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The Status of Analytical Preparation for Two-Dimensional Testing at High Transonic Speeds in the University of Southampton Transonic Self-Streamlining Wind Tunnel

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CONTENTS

1. Introduction

Validation data[1,2] from the Transonic Self-Streamlining Wind Tunnel (TSWT), at The University of Southampton (U of S), England, has proved the feasibility of streamlining two-dimensional flexible walls at low speeds and up to transonic speeds, the upper limit being the speed where the flexible walls are just supercritical. At this condition, breakdown of the wall setting strategy is evident in that convergence is neither as rapid nor as stable as for lower speeds, and our wall streamlining criteria are not always completely satisfied. At higher Mach numbers, supercritical flow extends 'through' the flexible walls invalidating the linearised theory used to compute the imaginary flowfields. However, supercritical flow at the walls is not a major practical problem since the aerofoil shocks so far observed, are locally normal to the flexible wall. Therefore, the shock is not reflected and the wall itself supports the pressure rise and prevents the flow direction change which might otherwise occur with a ventilated test section. At Mach numbers approaching unity the shocks on the upper and lower surface of the aerofoil will move towards the trailing edge and be oblique with respect to the flexible walls. For a 'streamlined' wall contour the oblique shocks will not be reflected, however, in practice it may be necessary to adjust the wall contour at the shock/wall impingement position to avoid reflection. Therefore the only major step necessary to permit the extension of two-dimensional testing into higher transonic speeds is the provision of a rapid algorithm to solve for mixed flow in the imaginary flowfields. This report outlines the status of two-dimensional high transonic testing in the Transonic Self-Streamlining Wind Tunnel, and in particular, details the progress of adapting an algorithm, which solves the Transonic Small Perturbation Equation, for predicting the imaginary flowfields.

2. Background

In 1980 an attempt was made to adapt a time marching finite area algorithm for use in the wall setting strategy of the TSWT. This effort by B. Mason was submitted as a third year undergraduate project at the University of Southampton in May 1983 and is entitled "Development of a Program for the Flexible Wall Tunnel at Transonic Speeds." The algorithm, original designed to predict transonic flow with shocks in two-dimensional turbomachinery flow, employed a time marching method developed initially by Denton.[3] Due to the problems encountered in the accuracy of shock placement (see Figure 1) and in the practical application of the algorithm to the wall setting strategy, the time marching method proved to be unsuitable for the needs of the TSWT. However, Mason did conclude that any future wall setting strategy for high transonic speeds would need to make an allowance for boundary layer growth at the flexible wall due to shock/boundary layer interaction.

Extensive attempts to modify an existing, locally written compressible subsonic streamline curvature algorithm followed, without success. However, the Royal Aircraft Establishment (RAE), Farnborough, provided Fortran listings of a numerical method that appeared to be suitable for the TSWT. Work relating to the adaptation of this method to our needs, and the validation of the resulting code, forms the subject of this report.

3. Transonic Small Perturbation Software

The software provided by RAE, Farnborough, was designed to predict two-dimensional irrotational flow past lifting aerofoils in wind tunnels.[4] 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[5] for free air applications only. This reduced memory requirements from 25.5K to 22.5K words, thereby reducing run times 18 sec/iteration to 10 sec/iteration as no overlay structure was required. The software was provided again by RAE, Farnborough.

The numerical method, in which the TSP equation is solved, is a modification of the work of Murman and Cole[6] and of Krupp.[7] The flow is treated as isentropic and irrotational, so that shocks should be weak. Strictly, the perturbations to the main-stream flow caused by the presence of the aerofoil should be small, and the main stream Mach number should be close to unity. In practice for free air it was found, that RAE TSP solutions for aerofoils with non-blunt leading edges compared favorably with those obtained by solving the exact equation for the velocity potential,[8] even when the perturbations were far from small and the free-stream Mach numbers were as low as 0.6 (see Figures 2 and 3). However, it was expected that TSWT application of the TSP method would provide a much less severe test, as typical wall shapes would be 'represented' by aerofoils with sharp leading edges and small thickness/chord ratios. The only serious limitations of the TSP method in relation to its application to TSWT is that it is confined to freestream Mach numbers below unity.

The RAE method involves transforming the infinite flowfield plane into a finite square plane and a uniform rectangular finite-difference mesh is superimposed on the transformed plane. The disturbance potential is computed with the aid of successive line over-relaxation, at points formed by the intersection of mesh lines. Therefore, the computing mesh is independent of aerofoil geometry, the only 'real' aerofoil data being required is the aerofoil slope at computing points in the x direction.

4. Adaptation of TSP Software for TSWT

4.1. Test Case

The RAE software assumed a few library functions that were not available on the DEC PDP 11/34. The necessary alterations, mainly to the computing mesh setting-up procedure, allowed comparison of RAE TSP results with those obtained at Southampton (see Figure 4). The reasons for the discrepancies in shock position and pressures at the foot of the shock are unknown. It was thought that the alterations to the software coupled with a change of hardware would have little or no effect on solutions. However, as a 'converged' solution was obtained after 300 iterations on the PDP 11/34 (1 hour), which was a vast improvement on the time marching method, development of this version of the TSP software to the TSWT continued.

4.2. Software Alterations

The RAE method divides the computing mesh into four regions (see Figure 5), new values for the scaled perturbation potential for points of each region being computed once per iteration. The iteration cycle completed by resetting the boundary conditions and modifying the internal points by an amount proportional to the change in circulation from the previous iteration. However for TSWT applications the aerofoil 'representing' the wall shape would be symmetrical and at zero incidence, hence without circulation. This allowed the deletion of the modification to scaled perturbation potential from the software, whilst reducing the computing mesh to three regions (see Figure 6). The other major alteration was to create a uniform concentration of mesh points over the aerofoil, instead of having a concentration at the leading edge where the gradients are largest, as accuracy in the prediction of shock location was of paramount importance for TSWT applications, whilst there is no equivalence to the leading edge activity. It may become necessary to concentrate points around the expected shock position. The above alterations coupled with many minor ones reduced the required memory of the TSP software for TSWT applications to 15K words and reduced run time to 4 sec/fine mesh iteration.

5. Validation of TSP Method for TSWT Applications

5.1. Run 184

Initial validation of the U of S TSP software used existing data from an earlier run of the test section at an appropriately high Mach number (Run 184). For this run the aerofoil being tested was a NACA 0012-64 section at 4.0^{o} incidence with a freestream Mach number of 0.8862. At this condition supercritical flow had reached both flexible walls but the existing wall setting strategy had contoured the walls to what it declared to be 'streamlined' shapes. This was believed to be reasonable since there was fair agreement with the pressure distribution on the aerofoil tested in TSWT and the data derived independently in a conventional slotted test section (see Figure 7). It should be noted that no allowance was made by the wall setting strategy for wall boundary layer thickening due to shock interaction. Mason did experiment in making crude provision for wall boundary layer growth for Run 184 with some success. Therefore 'exact' agreement of Run 184 data with results obtained from the TSP method was not expected. Also it would not be expected to predict the rise in Mach number just downstream of the shock exhibited by the top wall of Run 184 (see Figure 1) as this was due to choking of the flow between the thickening model wake and the wall boundary layer. Initial validation of the TSP method was confined to the top wall of Run 184, as this was a more critical case than the bottom wall.

5.2. Wall Representation

During early validation of the TSP method the top was represented in the software by an aerofoil incorporating a 'closer' scheme or by an aerofoil with a 'open' (blunt) trailing edge. Later work included an aerofoil with an 'open' extension. The various geometries are illustrated on Figure 8.

