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Summary

This report briefly outlines the progress made during the last two years in extending the operational range of the Transonic Self-Streamlining Wind Tunnel (at the University of Southampton) into high subsonic speeds. Analytical preparation completed in order to achieve such an extension is outlined and a summary of the preliminary model validation tests is presented. Future work necessary to allow further validation and development is discussed.

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. In addition to the elimination of wall interferences it is argued that the TSWT offers improved flow quality and reduced power requirements or increased Reynolds number compared to conventional ventilated test sections. Interferences created by an impervious flexible wall depend on its loading which is determined locally by the differences in velocities between the real (test section) flow and an imaginary flow over the outside of the wall. The wall loading is brought rapidly to zero by adjusting the wall according to Judd's[3] predictive wall adjustment strategy, which also computes the imaginary flowfields. The nature of the computations limits the maximum operational speed of the TSWT to speeds where the flexible walls are just supercritical. At higher speeds supercritical flow extends 'through' the walls invalidating the linearised theory used by Judd's predictive wall adjustment strategy to compute the imaginary flowfields. Hence, the major step necessary to permit the extension of two-dimensional testing in the TSWT into higher transonic speeds is the provision of an algorithm to solve for mixed flow in the imaginary flowfields.

This report briefly outlines the analytical preparation completed in order to achieve such an extension, and presents a summary of the preliminary model validation tests. Future work necessary to allow further validation and development is discussed.

2. BACKGROUND

Two-dimensional transonic testing by Wolf[3] demonstrated that Judd's predictive wall adjustment strategy limits the operational speed of the TSWT to speeds where the flexible walls are just supercritical. At this condition, breakdown of the wall adjustment strategy is evident in that convergence is neither as rapid nor as stable as for lower speeds, and the adopted wall streamlining criteria are not always completely satisfied. However, at this upper limit condition the aerofoil shocks are locally normal to the flexible wall, therefore the shocks are not reflected and the wall itself supports the pressure rise, hence the flow direction which might otherwise occur with a ventilated test section is prevented.

In 1980 Mason[4] attempted to adapt a time marching finite area algorithm (developed by Spurr[5] and capable in principle of introducing supercritical flow) for use in the wall adjustment strategy of the TSWT at high subsonic speeds. Due to the problems encountered in the accuracy of shock placement and in the practical application of the algorithm, the time marching method proved to be unsuitable for the needs of the TSWT. However Mason did conclude that any future high speed wall adjustment strategy would need to make an allowance for boundary layer growth at the flexible walls due to shock/boundary layer interaction.

3. PREDICTION OF MIXED FLOW IN THE IMAGINARY FLOWFIELDS

3.1 Goodyer Streamline Curvature Algorithm

Extensive attempts to modify an existing, locally written compressible subsonic streamline curvature algorithm in order to compute the mixed flow of the imaginary flowfields failed.

3.2 Transonic Small Perturbation (TSP) Software

TSP software, provided by RAE Farnborough, was designed to predict two-dimensional irrotational flow past lifting aerofoils in wind tunnels[6] (RAE TSP 1), by solving the Transonic Small Perturbation equation. It was planned to utilise the free air option of the software in order to compute the imaginary flowfields of the TSWT. Once installed and run on the TSWT computer (DEC PDP 11/34) it became apparent that an algorithm requiring less memory with faster run times would be required for practical testing. Therefore, it was decided to employ a less refined algorithm which was developed by Albone[7] for free air applications only (RAE TSP 2). This reduced memory requirements of the software from 25.5K to 22.5K words, thereby reducing run times from 18 seconds per iteration to 10 seconds per iteration. The numerical method, in which the TSP equation is solved, is a modification of the work of Murman and Cole[8] and of Krupp[9]. The flow is treated as isentropic and irrotational, so the shocks should be weak and the perturbations caused by the aerofoil should be small whilst the main stream Mach number should be close to unity. For TSWT applications the TSP program is applied once to each wall, a wall being 'represented' in the software as a symmetrical non-lifting aerofoil. Typical wall contours are 'represented' by aerofoils with small thickness/chord ratios. Therefore the RAE TSP 2 software appeared to be more than adequate for the next proposed extension of test Mach number where mixed flows with weak shocks would begin to intrude into the imaginary flowfields.

3.3 RAE Test Case

Installation of the RAE software into the TSWT computer allowed comparisons of RAE TSP 2 results obtained on a CDC 6600 computer with those obtained at Southampton. The change of **computer hardware results in** discrepancies in shock position and pressures at the foot of the shock (see Figure 1), the reasons for the discrepancies are at present unknown.

However, it was decided that development of the RAE TSP 2 software to the TSWT should be continued because a 'converged' solution was obtained after 300 iterations (1 hour approx.), which was a vast improvement on the time marching method.

3.4 Adaptation of RAE TSP 2 Software for TSWT Applications

3.4.1 Computing Mesh Regions:-

The RAE method divides the computing mesh into four regions (see Figure 2). However for TSWT applications the aerofoil 'representing' the wall contour would be symmetrical and at zero incidence, hence without circulation. This allowed the computing mesh to be reduced to three regions (see Figure 3), thereby reducing the required memory of the TSWT TSP software★ to 15K words and reducing run times to 4 seconds per fine-mesh interation.

3.4.2 Uniform Mesh Concentration:-

A uniform concentration of mesh points over the aerofoil 'representing' the wall contour was created (instead of having a concentration around the leading edge) as the accuracy in the prediction of shock location was of more importance for TSWT applications.

3.4.3 Relaxation Parameters:-

The rate of convergence to an 'acceptable' solution is accelerated by adopting the standard technique of successive line over-relaxation. During initial validation tests of the TSWT TSP software relaxation parameters suggested by Albone[7] resulted in non-convergence. This problem was rectified by adjusting the relaxation values until values resulting in convergence were obtained for 'typical' TSWT applications.

3.4.4 Convergence Parameter:-

For TSWT applications the value of the convergence parameter was taken to be the value that obtained Mach number results that were no more than ± 0.05% different from results obtained using the convergence parameter suggested by Albone[7]. This

★ TSWT TSP software:- RAE TSP2 software fully adapted for TSWT applications.

reduction is thought to be reasonable in relation to the accuracy of data acquisition of the TSWT, and has the effect of reducing computing times by more than two thirds.

3.5 Initial Validation of TSWT TSP Software for TSWT Applications

Initial validation of the TSWT TSP software used existing data from an earlier TSWT run (Run 184). For this run the aerofoil being tested was a NACA 0012-64 section at 4.5° incidence with a reference Mach number of 0.8862. At this condition supercritical flow had penetrated both flexible walls but the existing wall adjustment strategy (Judd's predictive strategy) had just succeeded in contouring the walls to 'near' streamlined shapes. This claim was believed to be reasonable since there was fair agreement with the pressure distribution on the aerofoil tested in the TSWT and the reference data.★ However, confident validation of the TSWT TSP software by means of comparisons between Mach number distributions computed several ways was not possible. It was, however, concluded that TSWT TSP software did offer real potential for TSWT applications and that the wall contour could be 'represented' in the software by an aerofoil incorporating a 60" 'closer' scheme. (See Reference 10 for greater detail). Further encouragement was gained from the following:-

a) A consistently predicted shock location in the imaginary flow downstream of the experimental position reinforced the view that an allowance for wall boundary layer growth due to shock impingement (as suggested by Mason and Wolf) should be made. Past experimental evidence[3, 4] indicated that the predicted shock would be further upstream if such an allowance was made.

b) The iterative nature of the streamlining process demands that computing times should be short. Extensive development of the TSWT TSP software (see Reference 10 for details) has reduced computing times from hours to 5-15 minutes. This time is adequate for practical testing.

★ See Section 7.1 for details of reference data.

4. PREDICTION OF WALL BOUNDARY LAYERS

The existing wall adjustment strategy (Judd's predictive strategy) references the wall displacement to 'aerodynamically-straight'★ contours, and assumes that the imaginary flowfields over these 'straight' contours are undisturbed. Variations in wall boundary layer displacement thickness due to model influences are calculated but are not employed in the existing wall adjustment strategy. However, it is expected that any future high subsonic wall adjustment strategy will have to make an allowance for variations in wall boundary layer displacement thickness due to model influences, because variations become significant when the model shock impinges on the flexible wall. The calculations of the existing wall adjustment strategy use a numerical solution of the Von Karman Momentum Integral equation for a turbulent boundary layer (TSWT BL Program). This method predicts the boundary layer displacement thickness to increase by about 20% across the shock impinging on the top wall during Run 184. For the same conditions, values predicted by Green[11] (RAE Bedford) and Reshotko and Tucker[12] are in the region of 40% to 50%. The existing method for calculating variations in wall boundary layer displacement thickness (TSWT BL Program) may therefore be inadequate for adaptation into any future high transonic wall adjustment strategy. With this in mind, the RAE Lag Entrainment turbulent boundary layer program (RAE BL Program) was installed into the TSWT computer. Model tests will be necessary to verify methods for predicting variations in wall boundary layer displacement thickness before they are incorporated permanently into any future high subsonic wall adjustment stragegy.

★ See Section 5 for definition of aerodynamically-straight.

5. AERODYNAMICALLY-STRAIGHT WALL TESTS

The aim of determining 'aerodynamically-straight' 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 constant Mach number along the walls of the empty test section equal to the reference value. For the TSWT the divergence is a function of the reference Mach number, but it has proved adequate to determine only a few straight contours and to designate each as the aerodynamically-straight contours for a band of reference Mach number. Since aerodynamically-straight contours had not been determined for reference Mach numbers above 0.875 further straight wall tests were required before high subsonic model tests could be contemplated. The wall adjustment strategy employed in such tests was the old 'imbalance' streamlining method which 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. Wall movement is made proportional to the local error in Mach number. Employment of the 'imbalance' strategy with the imaginary wall Mach numbers set to the reference value resulted in satisfactory aerodynamically-straight contours up to a reference Mach number of 0.95 (see Table 1 and Figure 4 for more information). The sensitivity of Mach number to flow area prevented aerodynamically-straight streamlining at higher reference Mach numbers. Moreover as the variations of the contours are rather weak functions of reference Mach number, it is believed that the new aerodynamically-straight contours may be adequate for model tests up to a reference Mach number of unity.

6. SUPERSONIC TESTS

Supersonic flow was achieved in the TSWT by adjusting the walls to form a throat at the first jack position, the maximum downstream average Mach number achieved being 1.3. As was expected, the 'imbalance' wall adjustment strategy (with the wall movement direction reversed) proved to be inappropriate for supersonic aerodynamically-straight streamlining (see Figure 5). The inadequacy of the strategy arises from the propagation downstream of the effects of local wall adjustments, while in subsonic flow local wall movement has a global effect. However the supersonic tests did reinforce the view that aerodynamically-straight contours are a rather weak function of reference Mach number (see Figure 6) and that supersonic self-streamlining research may be feasible in the TSWT.

In future supersonic tests it is likely that the supersonic test diamond will be produced by a nozzle formed by the first 4 or 5 jacks of each wall, because wall streamlining is likely to be confined to regions of the walls beginning just upstream of the leading edge. Supersonic streamlining depends on an appropriate wall adjustment strategy being developed.

7. NACA 0012-64 AEROFOIL TESTS

7.1 Validation Model and Reference Data

The validation model for the high subsonic tests was a NACA 0012-64 aerofoil of 4 inch chord and 6 inch span. The model had been used for previous TSWT lower speed (below $M_\infty = 0.85$) validation and had earlier been tested in the NASA Langley Research Center 19" x 6" blowdown transonic wind tunnel fitted with a slotted test section. Therefore reference data was available taken with a ratio of test section height to model chord of 4.75 compared to 1.5 in the TSWT. However the Reynolds number of the reference data is higher than that for TSWT data. As the shock positions are sensitive to transition, which for a clean aerofoil is dependent on Reynolds number, the validation model has a transition band positioned around the leading edge to 3% chord. Any comparisons of transonic TSWT data with reference data should be made when transition is fixed, thereby reducing discrepancies caused by differing Reynolds number.

7.2 The Measure of the Quality of Streamlining (E)

The quality of streamlining is primarily determined from the wall loadings given by the pressure coefficient (Cp) imbalance between the real and imaginary flows. Therefore the measure of the quality of streamlining of each wall which is used is the average modulus of the Cp imbalance between the real and imaginary flows, at the jack stations (E). In all previous lower speed (below $M_\infty = 0.85$) TSWT model tests the level of streamlining has been judged adequate when the value of E for each wall is below 0.01.

7.3 TSWT Control Software

The TSWT TSP software has been incorporated into the TSWT high subsonic control software and now contains optional wall adjustment strategies for model tests; either the 'imbalance' strategy is used in the aerodynamically-straight tests, or a development of Judd's predictive strategy can be selected. Both options use the TSWT TSP software to compute the imaginary flow, the wall contours being 'represented' in the software by an aerofoil incorporating a 60" 'closer' scheme (see Reference 10 for greater detail).

Therefore the TSWT operator has the following options:-

a) Existing TSWT Control Software

Wall Adjustment Strategy	1)	Judd's predictive strategy:-	Strategy A
	2)	'Imbalance' strategy:-	Strategy B

Strategy B is used only when setting aerodynamically-straight walls with an empty test section.

The existing TSWT control software routinely calculates the variations in boundary layer displacement thickness due to model influences, by use of a numerical solution of the Von Karman Momentum Integral equation for a turbulent boundary layer (TSWT BL program). However, both strategies make no use of the calculated boundary layer variations.

b) TSWT High Subsonic Control Software

Wall Adjustment Strategy	1)	'Imbalance' strategy:-	Strategy C
	2)	Judd's modified strategy:-	Strategy D

Strategy C is used when setting aerodynamically-straight walls with an empty test section and during some development model streamlining tests.

The TSWT high subsonic software calculates the variations in boundary layer displacement thickness due to model influences by 2 methods:-

1) 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)

An allowance for the variations in boundary layer displacement thickness (predicted by either method) can be made using Strategy C or Strategy D. When no such allowance is made the imaginary flows are computed (by TSWT TSP software) over wall contours referenced to the appropriate aerodynamically-straight wall contours. However when an allowance is made the imaginary flows are computed over contours which are the wall contours modified by the predicted (by either method) changes in wall boundary layer displacement thickness between the test and empty test section at the same Reynolds number.

7.4 TSWT High Subsonic Control Software Validation

Albone[7] had shown that RAE TSP solutions compared favourably with those obtained from Full Potential methods even when the perturbations were far from small and freestream Mach numbers were as low as 0.6. Therefore to further validate the concept of predicting the imaginary flowfields by 'representing' each wall contour in the TSWT TSP software by an aerofoil , low speed (below $M_\infty = 0.85$) streamlined model data (obtained using the newly developed wall adjustment strategies C and D) was compared with data obtained using Strategy A. For the results to be comparable, the high subsonic control software did not make an allowance for variations in boundary layer displacement thickness due to model influences, since wall adjustment strategy A makes no such allowance. The results (see Figures 7 and 8 for summary) demonstrate, as should be the case, that streamlined model data is independent of wall adjustment strategy. Therefore the view that the imaginary flowfields can be adequately predicted by TSWT TSP software is reinforced. In fact, the TSWT TSP software provides comparable streamlined model data for reference Mach numbers as low as 0.5, however the computing times were considerably greater than those required by wall adjustment strategy A, which has had the benefit of considerable development.

7.5 Preliminary High Subsonic Model Validation Tests

7.5.1 High Subsonic Testing

Preliminary high subsonic model validation tests were carried out in a Mach number band not before explored in two-dimensional aerofoil adaptive wall research, that is Mach number 0.9 to 0.97, where at all times the flow channels over and under the aerofoil were choked. Contrary to the fears experienced in some quarters that in these circumstances control would be lost over freestream Mach number, no such difficulty was experienced. Once a modest level of wall streamlining was achieved for a given high subsonic value of reference Mach number and model attitude, raising the inducing air pressure increased the reference Mach number by a small increment. Further streamlining iterations at the new value of reference Mach number are required to restore the quality of wall streamlining (E) to its original level. Therefore the achievement of high subsonic reference Mach numbers requires a few streamlining iterations at reference Mach numbers below that ultimately required.

This, however, is something of an unreal test of the streamlining process. For instance if a model is to be tested at constant incidence over a range of values of Mach number then the logical procedure is to begin by streamlining at a low value and to then move to high values, streamlining at each. Alternatively, if the model is to be tested at constant Mach number over a range of incidences then the procedure of the above paragraph would be followed initially with the model at low lift, followed by streamlining cycles at progressively higher incidences.

