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SENSITIVITY STUDIES OF METHODS FOR PREDICTING SEPARATION IN DISCRETE VORTEX MODELS

by

Charles B. Franks

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COMPUTATION, MATHEMATICS AND LOGISTICS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

October 1983

DTNSRDC-83/093

DTNSRDC-83/093

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IN DISCRETE VORTEX MODELS

AD-A134 844

83 [illegible] 004

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REPORT DOCUMENTATION PAGE

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3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
SENSITIVITY STUDIES OF METHODS FOR PREDICTING SEPARATION IN DISCRETE VORTEX MODELS

5. TYPE OF REPORT & PERIOD COVERED
Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
Charles B. Franks

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
David W. Taylor Naval Ship Research
and Development Center
Bethesda, Maryland 20084

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
Program Element 61153N
Task Area SR040301
Work Unit 1808-010

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Sea Systems Command
J. Sejd (SEA05R24)
Washington, D.C. 20362

12. REPORT DATE
October 1983

13. NUMBER OF PAGES
21

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Separation
Discrete Vortex Methods
Point Vortices

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The methods currently used for calculating the inception and location of separation in the discrete vortex model developed by Shoaff and Franks are described. Sensitivity studies of these methods were conducted to determine whether they cause the differences between experimental and numerical results seen during early flow development for the non-circular cylinders A and B. The method for calculation of the inception of separation was found to cause some differences in the data for both bodies. The

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ABSTRACT

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ADMINISTRATIVE INFORMATION

The work presented in this report was conducted with funding from Naval Sea Systems Command (03R22) under Task Area SR040301, Program Element 61153N, and Work Unit 1808-010 at the David W. Taylor Naval Ship Research and Development Center (DTNSRDC).

INTRODUCTION

This report deals with the discrete vortex modeling of two-dimensional impulsively-started flow about bluff bodies. This type of modeling is of interest to the Navy because of its applicability to maneuvering underwater vehicles. Other numerical methods, such as finite differencing of the Navier-Stokes equation, show promise for application to realistic Navy problems but are now limited to relatively low Reynolds numbers and require large computation times. The discrete vortex method does not share these limitations and has shown good results in predicting loads on a circular cylinder.[1],[2]* Telste and Lugt[3] extended the discrete vortex method to finned circular cylinders using exact conformal mapping techniques, and Shoaff and Franks[4] applied the method to other non-circular bodies by using both exact and numerically generated conformal transformations. At Reynolds numbers on the order of 10^4, Kline[5] carried out experiments on cylinders A and B, shown in Figure 1, which are the same bodies studied by Shoaff and Franks.[4] Sarpkaya and Kline[2] published an

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*A complete listing of references is given on page 15.

encouraging comparison of the experimental results from Kline's[5] work with the numerical results from Shoaff and Franks.[4] They showed that the discrete vortex model gives promising predictions of the asymptotic flow period but that significant differences between numerical and experimental results occur during the early flow development.

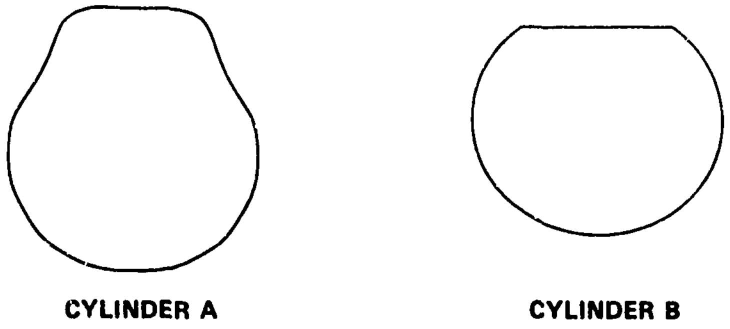

Figure 1 - Non-Circular Cylinders

Some of these differences noted by Sarpkaya and Kline[2] can be attributed to empirical assumptions needed in the model. This report presents the results of an investigation of the sensitivity of discrete vortex method calculations to assumptions dealing with the inception and location of flow separation. The details of the method are not described here but are given in the paper by Shoaff and Franks.[4]

PREDICTION OF INCEPTION AND LOCATION OF SEPARATION

The prediction of the inception of flow separation and the computation of the location of separation points are important for discrete vortex method calculations. The method is not used until separation occurs and shear layer development begins. Thereafter, the amount of vorticity introduced into the separating shear layers will depend on where these layers originate. For bodies with sharp corners, separation occurs at these corners and can, for practical purposes, be assumed to start instantly. For smooth bodies, however, the location of separation must usually be computed. Other difficulties arise with cylinders A and B which are not symmetric with respect to the longitudinal axis, but are symmetric only with respect to the centerplane.

