NASA CR-181,681

NASA Contractor Report 181681

NASA-CR-181681
19880016055

THE EXPERIMENTAL VERIFICATION OF WALL MOVEMENT INFLUENCE COEFFICIENTS FOR AN ADAPTIVE WALLED TEST SECTION

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Grant NSG-7172
July 1988

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SUMMARY

Flexible walled wind tunnels have for some time been used to reduce wall interference effects at the model. A necessary part of the 3-dimensional wall adjustment strategy which is being developed for the Transonic Self-Streamlining Wind Tunnel (TSWT) of Southampton University is the use of influence coefficients. The influence of a wall bump on the centreline flow in TSWT has been calculated theoretically using a streamline curvature program. This report details the experimental verification of these influence coefficients and concludes that it is valid to use the theoretically determined values in 3-dimensional model testing.

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LIST OF SYMBOLS

M_∞	Reference Mach number.
M_u	Perturbation Mach number in the streamwise direction (x-direction).
M_w	Perturbation Mach number in the cross-streamwise direction (z-direction).
M_u/M_∞	The u-influence coefficient
M_w/M_∞	The w-influence coefficient
M	Mach number
C_p	Pressure coefficient

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CONTENTS

1. INTRODUCTION

The use of influence coefficients in selecting interference-free and interference-reducing wall contours in 2 and 3-dimensional (3-D)* adaptive tunnel testing in TSWT** has been discussed for some six years. Whilst it is possible to use influence coefficient information during 2-dimensional (2-D) testing, the real need lies in 3-D testing where there is no alternative wall contouring method yet available at Southampton. Over the past five years a set of theoretical packages for 3-D testing including theoretical estimates of influence coefficients, have been developed to the point where they are now being used in researching a workable 3-D wall interference reducing algorithm. During the further development of these 3-D theories the need has arisen to experimentally verify the theoretically determined influence coefficients.

The influence coefficients described in this report can be defined as the Mach number perturbation in tunnel centreline flow due to an applied wall bump non-dimensionalised by the freestream Mach number. With the 2-D wall curvature available with TSWT and using the co-ordinate system shown in Figure 1, the two relevant influence coefficients*** are: M_u/M_∞ the u-influence coefficient, M_w/M_∞ the w-influence coefficient.

The theoretical influence coefficients had been calculated using a streamline curvature program**** which was used in the main to produce results for small wall jack movements of order 0.02 inches as shown in Figures 2 to 16. The report by Goodyer[1] indicates the linear variation of centreline flow perturbation with wall bump amplitude for small bumps. This is an assumption made throughout the 3-D wall setting algorithms and is reasonably valid for the larger wall movements necessary for contouring.

* wall adaption in TSWT uses only single curvature of the top and bottom walls hence this refers to the testing of a 3-Dimensional model.

** the transonic self-streamlining wind tunnel at Southampton University.

*** strictly the influence coefficient describes the centreline perturbation per inch of movement of one jack among a set spaced at 1-inch intervals. In this report, however, the term is used more generally, to describe the centreline flow perturbation due to the various smaller wall bumps used in the experimental verification work.

**** developed by M J Goodyer, the theoretical influence coefficients being described in Reference 1.

The streamline curvature program[1] uses a longitudinally spaced grid system of half inch mesh representing the test section of TSWT which is 6 inches square in cross-section and 44 inches long. One can therefore define a wall contour only at these points. Since TSWT's jacks are spaced at one inch intervals (in the region of interest) a single jack wall bump is described only by the bump height, the program assuming the wall shape to be of sinusoidal distribution between the wall jacks, giving a wavelength of two inches. The theory indicated that the quantities being measured are so small that the experimental results would necessarily be scattered because of difficulties in resolution. The purpose of the testing therefore became one of verifying the theoretically determined influence coefficients rather than replacing them with an experimental set. It is noted that the ultimate accuracy of the associated streamlining technique does not rely on great precision in the influence coefficient theory.

This report contains the results of experimental research into the u and w-influence coefficients at the tunnel centreline, with wall bumps applied to generally straight test section walls. Streamwise velocities were measured using a series of sidewall static pressure tappings whereas measurements of vertical velocity components were based on the use of a high sensitivity yaw meter*.

* The new CEA high sensitivity yaw meter.

2. W-INFLUENCE COEFFICIENTS

2.1 Description of Testing Procedure

For 3-D model testing in TSWT, the aim is to quantify and reduce 4-wall induced interference in the region of the tunnel centreline by suitable movements of the flexible top and bottom walls. One is therefore interested in measuring the influence on the centreline flow of single and multiple wall jack movement into and out of the otherwise straight walls of the test section. The idea is that combining the calculated wall interferences with the influence coefficients will enable interference-reducing wall contours to be found[1]. The insensitivity of sidewall static pressures to small variations in cross-stream velocity means it is necessary to use a flow direction device such as a yaw meter to measure the w-influence coefficients (see Figure 1). A suitably sensitive yaw meter was calibrated in TSWT up to Mach 0.76 and flow angles of up to four degrees. For the wall bumps applied during this verification work, typically flow angularity of much less than four degrees was expected hence a standard yaw meter was not suitable as these are usually able to resolve about 0.1°. (Maximum angularity in centreline flow due to a 0.068 inch wall bump at mach = 0.7 was only 0.34°). The theoretical work described in Reference 1 is mostly concerned with the effect of moving only one wall jack of an empty and straight walled test section, causing both u and w-flow perturbations in all regions. Although it was possible to measure the coefficients in this way it was better to measure the coefficients in separate tests by use of equal sized collective or differential movement of opposite wall jacks (Figure 1). This would cause twice the flow perturbation of one component by a single wall bump of the same size without a significant perturbation in the other component.

Theory showed that for small wall bumps a collective up or down movement of opposite wall jacks would result in w-flow perturbations but at the same time very small u-perturbations at the tunnel centreline. Similarly, when determining u-influence coefficients, differential movement of opposite wall jacks into or out of the test section would produce a zero w-perturbation at the centreline. This presumes that the effective distance moved by each jack is the same.

The structural properties of the flexible walls plus the spacing of existing wall jacks determined the maximum permissible amplitude of the wall bump. Since the program calculating theoretical influence coefficients is only valid for local Mach numbers up to unity this further limited the maximum applied bump size for a given tunnel freestream Mach number especially in the case of jack movement towards the centreline.

The structural limitations could be overcome by forming a wall bump from three 'inchly-spaced' wall jacks, on each wall. It was important to set the relative jack movements in each bump to 1:2:1 to retain the sinusoidal type wall bump distributions as defined in the streamline curvature program. The smallest bump size which could be applied was determined by the practical consideration of signal-to-noise ratio. The above limitations suggested for a single jack a maximum movement of 0.071 inches, and a minimum of around 0.02 inches. The maximum height of bumps formed by 3 jacks were set at around 0.128 inches.

Most w-influence coefficient testing and results shown in this report are for single jack bumps of 0.071 inches on each wall although 3-jack bumps of maximum movements 0.06 and 0.128 inches on each wall were also applied. Initial testing used bumps moved upwards and later bumps downwards with respect to the tunnel centreline. No appreciable difference was detected in the distribution of w-influence coefficients in terms of magnitude (the direction or sign of the flow perturbation was naturally reversed) which was encouraging because for practical reasons the yaw meter could not be accurately placed at the centre of the test section. Following those exploratory test runs testing proceeded with wall bumps set upwards, a selection of the results being displayed in this report. To examine the variation of the w-influence coefficient in the x-direction it was necessary to move the wall bump relative to the yaw meter, because the yaw meter was in a fixed position mounted from a tunnel sidewall. The physical location of the wall jacks thus determined the streamwise positions at which w-influence coefficients could be measured relative to the bump.

The experimental technique used was to test with the walls set at an aerodynamically straight* contour valid for Mach number 0.5, throughout the entire Mach number test range. The contour was only modified around the yaw meter support strut to raise the test-section choking Mach number.

* aerodynamically straight wall contours are those that give constant indicated Mach numbers at the centrelines of the contoured top and bottom flexible walls.

The modification to the walls took the form of a divergence which began two inches downstream of the yaw meter to minimise any effect on the u-component of flow at the yaw meter. The yaw meter support strut was basically a 0.75 inch diameter circular cylinder spanning the test section. The yaw meter was nominally set at zero angle of attack on the tunnel centreline and flow angularity measurements were made in the Mach number range 0.3→0.75, using yaw meter calibration data. Strictly each test Mach number should have had its own aerodynamically straight contour set to minimise any u-perturbations at Mach numbers different to M = 0.5. However, it is known that the variations in Mach number along the test section are small when the incorrect aerodynamically straight contour are used[3]. This coupled with the desire to accelerate the testing programme led to the simplification of using just one straight contour for all Mach numbers. Wall bumps were on occasion measured with a micrometer. Differences between the amplitude and that indicated by the usual wall position sensors were found of up to ±0.003 inches. This is consistent with design aims[2,3], but is a significant source of error in this work.Figures 2, 3 and 5 to 16 refer to bumps of 0.068 inches corresponding to a movement of 0.071 inches demanded through the usual wall-control hardware. The other bump sizes quoted refer to demanded rather than actual bumpsizes.

The yaw mater was aligned nominally with the centreline of the test section and its reading, in the form of a pressure difference between the tube pair indicating angularity, read with the walls straight and then with bumps present. The change in reading, expressed as a pressure coefficient, was then used with yaw meter calibration data to give the flow angle induced by the bumps.

M_W - data is included in Figures 2 to 9, where experimental data points are compared with theory, each data point representing the average of several individual tunnel runs. Table 1 summarises the number of data runs used to compile the figures in this report. Included in the table are yaw meter calibration tests, u-influence coefficient tests and w-influence coefficient tests are summarised.

2.2 Sources of Error

The precise streamwise location at which the yaw mater measures the angularity of flow is not known. It is estimated that an uncertainty of ±0.125 inches exists. Evidence for this is seen in all w-influence coefficient plots where there is clearly a substantial angularity indicated above the bump, at its crest, where there should be no angularity. During the testing it was visually noticed from manometers that there was a long cycle fluctuation in the yaw meter pressure tubes. This was of the order of seconds whereas the tunnel transducers measured the pressures producing an average value over a one second period. A much longer time average would have taken the above fluctuation into account but was impractical with the existing TSWT software Thus, the technique employed was to average the results from many separate runs. At small wall induced flow angularities especially, where the effective signal-to-noise ratio is smaller, the error caused by this practice led to large scatter seen in all plots.

The change in boundary layer growth due to the bump was input into the streamline curvature program as a difference in bump size to that physically set in the flexible walls. Normally during testing with aerodynamically straight wall contours set the boundary layer growth on all four walls has effectively been absorbed. A bump in the wall however causes a change in boundary layer growth changing the effective wall bump shape and hence the induced flow perturbations. With the bumps set for w-influence coefficients in the manner shown in Figure 1, boundary layer thinning occurs at the crest of the protruding bump with thickening either side of it, with the opposite effect at the other bump. The standard TSWT software calculates boundary layer changes using the Von Karman momentum integral equation enabling this boundary layer allowance to be used for the theoretically determined influence coefficients. All theoretically derived coefficients shown in the plots include this boundary layer allowance, unless stated otherwise. The total effect is however very small as the combined effects of opposite bumps tend to cancel one another as shown in Figure 9.

