FINAL REPORT

on Contract N00014-83-K-0418

TURBULENT BOUNDARY LAYERS DEVELOPING OVER COMPLIANT SURFACES

by

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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.

6. REFERENCES

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

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8. Papadimitrakis, Y.A., "Velocity and Pressure Measurements in the Turbulent Boundary Layer Above Mechanically Generated Water Waves," Ph.D. Dissertation, Stanford University, 1982.

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.

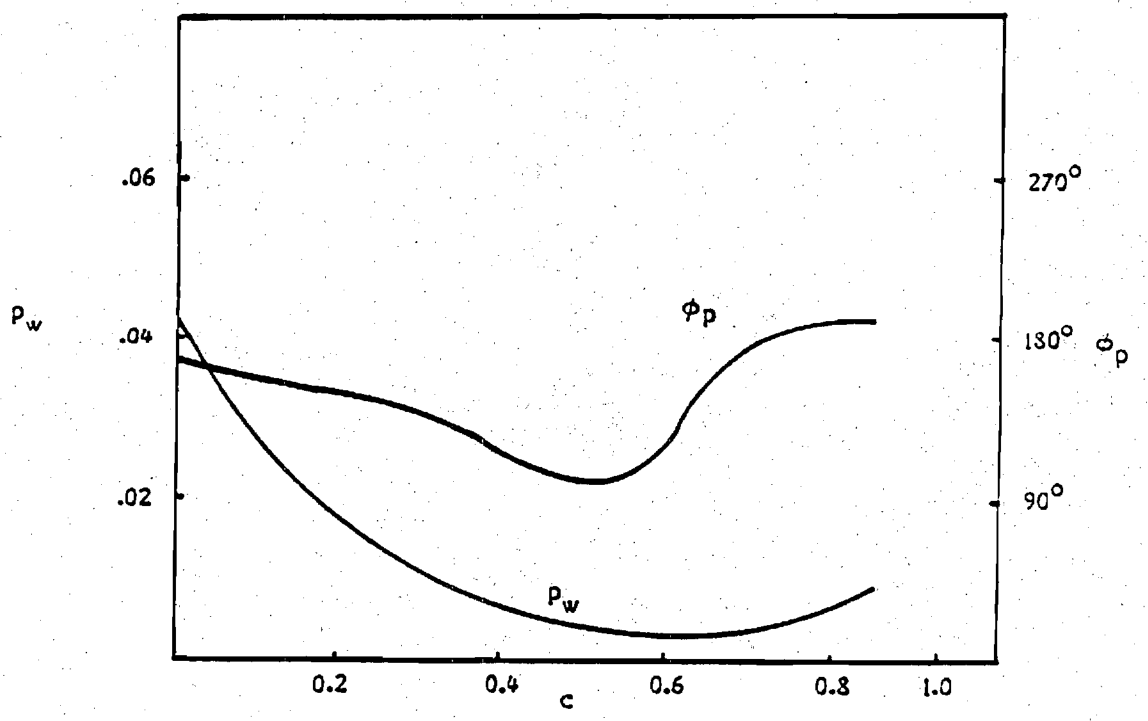

Figure 1. The amplitude of the pressure oscillation and the location of the maximum pressure (degrees upstream of the crest) versus the phase speed.