When the direction of the oncoming flow is not parallel to the centerplane of such a non-circular cylinder, the two or more shear layers emanating from this type of body begin to develop at different times. For such a case, an accurate time history of forces can be obtained only if the time difference for inception of separation for the shear layers can be computed accurately. Sarpkaya and Kline[2] speculated that the differences that they noted between numerical and experimental results could be due to inaccurate computation of this time difference. Their speculation is based on the fact that cylinders A and B each exhibit time histories of drag which have two peaks early in time, each peak corresponding to the development of one shear layer. In this time span the difference between numerical and experimental results is greatest.

The method presently used by Shoaff and Franks[4] to calculate the time at which each shear layer starts to evolve consists of two parts. The first part computes the time necessary for the boundary layer to develop and initially separate. This initial separation occurs at the point of maximum adverse pressure gradient at a time (t_1) of

$$t_1 = \left(\left[1+\frac{4}{3\pi}\right]\left|\frac{du}{dx}\right|_{max}\right)^{-1}$$

where $|du/dx|_{max}$ is the maximum adverse velocity gradient. This equation is derived in Schlichting[6] using the second approximation to the velocity distribution calculated by Blasius.[7] The second part of the method computes the time it takes the separation point to move upstream to a location at which distinct shear layer development begins. During this time the boundary layer is still growing but there has yet to be any noticeable development of a separated shear layer. This value (t_2) is calculated according to Schuh's[8] analysis. Schuh[8] devised a method for calculation of an unsteady boundary layer using the integral form of the unsteady momentum equation. Schuh's[8] method is used to calculate the growth of boundary layers for instantaneous flow so that the time taken for the separation point to travel from its initial location to the location at which shear layer development begins can be determined. The inception time of each shear layer is the sum of t_1 and t_2.

The high curvature at the top of cylinder A presents additional difficulties. The irregular shape of this region made it necessary to run an extensive boundary layer analysis to determine the separation location. The initial assumption was that separation would occur at both regions of large curvature during early development of the flow, similar to the development of two shear layers on the top of cylinder B. However, results from a boundary layer program by Cebeci[9] and experimental results from Kline[5] show that only one shear layer separates from the top region. Because Cebeci's[9] program used too much computer time to be used at every time step in calculating the separation point, another method had to be devised. On the basis of results from numerous velocity profiles run on Cebeci's[9] program, the separation point is predicted to be just downstream of the point of the maximum velocity where the velocity is 97.5% of the maximum.

To determine the model's sensitivity to both the inception and location of separation, and to determine whether the differences between experimental and numerical results are directly related to these phenomena, two sensitivity studies were carried out. To investigate the importance of the difference between the start times of the shear layers, the model was run for both bodies holding the starting time fixed for one shear layer while varying the starting time of the other. In addition, several runs were made for cylinder A using different percentages of the maximum velocity to locate the separation point at the top. The results of these studies are presented in the following sections.

SENSITIVITY TO SEPARATION INCEPTION

CYLINDER A RESULTS

For cylinder A the method described in the preceding section for the calculation of the inception time of each shear layer produced a normalized inception time (Ut/c) of 0.35 for the upper shear layer and 1.0 for the lower shear layer, where time is normalized by the free stream velocity (U) and the body radius (c). However, Sarpkaya and Kline[2] state that, based on the experimental data, shear layer development does not start on this body until a normalized time of 0.6 and that when it does, it starts on the upper protrusion of the body. Therefore, for this analysis the upper shear layer was set to start at a normalized time of 0.6 for all runs, while the lower shear layer was varied with values of 0.6, 1.1, 1.6, and 2.6. The results are shown in the lift and drag curves in Figures 2 and 3, respectively. The lift and drag forces are nondimensionalized by density (ρ), free stream velocity (U), and body radius (c) as shown on the figures. Both experimental and numerical results show a drag overshoot in Figure 3, which, as pointed out by Sarpkaya and Kline,[2] is due to the rapid increase in vorticity in the first two shear layers. The double peak region seen in the experimental data shows up in the numerical results as the time difference is increased, although the numerical results still do not compare well with the experimental data. The computed peaks occur at different times and at different magnitudes than the observed peaks. A possible cause of these differences may be the inaccurate modeling of the vorticity generation during the early shear layer development. This explanation is indicated by the differences in the slopes of the drag and lift curves in the early development. An unrealistically high slope, indicating a high rate of vorticity generation, causes the numerical results to peak too early. The lift and drag curves do show that the forces are sensitive to the relative inception times of the two shear layers and that this phenomenon must be modeled correctly before reliable force values can be obtained for the early flow development.