2.3 Discussion of Results of W-Influence Coefficients

The results for w-influence coefficients from the series of tests are summarised in Figures 3 to 8 which show experimental and theoretical results.

One important trend observed in the determination of the perturbations, typified by Figure 2, is their rather strong Mach number dependence at higher mach numbers. One can clearly see that the peak disturbance to Mach number has risen by the same percentage from $M = 0.6$ to 0.7 as from 0.3 to 0.6. The trend continues to higher Mach numbers as Figures 7 and 8 suggest. The experimental data shows a similar Mach number dependence. Figures 2 and 4 demonstrate how the character of the theoretical curves changes somewhat with Mach number, the peak disturbance travelling towards the bump centre with increase in Mach number.

All experimentally determined w-influence coefficients shown in the figures are generally lower than the corresponding theory with the difference being more apparent around the peak of the perturbation plot. Evidently the trend continues throughout the

Mach number range as shown in Figures 7 and 8. Figure 9 clearly shows by two computed cases that the aforementioned boundary layer effects on each wall cancel one another making their plots virtually coincident.

In summary, it seems valid to continue using the theoretically determined w-influence coefficients as part of the 3-D wall adjustment strategy because their magnitudes are of the same order as the experimental check points.

3. U-INFLUENCE COEFFICIENTS

3.1 Description of Testing Procedures

To measure flow perturbations in the streamwise direction, induced by oppositely placed wall jacks moved into the test section, it was convenient to use existing sidewall static pressure tappings. These are in the form of five vertical and eighteen streamwise tappings, the vertical spacing being 1 inch with the horizontal spacing being of 1 and 2 inch gaps. Normally the complete grid is used to measure wall pressures during 3-D model testing, but for this work it was only necessary to use the centreline row of tappings. The locations of the wall jacks and the sidewall pressure tappings effectively fixed the relative locations at which u-influence coefficients could be verified. The fact of having measurements at several streamwise stations accelerated this testing programme in comparison with the w-perturbation measurements to the extent that it allowed the correct aerodynamically straight wall contour to be set for each Mach number. Even though it has been argued that the variations in the test section flow between one set of contours and another are small, for measuring small perturbations in the u-component it was judged advisable to use the best available wall contours.

The technique was again employed of removing the sidewall C_p record taken with aerodynamically straight walls from that with the bumps applied at the same Mach number. This helped to remove spurious results from tapping/transducer anomalies.

3.2 Sources of Error

All theoretical curves for u-influence coefficients include an allowance for the boundary layer thickening/thinning effect. Although the resultant effect on the centreline flow perturbations is small in this case the combined effects of both walls do not cancel, as shown in Figures 10 and 11.

The maximum test Mach number was limited by reaching sonic velocity over the bumps, beyond which the theory was invalid. With a single jack moved in on each wall by 0.068 inches the limit was about Mach 0.82.

The largest error which caused the quite severe scatter on all u-influence coefficient plots, was due to background noise in the readings. The centreline pressure coefficient was only of order -0.02 above the bump whilst the variability between runs at the same nominal condition could be as much as ±0.004. TSWT standard software calculates a pressure coefficient from a Mach number taken during the run but not taken at the precise instant that each sidewall pressure was measured. (A run would last the length of time taken for the scanivalves to rotate through a whole pressure taking cycle). Even by averaging many 'bump in' runs and many aerodynamically straight wall contour runs at approximately the same Mach number, the variation in data was quite large. To reduce the effect of noise, 3-jack wall bumps of 0.128 inches amplitude were used giving less scattered data. This enabled more confidence to be placed in the more numerous, but more scattered single jack bump data.

3.3 Discussion of Results

Figures 12, 13 and 14 clearly show that the scatter, especially at the lower levels of perturbations, where the signal-to-noise ratio is relatively smaller than at the higher levels of perturbations is larger than for the equivalent w-case. This is more easily seen by comparing the different experimental symbols on the plots. (Rather than just displaying an average of all results for each influence coefficient, a 'most negative'* value is shown to emphasize the scatter). In Figures 12, 13 and 14 'Jack 11' data refers to the wall bumps being set at jack 11 whereas 'Jack 8' data is from tests with the bump centre located at jack 8. The peak influence coefficients that occur above the bump centre were not available but have been estimated, as the sidewall static pressure tappings were offset by half an inch from the jack locations. The estimated peak u-perturbations are plotted against Mach number in Figure 16, clearly confirming their strong Mach number dependence at high Mach numbers as suggested by theory[1].

* the 'most negative' set of data runs were simply those giving the largest deviation from the average values of perturbation In most plots they result in more positive u-perturbations. 'Spot checks' refers to a series of tests taken at random Mach numbers to ensure a series of testing had not been incorrectly applied.

4. CONCLUSIONS

The accuracy of the 3-D wall adjustment strategy does not depend on the precise value of the influence coefficients. This work has shown however that the magnitudes of theoretically determined and experimentally determined influence coefficients are close, meaning it is valid to continue using the theoretically determined ones in 3-D wall adjustment strategies.

The 'spot check' nature of this work was sufficient to confirm the continuous theoretical influence coefficients in the range Mach number 0.3 to 0.8 and suggests the trend continues to sonic velocity.

REFERENCES

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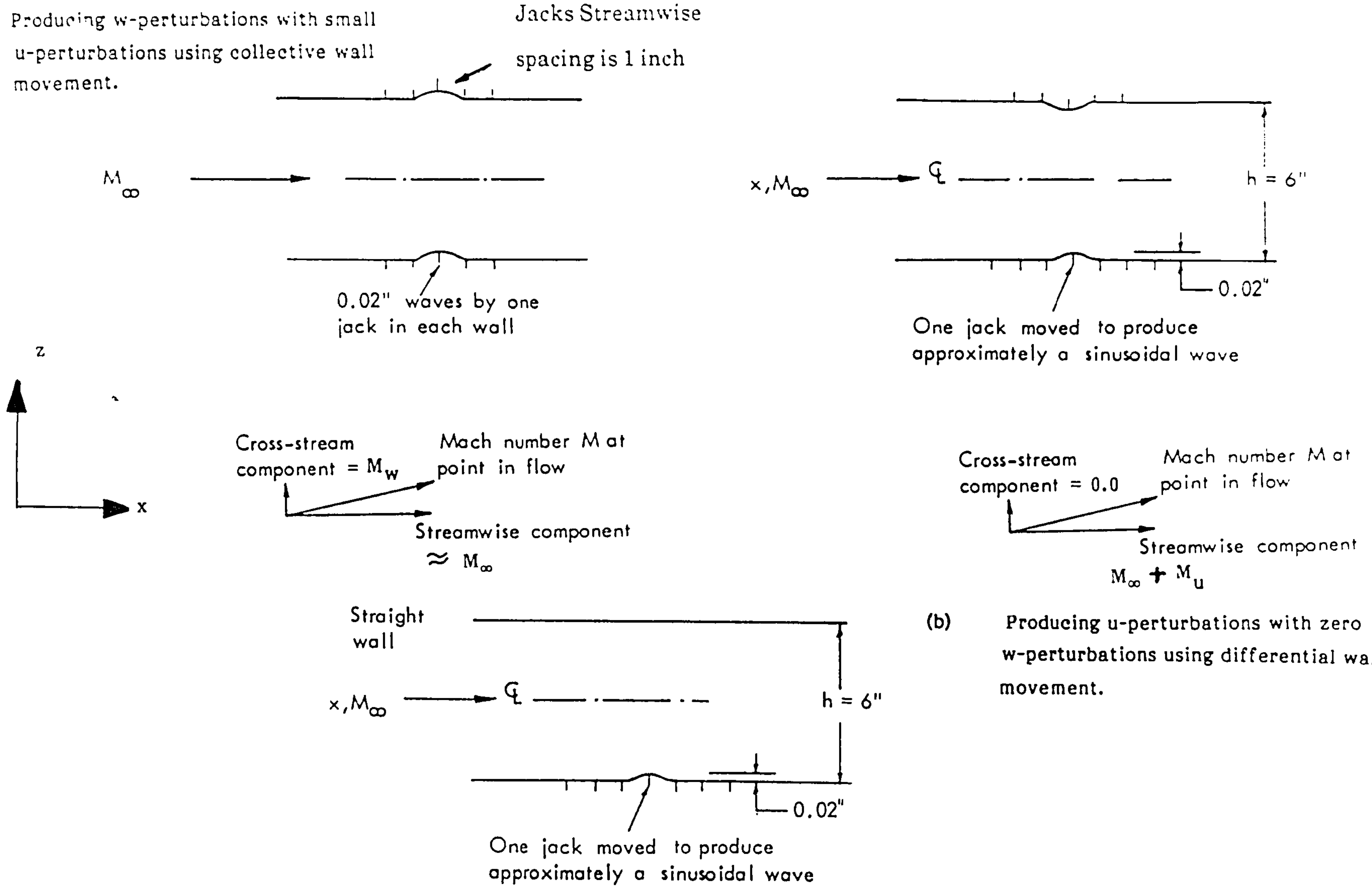
2. 'The design and operational development of self-streamlining two-dimensional flexible walled test sections', NASA contractor report 172328, March 1984 by S W D Wolf.

3. 'Empty test section streamlining of the transonic self-streamlining wind tunnel fitted with new walls', NASA Contractor Report 181680, July 1988 by M C Lewis.