For test conditions when fully streamlined wall contours results in supercritical flow just reaching the flexible walls (i.e. upper limit of strategy A), wall adjustment strategies C and D require fewer streamlining iterations than strategy A to reach a given value of E. The reason being, the limitation of no supercritical flow in the imaginary flowfields of strategy A, which may occur during early streamlining iterations, does not apply to strategies C and D. Therefore the first streamlining iteration of both strategies C and D may be at the reference Mach number at which, for the test configuration, the channels over and under the aerofoil become choked. Strategy A requires many streamlining iterations to obtain this reference Mach number.

7.5.2 High Subsonic Model Validation Tests

7.5.2.1 Quality of Streamlining

The quality of streamlining achieved during the preliminary high subsonic model validation tests never reached the same level achieved during lower speed validation tests (see Table 2). Although localised discrepancies sometimes exist between the real and imaginary wall Mach number distributions at the best achieved level of streamlining (E min.), especially as the reference Mach number approaches unity, the results are encouraging (see Figures 9 to 14).

7.5.2.2 Variations in Boundary Layer Displacement Thickness

E min. was achieved when an allowance for variations in boundary layer displacement thickness due to model influences (predicted by RAE lag Entrainment turbulent boundary layer program) was made (the Von Karman Momentum Integral equation was not used in streamlining). As Mason[4] suggested the effect on the model of making such an allowance was to move the upper surface shock upstream (see Figure 15). In all cases the RAE Lag Entrainment program (RAE BL Program) predicted greater boundary layer displacement thickness growth due to shock/wall interaction than values obtained from solutions to the Von Karman Integral equation (TSWT BL Program); for typical comparisons see Figure 16.

7.5.2.3 Wall Adjustment Strategy

The achievement of 'near' streamlined wall contours at high subsonic speeds required the values of Movement/Mach number factor (wall adjustment strategy C)and **Scaling** and Wall Coupling factor (wall adjustment strategy D) to be considerably less than those used for lower speed streamlining. This results in many streamlining iterations being required by both strategies for a given level of streamlining. However, strategy D required less streamlining iterations than strategy C, therefore all the 'near' streamlined high subsonic data presented in this report was achieved by the use of strategy D.

7.5.2.4 Reference Mach Number Range 0.9 - 0.94

In this range the only significant discrepancies between the real and imaginary wall Mach number distributions at E min. occurred near to the shock/wall inpingement position (See Figures 9-11). It is likely that the model shock is still locally normal to the flexible walls in this Mach number band.

The sensitivity of model shock position to the quality of streamlining (E) is illustrated in Figure 17a. For the test condition described (in Figure 17a) 3 streamlining iterations from aerodynamically-straight contours were required before the reference Mach number of 0.9 could be reached. The achievement of E min. required another

12 streamlining iterations, this number of streamlining iterations being typical for 'near' streamlining at high subsonic speeds. Comparison of aerofoil data taken at streamlining iteration numbers 10 and 15 (see Figure 17b), suggests that E min. for a reference Mach number of 0.9 may be adequate, because the reduction of E for the top wall from 0.0206 to 0.0139 results in no significant movement in the upper surface shock and little change of model upper surface pressure distribution. More experimental experience is required before being sure of the required standards of streamlining, with particular reference to the sensitivity of aerofoil data to wall loadings localised around the shock/wall impingement position.

7.5.2.5 Reference Mach Number Range 0.94-0.97

In this reference Mach number range the shocks on the upper and lower surfaces of the aerofoil have moved to the trailing edge (Figure 18 is typical) and are likely to be oblique. When the walls are 'fully' streamlined the shocks will not be reflected but it is clear from this data that 'fully' streamlined wall contours have not yet been achieved. Shock reflection may well have occurred as can be seen from Figures 12-14 where significant discrepancies exist between real and imaginary flows downstream of the shock/wall impingement position. The Schlieren system was not in use during these tests and therefore no confirmation regarding reflection of shocks is available. Future tests will involve the use of the Schlieren system.

7.6 Comparison of High Subsonic TSWT Data with Reference Data

To complete the high subsonic validation, the TSWT data must be compared with reference data. Comparison is not straightforward because in the case of the TSWT uncertainty exists about the model angle of attack. This is clearly illustrated in Figure 7 where the model pressure distribution of the upper and lower surfaces indicate that the real angle ('aerodynamic **angle') of incidence** ($\approx 0.44^{\circ}$) is not the geometrically set angle of zero. Therefore when model pressure distributions are compared with reference data, the normal force coefficients should be matched in order to remove uncertainty about the angle of incidence.

When comparisons are made it should be noted firstly that the condition of the transition band may have changed since the reference data tests, and secondly that recent work at NASA Langley Research Center[13] suggests that the reference data requires correction. The corrections have not yet been applied and in view of this situation it must be concluded that the reference data can only be used as an approximate indication of model performance. For these various reasons this report does not present any comparisons of TSWT data with reference data.

7.7 Future High Subsonic Validation Tests

Future high subsonic validation tests will initially concentrate on the reference Mach number range of 0.9 to 0.94. Emphasis will be placed on determining the effect of the localised differences between the real and imaginary flowfields (exhibited around the model shock/wall impingement position) on model pressure distribution. Due to the sensitive nature of the flow in this region and its close location to the model, it may well prove necessary to improve the present level of streamlining to reduce the wall loading around the shock/wall impingement position.

8. POSSIBLE MODIFICATIONS TO TSWT HIGH SUBSONIC CONTROL SOFTWARE

8.1 Relaxation Parameters

The TSWT TSP rate of convergence to an 'acceptable' solution is accelerated by adopting the standard technique of successive line over-relaxation. Present relaxation parameters, determined during initial TSWT TSP software validation which used TSWT data (Run 184), results in converged solutions within 50 fine mesh iterations (4 minutes per wall) for reference Mach numbers below 0.9. However high subsonic model validation tests have suggested a strong inverse Mach number/fine mesh iteration relationship; 250 fine mesh iterations (17 minutes per wall) were not uncommon for a converged solution at reference Mach numbers greater than 0.94. Therefore to reduce TSWT TSP computing times for reference Mach numbers above 0.9 a new set of relaxation parameters need to be developed.

8.2 Wind-On Wall Movement

At present the high subsonic control software assumes the position of the flexible walls remains unchanged between the wind-on and wind-off stages of a streamlining iteration. However during high subsonic model tests wind-on wall deflections of 0.015" were found, the wall deflection nearly always being inwards indicating a greater plenum chamber pressure than test section pressure. The observed wind-on wall deflection magnitudes are likely to have significant effects on the aerodynamic properties of the walls, therefore it will be necessary to account for, or reduce, wind-on wall deflections. The former may be achieved by modifying the contours that the imaginary flowfields are computed over. An investigation into the sensitivity of TSWT TSP computation to localised wall movement, to determine if uncertainty in wall position can cause large errors in imaginary flow calculations, is planned in the near future.

8.3 Future Wall Adjustment Technique

The proposed technique to further improve the level of streamlining during future high subsonic validation tests is to use wall adjustment strategy D until E min. is reached; then to apply stratety C to individual jacks which exhibit unacceptable local differences between the real and imaginary flows.

9. FURTHER DEVELOPMENT OF TSWT TSP SOFTWARE

9.1 Wall Representation

Initial validation of the TSWT TSP software, which used TSWT data (Run 184), suggested that wall contours could be adequately represented in the software by aerofoils incorporating a 60" 'closer' scheme. This type of wall representation scheme was used during all high subsonic model validation. However, since the validation tests an investigation into the possible use of other wall representation schemes has been carried out. The aim was to increase the density of mesh points along the wall contour, and hence improve the precision with which the position of the shock can be fixed, by reducing the chord of the aerofoil representing the wall contour. This is achieved because the present mesh setting up procedure produces a uniform concentration of mesh points along the aerofoil representing the wall contour (Existing Mesh). Comparisons of performance between various wall representation schemes (see Figure 14 for various geometries) were made for 2 TSWT wall contours:-

Test Case 1 :- $M_\infty = 0.8143$, $\alpha = 4.0^\circ$ } Giving entirely subsonic imaginary flowfields

Test Case 2 :- $M = 0.9228$, $\alpha = 4.0^\circ$ } Giving mixed imaginary flowfields

The only discrepancy in computed Mach number distribution between the various wall representation schemes, for both test cases, was in the peak Mach numbers (see Table 3:- Existing Mesh). However, good agreement was obtained between wall representation schemes that increased the density of mesh points over the wall contour (Schemes B, C, D). Therefore it was concluded that future validation tests should represent the wall contour in the TSWT TSP software by Scheme C (see Figure 19). This increases the density of mesh points by a small amount in the vicinity of the expected shock position, the improvement being from 1.04" per mesh point (Scheme A) to 0.812" per mesh point (Scheme C).

9.2 Further Alterations to Mesh Concentration

To further improve the precision with which the position of the shock can be fixed a new mesh setting up procedure was developed (New Mesh). The new mesh results in a variable density of mesh points along the wall contour; for wall representation scheme C the mesh density just in the vicinity of the shock is increased from 0.812" per mesh point (Existing Mesh) to 0.710" per mesh point (New Mesh). Comparison of new mesh computed Mach number distributions with those obtained using the existing mesh are inconclusive (see Table 3:- Scheme C). The new mesh raises the peak Mach number of Test Case 1 from 0.9894 to 1.0037 while has no significant effect on peak Mach number of Test Case 2.

9.3 Comparisons With Goodyer Compressible Streamline Curvature Program

9.3.1 Goodyer Compressible Streamline Curvature Program (SCP)

This program was developed in order to provide a source of inviscid subsonic compressible flow solutions for two-dimensional fields, both internal and external, for use with a mini-computer. Its predictions for external flows of the imaginary flowfield type have been compared with longer-established Full Potential codes (e.g. Garabedian and Korn, N.Y.U.), showing good agreement. An example is shown on Figure 20 where flow has been computed by the above two methods around a 10% thick circular arc aerofoil at zero angle of attack.

9.3.2 Comparisons of Mach Number Distributions

Good agreement between Mach number distributions computed by the TSWT TSP software (wall representation schemes A and C with Existing Mesh) and those computed by SCP is obtained for Test Case 1 (see Figures 21a - 21b). The only significant discrepancy between the computed Mach number distributions between the various methods was in the peak Mach numbers. However wall representation scheme C (Existing Mesh) results in a smaller peak Mach number discrepancy than scheme A (Existing Mesh). While results obtained for another TSWT wall contour (Test Case 3:- $M\infty = 0.8247$, $\alpha = 4.0^{\circ}$) indicate that the peak Mach number discrepancy can be further reduced when TSWT TSP computations use the new mesh (see Figures 22a - 22b). Therefore it is intended that for any future high subsonic tests the TSWT TSP software should use wall representation scheme C with the new mesh.

10. FUTURE WORK NECESSARY TO ALLOW FURTHER MODEL VALIDATION TESTS

10.1 Model Transition Band

A prerequisite of future model validation tests is the re-application of the transition band to the NACA 0012-64 model according to original specifications, thereby increasing confidence in TSWT data comparisons with reference data.

10.2 New Flexible Walls

The present flexible walls have been in operation for over 6 years and are showing signs of wear. The new walls with their new jack/wall linking mechanism should allow more reliable two-dimensional testing, especially at high subsonic speeds. Installation should be completed early in the New Year, thereby allowing wind-on wall movement investigations and model tests.

10.3 Schlieren System

Re-commissioning of the TSWT Spark Schlieren system will allow more confident fixing of shock positions and confirm, or otherwise, the existence of shock reflections during tests in which the reference Mach number approaches unity.

10.4 Secondary Throat

At high subsonic speeds where the channels above and below the model are choked, fluctuations as high as 0.015 in the indicated reference Mach numbers were experienced during any one tunnel run, which last typically 15 seconds. While this may have been due to faulty instrumentation, future high subsonic tests may require a secondary throat to be formed at the last jack position in order to reduce the fluctuations.

10.5 Modifications to High Subsonic Control Software

See Section 8.

11. CONCLUSIONS

The quantity and quality of high subsonic model validation data presently in hand is limited. However it has been demonstrated that:-

a) streamlining of an impervious flexible walled test section, when supercritical flow has reached both walls and extended with the attandant shocks into the imaginary flowfields, is feasible.

b) the newly developed high subsonic control software has already shown real potential for extending the operational range of the TSWT into the high subsonic range to at least Mach 0.94.

Future validation tests, designed to allow further development and refinement of high subsonic testing in TSWT, will intially concentrate on the reference Mach number band of 0.9 to 0.94 with exploratory testing in the band 0.94 to unity.

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"Validation of a Wall Interference Assessment/Correction Procedure For Aerofoil Tests in the Langley 0.3m Transonic Cryogenic Tunnel"
AIAA 84-2151 (1984).

TABLE 1: AERODYNAMICALLY-STRAIGHT WALL CONTOUR INFORMATION

Record Designation	Allocated Reference Mach Number Range	Test Reference Mach Number During Streamlining	Standard Deviation (of Real Mach Number Distribution)	
			Top Wall	Bottom Wall
A	0 to below 0.6	0.58	0.0030	0.0028
B	0.6 to below 0.85	0.8	0.0031	0.0048
C	0.85 to below 0.895	0.89	0.0048	0.0058
D	0.895 to below 0.935	0.93	0.0044	0.0060
E	0.935 and above	0.95	0.0176	0.020

TABLE 2: SUMMARY OF HIGH SUBSONIC MODEL VALIDATION TESTS

Reference Mach Number	Angle of Attack (deg)	Average Cp Imbalance Between Real and Imaginary Flowfields (E) After Wall Streamlining			
		No boundary layer allowance		With boundary layer allowance	
		Top Wall	Bottom Wall	Top Wall	Bottom Wall
0.9	4.0	0.0155	0.0117	0.0139	0.0082
0.925	4.0	0.0161	0.0069	0.0120	0.0055
0.94	4.0	0.0190	0.0172	0.0136	0.0123
0.95	4.0	-	-	0.0152	0.0129
0.96	4.0	-	-	0.0170	0.0171
0.97	4.0	-	-	0.0166	0.0153

Note: Validation model tests for reference Mach numbers above 0.97 have failed due to problems encountered with supersonic flow and shocks being formed at the first jack station.