CYLINDER B RESULTS

For cylinder B the top shear layers were held at an inception time of 0.0, because they are generated at sharp edges. The bottom shear layer inception was varied with times of 0.5, 1.0, 1.5, and 3.0. The results are shown in the lift and drag curves in Figures 4 and 5, respectively. Cylinder B experimental data show a more distinct double peak in the drag overshoot region (Figure 5) than do the data for cylinder A. Again the reason for this double peak is the time difference between the starting of the upper shear layers and of the lower shear layer. In cylinder B numerical results a distinguishable double peak appeared as the time difference was increased. As with cylinder A, cylinder B numerical results do not agree with the experimental data in magnitude and time of occurrence of the peaks. Thus the results of both bodies show that the model is very sensitive to the time difference between inceptions and that the early vorticity generation is not modeled accurately.

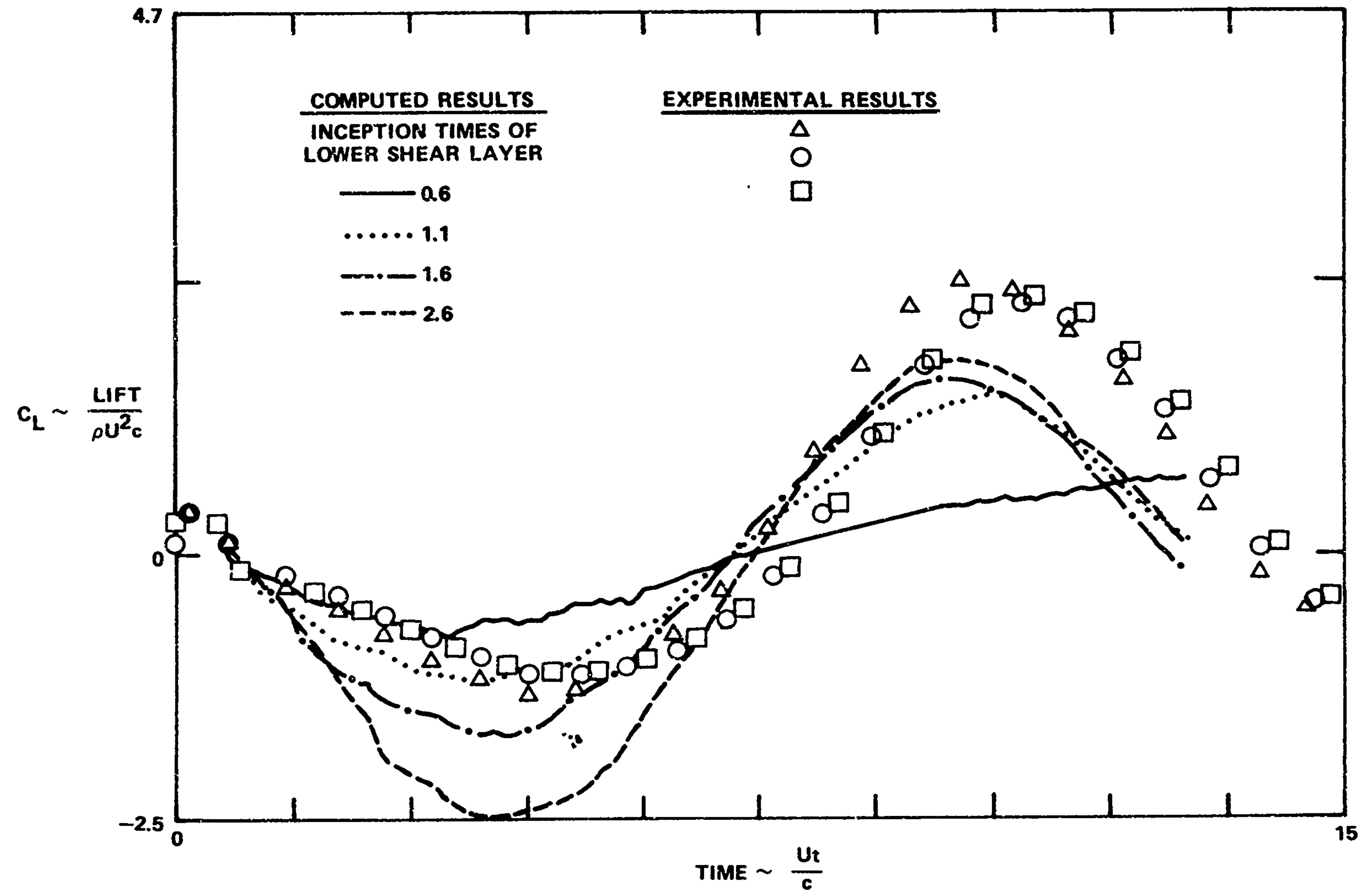

Figure 2 - Computed Results with Different Inception Times for the Lower Shear Layer Compared to Experimental Results.[2] Lift Curves for Cylinder A.

