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PROJECT ADMINISTRATION DATA SHEET

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Project No. E-16-647 GTRI/~~GIT~~ DATE 7/ 11/ 83

Project Director: Dr. Spyridon Lekoudis School/~~Lab~~ AE

Sponsor: Office of Naval Research

Arlington, VA 22217

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Award Period: From 5/15/83 To 7/14/84 (Performance) ______ (Reports)

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Title: "Turbulent Boundary Layers Developing Over Compliant Surfaces"

ADMINISTRATIVE DATA

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GEORGIA INSTITUTE OF TECHNOLOGY OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION/CLOSEOUT SHEET

Date 8/10/84

Project No. E-16-647 School/~~Lab~~ AE

Includes Subproject No.(s) N/A

Project Director(s) Dr. Spyridon Lekoudis GTRI ~~/GIT~~

Sponsor Office of Naval Research

Title Turbulent Boundary Layers Developing Over Compliant Surfaces

Effective Completion Date: 5/15/83 - 7/14/84 (Performance) 7/14/84 (Reports)

Grant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
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- [X] Govt. Property Inventory & Related Certificate
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E-16-647

TURBULENT BOUNDARY LAYERS DEVELOPING OVER COMPLIANT SURFACES

Semi-Annual Progress Report on
Contract N00014-83-K-0418 (GT-E-16-647)
(Period: May 15, 1983 to November 15, 1983)

by

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for

The Compliant Coating Drag Reduction Program
Office of Naval Research
Washington, D.C.

1. Introduction

The objective of the present effort is to develop drag prediction methods for high Reynolds number turbulent flow over compliant surfaces. Because the interest is in high Reynolds number flow, traditional closure assumptions are used. As a consequence, results have to be always compared with measurements whenever this is possible. Otherwise the predictive capabilities of the method cannot be trusted.

The method, developed mainly during the first year of this effort, is essentially a steady-streaming calculation in turbulent flow. Motivation for its development comes from experimental evidence. The evidence is that the first harmonic dominates flows over rigid sinusoidal wavy surfaces, even close to separation (References 1, 2). The method uses the wave-induced stresses, due to that harmonic, to modify the mean flow. The mean flow is a turbulent boundary layer in a coordinate system that is conforming to the shape of the wall. Therefore, the coordinate system is time-dependent for the case of moving walls. Details of the method are given in Reference 3.

This report describes some results obtained from this method for the case of the two-dimensional problem, and its extension to the case of swept wavy walls. The personnel currently involved is the author, T. Sengupta and N. Hazarika. The last two are graduate students in the School of Aerospace Engineering. T. Sengupta successfully defended a Ph.D. thesis proposed on December 2, 1983. The proposal committee consisted of Professors Warren Strahle, J. C. Wu, and the author. N. Hazarika joined the School in September 1983 and he is a candidate for a M.S. degree.

2. The Two-Dimensional Problem

Calculations for turbulent flows over rigid wavy surfaces were reported in Reference 3 and they are in excellent agreement with recent measurements (Reference 4). Because the main interest is in the case of compliant walls, a study was made for turbulent flow over a surface with motion. The motion of the surface corresponds to the motion of a water-wave. The surface particles travel on a circular orbit (deep water-wave) or elliptical orbit (water-wave with finite channel depth). This motion closely approximates the motion Kendall observed in his measurements (Reference 5). For the mean flow conditions given by Kendall, the present method predicted flow separation. However, small variations in the mean shear can cause this to happen. Calculations based on time-averaged Navier-Stokes show reasonable agreement with Kendall's data in Reference 7. The upper boundary in these calculations was not the freestream but a location in the log-low region. The author believes that the present method should not be applied to waves with amplitude to wavelength ratio higher than about .025, unless the mean shear is such that the flow is not approaching incipient separation.

There seems to be a controversial issue regarding the turbulence model. References 3, 6 and 7 report a need to use lag constants in the algebraic eddy-viscosity model in order to obtain good agreement with the available data. References 4 and 8 report that this is not so. The question can be translated into how close to equilibrium such turbulent flows are. Because the measurements reported in Reference 4 do not include variations of the shear over the surface, and because comparisons of the variation of the shear in Reference 8 are confined to Sigal's data, the issue is not easy to resolve. The drag values depend mainly on the mean shear and, hence, the oscillatory part of the shear is not important for drag predictions. The oscillatory pressure is very important, because it creates the wave drag. Excellent pressure predictions are reported in References 3, 4, 6, 7 and

8 for rigid wall experiments. The role of the turbulence model is much more important for the pressure.

A summary of the drag prediction results for the case of a surface that moves like the free surface of a deep-water wave is given in Figure 1. The small skin friction reduction that exists for the case of rigid walls is computed for this case too. However the pressure drag overpowers this reduction and that results in a net drag increase. This drag increase is not predicted for the case of high positive phase speeds. These speeds seem to necessitate a very passive coating (speeds in the range of "large" structure motions inside the turbulent boundary layer). The use of the turbulence models in these wave speeds is also somewhat questionable. This is because checkout of these models is done for phase speeds less than half of the freestream. In order to examine their applicability we applied them to a set of recent experiments, reported in References 9 and 10.

Some preliminary results are shown in Figures 2 through 9. In these figures the oscillatory part (phase-averaged minus time-average) the flow is plotted. It is in a cartesian-like system (References 9 and 10) and thus the velocities are denoted by tildas. The trends are reproduced by the calculations, but the quantitative agreement is not always good. The abrupt changes in the phase in some figures is due to the fact that the lag equations are used only in the inner part of the boundary layers.

The uncertainty in comparing with wind/water-wave experiments is due to two sources. First, there is a mean-drift in the water surface. This was simulated by a mean surface motion in the code, until the computed friction velocity agreed with the measurement. Second, large uncertainty exists because a surface boundary layer in the water can change the phase of the surface motion. This problem is currently investigated. The thrust of the effort is to examine the predictive capabilities of the method by comparing not only with measured surface quantities, as it was the case in the past, but with quantities measured inside the turbulent boundary layer.

3. The Three-Dimensional Problem

The analytical formulation is complete and follows below. The coordinate system used is shown in Figure 10. The undisturbed flow is, from top to bottom in the cartesian x-direction. The constant phase angles are swept at an angle Λ with respect to the x-axis. The final coordinate system is made of body conforming, orthogonal, curvilinear coordinates. This is accomplished by the following series of transformations:

$$\begin{Bmatrix} x_1 \\ y_1 \\ z_1 \end{Bmatrix} = \begin{bmatrix} \cos\Lambda & 0 & -\sin\Lambda \\ 0 & 1 & 0 \\ \sin\Lambda & 0 & \cos\Lambda \end{bmatrix} \begin{Bmatrix} x \\ y \\ z \end{Bmatrix} \qquad (1)$$

$$\begin{aligned} \xi &= (x - ct) - i\,\varepsilon e^{-ky_1} e^{ik(x_1 - ct)} \\ \eta &= y_1 - \varepsilon e^{-ky_1} e^{ik(x_1 - ct)} \\ \zeta &= z_1 \\ \tau &= t \end{aligned} \qquad (2)$$

Also ε is the waveamplitude, k the wavenumber and c is the phase speed of these waves.

To obtain the governing equations we start with the Navier-Stokes equations in conservation form.

$$\frac{\delta W}{\delta t} + \frac{\delta F}{\delta x} + \frac{\delta G}{\delta y} + \frac{\delta H}{\delta z} = \frac{\delta F_1}{\delta x} + \frac{\delta G_1}{\delta y} + \frac{\delta H_1}{\delta z} \tag{3}$$

where W, F, G, H, F_1, G_1, and H_1 are the four component vectors

$$W = \begin{Bmatrix} 1 \\ u \\ v \\ w \end{Bmatrix} \quad F = \begin{Bmatrix} u \\ u^2 + p/\rho \\ uv \\ uw \end{Bmatrix} \quad G = \begin{Bmatrix} v \\ uv \\ v^2 + p/\rho \\ vw \end{Bmatrix} \quad H = \begin{Bmatrix} w \\ uw \\ vw \\ w^2 + p/\rho \end{Bmatrix}$$

$$F_1 = \begin{Bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ \tau_{xz} \end{Bmatrix} \quad G_1 = \begin{Bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ \tau_{yz} \end{Bmatrix} \quad H_1 = \begin{Bmatrix} 0 \\ \tau_{xx} \\ \tau_{yz} \\ \tau_{zz} \end{Bmatrix} \tag{4}$$

with $\tau_{ij} = \nu \left(\frac{\delta u_i}{\delta x_j} + \frac{\delta u_j}{\delta x_i}\right)$ for incompressible flow.

A general conservative form of the Navier-Stokes equations in a time-dependent coordinate system is obtained by using the definitions:

$$\hat{W} = W/J \qquad \hat{H} = \frac{1}{J}(F\zeta_x + G\zeta_y + H\zeta_z)$$

$$\hat{F} = \frac{F\xi_x}{J} + \frac{G\xi_y}{J} + \frac{H\xi_z}{J} \qquad \bar{F}_1 = \frac{1}{J}(F_1\xi_x + G_1\xi_y + H_1\xi_z)$$

$$\hat{G} = \frac{F\eta_x}{J} + \frac{G\eta_y}{J} + \frac{G\eta_z}{J} \qquad \bar{G}_1 = \frac{1}{J}(F_1\eta_x + G_1\eta_y + H_1\eta_z) \tag{5}$$

$$\bar{H}_1 = \frac{1}{J}(F_1\zeta_x + G_1\zeta_y + H_1\zeta_z)$$

We then obtain the form

$$\frac{1}{J}\frac{\delta W}{\delta t} + \frac{\delta \hat{F}}{\delta \xi} + \frac{\delta \hat{G}}{\delta \eta} + \frac{\delta \hat{H}}{\delta \zeta} = \frac{\delta \hat{F}_1}{\delta \xi} + \frac{\delta \hat{G}_1}{\delta \eta} + \frac{\delta \hat{H}_1}{\delta \zeta} \tag{6}$$

We decompose the flow quantities into a mean, time independent part, a "random" part and an oscillatory part that is due to the wall waviness. Also the mean flow is assumed to be locally parallel. In the following relations bars denote time-averaged quantities, primes denote "random" quantities and what is left is the difference between phase-averaging and time-averaging the flow quantities.

$$v_\xi(\xi,\eta,\zeta,t) = \bar{U}(\eta) + u'(\xi,\eta,\zeta,t) + \frac{\varepsilon}{2}(\hat{u}(\eta)e^{ik\xi} + \text{C. C.})$$

$$v_\eta(\xi,\eta,\zeta,t) = v'(\xi,\eta,\zeta,t) + \frac{\varepsilon}{2}(\hat{v}(\eta)e^{ik\xi} + \text{C. C.})$$

$$v_\zeta(\xi,\eta,\zeta,t) = \bar{W}(\eta) + w'(\xi,\eta,\zeta,t) + \frac{\varepsilon}{2}(\hat{w}(\eta)e^{ik\xi} + \text{C.C.}) \tag{7}$$

$$p(\xi,\eta,\zeta,t) = \bar{P}(\xi,\eta,\zeta) + p'(\xi,\eta,\zeta,t) + \frac{\varepsilon}{2}(\hat{p}(\eta)e^{ik\xi} + \text{C. C.})$$

By substituting these expressions into the equations of motion, time-averaging, and assuming a boundary layer flow, we obtain the boundary layer equations. These include both the conventional Reynolds stresses and wave-induced stresses due to the oscillatory component of the flow. Details about the two-dimensional problem, which is identical for the meanflow, is given in Reference 3. By subtracting the time-averaged equations from the phase-averaged equations and neglecting squares of the quantities that represent the oscillatory flow, we obtain the linear momentum equations. These equations can be written as an inhomogeneous Orr-Sommerfeld system. The system is of sixth order (as opposed to fourth order for the two-dimensional problem) as follows:

$$\frac{dz_i}{d\eta} = \sum_{j=1}^{6} A_{ij} Z_j + B_i \qquad i=1,6 \tag{8}$$

where

$$\begin{aligned} z_1 &= \hat{u} & z_5 &= \hat{w} \\ z_2 &= \frac{d\hat{u}}{d\eta} & z_6 &= \frac{d\hat{w}}{d\eta} \\ z_3 &= \hat{v} & & \\ z_4 &= \hat{p} & & \end{aligned} \tag{9}$$

The A_{ij} and the B_i are very lengthy expressions. The B_i terms are due to the curvature of the coordinate system. The system (8) is stiff and the special procedures used for solving Orr-Sommerfeld systems have been implemented.

The boundary conditions are as follows. The disturbance flow is bounded away from the wavy surface. At the wavy surface the velocity vector of the surface is equal to the fluid velocity vector at the surface. At the freestream the velocity is equal to the local freestream velocity.