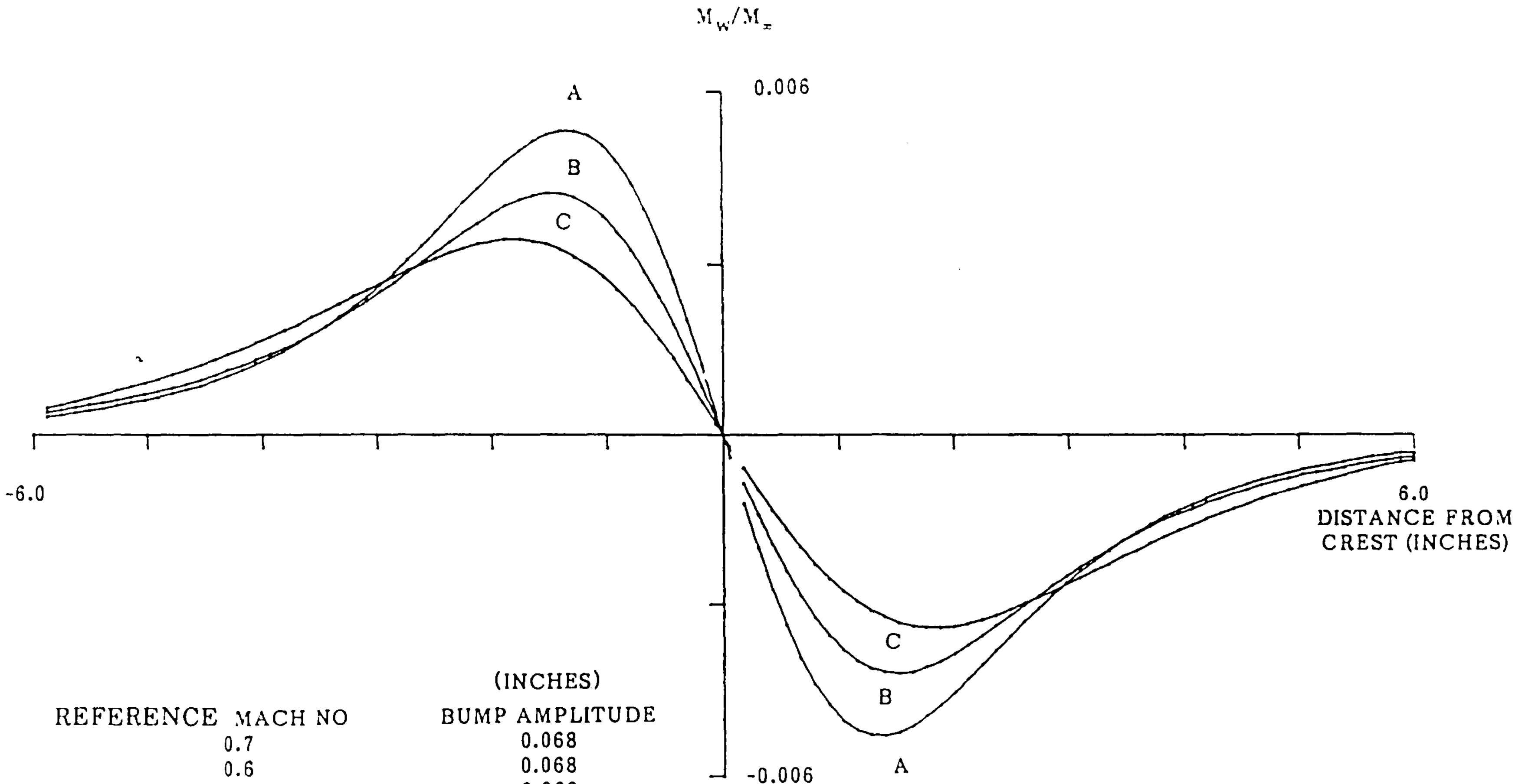


(a) Producing w-perturbations with small u-perturbations using collective wall movement.

(b) Producing u-perturbations with zero w-perturbations using differential wall movement.

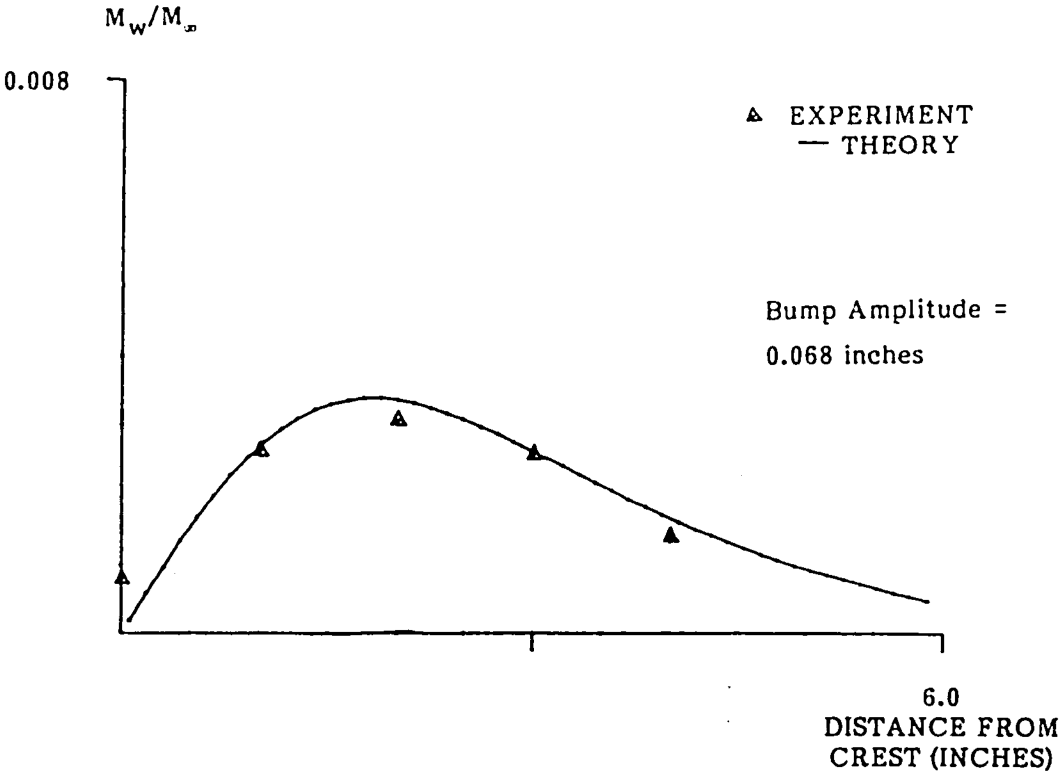
(c) A single wall bump produces both u and w-perturbations.

FIGURE 1

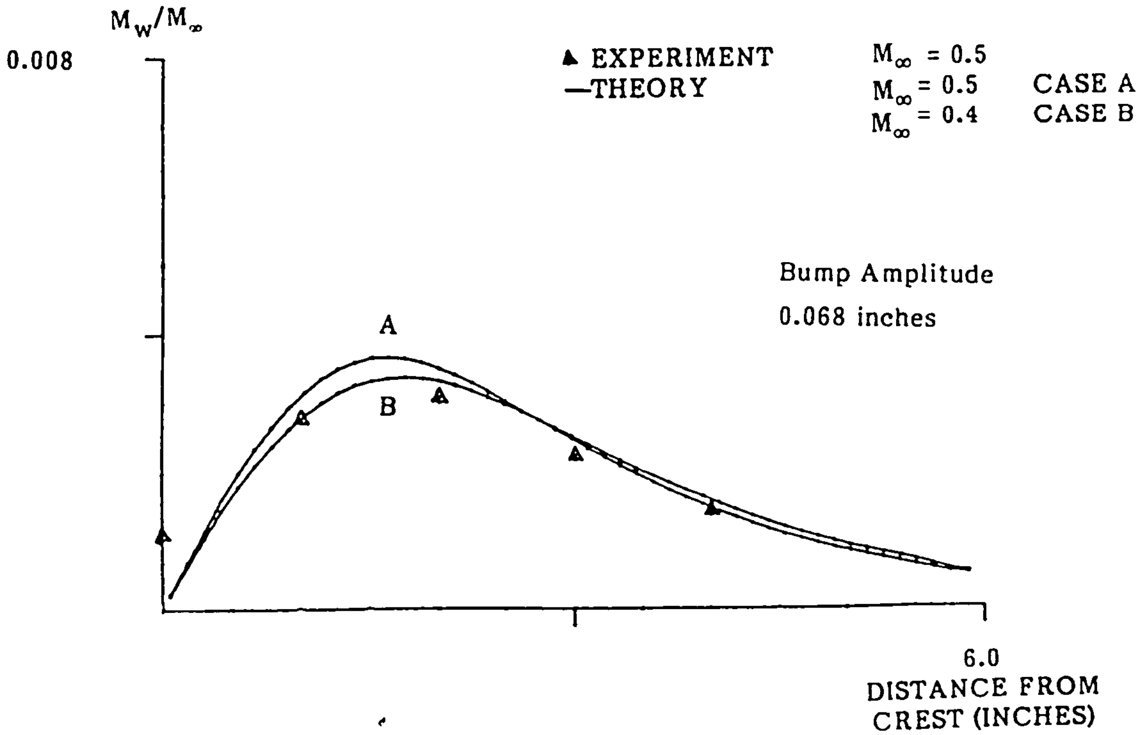


CASE	REFERENCE MACH NO	(INCHES) BUMP AMPLITUDE
A	0.7	0.068
B	0.6	0.068
C	0.3	0.068

FIGURE 2 THEORETICAL W-PERTURBATIONS (INCLUDING BOUNDARY LAYER EFFECTS)

