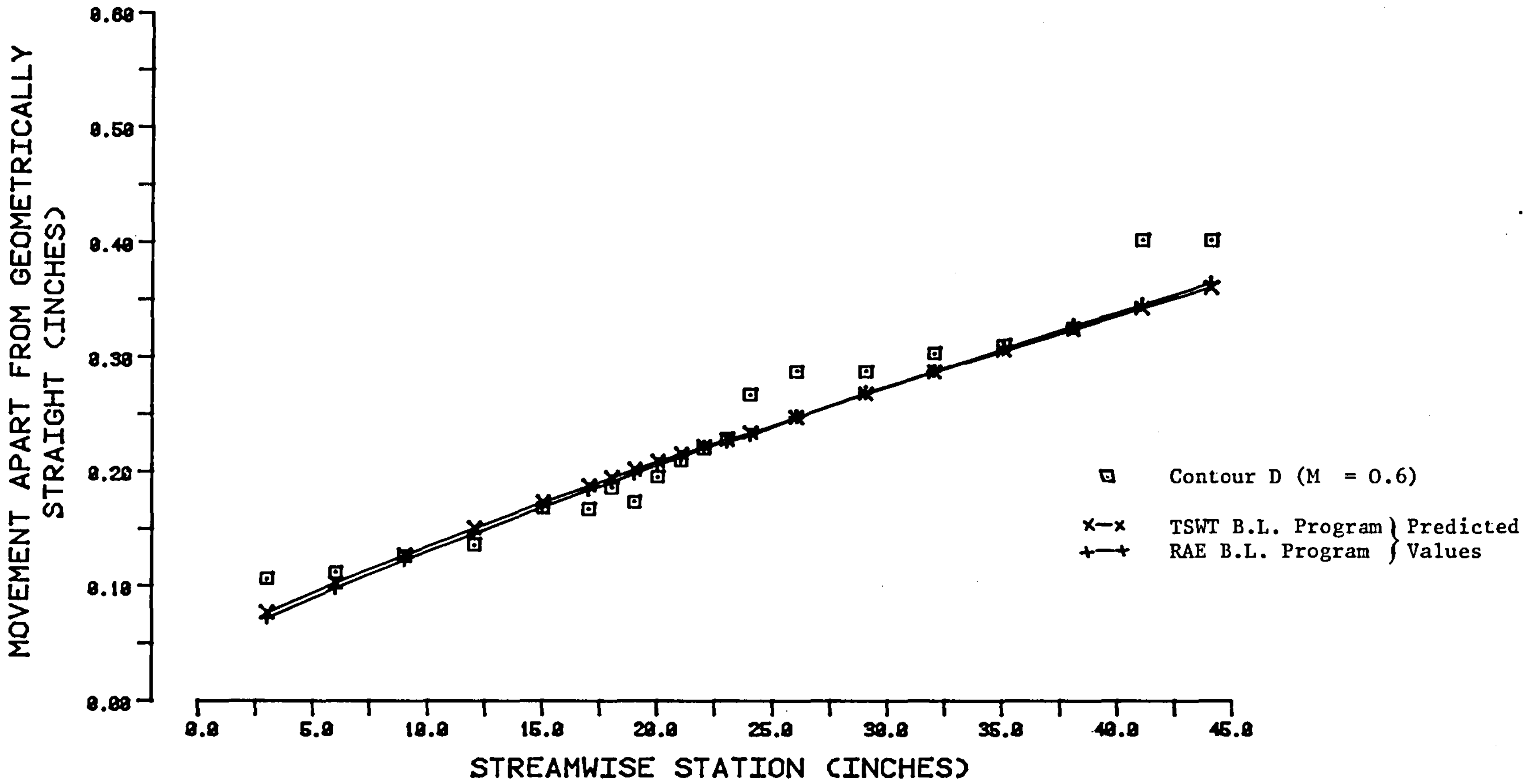


Figure 7:- Total Wall Movement of "Aerodynamically Straight" Contour D

