MISCELLANEOUS PAPER H-78-11

FEASIBILITY STUDY OF A NUMERICAL TOW MODEL

by

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September 1978

Final Report

Prepared for Assistant Secretary of the Army (R&D)
Department of the Army
Washington, D. C. 20310

Under Project No. 4A161101A91D

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper H-78-11	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) FEASIBILITY STUDY OF A NUMERICAL TOW MODEL		5. TYPE OF REPORT & PERIOD COVERED Final report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Thomas D. Ankeny, Carl J. Huval, Larry L. Daggett		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Hydraulics Laboratory P. O. Box 631, Vicksburg, Miss. 39180		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 61101A Project No. 4A161101A91D Task 02, Work Unit No. 103
11. CONTROLLING OFFICE NAME AND ADDRESS Assistant Secretary of the Army (R&D) Department of the Army Washington, D. C. 20310		12. REPORT DATE September 1978
		13. NUMBER OF PAGES 52
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)

Approved for public release; distribution unlimited.

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)

Barges
Feasibility studies
Mathematical models
Model basins
Towboats
Tows and towing

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

The objective of the study described in this report was to explore the feasibility of developing a numerical hydrodynamic model of a typical push towboat-barge combination for use in engineering planning and design studies. Such a model might be used to simulate tow movements in restricted waterways in critical river reaches such as bends, bridges, and near navigation locks and dams to determine the adequacy and/or economic efficiency of channel designs.

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Unclassified

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20. ABSTRACT (Continued).

A literature search was conducted and it was found that no information was available at the beginning of this study on numerical models of tow hydrodynamics or on towing tank or prototype tests of the maneuverability of tows. During the course of the study several numerical models did become available and further research in this area was initiated by the U. S. Coast Guard Research and Development office. This work is described herein.

Since no information was available for the development or testing of a numerical tow maneuvering model, a series of measurements were made of radio-controlled scale model tows used in physical model studies at the Waterways Experiment Station as they executed standard ship hydrodynamic maneuvers. Data from these measurements and computations were used to determine estimates of hydrodynamic coefficients of a linear model of ship maneuverability.

It was found that it is feasible to predict tow maneuvers using a numerical model of tow maneuverability; however, additional measurements of tow response characteristics are required before a model that would be useful in engineering studies can be developed. Comparisons of such a model with recent measurements of full-scale tow maneuvers could demonstrate the validity of this model.

PREFACE

The investigation reported herein was conducted under Department of the Army Project No. 4A161101A91D, In-House Laboratory Independent Research (ILIR) Program. The program is sponsored by the Assistant Secretary of the Army (R&D). The research was performed at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi.

The study was conducted by Messrs. Carl J. Huval and Thomas D. Ankeny and Dr. Larry L. Daggett of the Math Modeling Group under the general supervision of Mr. H. B. Simmons, Chief of the Hydraulics Laboratory and Mr. M. B. Boyd, Chief of the Hydraulic Analysis Division. Mr. M. B. Savage, Instrumentation Services Division, designed the instrumentation for recording the tow test data and Mr. L. L. Friar, Instrumentation Services Division, assisted in recording the data during the tests.

Directors of WES during the conduct of this investigation and the preparation of this report were COL G. H. Hilt, CE, and COL John L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	25.4	millimetres
knots (international)	0.5144444	metres per second
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square metres

FEASIBILITY STUDY OF A NUMERICAL TOW MODEL

PART I: INTRODUCTION

Background

1. The inland waterway system is composed of ports, locks, and the connecting channels between them. As the system has grown both in traffic density and miles of navigable waterway, the need to have a viable means of designing navigation improvements to the channels has become more acute. Proposed channel improvements have been tested by physical hydraulic models and model towboats with attached barge flotillas. Figure 1 shows a photograph of one of the model tows being tested. This type of testing and analysis has been useful for comparative channel improvements giving a good indication of tow response, especially in high current regions. The reproducibility of tow navigability results is difficult due to the model piloting variables that affect the tests. Physical scale modeling is also very expensive, due to the high model construction cost.

Purpose of Study

2. The numerical tow model project was initiated, in part, to assess the benefits that would result from channel improvements (straightening, widening, or lengthening radii of bends) over a major segment of the inland waterway system instead of or in addition to replacement or upgrading of lock facilities. It is presently not feasible to build a scale model to study the impact of channel improvements on navigation benefits. Economic analysis of channel improvements requires the computation of corresponding decrease in transit time. The relative use of steering and flanking rudders and towboat power setting also influences the economy of tow operation. The purpose of this study was to explore the feasibility of developing a mathematical model to simulate tow behavior.

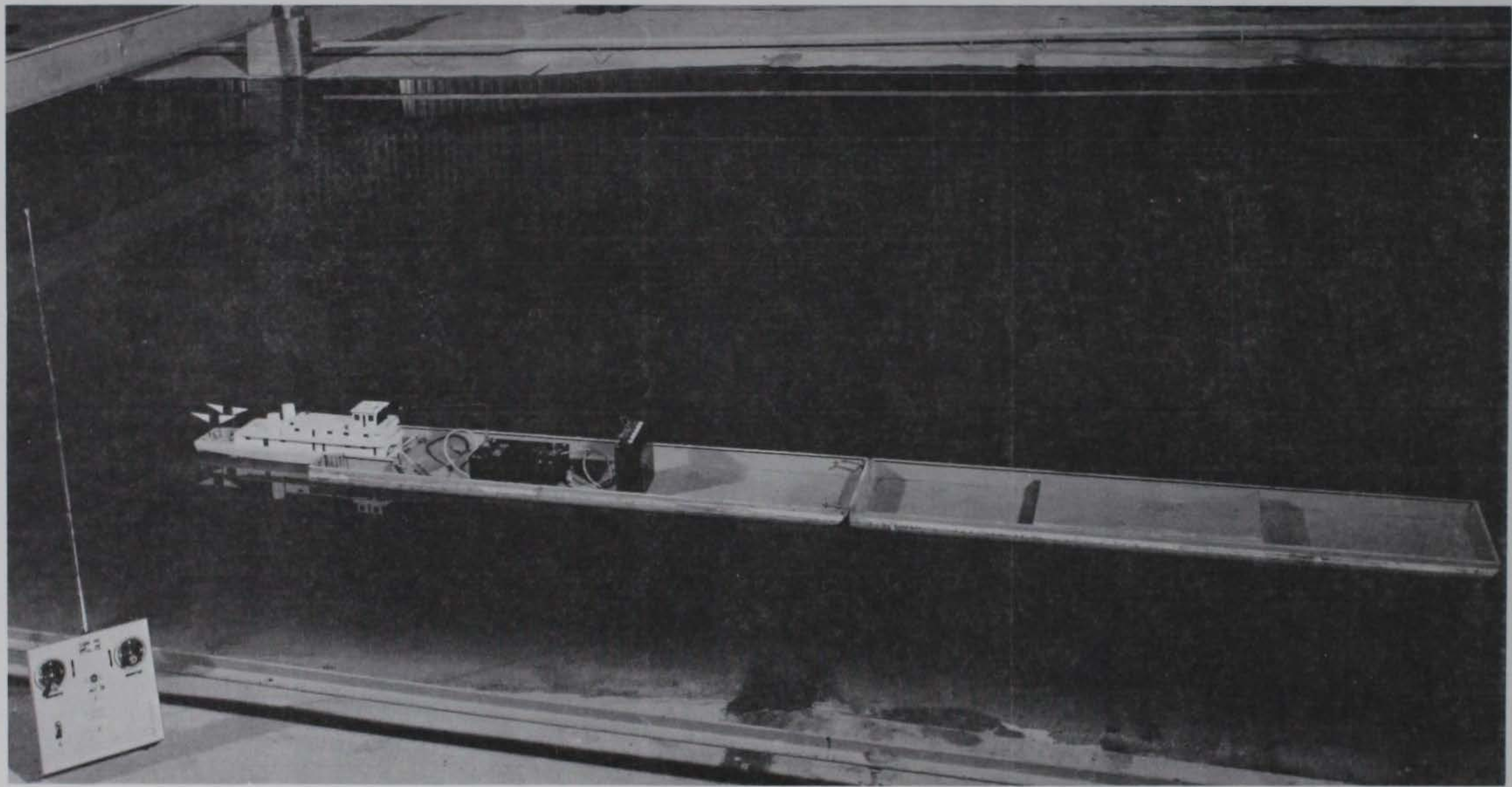

Figure 1. Towboat and barges with remote controlled steering

3. This report describes the work that has been completed on the project to study the feasibility of developing a numerical hydrodynamic model of the towboat-barge combination. The report covers a brief assessment of relevant literature on mathematical ship models and the efforts to develop numerical models for inland tows. A series of tests using a scale tow model are described and the resulting data analysis is also presented. The numerical model used is described and the results of typical ship and tow simulations are presented. Methods of calculating the required tow hydrodynamic coefficients are discussed in Appendix A.

PART II: REVIEW OF LITERATURE

Research Results

4. Some of the results of research on ship hydrodynamics has been presented in the book edited by Comstock.[1] Ship design has been improved by using test results from large ship model towing tanks where data on hull forms, rudders, propellors, ship stability, and ship maneuverability are systematically developed. The mathematical modeling of ships has been fairly well developed and reports on the results of such research are numerous. Most ship modeling has been concerned with ship design problems in open water navigation; however, shallow water and bank effects have been included in some of the more recent mathematical models.

Mathematical Models

5. The mathematical models developed for ships are based on general hydrodynamic principles and are equally applicable for use in a numerical tow model. The hydrodynamic coefficients that are required in the numerical model are expected to be substantially different than those found for ships. Some examples of differences which may influence the numerical model are given below. Towboat steering systems usually require a higher level of maneuverability than ships. Combination steering and flanker rudders with Kort nozzles have been developed for towboats involved in river service. Typical river barge flotilla bows are much blunter than ship type forms and operate at much shallower drafts than ships. The large variability of barge flotilla configuration is another factor to consider in a numerical model. Towboat propulsion systems are also designed considerably different from ships with tunnel hulls and higher power/load ratios.

6. A review of the literature on mathematical models of towboat maneuverability has produced very few studies in this area; at the

beginning of the study, no work towards developing a mathematical model of tows had been reported. This review has shown that towboat design has evolved without any detailed research on maneuverability, such as that with ship design. This may be due to the fact that river push towing has developed relatively recently compared to ocean shipping. There appears to have been a lack of incentive in the industry to investigate the maneuvering characteristics of barge flotillas. It was learned by correspondence and personal contacts with some of the representatives* in the towboat construction industry that some research work has been accomplished at the Netherlands Ship Model Basin to improve towboat propulsion and steering efficiency. Some design improvements resulting from these studies include the development of tunnel hulls, Kort nozzles, large engines (up to 10,000 hp), large towboats, and integrated tows. Some of these improvements have enhanced the maneuvering characteristics of the tows; but there apparently has been little effort by the towing industry towards systematic study of tow maneuverability.

7. Petrie's towboat and barge flotilla model[2] became available during the course of this study. This model appears to be the first to address tow maneuverability and is reviewed in some detail below. The model is configured to predict transit times through a series of maneuvers for various barge, towboat and bow thruster combinations. It is suited for assessing the influence of several parameters describing the physical characteristics of the tow, such as its length, width, towboat horsepower, and the presence or absence of a bow thruster. The channel through which the tow is to maneuver can be described by a combination of straight and circular segments, and a uniform current velocity can be specified. The model does not simulate all of the hydrodynamic tow characteristics and channel depth variations; shallow water and bank suction effects are not included. The mathematical model integrates the three force and moment equations in the horizontal

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* Dravo Corporation, Nashville Bridge and Iron Co., Netherlands Ship Model Basin, personal communication, 1977.

plane to determine motion and position of the flotilla. The hydrodynamic coefficients used in the model can be either based on towing tank test results or calculated by first order approxmations which ignore non-linear effects. The model has not been verified against laboratory or field data.