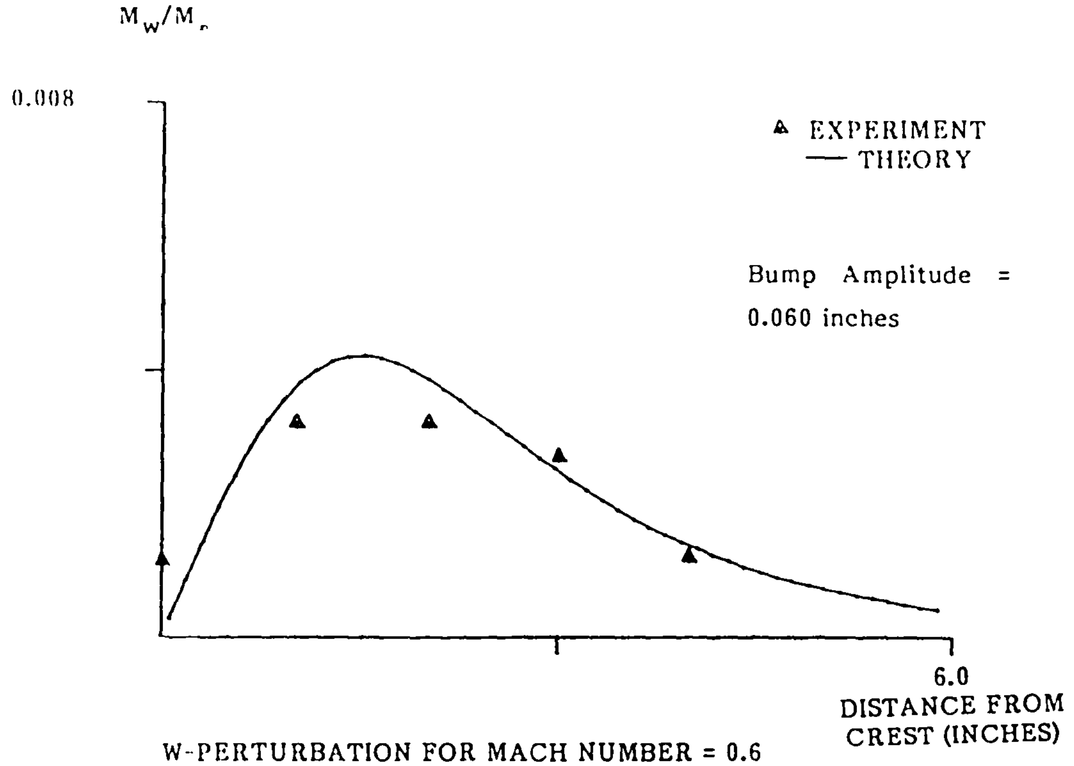


W-PERTURBATION FOR MACH NUMBER = 0.3

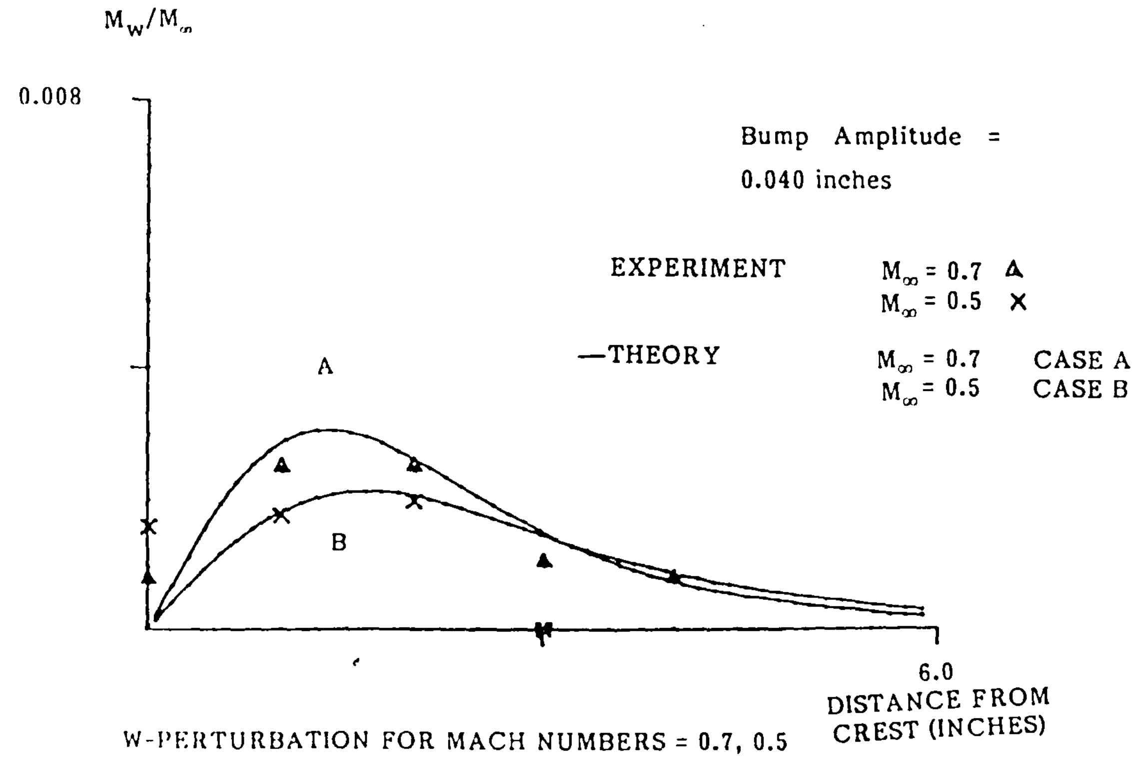


W-PERTURBATION FOR MACH NUMBER = 0.5

FIGURE 3

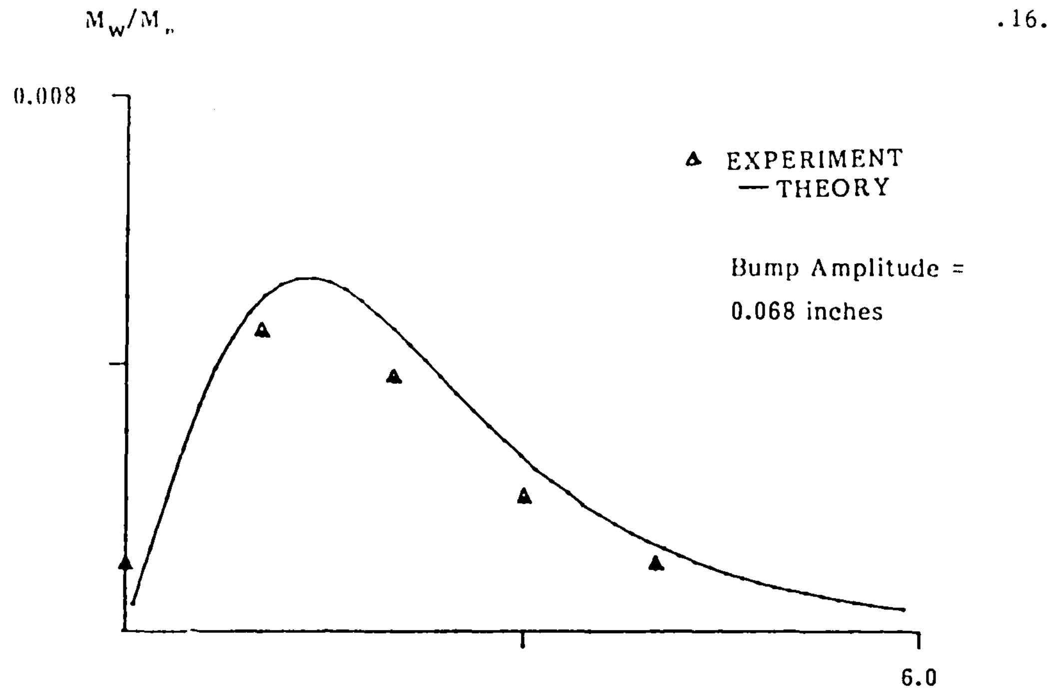


W-PERTURBATION FOR MACH NUMBER = 0.6

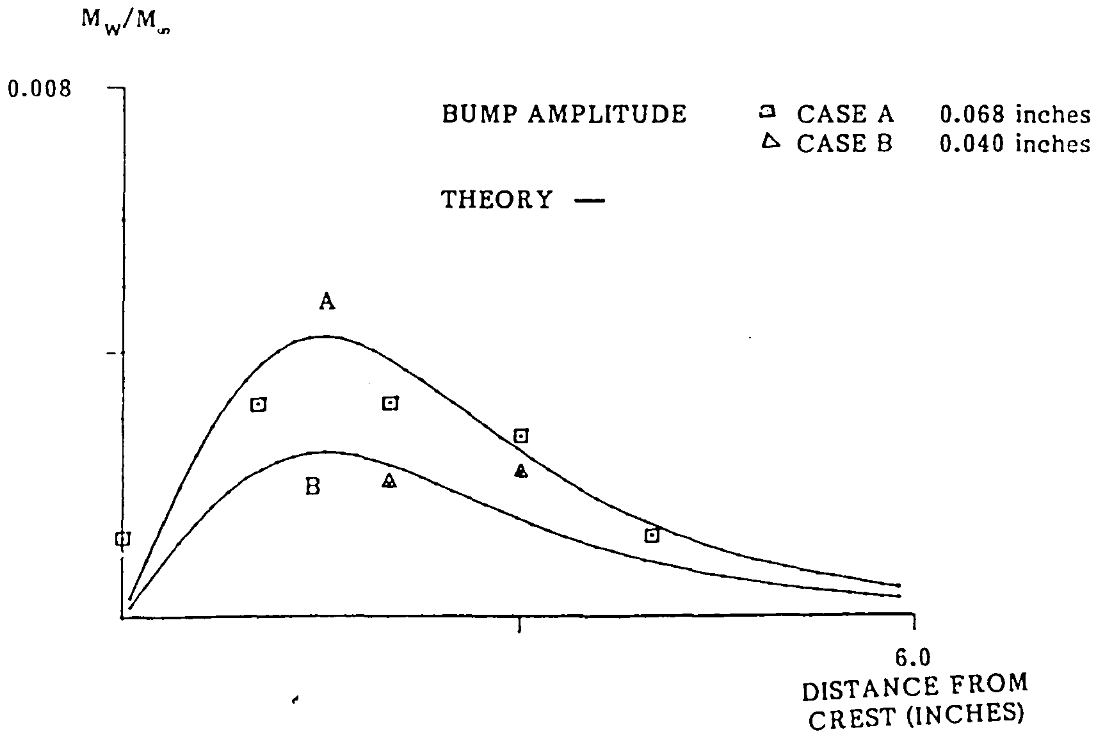


W-PERTURBATION FOR MACH NUMBERS = 0.7, 0.5

FIGURE 4

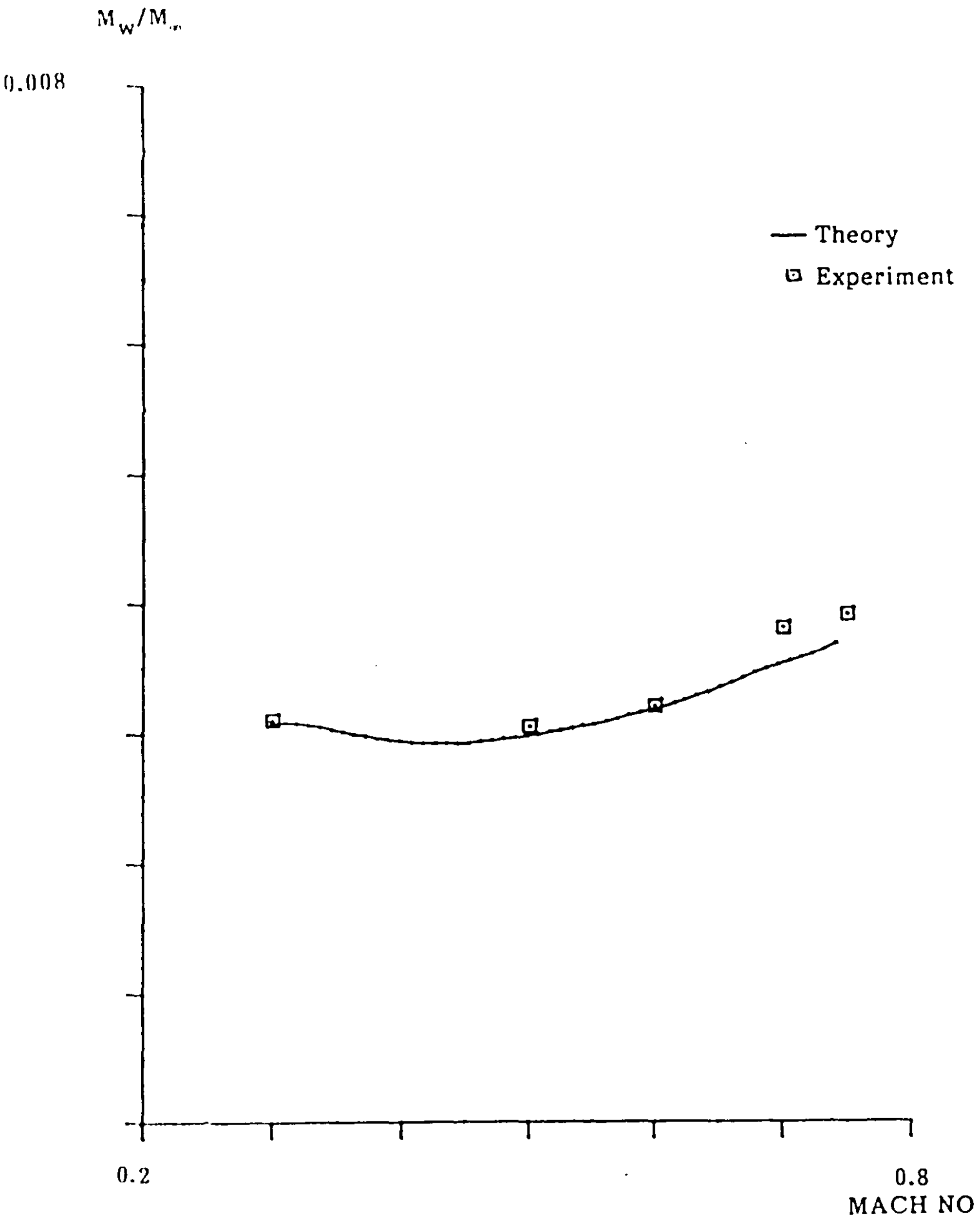


W-PERTURBATION FOR MACH NUMBER = 0.7