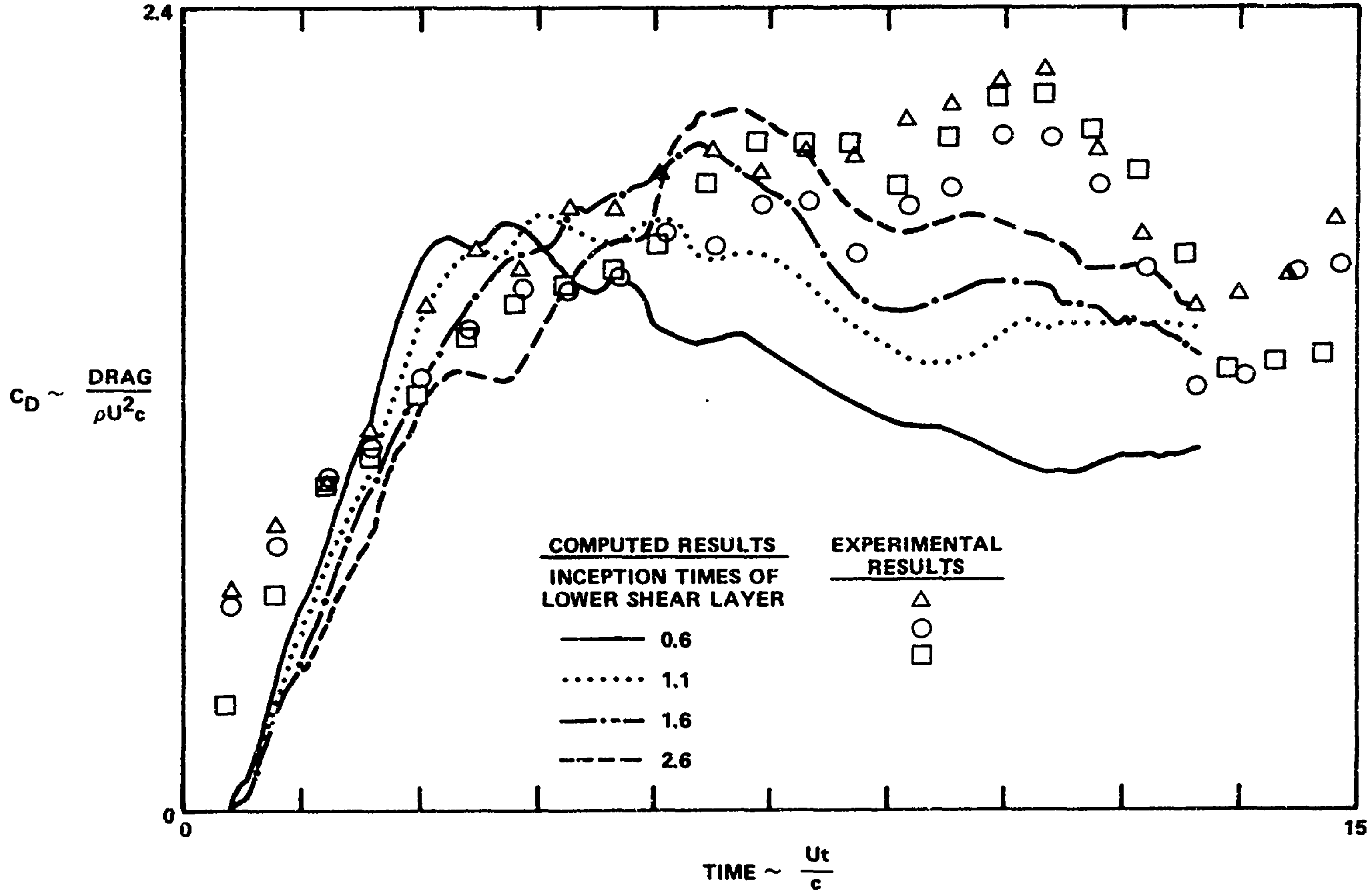

Figure 3 - Computed Results with Different Inception Times for the Lower Shear Layer Compared to Experimental Results.[2] Drag Curves for Cylinder A.