8. The Petrie model was procured and studied for possible adaptation to the numerical tow model development. It was concluded that this model could be of some use in river planning studies. However, the determination of hydrodynamic force and moment coefficients would require refinements. Model comparisons and validation against field or model results would be required. A much simpler model was desired for this feasibility study of tow maneuvering simulation. However, the model represents a useful step towards the eventual goal of studying the economic impact of waterway channel improvement. As indicated in Appendix A, the hydrodynamic coefficients were estimated for this study using Petrie's calculation method.

9. Recent information from the Coast Guard indicates that the Petrie model is being modified in the following areas:

- a. Develop more generalized channel description with variable cross currents,
- b. Modify propellor and rudder model to allow astern operation,
- c. Improve hydrodynamic coefficients estimations,
- d. Incorporate variable wind field and force on tow, and
- e. Develop a manual pilot control capability.

The modified model software will be available to the Coast Guard at the end of the development.

10. Eda's ship motion simulation model[3] also became available and was procured during the course of this study for possible adaptation. The model formulation is presented along with typical tanker maneuvering simulation results. Methods to generalize the model to include shallow water, bank suction, current and wind effects are outlined in the report. It is understood that these efforts are presently under way. A suggested set of hydrodynamic coefficients for a typical

80,000 DWT tanker are presented. The details of the ship numerical model are described by Eda[4], including computer code listings. Two programs are available; one program simulates standard maneuvers while the other simulates typical harbor entering maneuvers. New York Harbor is used for input as an example of harbor entrance computations.

11. The details of the mathematical ship motion model developed by Eda were studied. It was concluded that the model for the standard maneuvers (TURNCG) could be adapted to the towboat numerical modeling development. Accordingly, the listed computer code was implemented on the Waterways Experiment Station (WES) timesharing system. The model can be used for a towboat as well as ship motion simulation of standard maneuvers given the appropriate hydrodynamic coefficients.

12. The program NYHARB for harbor entrance modeling is longer and somewhat more complex, but could also be implemented for specific channel waterway studies. The model[5], as modified by the Coast Guard, can simulate the behavior of a vessel negotiating a user defined harbor or channel system. The program produces a report identifying the periodic location and status of the simulated vessel over time. The model incorporates shallow water and bank suction effects. Because the ship must negotiate a harbor system, a steering or pilot module is included to provide rudder commands. Elements within the steering module permit the inclusion of probabilistic navigational errors if desired. The effects of wind or current are presently not incorporated in the program; nor is squat simulated. Presently the hydrodynamic coefficients are available only for an 80,000 DWT tanker, but work is under way to provide the capability to simulate a variety of types and sizes of ships.

Other Studies in Progress

13. Recent contact with the Coast Guard also indicates a river tow numerical model development effort under way at Hydronautics, Inc.[6] The research includes the following tasks:

a. Modify existing ship maneuvering mathematical models to simulate tow motions,

b. Planer motion mechanism (PMM) tests to determine hydrodynamic coefficients for an available tow model, and

c. Simulation study of river tow maneuvering at certain specific bridge sites.

14. The model as presently developed is for deep water and does not simulate shallow water or bank suction conditions, but does allow cross velocity shear on the tow. The model will allow both ahead and astern thrusts and therefore includes flanking maneuvers. The basic model software is proprietary and will not be available under the present research contract with the Coast Guard.

15. Due to the lack of full scale tow or model maneuverability data, a cooperative effort was initiated for WES to participate through contract in a series of tow performance tests. The tow performance test program was expanded to include tow maneuvers and the measurement of parameters that would provide data on tow maneuverability characteristics. While not a specific activity of the tow modeling project, it is mentioned briefly here to show how the WES modeling effort led to significant advances in basic tow performance information. These tow performance data can be used to validate both numerical or scale tow models for use by WES to improve navigation simulation validity. These trials were conducted on the Mississippi River at Baton Rouge, Louisiana, in November 1976. A report on the field data by the contractor[7] has been furnished WES.

16. The 3360 hp towboat MV Exxon Memphis, which was used in these tests, is powered through twin screws and fitted with Kort nozzles. The tow flotilla consisted of four loaded integrated barges with a total length of 1160 ft and beam of 54 ft.* Tests were conducted for the following conditions:

a. Steady ahead, straight course at various power settings, up river and down river.

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* A table for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

_b_. Full power zig-zag, up river and down river, and

_c_. Half power turns up river and down river.

Measurements were made of engine speed and power, shaft speed, and rudder angle. The tow position and attitude were obtained from electronic distance measuring equipment.

17. Additional field tests were conducted in November 1977 with two additional tows, using an improved data collection system and involving an expanded test program. It is expected that all data will be published and distributed for use by the industry and research laboratories.

PART III: MATHEMATICAL MODELS

Linear Model

18. The equations describing ship and tow motion were originally derived by Abkowitz[8] and the details are presented by Mandel.[1] A method of solving these equations for ship motion with a computer program has been presented in a David Taylor Model Basin report[9] for the more complete nonlinear model. For the purpose of this feasibility study, the linear model can be used to determine whether the concepts used for ship motion simulations can be used for towboat-barge flotillas. The equations of motion are formulated for a tow with rudders for control and propellers to provide thrust. Tow motion is translational in the x-y plane and rotational about the z-axis, without any vertical motion. It has been found that these three equations are adequate for maneuverability simulation of large surface ships. Figure 2 shows a definition sketch and the coordinate axis about the tow center of gravity.

19. The forces and moments exerted on the tow are composed of:

   a. Hydrodynamic forces and moments, due to the motion of the tow,

   b. Rudder and propeller forces, and

   c. Disturbances caused by wind, waves, current, channel banks, passing tows, etc.

20. For this study, the model will be simplified to consider the first two forces only. Disturbances can be incorporated after further model development. The model under consideration will be formulated for a tow traveling at a constant speed in deep, slack water with no cross current or wind. Hydrodynamic and rudder forces may be expressed in a linear form by expanding the equations of motion in a Taylor series about the tow center of gravity and considering only the first order terms. Mandel[1] gives details of the linear model. If a tow running with only small deviations from a straight course at constant speed

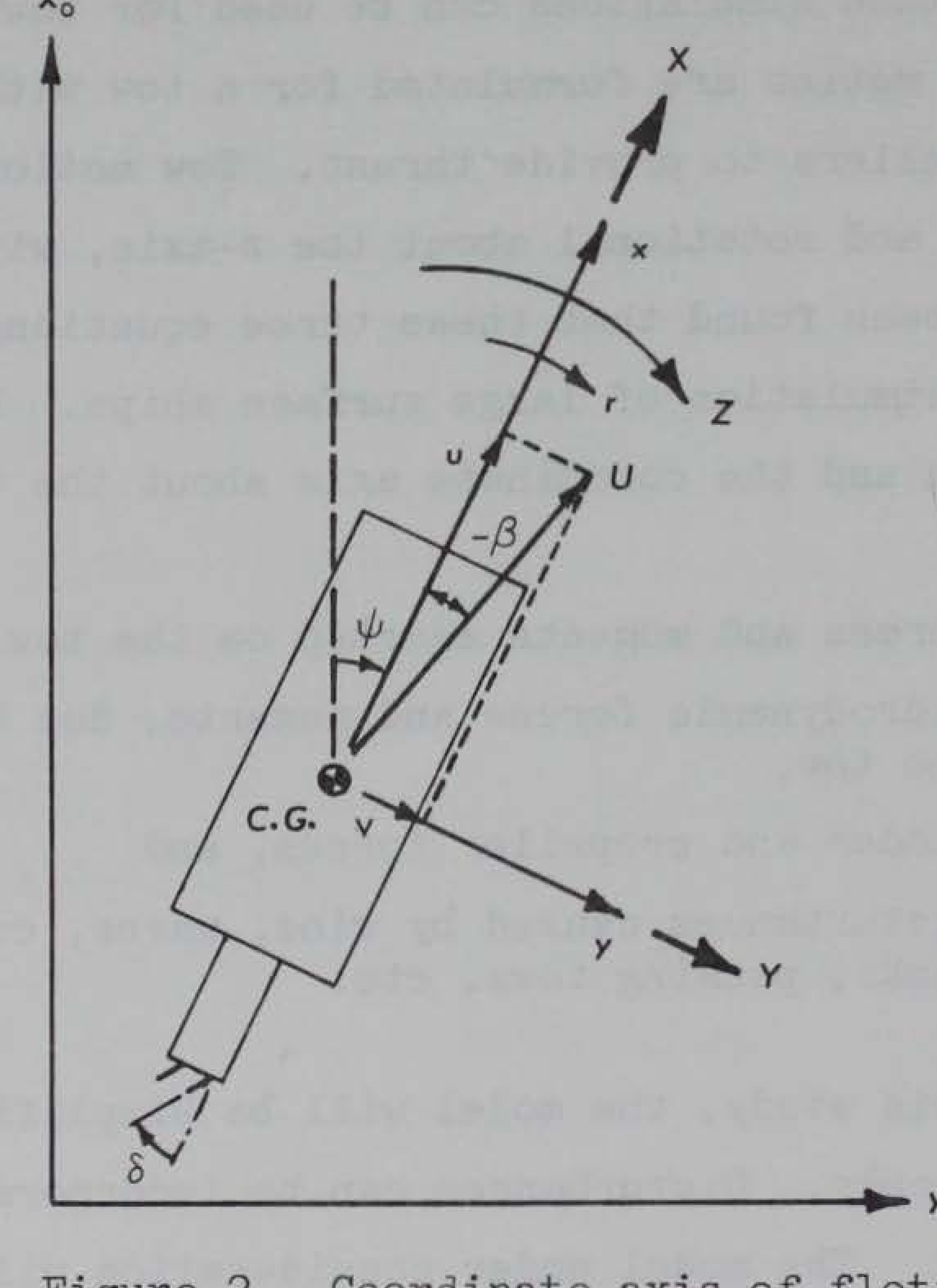

Figure 2. Coordinate axis of flotilla

is considered, two linear dimensional equations describing the sway and yaw motions result:*

$$(m - Y_{\dot{v}})\,\dot{v} - Y_{\dot{r}}\dot{r} - Y_v v - (Y_r - mU)\,r - Y_\delta \delta = \Sigma Y_i \qquad (1)$$

$$(I_z - N_{\dot{r}})\,\dot{r} - N_{\dot{v}}\dot{v} - N_v v - N_r r - N_\delta \delta = \Sigma N_i \qquad (2)$$

where

ΣY_i, ΣN_i are external forces and moments, respectively,

U is the speed of the tow,

$Y_{\dot{v}}$, $Y_{\dot{r}}$ are added masses,

$N_{\dot{r}}$, $N_{\dot{v}}$ are added moments of inertia,

Y_v, Y_r, N_v, N_r are damping coefficients, and

Y_δ, N_δ, are rudder coefficients.

Definitions of the terms are given in Figure 2 and Appendix B. In a linear model the axial equation (x direction) is not necessary since the tow is assumed to proceed at constant speed U so that $U = \frac{dx}{dt}$.

