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THESIS

**PARAMETRIC STUDY OF THE DYNAMIC
STABILITY OF TOWED SHIPS**

by

David L. Kolthoff

June, 1989

Thesis Advisor:

Prof. F. A. Papoulias

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Parametric Study of the Stability of Towed Ships

by

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Lieutenant Commander, United States Navy
B.S.E., University of Michigan, 1977


Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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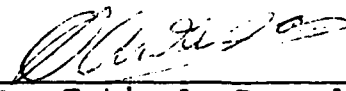
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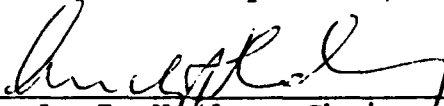


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PARAMETRIC STUDY OF THE DYNAMIC STABILITY OF TOWED VESSELS

Several accidents in towing operations of barges or disabled ships in restricted and open waters have made necessary the investigation of the course keeping stability of towed vessels. In this work a non-linear mathematical model is used to simulate the slow surge, sway, and yaw motions of a vessel towed by a heavy catenary towline. The effect of geometric parameters of the system on the stability of equilibrium configurations is analyzed.

It is shown that for certain choices of towing system parameters, dynamic loss of stability may occur which results in qualitatively different asymptotic response. The results of this study identify regions in the parameter space that lead to either safe operations or hazardous system response.

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TABLE OF CONTENTS

I.	INTRODUCTION.....	1
	A. BACKGROUND.....	1
	B. PROBLEM CONDITIONS.....	2
II.	PROBLEM FORMULATION AND METHOD OF APPROACH.....	6
III.	RESULTS AND DISCUSSION.....	12
	A. BARGE WITH SKEG.....	12
	B. TANKER.....	18
	C. BARGE WITHOUT SKEG.....	24
	D. PRACTICAL CONSIDERATIONS.....	27
IV.	CONCLUSIONS AND RECOMMENDATIONS.....	30
	A. CONCLUSIONS.....	30
	B. RECOMMENDATIONS.....	32
	APPENDIX.....	34
	LIST OF REFERENCES.....	42
	INITIAL DISTRIBUTION LIST.....	43

LIST OF FIGURES

Figure No.	Title	Page
1	Problem Geometry	3
2	Body Plans of Vessels Studied	5
3	Critical Real Part vs. x_p - Barge with skeg	13
4	y_p vs. x_p , L_w as parameter	15
5	L_w vs. x_p , y_p as parameter	16
6	Critical Real Part vs. x_p - Tanker	19
7	L_w vs. x_p , $y_p > 0$ as parameter	20
8	Critical Real Part vs. x_p - $y_p < 0$	22
9	L_w vs. x_p , $y_p < 0$ as parameter	23
10	L_w vs. x_p , $y_p < 0$, Close-up	25
11	Critical Real Part vs. x_p - Barge w/o skeg	26
12	L_w vs. x_p , y_p as parameter	28

I. INTRODUCTION

A. BACKGROUND

A long history of towing accidents resulting in loss of life, damage to property, and pollution of the environment have prompted many studies into the dynamics of towing operations. Of primary concern was the motions of the towed vessel in the horizontal plane (yaw, sway, and surge). Excessive and unstable motions could lead to collisions and capsizing. The ability to predict the motion of a particular towing system would be of particular benefit to ship designers and towing operators, by identifying those situations where the towing operations would be the safest, or those which must be avoided.

Previous studies at the University of Michigan and elsewhere had developed mathematical models and numerical techniques to analyze towing dynamics, and had identified those parameters which are of primary importance to the stability of the towing system. The linear model usually used to describe ship motions [Ref. 1, Chapter 7] is inadequate for the towing problem. Non-linear models, as in [Ref. 2], must be utilized to accurately describe the towing system. These studies had identified the position of

the towline attachment point on the towed vessel and the towline tension as the most significant (and controllable) parameters of the towing system.

B. PROBLEM CONDITIONS

In this study, computer programs developed in [Ref. 3] were used to analyze the effect of different parameter combinations on the towed stability of three vessels. These programs use bifurcation to identify the unstable and stable regions of the parameter space. The principal parameters studied were (Fig.1):

1. longitudinal position of the towline attachment point forward of the towed vessel's center of gravity, x_p ;
2. athwartships position of the towline attachment point port or starboard of the towed vessel's centerline, y_p ;
3. length of the towline, L_w .

In the model used in this study, unlike [Ref. 2], the towline is modeled as an inextensible catenary, thus making towline tension a function of its length. The model conditions were:

1. speed of towing vessel of 2 knots;
2. towing vessel on steady course;
3. calm seas, no wind; i.e., no external environmental forces.

Characteristics of the towed vessel were inputted into the programs from a data file containing hydrodynamic coefficients, resistance data, towline characteristics, and

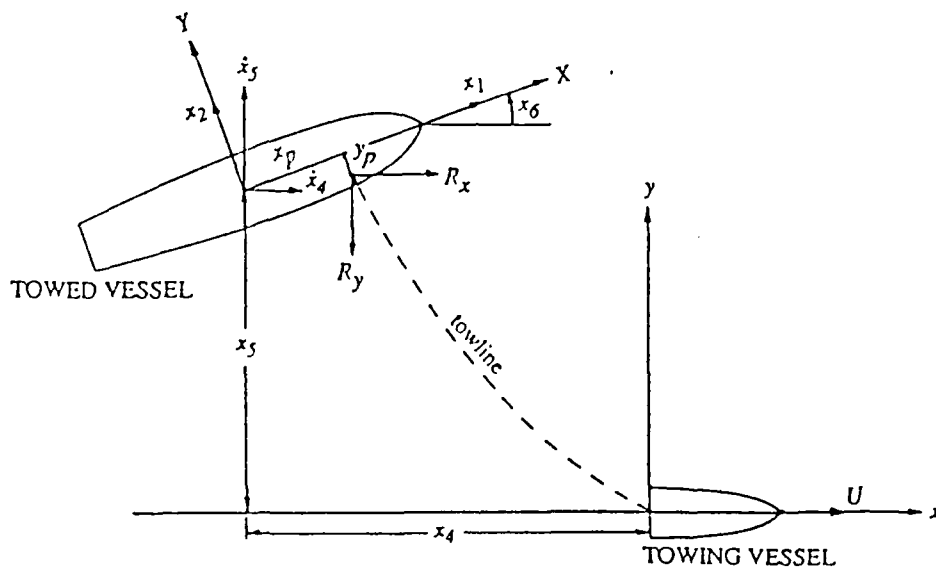


Figure 1. Problem Geometry

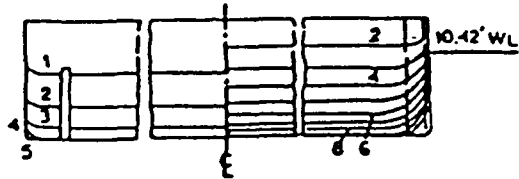
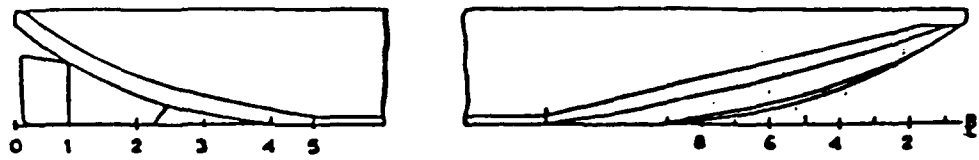
skeg data, if applicable. The effect of asymmetrical forces acting on the towed vessel, such as the presence of a propellor or an environmental force, are introduced through a bias in the data file. All dimensions are nondimensionalized with respect to the towed ship's length between perpendiculars (LBP).

Three vessels were studied (Fig.2):

1. a 191 foot barge with a skeg, with no propellor (i.e., no bias);
2. a 1066 foot tanker with no skeg, but with a propellor (i.e., with a bias);
3. the same barge as in 1), but without the skeg and with a propellor (i.e., with a bias).