5.3. Relaxation and Convergence Parameters

The rate of convergence to an 'acceptable' solution is accelerated by adopting the standard technique of successive line over-relaxation. The relaxation parameter value being varied according to whether the equation is hyperbolic or elliptic and whether coarse of fine mesh calculations are being performed. The relaxation parameter values suggested by Albone[4] for typical aerofoils when applied to aerofoils 'representing' the top wall of Run 184 resulted in non-convergence. This problem was rectified by adjusting the relaxation values until optimum values resulting in convergence were obtained for this application.

After each iteration the maximum change in scaled perturbation potential on the aerofoil surface is calculated, convergence being achieved when the s value is considered suitably small, this value being known as the convergence parameter. For Run 184 the convergence parameter was taken to be the value that obtained results that were no more than ±0.05% different from results obtained using the convergence parameter suggested by Albone.[4] This reduction is thought to be reasonable when the accuracy of data acquisition of the TSWT is considered, and has the effect of reducing the required number of iterations by more than two thirds. As the wall shape of Run 184 is thought to be fairly 'typical' for high transonic testing, the relaxation and convergence parameters of Run 184 should be applicable to a wide range of tests involving supercritical flow at the walls.

5.4. Validation Results

Whilst confident validation using existing data is not possible, it appears that the TSP method offer real potential for TSWT applications (see Table 1 and Figures 9, 10, 11).

Encouragement can be gained from the following:-

a) Solutions obtained from the various aerofoils 'representing' the wall shape do no differ significantly.

b) Consistent prediction of shock location being downstream of the experimental position reinforces the view that an allowance should be made for wall boundary layer growth due to shock impingement. Experimental evidence indicates that the predicted shock would move upstream if such an allowance was made.

c) The iterative nature of the streamlining cycle demands that run times for computing the imaginary flowfields should be short. Present TSP computing times of 3 to 6 minutes with this tunnel/computer combination are more than adequate for practical testing.

It should be noted that the chord of the aerofoil 'representing' the wall contour will be at least 44", whilst the chord of the aerofoil being tested will be in the region of 4". Therefore a small error in shock location relative to chord in the imaginary flow calculation may become significant when compared to the actual shock position of the aerofoil being tested. Therefore concentration of mesh points around the expected shock position may be necessary for our application of the TSP method.

5.5 Mach Number Range

The intended range of application of the TSP method for TSWT purposes is from when the walls first become supercritical, to free-stream Mach numbers just below unity. For the top wall contour set for Run 184 the former condition is predicted by the TSP method to be reached when the free-stream Mach number is just 0.82. Therefore, as Run 184 wall shape is thought to be fairly 'typical' for high transonic testing the likely Mach number operational range of the TSP method is from about 0.8 to 1.0. Converged solutions for this wall have been obtained for Mach numbers up to 0.95 when an aerofoil with a 'closer' scheme has represented the wall and 0.92 for an 'open' aerofoil. The computing times at these Mach numbers were 15 and 25 minutes respectively, experiences suggesting an inverse Mach number/iteration relationship.

Attempts to achieve convergence at higher Mach numbers by adjusting the relaxation parameters during computation have failed. This may not prove to be a problem in practice, since the streamlined wall shapes at Mach numbers approaching unity are likely to be significantly different from those of Run 184.

6. Prediction of Wall Boundary Layers

It has become apparent that the extension of two-dimensional testing into high transonic speeds not only requires the provision of a rapid algorithm to solve for mixed flows in the imaginary flowfields, but the prediction of wall boundary layer growth due to shock impingement is also necessary.

The existing wall setting strategy references the wall displacements to 'aerodynamically straight' contours[2] and assumes that the imaginary flowfields over the 'straight' contours are undisturbed. Variations in wall boundary layer displacement thickness are calculated but are not employed by the wall setting strategy. The calculations use a numerical solution of the Von Karman Momentum Integral equation for a turbulent boundary layer and predicts the ratio of boundary layer displacement thickness across the shock to be in the region of 1.2 for the top wall of Run 184 (see Figure 12). For the same conditions values predicted by the more modern Green[9] and Reshotko and Tucker[10] methods are in the region of 1.4 to 1.5. Therefore the existing method for calculating wall boundary layer displacement thickness is considered inadequate for adoption into any future wall setting strategy designed for high transonic testing.

Green's[9] method for predicting the behaviour of turbulent layers in two-dimensional and axi-symmetric, adiabatic compressible flow takes account of the influence of the upstream flow history on the turbulent stresses. The method employs the momentum integral equation, the entrainment equation and an equation for the streamwise rate of change of entrainment coefficient. The accuracy of the method in flow at constant pressure is ensured by its derivation, but the available experimental data does not enable its accuracy in flow with strong pressure gradients to be assessed with any finality. However, as the main virtue of the method is its speed and that it takes account of longitudinal surface curvature, it is intended to use the method in the wall streamlining strategies used in high subsonic testing. Prediction of wall boundary layers for TSWT purposes should be within its capabilities. The software has already been installed in the computer and the run time for a typical case is twenty seconds (see Figure 12).

7. Proposed Future Work

Present high transonic data obtained from the TSWT is inadequate for further validation of the TSP method. Therefore to allow high speed operation of the tunnel and hence further validation, it will be necessary to:-

a) incorporate the TSP software into the existing control software of the TSWT.

b) utilise Green's method for predicting the development of wall boundary layer in the wall setting strategy, in order to make an allowance for wall boundary layer growth due to shock impingement.

Implementation of the above will allow further high speed validation testing, which is planned to commence in late 1983. During further validation it may become necessary to increase the concentration of mesh points around the expected shock position in order to increase the accuracy of shock location predicted by the TSP method.

8. Concluding Remarks

Initial validation suggests that the TSP algorithm does offer real potential in extending the two-dimensional operational range of the TSWT into higher transonic speeds. Prediction of the wall boundary layer growth due to shock impingement should allow further progress.