21. The dimensional model is usually made dimensionless and presented as follows if external forces and moments are ignored:

$$(m' - Y'_{\dot{v}})\,\dot{v}' - Y'_{\dot{r}}\dot{r}' - Y'_v v' - (Y'_r - m')\,r' = Y'_\delta \delta \qquad (3)$$

$$(I'_z - N'_{\dot{r}})\,\dot{r}' - N'_{\dot{v}}\dot{v}' - N'_v v' - N'_r r' = N'_\delta \delta \qquad (4)$$

Definitions of the dimensionless hydrodynamic coefficient terms are given in Table 1 and Appendix B.

22. The linear model outlined above requires the specification of at least nine hydrodynamic coefficients. Theoretical methods can be

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* For convenience, symbols and unusual abbreviations are defined in the Notation (Appendix B).

used to obtain some of the coefficients, but towing tank tests are required for reliable tow simulation. A great deal of testing would be necessary to measure the coefficients to produce a fairly complete linear model using these equations.

23. It is possible to simplify the mathematical model further by using the Nomoto equations.[10] These equations consider the hydrodynamic characteristics of the tow and rudder(s) to be characterized by two coefficients, K and T. The Nomoto equations are much simpler than the complete linear model and closed form solutions have been obtained for some of the definitive maneuvers.[11] The two equations for yaw and sway are

$$T\ddot{\psi}(t) + \dot{\psi}(t) = K\delta(t) \tag{5}$$

$$T_\beta \dot{\beta}(t) + \beta(t) = K_\beta \delta(t) \tag{6}$$

where

ψ is the heading angle,

β is the drift angle, and

T, T_β, K, K_β are coefficients based on the hydrodynamics of the tow and rudder(s).

The drift angle $b = -\frac{v}{U}$ (in radians) for a linear system. Dimensionless forms of these equations can also be obtained. Nomoto[11] showed how the four hydrodynamics coefficients K, K_β, T, T_β in this model could be related to complex relations involving the linear hydrodynamic coefficients.

24. The attractiveness of the simple K-T Nomoto model is its simplicity and the ability to obtain the four coefficients from tow field trials or free-running scale model data. Data concerning rudder angle δ, drift angle β, and heading angle ψ, could be recorded for a particular maneuver or series of maneuvers. By reducing the data, $\dot{\psi}$, $\ddot{\psi}$, and $\dot{\beta}$ can be found for particular values of δ. Using data from several tests and the Nomoto equations, a system of simultaneous linear equations can be solved to produce the coefficients (K, K_β, T, and T_β). Once the

coefficients have been calculated, the solution of the equations for surge and sway as a function of rudder settings can be obtained by well known finite difference time stepping procedures if initial conditions are known. However, to produce reliable K-T coefficients would require a rather large volume of model data.

Nonlinear Model (Eda)

25. The complete linear model and the simpler Nomoto model version of the linear model are applicable only at small rudder and yaw angles. More complete nonlinear models have been formulated and used to simulate ship motions under a variety of maneuvering conditions. The derivation and method of model formulation is presented in detail by Mandel[1]. Several fairly complete nonlinear models are known to have been developed using square or cubic polynomials to approximate the hydrodynamic force and moment functional relations. Eda[3,4] has presented details of a model for ship maneuvering simulation that was recently developed. As noted above, the TURNCG program was implemented on WES timesharing system. The model will execute either a turning circle or z-maneuver with a pre-specified sequence of rudder angles. Figure 3 shows numerical ship model computational results for an 80,000 DWT tanker.

26. The mathematical model TURNCG requires several kinds of input data to simulate turning circle or z-maneuvers of tows. The program allows a choice of the kinds of maneuvers and rudder angle settings. Table 2 gives the details of the input data requirements. The ship hydrodynamic coefficients and principal dimensions are required as input data. Initial conditions and certain control parameters to stop the computations are also part of the input data.

27. The computational cycle of the model calculates the hydrodynamic moment and forces at each time step. From these dimensional forces and moments, the linear and angular accelerations are given as follows:

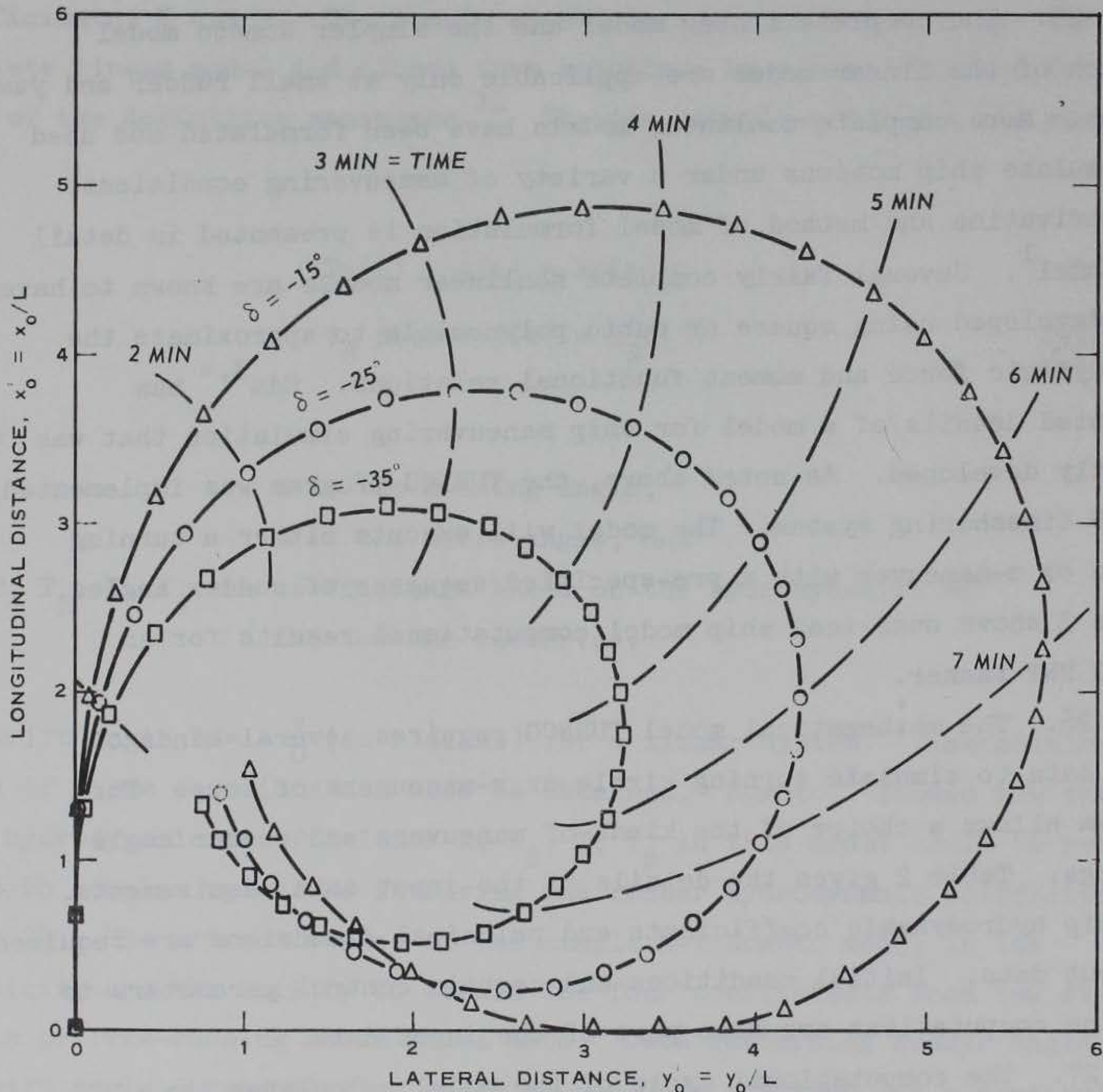


Figure 3. Results of turning circle computations

$$UDOT = \frac{XT}{MX} \tag{7}$$

$$VDOT = \frac{YT}{MY} \tag{8}$$

$$RDOT = \frac{NT}{IZ} \tag{9}$$

where XT, YT, and NT are the sum of all the hydrodynamic forces and moments acting on the tow and MX, MY, and IZ are the tow mass plus added mass due to acceleration or tow inertia in yaw plus added moment of inertia. These can be integrated by an Euler forward difference technique to calculate the linear and angular velocities as follows:

$$U = U_{i-1} + UDOT*DELT \tag{10}$$

$$V = V_{i-1} + VDOT*DELT \tag{11}$$

$$R = R_{i-1} + RDOT*DELT \tag{12}$$

The tow attitude is given by the following since R = PSIDOT,

$$PSI = PSI_{i-1} + R*DELT \tag{13}$$

The distance traveled in relation to the fixed axis x_o, y_o by the tow can be calculated from

$$X_o = X_{o(i-1)} + UF*DELT \tag{14}$$

$$Y_o = Y_{o(i-1)} + VF*DELT \tag{15}$$

where

$$UF = U \cos PSI - V \sin PSI \tag{16}$$

$$VF = U \sin PSI + V \cos PSI \tag{17}$$

28. The output of the model gives the following quantities (see Table 3 for an example of the model output)

TIME - elapsed time from beginning of maneuver, sec,

DELDEG - rudder angle, in degrees,

PSIDEG - heading angle, in degrees,

YP - dimensionless lateral distance, y_o/L,

XP - dimensionless longitudinal distance, x_o/L,

RP - dimensionless rate of turn, $r' = rL/U$ (note that r is in radians per second and not degrees per second),

BETA - drift angle from tow speed vector to tow axis, in degrees,

U/UO - dimensionless speed as a function of initial straight course speed (speed loss), and

TP - dimensionless time, $t' = tU/L$.

The output file could be easily modified to include ship path plots and time histories of tow variables.

PART IV: TOW MODEL TESTS

29. The literature study and personal contacts with various companies and institutions showed that no data on towboat maneuverability was available. Thus, it was decided to conduct a series of tests in the laboratory using a model towboat barge combination in a deep water test basin for slack water condition. Slack water conditions are different from river operations which have strong to moderate current patterns; however, these conditions were considered adequate since the purpose of the present study was to determine the applicability of hydrodynamic models of ships to shallow draft tows. The model test results, while limited, would allow the development of a first stage numerical towboat model to be refined as data become available.

Test Facility and Conditions

30. This section describes the test facility, test conditions, model tow, variables instrumented, and data acquisition. Tow tests were conducted with two of the ship type standard maneuvers, the circle test being the primary maneuver. These tests can be used to determine the performance of the tow at various rudder settings. Testing was conducted in a large tidal inlet physical model facility at WES during February and March 1977. The overall dimensions of the testing basin were 60 ft x 128 ft. The actual area used varied from test to test depending on the particular maneuver being simulated. The water level was maintained so that the depth during testing was 7-1/2 to 8 in. A reference grid system, composed of numbers (y-axis) and letters (x-axis), was painted on the horizontal concrete bottom with an interval of 2 ft. The basin was located in an inclosed building where no wind was present. An observation area for the video tape camera operator was provided by cat walks above the model area.

Model Tow

31. The model tow consisted of a towboat and flotilla of barges as used in physical model studies and is shown in Figure 1. Dimensions of the towboat and barge flotilla are given on Table 4. The towboat was constructed of plastic having two propellers fitted with Kort nozzles, with a steering rudder aft and a flanking rudder forward of each propeller. Figure 4 presents a drawing of the model towboat. The propellers were driven by an electric motor whose shaft was geared directly to each propeller shaft. The motor could be controlled at a constant speed either in the forward or reverse direction by a remote control unit. The rudders operated as a unit (steering or flanking) and were also actuated by the remote control unit. The flotilla was modeled as a single unit integrated barge. The dimensions are given on Table 4 and a definition sketch presented in Figure 5. The barge was raked at the bow with a smooth, flat bottom and straight sides and stern, typical of modern integrated barges. The barge was constructed of sheet metal and held the power supplies for the boat and the instrumentation as well as the data transmitter. Additional ballast was provided by bricks that were positioned to balance the barge both longitudinally and transversly. This towboat-barge combination has been used by the Waterways Division of the Hydraulics Laboratory to simulate a 600 ft x 105 ft tow pushed by a 5000 hp towboat (approximate scale 1:70) for studies at lock approaches in bendways, and other navigation problems. During testing only the forward drive and the steering rudders were used. The flanking rudders remained in a neutral position.