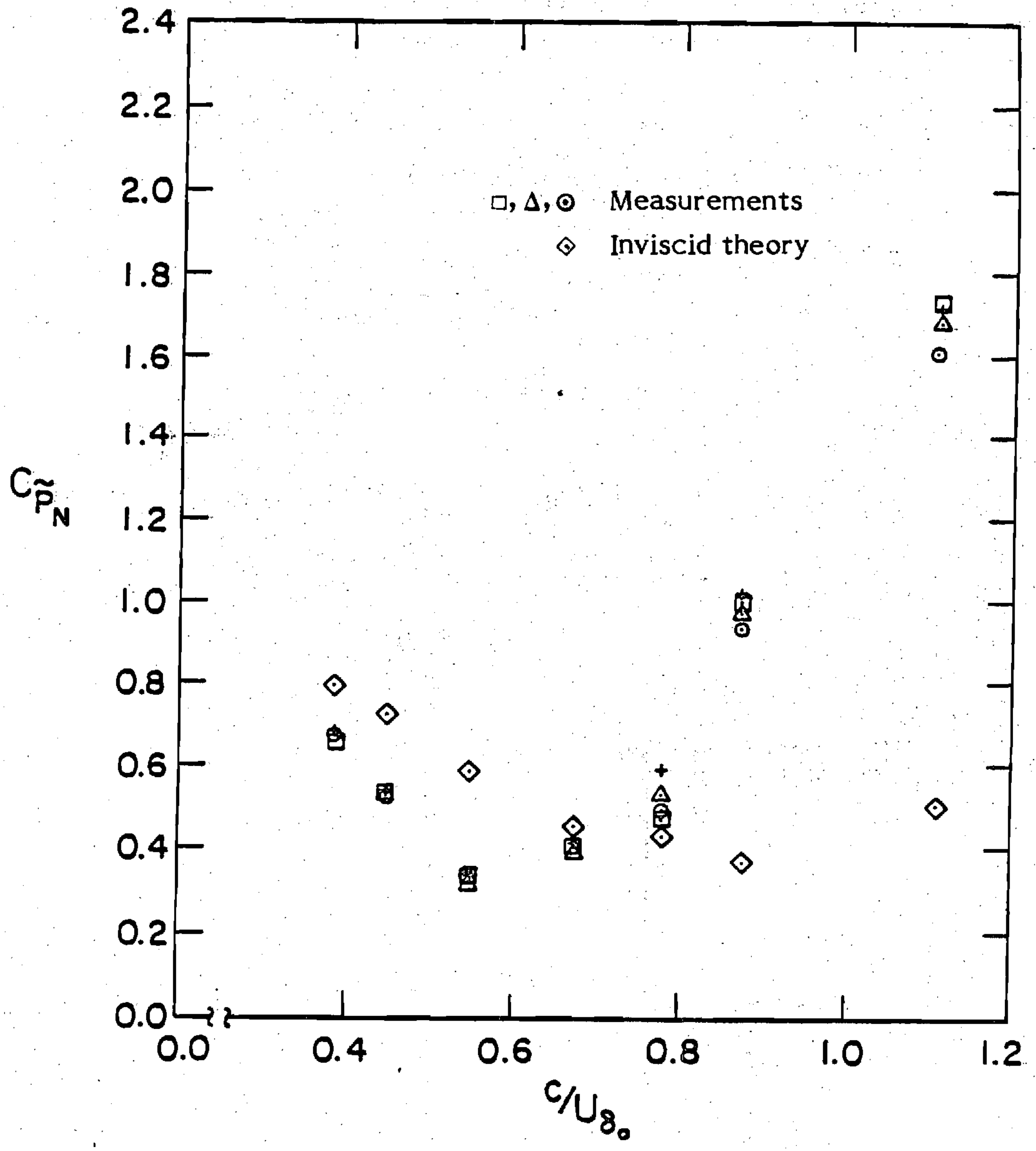

Figure 2. The variation of the pressure coefficient with the phase speed, close to the surface of a water-wave (from Reference 8).