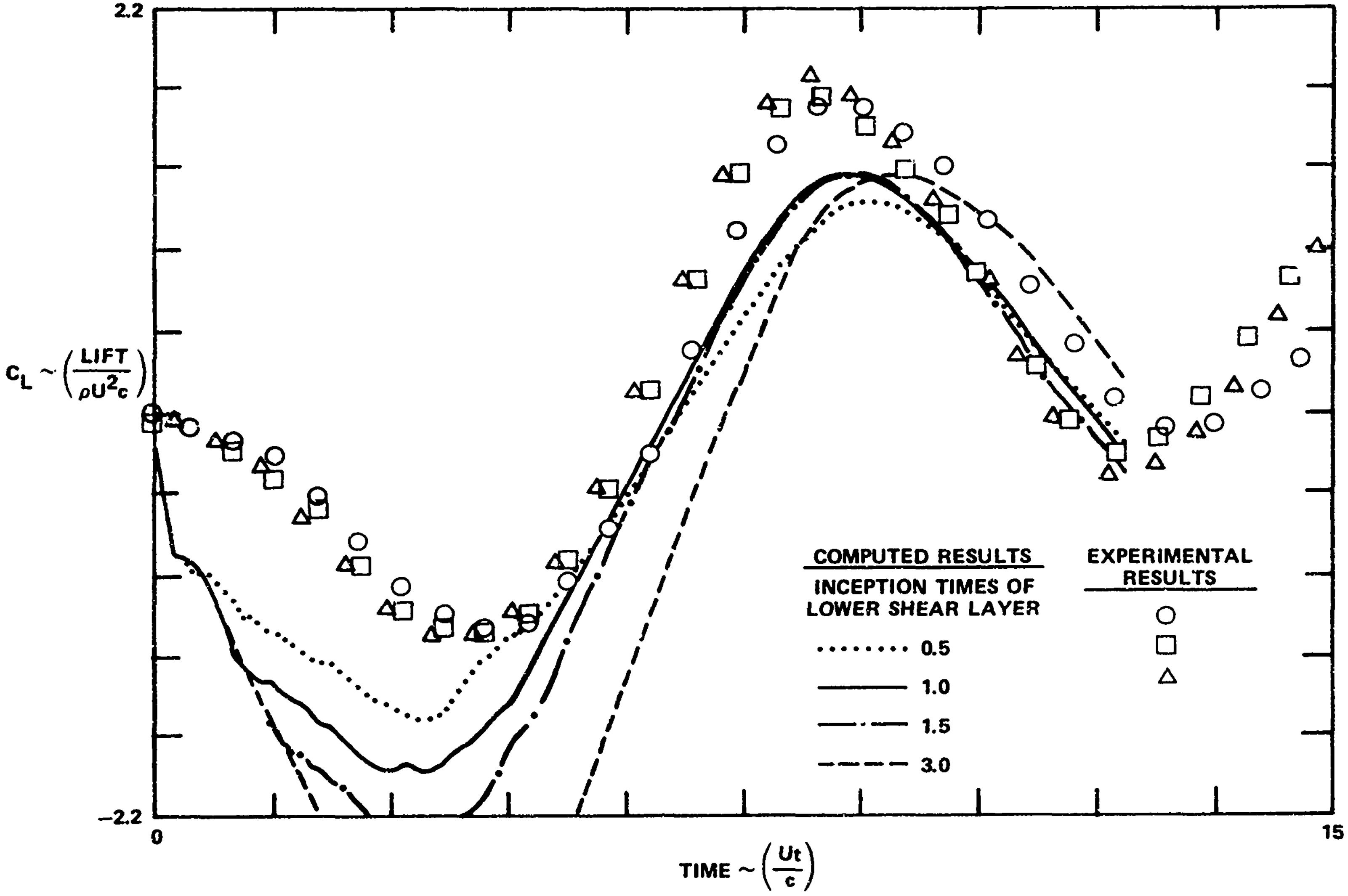

Figure 4 - Computed Results with Different Inception Times for the Lower Shear Layer Compared to Experimental Results.[2] Lift Curves for Cylinder B.