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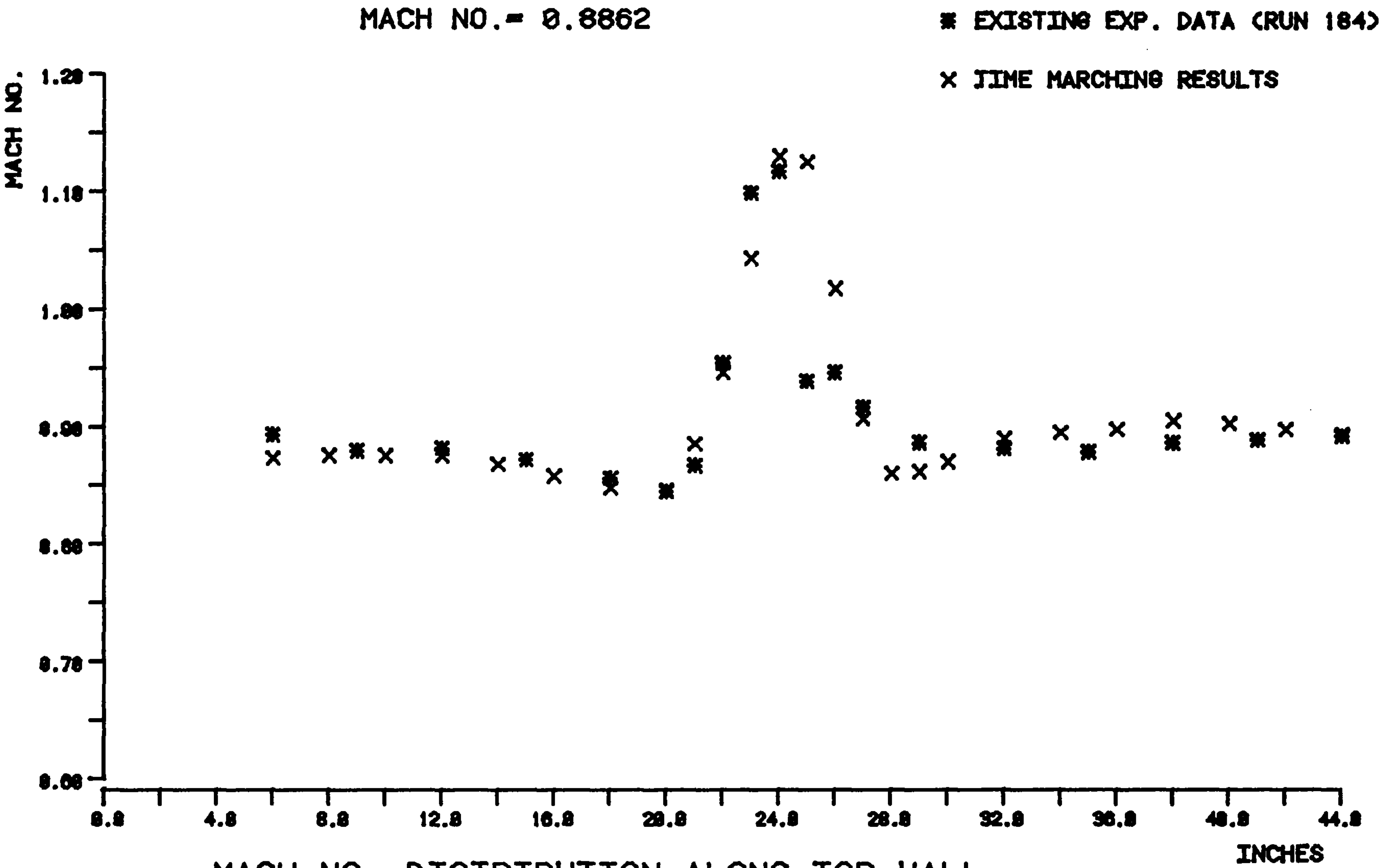
Type of Wall Representation	Convergence Parameter	Max. Coarse Mesh Iterations	Fine Mesh Iterations required for Convergence	Computing Time	Approximate Position of Shock Relative to Run 184 Data
Aerofoil with 'Closer' Scheme	0.0001	45	31	3 mins	1" downstream
Aerofoil with 'Open' Trailing Edge	0.00007	70	17	2.5 mins	1.5" downstream
Aerofoil with 'Open' Extension	0.00007	70	73	6 mins	1.2" downstream

Table 1: Validation Results of Run 184 ($M_\infty = 0.8862$)

FIG. 1 VALIDATION OF TIME MARCHING PROGRAM



MACH NO. DISTRIBUTION ALONG TOP WALL

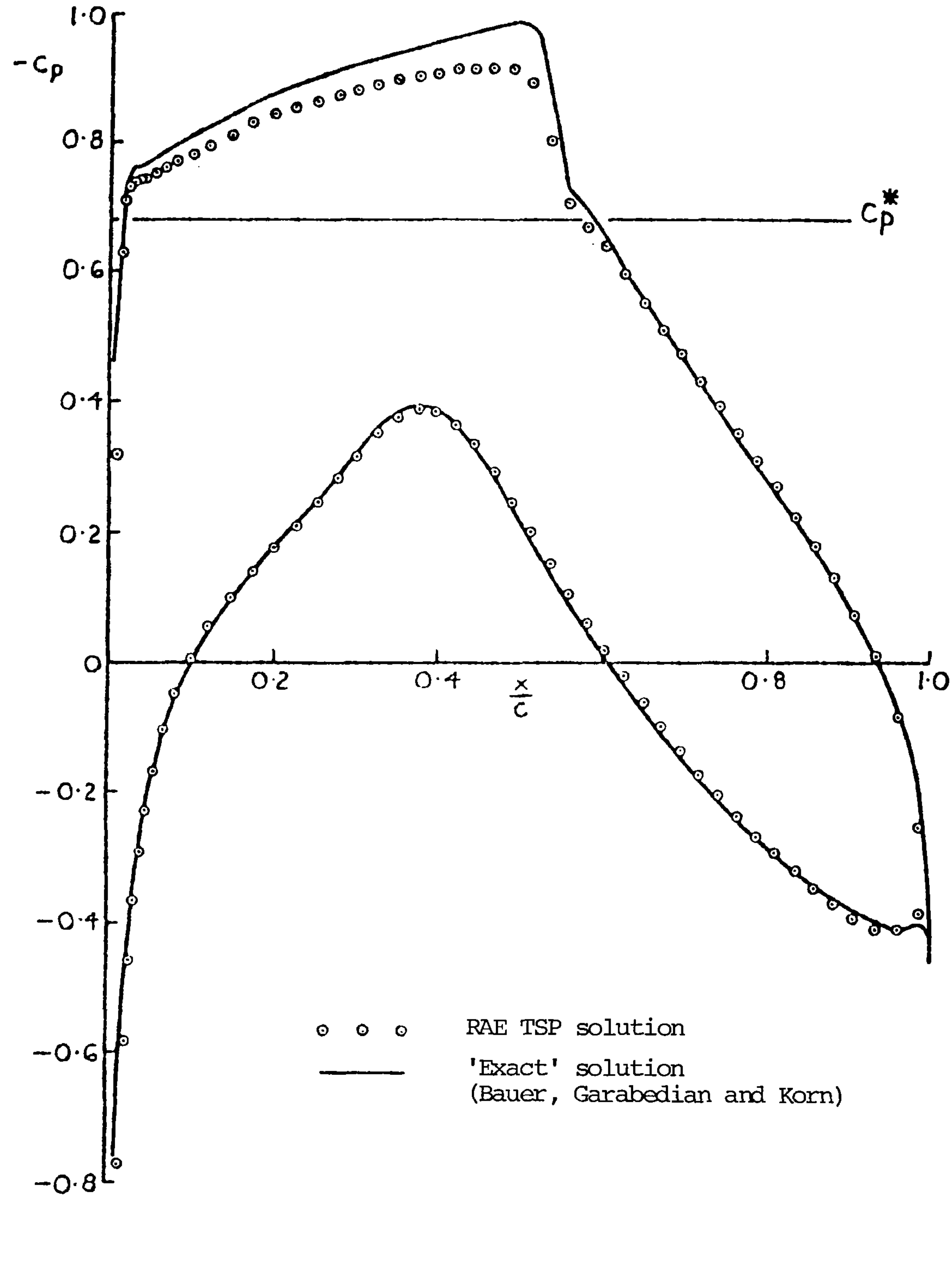


Fig. 2: Comparison of calculated pressure distributions
RAE 2822 $M_\infty = 0{\cdot}725$, $\alpha = 1{\cdot}00^\circ$