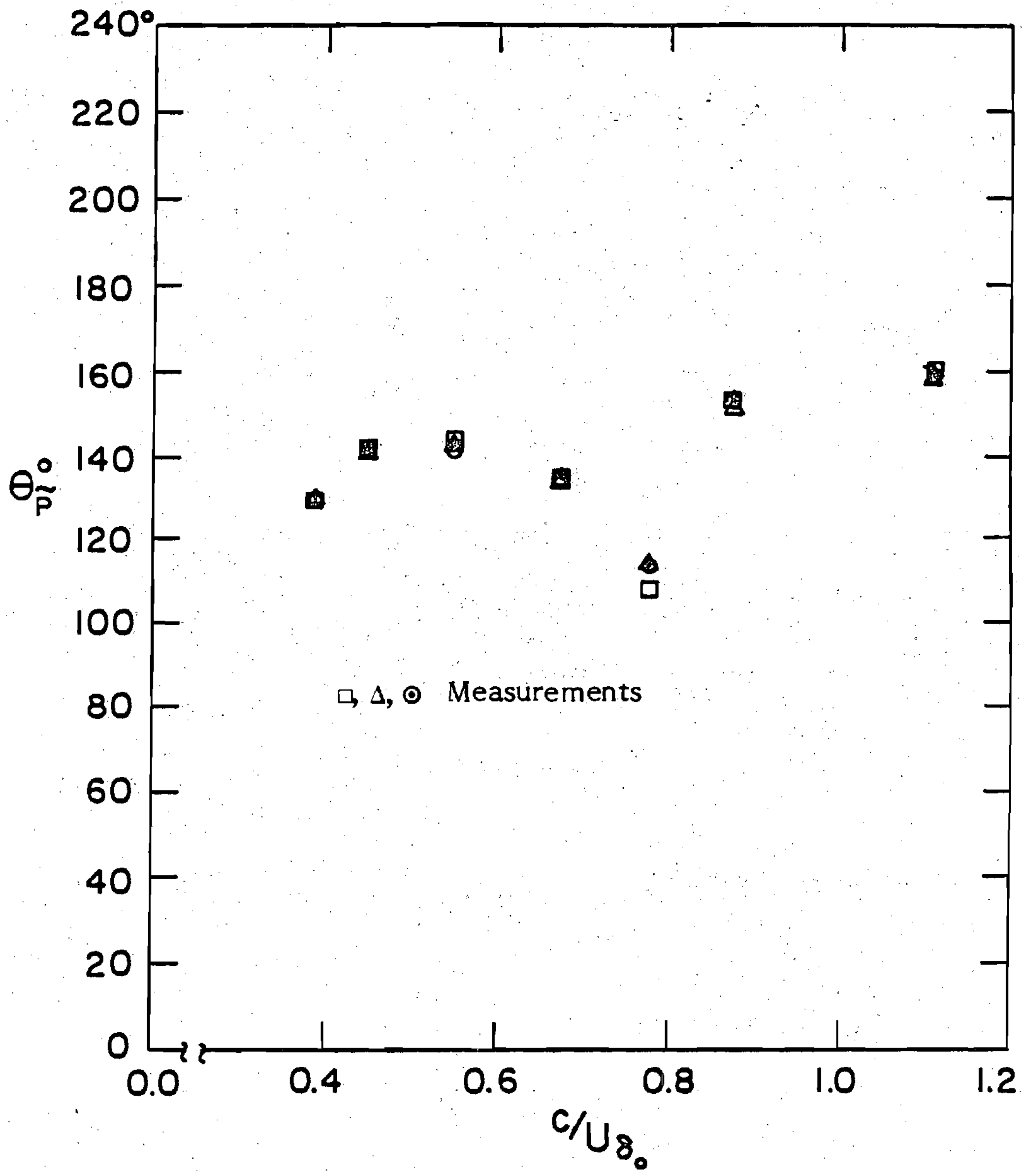

Figure 3. The location of the maximum pressure, in degrees upstream of the crest, for the case of the water-wave (from Reference 8).

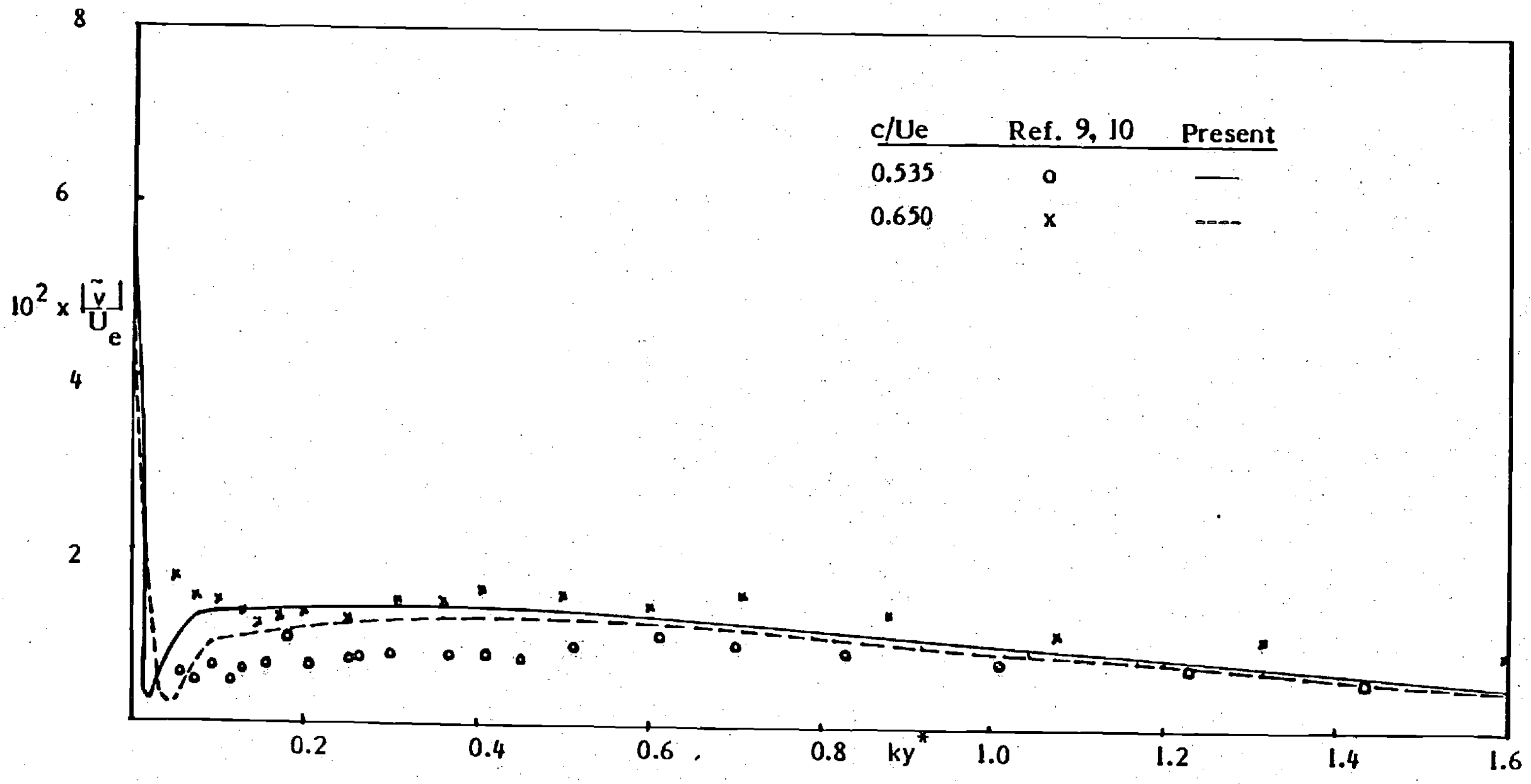

Figure 4. Comparison of calculation and measurement for normal velocity perturbation across the boundary layer.