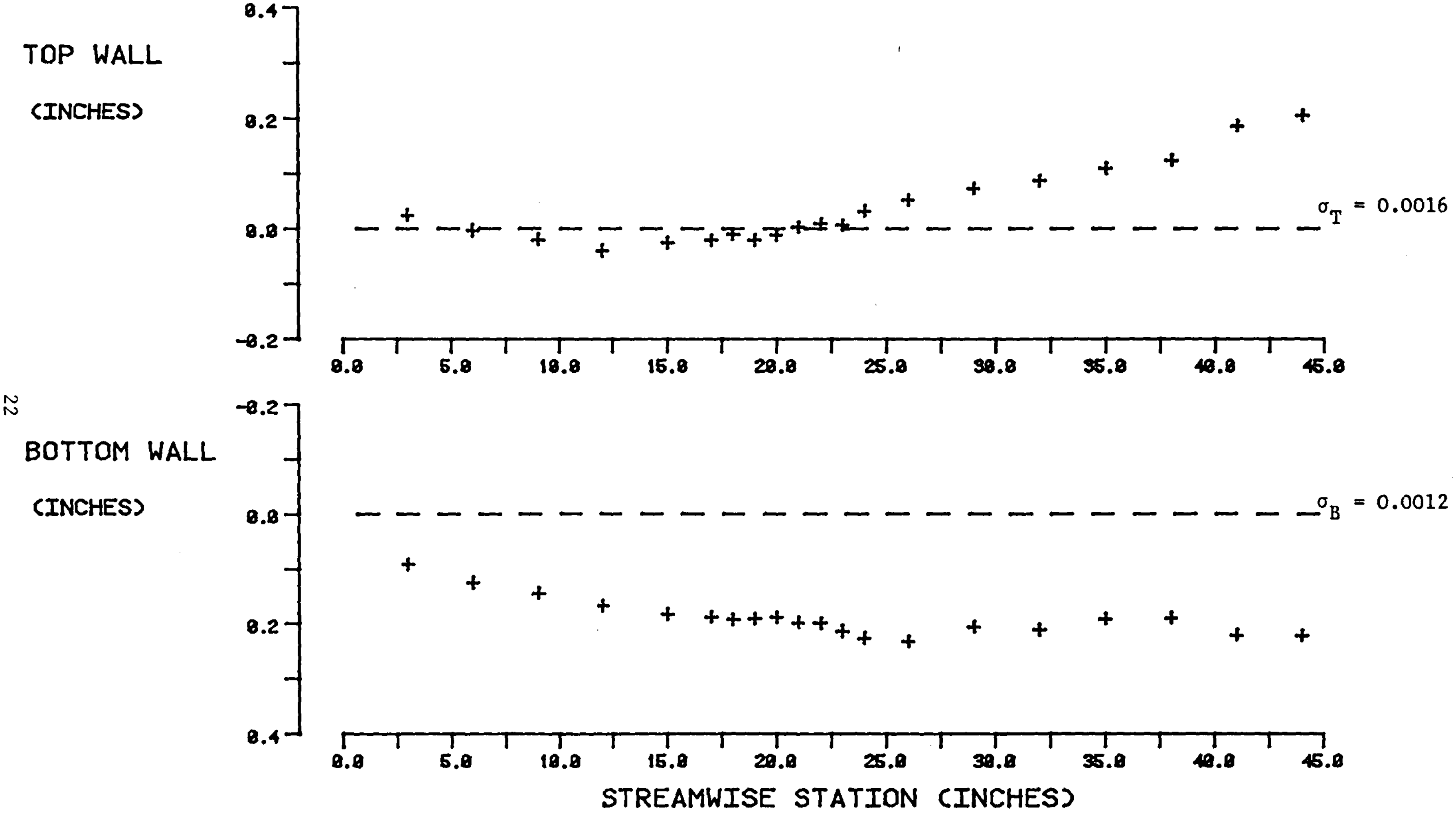


Figure 8:- Flexible Wall Contour Resulting in a Weighted Deviation Value of 0.0023 ($M_\infty = 0.6$)