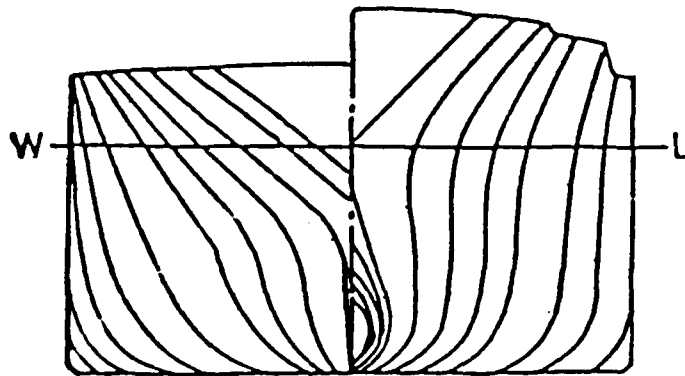
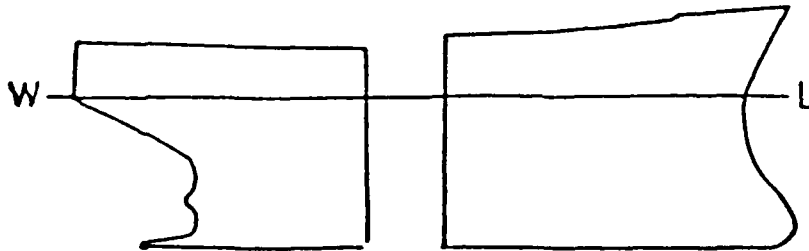
Unlike previous studies, this work includes the effect of athwartship position of the towline attachment point in the stability of the towing system.

Chapter II provides background into the problem formulation and stability analysis used in this study. Chapter III presents the results of the analysis and discusses some practical aspects of these results. Chapter IV discusses the conclusions which can be made from the results of this study on the stability of the towing system and the use of the techniques used herein.



* Barge with skeg, no bias

* Barge with no skeg, with bias



* Tanker with bias

Figure 2. Body Plans of Vessels Studied

II. PROBLEM FORMULATION AND METHOD OF APPROACH

Slow motions of a towed vessel in the horizontal plane are described by a system of six nonlinear, coupled, differential equations. [Ref. 4 and 5] In its standard form this system is

$$\begin{aligned} \dot{x}_1 &= \frac{1}{m - X_u^*} [F_1(x_1, x_2, x_3) + T_{\text{surge}}(x_4, x_5, x_6)] \\ \dot{x}_2 &= \frac{I_z - N_r^*}{D} [F_2(x_1, x_2, x_3) + T_{\text{sway}}(x_4, x_5, x_6)] \\ &+ \frac{Y_r^*}{D} [F_3(x_1, x_2, x_3) + x_p T_{\text{sway}}(x_4, x_5, x_6) - Y_p T_{\text{surge}}(x_4, x_5, x_6)], \\ \dot{x}_3 &= \frac{N_v^*}{D} [F_2(x_1, x_2, x_3) + x_p T_{\text{sway}}(x_4, x_5, x_6)] \\ &+ \frac{m - Y_v^*}{D} [F_3(x_1, x_2, x_3) + x_p T_{\text{sway}}(x_4, x_5, x_6) - Y_p T_{\text{surge}}(x_4, x_5, x_6)], \\ \dot{x}_4 &= x_1 \cos x_6 - x_2 \sin x_6 - U, \\ \dot{x}_5 &= x_1 \sin x_6 + x_2 \cos x_6, \\ \dot{x}_6 &= x_3, \end{aligned}$$

where

$$T_{\text{surge}}(x_4, x_5, x_6) = R_x(x_4, x_5, x_6) \cos x_6 + R_y(x_4, x_5, x_6) \sin x_6,$$

$$-T_{\text{sway}}(x_4, x_5, x_6) = R_x(x_4, x_5, x_6) \sin x_6 - R_y(x_4, x_5, x_6) \cos x_6,$$

D denotes the known quantity

$$D = (m - Y_v)(I_z - N_r) - Y_r N_v,$$

and

$$F_1(x_1, x_2, x_3) = X_u x_1 + \frac{1}{2} X_{uu} x_1^2 + \frac{1}{6} X_{uuu} x_1^3 + \frac{1}{2} X_{vv} x_2^2 + \frac{1}{2} X_{vvu} x_2^2 x_1 \\ + \frac{1}{2} X_{rr} x_3^2 + \frac{1}{2} X_{rru} x_3^2 x_1 + (X_{vr} + m) x_2 x_3 + X_{rvu} x_1 x_2 x_3,$$

$$F_2(x_1, x_2, x_3) = Y_0 + Y_{0u} x_1 + Y_{0uu} x_1^2 + Y_v x_2 + \frac{1}{6} Y_{vvv} x_2^3 + \frac{1}{2} Y_{vrr} x_2^2 x_3 \\ + Y_{vu} x_1 x_2 + \frac{1}{2} Y_{vuu} x_2^2 x_1^2 + (Y_r - m x_1) x_3 + \frac{1}{6} Y_{rrr} x_3^3 + \frac{1}{2} Y_{rvv} x_3^2 x_2 \\ + Y_{ru} x_3 x_1 + \frac{1}{2} Y_{ruu} x_3^2 x_1^2,$$

$$F_3(x_1, x_2, x_3) = N_0 + N_{0u} x_1 + N_{0uu} x_1^2 + N_v x_2 + \frac{1}{6} N_{vvv} x_2^3 + \frac{1}{2} N_{vrr} x_2^2 x_3 \\ + N_{vu} x_1 x_2 + \frac{1}{2} N_{vuu} x_2^2 x_1^2 + N_r x_3 + \frac{1}{6} N_{rrr} x_3^3 + \frac{1}{2} N_{rvv} x_3^2 x_2 \\ + N_{ru} x_3 x_1 + \frac{1}{2} N_{ruu} x_3^2 x_1^2.$$

In the above equations, x_1 denotes the sway velocity in surge (longitudinal motion) of the towed vessel, x_2 the velocity in sway (lateral motion), x_3 the angular velocity in yaw (turning motion about the vertical axis), x_4 and x_5 the coordinates of the center of gravity of the towed vessel

with respect to an (x,y) -coordinate system moving with the towing vessel, and x_6 the towed vessel yaw angle. Further, U is the steady towing vessel velocity in the x -direction, x_p and y_p are the coordinates of the towline connection point on the towed vessel with respect to an (X,Y) -coordinate system with its origin at the towed vessel center of gravity, and R_x, R_y are the towline restoring forces. The towing system configuration and notation conventions are shown in Figure 1. Expressions for F_1, F_2, F_3 are derived by Taylor expansion in terms of the relative velocities x_1, x_2, x_3 of the towed vessel with respect to the water. In nonlinear analysis terms up to third order are used whereas terms beyond third order and second- and higher-order acceleration terms are usually neglected. Subscripts u, v, r indicate derivative of force-moment component with respect to x_1, x_2, x_3 respectively, and subscript c indicates propellor dependent terms., which represent a source of system asymmetry. These terms are zero in the absence of a propellor. Terms $X_{abc}, Y_{abc}, N_{abc}$, where a, b, c are dummy independent variables representing u, v, r , are usually called slow motion derivatives. In unsteady reference motion, slow-motion derivatives are considered as functions of the frequency of motion. In our study of slowly varying reference motions, we assume that slow motion derivatives are time independent. This is a good approximation for ships with usual hull shapes and moderate speeds.

R_x and R_y denote restoring forces from the towline, and for a quasistatic towline response they are expressed as implicit functions of x_4, x_5, x_6 . In this study, the model used for the towline is that of an inextensible heavy catenary with nonlinear force-displacement characteristics as given in [Ref. 3].

In compact notation the above system of six ordinary differential equations is denoted as

$$\dot{x}=f(x) \tag{1}$$

where x and f are six dimensional vectors. To analyze the stability properties of (1), the first step is to identify the equilibrium configuration of the system. For this we have to solve a system of six nonlinear, coupled algebraic equations

$$f(\bar{x})=0 \tag{2}$$

where \bar{x} denotes an equilibrium configuration. It can be shown [Ref. 5] that system (2) has at most three solutions in \bar{x} corresponding to three distinct equilibrium positions. In this study we concentrated our efforts on one of these equilibrium positions, namely the one which, in the absence of a bias in the system, corresponds to the towed vessel being located directly astern of the tow-tug. This is the most interesting in applications. Having computed \bar{x} , its stability properties can be established as follows:

Linearization of (1) around \bar{x} leads to the linear system

$$\dot{z}=Az \tag{3}$$

where z represents the excursion from the equilibrium \bar{x} , and A is a constant 6×6 matrix. If all eigenvalues of A have negative real parts, then \bar{x} is stable; otherwise it is unstable.