Test Variables

32. The data items recorded both on magnetic tape and strip charts were: angular position of steering and flanking rudder(s), speed of the motor in rpm, and the motor current and voltage. Rudder angles were obtained by recording voltages from constant rotation potentiometers

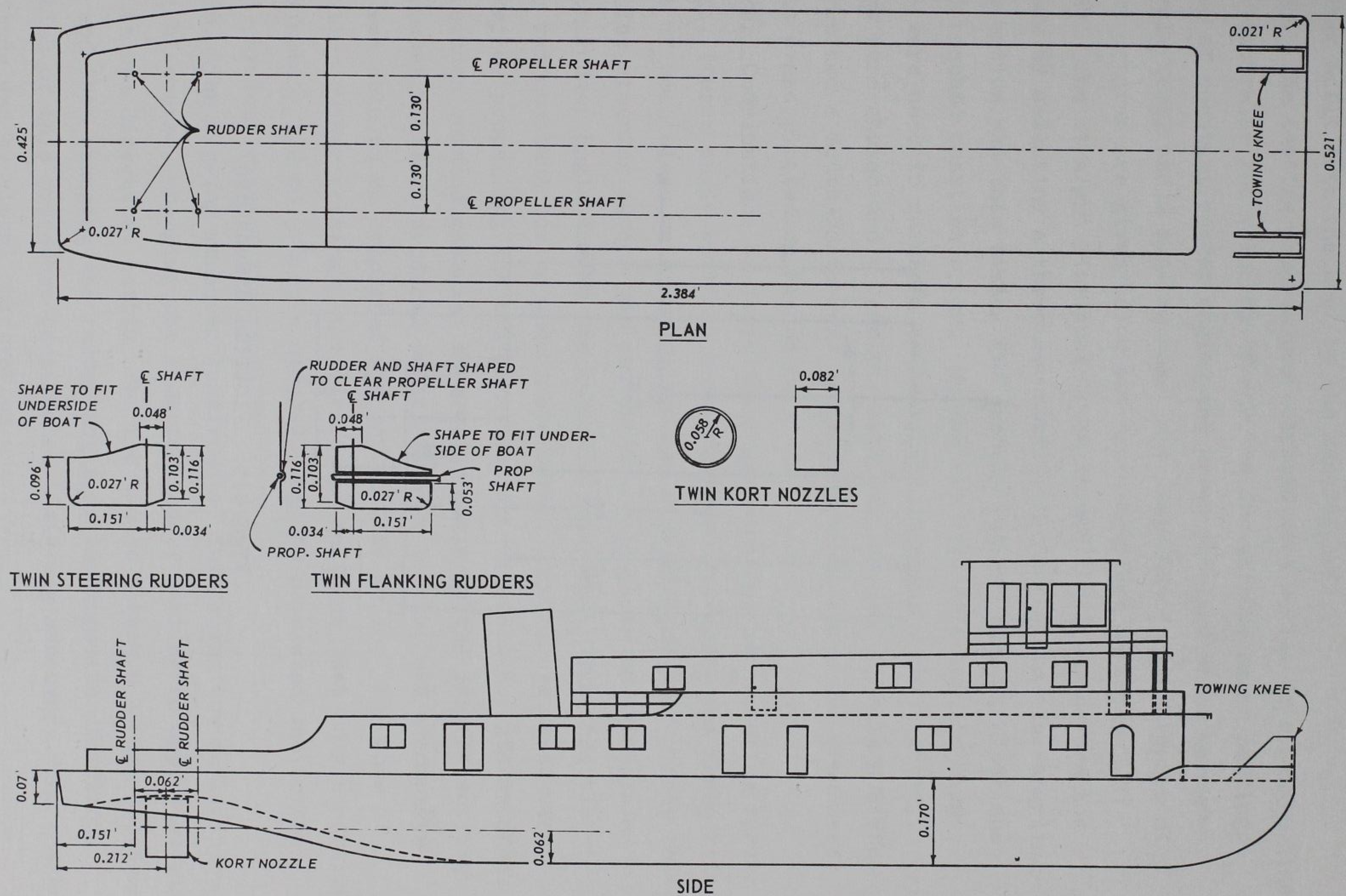


Figure 4. Model towboat characteristics

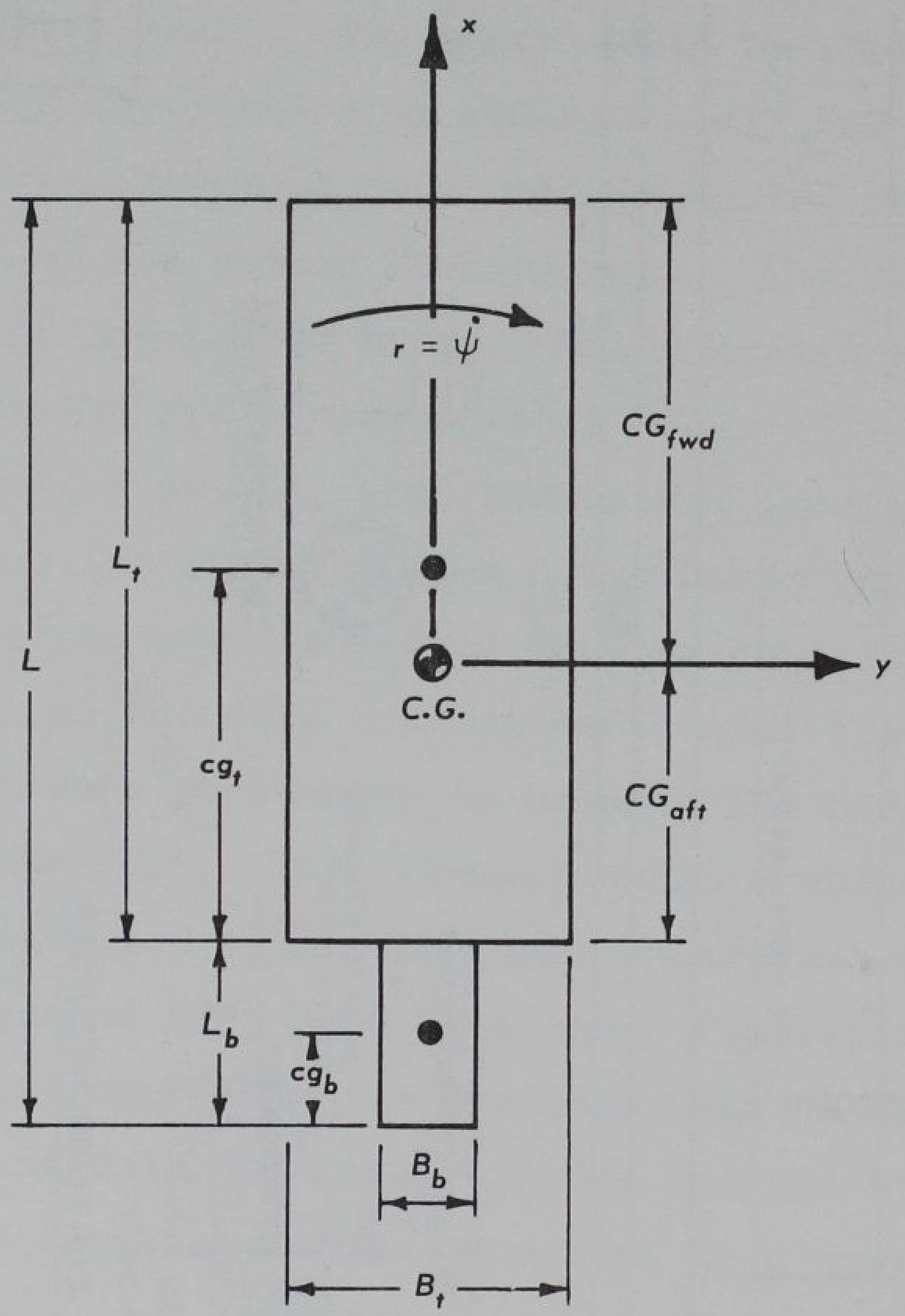


Figure 5. Flotilla dimensions

attached to the steering mechanisms. Speed of the motor was from the tachometer built into the boat by the manufacturer.

33. The testing program was composed of a series of straight line runs to determine the velocity of the tow for various motor settings; a series of constant rudder angles and speed settings which produced the circle test, and a zig-zag run. More details of each segment of the test program are given below and are summarized in Table 5.

34. The straight line runs to calibrate the speed of the tow were made by selecting a throttle setting, lining up the tow, starting forward motion and then timing the transit between markers after the tow had reached constant speed. During the test only the steering rudders were used to maintain the straight course. Four throttle settings were chosen and a complete test was composed of both a North-South run and a South-North run. Data from these tests are presented in Table 6 and plotted on Figure 6.

35. Combinations of three throttle settings, six steering rudder settings, (three angle settings both starboard and port) and three trials per set of conditions were run to produce a large number of circle test data. The steering rudder was set using a stop-plate to maintain a constant rudder angle during the entire circle test. The throttle setting was constant during the circle tests. The circle tests were conducted by propelling the tow on a straight line course, steady ahead with a sudden command changing the rudder angle to the desired setting. Large rudder settings produced small diameter circles and a complete circle was able to be completed within the test basin. For some of the smaller rudder settings, the circle was so large that only a portion (approximately 1/2 to 3/4 of a circle) could be completed due to the limited physical size of the facility.

36. The zig-zag maneuver consisted of initiating tow motion along a straight course, changing the steering rudder setting to approximately 10 deg in one direction, waiting for the tow to attain a 10-deg attitude change and then changing the rudder angle in the opposite direction. Repetition of this procedure constituted a zig-zag maneuver. The change in attitude was by visual observation only.