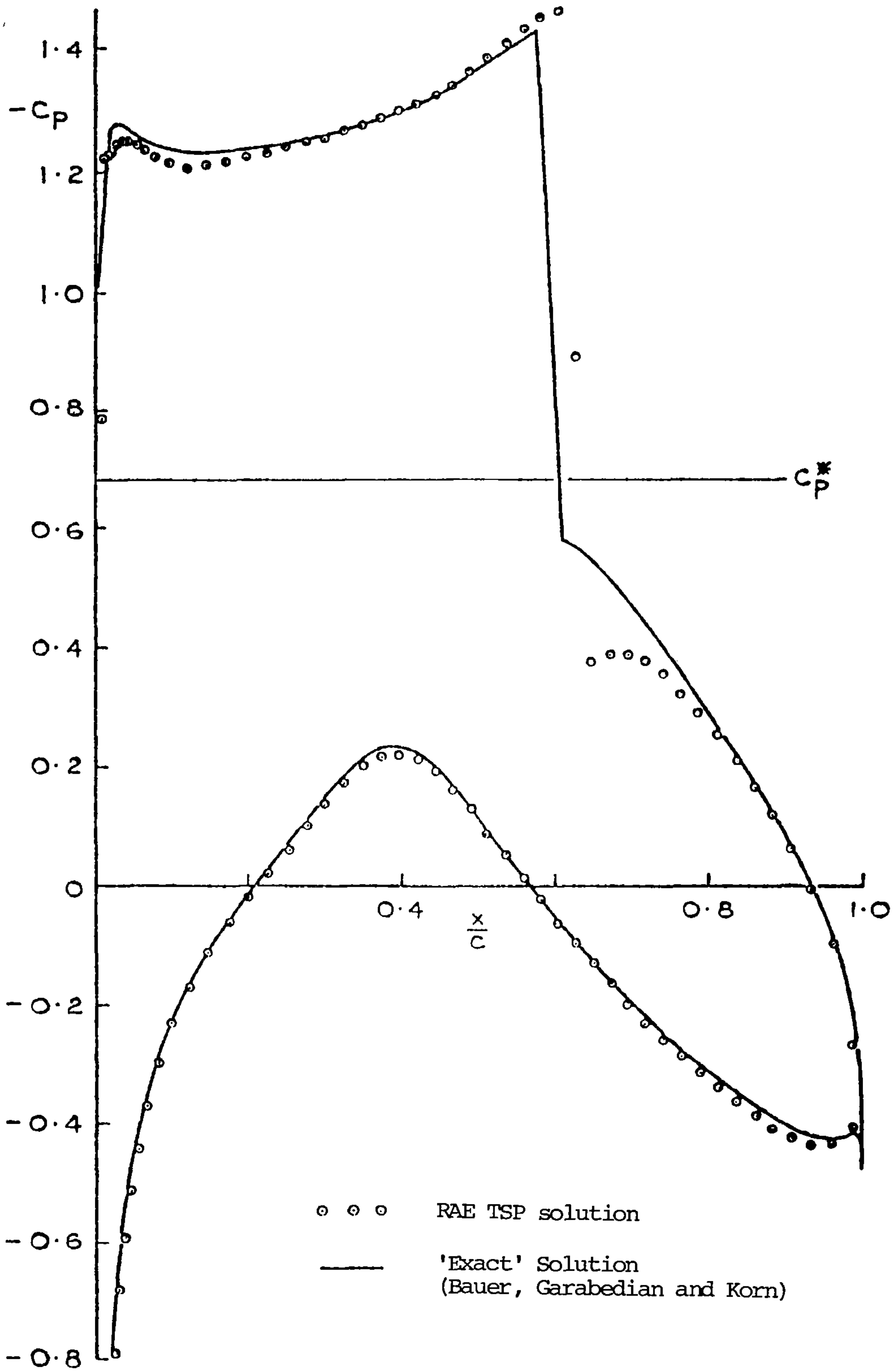


Fig. 3: Comparison of calculated pressure distributions RAE 2822, $M_\infty = 0\cdot725$, $\alpha = 2\cdot62^\circ$

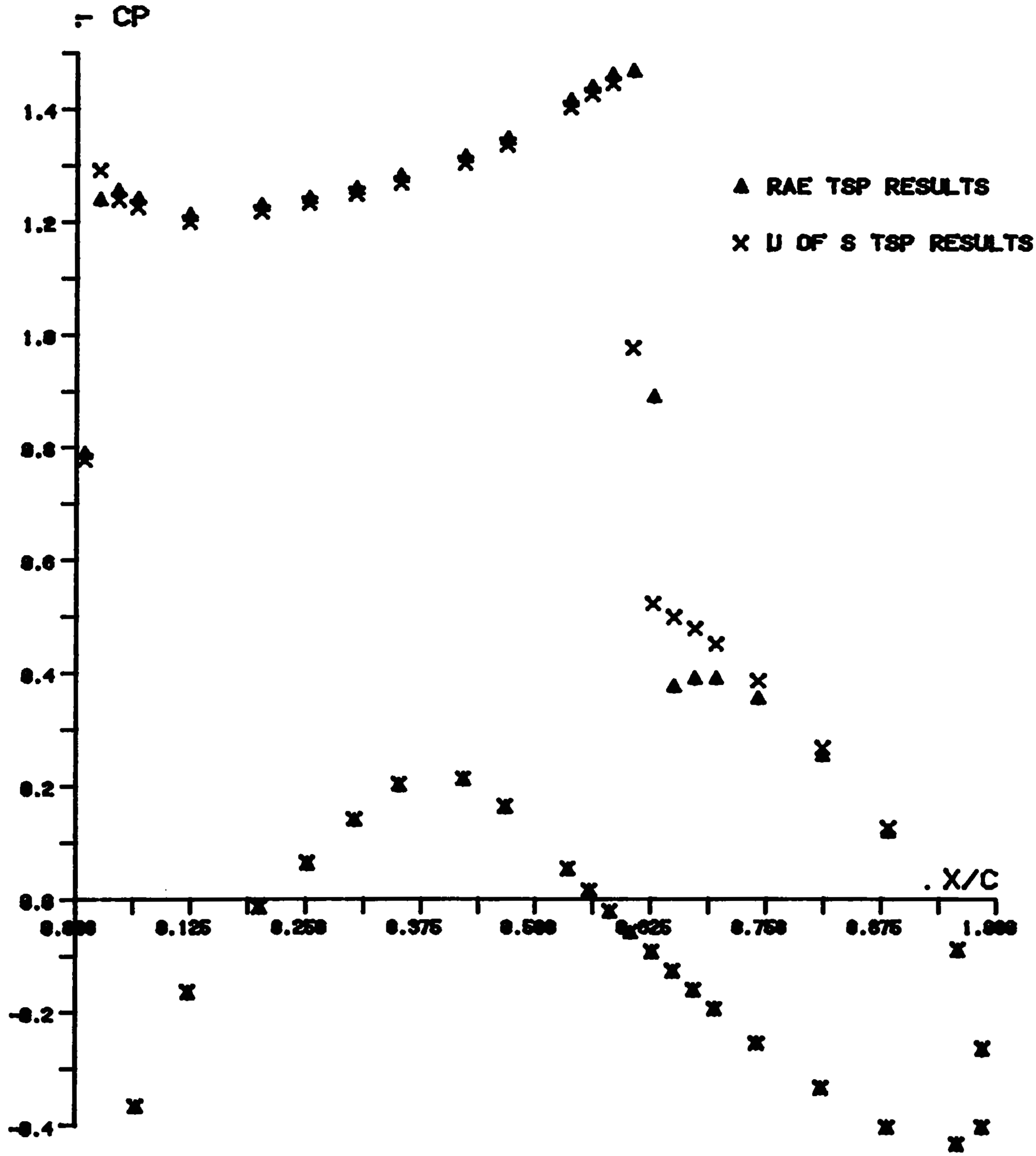


FIG 4 COMPARISON OF TSP TEST CASES

(RAE 2822, M=0.725, α=2.62)