TABLE 3: TSWT TSP RESULTS FOR VARIOUS WALL REPRESENTATIONS

Wall Representation Scheme	Peak Mach Number			
	Test Case 1 (Subsonic Flow)		Test Case 2 (Mixed Flow)	
	Existing Mesh	New Mesh	Existing Mesh	New Mesh
A (60" 'Closer')	0.9540	-	1.2493	-
B (50" 'Closer')	0.9833	-	-	-
C (47" No 'Closer')	0.9894	1.0037	1.2654	1.2656
D (50" No 'Closer')	0.9813	-	1.2669	-

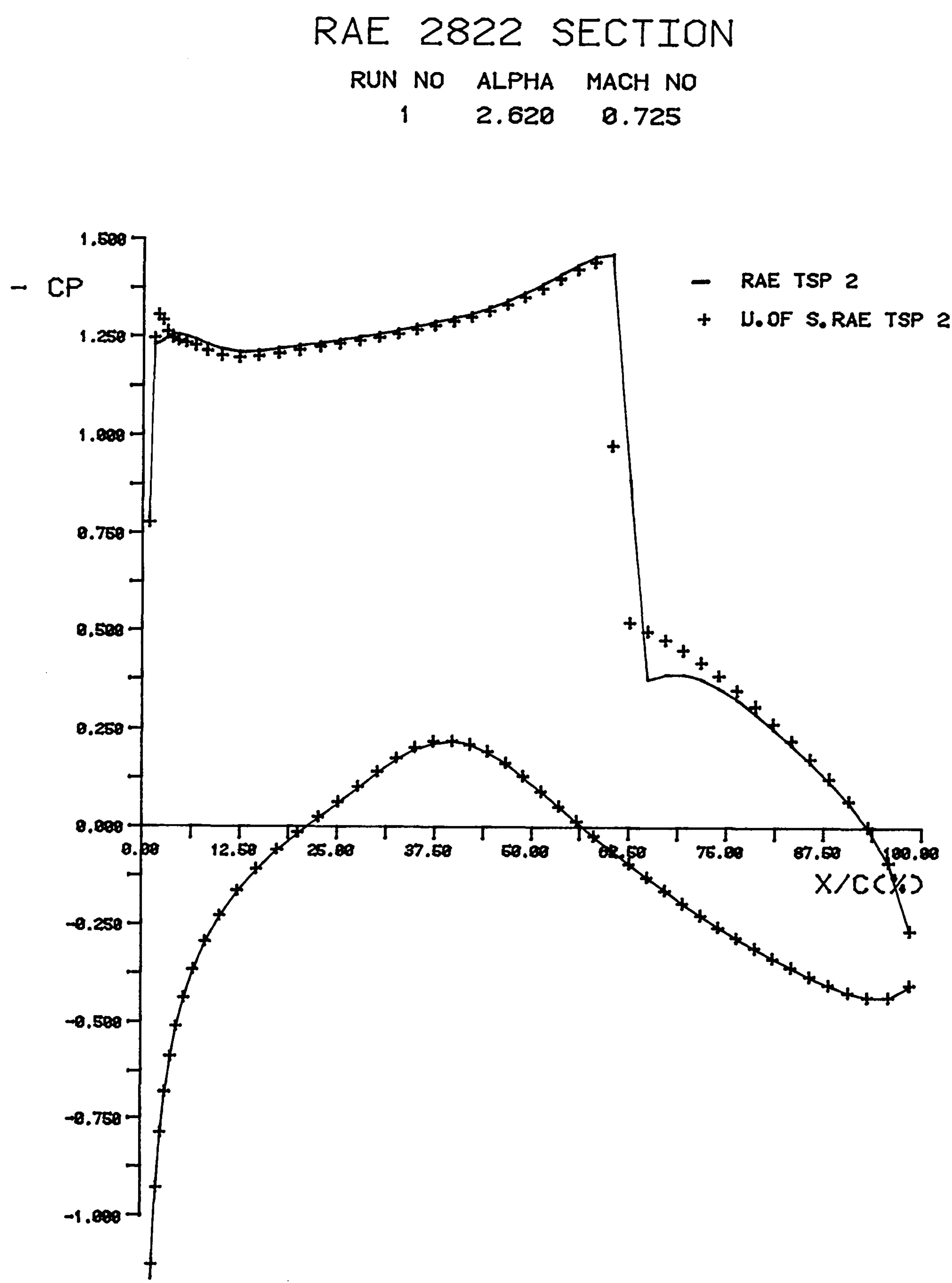
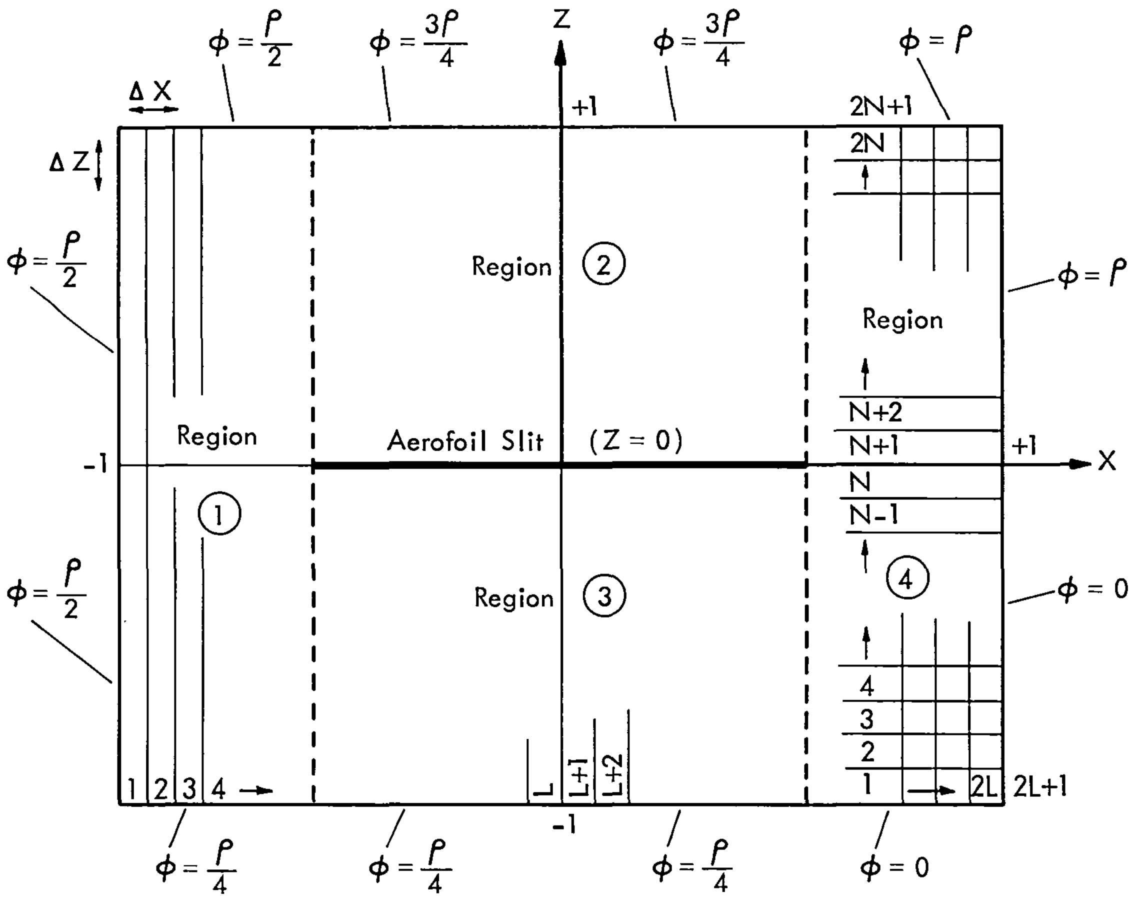


Figure 1: - RAE TSP Test Case



L = 20
N = 10 } Coarse Mesh

L = 40
N = 20 } Fine Mesh

ρ = Normalised Circulation
ϕ = Perturbation Potential

FIG. 2:- RAE COMPUTING PLANE (Z - X)

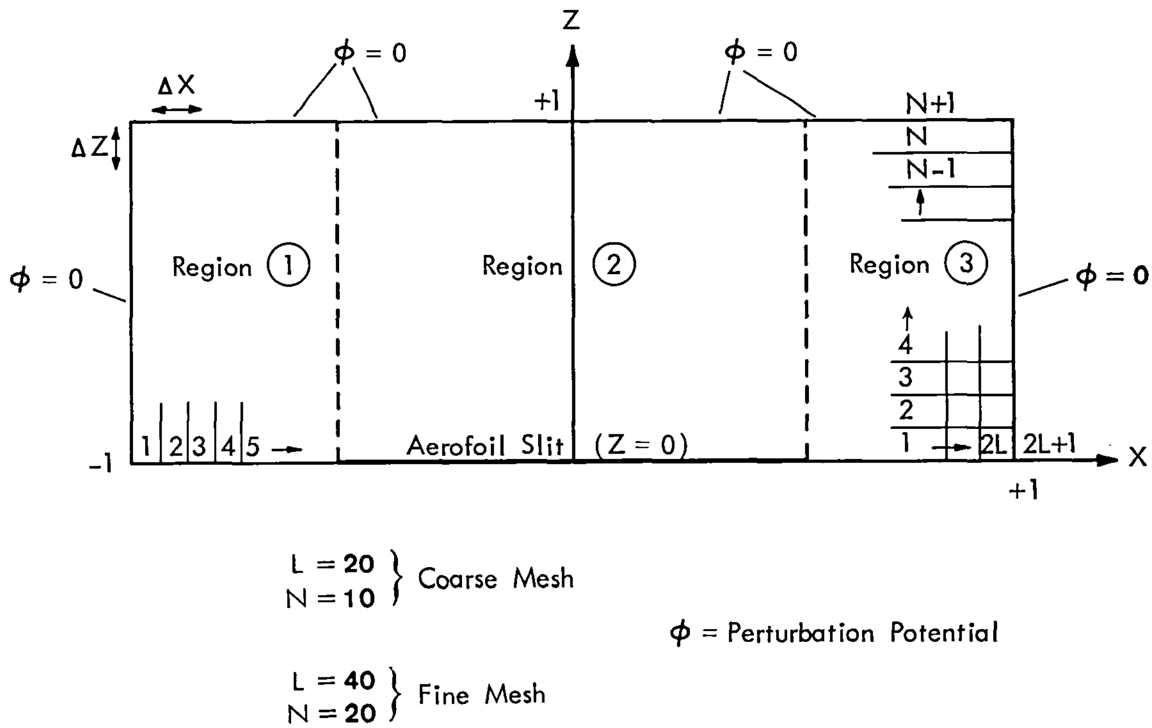


FIG. 3:- UNIVERSITY OF SOUTHAMPTON COMPUTING PLANE (Z - X)

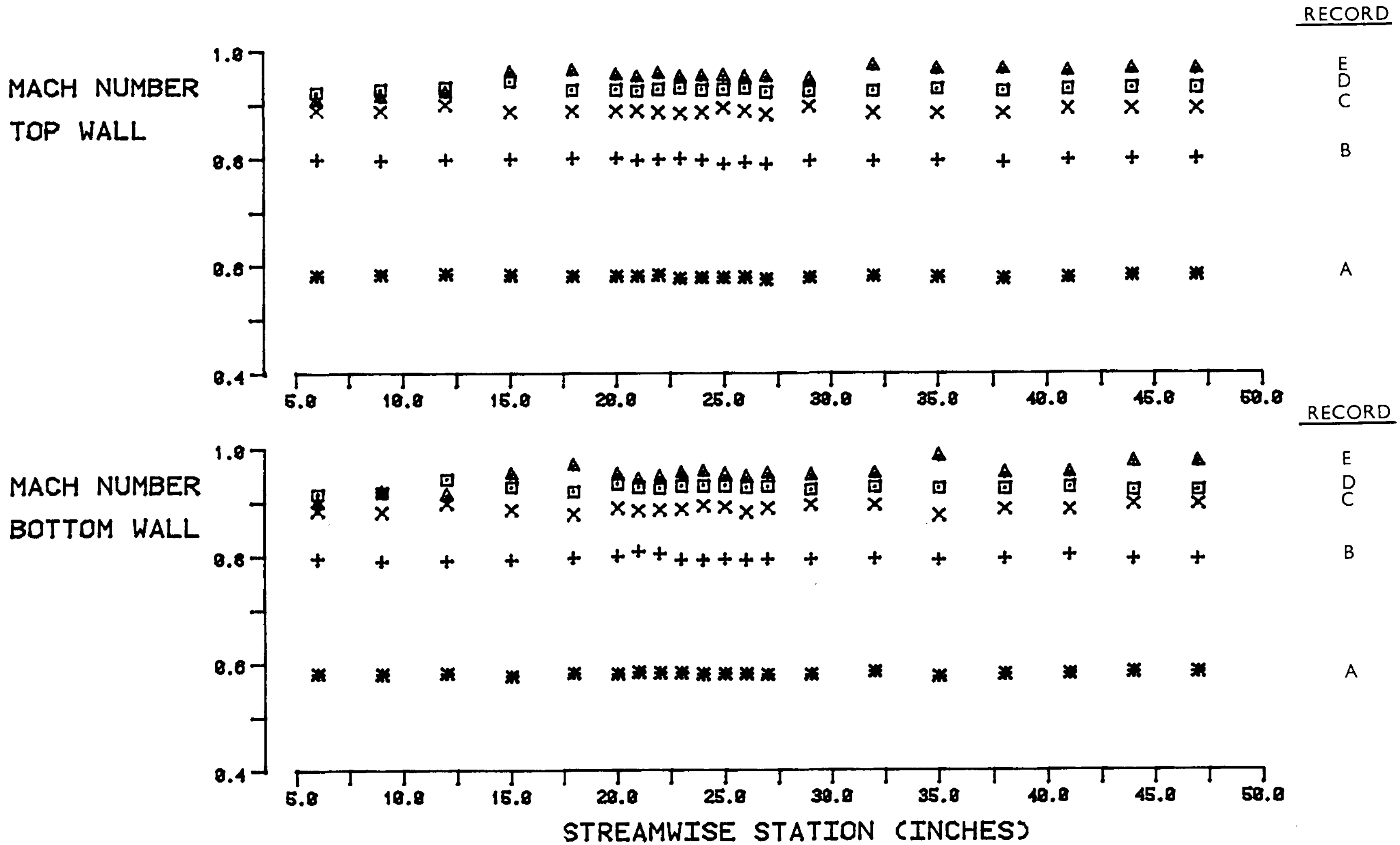


Figure 4:- Mach Number Distributions Along Walls Set to Aerodynamically-Straight Contours

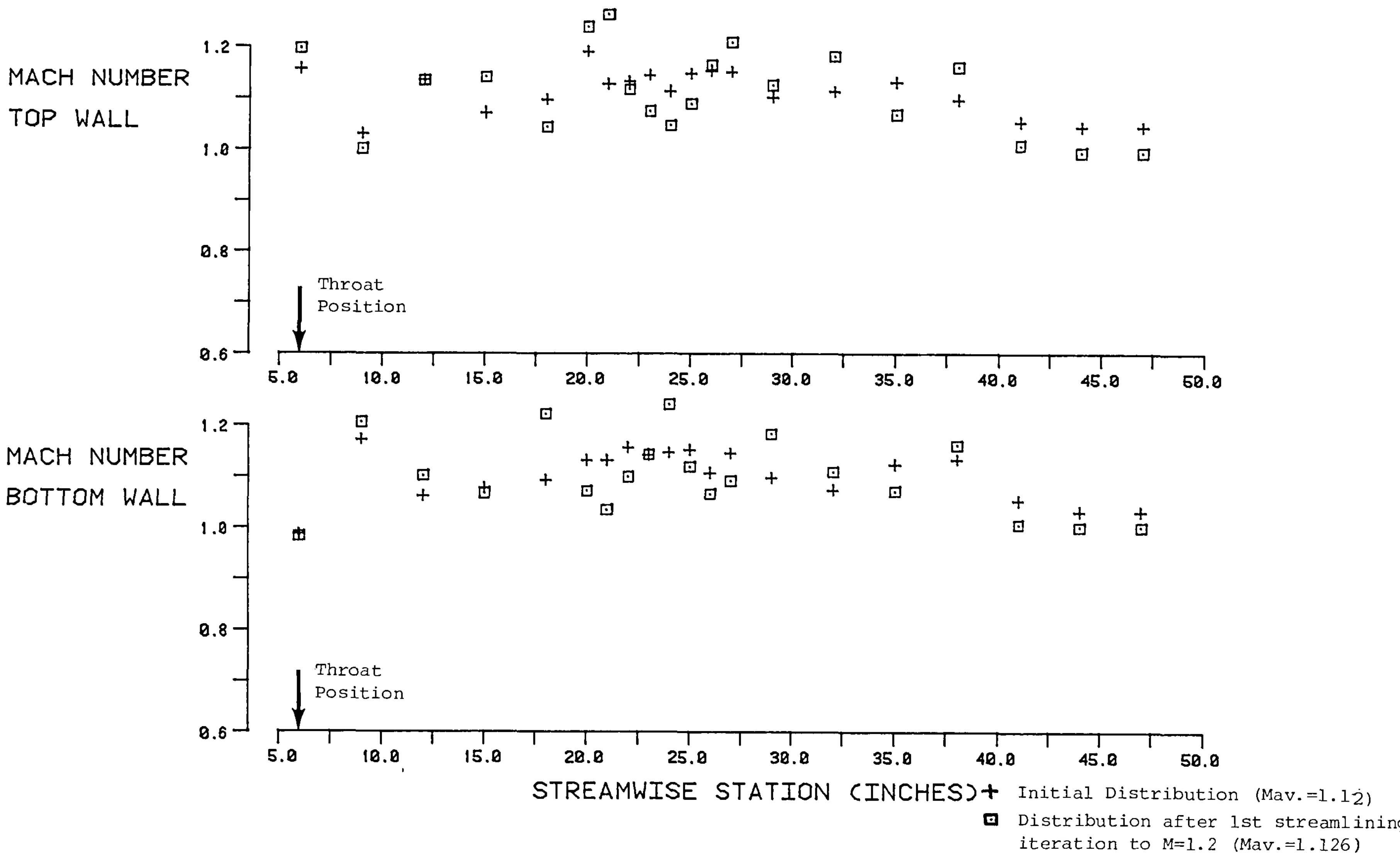


Figure 5:- Attempted Aerodynamically-Straight Streamlining of Supersonic Flow
(using 'Imbalance' Wall Adjustment Strategy)