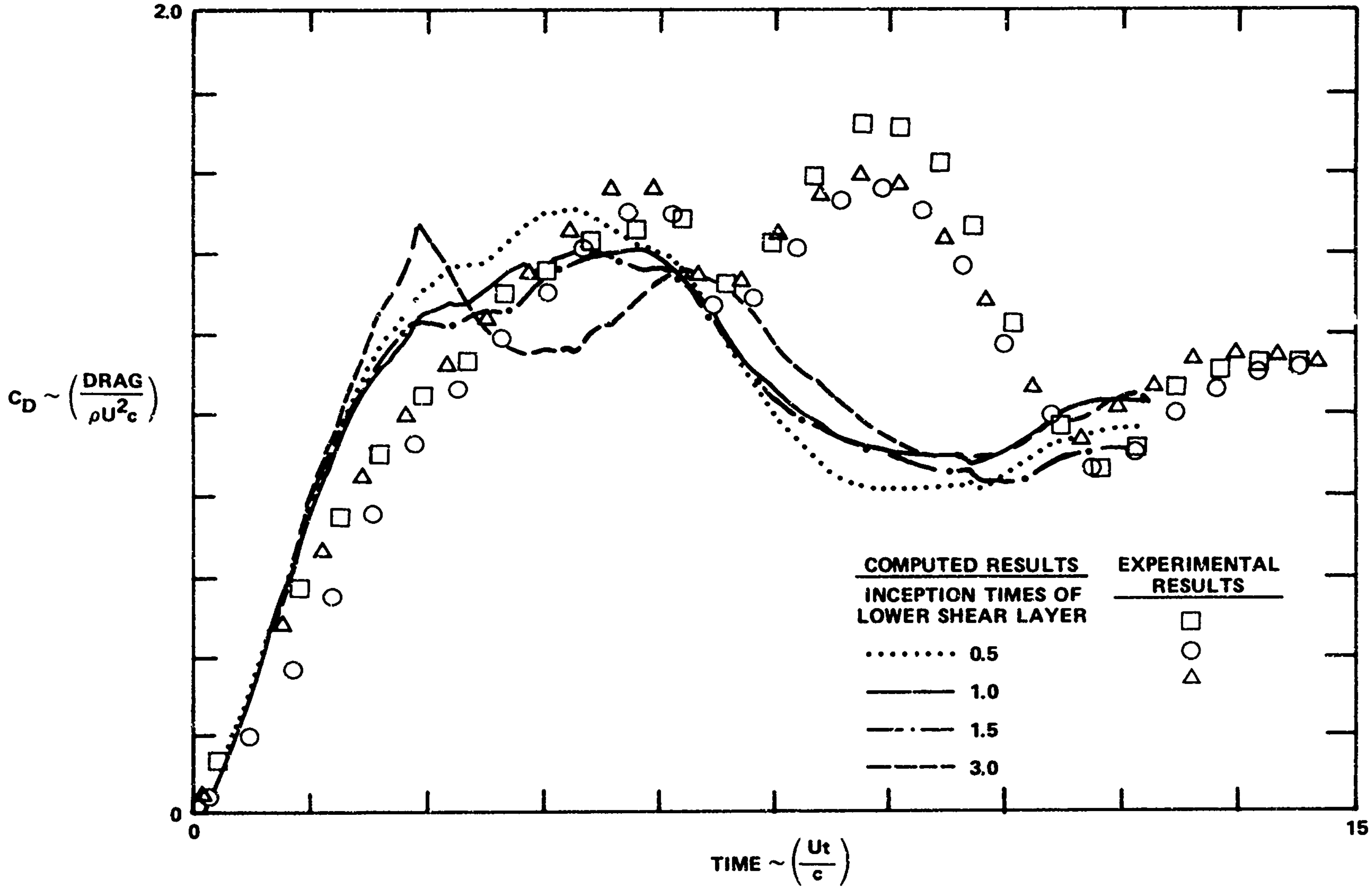

Figure 5 - Computed Results with Different Inception Times for the Lower Shear Layer Compared to Experimental Results.[2] Drag Curves for Cylinder B.

SEPARATION LOCATION RESULTS FOR CYLINDER A

In runs for cylinder A the upper separation point was assumed to be located where the velocity decreased to 100%, 97.5%, 95%, and 90% of the maximum velocity. The results are shown in the lift and drag curves in Figures 6 and 7, respectively. These results show that the forces are relatively insensitive to variation between 95 and 100 percent of the maximum velocity. For 90 percent the numerical results were substantially below the experimental data. The separation point varied about 2 to 3 degrees with each increment, showing that for this particular body the separation point can vary within a 4-degree region without affecting the results. However, this range probably depends on the severity of the curvature of the body in the region of separation. Therefore, whenever an arbitrary method like this must be used, a sensitivity study should be included. These results indicate that the current prediction scheme for this particular body is reasonable.

CONCLUSION

The discrete vortex model described by Shoaff and Franks[4] has been shown to be very sensitive to the modeling of the difference between the starting times of the shear layers. This time difference is important when modeling bodies that are nonsymmetric with respect to the oncoming flow, and small errors in it can lead to large errors in the early time force calculations. But this is not the only cause of differences seen between numerical and experimental results. Also suspect is inaccurate modeling of the early vorticity generation. Both of these inaccuracies are seen in the early development of the flow during the drag overshoot time period. After this period the model appeared to predict a level of drag very similar to that of the experimental data.