In this study, we performed parametric analysis of the central equilibrium in terms of towline length L_w , and the towing point coordinates with respect to the center of gravity of the towed vessel, x_p and y_p . These parameters can be easily changed before or during towing operations and can provide a means of passive control of the towing system. Parameter L_w directly affects the amount of tension developed by the towline. Parameter x_p is directly related to the towline restoring force and moment. A small value for x_p may not be able to provide adequate restoring moment and may not guarantee system stability. On the other hand a very large value for x_p may result in over-compensation and therefore instability. Nonzero y_p values result in a source of asymmetry introduced in the system. For a biased system (for example due to the presence of a propeller or environmental forces), it should be expected that an extra appropriate bias introduced via a nonzero y_p helps counteract the effect of the former bias, and hence improve stability.

The particular equilibrium position will lose its stability when an eigenvalue of the A matrix in (3) changes its sign from negative real part to positive real part. The case when a real eigenvalue crosses zero has been analyzed in detail in [Ref. 5]. This corresponds to a static loss of stability with generation of additional equilibrium positions in the form of solution branching. In this study we focussed our attention on the case when a complex conjugate pair crosses the imaginary axis. This corresponds to a Hopf bifurcation: the particular equilibrium experiences a dynamic loss of stability and the system begins to oscillate. The resulting periodic solutions can be stable or unstable, but at any rate, such a situation is hazardous and should be avoided during towing operations.

III. RESULTS AND DISCUSSION

A. BARGE WITH SKEG

The first vessel to be studied was an unpowered barge with a skeg aft. Since there is no propellor to introduce a bias, the barge has athwartship symmetry.

1. Figure 3: Critical Real Part vs. x_p

Program TOWBIF1 calculates eigenvalues for specific L_w and y_p , creates a file for each of six real and six imaginary parts, and creates a separate file containing the largest real part. The real part with the largest value is the critical indicator of the system's stability: if it is greater than zero, the system will be unstable; if less than zero, the system will be stable.

Figure 3 shows plots for the critical parts for $y_p=0.05$ and three values for L_w . The region where the plot is greater than zero indicate that range of x_p where the system is unstable. For example, for $L_w=0.5$ the critical real part is greater than zero for the range of $x_p=0.18$ to $x_p=0.48$, so the system is unstable within this range.

Note that as L_w increases, the unstable range becomes smaller, until for $L_w=3.0$ there is no region greater than zero. Therefore, the system will be stable for all values of x_p ; i.e, the barge should exhibit no unstable motion.

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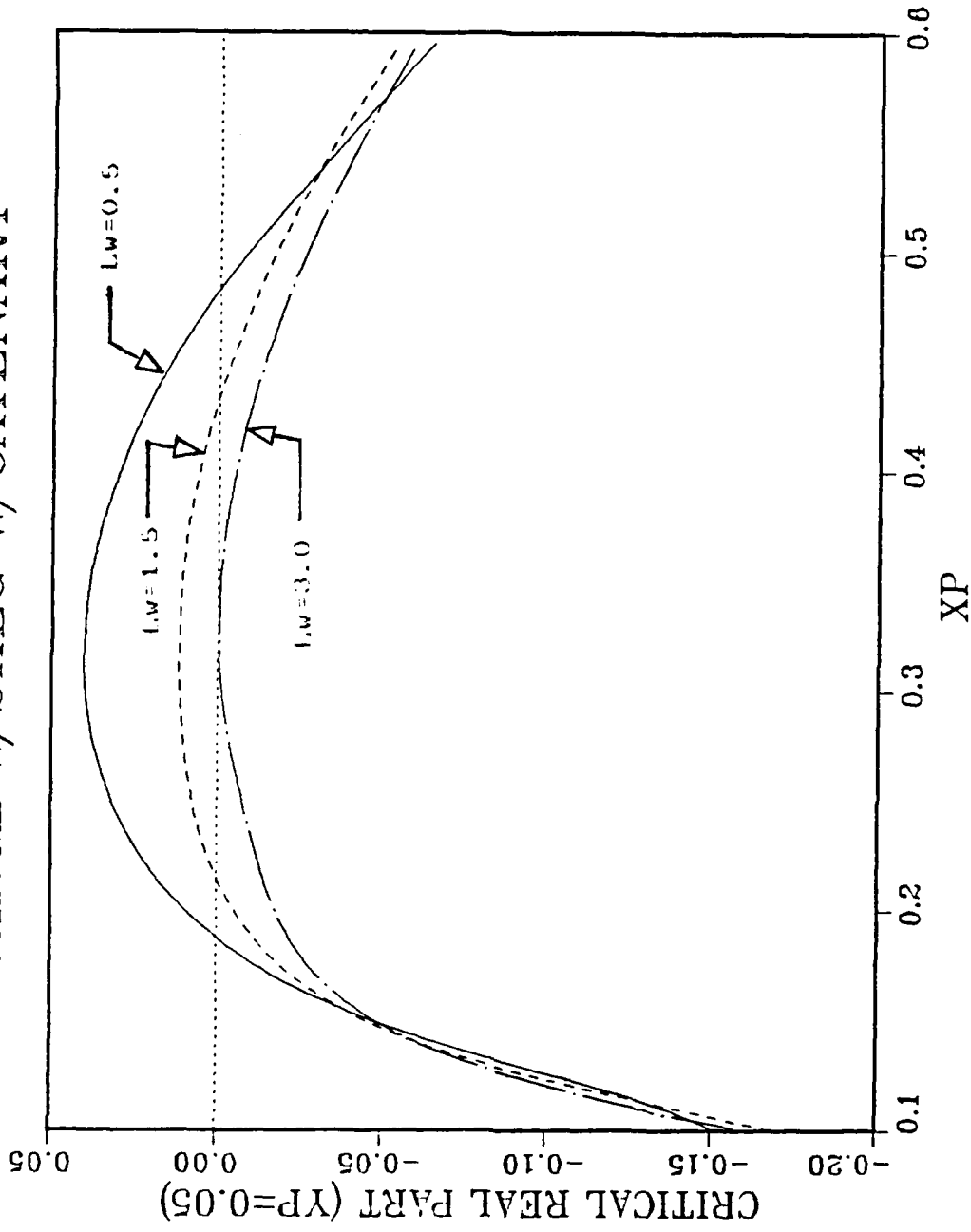


Figure 3. Critical Real Part vs. xp - Barge with skeg

2. Figure 4: y_p vs. x_p , Lw as Parameter

Program TOWBIF2 does the same calculations as TOWBIF1 over a range of values of y_p with a given Lw , instead of a single value of y_p and Lw . In essence, Figure 3 represents a cut of Figure 4 at a single value of y_p and Lw . Unlike TOWBIF1, TOWBIF2 writes a point only where the critical real part changes sign. When plotted, these produce a curve delineating stable and unstable regions of the parameter space. This is the point of the process; we are more interested in finding what parameters produce stable or unstable system than the actual results of the equations of motion.

Recalling Figure 3, The area inside the curves represent the unstable region. For example, for $Lw=0.5$, the system is unstable for all values of y_p within the range $x_p=0.2$ to $x_p=0.5$. Increasing Lw first decreases the unstable range of x_p for high y_p , then decreases the unstable range of y_p . For large Lw (>4.0), the unstable range virtually disappears.

3. Figure 5: Lw vs. x_p , y_p as parameter

Program TOWBIF3 performs the same calculations as TOWBIF2, but with Lw as the ordinate and y_p as the parameter. Thus Figure 5 provides the same information as Figure 4 but with a different perspective.