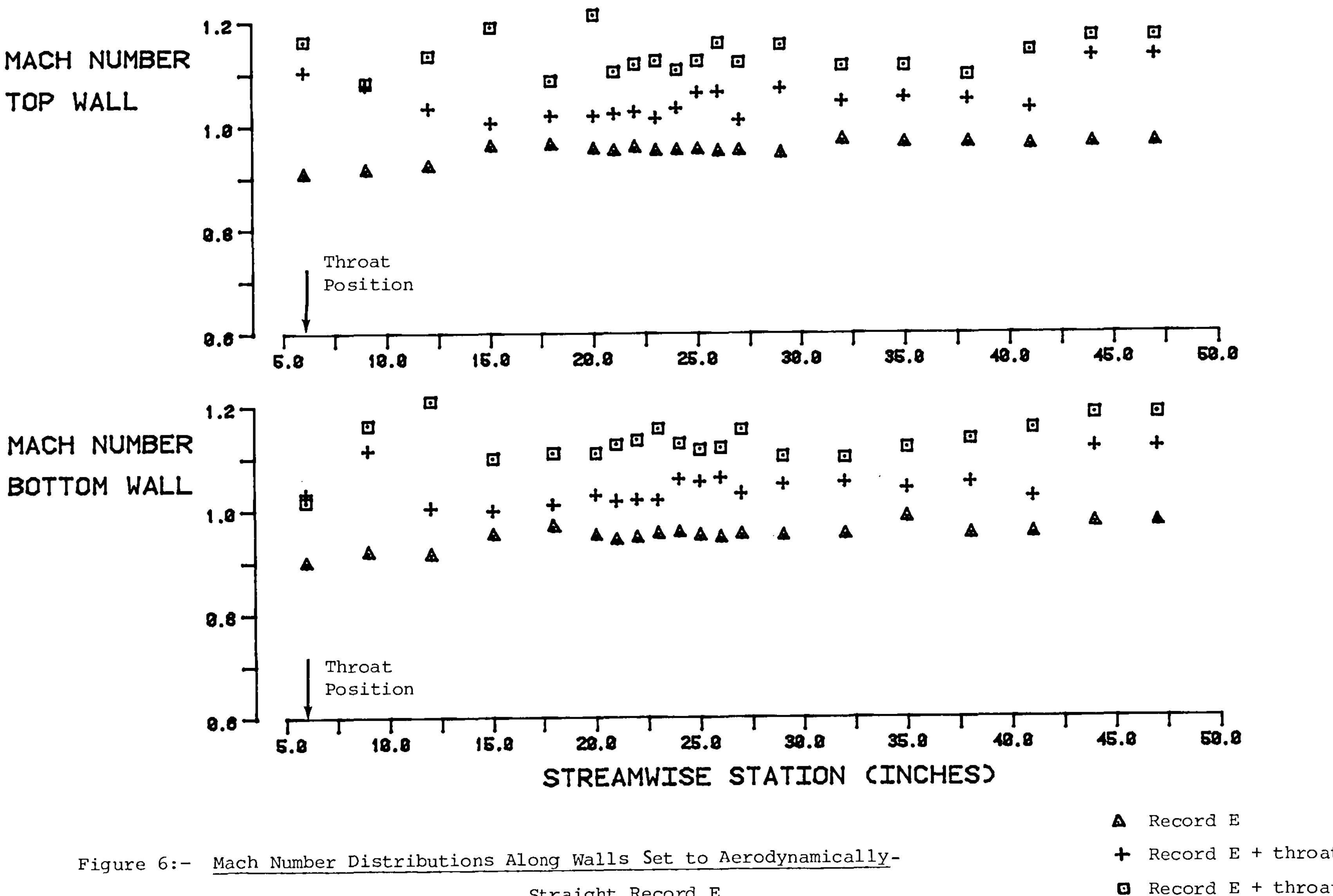


Figure 6:- Mach Number Distributions Along Walls Set to Aerodynamically-Straight Record E

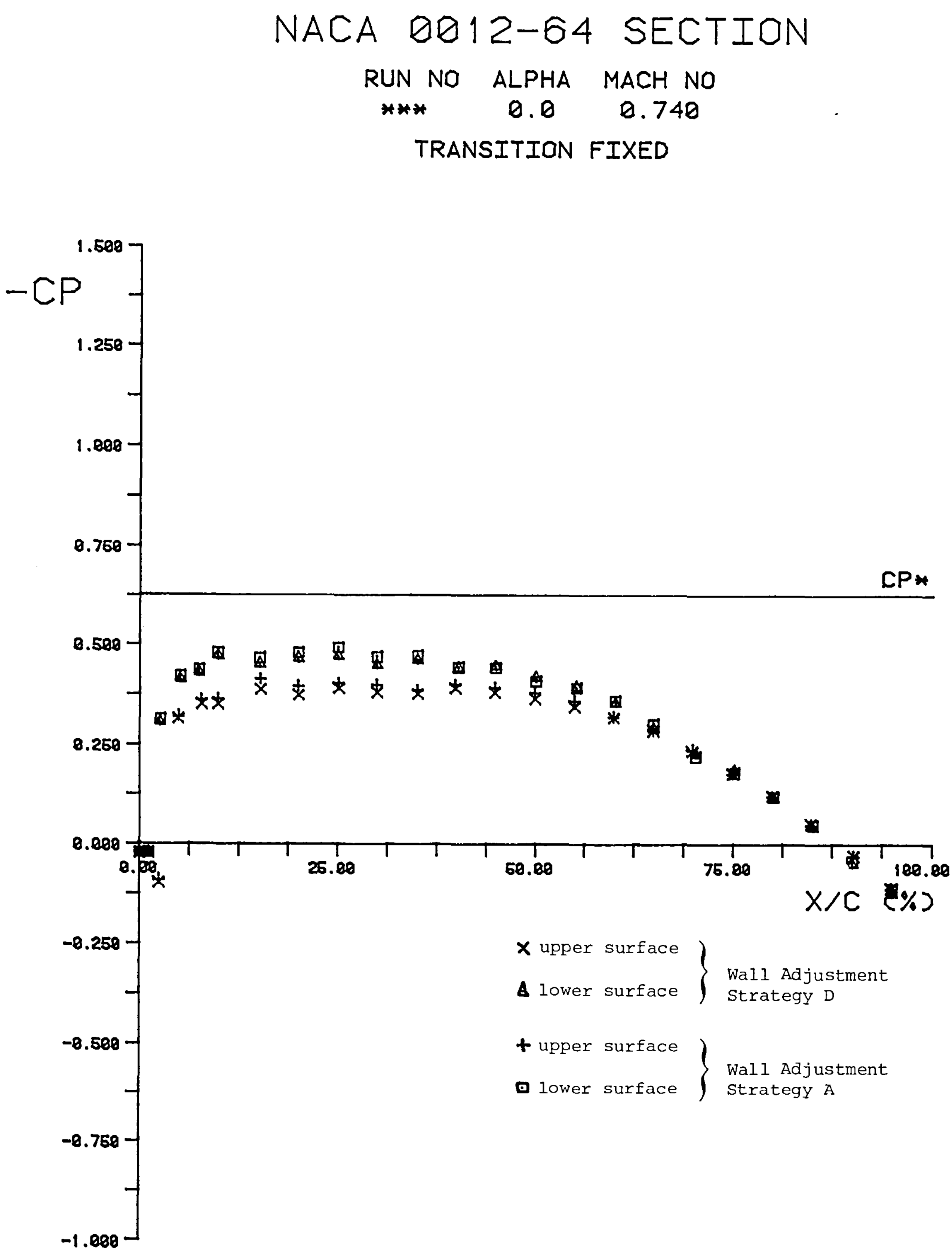


Figure 7:- Comparison of Model Pressure Distribution With Walls Streamlined

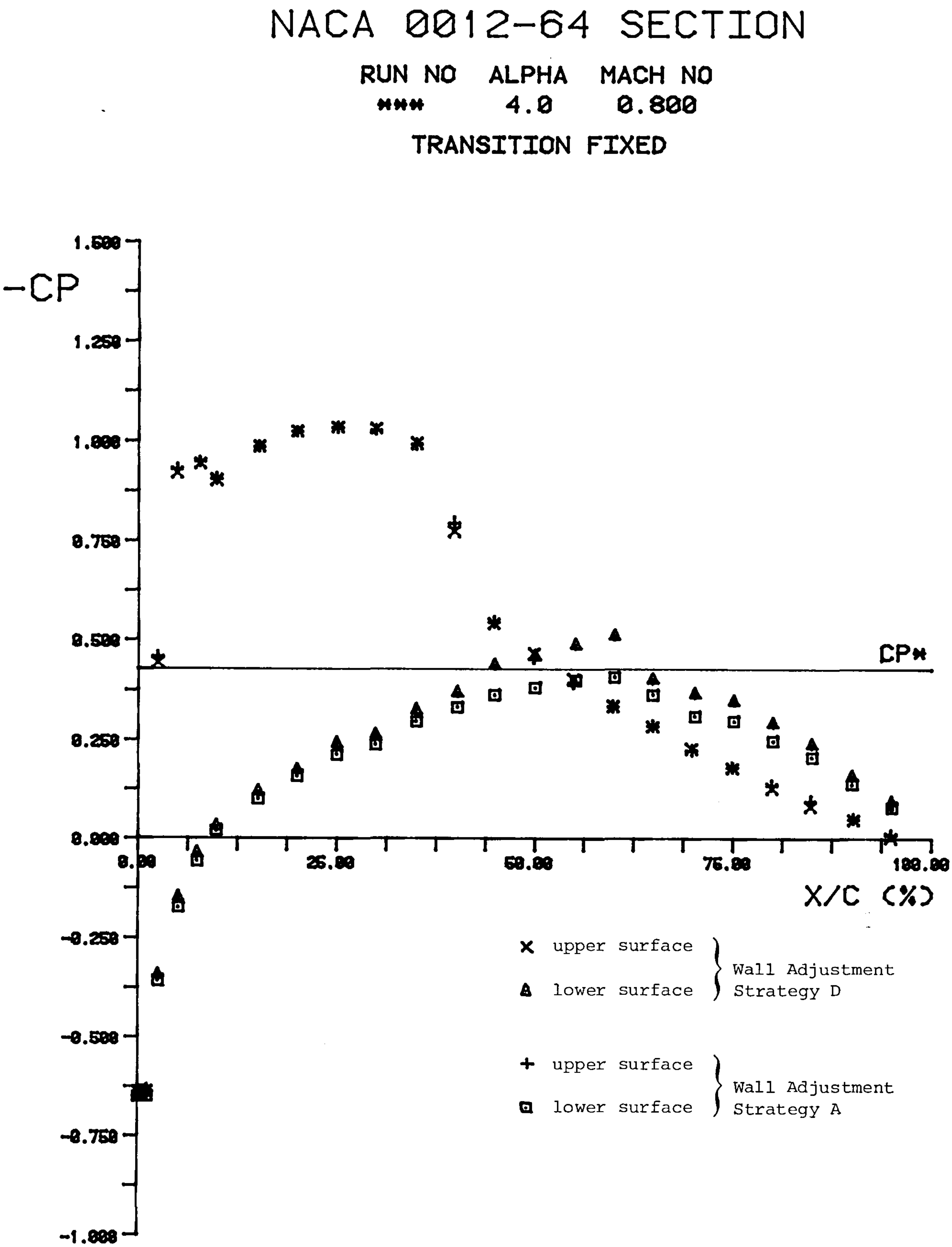


Figure 8:- Comparison of Model Pressure Distribution With Wall Streamlined

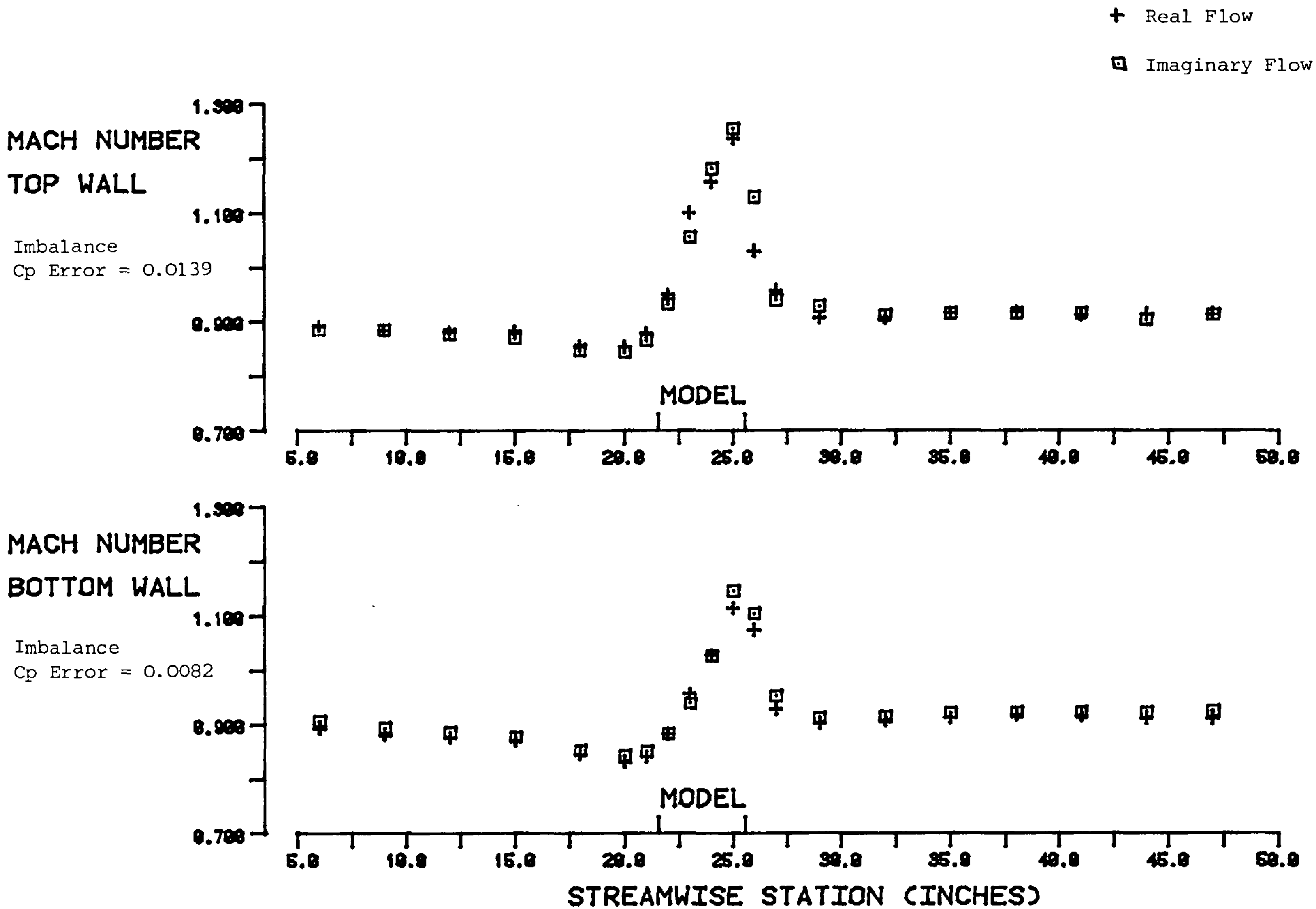


Figure 9:- Real and Imaginary Mach Number Distributions Along Flexible Walls

(Min. Cp Imbalance Error for $M_\infty = 0.9$, $\alpha \simeq 4.0^\circ$)