4. Publications and Presentations

The following publications and presentations resulted from the work reported:

Publications

1. "Two-Dimensional Turbulent Boundary Layers Over Rigid and Moving Swept Wavy Surfaces," by T. K. Sengupta and S. G. Lekoudis, Abstract submitted to AIAA for a paper presentation at the 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference, June 1984.

Presentations

1. In FY '83 Compliant Coating Drag Reduction Program Review, at the NRL, October 24-26, 1983.

2. In the 36th Annual Meeting of the Division of Fluid Dynamics of the APS, at the University of Houston, November 20-22, 1983.

5. References

1. Zilker, D.P., Cook, G.W. and Hanratty, T.J., "Influence of the Amplitude of a Solid Wavy Wall on a Turbulent Flow, Part 1, Non-Separated Flows," J. Fluid Mechanics, Vol. 82, Part 1, pp. 29-51, 1977.

2. Zilker, D.P. and Hanratty, T.J., "Influence of the Amplitude of a Solid Wavy Wall on a Turbulent Flow, Part 2, Separated Flows", J. Fluid Mechanics, Vol. 90, Part 2, pp. 257-271, 1979.

3. T. Sengupta and S. G. Lekoudis, "Calculation of Turbulent Boundary Layers Over Moving Wavy Surfaces," AIAA Paper 83-1670.

4. Lin, J.C., Walsh, M.J., Watson, R.D. and Balasubramanian, R., "Turbulent Drag Characteristics of Small Amplitude Rigid Surface Waves," AIAA Paper 83-0228.

5. Kendall, J., "The Turbulent Boundary Layer Over a Wall with Progressive Surface Waves," J. Fluid Mechanics, Vol. 41, Part 2, pp. 259-281, 1970.

6. Thorsnees, C.B., Morriscoe, P.E. and Hanratty, T.J., "A Comparison of Linear Theory with Measurements of the Variation of Shear Stress Along a Solid Wave," Chemical Engineering Science, Vol. 33, pp. 579-592, 1978.

7. McLean, J.W., "Computation of Turbulent Flow Over a Moving Wavy Boundary," Physics of Fluids, Vol. 26 (8), pp. 2065-2073, 1983.

8. Balasubramanian, R. and Orszag, S., "Numerical Studies of Laminar and Turbulent Drag Reductions," NASA CR 3498, 1981.

9. Hsu, C.T., Hsu, E.Y. and Street, R. L., "On the Structure of Turbulent Flow Over a Progressive Water Wave: Theory and Experiment in a Transformed, Wave-Following Coordinate System," J. Fluid Mechanics, Vol. 105, pp. 87-117, 1981.

10. Hsu, C.T. and Hsu, E.Y., "On the Structure of Turbulent Flow Over Progressive Water Wave: Theory and Experiment in a Transformed Wave Following Coordinate System. Part 2," J. Fluid Mechanics, Vol. 137, pp. 123-153, 1983.

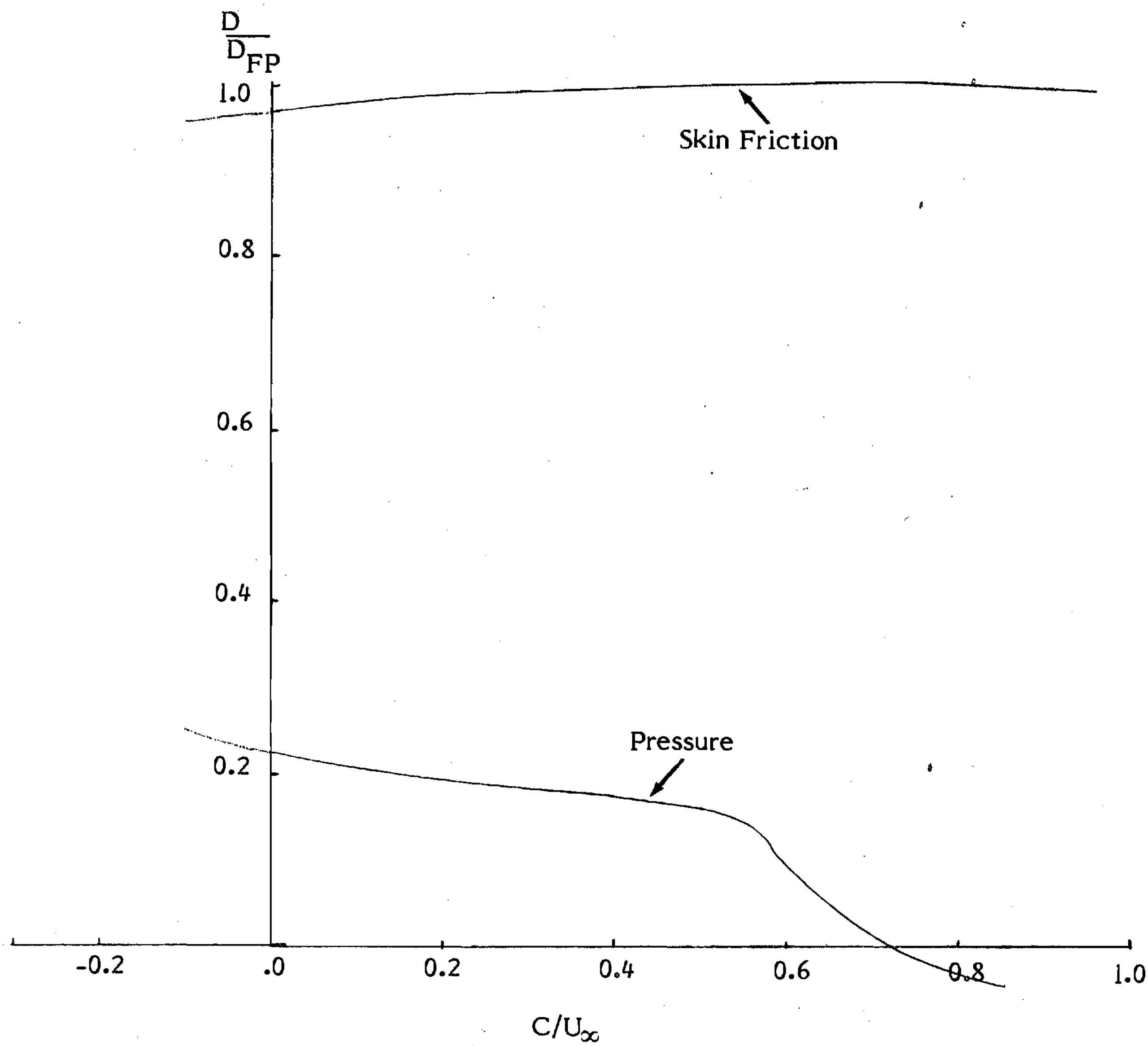


Figure 1. Ratios of drag/drag of flat plate for a surface executing water wave motion.

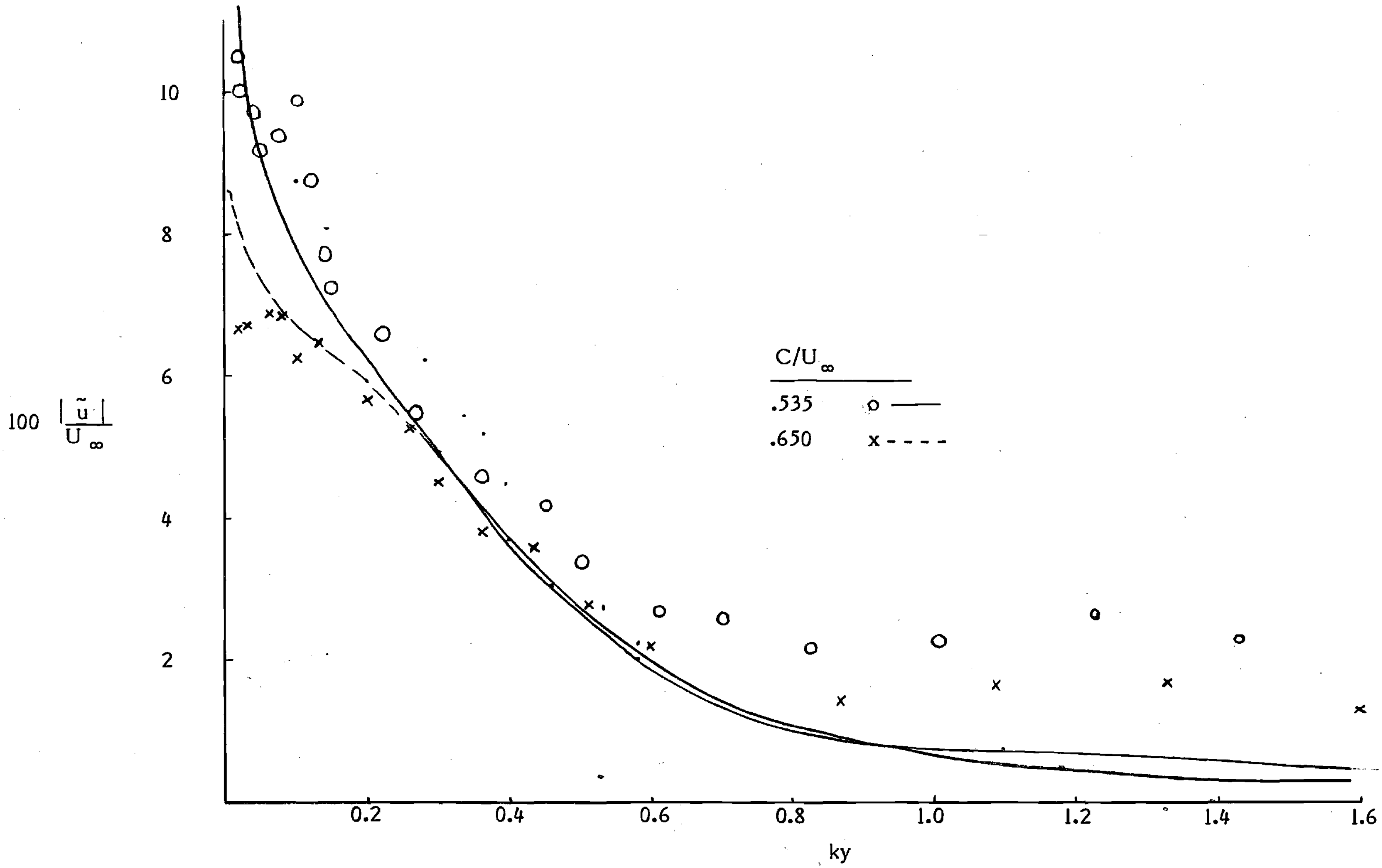


Figure 2. Comparison of Calculations and Measurements (the symbols indicate measurements)