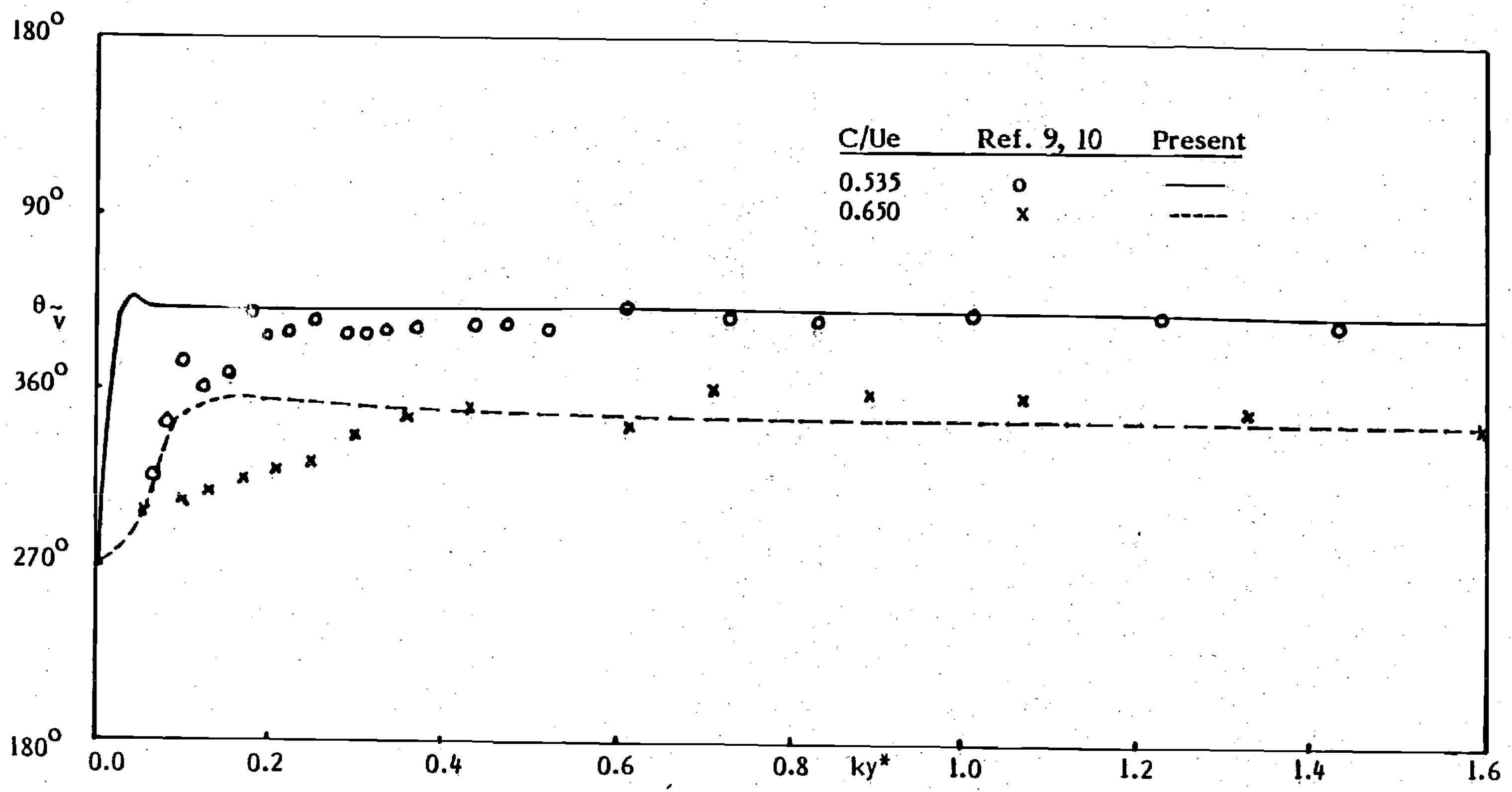

Figure 5. Comparison for calculation and measurement of the phase of normal velocity across the boundary layer.