The separation location problem depends on the shape of the body being tested. In most cases an extensive boundary layer analysis can be used to devise a method for predicting separation on irregularly shaped bodies. But for some highly irregularly shaped bodies, this analysis may not provide an adequate separation predictor, which would limit the model to certain shapes.

In general, this method currently does not accurately model the early development of forces for impulsively-started flow about bluff bodies. Most

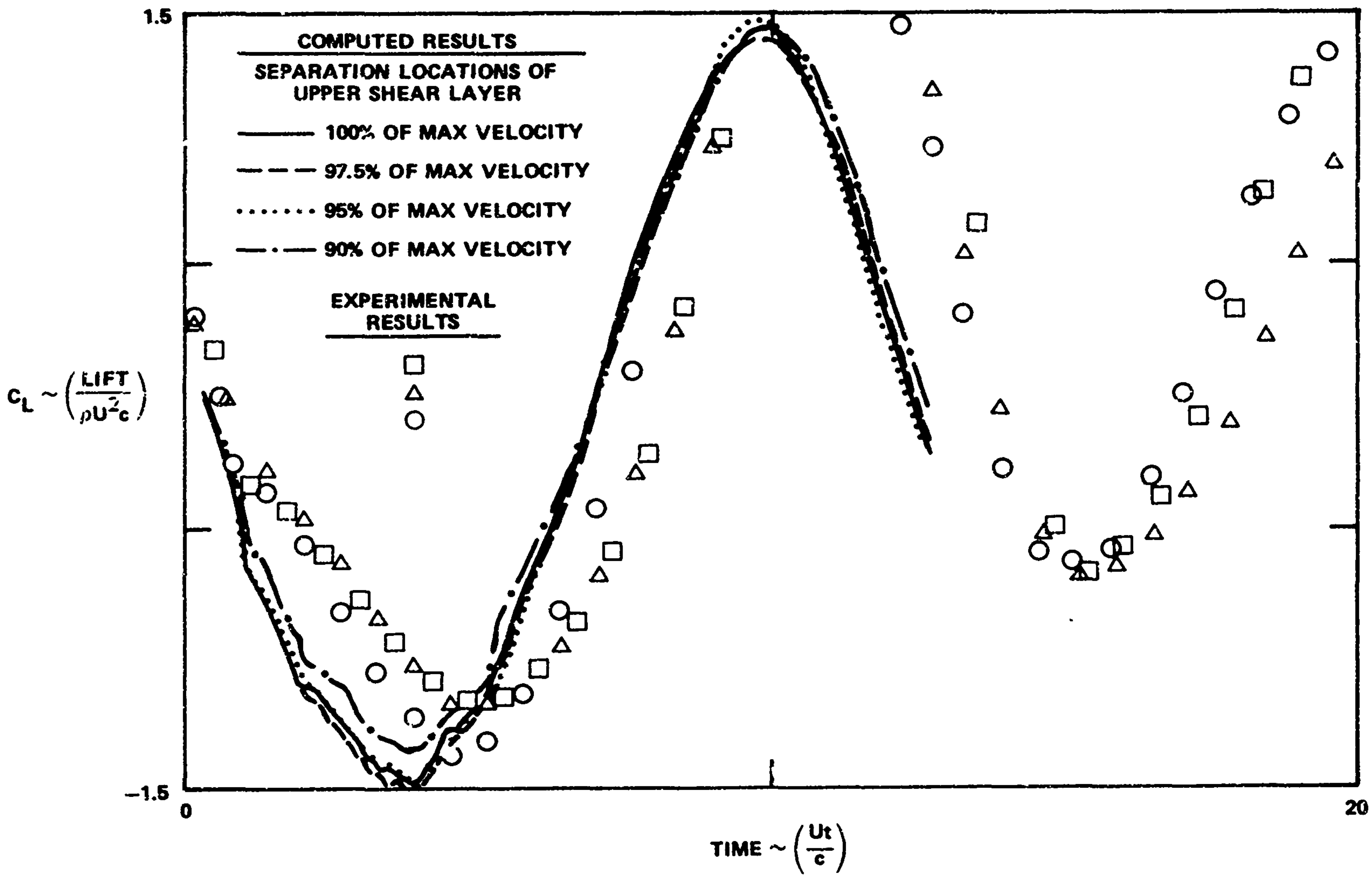

Figure 6 - Computed Results with Different Separation Locations for the Upper Shear Layer Compared to Experimental Results.[2] Lift Curves for Cylinder A.