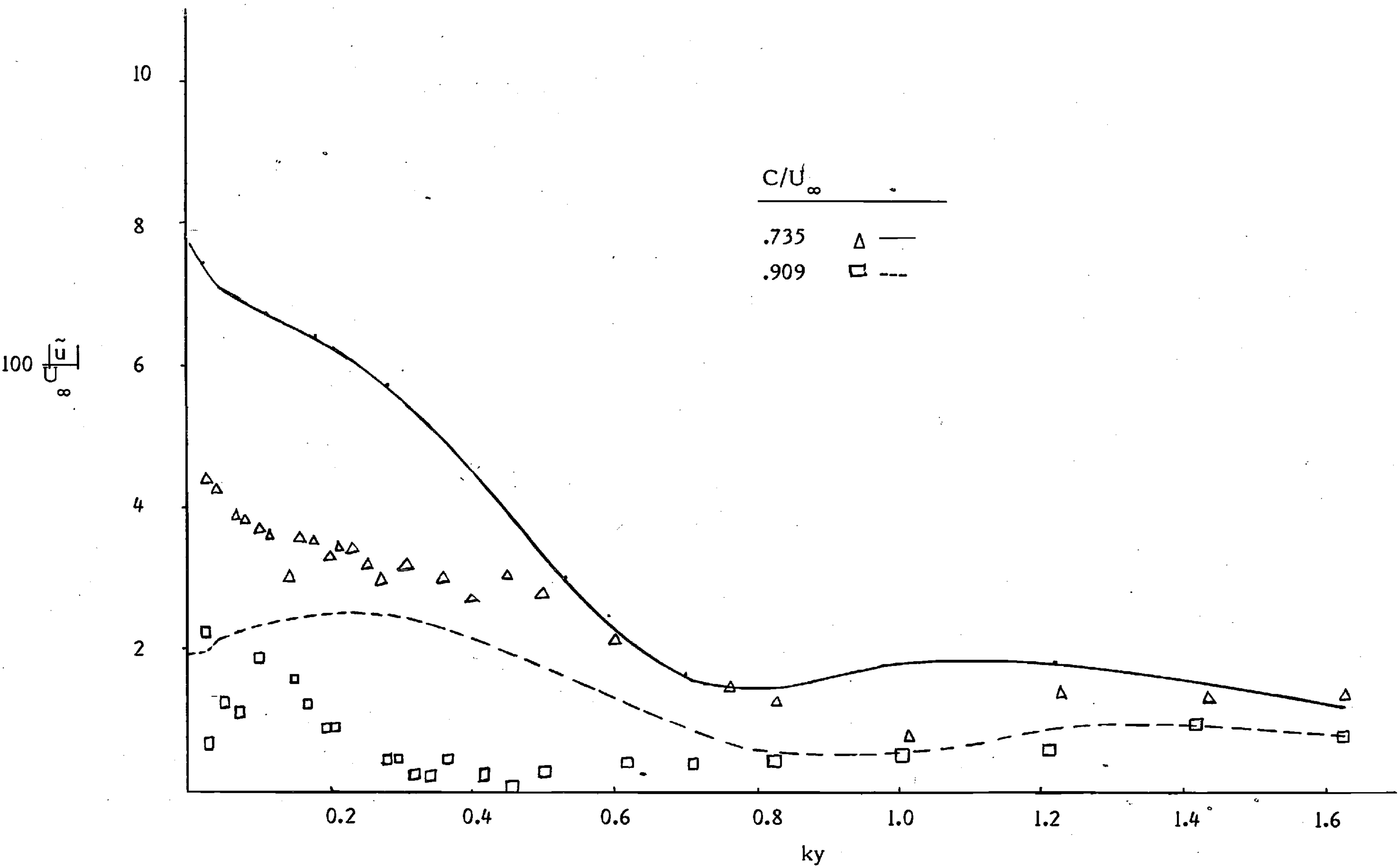
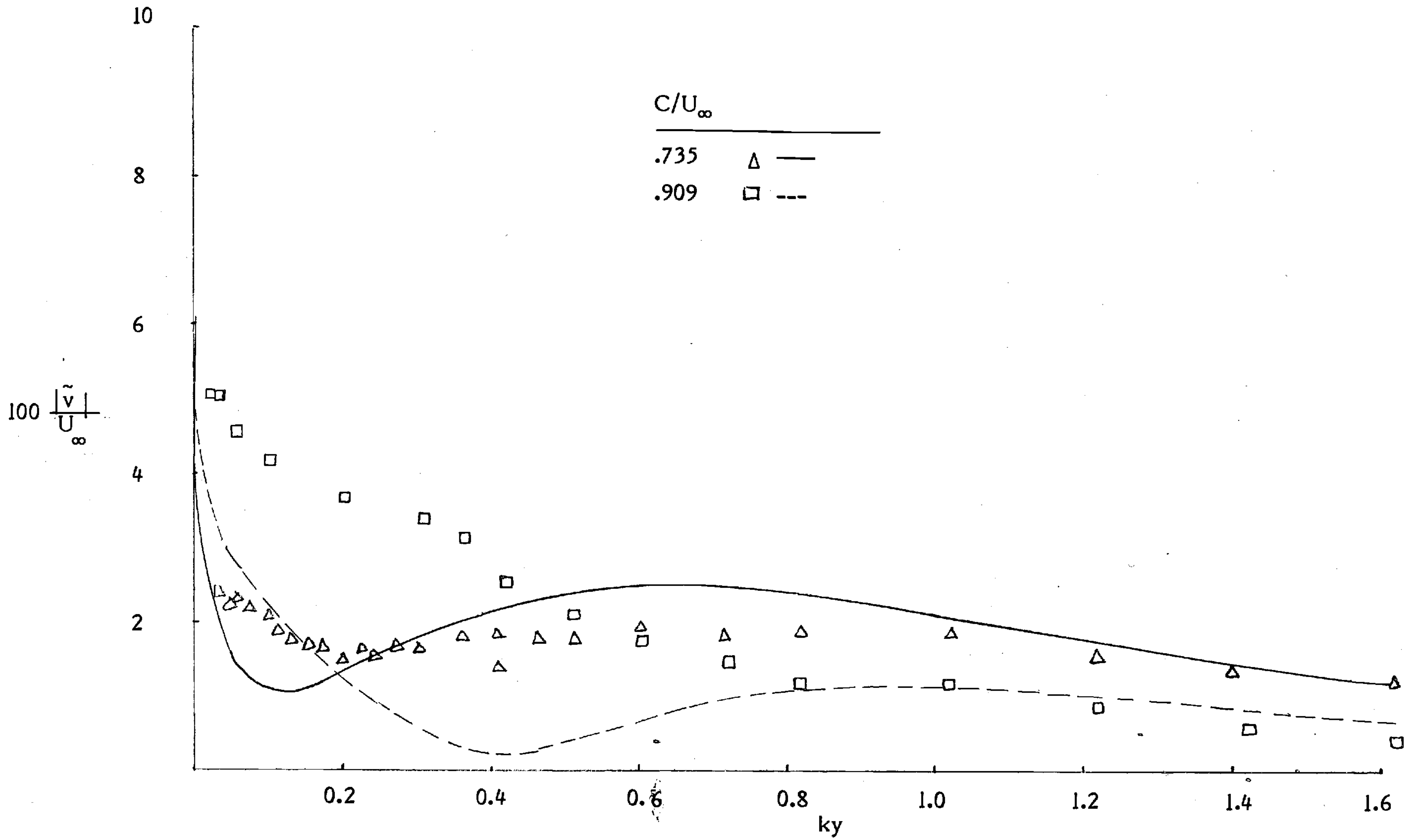


Figure 3. Comparison of Calculations and Measurements (the symbols indicate measurements)



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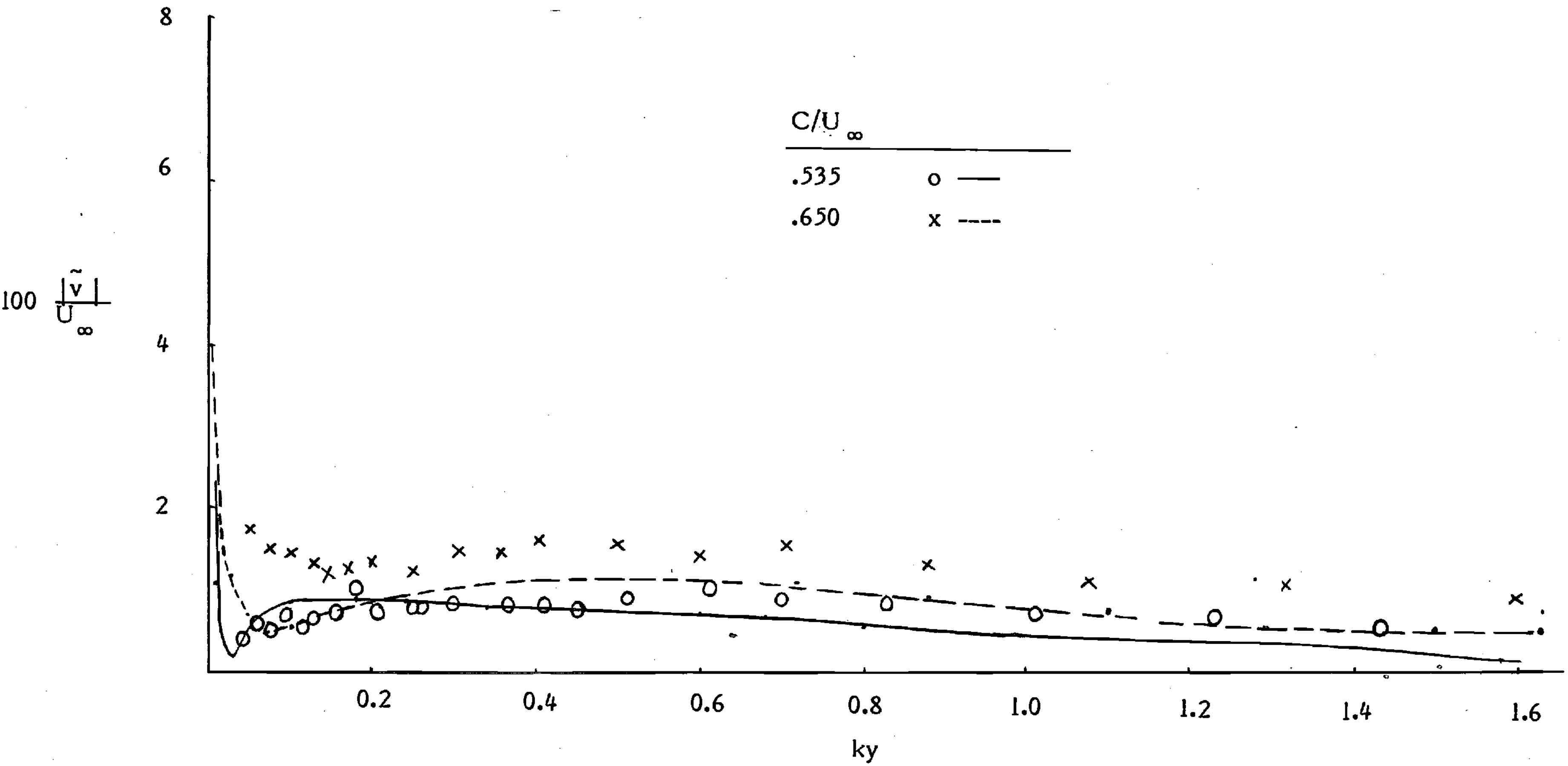

Figure 5. Comparison of Calculations and Measurements (the symbols indicate measurements)

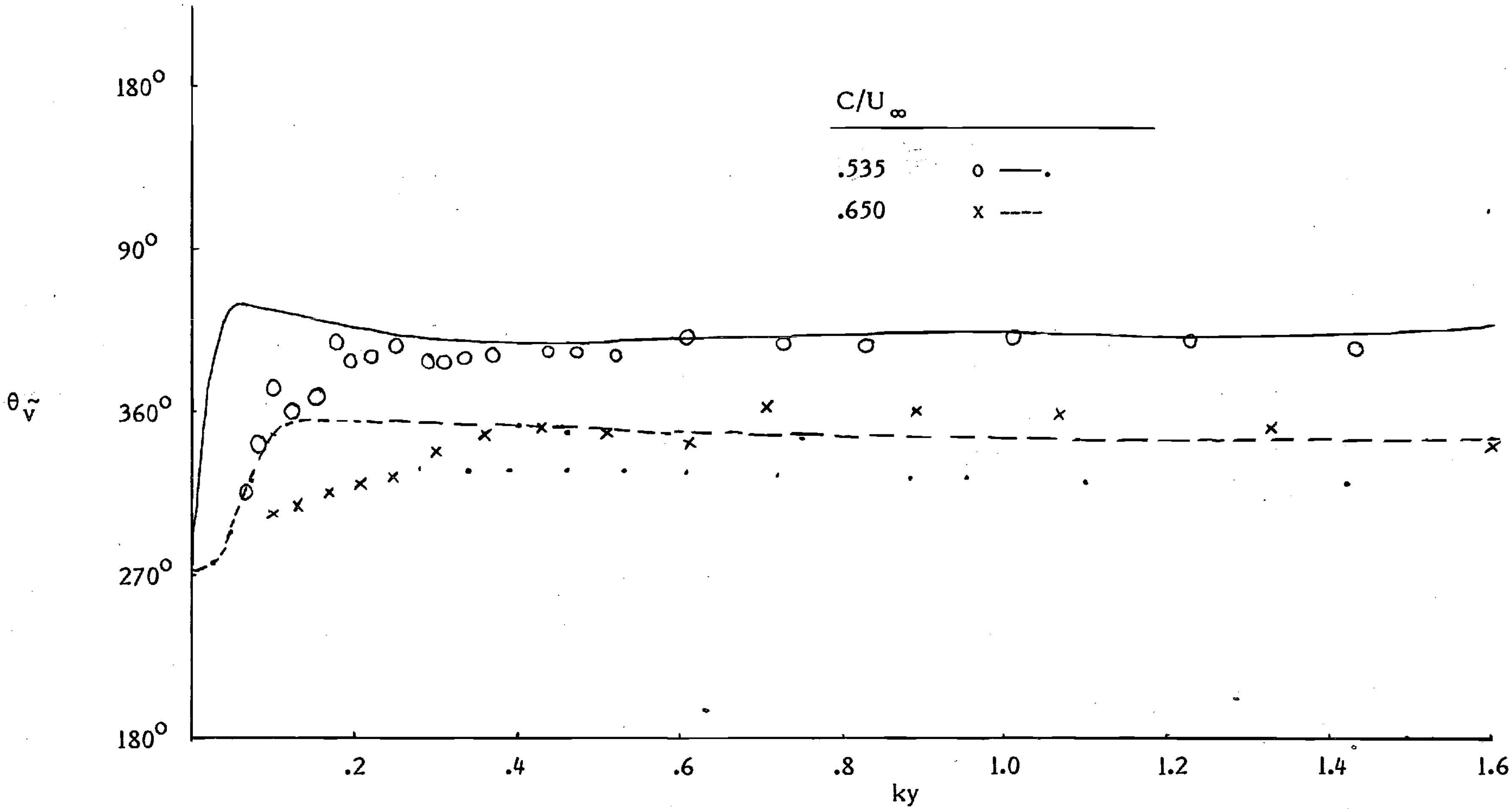

Figure 6. Comparison of Calculations and Measurements (the symbols indicate measurements)