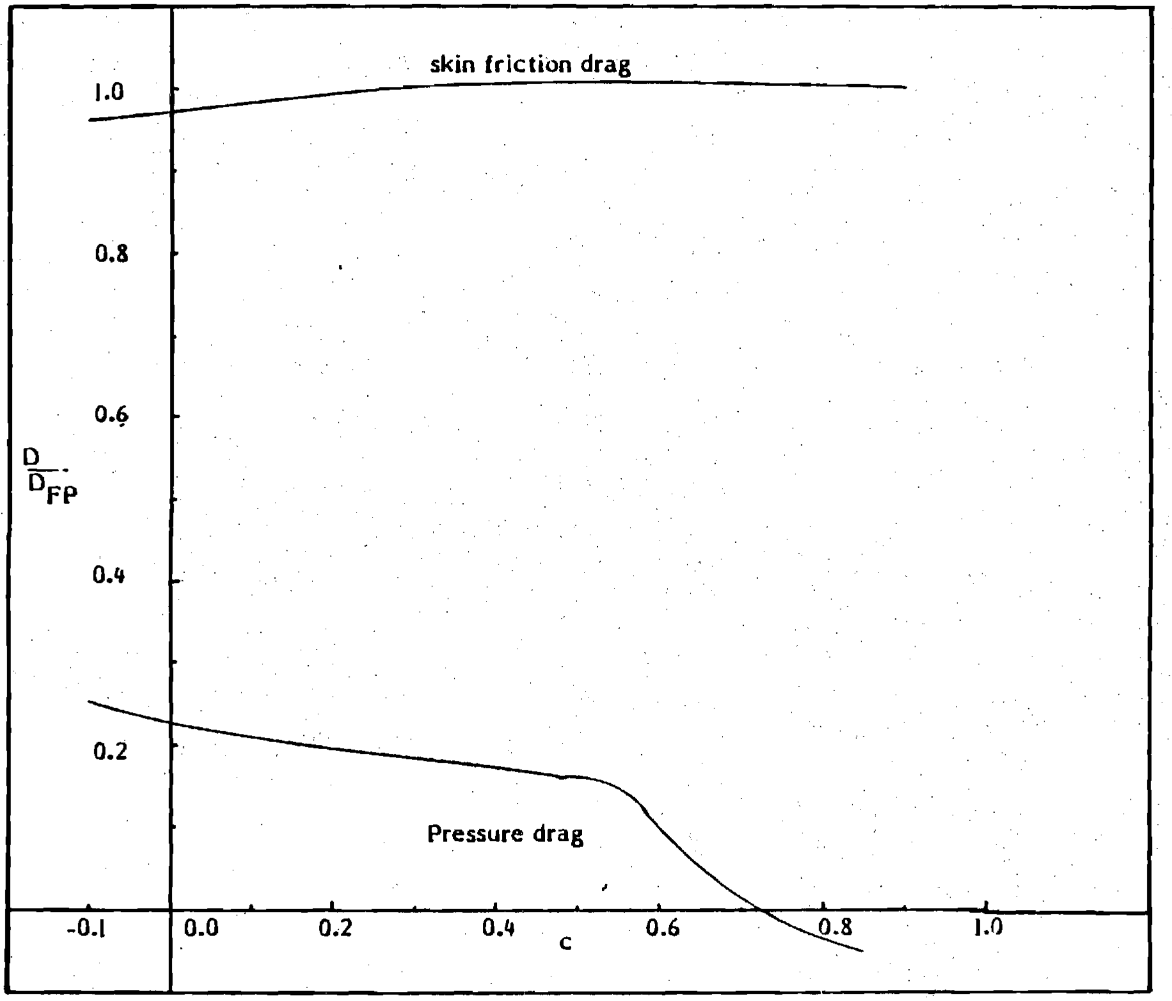

Figure 6. Pressure drag and skin friction drag for various phase speeds for a series of two-dimensional waves.