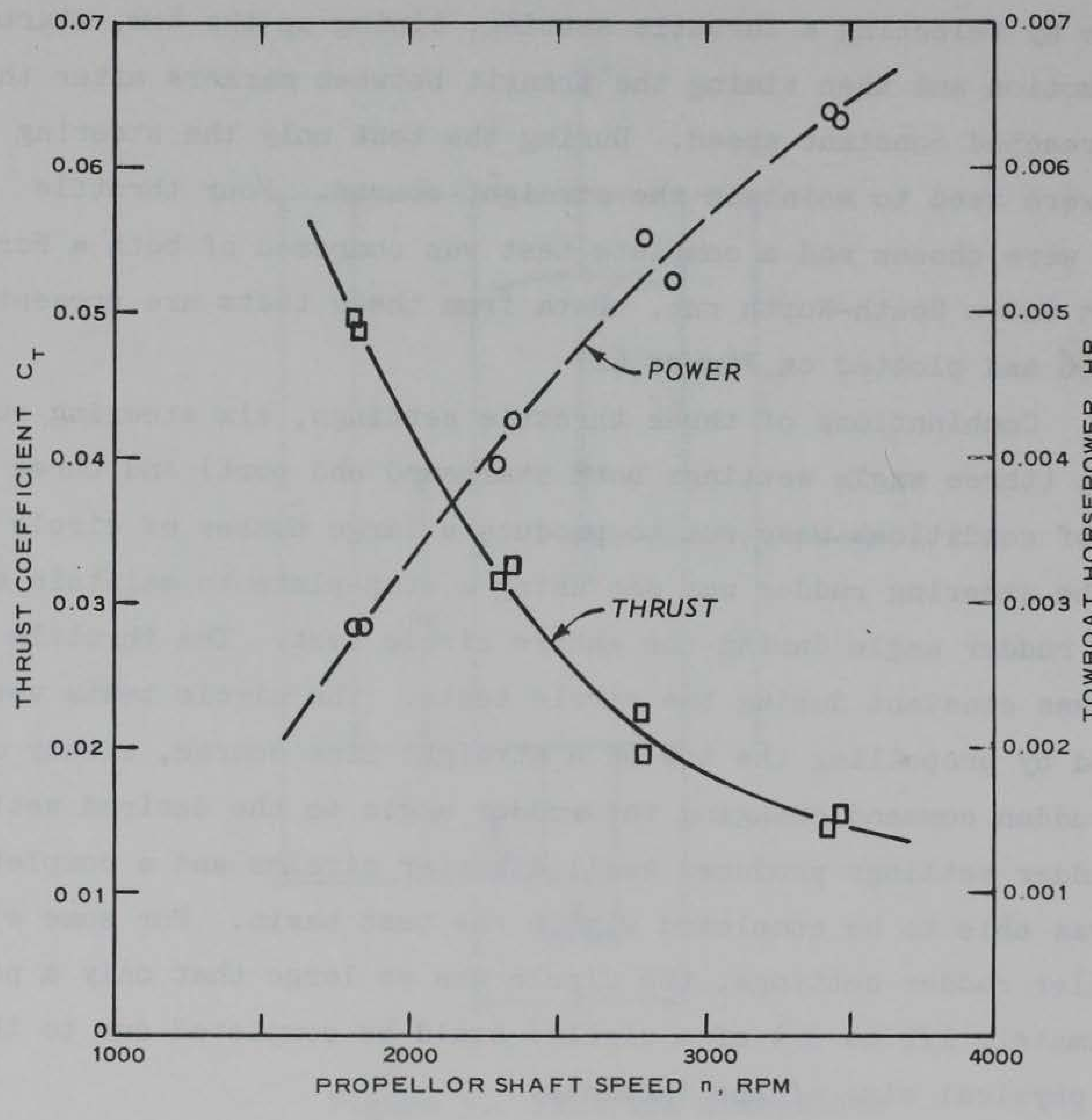


Figure 6. Model towboat propulsion characteristics

Data Acquisition

37. All tests were recorded on video tape to obtain position and attitude of the tow, and on magnetic tape and strip chart paper to record steering rudder angle, flanking rudder propeller angle, and motor voltage and current. Two specific tests were analyzed in detail for this report. The remaining test data are available for further analysis, if desirable.

38. The video tape was taken using a hand-held camera approximately 18 ft above the water surface. A time code generation device was incorporated with the taping so that the video could be correlated with the other recorded data. During the testing, it was found that the video time code generator was not in perfect synchronization with the code on the magnetic and paper tapes. The video indication of time was about 14 sec slow, i.e., an event recorded in slow code on the strip chart recorder at 1:00.00 would be recorded on video with a time indication of 1:00.14.

39. The data recorded on the strip chart from the tow was a function of a voltage measurement. Zeroes and calibration steps preceded each series of tests. The recorded voltages were translated to numerical values of the pertinent tow variable with the use of calibration curves. The chart data were analyzed from the strip chart record with samples every 10 sec. Visual inspection of the chart records revealed nearly constant values for the tow variables thus more frequent measurements were not required. The reduced data for the two tests that were analyzed are presented in Tables 7 and 8.

40. Analysis of the video tape to obtain the position and orientation of the tow during the test maneuvers was rather difficult and time consuming. This was due to the lack of adequate contrast on the video tape and difficulty in stopping the tape at a desired time for reading the tow position. Extraction of the position of the tow's bow, stern and center of gravity was obtained from still photographs taken at various times during the test maneuvers as recorded on the video tape. The positions were measured with respect to the grid that

had been created on the test basin floor. These grid locations were translated into x-y coordinates and calculations of ψ, $\dot{\psi}$, U, and β were based on these coordinates and rates of change in the coordinates using simple geometric relationships. Tables 9 and 10 present the reduced data from the video tape recordings.

PART V: RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

Computation and Scale Model Results

41. The data from the reduced scale model test No. 17 are shown on Figure 7 compared with the numerical tow model computations. As explained in Appendix A, the rudder force and moments were corrected on the basis of the observed model data. In addition, as shown in Appendix A, only linear tow coefficients could be calculated; thus, the computations result from a linear model. The coefficients used to obtain the results shown in Figure 7 are those resulting after all adjustments and are the last values listed for each coefficient in Table 1. The coefficients were used in Eda's[4] TURNCG model to calculate the tow's turning circle.

42. The linear mathematical model can be used to find several important stability and steering qualities of ships and tows. In particular, the relation between a turning circle radius and the hydrodynamic coefficients have been derived[1] and are given below:

$$R = -\frac{L}{\delta}\left[\frac{Y_v'(N_r') - N_v'(Y_r' - m')}{Y_v' N_\delta' - N_v' Y_\delta'}\right] \tag{18}$$

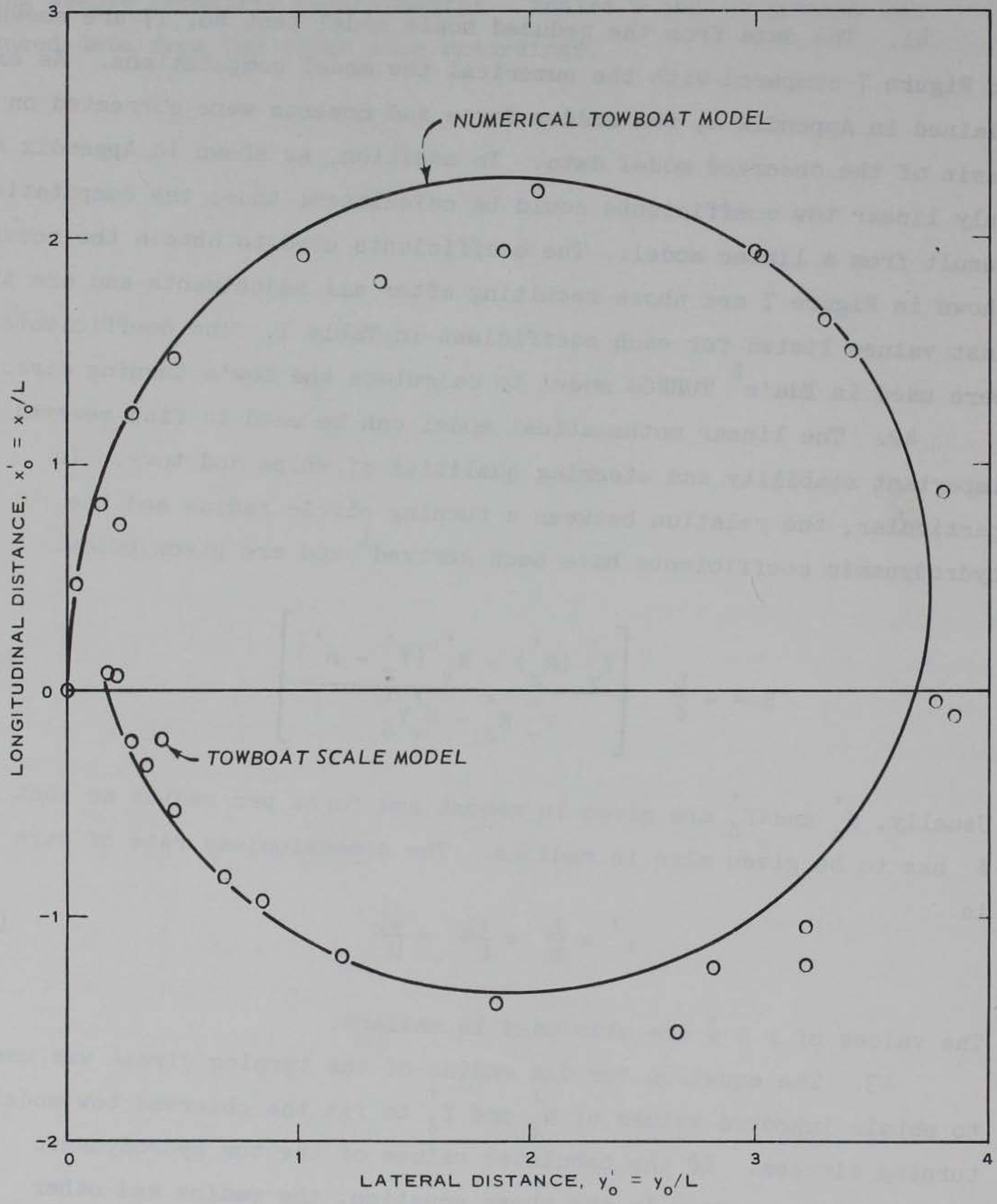
Usually, N_δ' and Y_δ' are given in moment and force per radian so that δ has to be given also in radians. The dimensionless rate of turn is

$$r' = \frac{L}{R} = \frac{rL}{U} = \frac{\dot{\psi}L}{U} \tag{19}$$

The values of $r \equiv \dot{\psi}$ are also used in radians.

43. The equation for the radius of the turning circle was used to obtain improved values of N_δ' and Y_δ' to fit the observed tow model turning circles. If the tabulated values of the tow hydrodynamic coefficients are used in the above equation, the radius and other wide-turn test values are found to be

$$R = 14.39 \text{ ft},\ D = 28.8 \text{ ft},\ R/L = 1.81,\ r' = 0.554$$



NOTE: $\delta = 20°$, APPROACH SPEED = 0.6 FT/SEC

Figure 7. Physical and numerical model turning circle test comparison

It is also possible to calculate the rate of turn using the yaw angle as a function of time to obtain $\dot{\psi}$. The tow yaw data can be used to obtain the following angular rate of turns:

Test No.	$\dot{\psi}$ ($^\circ$/sec)	U (ft/sec)	r'	R (ft)	R/L
14	3.509	1.18	0.413	19.2	2.42
17	1.835	0.60	0.425	18.7	2.35

These results indicate that the tow speed has only a minor effect on, rate of turn. The rate of turn from the yaw rate data indicates a smaller rate of turn and longer turning circles by about 30 percent compared to the geometrically determined rate of turn. This is probably due to speed loss effects during the turning circle which are not properly simulated in the linear model.

44. Hydrodynamic coefficients have been published by Eda[12] for a barge model flotilla with a push tow. The configuration was quite different than the tow scale model used to obtain the circle test data presented in this report. Nevertheless, the comparison may be worth noting and is presented in Table 11. Also shown are preliminary towing tank results obtained with a typical river towboat and barge flotilla.[7] Also shown are computations of turning radius and rate of turn for a 20° rudder angle. Additional research effort will be required to properly interpret these computations.

45. One of the Exxon full scale tow tests previously mentioned[8] included a steady upriver turn with the following characteristics:

$$\dot{\psi} = -0.196^\circ/\text{sec},$$
$$\delta = +14.9^\circ,$$
$$L = 1160 \text{ ft, and}$$
$$U \simeq 13.4 \text{ ft/sec (speed of approach through the water).}$$

From these data the rate of turn can be calcuated as

$$r' = \frac{\dot{\psi}L}{V} = 0.296 \qquad \text{radians}$$

If the rate of turn versus rudder angle is approximately linear, this would give $r' \approx 0.397$ at 20°.