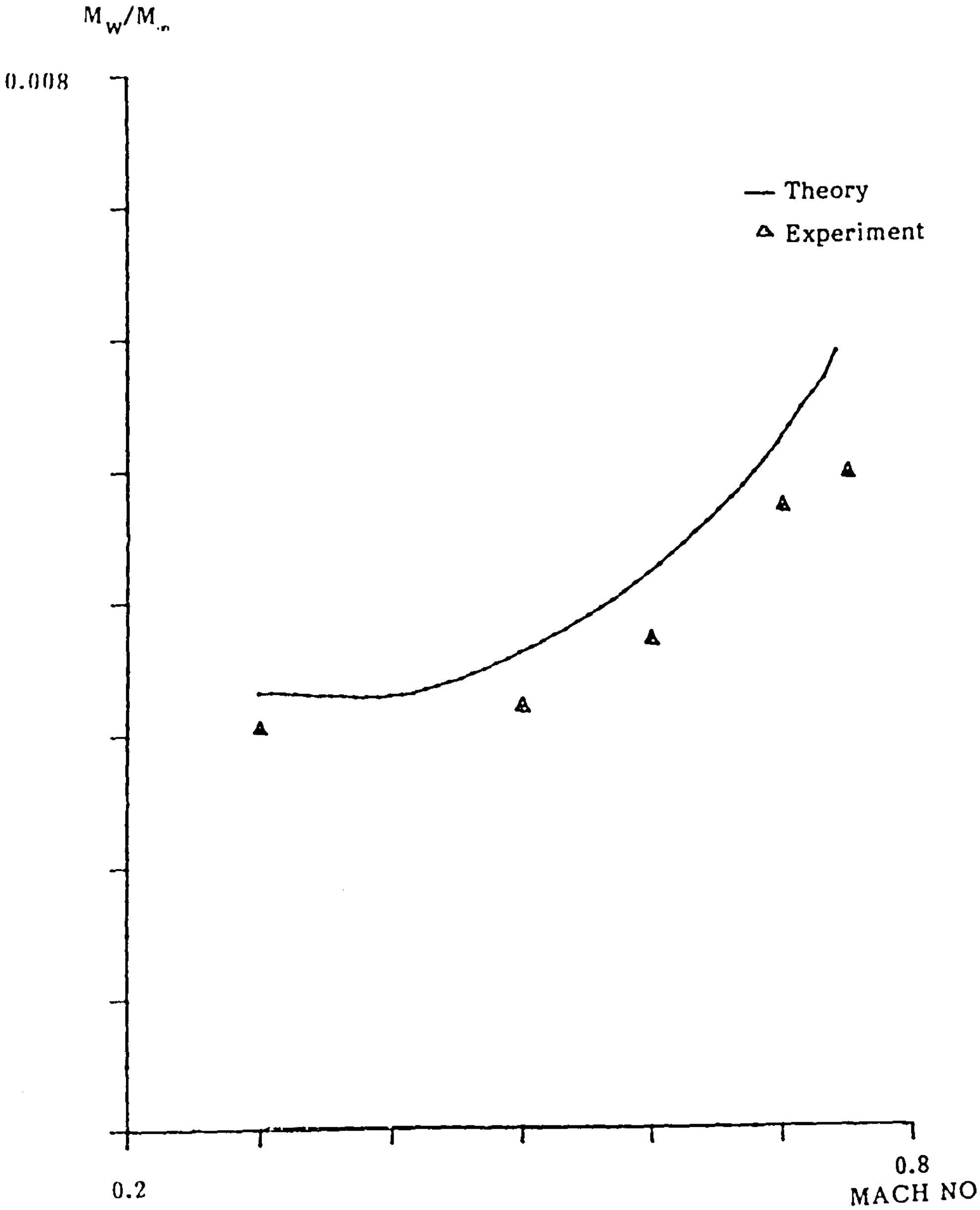
W-PERTURBATION FOR MACH NUMBER = 0.6

FIGURE 5



-Bump Amplitude 0.068 inches-

FIGURE 6 : W-PERTURBATIONS (2 INCHES FROM BUMP CREST) AGAINST MACH NUMBER



-Bump Amplitude 0.068 inches-

FIGURE 7 : W-PERTURBATIONS (1½ INCHES FROM BUMP CREST) AGAINST MACH NUMBER

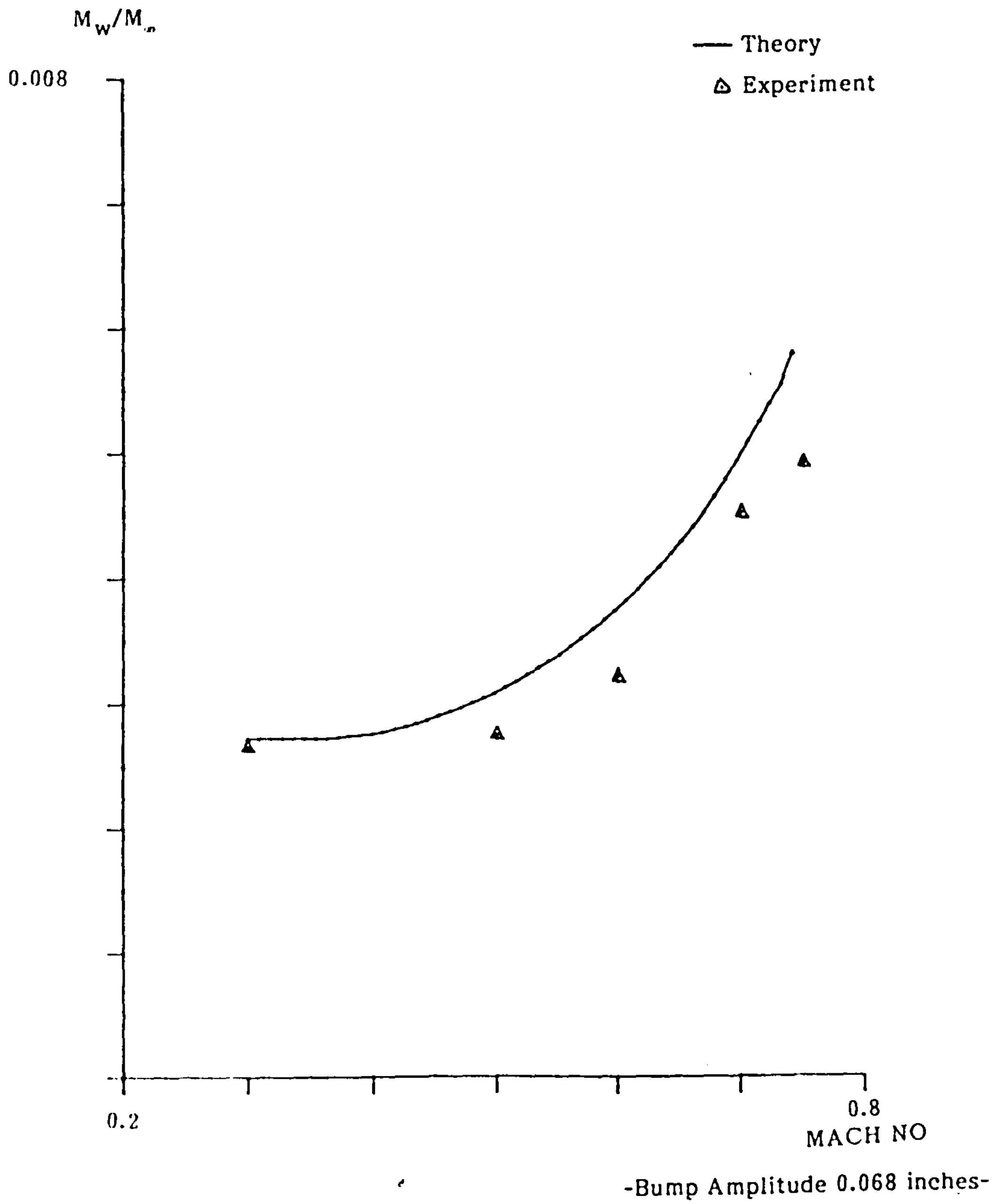


FIGURE 8 : W-PERTURBATIONS (1 INCH FROM BUMP CREST) AGAINST MACH NUMBER