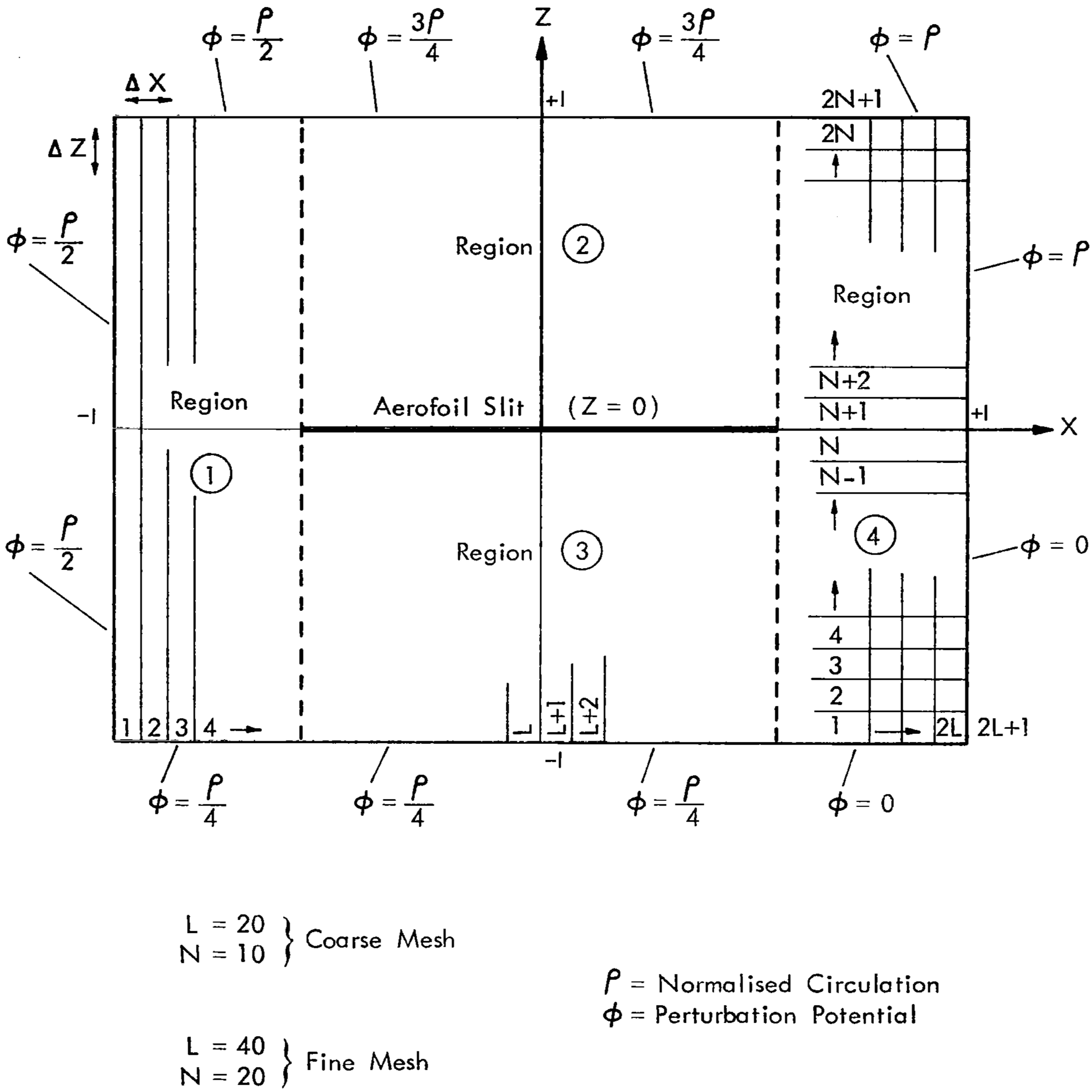


FIG. 5 RAE COMPUTING PLANE (Z - X)

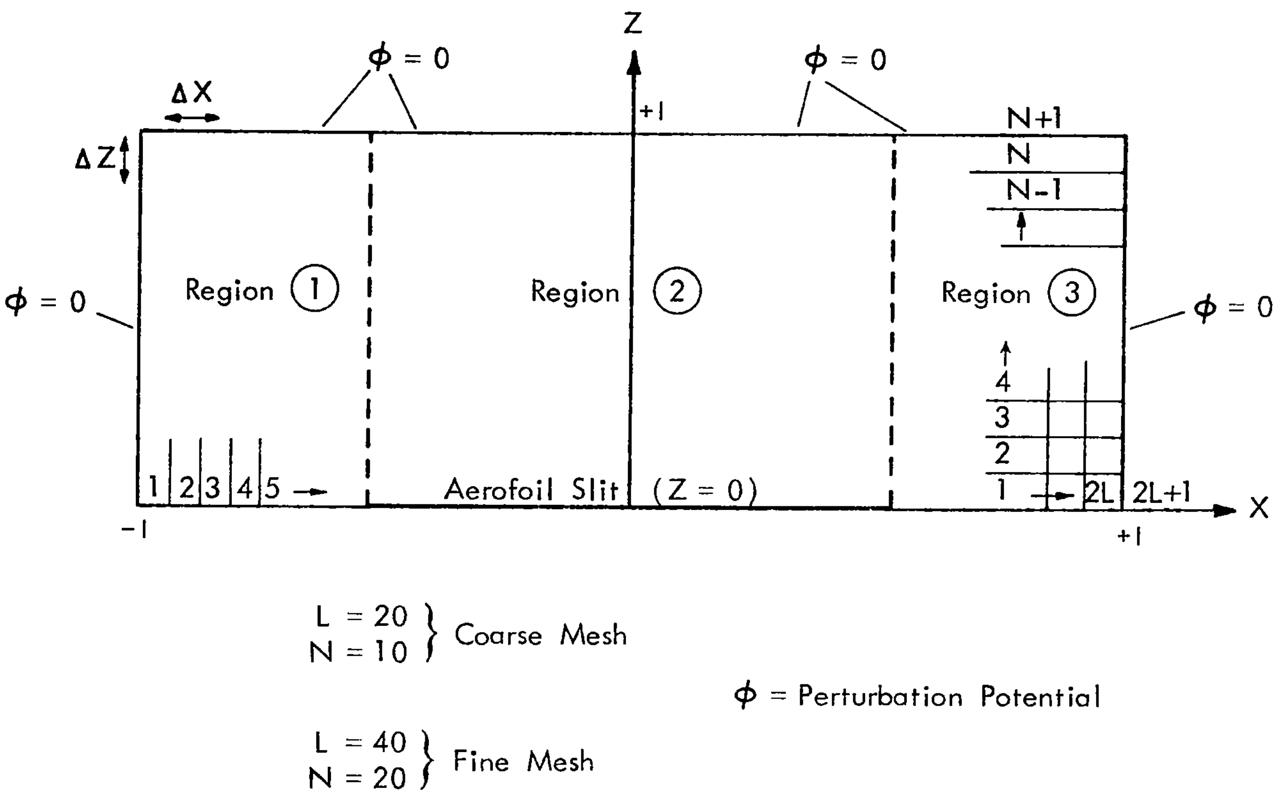


FIG. 6 UNIVERSITY OF SOUTHAMPTON COMPUTING PLANE (Z - X)