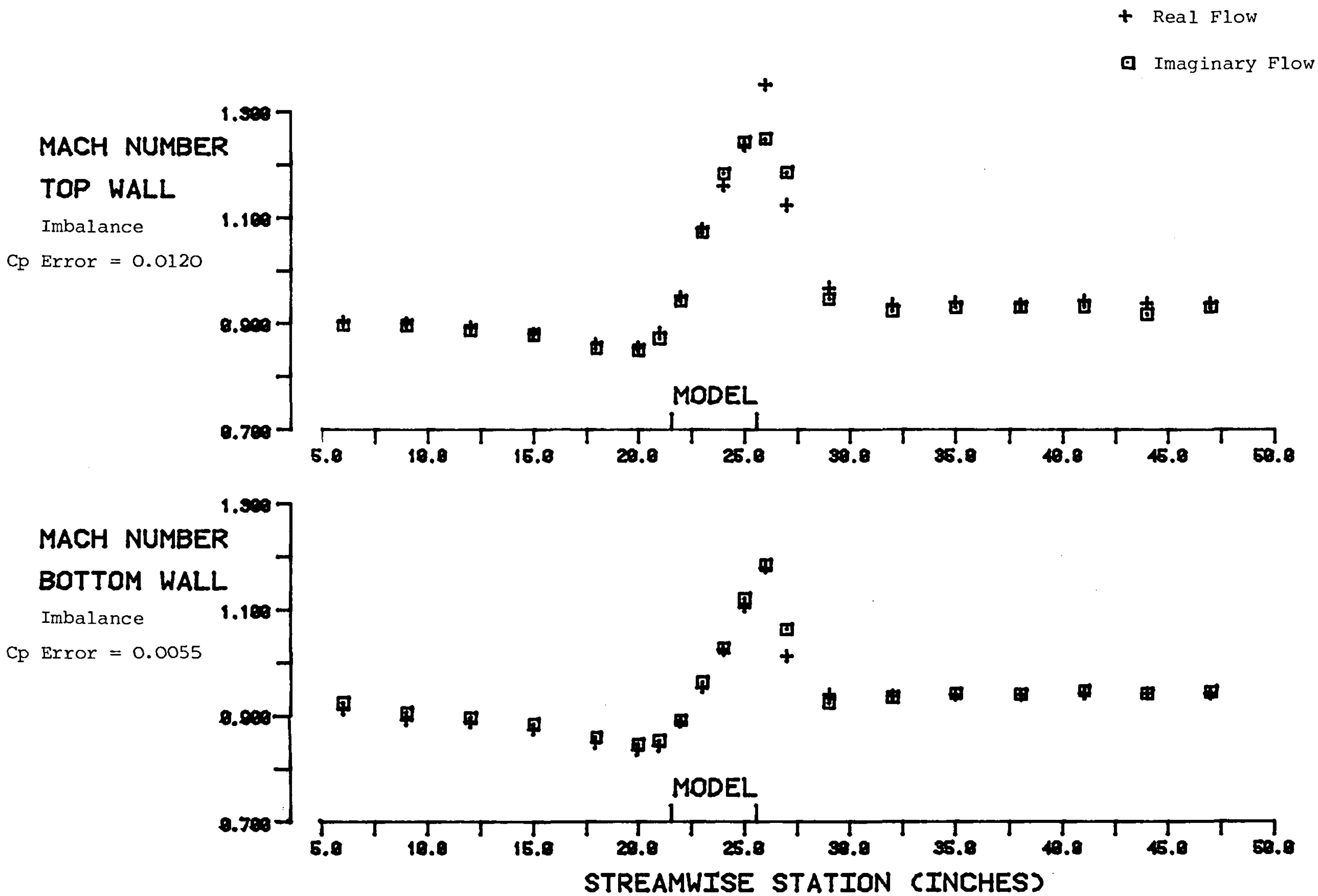


Figure 10:- Real and Imaginary Mach Number Distributions Along Flexible Walls

(Min. Cp Imbalance for $M_\infty = 0.925$, $\alpha \simeq 4.0^\circ$)

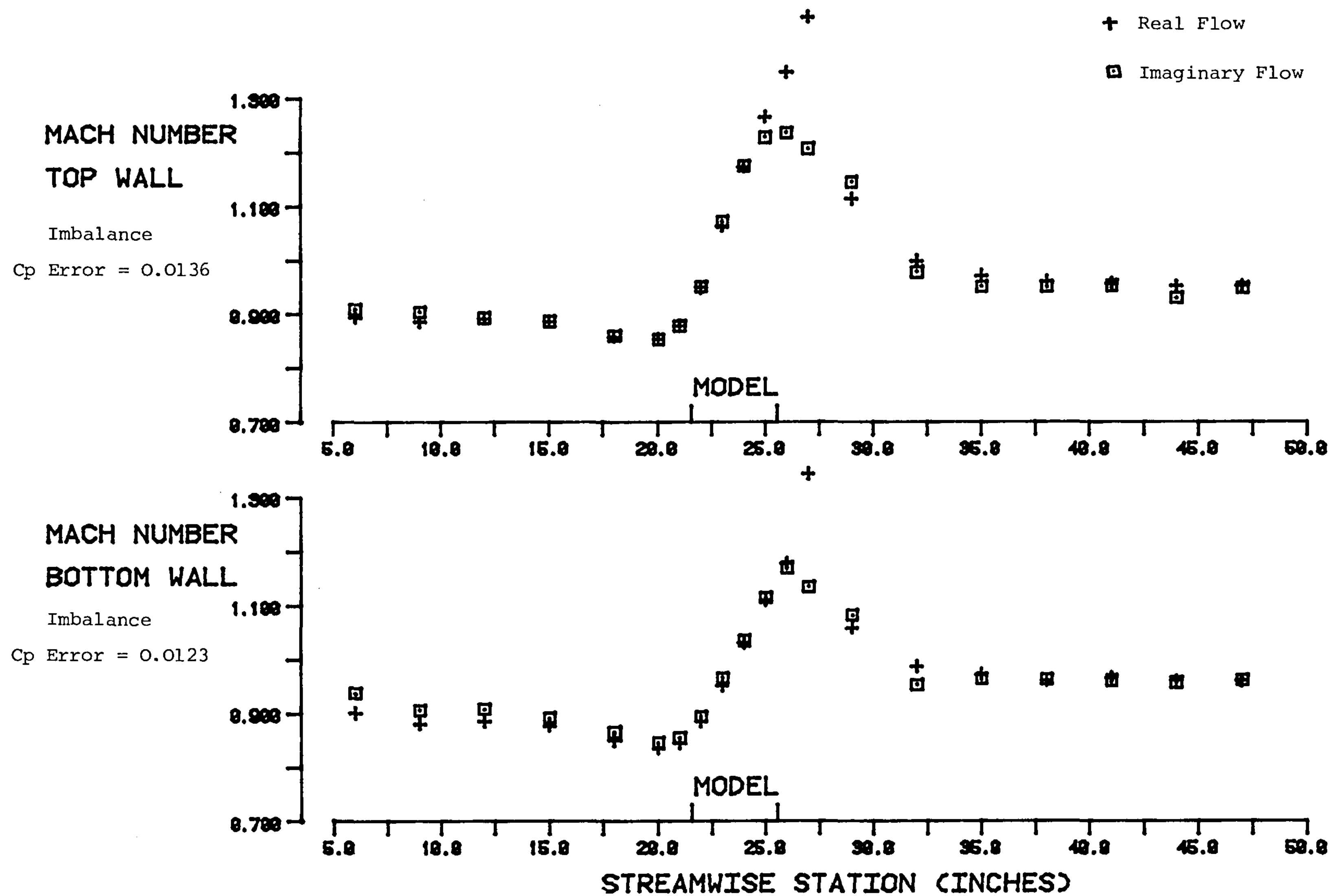


Figure 11:- Real and Imaginary Mach Number Distributions Along Flexible Walls

(Min. Cp Imbalance Error for $M_\infty = 0.94$, $\alpha \simeq 4.0^\circ$)

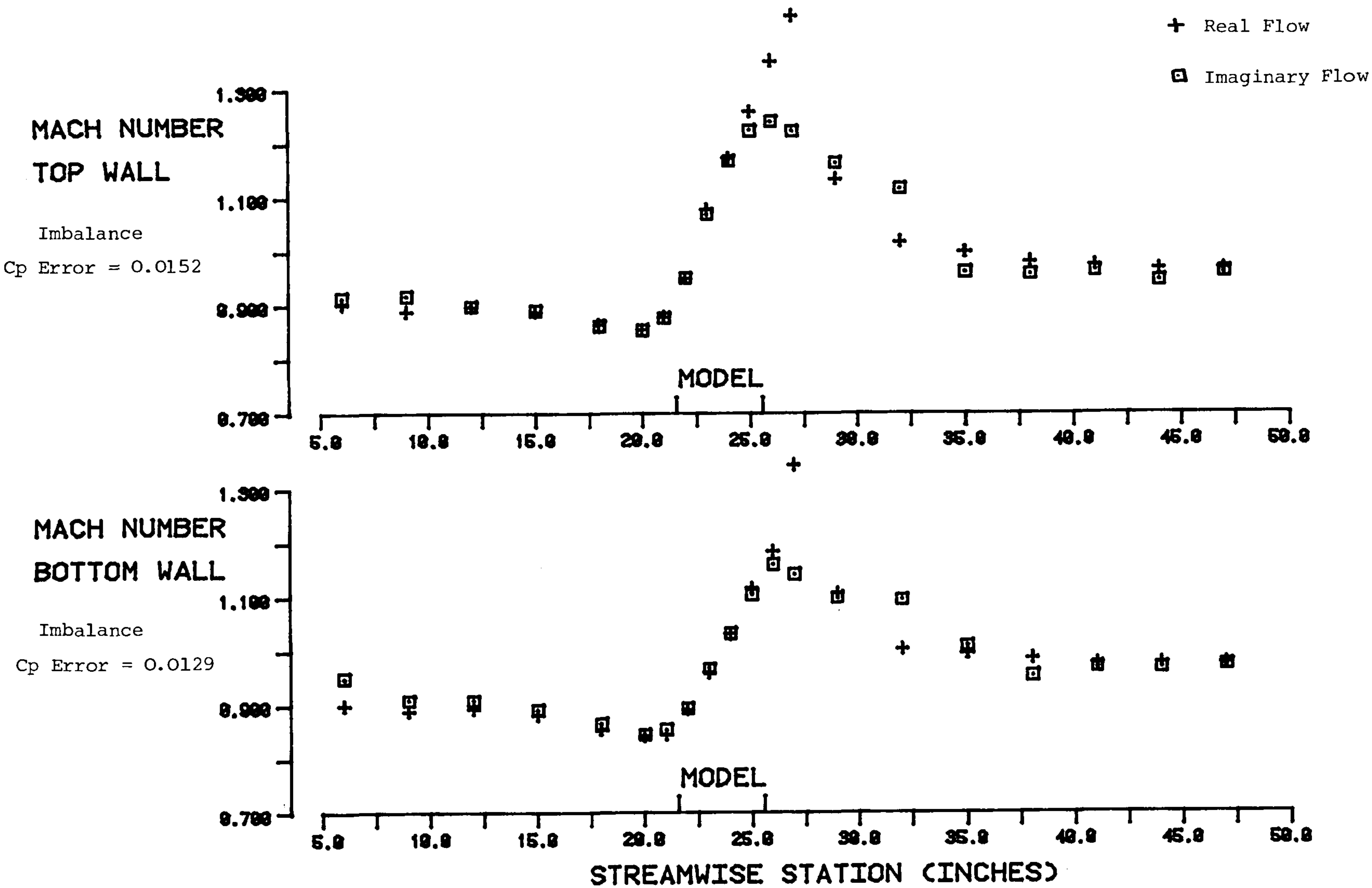


Figure 12:- Real and Imaginary Mach Number Distributions Along Flexible Walls

(Min. Cp Imbalance Error for $M_\infty = 0.95$, $\alpha \simeq 4.0^\circ$)

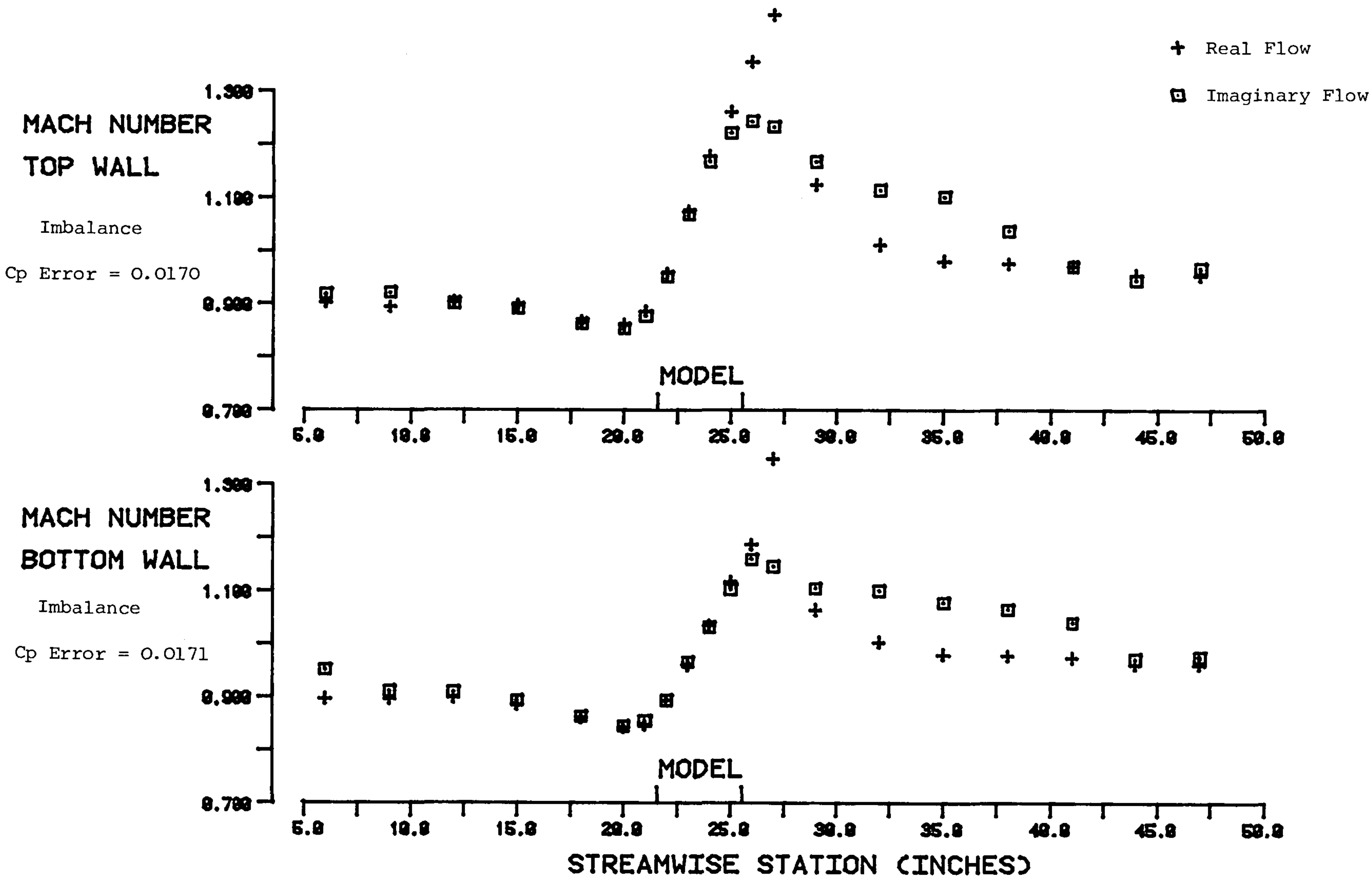


Figure 13:- Real and Imaginary Mach Number Distributions Along Flexible Walls

(Min. Cp Imbalance Error for $M_{\infty} = 0.96$, $\alpha \approx 4.0^{\circ}$)

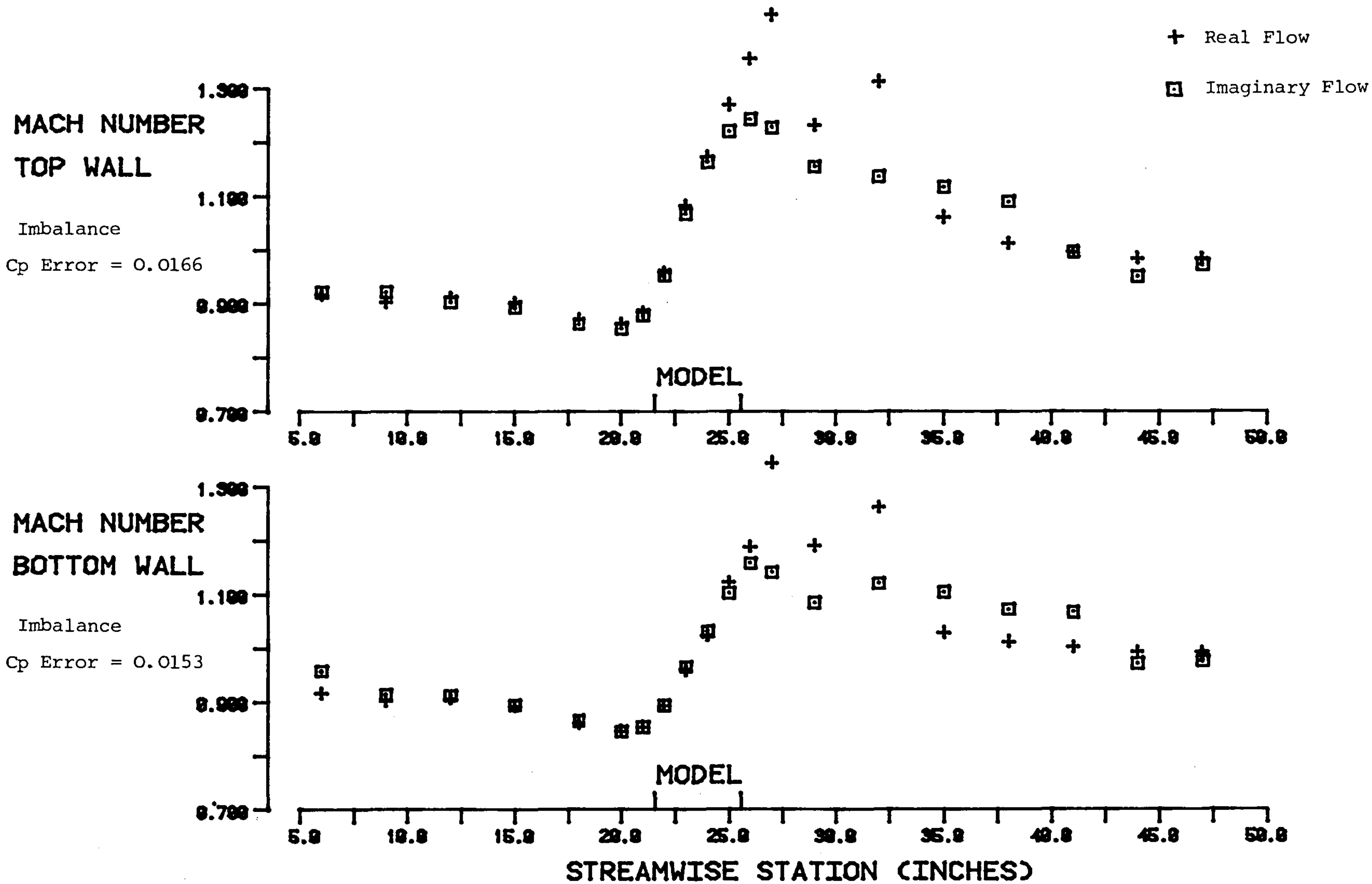


Figure 14:- Real and Imaginary Mach Number Distribution Along Flexible Walls

(Min. Cp Imbalance Error from $M_\infty = 0.97$, $\alpha \approx 4.0^{\circ}$)