BARGE W/SKEG W/CATENARY

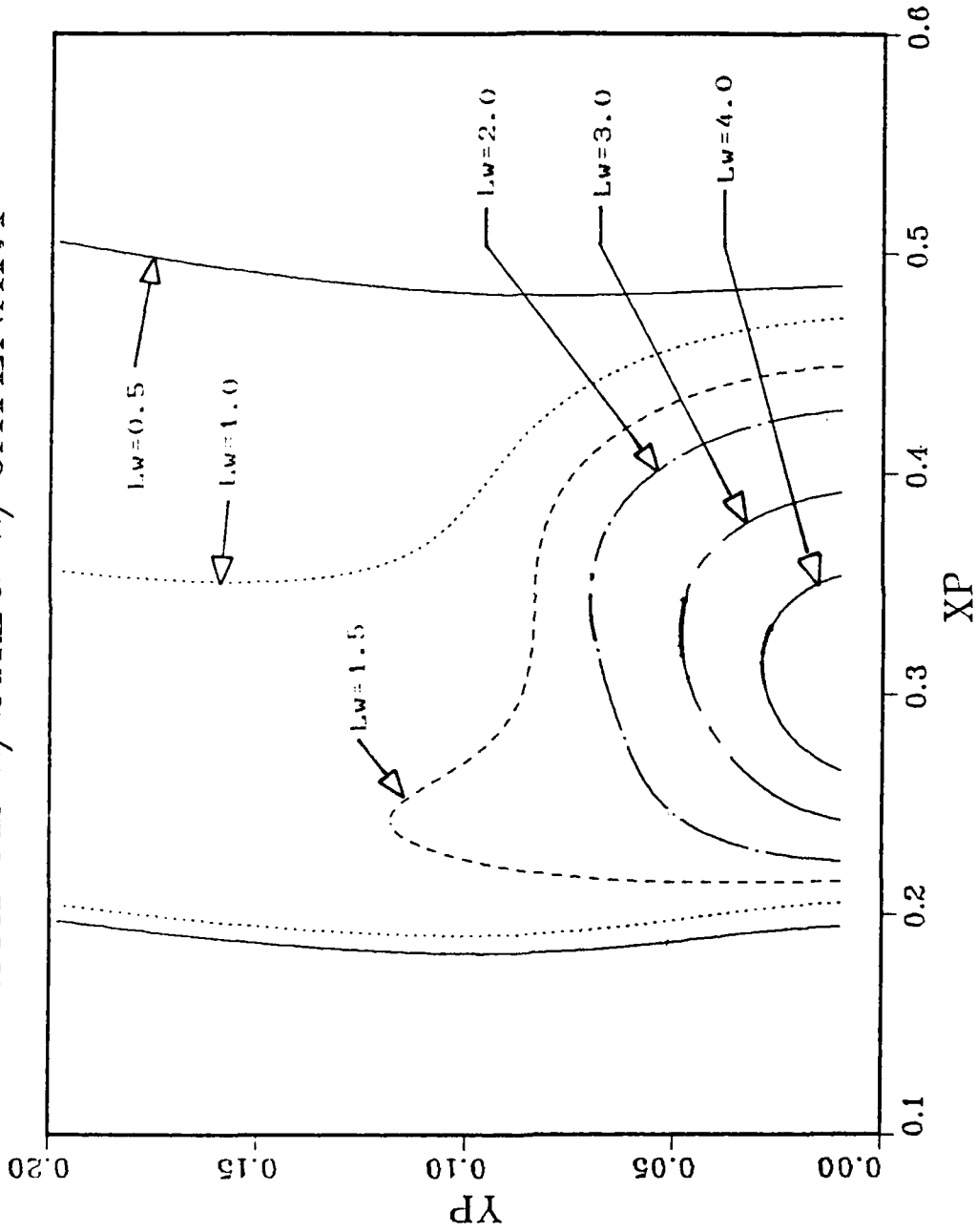


Figure 4. y_p vs. x_p , L_w as parameter

BARGE W/SKEG W/CATENARY

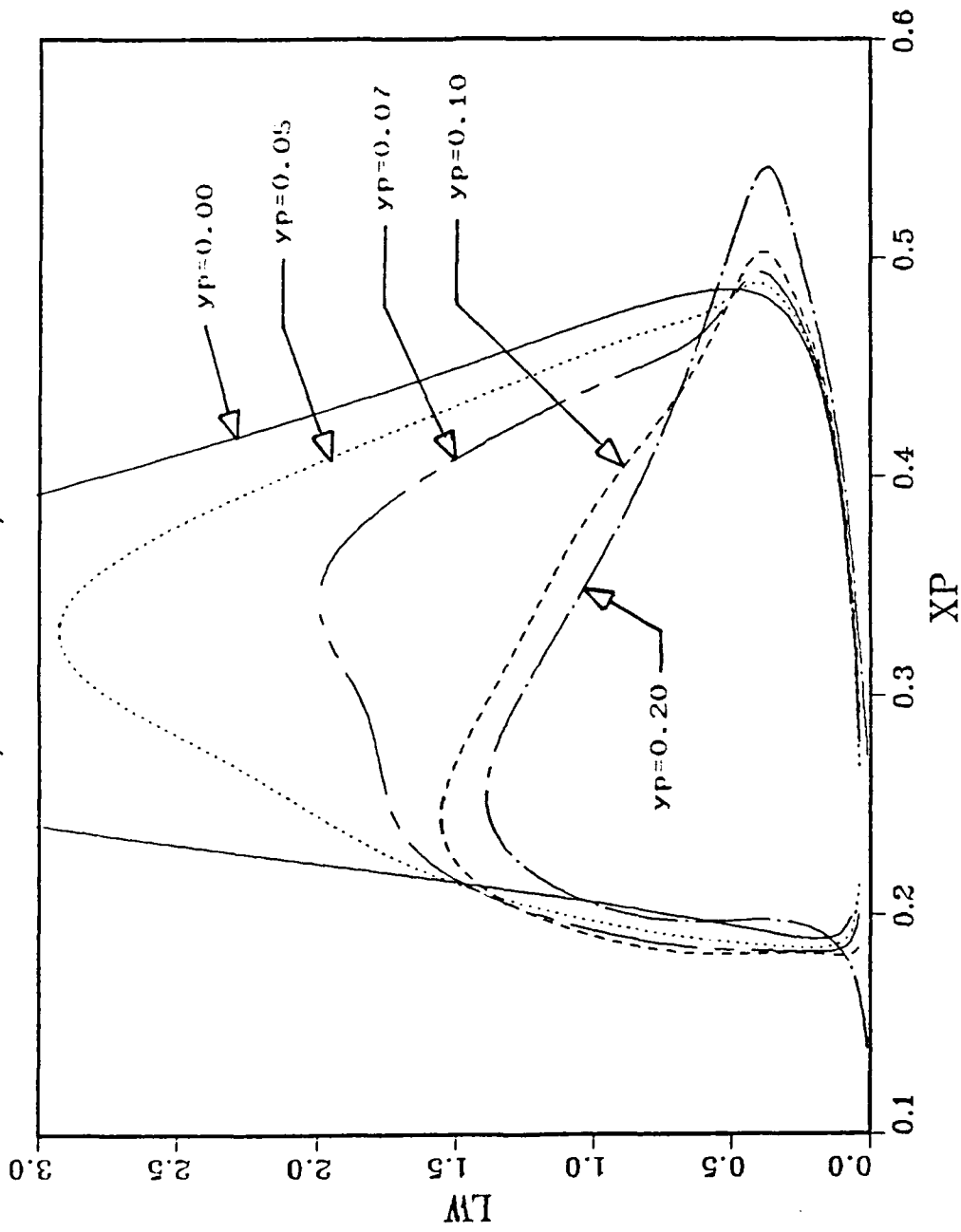


Figure 5. LW vs. xp, yp as parameter

As in Figure 4, the unstable region is inside the curves. It clearly shows how increasing L_w decreases the unstable range for a constant y_p , as was evident in Figure 4. It also shows that, for constant L_w greater than about 0.7, increasing y_p also decreases the unstable region. In the narrow range of L_w from 0.2 to 0.7, increasing y_p increases the extent of the unstable range of x_p . This effect is apparent in Figure 4, but more dramatically presented in Figure 5. It would appear that using two views of the data would emphasize aspects of the curve that may be overlooked with one view.

Since positive values of y_p represent port side placement of the towline attachment point, and negative values starboard side placement, both positive and negative values for y_p were studied. As expected from the port-starboard symmetry of the barge, curves for positive and negative values of y_p were identical, and only positive values were presented here.

From an operational point of view, one may conclude from these curves that for the unpowered barge, placing the towline on an attachment point to either side, as far forward as possible, will make the tow stable for the greatest range of towline length, but the towline should be kept no shorter than the length of the barge.

B. TANKER

The second vessel studied was a tanker typical of those now in service. The effect of the tanker's propellor makes the hull asymmetrical; this effect is represented by a bias included in the tanker data file.

1. Figure 6: Critical Real part vs x_p

Figure 6 plots data generated from TOWBIF1 with $y_p=0.10$ and two values for L_w . These plots show the stable region to be between the two zero values for the curve. Note that the stable region becomes smaller with increasing L_w .