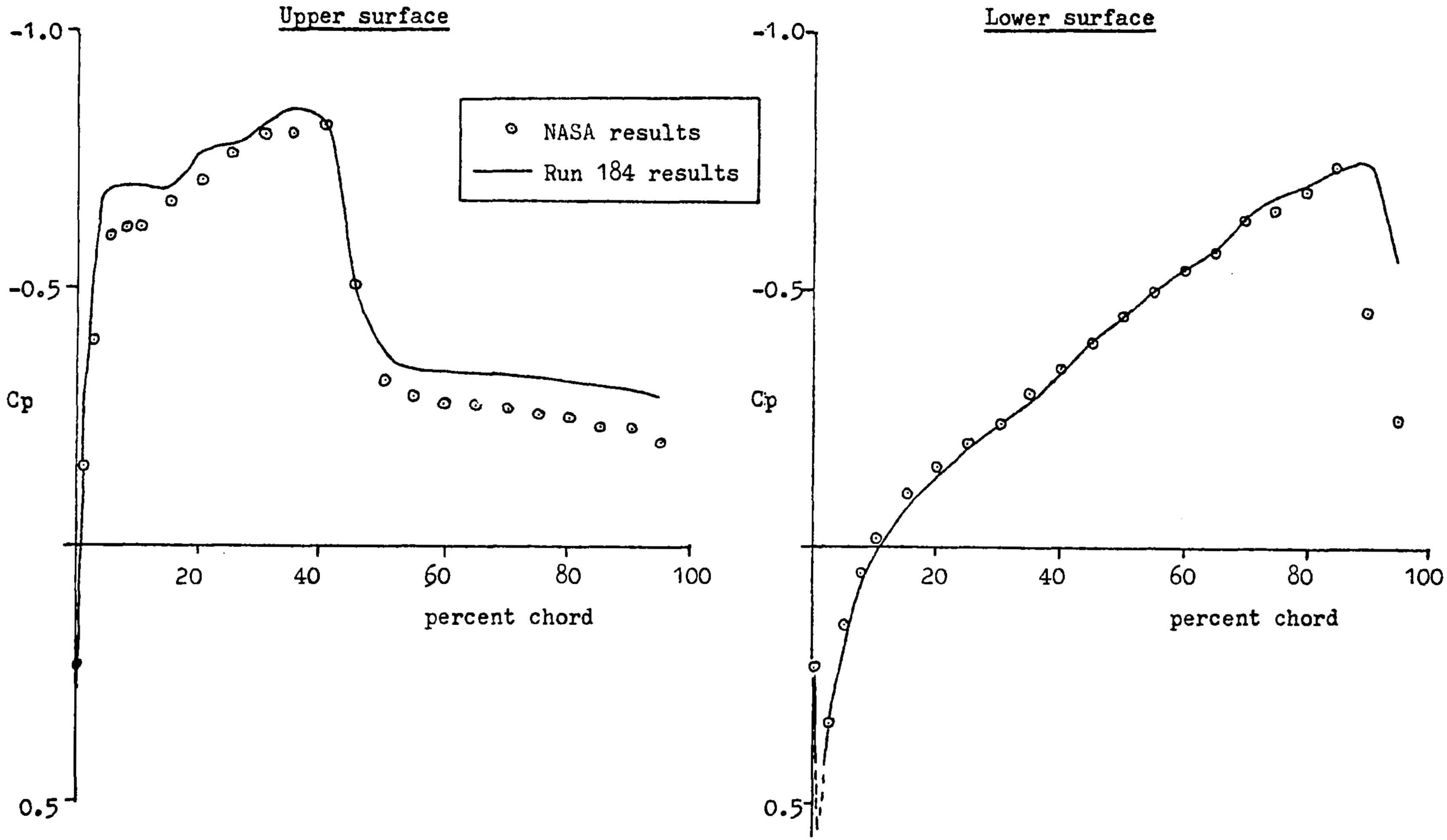


FIG. 7: COMPARISON OF NASA AND RUN 184 PRESSURE DATA FOR NACA 0012-64 SECTION AT 4° INCIDENCE, $M_\infty \approx 0.886$

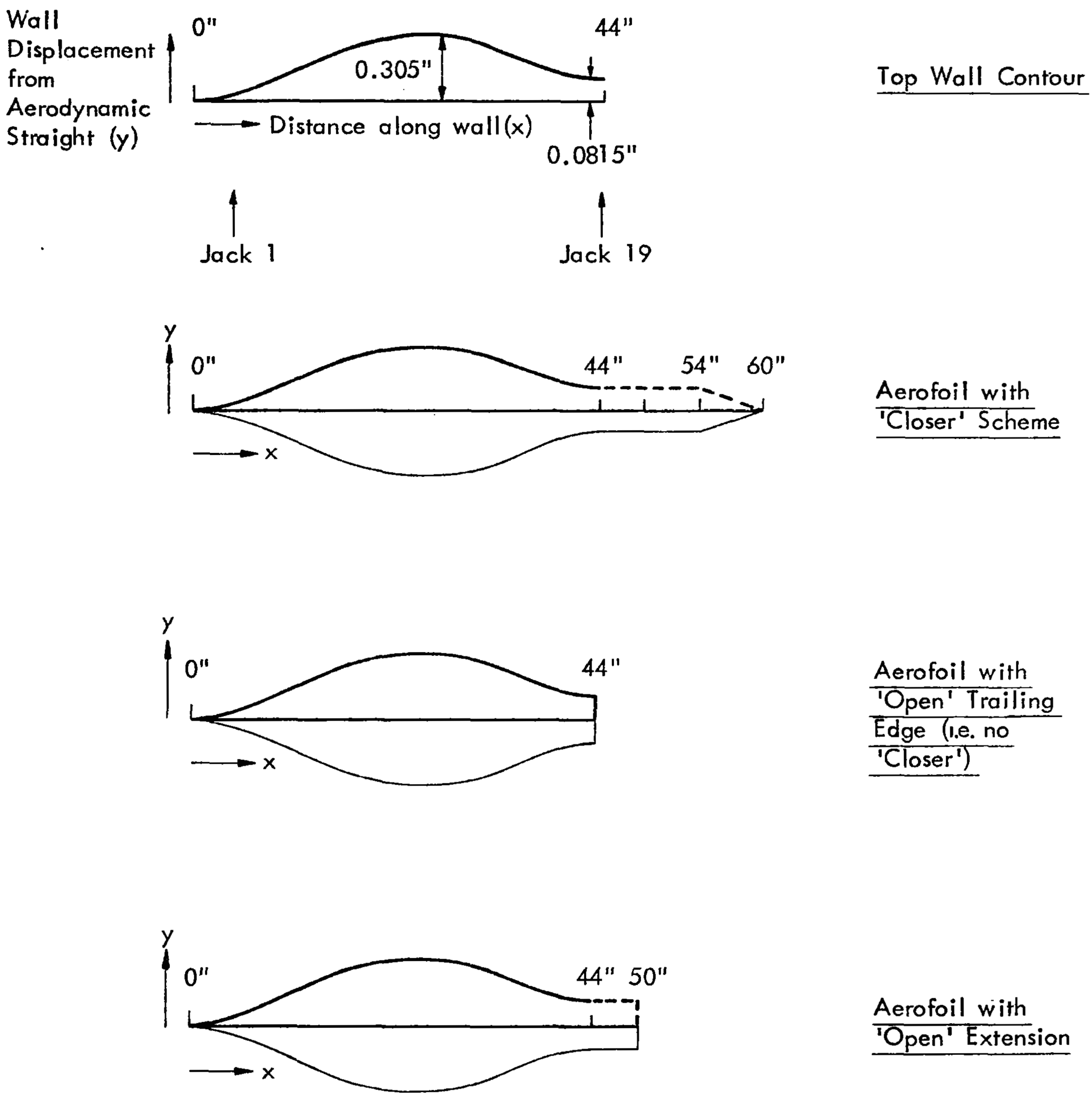


FIG. 8 TOP WALL REPRESENTATION OF RUN 184

FIG. 9 VALIDATION OF WALL TSP PROGRAM