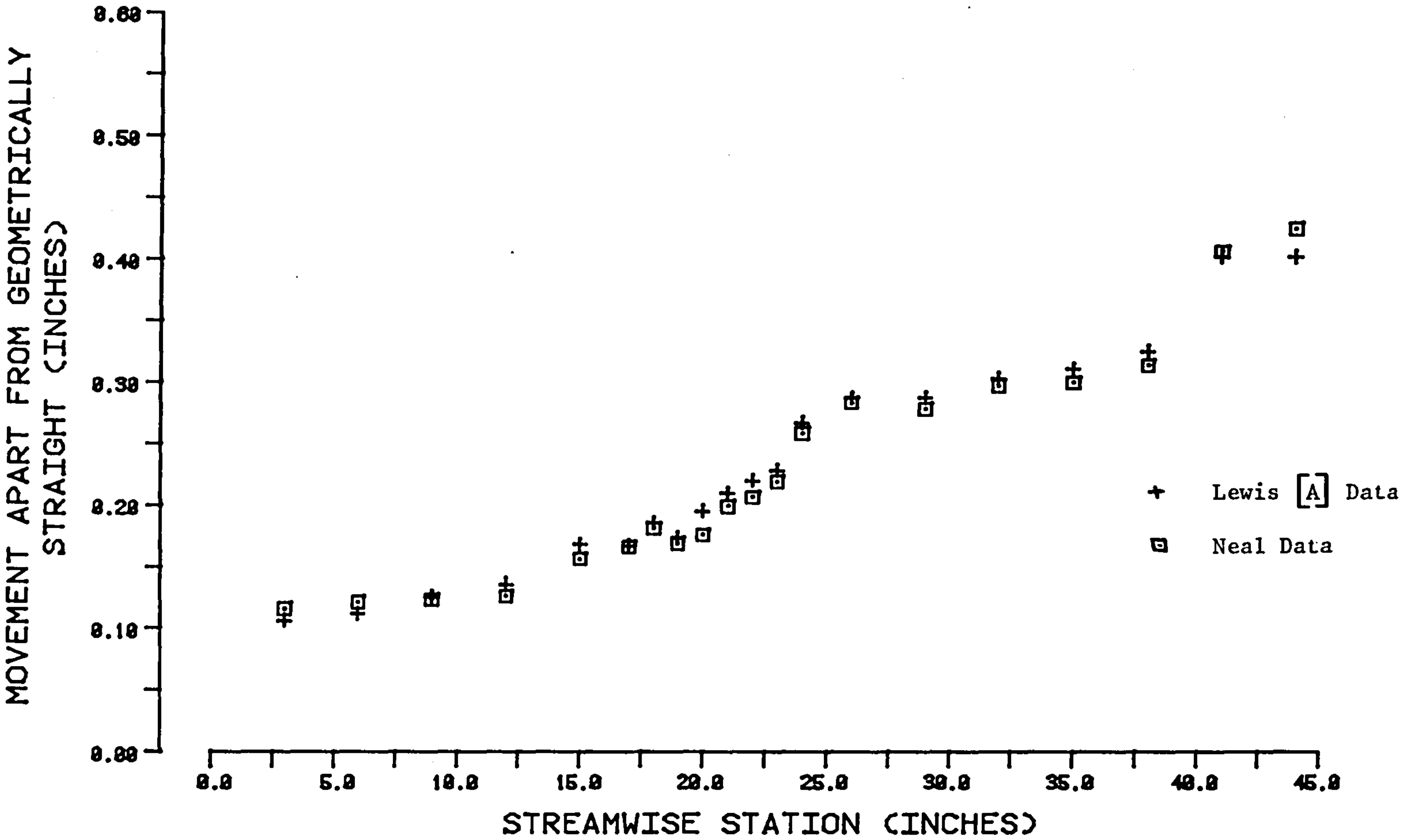


Figure 9:- Total Wall Movement of "Aerodynamically Straight" Contour D ($M_\infty = 0.6$)