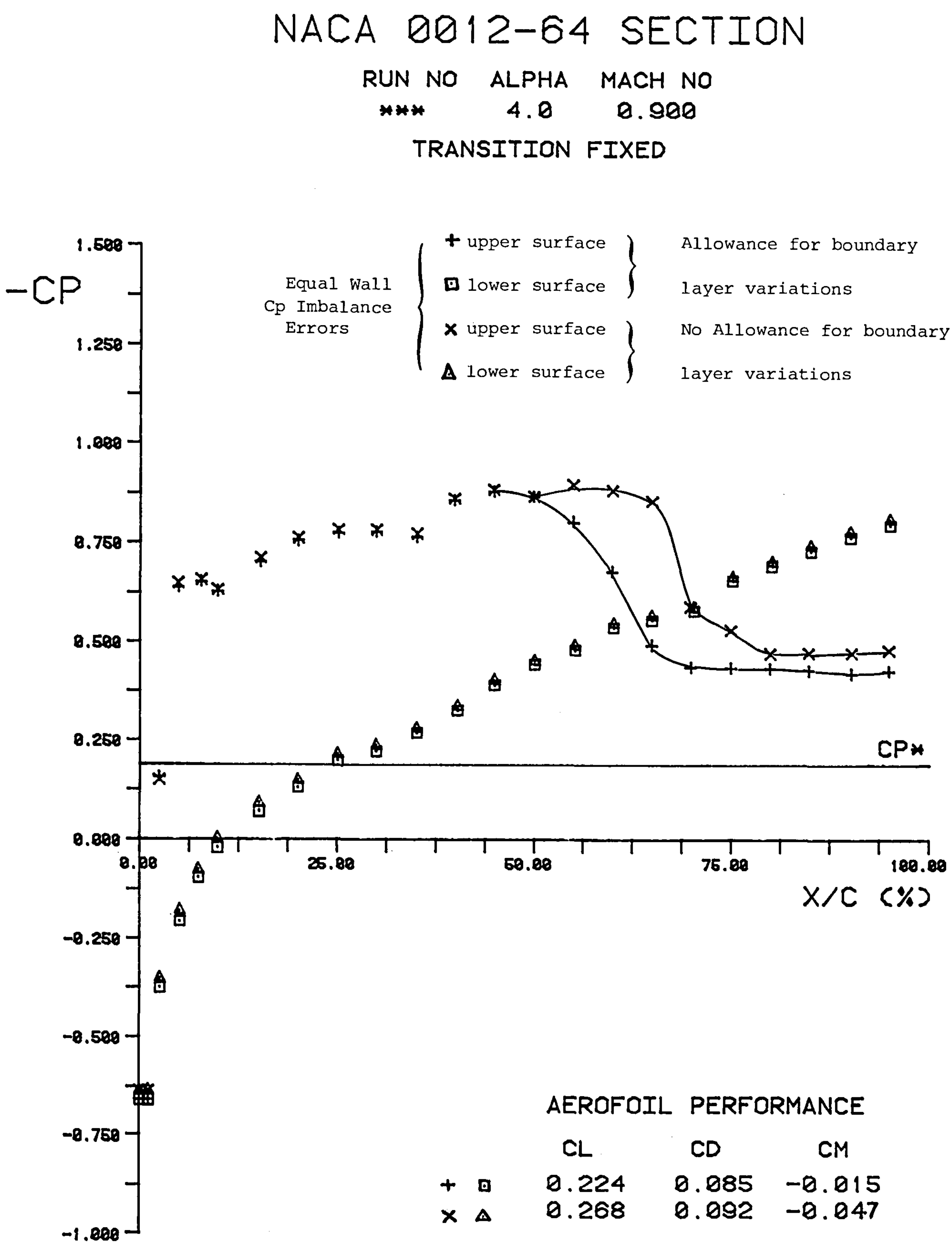


Figure 15:- Effects of Allowance for Variations in Wall Boundary Layer Displacement Thickness on Model Pressure Distributions

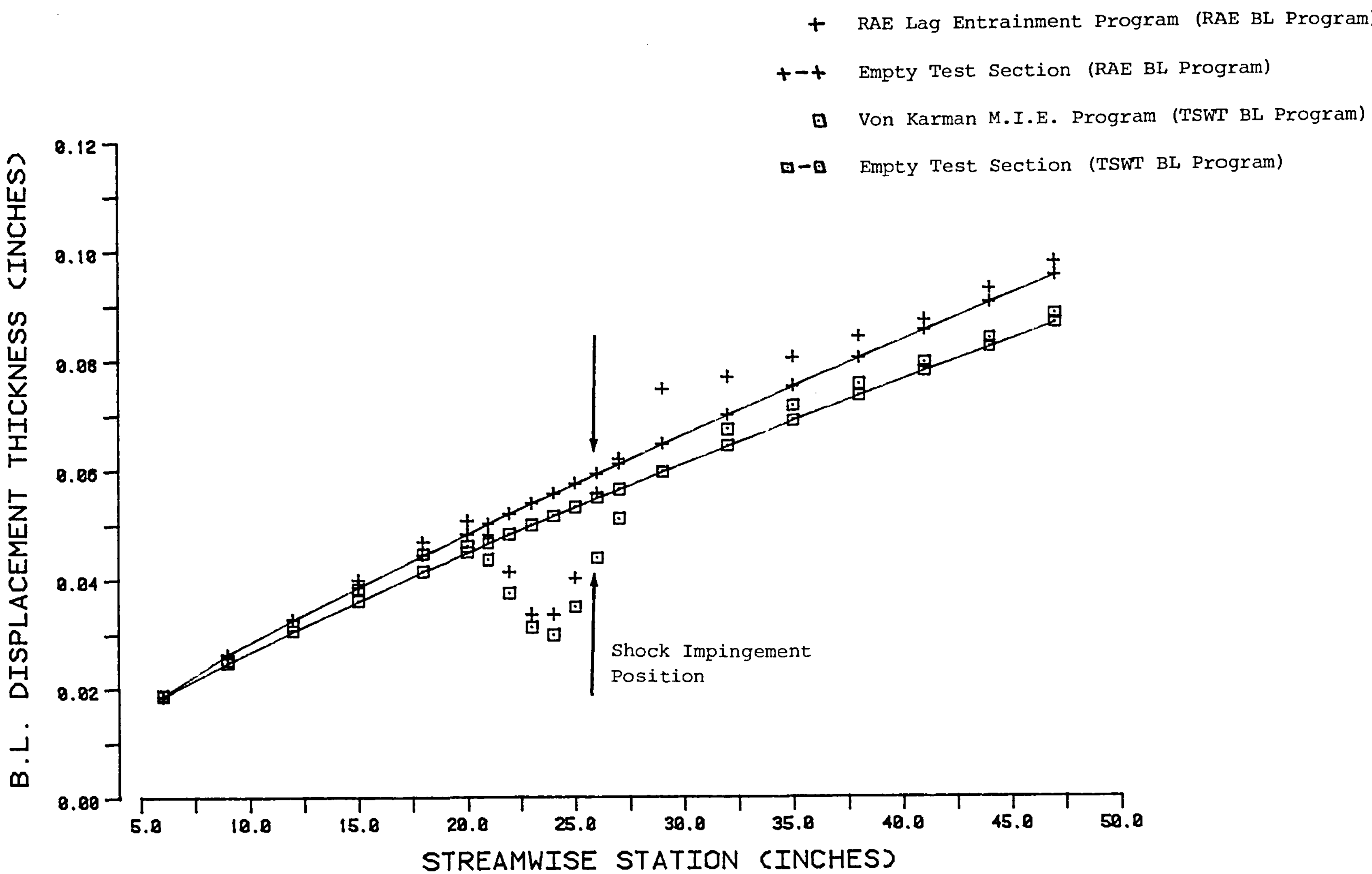
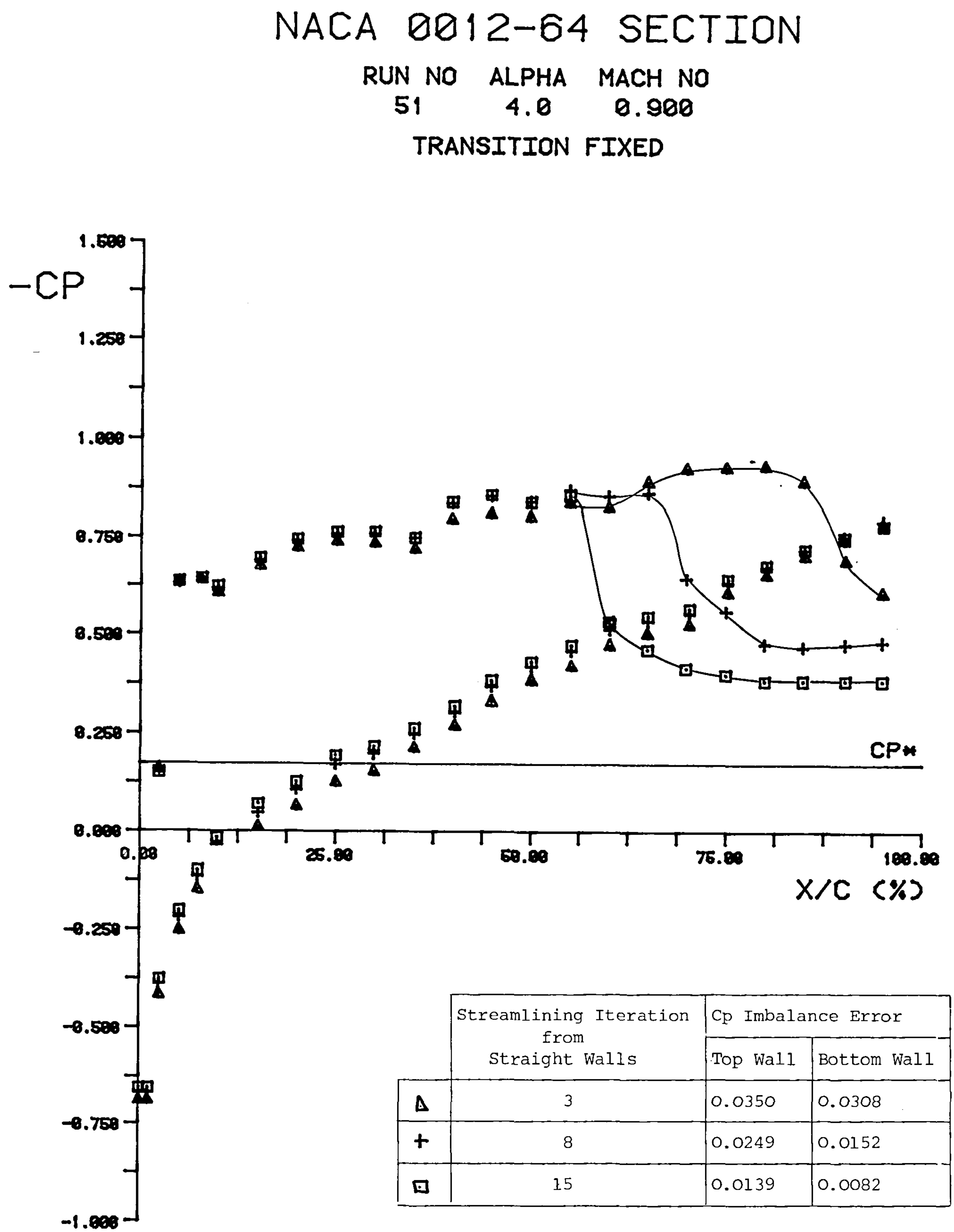


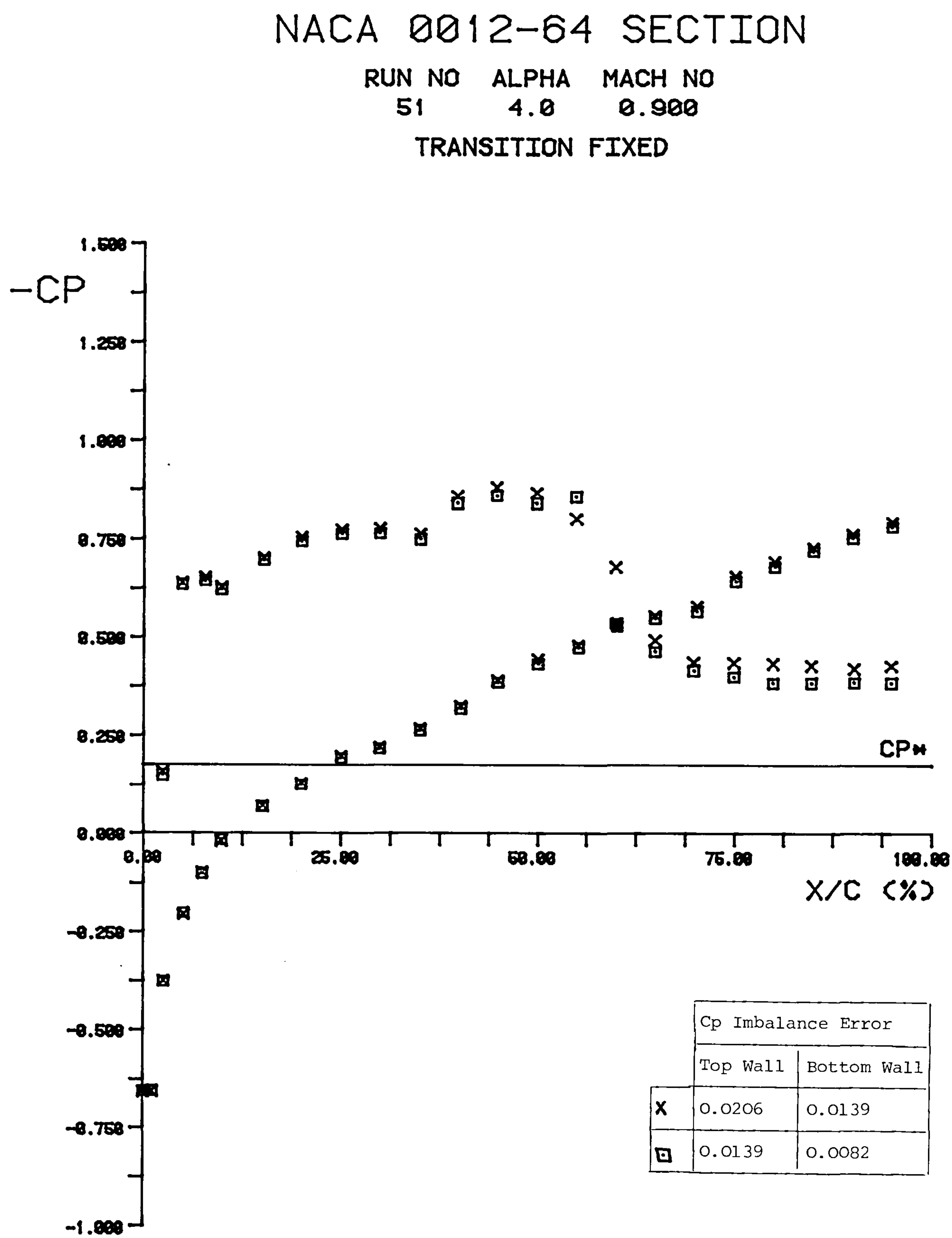
Figure 16:- Boundary layer Displacement Thickness Distribution Along Top Wall