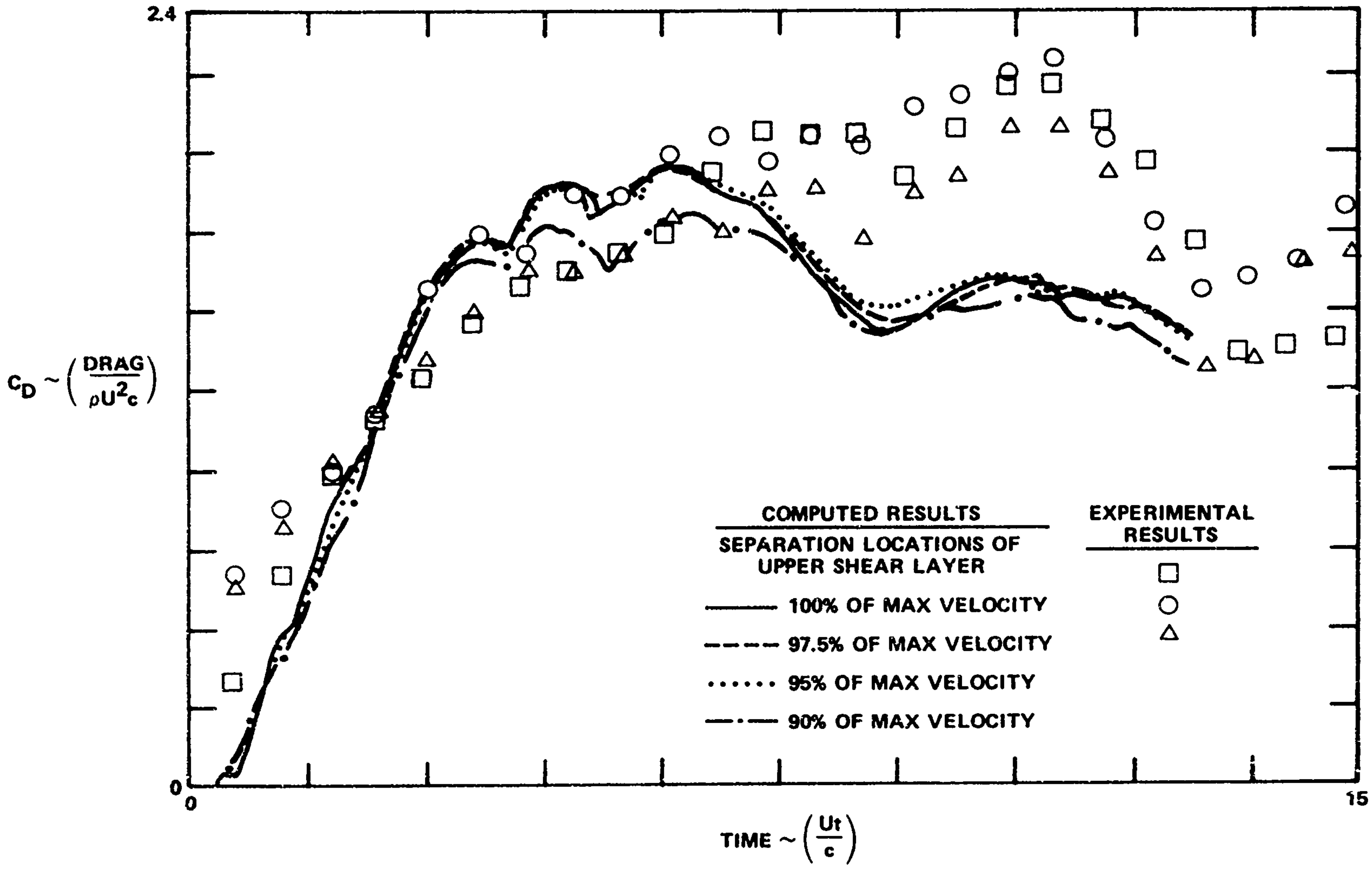

Figure 7 - Computed Results with Different Separation Locations for the Upper Shear Layer Compared to Experimental Results.[2] Drag Curves for Cylinder A.

of the improvements are needed in the initial flow development prediction where the drag overshoot occurs. Even with such improvements, this method requires experimental corroboration and guidance before the numerical results can be used with confidence.

ACKNOWLEDGMENT

The author wishes to express his appreciation to Dr. Raymond L. Shoaff for his suggestions on some of the computer runs and for valuable comments on the comparison of experimental and numerical results.

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