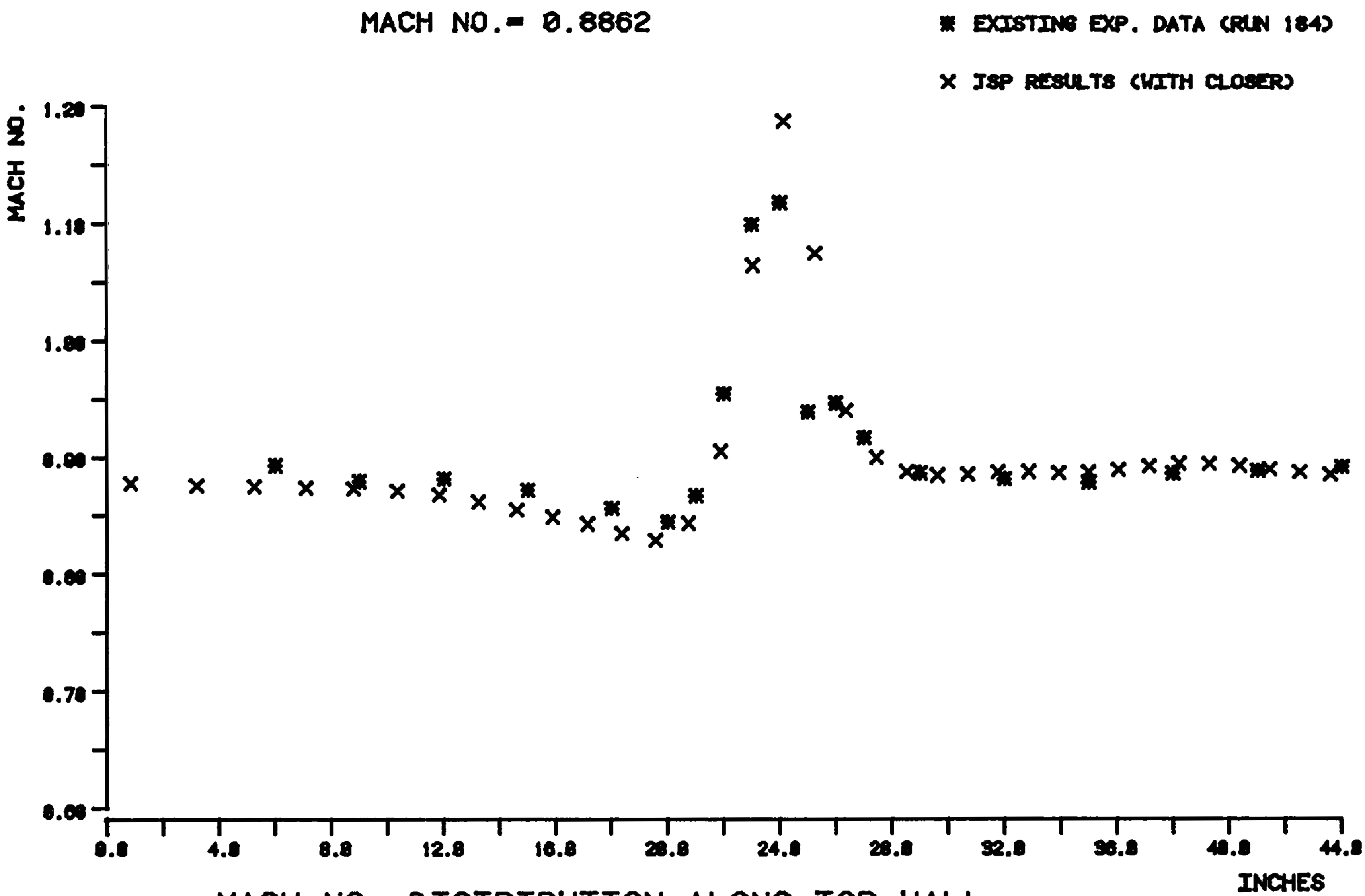


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FIG. 10 VALIDATION OF WALL TSP PROGRAM

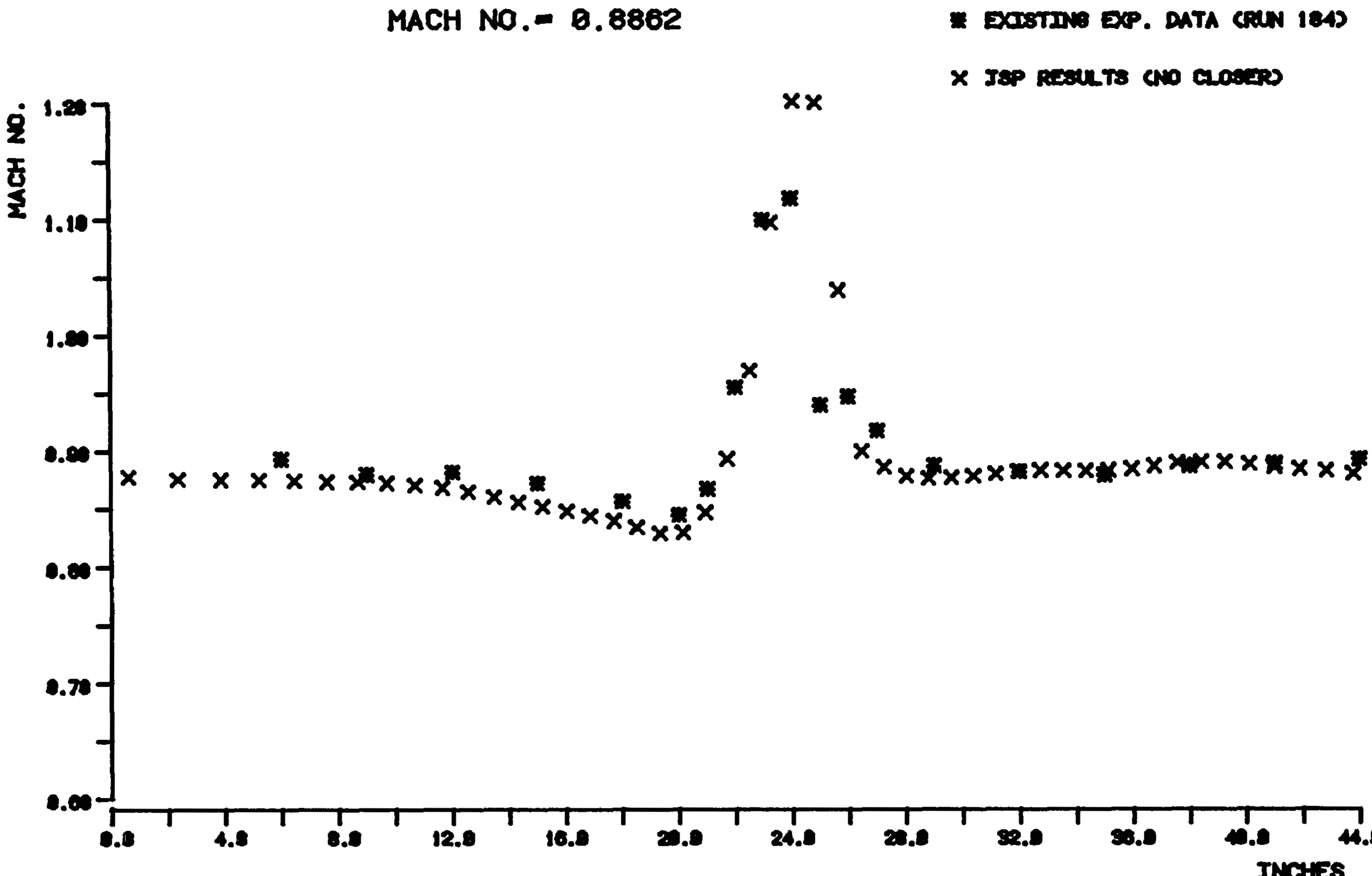

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FIG. 11 VALIDATION OF WALL TSP PROGRAM