($M_\infty = 0.9$, $\alpha \simeq 4.0^{\circ}$, Cp Imbalance Error = 0.0155)



	Streamlining Iteration from Straight Walls	Cp Imbalance Error	
		Top Wall	Bottom Wall
Δ	3	0.0350	0.0308
+	8	0.0249	0.0152
⊡	15	0.0139	0.0082

Figure 17a:- Effect of Streamlining on Model Pressure Distributions



Cp Imbalance Error		
	Top Wall	Bottom Wall
X	0.0206	0.0139
⊡	0.0139	0.0082

Figure 17b:- Effect of Streamlining on Model Pressure Distribution

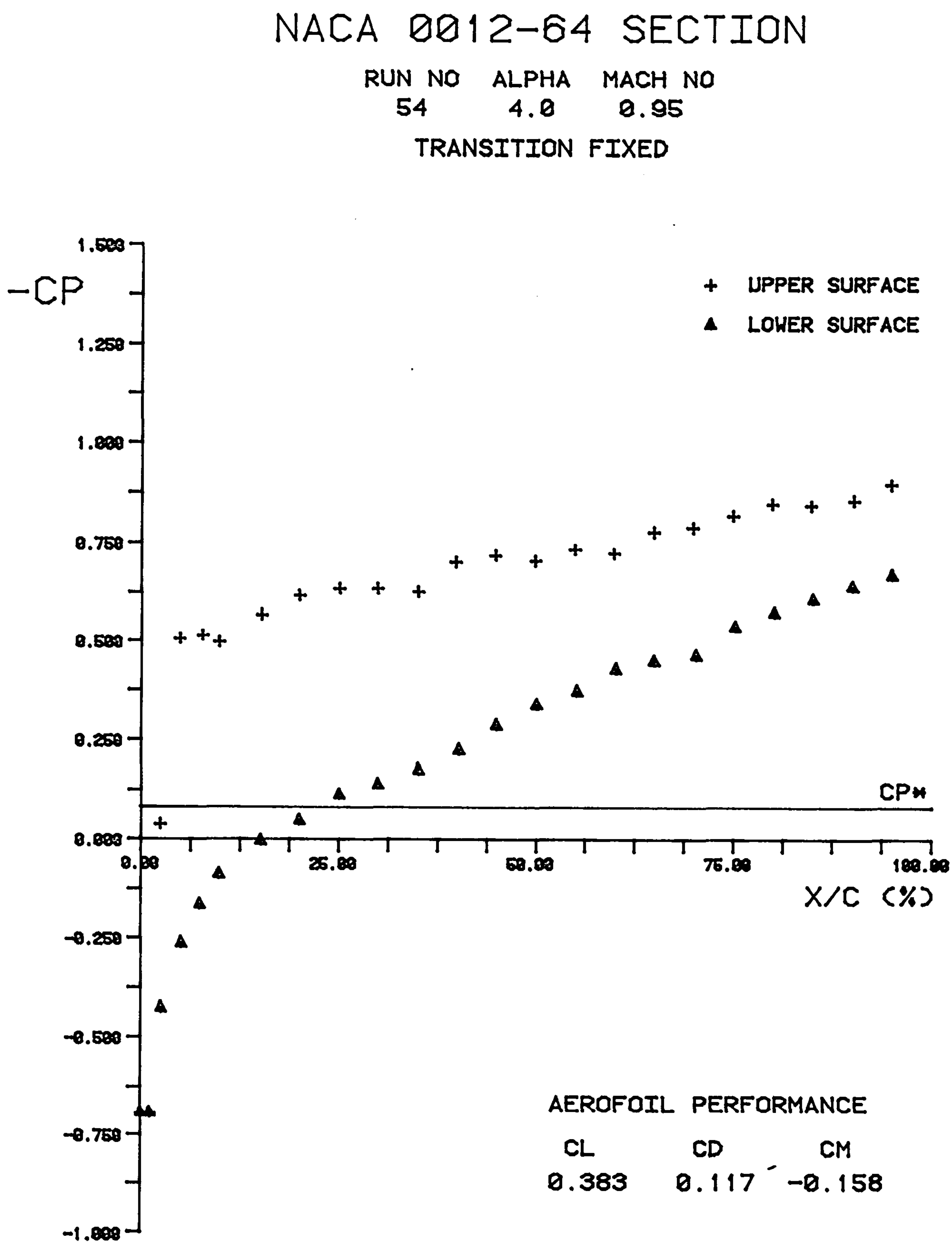


Figure 18:- Model Pressure Distribution

(for best attained level of streamlining)

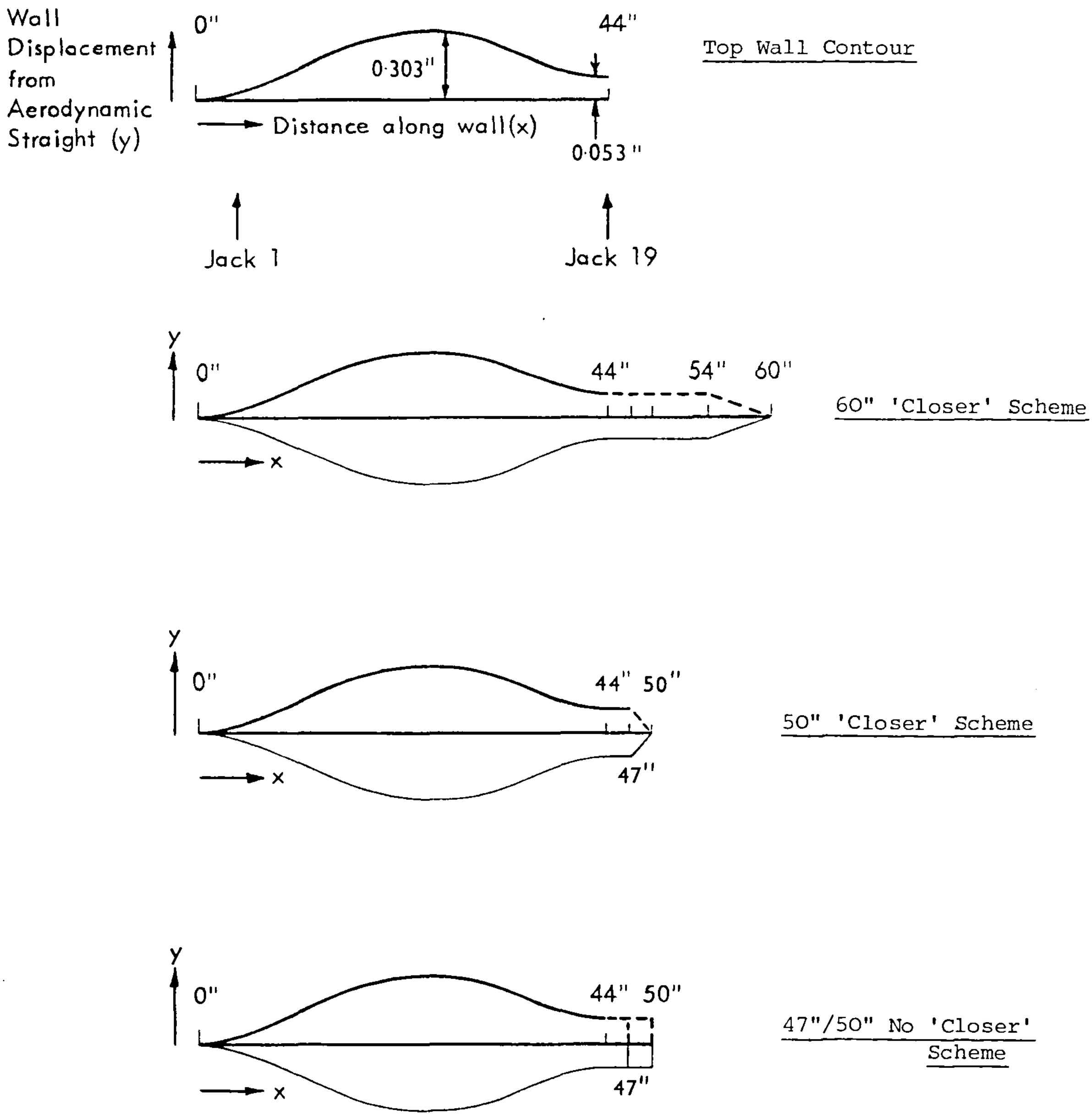


Figure 19:- Top Wall Representation of Test Case 1/2

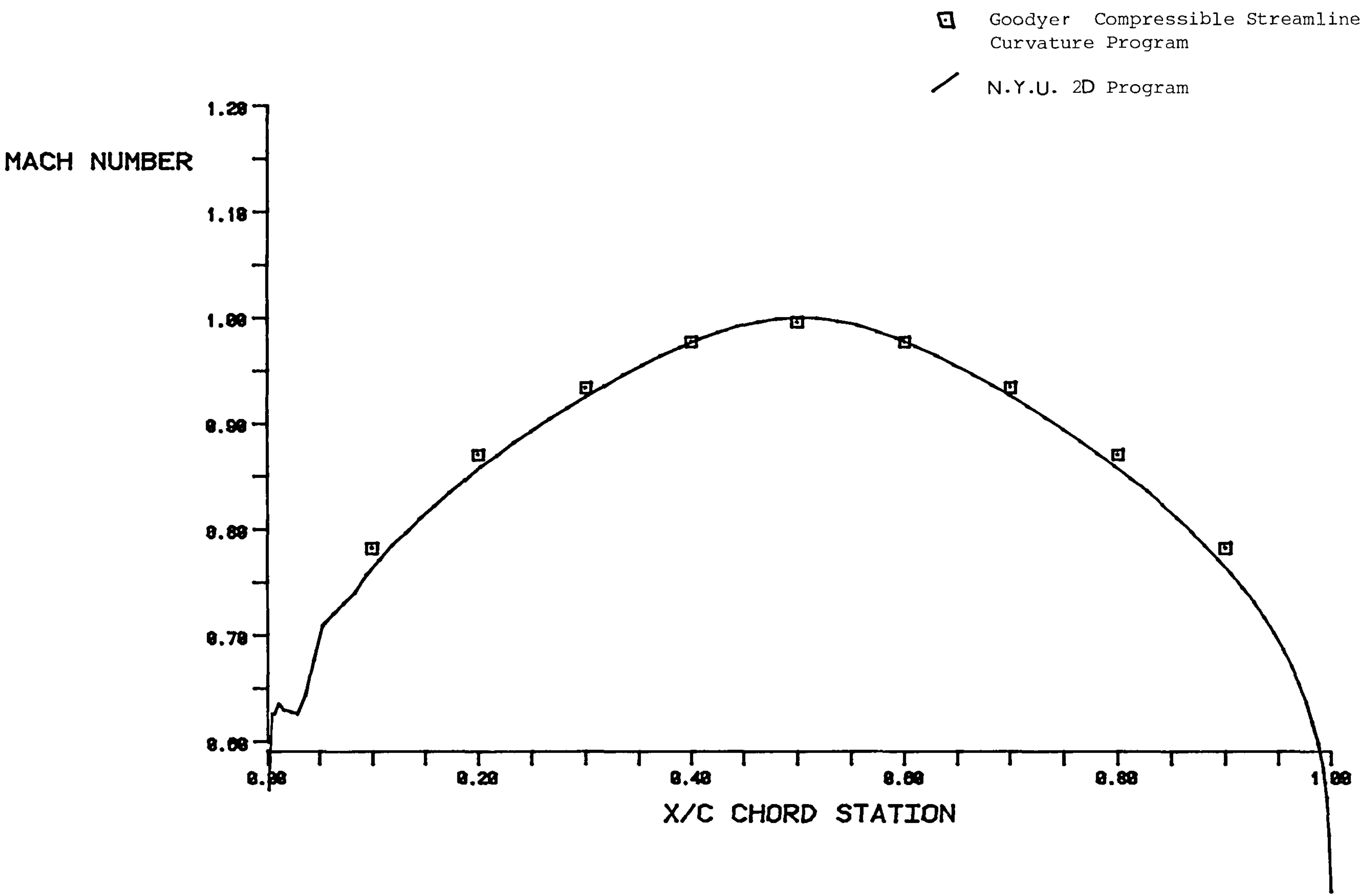


Figure 20:- <u>Comparison of Computing Methods for 10% Circ. Arc. Aerofoil</u>

(M_∞ = 0.77, α = 0.0)

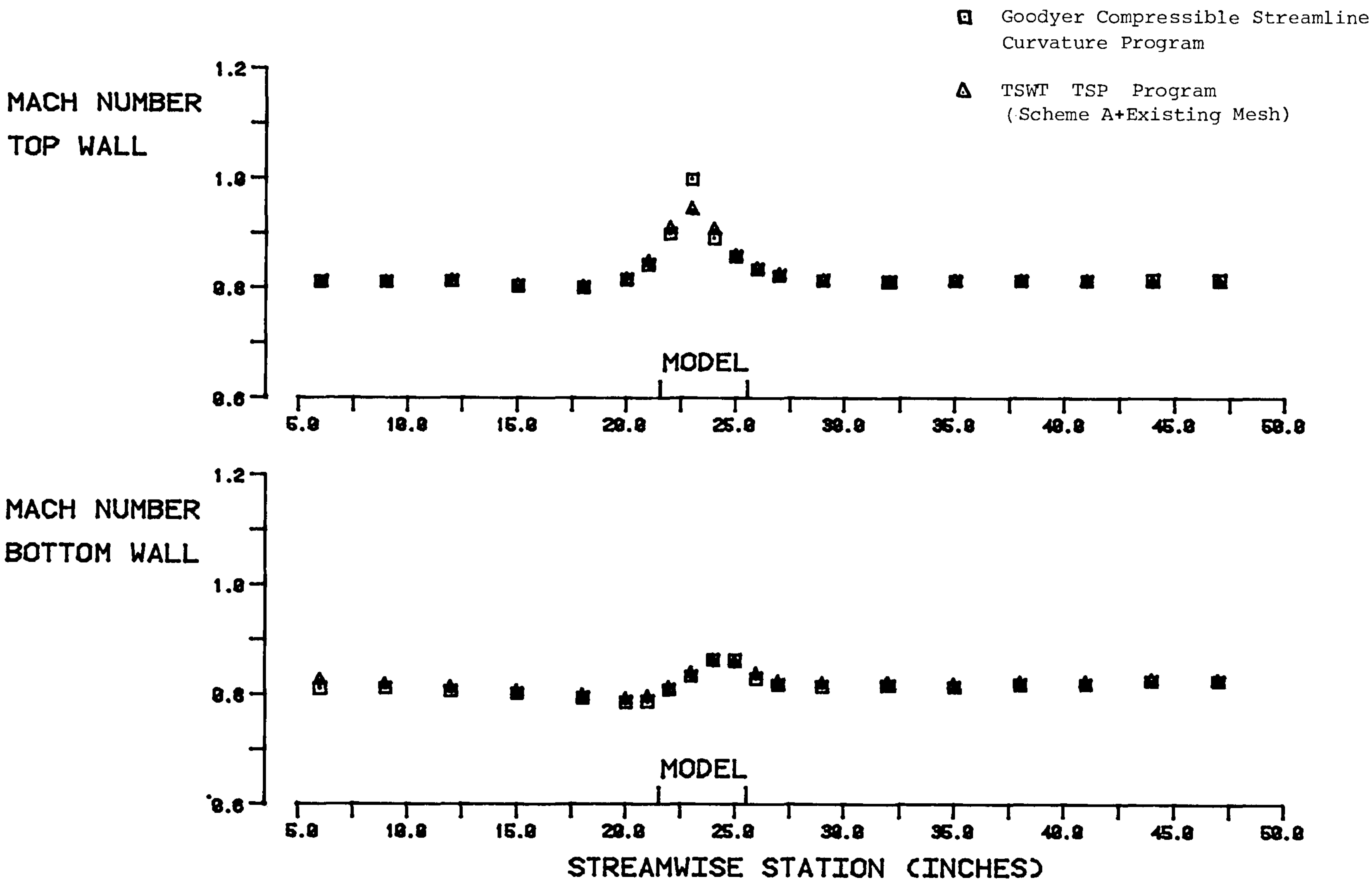


Figure 21a:- Comparison of Imaginary Flow Methods for Wall Contours of Test Case 1 (M_∞ = 0.8143)