Note also that both curves are discontinuous in their slopes. The critical real parts file is a composite of several results files, each of which is critical over a certain range. Each results file forms a smooth curve; thus the curves plotted on each TOWBIF1 figure may be combinations of the critical section of several results files.

Finally, note that the stable region occurs over a narrow range of x_p , unlike the barge with skeg discussed earlier.

2. Figure 7: L_w vs. x_p , y_p as Parameter

Figure 7 was produced from data generated by TOWBIF3 for positive values of y_p . As was shown in Figure 6, the stable region is inside the curves. The vertical line at

TANKER W/CATENARY

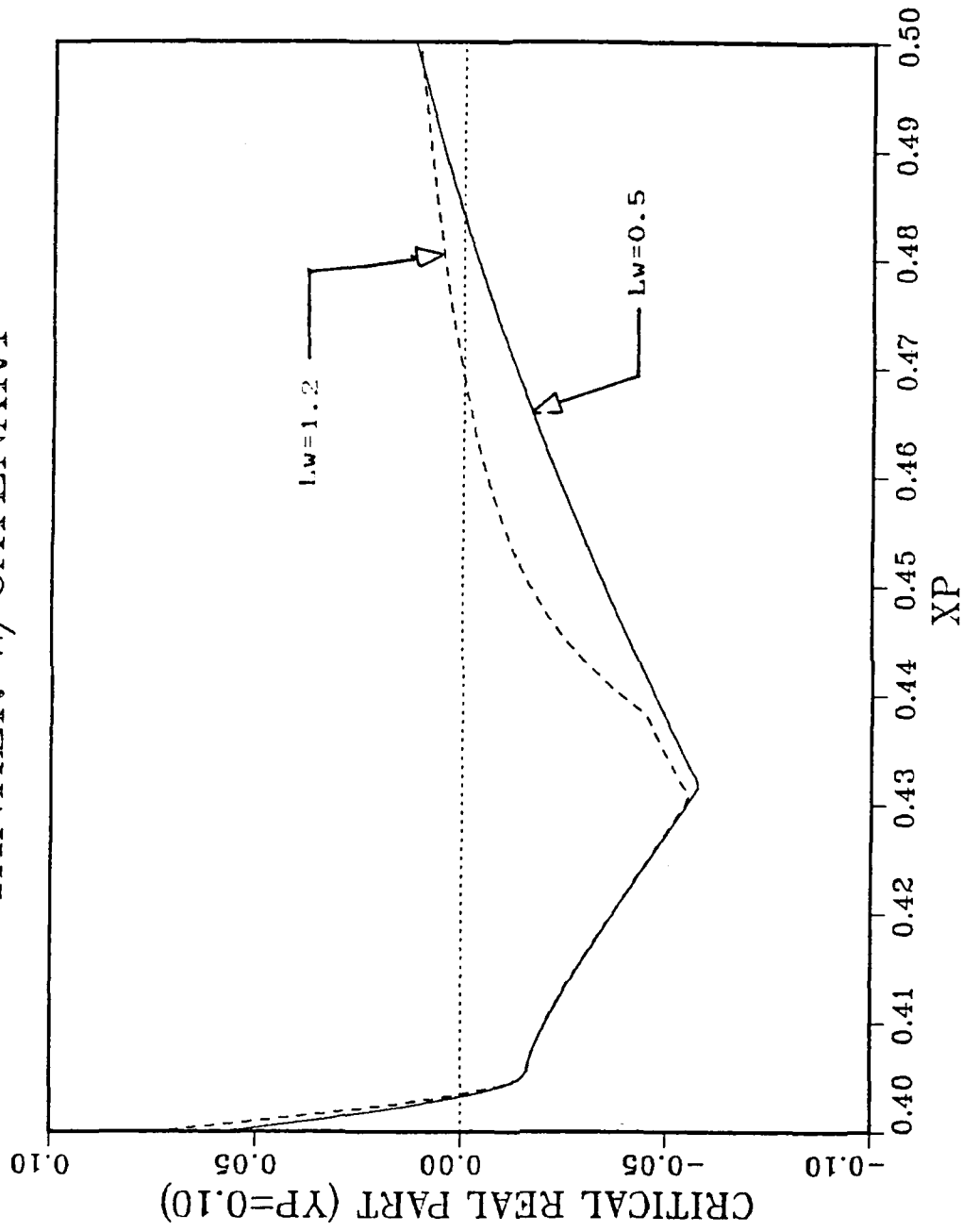


Figure 6. Critical Real Part vs. xp - Tanker

TANKER W/ CATENARY

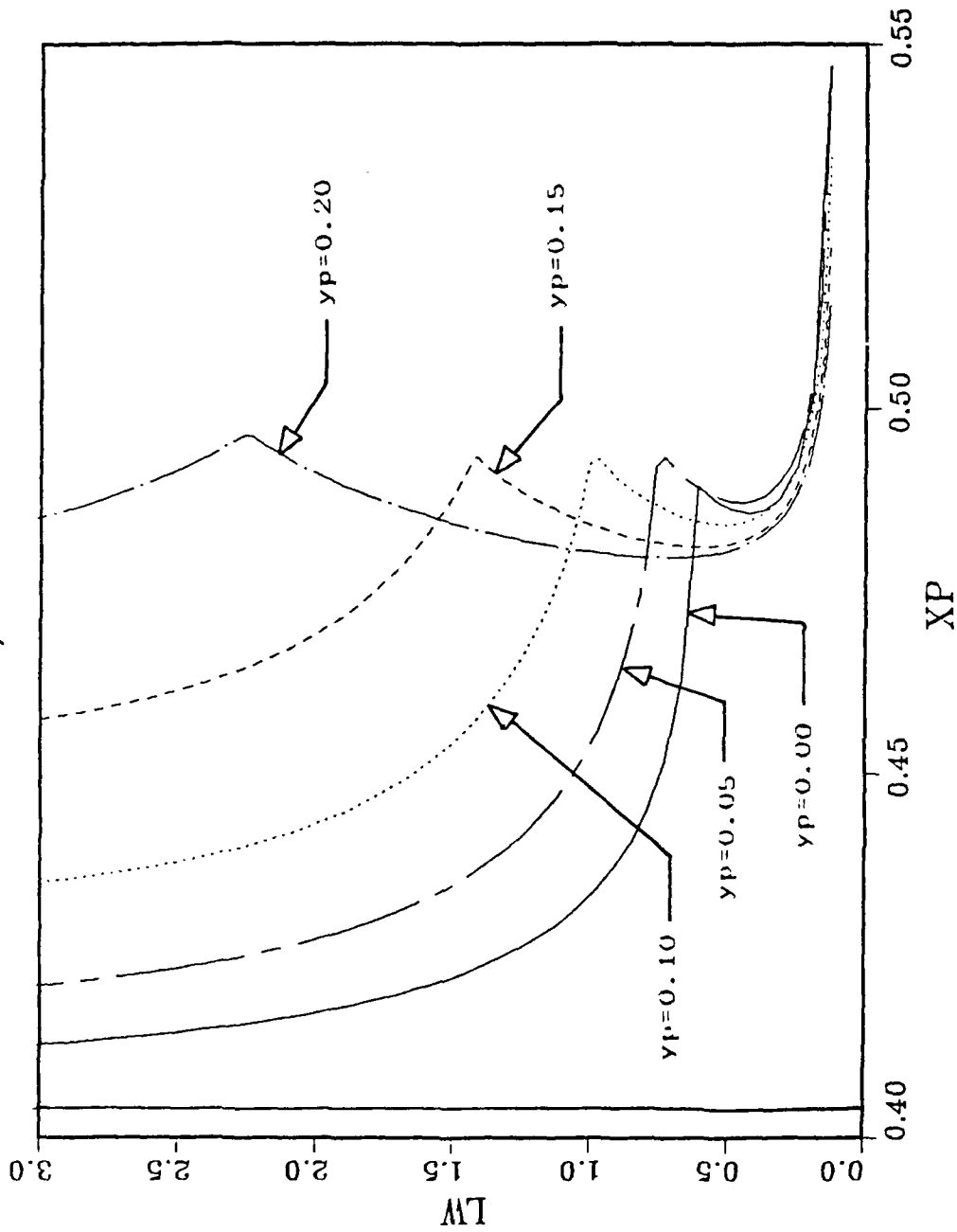


Figure 7. L_w vs. x_p , $y_p > 0$ as parameter

$x_p=0.404$ is a common crossing point for all curves. Each curve is formed by two cusps, with the upper cusp dominating with decreasing y_p . Each cusp is the plot of different critical pair of eigenvalues; the "nose" in the curves is the point where they intersect.