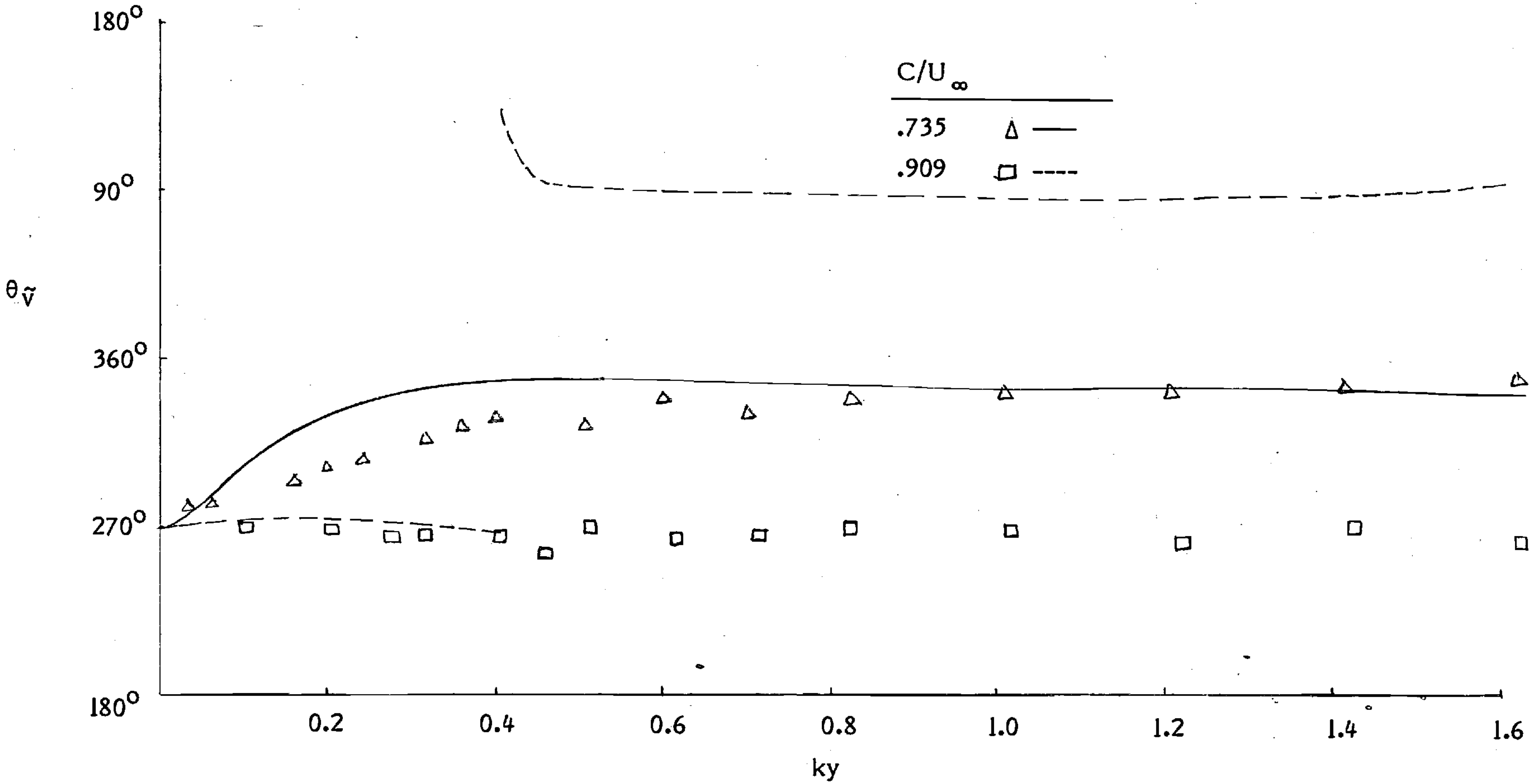

Figure 7. Comparison of Calculations and Measurements (the symbols indicate measurements)

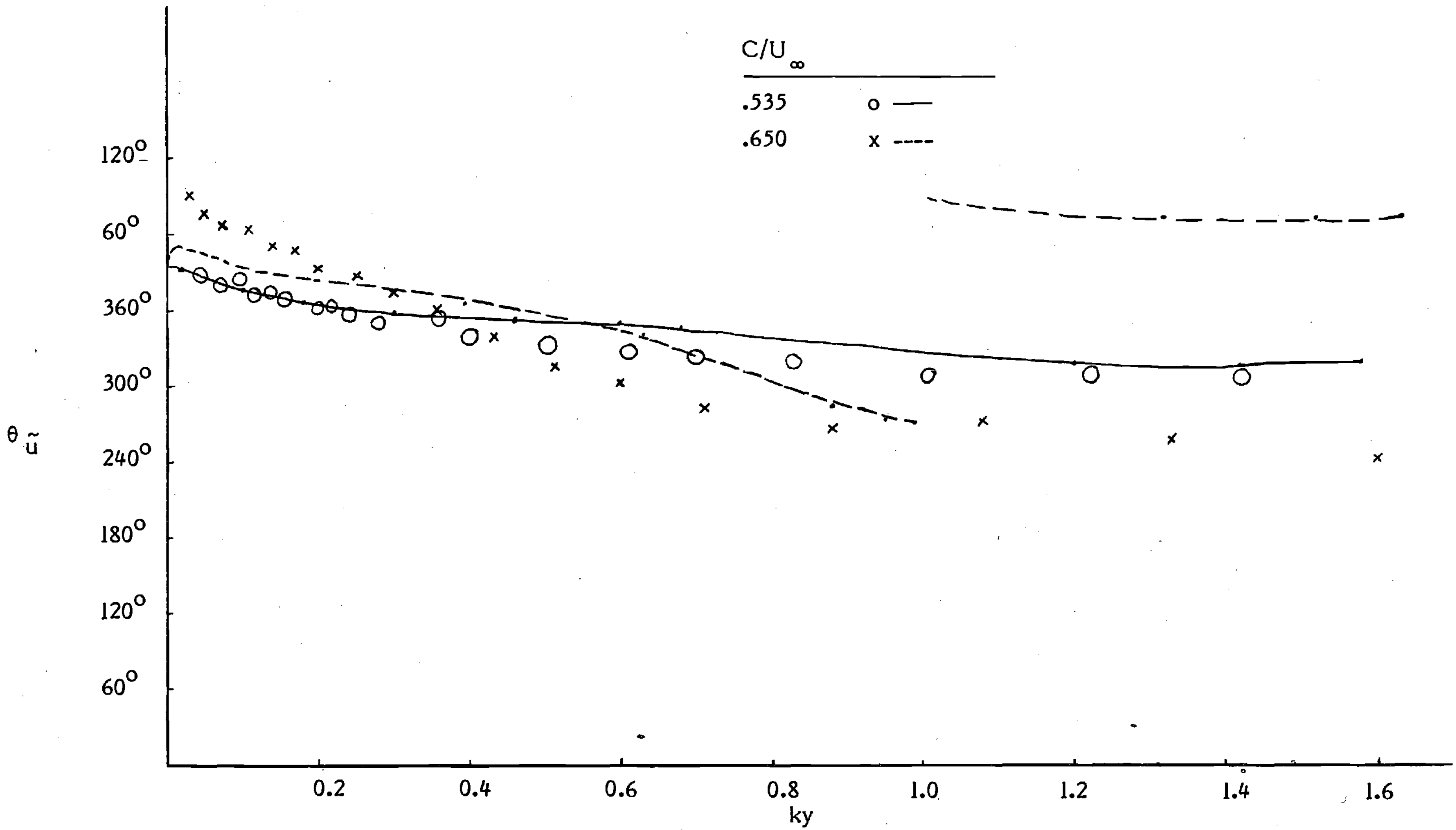

Figure 8. Comparison of Calculations and Measurements (the symbols indicate measurements)

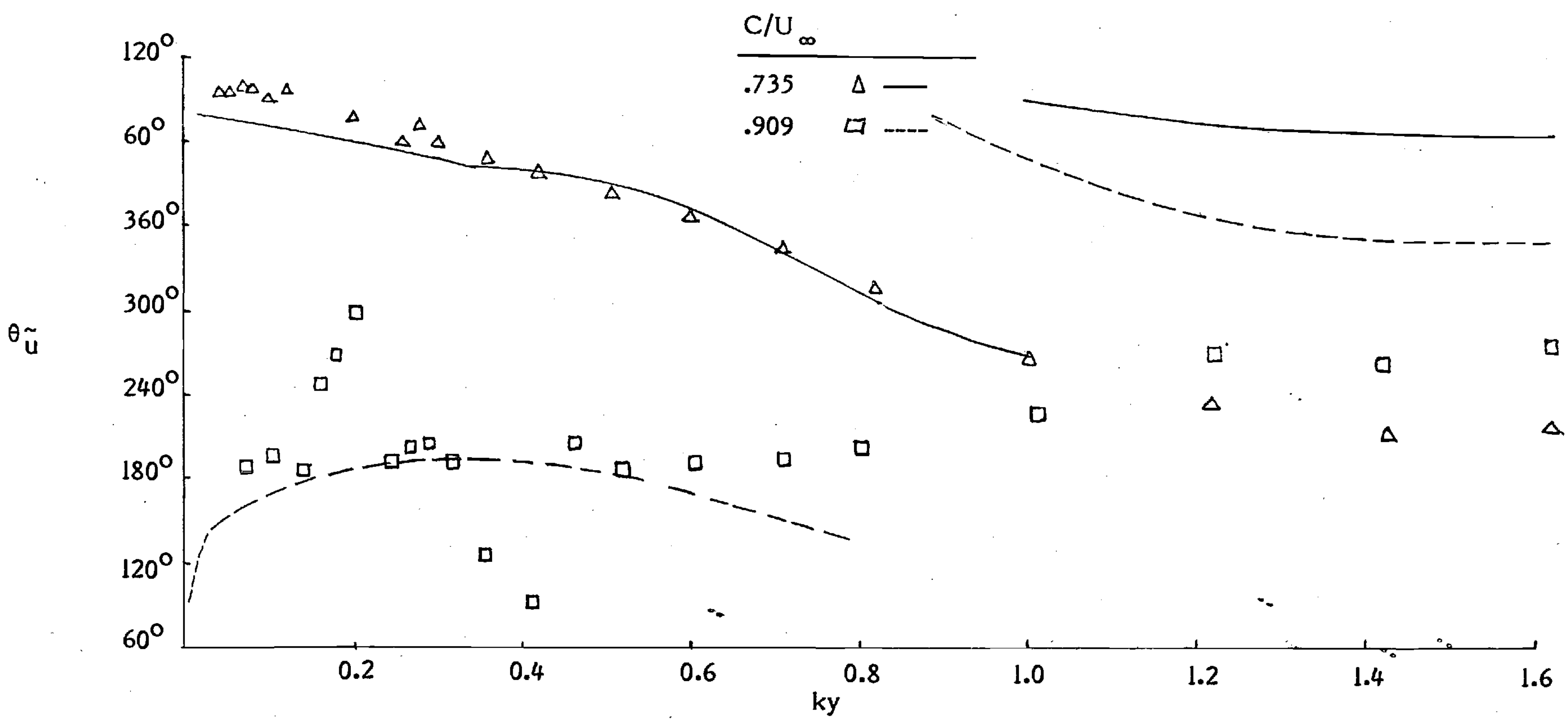

Figure 9. Comparison of Calculations and Measurements (the symbols indicate measurements)