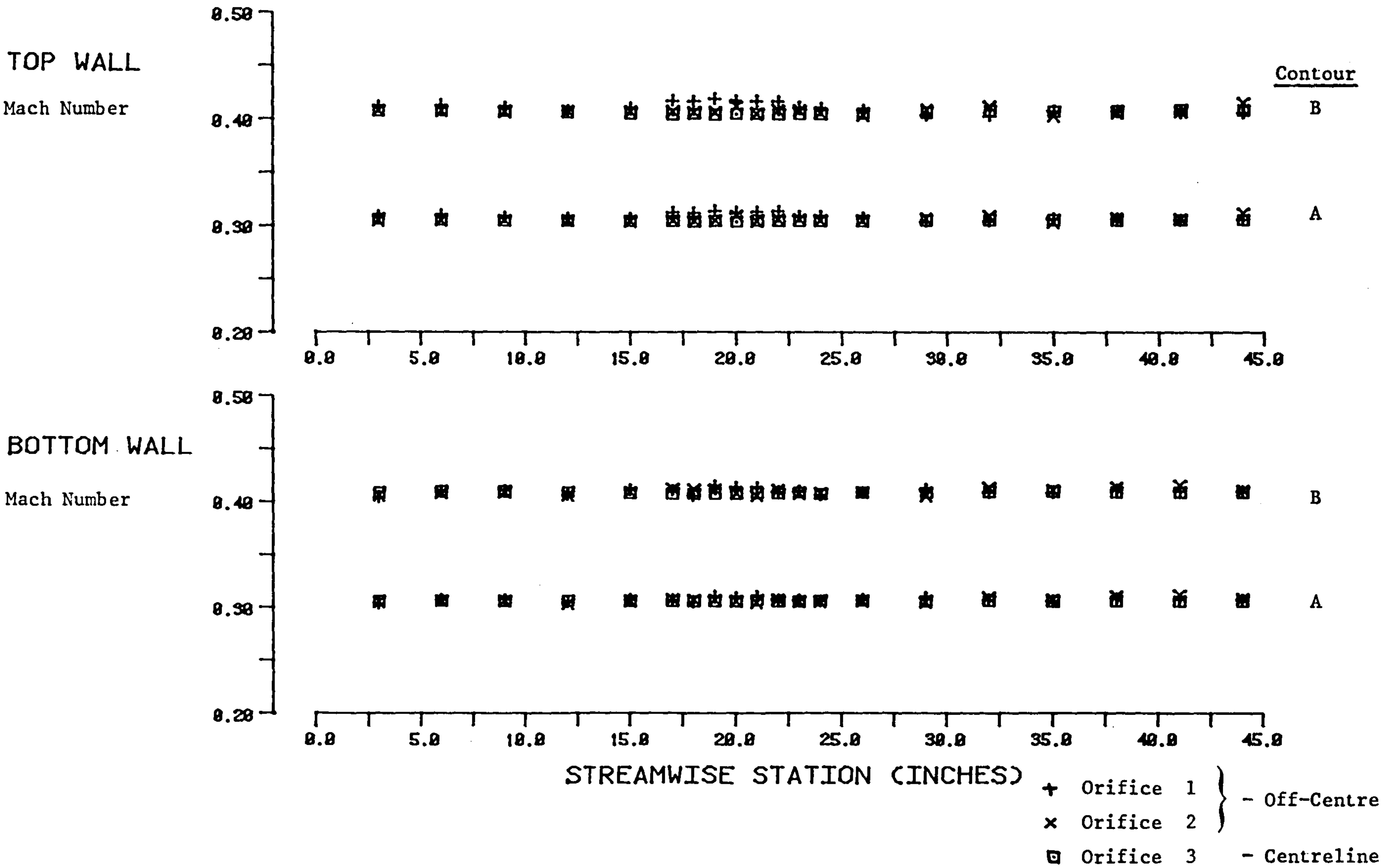


Figure 10a:- Off-Centre "Aerodynamically Straight" Performance of Contours A and B (M_∞ = 0.3, 0.4 respectively)