46. The comparative tow maneuverability data shown above are presented to show the preliminary nature of the numerical model. The need for more definitive information on tow hydrodynamic coefficients is obvious. However, the comparison of results shown on Figure 7 indicates a reasonably good fit of the scale model data is possible. Additional computations and comparisons to other model tests would be necessary to more completely validate the numerical model. Nevertheless, the results demonstrate the feasibility of such computations.

Study Conclusions

47. The study has shown that there were no known reliable numerical models specifically applicable to tow motion simulation at the time of this study. Mathematical models that are well developed for ship maneuverability can be adapted to tows, but require several tow hydrodynamic coefficients. Towing tank tests and numerical model development are being conducted under Coast Guard sponsorship. These measurements and the hydrodynamic coefficients are only now becoming available. Standard maneuver tests with free running models (such as those conducted in this study) can be valuable in validating a developed numerical tow model. Based on the results of this exploratory model development, it is concluded that a useful numerical tow model for tow motion simulation is feasible.

Recommendations

48. The ongoing research at several research laboratories should be monitored for hydrodynamic coefficient test results and improvements in numerical tow modeling. When the data and refined models become

available, additional development work should be undertaken to improve the capability for tow modeling. It is recommended that numerical tow models be validated against full-scale trial and free-running scale model data.

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TABLE 1

SUMMARY OF HYDRODYNAMIC COEFFICIENTS

Symbol	Definition	Magnitude($\times 10^{-3}$)	Remarks
N'_v	$\frac{N_v}{1/2\ \rho L^3 U}$	0.0961	Yaw moment due to sway
N'_r	$\frac{N_r}{1/2\ \rho L^4 U}$	-0.5899	Yaw damping
$N'_{\dot{r}} - I'_z$	$\frac{N_{\dot{r}} - I_z}{1/2\ \rho L^5}$	-0.0487 (-0.3608)* (-0.2291)**	Added yaw moment of inertia
N'_δ	$\frac{N_\delta}{1/2\ \rho L^3 U^2}$	-0.5695 (-0.98)***	Rudder moment
Y'_v	$\frac{Y_v}{1/2\ \rho L^2 U}$	-15.5325	Sway damping
Y'_r	$\frac{Y_r}{1/2\ \rho L^3 U}$	0.0961	Sway force due to yaw
$Y'_{\dot{v}} - m'$	$\frac{Y_{\dot{v}} - m}{1/2\ \rho L^3}$	-0.8027 (-7.127)* (-4.3662)**	Added mass in sway
Y'_δ	$\frac{Y_\delta}{1/2\ \rho L^2 U^2}$	0.9520 (1.63)***	Rudder force
X'_δ	$\frac{X_\delta}{1/2\ \rho L^2 U^2}$	-0.9520 (-1.63)***	Rudder drag
I'_z	$\frac{I_z}{1/2\ \rho L^5}$	0.1804	Moment of inertia
m'	$\frac{m}{1/2\ \rho L^3}$	3.5635	Mass of tow

* Estimated using $2I'_z$ and $2m'$, respectively.

** Calculated assuming Petrie's formulas calculated $N'_{\dot{r}}$ and $Y'_{\dot{v}}$, rather than $N'_{\dot{r}} - I'_z$, and $Y'_{\dot{v}} - m'$, (e.g., $N'_{\dot{r}} = -0.0487 - 0.1804 = -0.2291$).

*** Corrected on the basis of measured model turning diameter ($1.72 \times N'_\delta$, Y'_δ, and X'_δ).

TABLE 2

INPUT DATA INFORMATION
Numerical Tow Model

FORTRAN Symbol		Definition
SL	L	Total Tow length, ft
UI	U_i	Initial speed, ft/sec
PRDEL	Δt	Time increment for printing trajectory data, sec
FINTIM	t	Time limit to finish a computer run, sec
FINPSI	ψ	Heading angle limit to finish a run, degrees
RLB	L/B	Length-beam ratio
RBH	B/H	Beam-draft ratio
CB	C_b	Block coefficient = $\nabla/LBH = \Delta/\gamma LBH$
CP	C_p	Prismatic coefficient = $\nabla/A_M L$, A_M = area amidship section
AR	A_R/LH	Rudder area ratio
RHDW	H/D_w	Draft/water-depth (It is zero in deep water.)
RBW	B/W	Beam/channel-width (It is zero in open water.)
A(N)	N=1,13	Hydrodynamic moment coefficients in yaw equation
B(N)	N=1,13	Hydrodynamic force coefficients in sway equation
C(N)	N=1,8	Hydrodynamic force coefficients in axial or surge equation
NIDEL	--	Number of rudder angles
RUDI (N)	δ	Rudder angle in degrees, N=1, NIDEL
EXTNO	--	Execute number (1 and 5 for circle turn- and z-maneuver, respectively)
RUDZ	ψ	Heading angle in degrees which initiates rudder execution to the opposite direction during z-maneuver

TABLE 3

Example of Numerical Model Output for Turning Circle
80,000 DWT Tanker, L = 763 ft
Approach Speed = 16 Knots

TIME	DELDEG	PSIDEG	YP	XP	RP	BETA	U/U0	TP
0.	0.	0.	0.	0.	0.	0.	0.46	0.
20.00	-15.00	1.88	0.00	0.66	0.11	1.49	1.00	0.66
40.00	-15.00	7.54	0.02	1.32	0.19	3.74	0.99	1.32
60.00	-15.00	15.74	0.10	1.97	0.25	5.91	0.97	1.97
80.00	-15.00	25.51	0.25	2.58	0.29	7.74	0.94	2.60
100.00	-15.00	36.04	0.48	3.15	0.31	9.15	0.90	3.21
120.00	-15.00	46.85	0.78	3.64	0.33	0.21	0.87	3.80
140.00	-15.00	57.68	1.16	4.06	0.34	1.03	0.83	4.36
160.00	-15.00	68.44	1.58	4.40	0.35	1.66	0.79	4.90
180.00	-15.00	79.07	2.03	4.64	0.36	2.17	0.76	5.42
200.00	-15.00	89.55	2.50	4.80	0.37	2.59	0.73	5.91
220.00	-15.00	99.88	2.98	4.86	0.38	2.92	0.71	6.39
240.00	-15.00	110.07	3.44	4.85	0.39	3.19	0.69	6.86
260.00	-15.00	120.11	3.88	4.76	0.39	3.41	0.67	7.31
280.00	-15.00	130.04	4.29	4.60	0.40	3.59	0.66	7.75
300.00	-15.00	139.85	4.66	4.37	0.40	3.73	0.64	8.18
320.00	-15.00	149.56	4.98	4.10	0.40	3.84	0.63	8.60
340.00	-15.00	159.19	5.24	3.78	0.40	3.93	0.62	9.02
360.00	-15.00	168.75	5.45	3.42	0.41	3.99	0.62	9.43
380.00	-15.00	178.25	5.59	3.04	0.41	4.05	0.61	9.84
400.00	-15.00	187.69	5.67	2.65	0.41	4.09	0.60	10.24
420.00	-15.00	197.09	5.68	2.25	0.41	4.12	0.60	10.64
440.00	-15.00	206.45	5.63	1.86	0.41	4.14	0.60	11.04
460.00	-15.00	215.78	5.52	1.48	0.41	4.16	0.59	11.43
480.00	-15.00	225.09	5.35	1.13	0.41	4.17	0.59	11.82
500.00	-15.00	234.38	5.12	0.81	0.42	4.18	0.59	12.21
520.00	-15.00	243.65	4.85	0.54	0.42	4.19	0.59	12.60
540.00	-15.00	252.90	4.53	0.31	0.42	4.20	0.58	12.99
560.00	-15.00	262.15	4.19	0.13	0.42	4.20	0.58	13.38
580.00	-15.00	271.38	3.82	0.02	0.42	4.21	0.58	13.77
600.00	-15.00	280.61	3.44	0.04	0.42	4.21	0.58	14.15
620.00	-15.00	289.83	3.05	0.03	0.42	4.21	0.58	14.54
640.00	-15.00	299.04	2.67	0.03	0.42	4.22	0.58	14.92
660.00	-15.00	308.25	2.31	0.16	0.42	4.22	0.58	15.31
680.00	-15.00	317.46	1.97	0.34	0.42	4.22	0.58	15.69
700.00	-15.00	326.66	1.67	0.58	0.42	4.22	0.58	16.08
720.00	-15.00	335.87	1.40	0.86	0.42	4.22	0.58	16.46
740.00	-15.00	345.07	1.19	1.18	0.42	4.22	0.58	16.85
760.00	-15.00	354.26	1.03	1.53	0.42	4.22	0.58	17.23

TABLE 4

PRINCIPAL PARTICULARS
Model Towboat and Flotilla
(Approximate Scale 1:70)

	Dimension-less	ft	lbs	sq ft
Tow Length		5.583		
Towboat Length		2.384		
Total Length		7.967		
Tow Beam		1.500		
Towboat Beam		0.5208		
Tow Draft		0.1042		
Towboat Draft		0.09375		
Tow Center of Gravity (C.G.) Aft		2.813		
Towboat C.G. Aft		1.271		
Flotilla and Towboat C.G. Aft		2.391		
Location Tow plus boat C.G./Total Length	0.4011			
Tow Displacement			50.3	
Towboat Displacement			5.8	
Total Displacement			56.1	
Tow Block Coefficient	0.9240			
Towboat Block Coefficient	0.8016			
Total Area Steering Rudders (Twin)				0.03847
Total Area Flanking Rudders (Twin)				0.03201
Steering Rudder Area Coefficient $\left(\frac{LxH}{A_R}\right)$	20.909			
Steering Rudder Aspect Ratio (Span/chord)	0.5620			
Propeller Diameter (Twin Screws, Three-bladed, tips cut off)		0.1083		
Kort Nozzle Inside Diameter (Twin Screws)		0.1160		
Propeller Pitch/Diameter	1.814			

TABLE 5

Model Towboat Test Conditions

Index of Runs

Run #	Speed Setting	Rudder (°)	Maneuver	Remarks
1	8	0	St. Line	Speed Calibration
2	8	0	"	"
3	10	0	"	"
4	10	0	"	"
5	12	0	"	"
6	12	0	"	"
7	14	0	"	"
8	14	0	"	"
9	14	+20	F. Circle	Poor Video
10	14	+20	"	Brief Power loss, Poor video
11	14	+20	"	Brief Power loss
12	14	-20	"	OK
13	14	-20	"	OK
14*	14	-20	"	OK
15	8	+20	"	OK
16	8	+20	"	OK
17*	8	-20	"	OK
18	8	-20	"	OK
19	10	+20	"	Test aborted, Scratch video
20	10	+20	"	Power loss, Scratch video
21	10	+20	"	Scratch video
22	10	-20	"	Test aborted, Scratch video
23	10	+20	"	OK
24	10	+20	"	Brief power loss
25	10	-20	"	Brief power loss, Initial yaw?
26	10	-20	"	OK
27	14	+15	P. Circle	OK
28	14	+15	"	OK

Run #	Speed Setting	Rudder (°)	Maneuver	Remarks
29	14	+15	P. Circle	OK
30	10	+15	"	Reran test
31	--	--	--	No test w/this no.
32	10	+15	"	OK
33	8	+15	"	OK
34	8	+15	"	OK
35	14	-15	"	Poor test
36	14	-15	"	Poor test
37	14	-15	"	Brief power loss
38	14	-15	"	Brief power loss, Initial yaw
39	10	-15	"	Brief power loss
40	10	-15	"	Brief power loss
41	8	-15	"	OK
42	8	-15	"	OK
43	8	-13	"	Brief power loss
44	8	-13	"	OK
45	8	-13	"	OK
46	10	-13	"	OK
47	10	-13	"	Slight initial yaw
48	14	-13	"	OK
49	14	-13	"	Bad run
50	14	-13	"	Brief power loss
51	8	+13	"	OK
52	8	+13	"	OK
53	10	+13	"	OK
54	10	+13	"	OK
55	14	+13	"	Slight initial yaw
56	14	+13	"	OK
57	10	±12	Zig Zag	Rudder reversed when tow yaw reached previous rudder setting.
58	14	±12	"	
59	8	±12	"	
60	10	±12	"	
61	14	±12	"	

*Data reduced and analyzed.