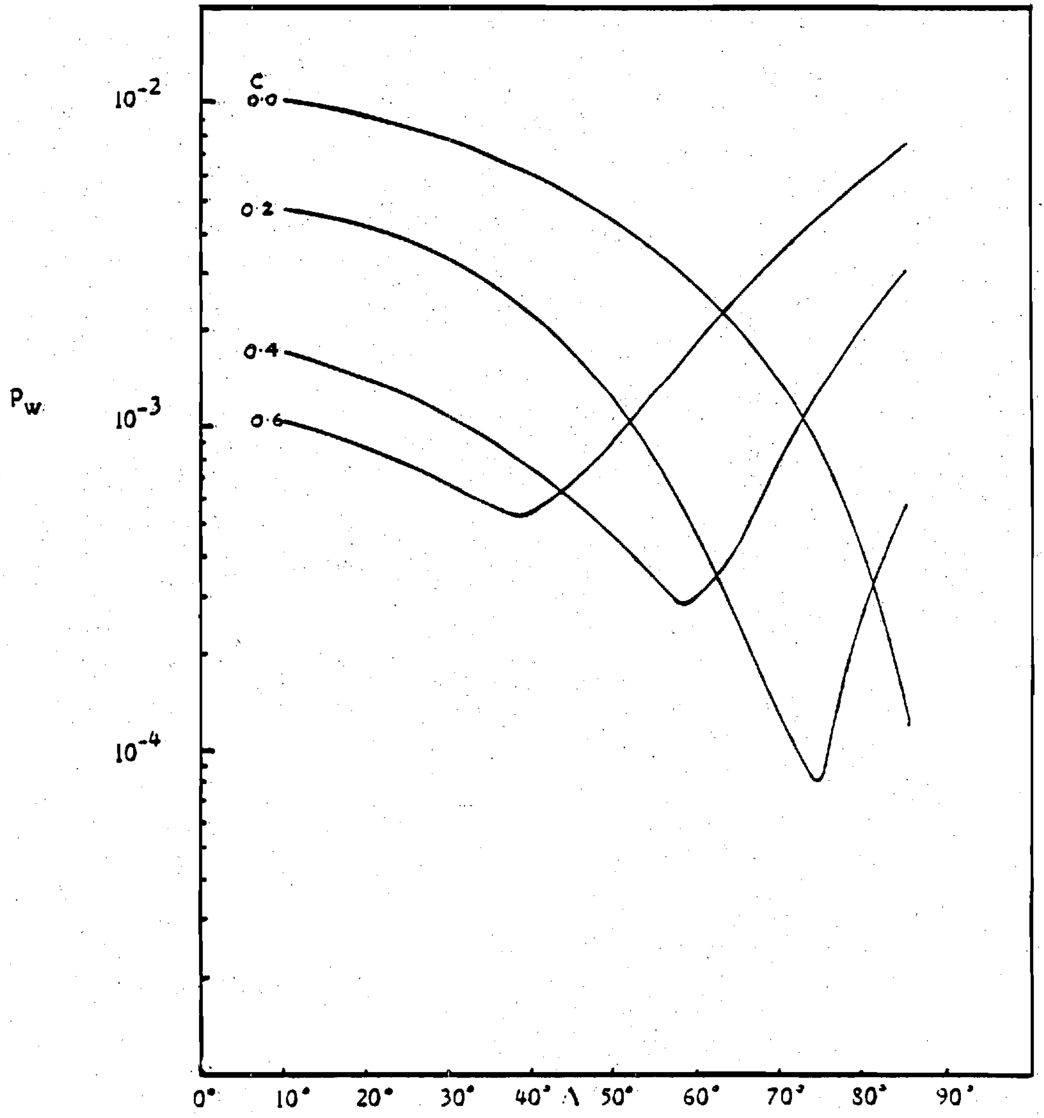

Figure 7. Typical variation of the pressure amplitude at the wall versus sweep angle for turbulent flow.