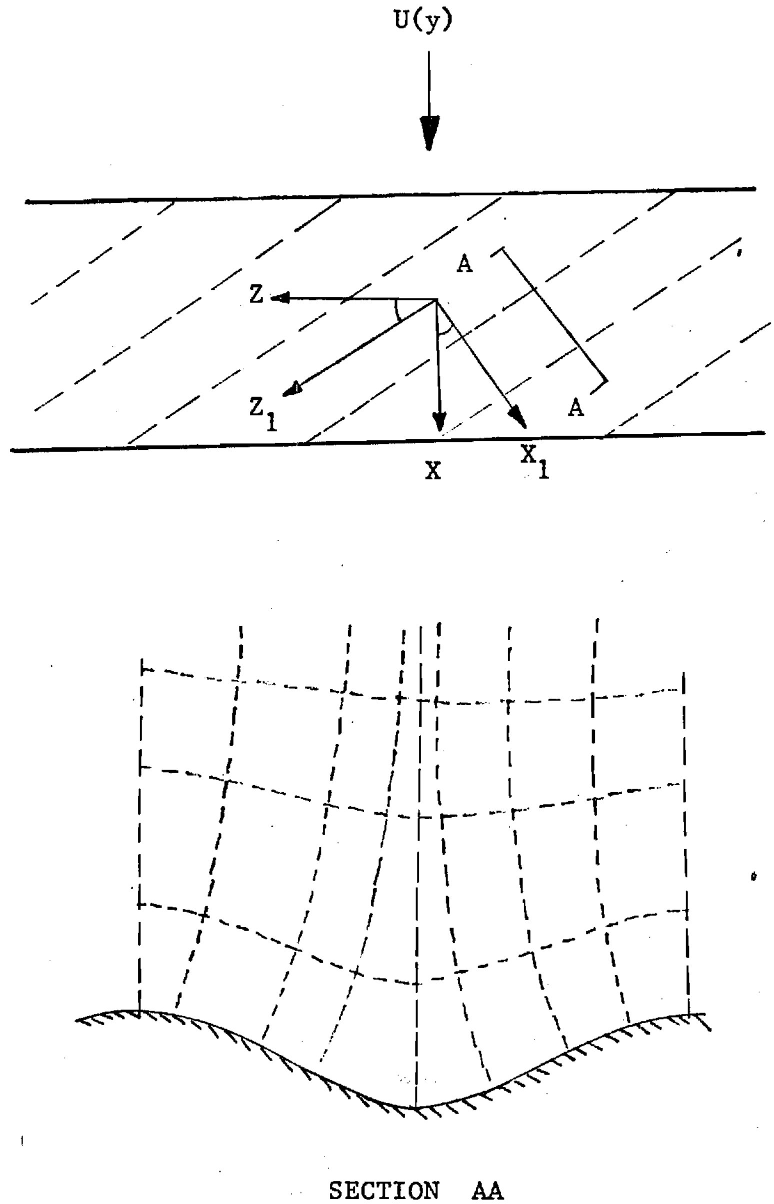

Figure 10. Coordinate System

FINAL REPORT

on Contract N00014-83-K-0418

TURBULENT BOUNDARY LAYERS DEVELOPING OVER COMPLIANT SURFACES

by

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for

The Office of Naval Research
Compliant Coating Drag Reduction Program

July 1984

SUMMARY

This report summarizes work done under the ONR Contract N00014-K-0418 to Georgia Tech, between May 15, 1983 and May 15, 1984. The objective of the research was to develop prediction methods for high Reynolds number turbulent flows over compliant surfaces.

Neep Hazarika, Tapan Sengupta and Spiro Lekoudis were involved in this project. Tapan Sengupta graduated with a Ph.D. in June 1984. Neep Hazarika is a candidate for an M.S. degree in Aerospace Engineering.

The flow examined is the two-dimensional turbulent boundary layer over sinusoidal wavy surfaces. The surfaces executed prescribed motion, that of a progressive water-wave. The main conclusions are as follows. The pressure dominates the small skin friction reduction that occurs. At wavespeeds about 7/10 times the freestream speed and higher, the pressure becomes thrust producing for the case of two-dimensional waves. When the waves are swept, the pressure becomes thrust producing as wavespeeds approach the component of the freestream in the direction normal to the wavefront. Therefore the larger the sweep, the smaller the wavespeeds at which the pressure produces thrust.

Because of lack of flexible wall experiments, with well defined motion of the sinusoidal wall and high wavespeeds, comparisons were made with water-wave experiments. Reasonable agreement was obtained for measured quantities <u>inside</u> the boundary layer.

It was estimated that the drag reduction, for the cases considered, is small. The limited comparison with available experiments indicates that the computed trends in the physical quantities are correct. Computations using other approaches and pressure measurements on wavy walls with well defined motion are needed, in order to examine if the turbulence model used in this study is adequate for detailed

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quantitative predictions. This is especially true given the small values of drag reduction computed in the present study. Based on the results of this study, a practical working system with a drag reducing surface with progressive waves does not seem feasible. However this conclusion is restricted to the cases of wall shapes and motions considered.

1. INTRODUCTION

Predictions of the high Reynolds number turbulent flow over compliant surfaces are necessary for estimating drag. They are also important in deciding on what shapes of surfaces and what kinds of surface motions should be examined in an experiment. Because direct simulation is impossible at the interesting Reynolds numbers, either conventional time-averaging or large-eddy simulations are the available tools. Conventional averaging is used in the present study with the following objectives. Predict surface quantities, like skin friction and pressure, for sinusoidal surface waves with prescribed motion; compare with measured data; and, finally, estimate the drag values for such surfaces. Some of the relevant work is described briefly in the next paragraph.

Small disturbance solutions of the Navier-Stokes equations vary because of the different approximations used (References 1-3). However, for wavy walls with amplitudes that do not cause local flow separation, the pressure drag can be predicted very accurately. Considering the close to zero truncation errors and the relatively small computer resources required for such solutions, it seems that if the (nonlinear) skin friction effects could be somehow computed, these solutions could become attractive. The next step is to use time-averaged Navier-Stokes solutions. Because of resolution requirements (things are happening very close to the surface) such solutions usually employ periodic boundary conditions in the streamwise direction (References 4-5). Therefore, streamwise pressure gradient effects are difficult to estimate, even if the Reynolds number is high.

A compromise between these two approaches has been developed and tested under a previous contract from ONR (N00014-82-K-0271) by the author. It consists of evaluating a steady-streaming effect on the mean shear. Drag values are in excellent agreement with recent measured data on rigid wavy walls

(Reference 6). However the range of applicability of the method is restricted to wave amplitudes that do not cause local flow separation. The scheme consists of solving the boundary layer equations with wave-induced stresses. These stresses are evaluated from the solution of the linear problem. Details about the formulation and the numerics are in Reference 6 and in Publication 3, 4 and 5.

The calculation procedure described has been applied to the problem of two-dimensional turbulent boundary layer flow over wavy surfaces in motion. Pure wall translation was not examined because it is rather impractical to implement. Progressive sinusoidal surface waves were investigated, with their wavefronts normal to the freestream direction (two-dimensional problem), or at a prescribed sweep angle (three-dimensional problem). The results from this investigation are described in the next sections of this report.

2. THE ANALYTICAL FORMULATION

Because a detailed description of the formulation and the numerics used can be found in References 6 and in Publications 3, 4 and 5, only a brief description of the procedure will follow. The description will be for the case of swept waves, because solutions of the two-dimensional problem can be obtained by approaching the case of zero sweep. This was also used to check the numerical procedures.

The coordinate system used consists of the streamlines and the isopotential lines of the irrotational flow normal to the direction of the wavefront. The third coordinate is parallel to the wavefront. Thus coordinate singularities are avoided and the freestream boundary conditions are appropriately applied. Moreover there is not transfer of boundary conditions to the mean interface, a very serious source of error for all but the smallest wave amplitudes.

Classical triple decomposition of all flow variables into a time-averaged part, a random part and an organized oscillation part is used. The time-averaged part is described as a boundary layer flow with wave-induced stresses that result from the organized oscillation. The organized oscillation part is obtained from the solution of the linear momentum equations. Conventional models are used for the random part which affects both the solution of the boundary layer part and the part due to the organized oscillation.

The linear problem for the case of sweep can be reduced to a two-dimensional problem by essentially using Squire's theorem. However the evalution of the wave-induced stresses requires the flow component parallel to the wavefront. Therefore a sixth order system of the Orr-Sommerfeld type has to be solved iteratively with the boundary layer flow. Convergence is rapid, primarily because the effect of the wave-induced stresses is confined to an area very close to the wall.

The following checks were made in order to evaluate the numerics. The linear two-dimensional solutions were compared with Benjamin's results (Reference 1) and more complete linear solutions (Reference 2). In both cases good agreement was obtained (Publication 4). Moreover the results from the code that handles the swept wave case approached the results for the two-dimensional case as the sweep approached zero.

3. RESULTS AND DISCUSSION

As mentioned in the Introduction, the two-dimensional problem for rigid wavy walls has been examined under a previous contract. Excellent agreement with recent experiments was obtained (Reference 6).

The most important result obtained for the case of moving walls is shown in Figure 1. The wall motion simulates the surface motion of a deep water wave. The Figure shows that the location of the maximum pressure moves towards the crest at the low phase speeds, and the trend is reversed at higher phase speeds. This reversal makes the pressure thrust producing, when the pressure maximum crosses the trough. The trend is in agreement with Kendall's measurements (Reference 7). However the measurements were done for phase speeds up to half of the freestream only. Thus, because of lack of experimental data on solid surfaces, comparisons were made with water wave experiments.

Pressure measurements close to the surface of a water-wave underneath a turbulent air boundary layer are presented in Reference 8. The variation of the pressure coefficient and the location of the maximum pressure are shown in Figures 2 and 3. The trends are the same as predicted in Figure 1. However direct comparison is meaningless because:

(a) There is a mean drift value of the water surface because of the mean wind shear. This value has to be estimated.

(b) The upper wall of the channel is close enough to affect the surface pressure distributions

(c) A reflected wave is present. Its amplitude is estimated at 6% of the incident (Reference 8). However, because it travels upstream, it generates large pressure variations.

The pressure dominated the mean shear reduction throughout the range of phase speeds and wall amplitudes considered. Both the amplitude and phase of the oscillating shear agrees with the measured trends in Kendall's data. However its contribution to drag is negligible. Direct comparison with Kendall's measurements was not possible because the solution indicated flow separation.

In an effort to access the computed solutions, the amplitude and phase of the computed velocities was compared with measurements inside the turbulent boundary layer. The measurements are described in References 9 and 10. Sample results are shown in Figures 4 and 5. The agreement is good at low phase speeds and becomes progressively worst at the higher phase speeds.

Drag values for a wavetrain are shown in Figure 6. Drag reduction seems possible only at the high phase speeds. However the benefit seems to be small. Notice that these calculations assume that the wall motion is a prescribed travelling wave. No equivalent drag values are estimated, for providing the energy for the wall motion.

The case of swept waves was also investigated. The linear theory for this case degenerates to the two-dimensional problem. Therefore the computational results shown in Figures 7 and 8 are reminiscent of the two-dimensional solutions. When the wave speeds approach the value of the component of the freestream normal to the wavefront, the phase of the pressure varies rapidly and the pressure produces thrust. Therefore the higher the sweep, the smaller the phase speeds at which this occurs. The solutions of the nonlinear problem are shown in Figures 9 and 10. The total reduction in drag is rather small.

Details about the results can be found in the Publications 3, 4 and 5.

4. CONCLUSIONS AND RECOMMENDATIONS

A method for computing turbulent boundary layers over rigid and moving swept wavy surfaces was developed. Comparisons were made with available experimental results. It is concluded that the predicted drag reduction is small and it occurs at wave speeds approaching the freestream speed velocity component normal to the wavefront. This conclusion is restricted to the cases considered. The following recommendations are made:

1. Because conventional modelling was used for closure, other numerical approaches have to be attempted. However the other approaches have to demonstrate equally good or better agreement with measurements than the one presented here. Pressure measurements are not enough for accessing turbulence models. Detailed shear distributions have to be measured and predicted before the validity of conventional turbulence modeling is established, especially for high wavespeeds.

2. Detailed pressure and shear measurements on wavy surfaces with well control motion are needed. Kendall's data were obtained over a decade ago. Unfortunately the water-wave experiments contain uncertainties that do not allow definitive evaluation of the turbulence models. However they support the predictions of the analysis developed. Because the estimated drag reductions are small, qualitative agreement with measurements is not adequate and direct quantitative comparisons are needed.

5. PUBLICATIONS AND PRESENTATIONS

The following publications and presentations resulted from the work supported by this contract.

1. Presentation at the FY'83 Compliant Coating Drag Reduction Program Review at NRL, October 24-26, 1983.

2. Presentation at the 36th Annual Meeting of the Fluid Dynamics Division of the American Physical Society, University of Houston, November 20, 1983.

3. "Two-Dimensional Turbulent Boundary Layers Over Rigid and Moving Swept Wavy Surfaces," by T. K. Sengupta and S. G. Lekoudis, AIAA Paper 84-1530, presented at the AIAA 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Snowmass, Colorado, June 25-27, 1984 (It was submitted for publication in the AIAA Journal).