Note how the stable region gets smaller with decreasing y_p for L_w less than 0.7, for example, with $y_p=0.0$ and L_w greater than 1.0, there is a very narrow range of x_p where stability can be assured.

3. Figure 8: Critical Real Part vs. x_p

TOWBIF1 was again used to form Figure 8, this time with one value for L_w ($L_w=0.6$) and three negative values for y_p . The negative y_p curves pass from stable to unstable regions, with the stable ranges for x_p getting smaller as x_p becomes more negative.

As in Figure 6, the curves are composites of those results curves which are critical over a particular range of x_p .

4. Figure 9: L_w vs. x_p , Negative Values of y_p as Parameters.

Figure 9 data was generated from TOWBIF3, with $y_p=0.0$ curve included to provide continuity with Figure 7.

The stable region gets smaller as y_p decreases from 0.0. At $y_p=-0.10$ the "nose" between upper and lower cusps appears to be tipping up, with the region inside the "nose"

TANKER W/CATENARY

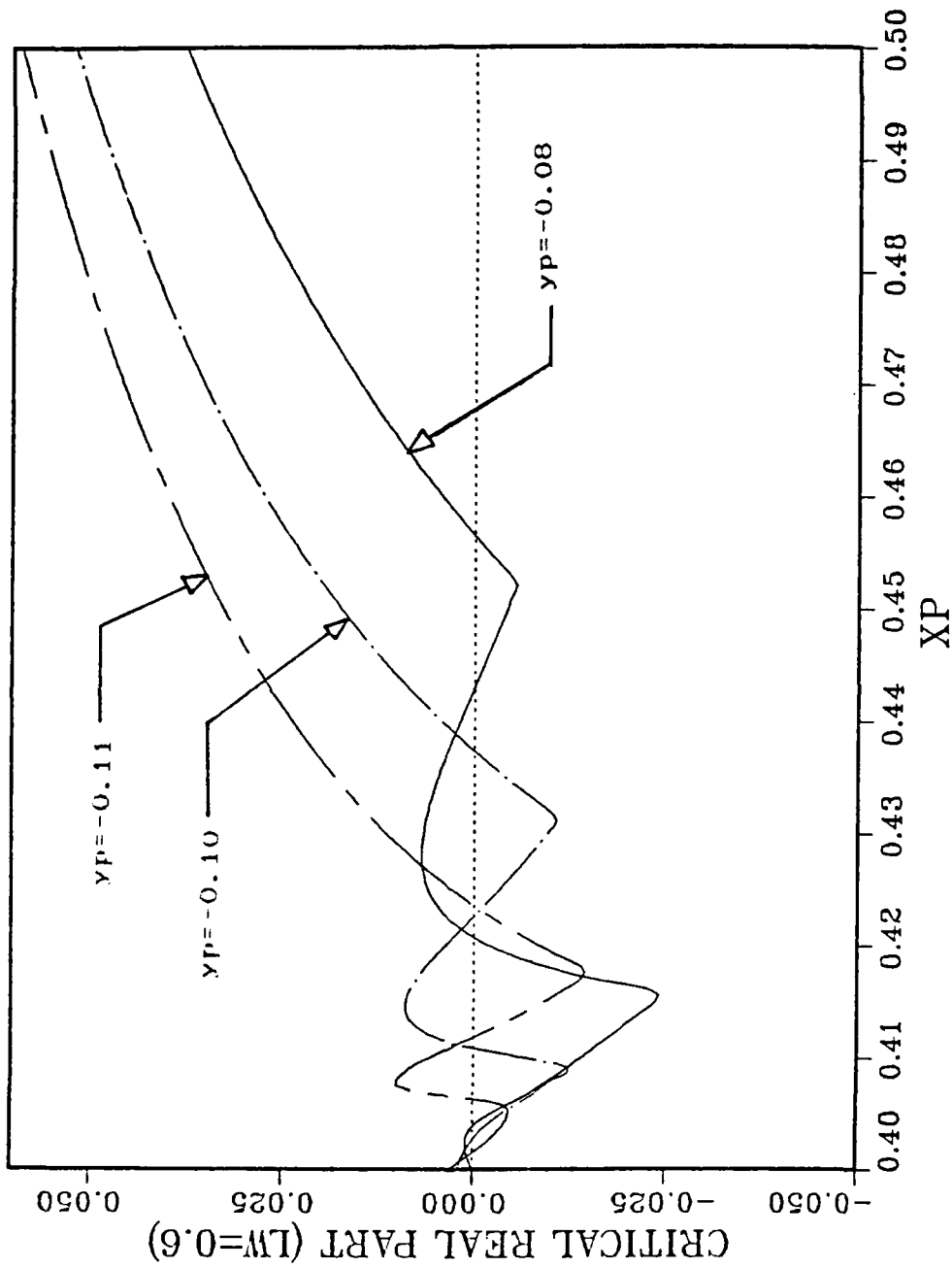


Figure 8. Critical Real Part vs. xp - yp < 0

TANKER W/CATENARY

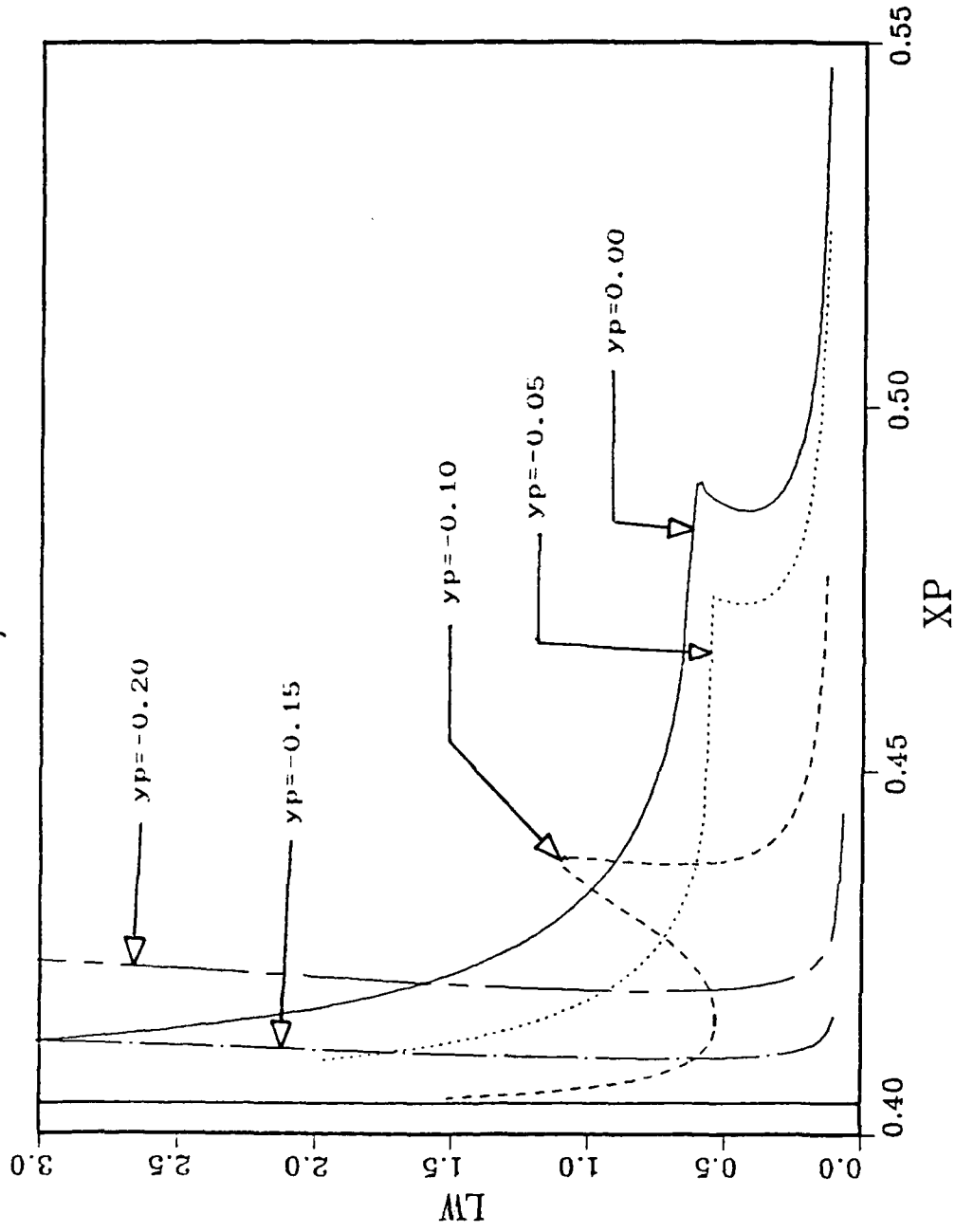


Figure 9. Lw vs. x_p , $y_p < 0$ as parameter

being stable. The curves plotted in Figure 8 were formed using a value of Lw which cut through this nose, thus forming the sinuous curves which pass in and out of the stable region. Note that for the most negative values of y_p , the cusps have disappeared, and the stable range of x_p is slightly increasing.