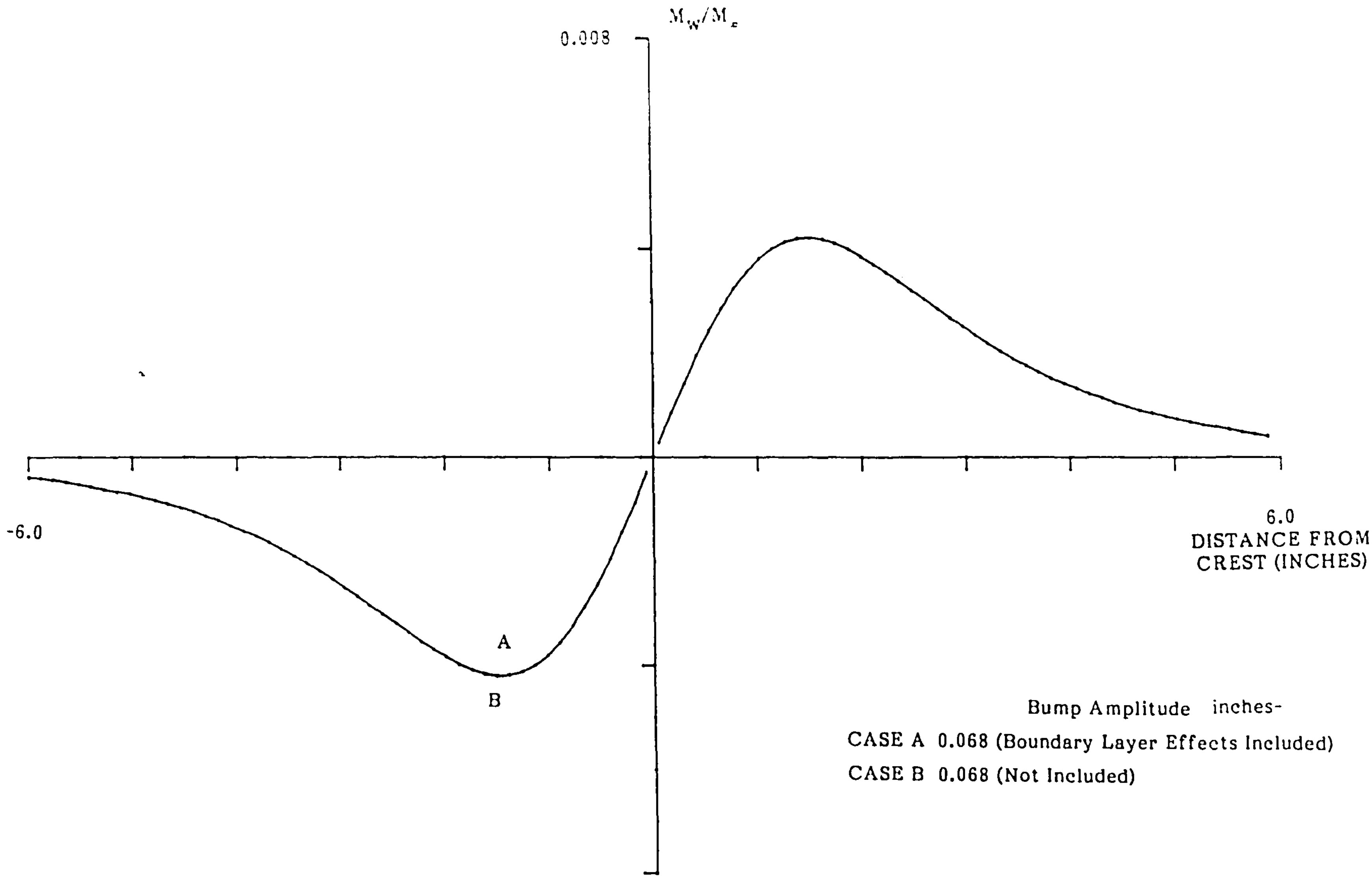
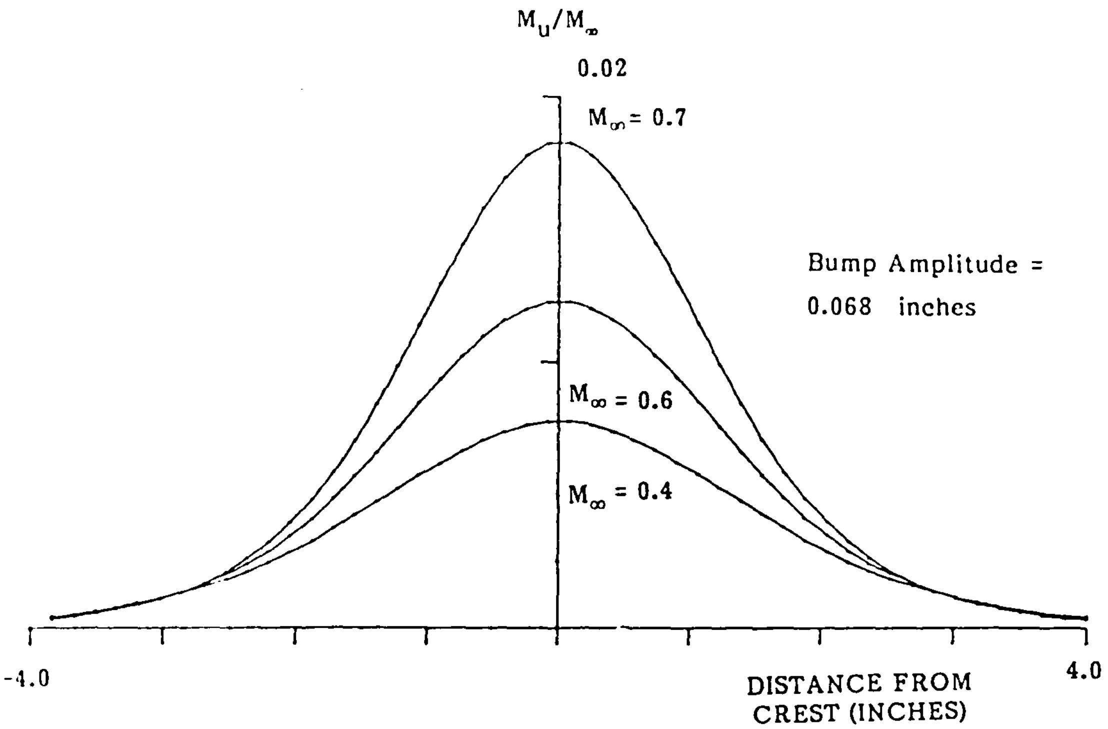


FIGURE 9 : THEORETICAL W-PERTURBATIONS AGAINST DISTANCE FROM BUMP CREST



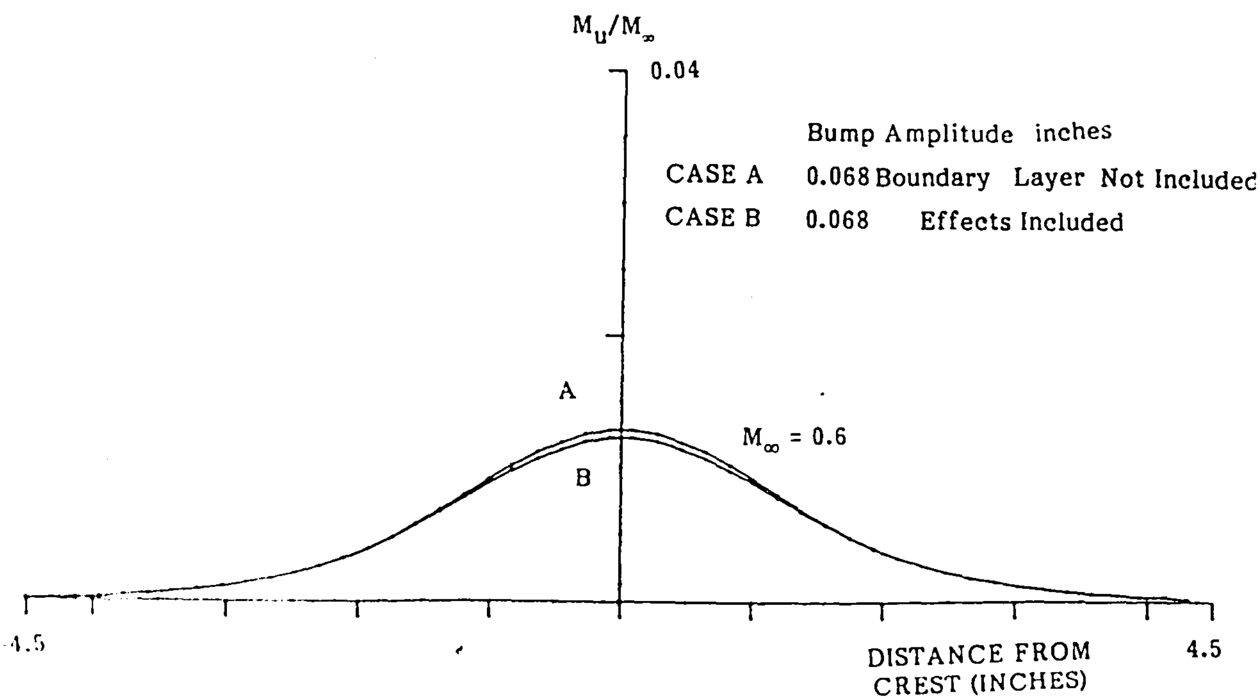


FIGURE 10 THEORETICAL U-PERTURBATIONS VS DISTANCE FROM BUMP CREST

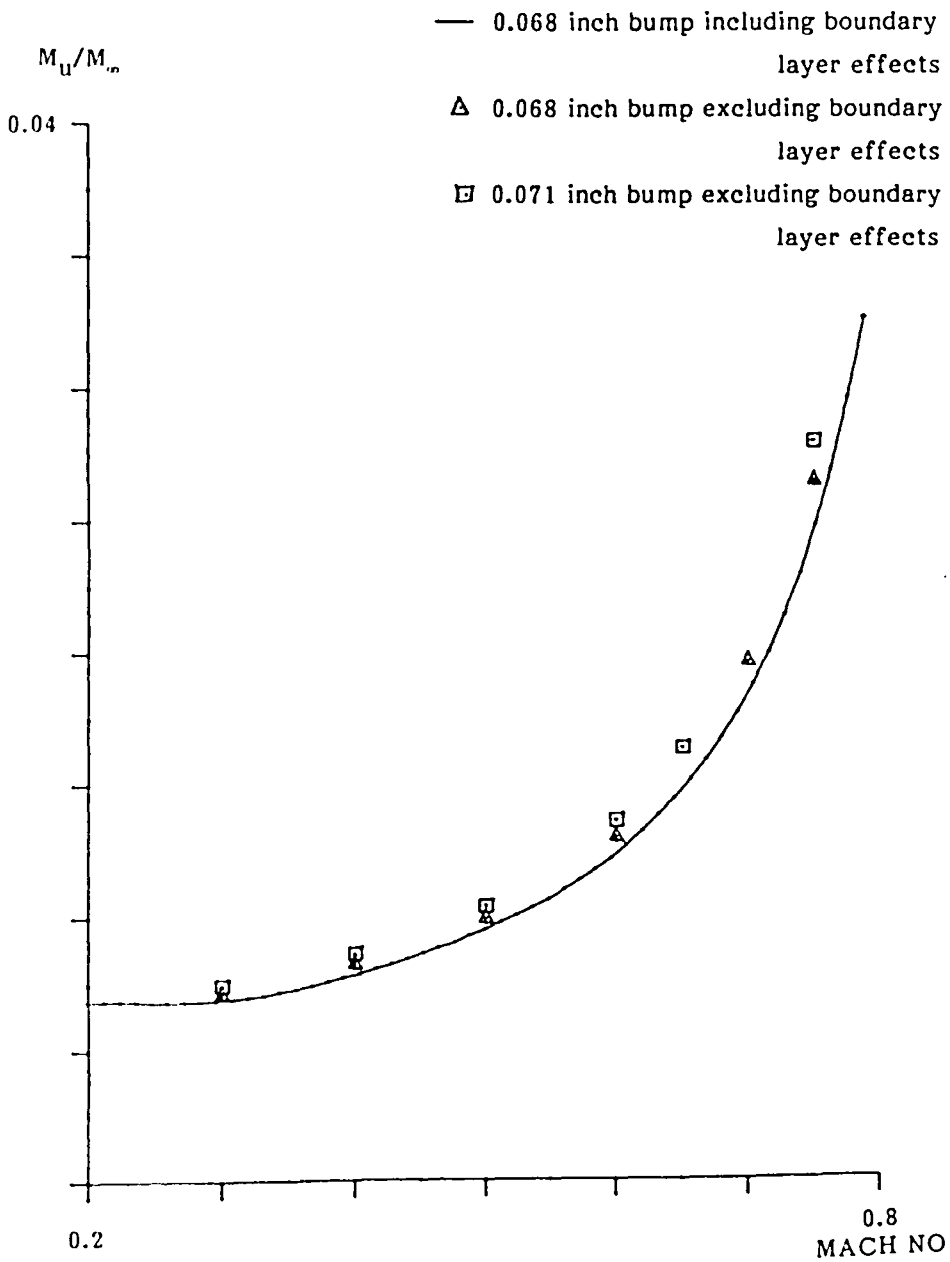


FIGURE 11 : THEORETICAL ESTIMATES OF THE EFFECT OF MACH NUMBER AT THE U-PERTURBATION AT THE TUNNEL CENTRELINE IN LINE WITH THE BUMP CREST