4. "Calculation of Two-Dimensional Incompressible Turbulent Boundary Layers Over Rigid and Moving Sinusoidal Wavy Surfaces," by T. K. Sengupta and S. G. Lekoudis. Scheduled to appear in the AIAA Journal in February 1985.

5. "Turbulent Boundary Layers Over Rigid and Moving Wavy Surfaces," by T. K. Sengupta, Ph.D. Dissertation, School of Aerospace Engineering, Georgia Institute of Technology, June 1984.

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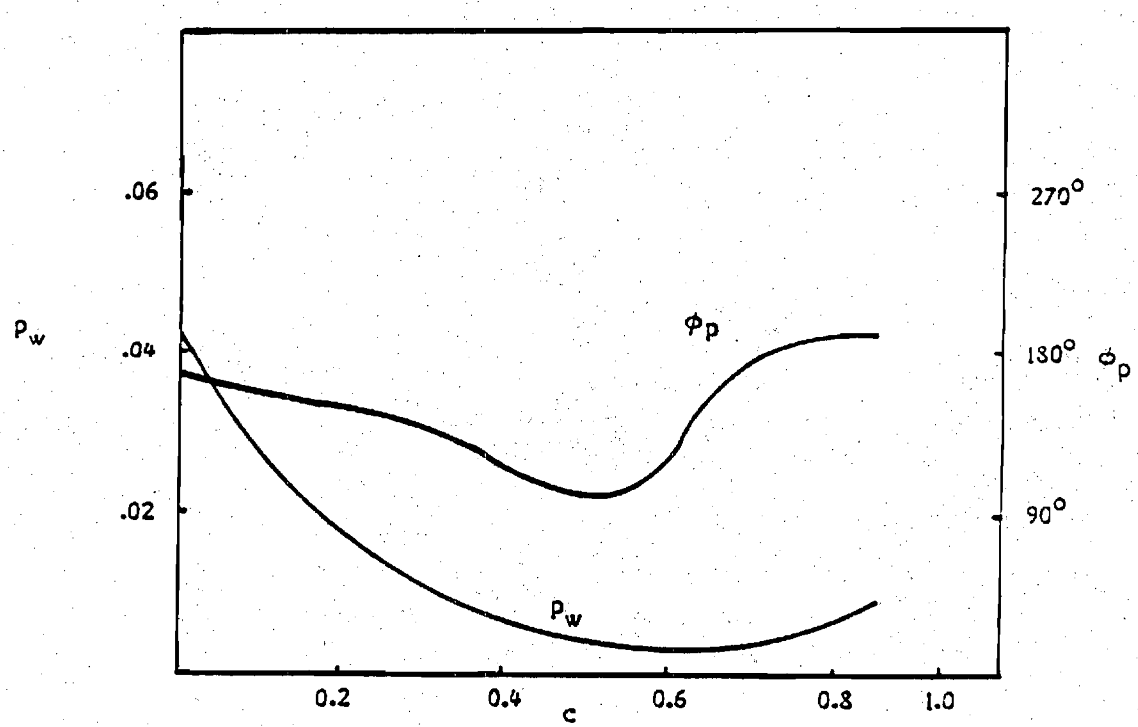

Figure 1. The amplitude of the pressure oscillation and the location of the maximum pressure (degrees upstream of the crest) versus the phase speed.

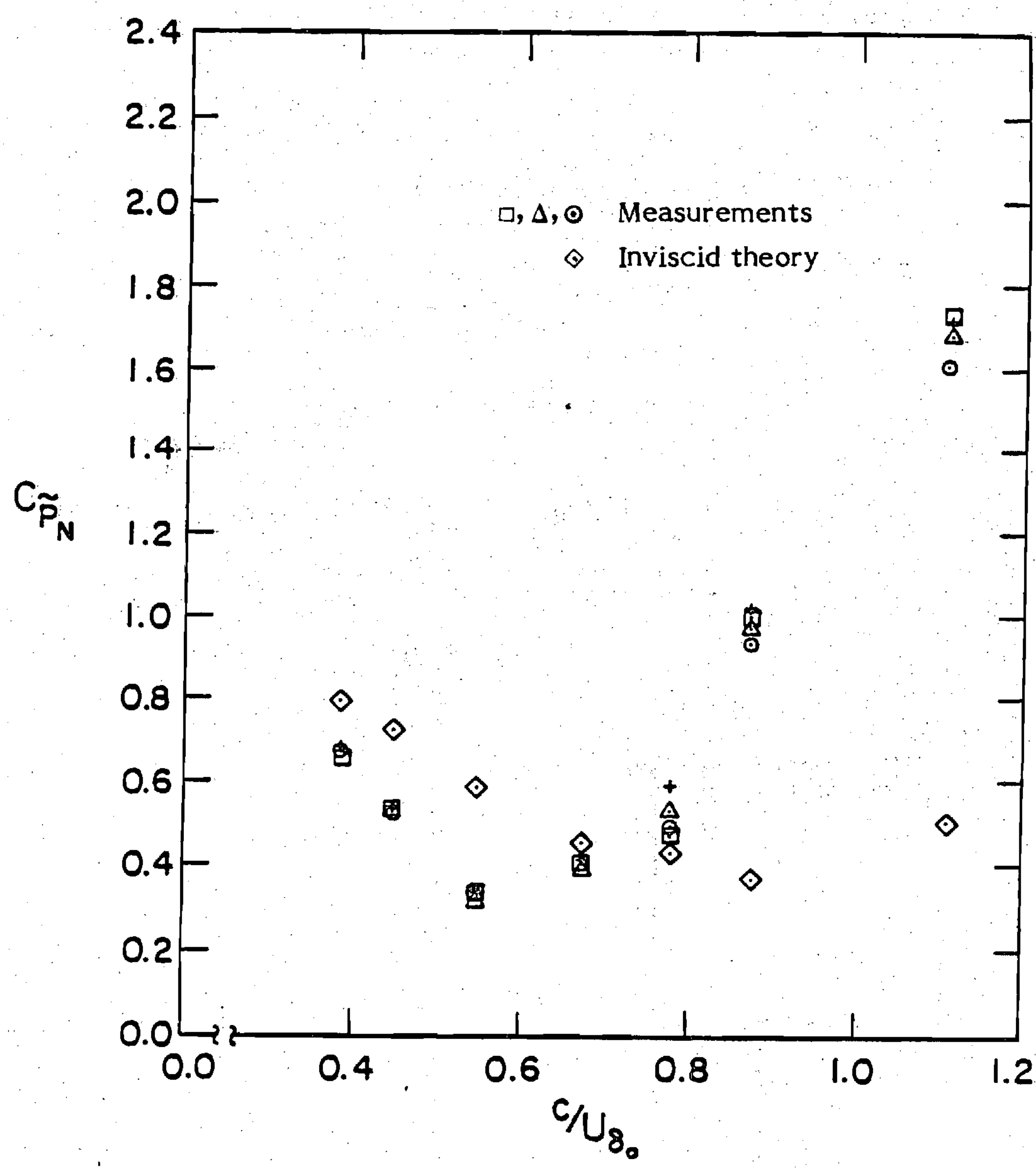

Figure 2. The variation of the pressure coefficient with the phase speed, close to the surface of a water-wave (from Reference 8).

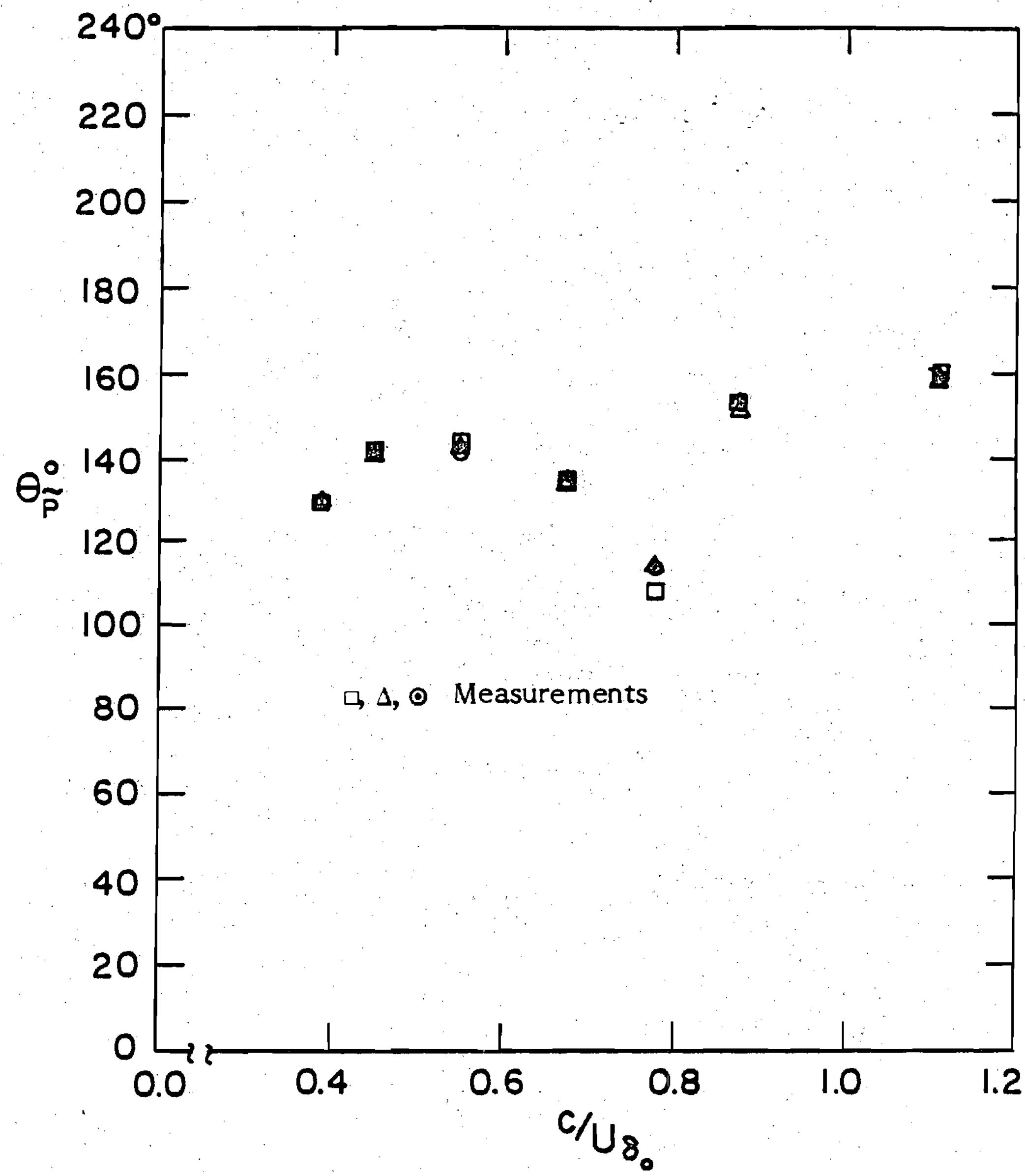

Figure 3. The location of the maximum pressure, in degrees upstream of the crest, for the case of the water-wave (from Reference 8).