5. Figure 10: Lw vs x_p , Negative Values of y_p as Parameters.

Figure 10 is a "close-up" of Figure 9, focusing on what is happening around $y_p = -0.10$. The lower cusp tips up and merges with the upper to form a single curve. Note how the stable range of x_p virtually disappears for Lw greater than 0.5 for $y_p = -0.10$ and -0.11 . As was seen in Figure 9, stable range for x_p for Lw greater than 0.5 reappears with y_p less than -0.15 .

C. BARGE WITHOUT SKEG

The third vessel was a self-propelled version of the barge studied in Section A (not under power during tow), but without the skeg. As with the tanker, the presence of the propellor, simulated by a bias in the data file, introduces port-starboard asymmetry.

1. Figure 11: Critical Real Part vs x_p for $Lw=1.5$

Figure 11 shows curves for three values of y_p (greater than zero, zero, and less than zero) and one value of Lw . The curves show the stable range of x_p to be between

TANKER W/ CATENARY

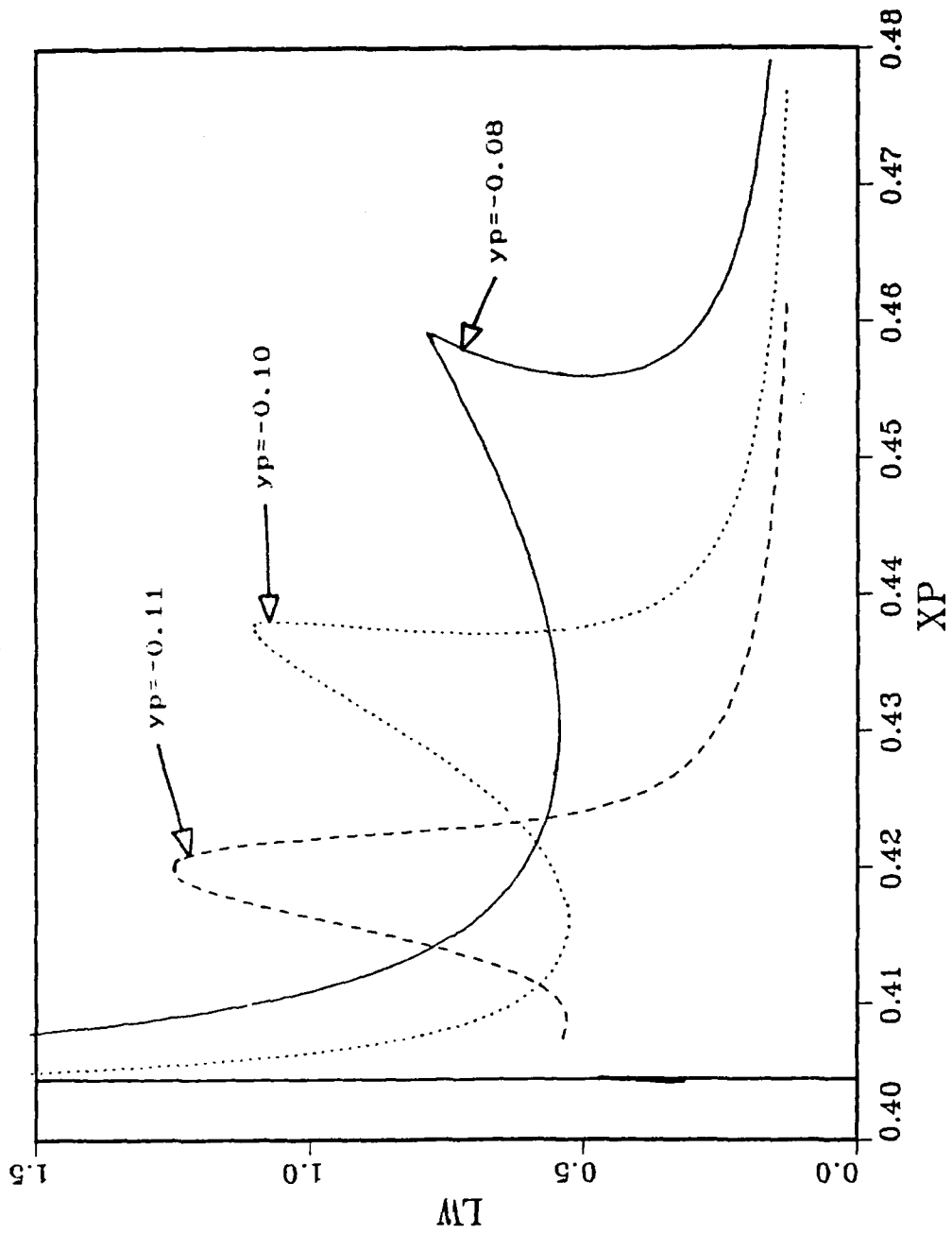


Figure 10. Lw vs. x_p , $y_p < 0$, Close-up

BARGE W/CATENARY, NO SKEG

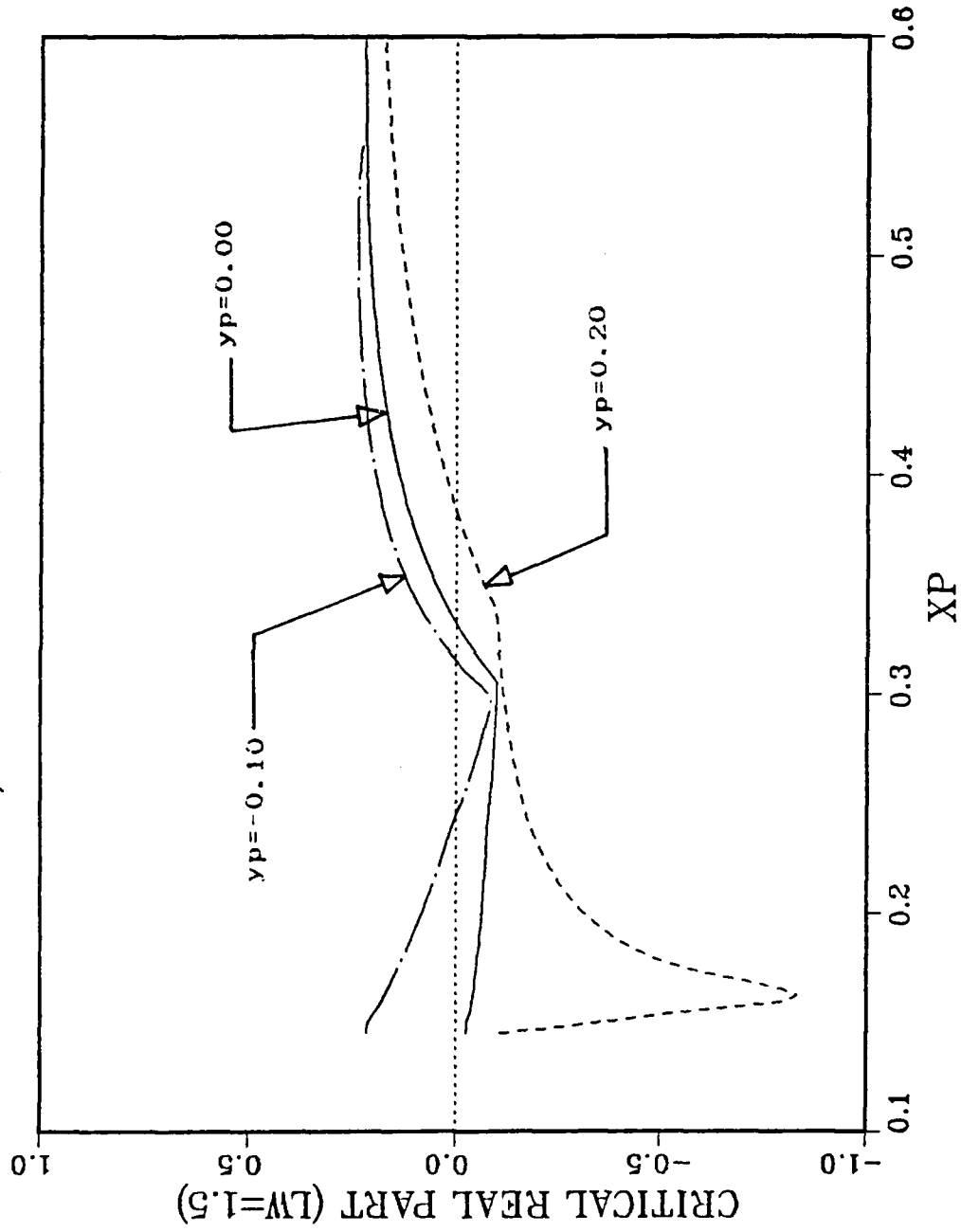


Figure 11. Critical Real Part vs. x_p - Barge w/o skeg

the zero crossing points of the critical real parts, as in the tanker case. Also similarly to the tanker, the stable region increases with increasing y_p . These results are opposite to the propellor-less barge with the skeg.

2. Figure 12: L_w vs x_p

Figure 12 dramatically shows how decreasing y_p reduces the stable region. The vertical line at $x_p=0.14$ was common to all values of y_p greater than and equal to zero. For values of y_p less than zero, the smooth shape of the curve is apparent.

The tanker and self-propelled barge cases dramatically demonstrate the effect that a bias, like a propellor, can introduce to the stability of the system.

D. PRACTICAL OBSERVATIONS

Analysis of the graphs suggests some general principles which may be applied when conducting slow speed towing operations with the vessels discussed in this chapter. While these principles are of course not generally applicable to all vessels, they illustrate how the analysis techniques employed in this work can be applied to other vessels.

For the unpowered, symmetric barge with a skeg, the operator should have the towline attachment point as far out to either side as possible and the towline as long as

BARGE W/ CATENARY, NO SKEG

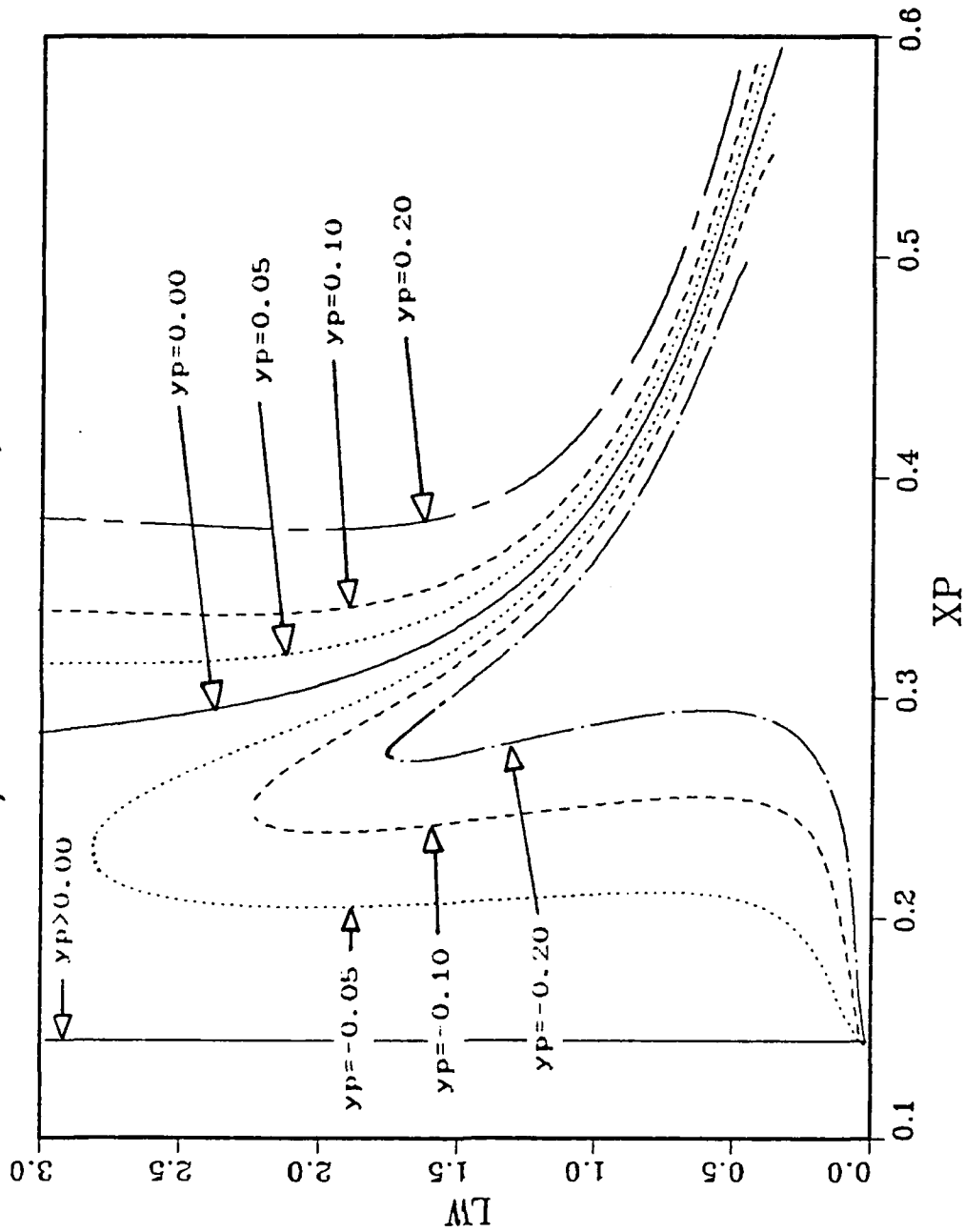


Figure 12. LW vs. xp, yp as parameter

practical. The attachment point can then be placed at any location forward of the center of gravity with stability assured. Conversely, if the attachment point must be on the centerline, placing it as far forward as possible (about half the barge's length forward of the center of gravity) will assure stability for all towline lengths.