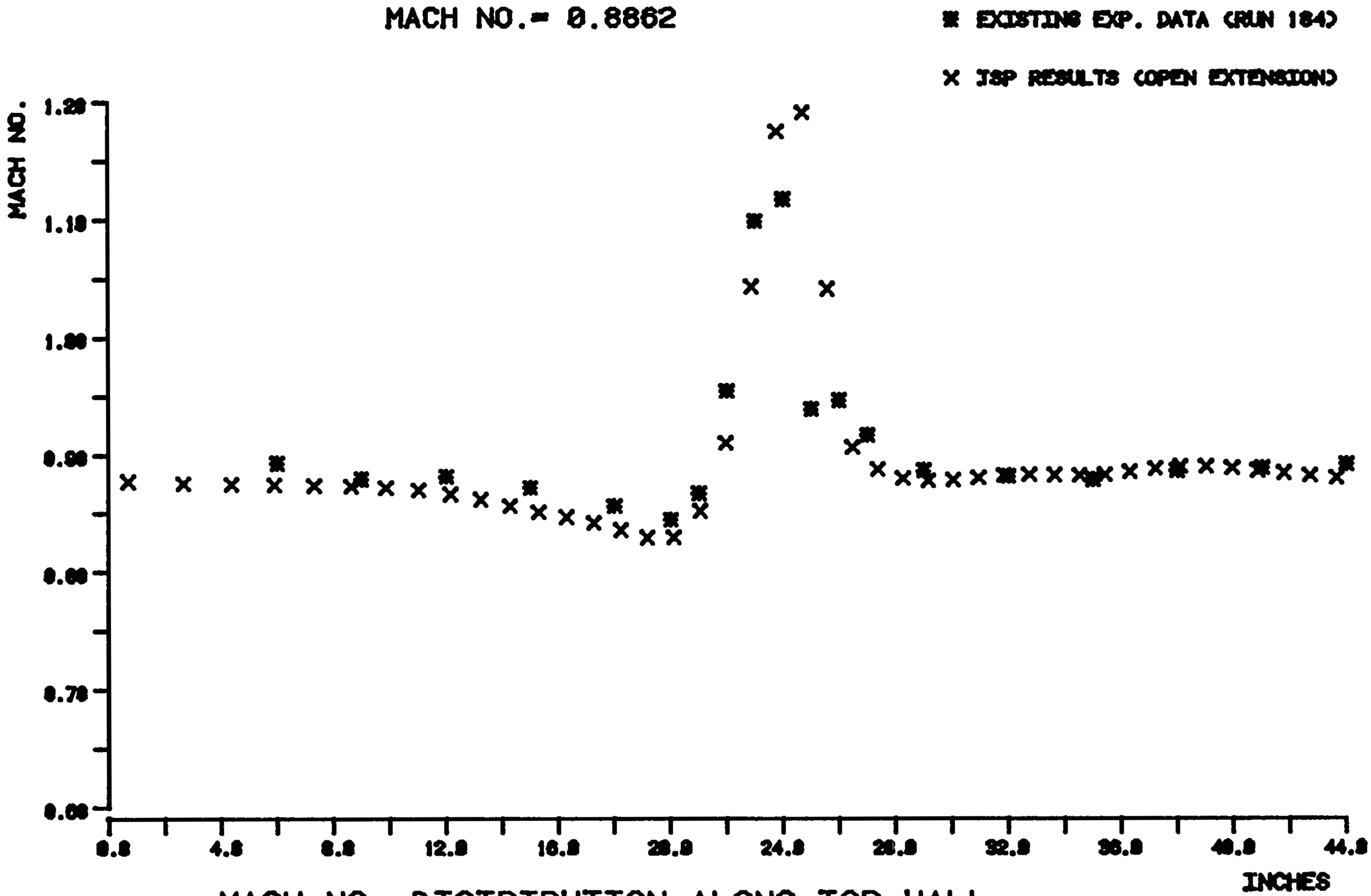

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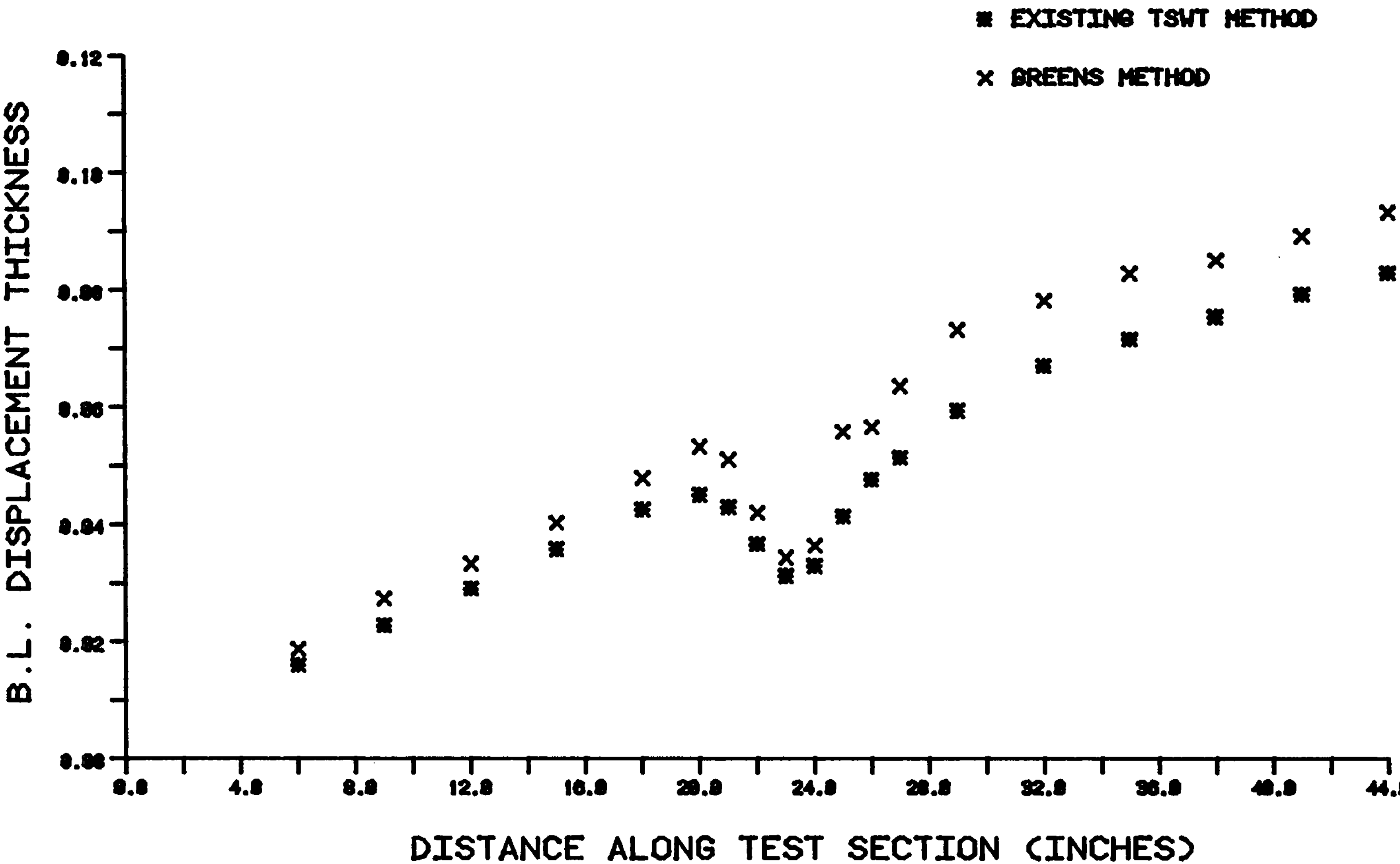
FIG. 12 COMPARISON OF B.L. CALCULATIONS

(RUN 184 - TOP WALL)



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16. Abstract

Validation data from the Transonic Self-Streamlining Wind Tunnel, at The University of Southampton, England, has proved the feasibility of streamlining two-dimensional flexible walls at low speeds and up to transonic speeds, the upper limit being the speed where the flexible walls are just supercritical. At this condition, breakdown of the wall setting strategy is evident in that convergence is neither as rapid nor as stable as for lower speeds, and our wall streamlining criteria are not always completely satisfied. The only major step necessary to permit the extension of two-dimensional testing into higher transonic speeds is the provision of a rapid algorithm to solve for mixed flow in the imaginary flowfields. This report outlines the status of two-dimensional high transonic testing in the Transonic Self-Streamlining Wind Tunnel and, in particular, details the progress of adapting an algorithm, which solves the Transonic Small Perturbation Equation, for predicting the imaginary flowfields.

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