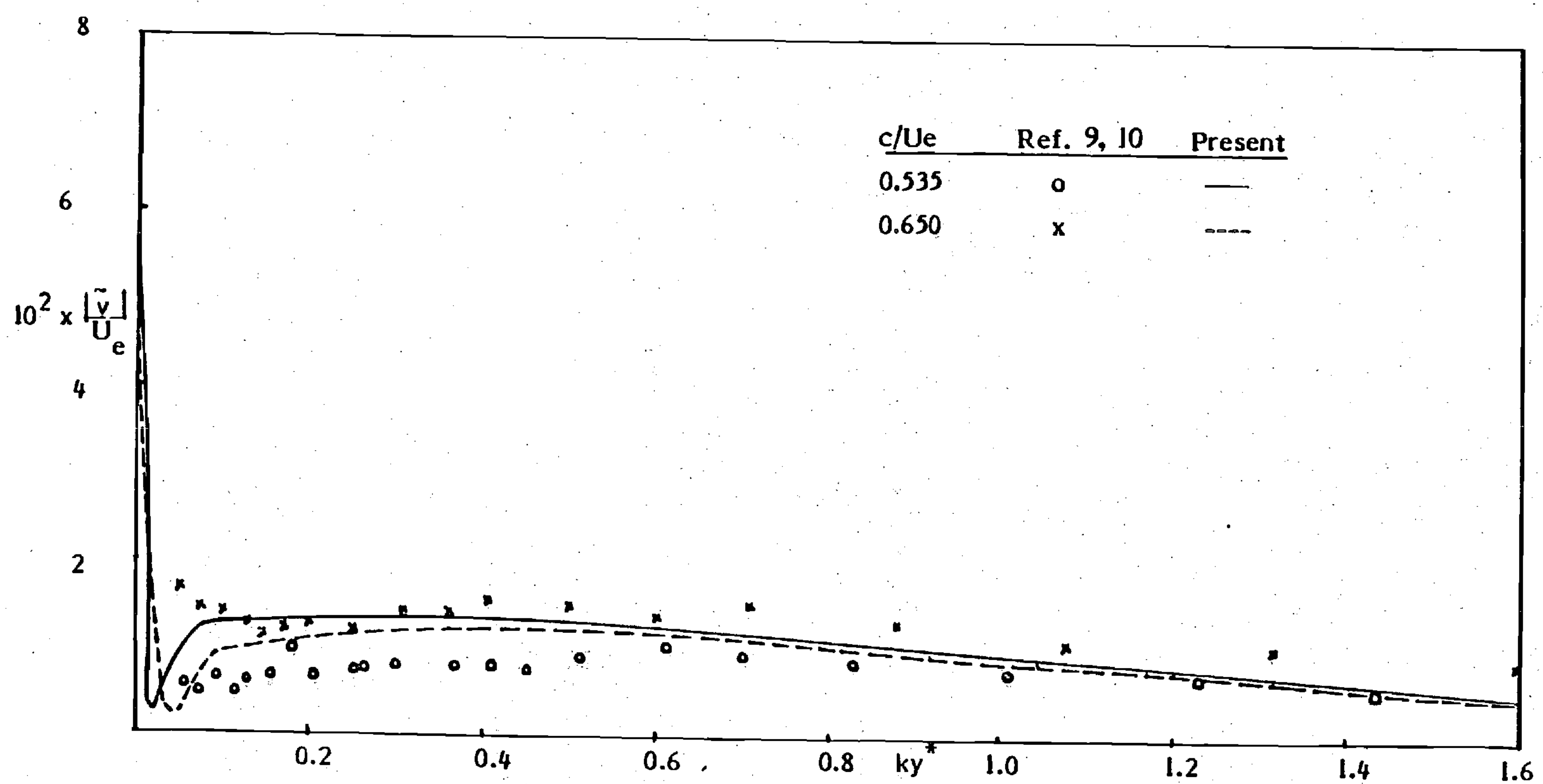

Figure 4. Comparison of calculation and measurement for normal velocity perturbation across the boundary layer.

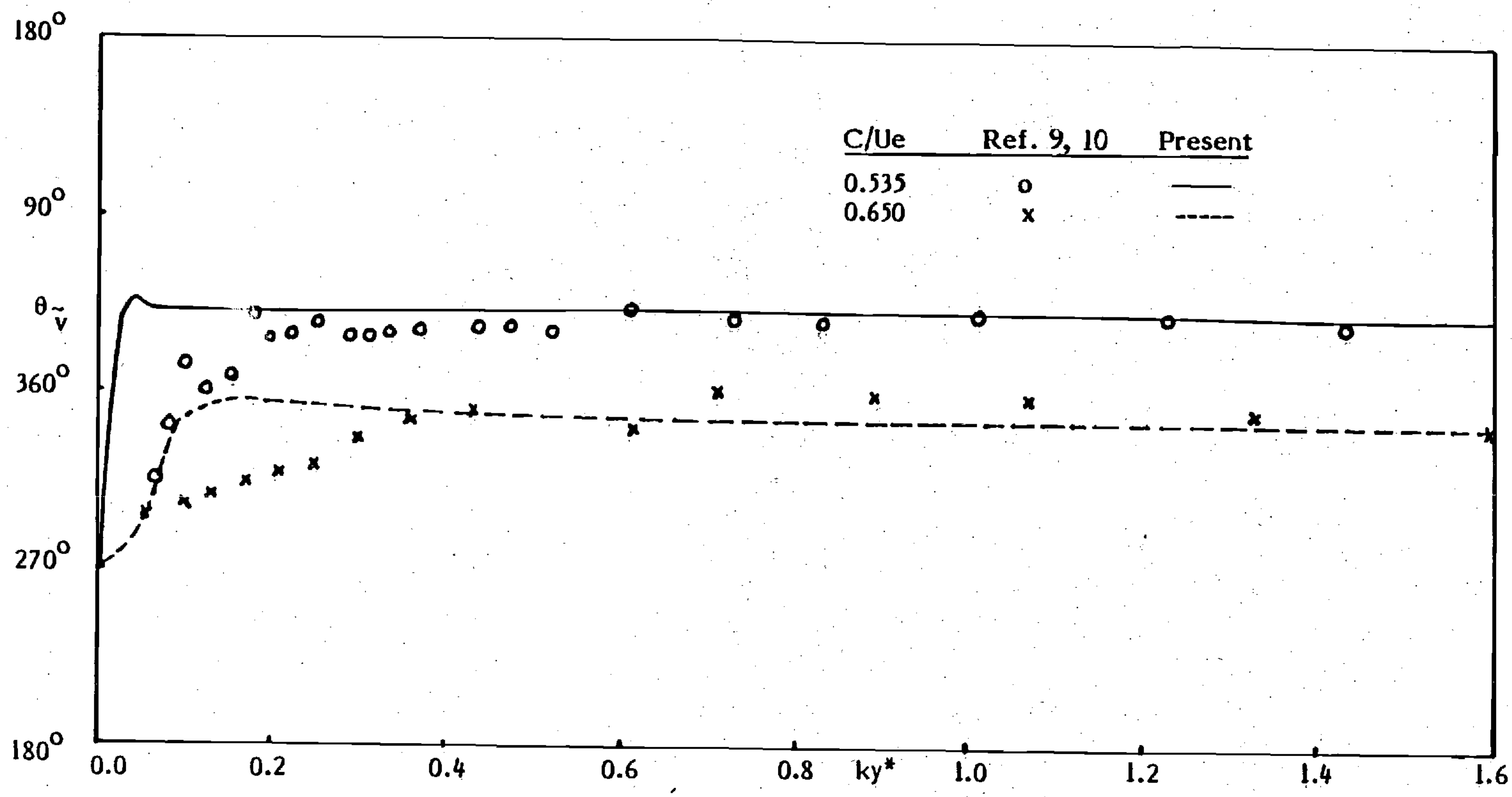

Figure 5. Comparison for calculation and measurement of the phase of normal velocity across the boundary layer.

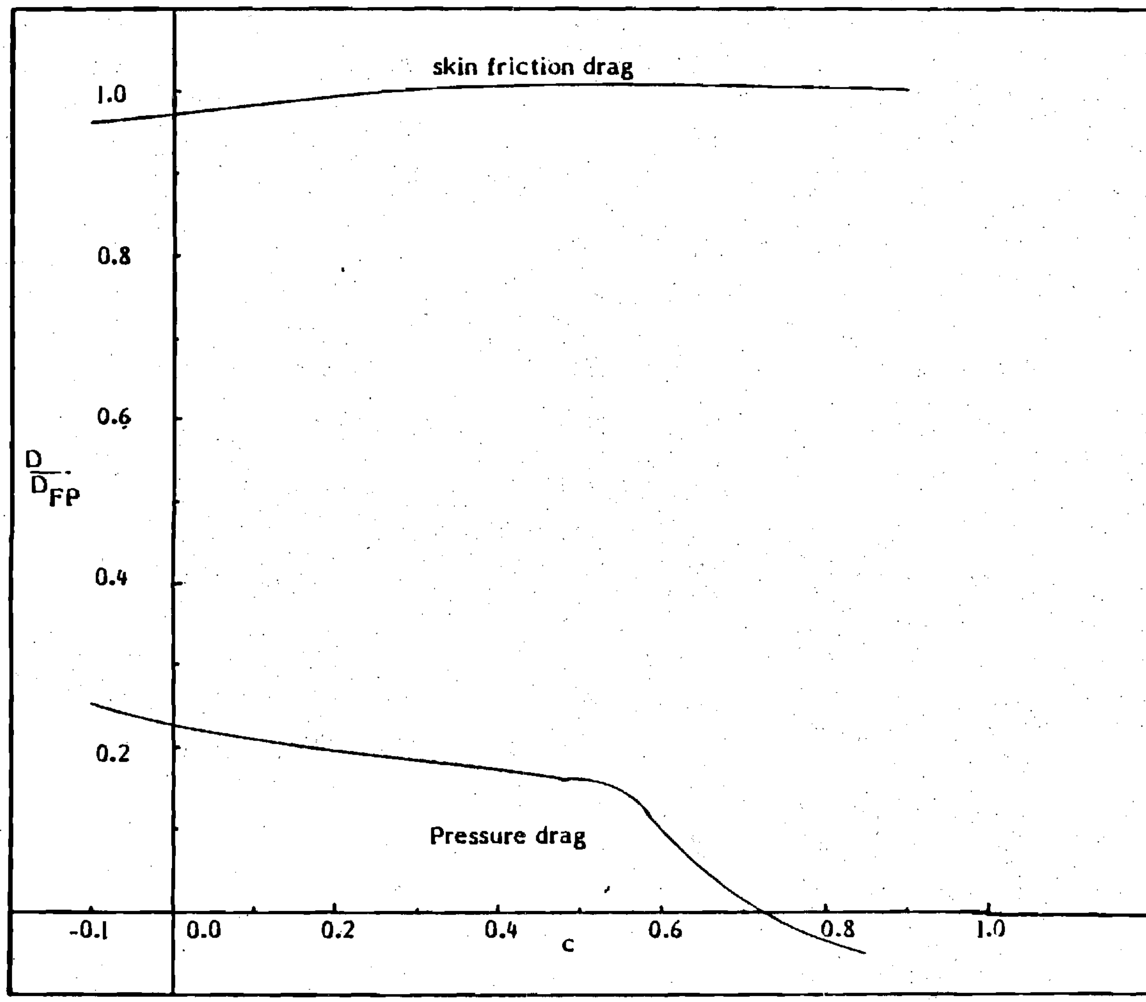

Figure 6. Pressure drag and skin friction drag for various phase speeds for a series of two-dimensional waves.

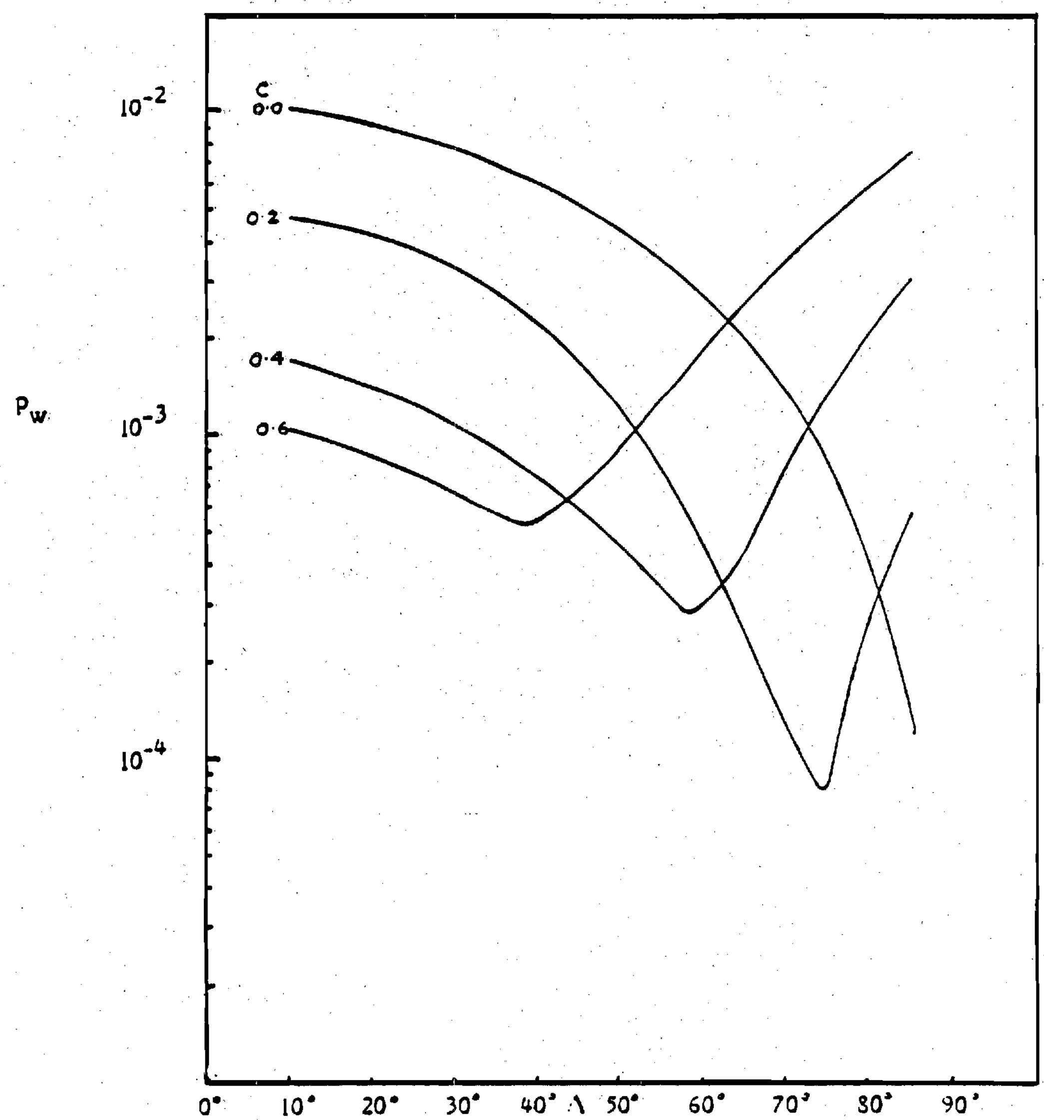

Figure 7. Typical variation of the pressure amplitude at the wall versus sweep angle for turbulent flow.