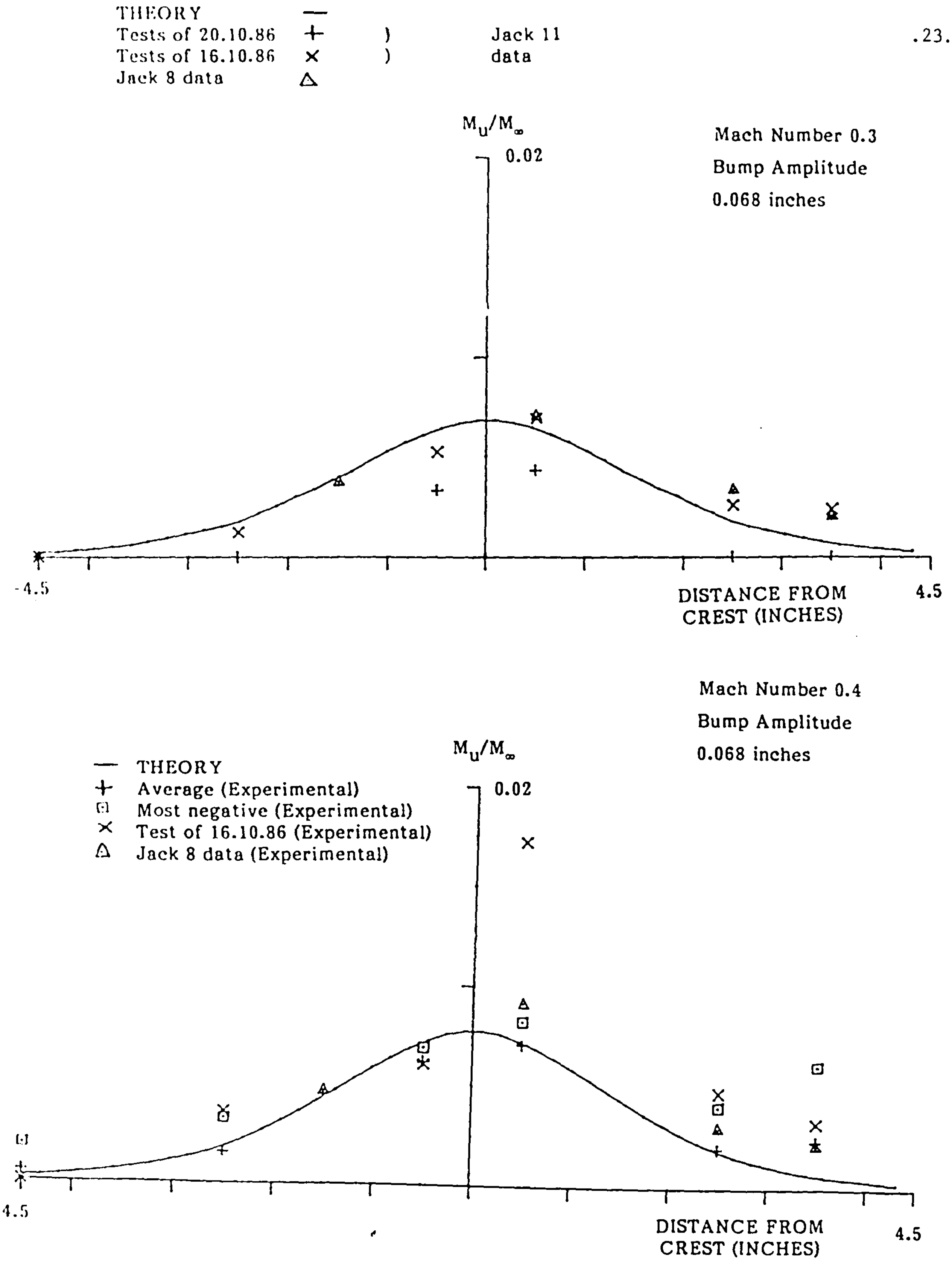


FIGURE 12 : U-PERTURBATION AGAINST DISTANCE FROM BUMP CREST

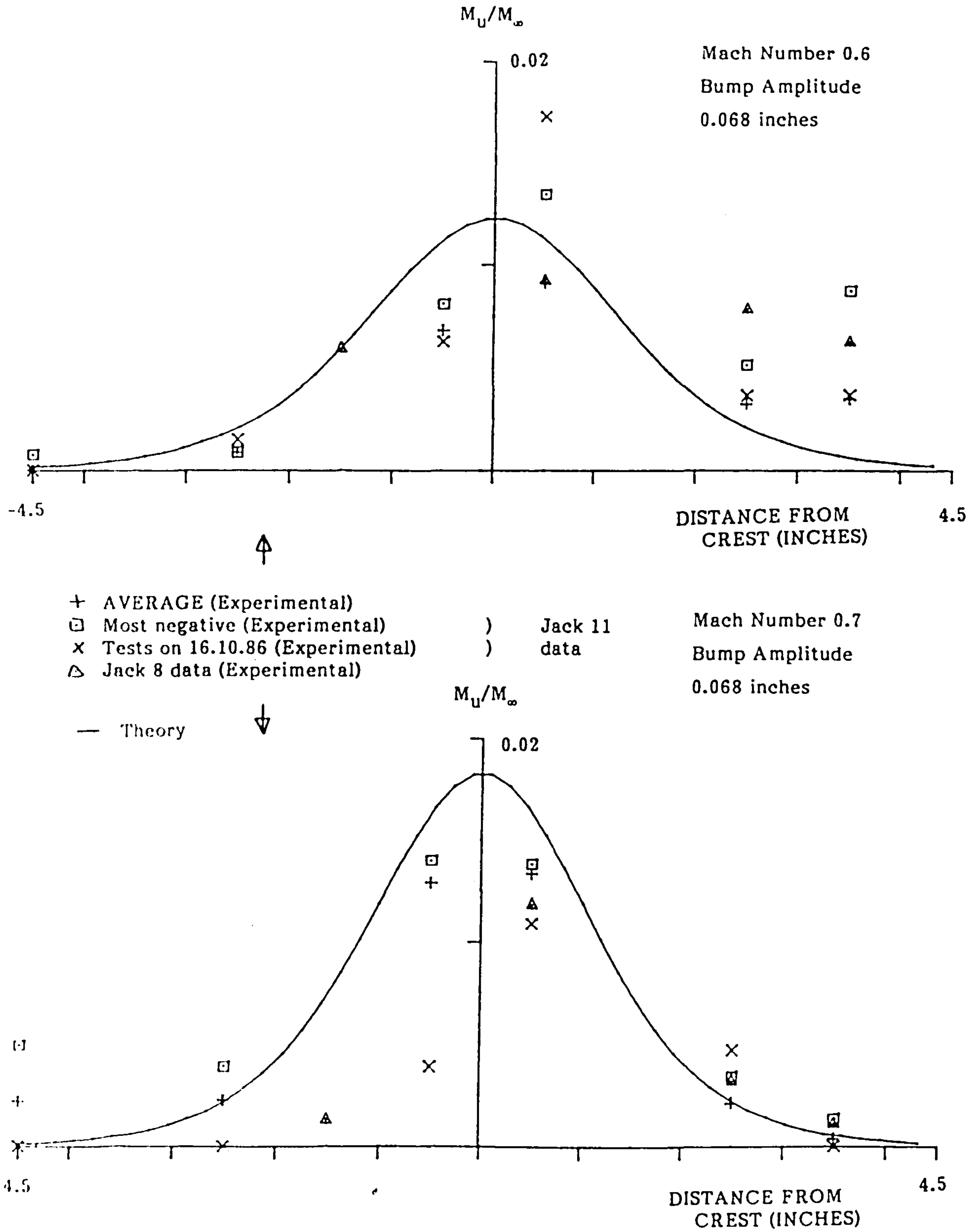


FIGURE 13 : U-PERTURBATIONS AGAINST DISTANCE FROM BUMP CREST

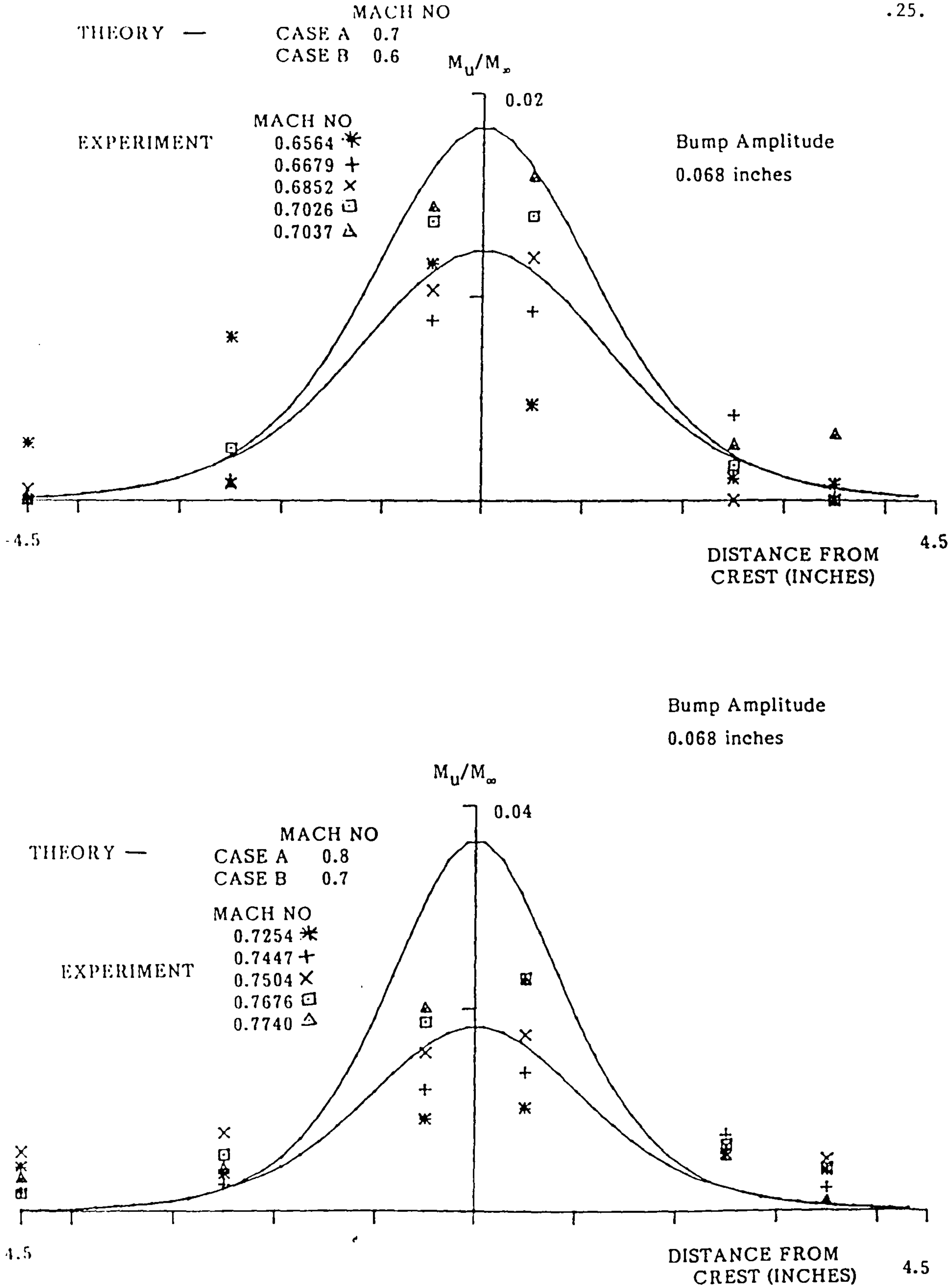


FIGURE 14 : U-PERTURBATIONS AGAINST DISTANCE FROM BUMP CREST

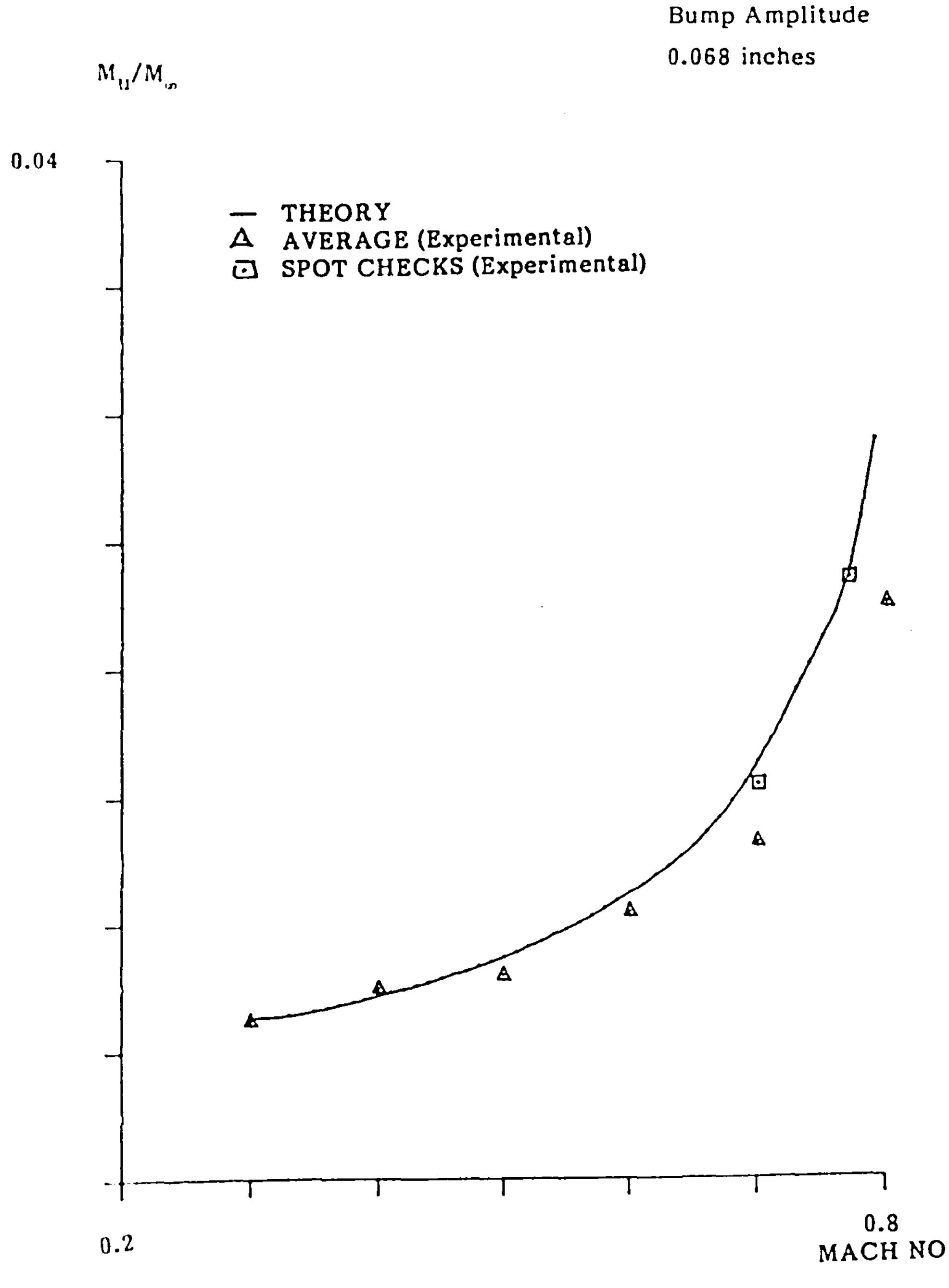


FIGURE 15 : U-PERTURBATIONS (½ INCH FROM BUMP CREST) AGAINST MACH NUMBER

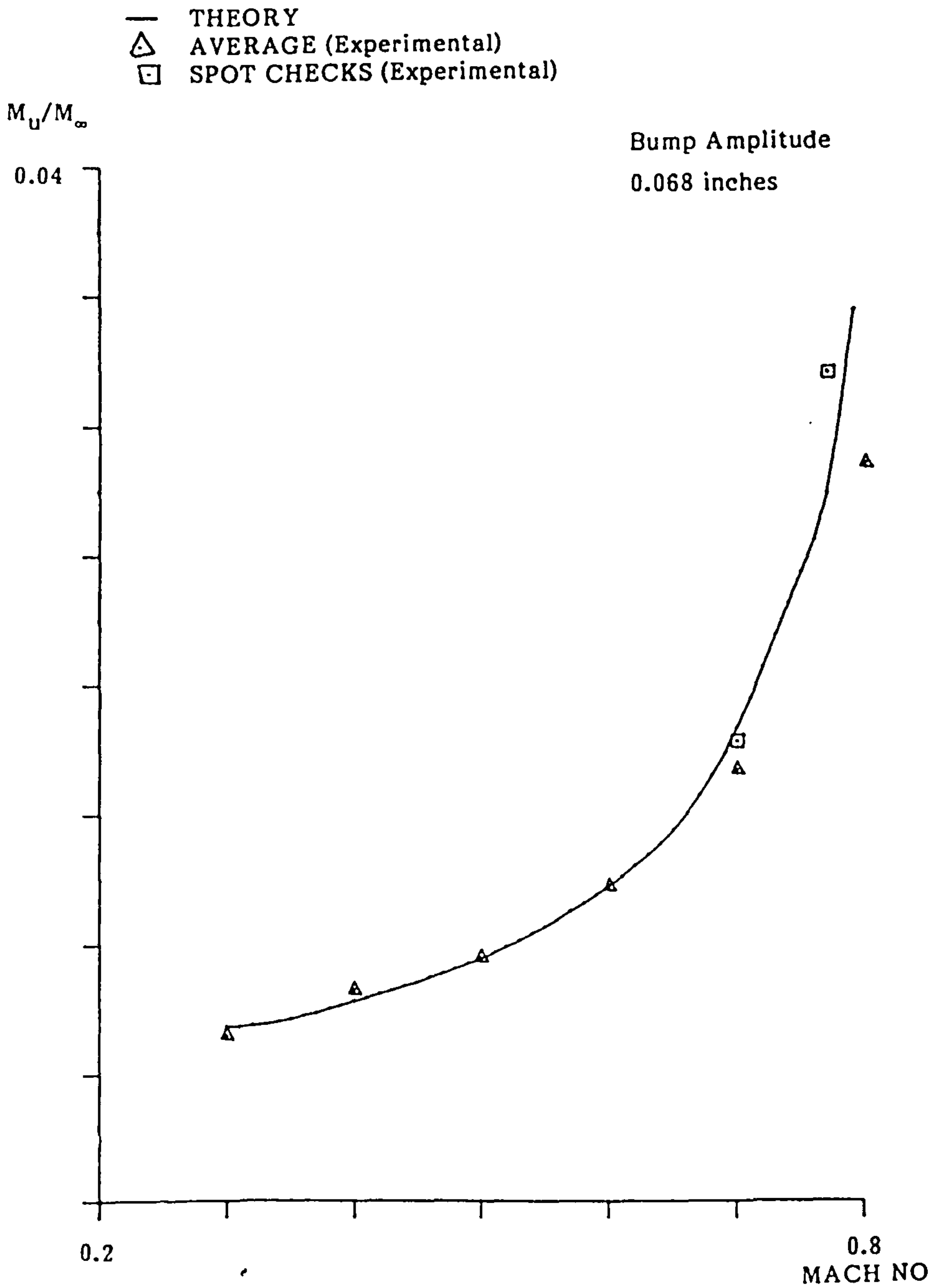


FIGURE 16 : U-PERTURBATIONS IN LINE WITH BUMP CREST AGAINST MACH NUMBER

NASA

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-181681		

4. Title and Subtitle

The Experimental Verification of Wall Movement Influence Coefficients for an Adaptive Walled Test Section

5. Report Date

July 1988

6. Performing Organization Code

7. Author(s)

G. Neal

8. Performing Organization Report No.

AASU Memo 87-4

10. Work Unit No.

505-61-01-02

9. Performing Organization Name and Address

University of Southampton
Department of Aeronautics and Astronautics
Southampton, Hants, S09 5NH
ENGLAND

11. Contract or Grant No.

NSG-7172

13. Type of Report and Period Covered

Contractor Report

12. Sponsoring Agency Name and Address

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 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

Flexible walled wind tunnels have for some time been used to reduce wall interference effects at the model. A necessary part of the 3-dimensional wall adjustment strategy which is being developed for the Transonic Self-Streamlining Wind Tunnel (TSWT) of Southampton University is the use of influence coefficients. The influence of a wall bump on the centerline flow in TSWT has been calculated theoretically using a streamline curvature program. This report details the experimental verification of these influence coefficients and concludes that it is valid to use the theoretically determined values in 3-dimensional model testing.

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	33	A03

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