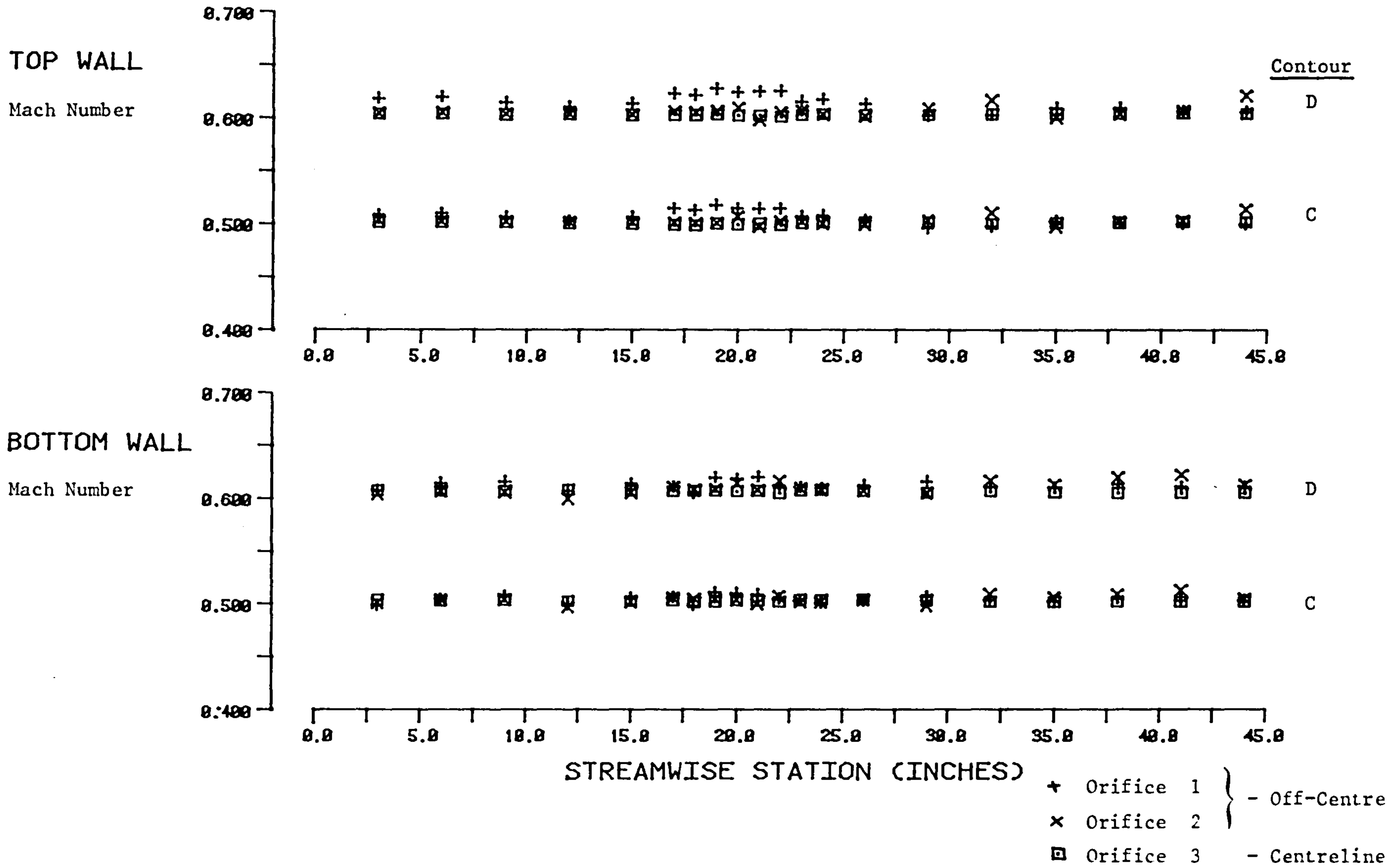


Figure 10b:- Off-Centre "Aerodynamically Straight" Performance of Contours C and D (M_∞ = 0.5, 0.6 respectively)