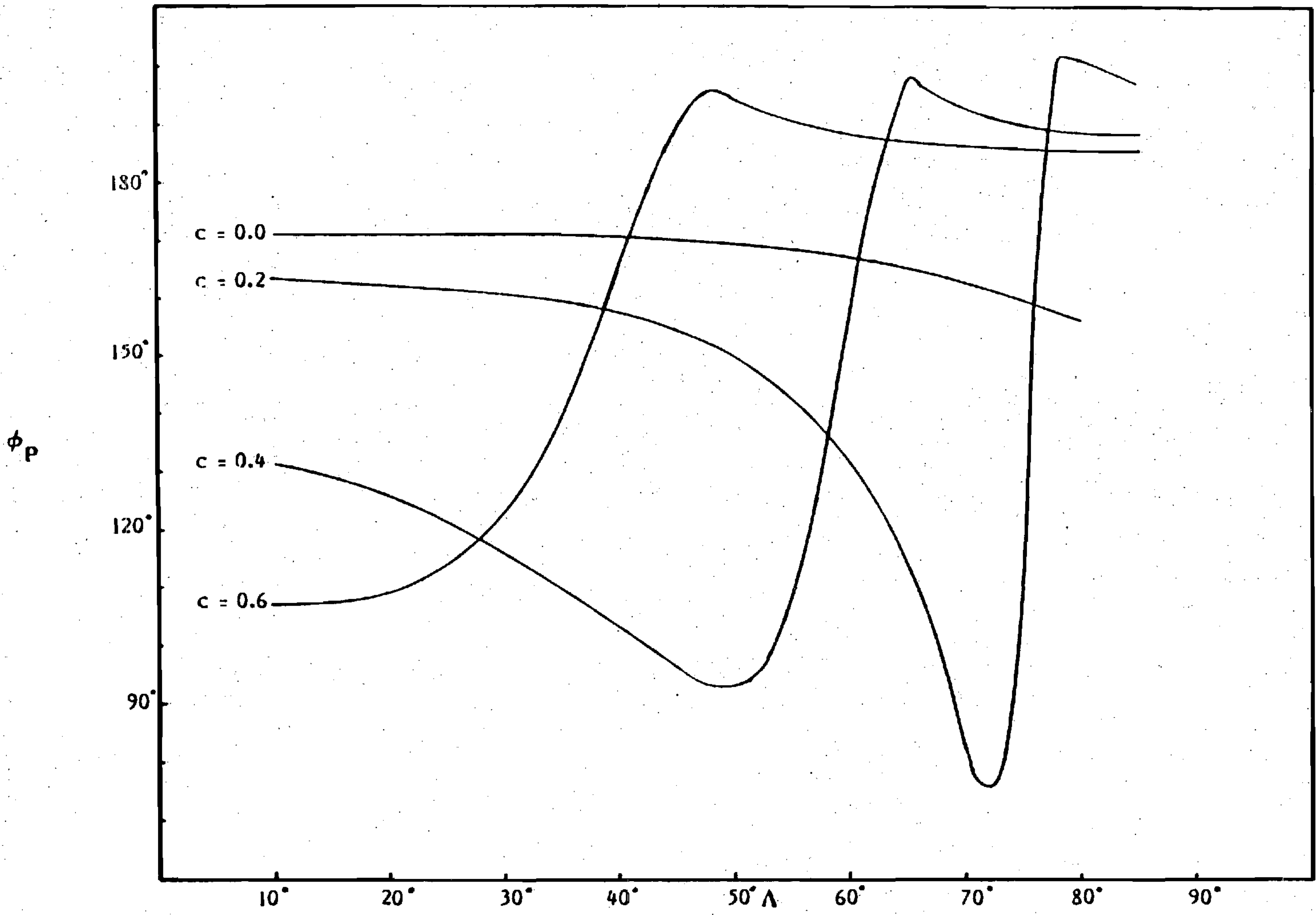

Figure 8. Typical variation of the phase of pressure versus sweep angle for various phase speeds for turbulent flow over a wavy wall.