TABLE 6

Model Towboat Characteristics
Steady Ahead Test Data

Speed Setting	Time[(1)] sec	Tow Speed ft/sec (U)	Shaft RPM	Motor Volts	Motor Current	HP[(2)] X10^{-3}	Resis-tance[(3)] lbs	Thrust[(4)] Coeff C_T	Rudder Angles Steering (Deg)	Flanker (Deg)
8	145.0	0.634	1811.7	2.21	0.95	2.815	2.442	0.0495	-1.3	-7.2
8	145.0	0.634	1832.0	2.30	0.91	2.807	2.435	0.0493	+1.5	-8.5
10	110.6	0.832	2298.4	2.89	1.02	3.953	2.613	0.0307	+0.9	-9.0
10	110.0	0.836	2399.8	2.97	1.07	4.262	2.804	0.0326	+2.3	-11.2
12	89.0	1.034	2791.9	3.45	1.19	5.506	2.928	0.0223	+1.5	-9.2
12	87.0	1.057	2778.4	3.44	1.13	5.213	2.712	0.0197	+3.8	-9.0
14	73.4	1.253	3413.8	4.04	1.18	6.393	2.806	0.0146	+1.7	-9.0
14	74.8	1.230	3454.4	4.00	1.18	6.330	2.830	0.0153	+4.7	-9.5

Notes:

(1) Time to cover measured 92.0 ft course.

(2) Total tow horsepower = $\dfrac{\text{Watts}}{745.7} = \dfrac{\text{Volts x Current}}{745.7}$

(3) Total tow resistance = $\dfrac{\text{HP x 550}}{\text{Tow speed}} = \dfrac{\text{HP x 550}}{U}$

(4) Thrust Coeff C_T per screw = $\dfrac{\text{Resistance}/2}{\frac{1}{2}\rho L^2 U^2}$

(Twin screwed towboat)

TABLE 7

Circle Test No. 14, Speed Setting = 14
Reduced Strip Chart Data

Time (min:sec)	Shaft RPM	Motor Volts	Motor Current	HP $x10^{-3}$	Rudder Angles Steering (°)	Rudder Angles Flanker (°)
00:20	3214	3.92	1.16	6.098	-19.0	-4.3
00:30	3148	3.88	1.12	5.828	-19.8	-7.1
00:40	3247	4.00	1.18	6.330	-19.8	-8.0
00:50	3247	4.00	1.16	6.222	-19.0	-8.0
01:00	3247	3.96	1.16	6.160	-19.8	-7.1
01:10	3247	3.96	1.16	6.160	-19.8	-7.1
01:20	3247	3.96	1.16	6.160	-19.8	-8.0
01:30	3247	3.96	1.14	6.054	-20.7	-8.0
01:40	3247	3.96	1.14	6.054	-19.8	-7.1
01:50	3247	4.00	1.14	6.115	-19.8	-5.3
02:00	3247	4.00	1.14	6.115	-20.7	-7.1
02:10	3281	4.00	1.16	6.222	-20.7	-7.1
02:20	3281	4.00	1.16	6.222	-20.7	-3.3
02:30	3314	4.04	1.18	6.393	-19.8	-5.3
02:40	3281	4.00	1.16	6.222	-19.8	-6.2
02:50	3281	4.04	1.16	6.285	-20.7	-7.1
03:00	3314	4.04	1.16	6.285	-19.8	-7.1
03:10	3314	4.04	1.16	6.285	-20.7	-7.1
03:20	3281	4.04	1.14	6.176	-19.8	-8.0
03:30	3247	4.00	1.16	6.222	-19.8	-7.1
03:40	3247	3.92	1:14	5.993	-19.8	-8.0
03:50	3247	3.96	1.16	6.160	-20.7	-7.1

TABLE 8

Circle Test No. 17, Speed Setting = 8
Reduced Strip Chart Data

Time (min:sec)	Shaft RPM	Motor Volts	Motor Current	HP x10-3	Rudder Angles Steering (°)	Rudder Angles Flanker (°)
39:30	1624	2.16	0.58	1.680	3.5	-5.3
39:40	1690	2.12	0.62	1.763	-20.7	-7.2
39:50	1690	2.16	0.60	1.738	-20.7	-7.2
40:00	1690	2.16	0.62	1.796	-20.7	-7.2
40:10	1690	2.16	0.64	1.854	-20.7	-7.2
40:20	1690	2.20	0.64	1.888	-19.8	-7.2
40:30	1690	2.16	0.64	1.854	-19.8	-5.3
40:40	1723	2.20	0.64	1.888	-19.8	-6.3
40:50	1723	2.20	0.62	1.829	-19.8	-7.2
41:00	1723	2.16	0.62	1.796	-19.8	-7.2
41:10	1723	2.16	0.64	1.854	-19.8	-5.3
41:20	1756	2.24	0.64	1.922	-19.8	-7.2
41:40	1723	2.16	0.60	1.738	-20.7	-6.3
42:00	1723	2.16	0.62	1.796	-19.8	-2.6
42:30	1657	2.16	0.60	1.738	-20.7	-6.3
43:00	1657	2.16	0.60	1.738	-20.7	-6.3
43:30	1690	2.16	0.58	1.680	-20.7	-6.3
44:00	1657	2.08	0.58	1.618	-19.8	-5.3

TABLE 9

Circle Test No. 14, Speed Setting = 14
Tow Position from Video Tapes

Time (Min:sec)	Δt (Sec)	Position of Center of Gravity ft Y_O	X_O	$\psi°$	U_{CG} ft/sec	$\beta°$
00:28		6.00	--	0.0		
00:30	2	4.00	32.10	0.0		
00:34*	4	4.15	37.17	4.3	1.27	2.6
00:37	3	5.30	40.84	23.6	1.28	6.2
00:40	3	4.10	44.36	15.0	1.24	-3.9
00:43	3	4.40	45.82	27.2	.50	15.6
00:44	1	6.34	50.40	39.3	4.97	16.3
00:47	3	6.10	50.88	37.5	.18	11.0
00:58	11	14.65	56.00	90.0	.91	30.9
01:00	2	16.58	58.21	88.4	1.47	47.3
01:12	12	27.20	56.29	139.3	.90	59.5
01:13	1	27.50	56.60	138.8	.43	94.7
01:21	8	32.20	51.00	164.0	.91	24.0
01:26	5	33.88	46.34	185.5	.99	25.4
01:31	5	34.00	42.56	207.9	.76	29.8
01:36	5	32.80	38.00	218.5	.94	23.8
01:48	12	25.61	30.82	263.3	.85	38.3
01:49	1	25.46	30.24	257.7	.60	63.2
02:00	11	15.20	30.34	302.2	.93	32.7
02:00	0	15.02	30.13	304.7	--	84.1
02:08	8	9.44	34.00	331.2	.85	26.5
02.12	4	7.38	36.42	346.4	.80	26.8
02.15	3	6.22	38.81	359.1	.89	24.9
02:15	0	5.96	39.60	355.2	--	13.4
02:22	7	5.62	45.16	22.1	.80	25.6
02:27	5	6.00	50.00	28.5	.97	24.0

*Rudder execute from strip chart at 00:20 = 00:34 video (14 sec apparent lag)

TABLE 10

Circle Test No. 17, Speed Setting = 8
Tow Position from Video Tapes

Time (Min:sec)	Δt (Sec)	Position of Center of Gravity (ft) Y_0	X_0	$\psi°$	U_{CG} ft/sec	$\beta°$
39:42		5.97	30.52	-3.0		
39:48	6	4.00	36.62	0.0	1.07	-17.9
39:50	2	4.00	35.02	0.0	.80	0.0
39:52	2	4.00	40.00	0.0	2.49	0.0
39:57*	5	4.00	39.20	15.9	.16	15.9
40:04	7	4.22	42.90	22.9	.53	19.5
40:09	5	5.18	45.40	37.1	.54	16.1
40:16	7	6.30	49.00	43.6	.54	26.3
40:20	4	7.66	50.84	57.1	.34	-26.2
40:29	9	14.72	53.55	67.0	.84	- 2.0
40:32	3	12.14	54.50	79.1	.92	9.3
40:34	2	19.04	54.60	114.7	3.45	25.6
40:50	16	20.23	56.72	103.7	.15	74.4
41:08	18	27.72	54.67	137.3	.43	32.0
41:08	0	27.98	54.50	139.2	--	16.0
41:15	7	30.20	52.22	146.6	.46	10.9
41:19	4	31.06	51.14	159.4	.35	17.9
41:32	13	34.24	46.16	179.6	.46	32.1
41:48	16	34.64	38.31	203.7	.49	26.6
41:48	0	33.94	38.73	204.8	--	83.8
42:08	20	29.54	29.48	232.7	.51	27.3
42:09	1	29.60	30.78	245.4	1.30	62.8
42:16	7	26.38	29.36	256.7	.50	10.3
42:19	3	25.07	27.00	270.0	.90	61.0
42:32	13	18.70	28.24	289.5	.50	8.5
42:44	12	13.45	29.76	314.8	.46	28.7
42:51	7	10.74	31.68	326.8	.47	21.5
42:54	3	9.45	32.61	332.3	.53	26.5
42:56	2	9.08	45.18	332.1	6.29	-26.2
43:01	5	7.65	35.02	338.6	.60	15.3
43:02	1	7.31	37.55	339.6	2.55	12.7
43:04	2	6.75	36.67	349.4	.52	22.2
43:06	2	6.29	37.34	354.5	.41	29.0
43:11	5	5.70	39.68	1.5	.48	15.6
43:11	0	5.52	39.76	.7	--	
43:22	11	5.80	45.00	30.6	.48	27.5

*Rudder execute from strip chart at 39.34 = 39.57 (23 sec apparent lag)

TABLE 11

Comparative Table of Linear Hydrodynamic Coefficients
and Computed Rates of Turn
(coefficients $\times 10^{-3}$)

Symbol	Free Running Model 8-ft Tow (1:70)	Rotating Arm Tests of Coastal Barges (3B+T) Models (1:50)	PMM Towing Tank Tests of Typical River Tow (1:12)
N'_v	+ 0.096	-0.5815	-0.185
N'_r	- 0.59	-1.099	-0.328
N'_δ	- 0.98	-0.6215	-0.100
Y'_v	- 15.53	-3.329	-1.580
Y'_r	+ 0.096	+0.0317	+0.619
Y'_δ	+ 1.63	+0.7444	+0.198
m'	3.564	1.1567	1.457
L	7.967 ft	687.19 ft	745.06 ft
δ	- 20°	- 20°	- 20°
R/L	1.81 (2.35)*	3.44	5.35
r'	0.554 (0.425)*	0.291	0.187

*Computed using $\dot{\psi}$ data from physical model results

APPENDIX A: CALCULATION OF HYDRODYNAMIC COEFFICIENTS

1. Mathematical models for ship motion calculations require the specification of several hydrodynamic coefficients. Generally, these coefficients have been obtained by captive model testing in towing tanks and theoretical computations. The planar motion mechanism (PMM), rotating arm and other methods for measuring these coefficients are explained in books on naval architecture.[1] The review of available information revealed that maneuverability tests had not been conducted for tow flotillas. Discussions and correspondence with some of the leading towing tank facilities and towboat manufacturers did not produce hydrodynamic coefficient or tow maneuverability data.