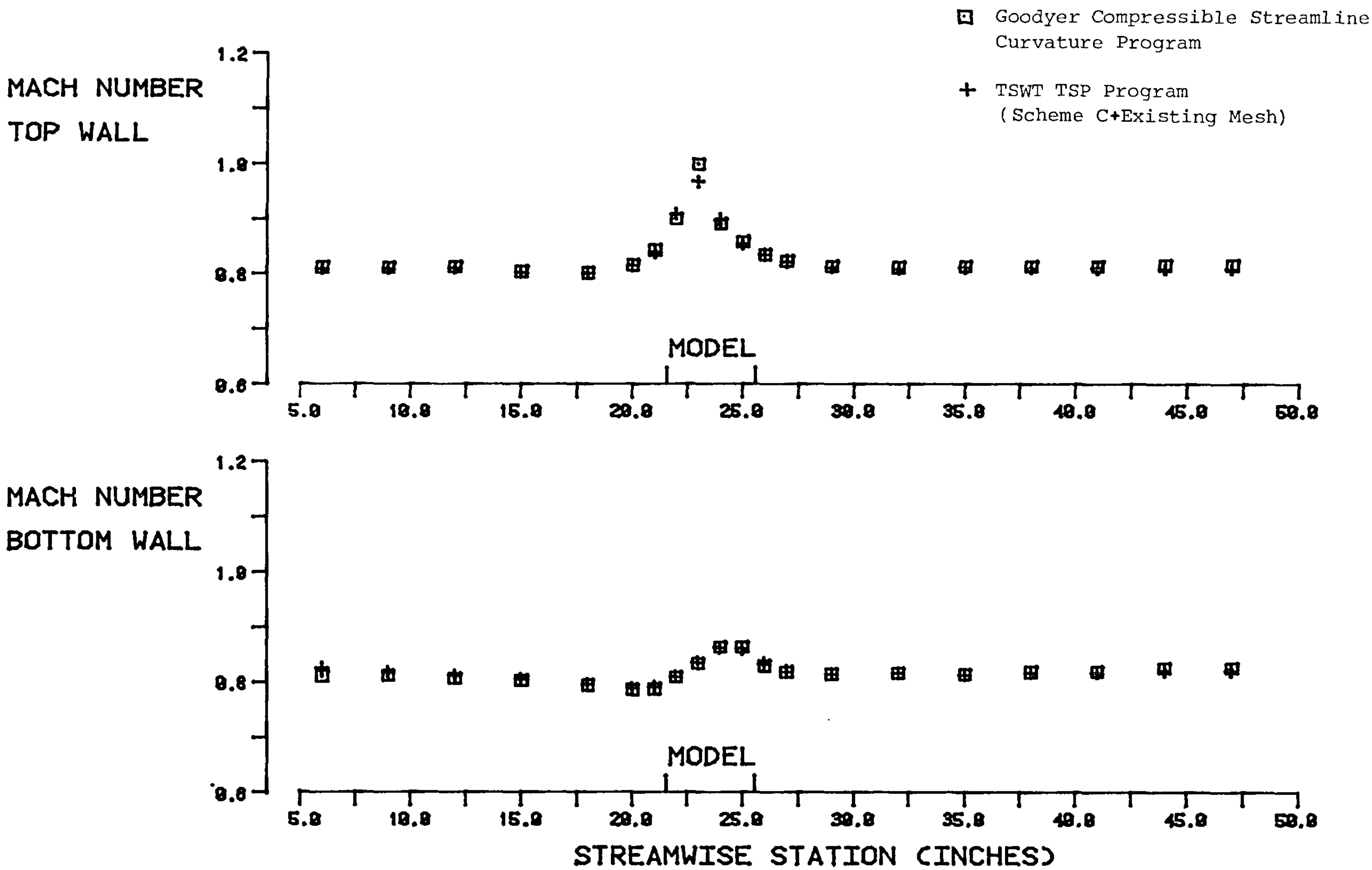


Figure 21b:- Comparison of Imaginary Flow Methods for Wall Contours of Test Case 1 (M_∞ = 0.8143)

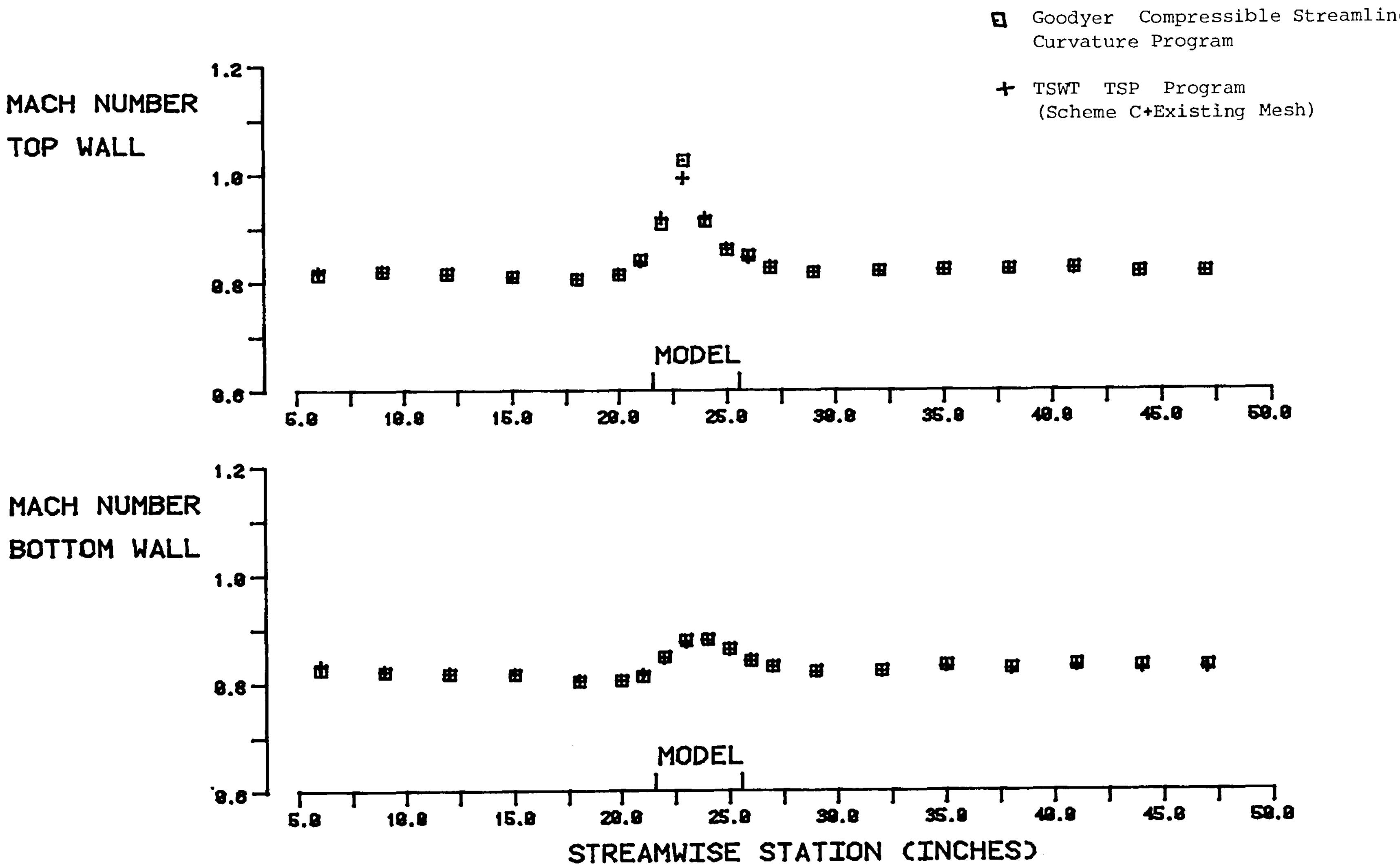


Figure 22a:- Comparison of Imaginary Flow Methods for Wall Contours of Test Case 3 ($M_\infty = 0.8247$)

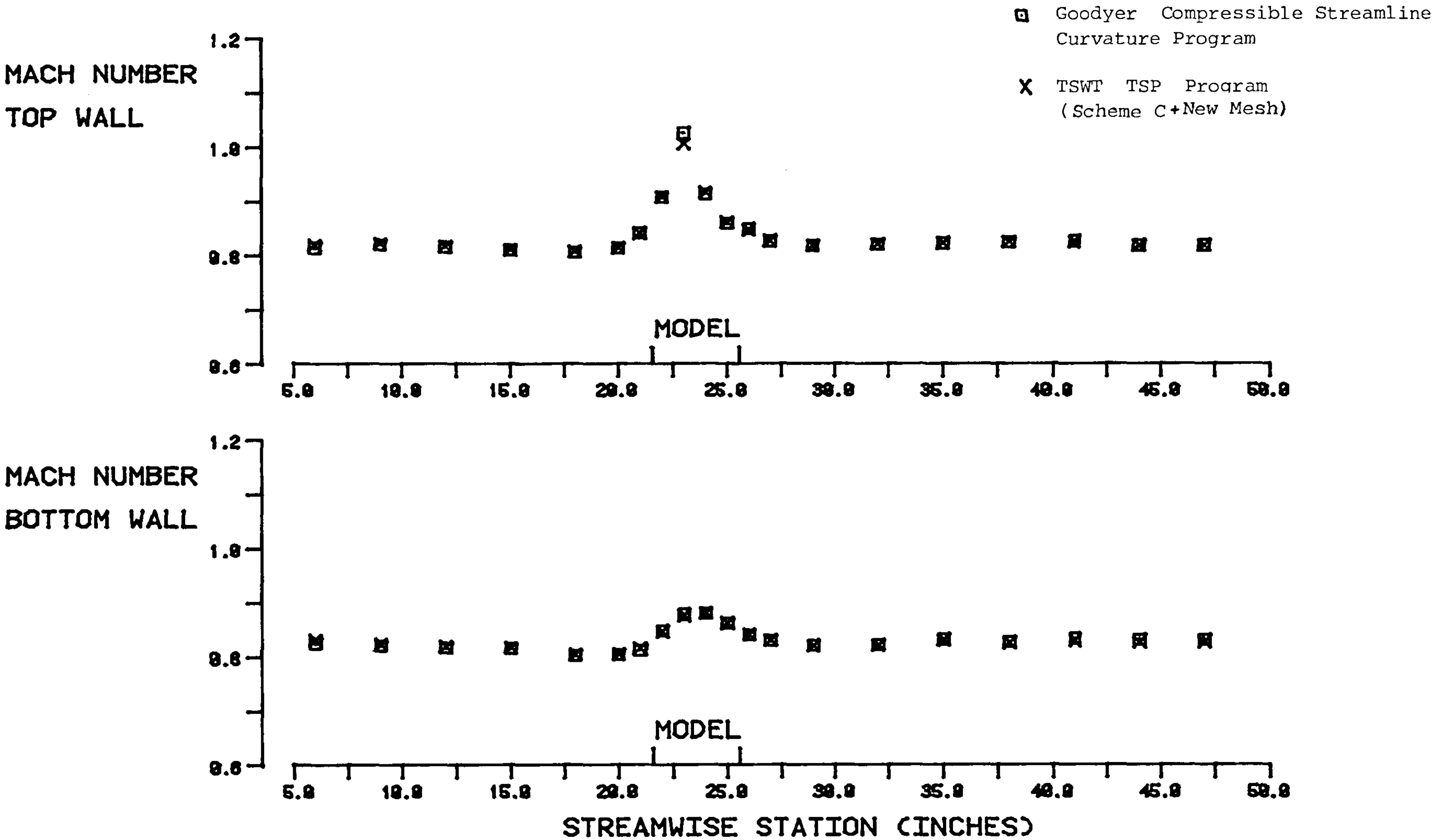


Figure 22b:- Comparison of Imaginary Flow Methods for Wall Contours of Test Case 3 (M_∞ = 0.8247)

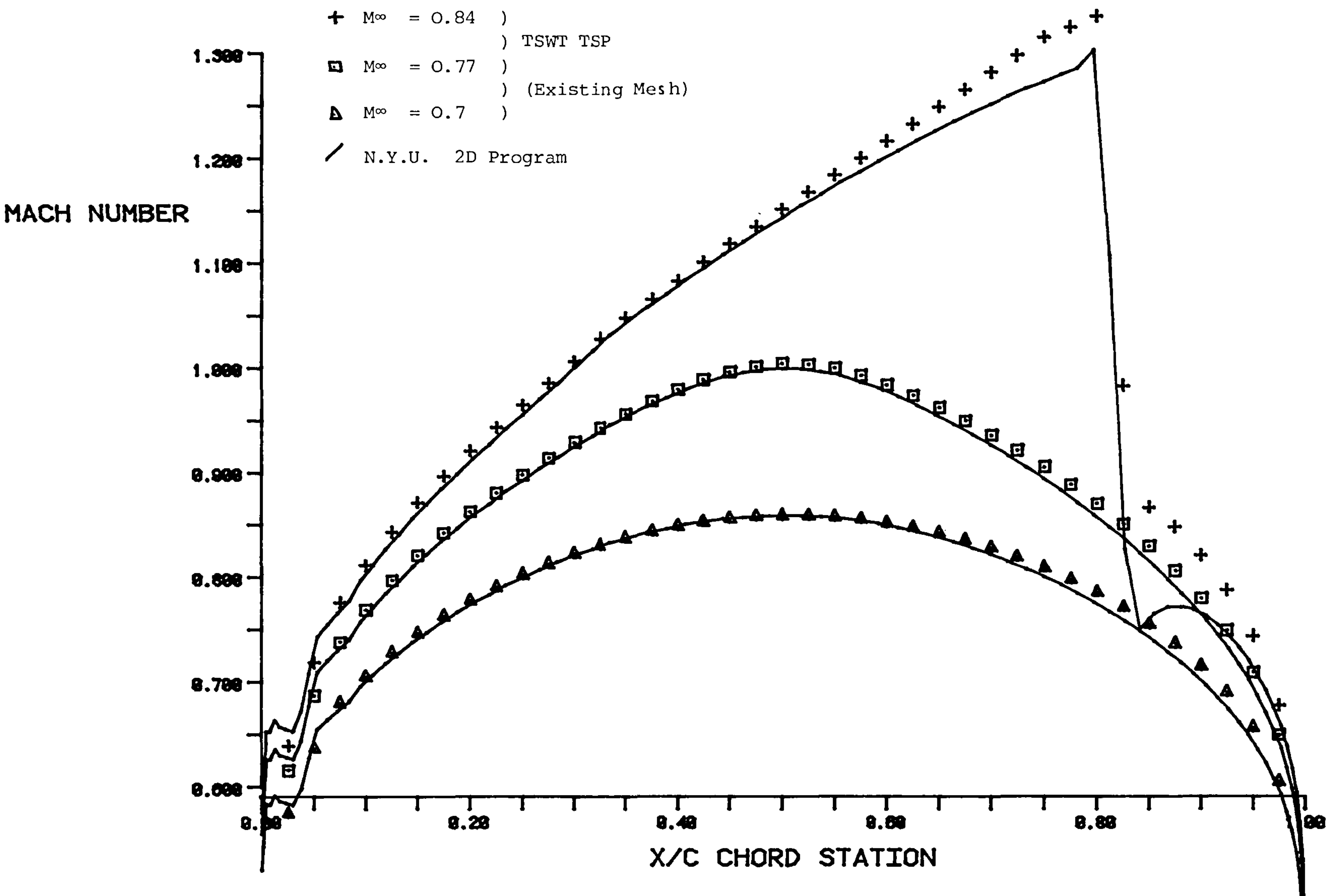


Figure 23:- TSWT TSP/N.Y.U. 2D Program (Adcock) Comparison (10% Circ. Arc. Aerofoil)

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15. Supplementary Notes

Langley 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."

16. Abstract

This report briefly outlines the progress made during the last 2 years in extending the operational range of the Transonic Self-Streamlining Wind Tunnel (at the University of Southampton) into high subsonic speeds. Analytical preparation completed in order to achieve such an extension is outlined and a summary of the preliminary model validation tests is presented. Future work necessary to allow further validation and development is discussed.

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