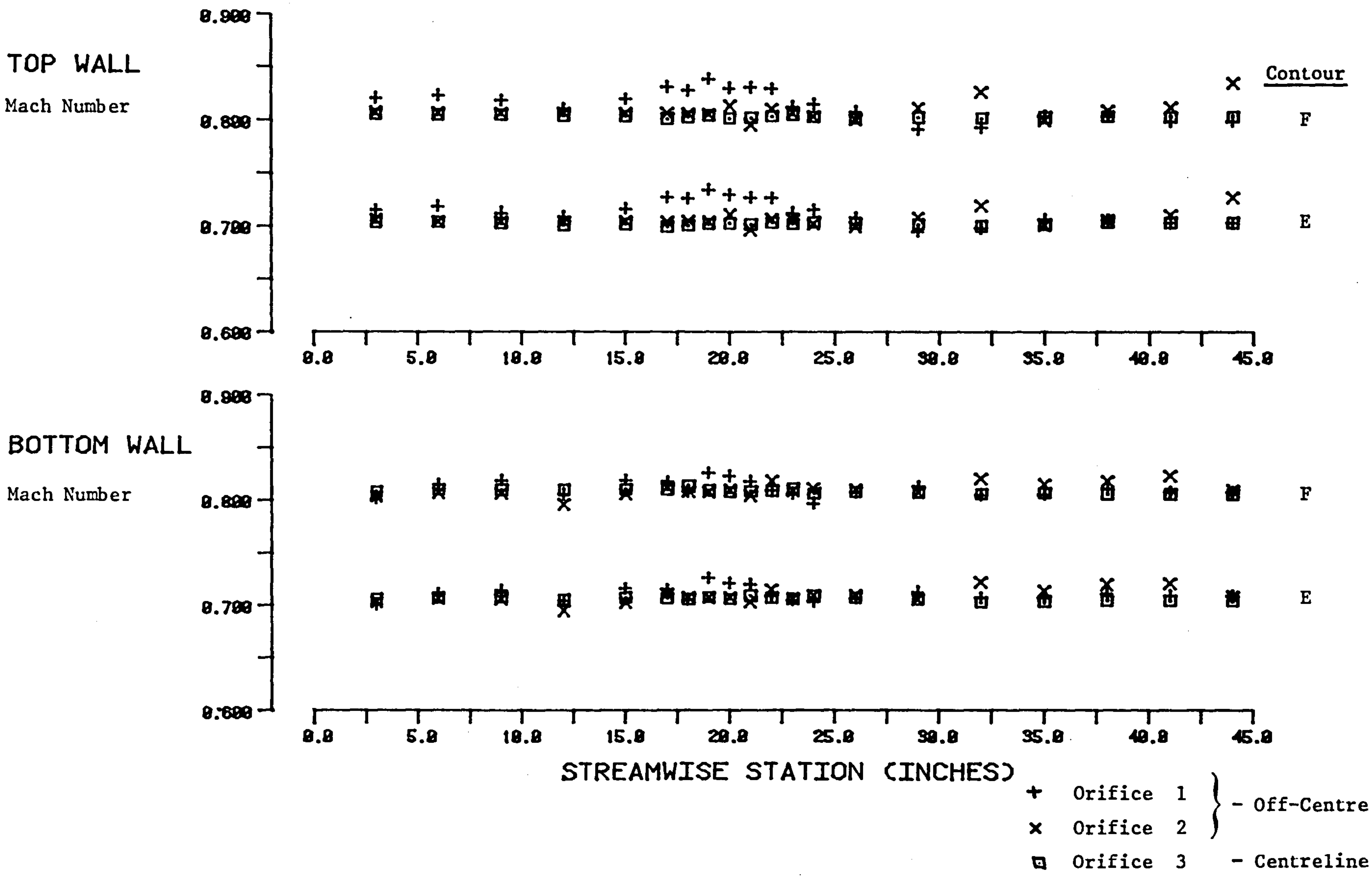


Figure 10c:- Off-Centre "Aerodynamically Straight" Performance of Contours E and F (M_∞ = 0.7, 0.8 respectively)

Report Documentation Page

National Aeronautics and Space Administration

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-181680		

4. Title and Subtitle	5. Report Date
Empty Test Section Streamlining of the Transonic Self-Streamlining Wind Tunnel Fitted with New Walls	July 1988
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
M. C. Lewis	AASU Memo 86/10
	10. Work Unit No.
	505-61-01-02
9. Performing Organization Name and Address	11. Contract or Grant No.
University of Southampton Department of Aeronautics and Astronautics Southampton, Hants, S09 5NH ENGLAND	NSG-7172
	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics and Space Administration Langley Research Center Hampton, VA 23665-5225	14. Sponsoring Agency Code

15. Supplementary Notes

NASA Langley Research Center Technical Monitor: Charles L. Ladson
This is a progress report on work undertaken on NASA Grant NSG-7172 entitled "The Self-Streamlining of the Test Section of a Transonic Wind Tunnel." The Principal Investigator is Dr. M. J. Goodyer.

16. Abstract

The original flexible top and bottom walls of the Transonic Self-Streamlining Wind Tunnel (TSWT), at the University of Southampton, have been replaced with new walls featuring a larger number of static pressure tappings and detailed mechanical improvements. This report outlines the streamlining method, results, and conclusions of a series of tests aimed at defining sets of "aerodynamically straight" wall contours for the new flexible walls. This procedure is a necessary prelude to model testing. The quality of data obtained compares favorably with the "aerodynamically straight" data obtained with the old walls. No operational difficulties were experienced with the new walls.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Adaptive walls/Flexible walls 2-D transonic	Unclassified - Unlimited Subject Category - 02

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	30	A03

NASA FORM 1626 OCT 86

End of Document