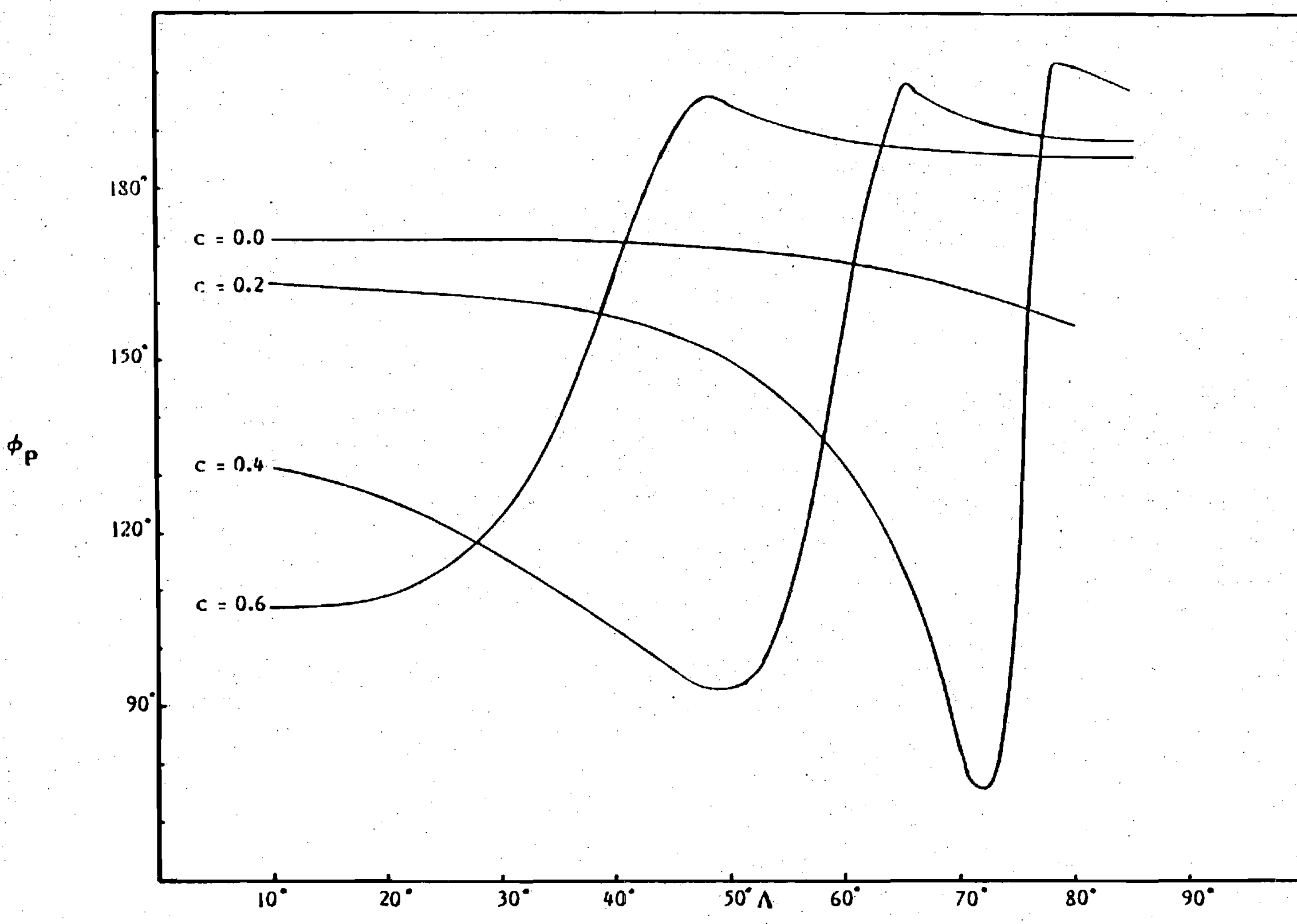

Figure 8. Typical variation of the phase of pressure versus sweep angle for various phase speeds for turbulent flow over a wavy wall.

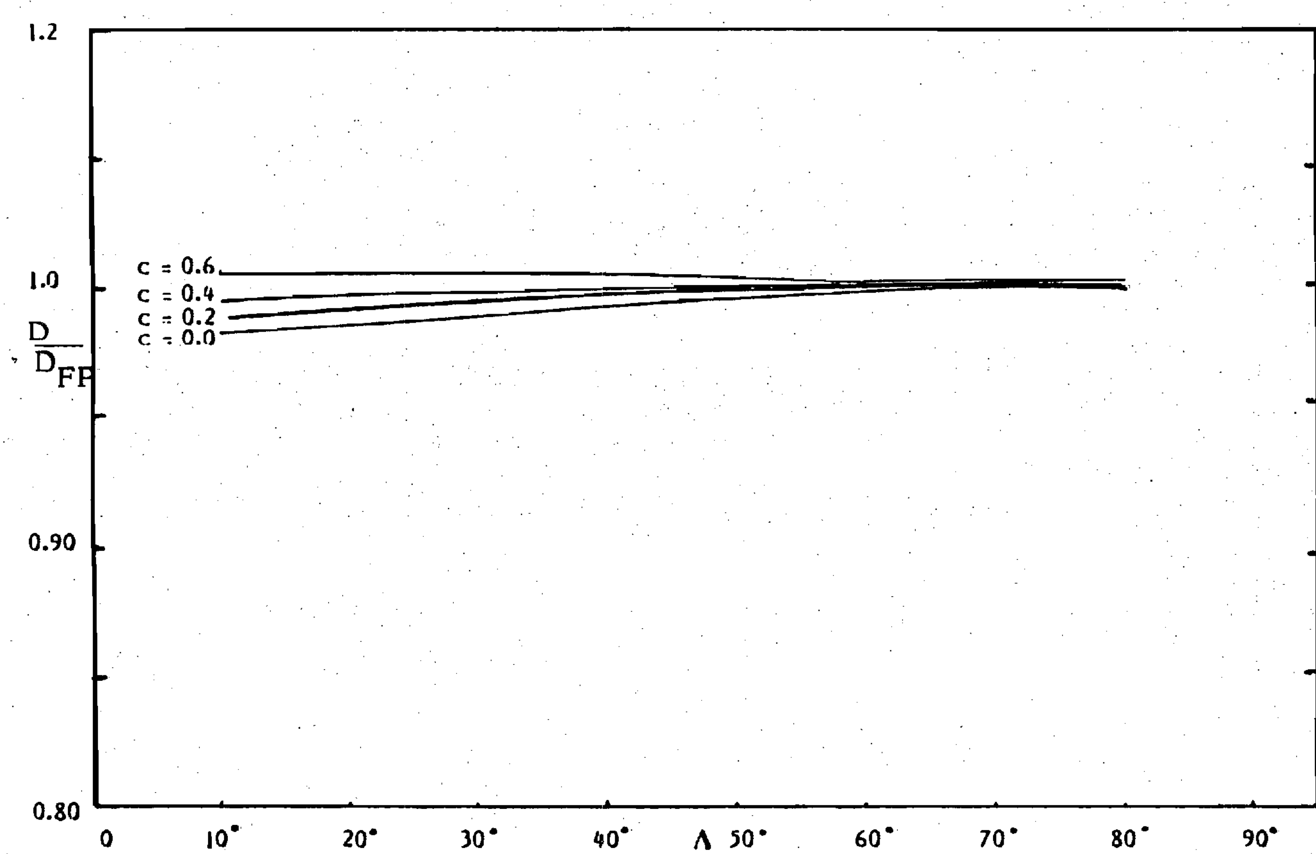

Figure 9. Skin friction drag, normalized with the equivalent flat plate drag, versus sweep angle for various phase speeds, for a series of waves.

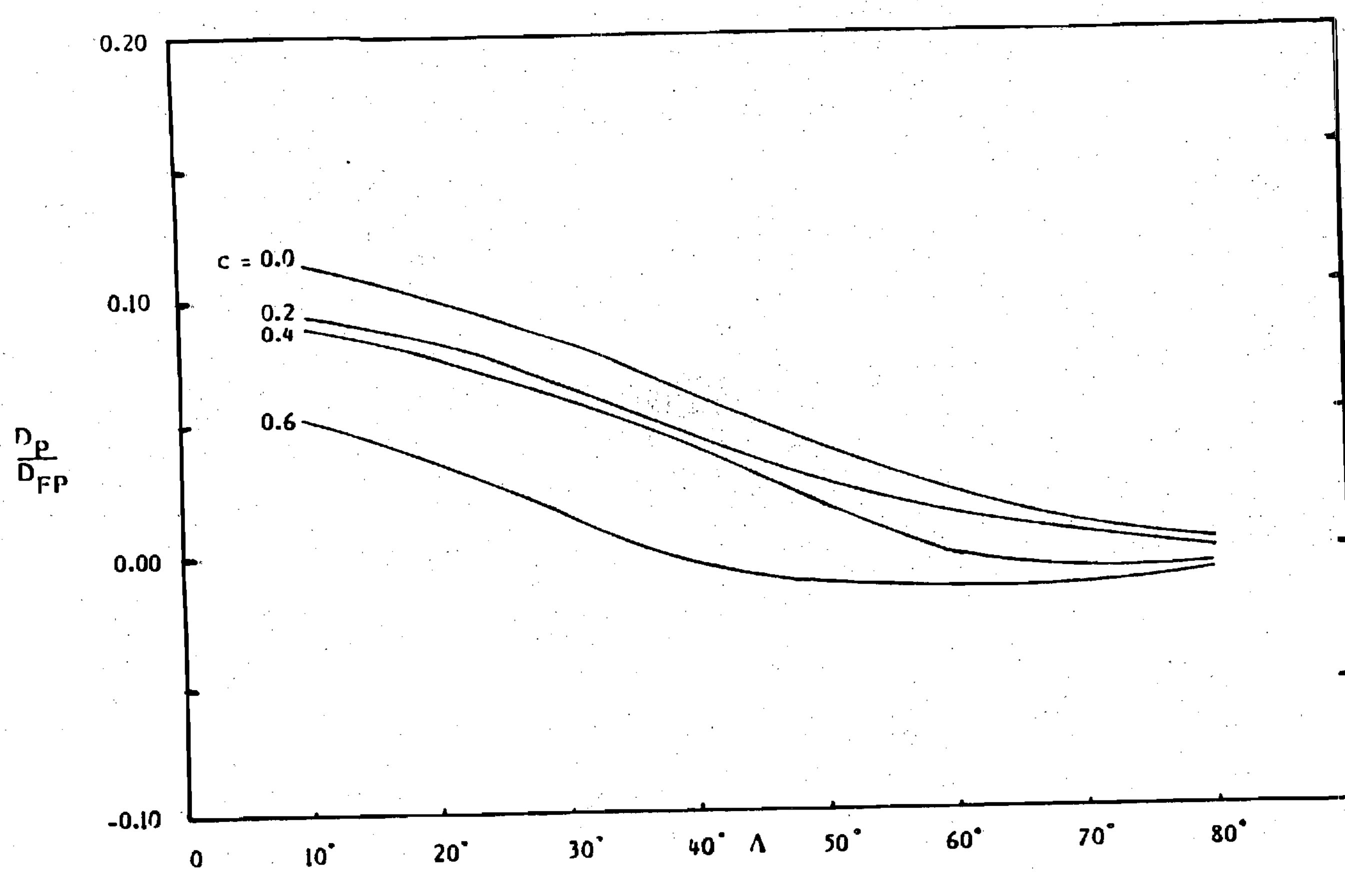

Figure 10. Pressure drag, normalized with the equivalent flat plate drag, versus sweep angle for various phase speeds, for a series of waves.