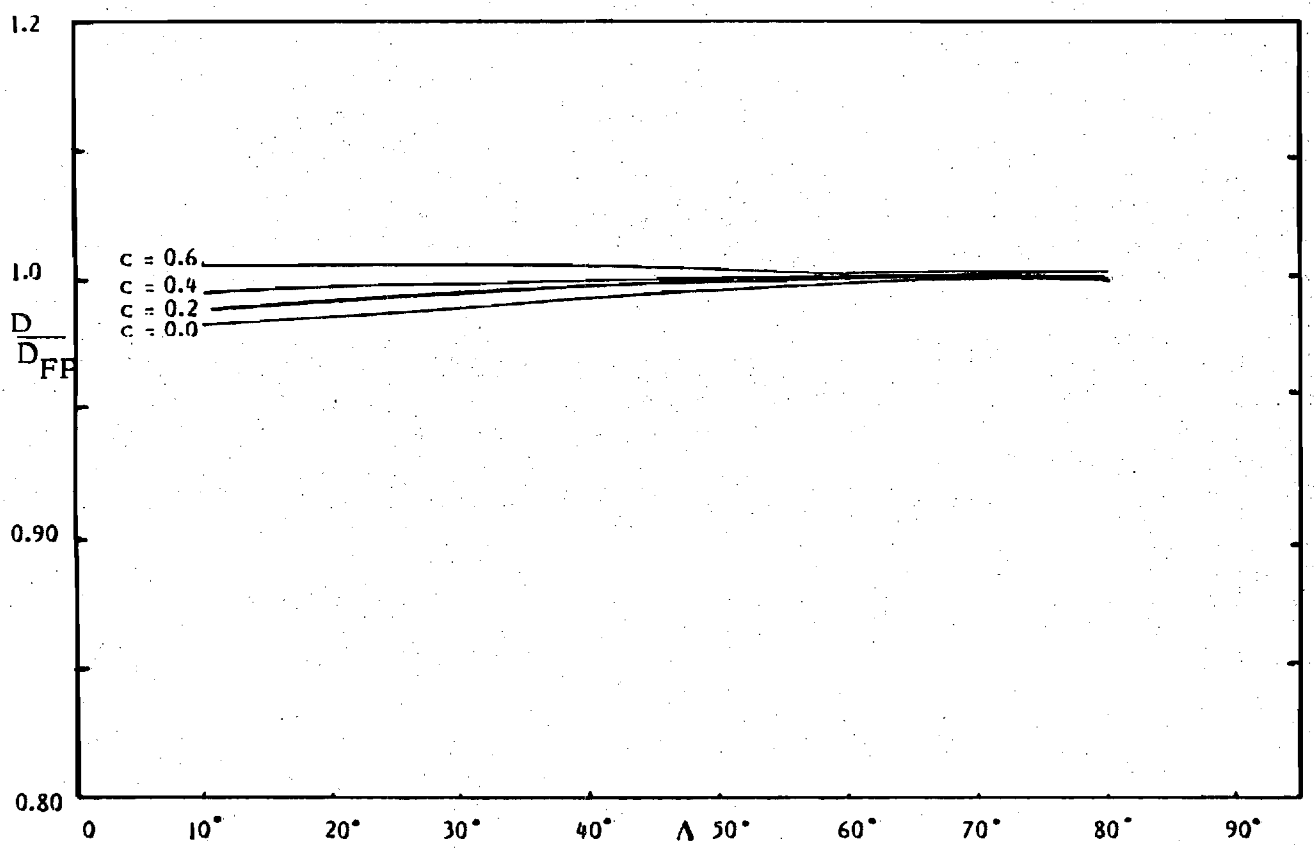

Figure 9. Skin friction drag, normalized with the equivalent flat plate drag, versus sweep angle for various phase speeds, for a series of waves.

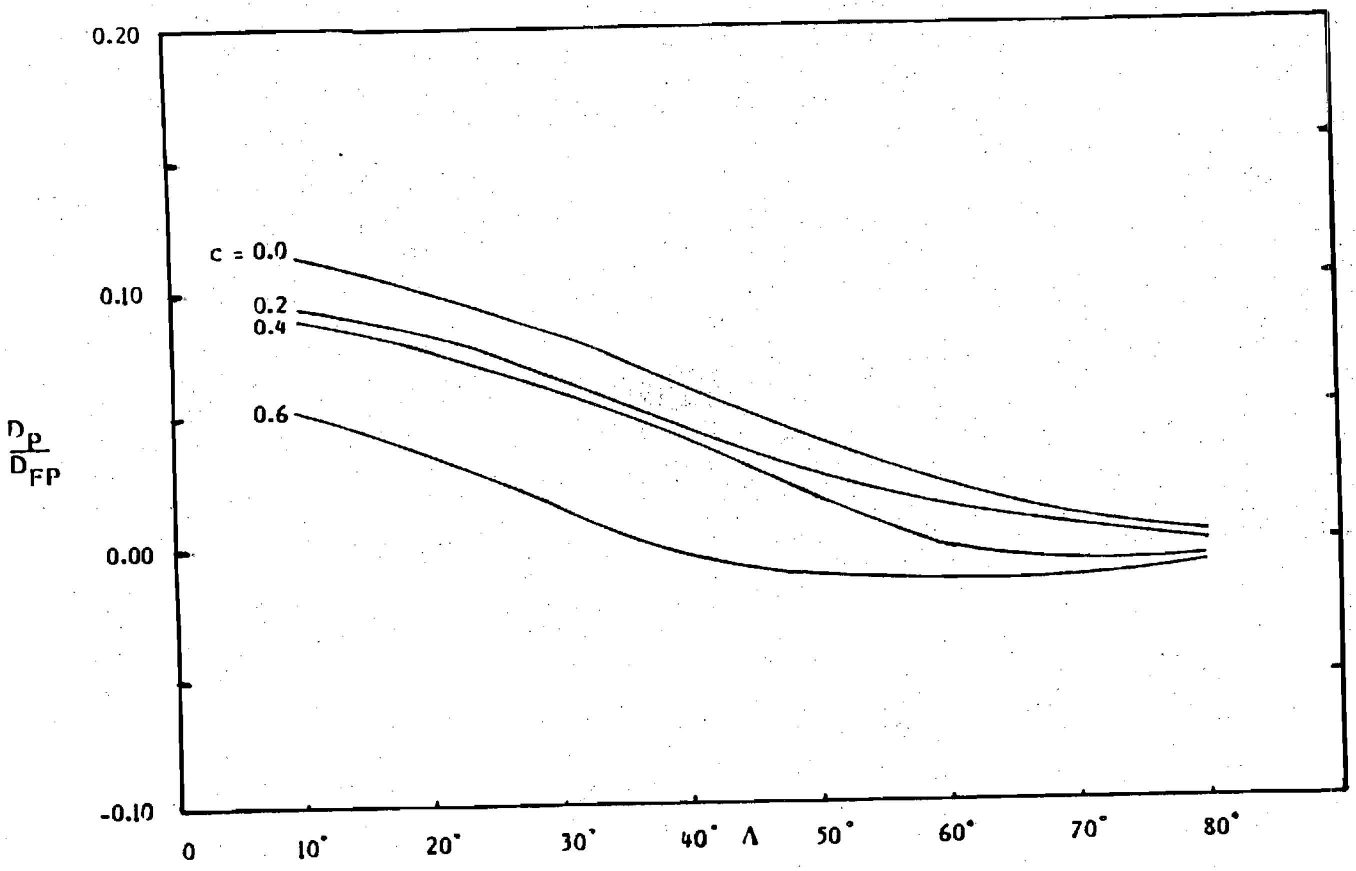

Figure 10. Pressure drag, normalized with the equivalent flat plate drag, versus sweep angle for various phase speeds, for a series of waves.