2. During the study, the mathematical model of tow maneuverability by Petrie[2] became available. A method of estimating the linear hydrodynamic coefficients was presented by Petrie. Higher order (nonlinear) terms were ignored in his model, probably due to the unavailability of measured tow flotilla forces and moments. The computation method presented by Petrie was used for calculating the hydrodynamic coefficients for this study.

3. The following equations were adapted from Petrie, based on a linear mathematical model (see eqs. 3 and 4 in the main text of the report):

(1) Yaw moment equation

$$N' = N_v' v' + N_r' r' + (N_{\dot{r}}' - I_z') \dot{r}' + N_\delta' \delta \tag{A1}$$

(2) Sway force equation

$$Y' = Y_v' v' + Y_r' r' + (Y_{\dot{v}}' - m') \dot{v}' + Y_\delta' \delta \tag{A2}$$

(3) Axial or surge force equation

$$X' = X_o' + X_\delta' \delta + X_p' \tag{A3}$$

Terms not listed in these equations compared to equations 3 and 4 in the main text were assumed to be zero by Petrie.[2] The formulas derived by Petrie to calculate these hydrodynamic coefficients are listed below:

$$N_v' = \frac{N_v}{\frac{1}{2}\rho L^3 U} = \frac{C_{db} H_b L_b \left(CG_{aft} + \frac{1}{2} L_b\right) - C_{dt} H_t L_t \left(CG_{fwd} - \frac{1}{2} L_t\right)}{(L_b + L_t)^3} \tag{A4}$$

$$N_r' = \frac{N_r}{\frac{1}{2}\rho L^4 U} = -\frac{C_{db} H_b \left[(CG_{aft} + L_b)^3 - CG_{aft}^{\ 3}\right]/3}{(L_b + L_t)^4} \tag{A5}$$

$$Y_v' = \frac{Y_v}{\frac{1}{2}\rho L^2 U} = -\frac{(C_{db} H_b L_b) + (C_{dt} H_t L_t)}{(L_b + L_t)^2} \tag{A6}$$

$$N_{\dot{r}}' - I_z' = \frac{(N_{\dot{r}} - I_z)}{\frac{1}{2}\rho L^5} = -\frac{C_{ab} \nabla_b \left[(CG_{aft} + L_b)^3 - CG_{aft}^{\ 3}\right]/3}{L_b (L_b + L_t)^5} - \frac{C_{at} \nabla_t \left(CG_{aft}^{\ 3} + CG_{fwd}^{\ 3}\right)/3}{L_t (L_b + L_t)^5} \tag{A7}$$

$$Y_{\dot{v}}' - m' = \frac{(Y_{\dot{v}} - m)}{\frac{1}{2}\rho L^3} = -\frac{\left[(C_{ab} \nabla_b) + (C_{at} \nabla_t)\right]}{(L_b + L_t)^3} \tag{A8}$$

$$Y_r' = N_v' \tag{A9}$$

The following values were used in these calculations:[2]

$$C_{dt} = 1.5$$

$$C_{db} = 0.5$$

$$C_{at} = 0.45$$

$$C_{ab} = 0.45$$

The resistance and propeller thrust forces were obtained from still water, steady ahead tow tests, assuming steady tow resistance is equal to propeller thrust. The resistance and thrust coefficients are given by:

$$X_o' = \frac{F_r}{\frac{1}{2}\ \rho L^2 U^2} \tag{A10}$$

$$X_p' = \frac{F_T}{\frac{1}{2}\ \rho L^2 U^2} \tag{A11}$$

Rudder coefficients were obtained from the theoretical lifting wing relations presented on page 518 of Mandel's chapter in Comstock's book.[1] The formulas used were:

$$Y_\delta' = \frac{\partial Y_\delta}{\partial \delta} = \frac{A_R(\pi/2)}{L^2} \tag{A12}$$

$$N_\delta' = \frac{(CG_{aft} + L_b)}{(L_t + L_b)}\ (Y_\delta') \tag{A13}$$

$$X_\delta' = Y_\delta' \tag{A14}$$

The dimensionless forms of the tow mass and moment of inertia are given below:

$$I_z' = \frac{I_z}{\frac{1}{2}\rho L^5} = \{\frac{\Delta_b}{g}\ [K_b^2 + (CG_{aft} + L_b - CG_b)^2] + \frac{\Delta_t}{g}\ [K_t^{\ 2} + (CG_t - CG_{aft})^2]\}/\ \frac{1}{2}\rho(L_t + L_b)^5 \tag{A15}$$

$$m' = \frac{m}{\frac{1}{2}\ \rho L^3} = \frac{(\Delta_b + \Delta_t)/g}{\frac{1}{2}\ \rho (L_t + L_b)^3} \tag{A16}$$

4. The results of these calculations are presented as Table 11. Several formulas presented in the text by Petrie[2] were corrected based on a comparison with his computer code. It is believed that the equations

for the sum of moment of inertia plus added moment of inertia and the mass and added mass are in error. It is known that in general these values should be about twice the tow moment of inertia and tow mass. Table 1 shows two alternate ways for correcting for this apparent error. In addition, the rudder effects were adjusted to give better agreement to the measured model turning-circle data. This is further discussed in the body of the report.

5. Petrie[2] presented a method of accounting for the increased velocity past the rudders located in the propeller race. Calculations using these formulas were tried but resulted in very large coefficients for the free running models. A study of the Mandel[1] chapter indicated that free running model data gave better correlation if the ship velocity is used rather than the propeller race velocity. The added resistance of the small scale free running models requires the propeller to provide added thrust to achieve proper speed. On the other hand, the approach flow to the propeller is influenced to a large extent by flow separation from the model due to added resistance. The two effects are believed to be compensating to some degree. The factor of 1.72 used to achieve better results with the observed model turning tests would indicate the propeller would have an effect on the rudder coefficients of about 30 percent ($\sqrt{1.72} = 1.31$) greater than the tow speed.

APPENDIX B: DEFINITION OF SYMBOLS

m	mass of the tow
$\dot{v}$	tow acceleration in the sway direction
v	component of tow speed in the sway (y-axis) direction
$\dot{r}$	tow rotary acceleration about the vertical axis $\equiv\ddot{\psi}$
r	tow rate of turn about the vertical axis $\equiv\dot{\psi}$
A_R	cross-sectional area of rudder in sq ft
U	magnitude of flotilla velocity vector
ψ	yaw or heading angle, relative to fixed axis, from axis to heading
β	drift angle or orientation of heading, relative to velocity vector, from velocity to heading ($\beta=-\sin^{-1}\frac{v}{U}$)
δ	rudder angle, of the tow
C_T	thrust coefficient per tow screw $\dfrac{\text{total tow resistance}/2}{1/2\ \rho L^2 U^2}$
∇_b	volume of displacement of towboat in cu ft
∇_t	volume of displacement of tow flotilla in cu ft
Δ_b	displacement (or weight in air) of tow flotilla in lbs (or prototype tons)
Δ_t	displacement (or weight in air) of tow flotilla in lbs (or prototype tons)
NOTE	$\Delta=\gamma\nabla$
ρ	density of water in lb-sec^2/ft^4
g	acceleration of gravity, ft/sec^2
γ	unit weight of water, lb/ft^3
C_b	block coefficient
C_{at}, C_{ab}	added mass coefficient of tow flotilla and towboat, respectively
C_{dt}, C_{db}	damping coefficient of tow flotilla and towboat, respectively
CG_{fwd}	location of the tow center of gravity from the bow of the tow
CG_{aft}	location of the tow center of gravity from the towboat/barge interface
L	total length (L_t+L_b), in ft
L_t, L_b	length of tow flotilla and towboat, respectively, in ft

H_t, H_b	draft of tow flotilla and towboat, respectively, in ft
B_t, B_b	beam of tow flotilla and towboat, respectively, in ft
K_t, K_b	the radius of gyration of the tow flotilla and towboat, respectively, in ft
T	time constant of yaw acceleration term for ship or tow in yaw equation
T_β	time constant of drift acceleration term for ship or tow in drift equation
K	rudder constant of ship or tow in yaw equation
K_β	rudder constant of ship or tow in drift equation
F_r	resistance force
F_t	propeller thrust force
X	axial or surge force on the tow in the x-axis direction
N	hydrodynamic yaw moment
I_z	moment of inertia referred to z-axis
u	component of tow speed in the axial or x-axis direction
N_r	derivative of hydrodynamic yaw moment with respect to yaw rate
$N_{\dot{r}}$	derivative of hydrodynamic yaw moment with respect to yaw acceleration
N_v	derivative of hydrodynamic yaw moment with respect to sideslip velocity
$N_{\dot{v}}$	derivative of hydrodynamic yaw moment with respect to sway acceleration
N_δ	derivative of hydrodynamic yaw moment with respect to rudder angle
R	radius of turning circle test, ft
Y	hydrodynamic lateral or sway force component on the tow in y-axis direction
Y_r	derivative of hydrodynamic force component in y-axis direction, with respect to yaw rate
$Y_{\dot{r}}$	derivative of hydrodynamic force coefficient with respect to yaw acceleration
Y_v	derivative of hydrodynamic force component in y-axis direction, with respect to sideslip velocity
$Y_{\dot{v}}$	derivative of hydrodynamic force component in y-axis direction, with respect to sideslip acceleration

Y_δ derivative of hydrodynamic force component in y-axis direction, with respect to rudder angle

Dimensionless Forms

The dimensionless form of a quantity is indicated by the prime of that quantity. Examples are shown in the following:

Quantity	Typical Symbol	Typical Dimension-less Form
Force - x-axis direction	X	$X' = X \Big/ \frac{\rho}{2} L^2U^2$
- y-axis direction	Y	$Y' = Y \Big/ \frac{\rho}{2} L^2U^2$
Moment	N	$N' = N \Big/ \frac{\rho}{2} L^3U^2$
Mass	m	$m' = m \Big/ \frac{\rho}{2} L^3$
Angular velocity	r	$r' = \frac{rL}{U}$
Static force rate	Y_v	$Y_v' = Y_v \Big/ \frac{\rho}{2} L^2U$
Static moment rate	N_v	$N_v' = N_v \Big/ \frac{\rho}{2} L^3U$
Rudder force rate	Y_δ	$Y_\delta' = Y_\delta \Big/ \frac{\rho}{2} L^2U^2$
Rudder moment rate	N_δ	$N_\delta' = N_\delta \Big/ \frac{\rho}{2} L^3U^2$
Damping force rate	Y_r	$Y_r' = Y_r \Big/ \frac{\rho}{2} L^3U$
Damping moment rate	N_r	$N_r' = N_r \Big/ \frac{\rho}{2} L^4U$
Inertial coefficient	$Y_{\dot{v}}$	$Y_{\dot{v}}' = Y_{\dot{v}} \Big/ \frac{\rho}{2} L^3$
Inertial coefficient	$N_{\dot{r}}$	$N_{\dot{r}}' = N_{\dot{r}} \Big/ \frac{\rho}{2} L^5$
Moment of inertia	I_z	$I_z' = I_z \Big/ \frac{\rho}{2} L^5$
Velocity - x-axis direction	u	$u' = u/U$
- y-axis direction	v	$v' = v/U$
Angular acceleration	$\dot{r}$	$\dot{r}' = \dot{r}L^2/U^2$
Time	t	$t' = tU/L$