For vessels with an asymmetrical bias (e.g., with a propellor), but without skegs, the attachment point needs to be as far to the biased side as possible (in the cases of the tanker and self-propelled barge, the +yp or port side) and placed forward of the center of gravity the distance indicated on the graph for all towline lengths. Placement of the attachment point on the opposite side (in the cases studied, the starboard side) will virtually assure the system to be unstable.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study highlighted the effect of athwartship position of the towline attachment point. The common assumption among ship operators prior to this research held that placing the towline on the centerline on the foremost point of the towed vessel would create the most advantageous towing situation. Studies such as [Ref. 2] have shown that towing stability can be dependent on the longitudinal placement of the attachment point. This research has shown that for certain conditions, attaching the towline off the centerline can also improve towed stability. The optimum towing configuration requires a combination of all three parameters - longitudinal and athwartship placement of the towline attachment point, and towline length.

The bifurcation technique used in this study can be used to produce stability information useful to ship designers and towing operators. Stability information can be assembled into a convenient graphical form that clearly defines the regions of stable and unstable operation based on the parameters the operator has the most control over - the placement and length of the towline.

For the ship designer, this technique can be useful in determining the implications particular design decisions would have on the vessel's performance under tow.

Depending on the vessel's use, adjustments to the design can be made to improve towing stability, or the customer can be forewarned to avoid certain kinds of operations. Since nearly all vessels are towed at some time, towing performance should be analyzed for all vessels.

For the towing operator, this technique can provide readily available information about how a particular vessel will respond under tow. The operator can then adjust the towing parameters (i.e., placement the attachment point and/or length of the towline) so the tow will be in its most stable condition, or, if unavoidable, know that a particular towing situation will be potentially dangerous and make preparations to deal with it.

Since ship data is inputted through a data file, the towed performance of any vessel can be analyzed with this method, including structures such as offshore oil platforms. Existing vessels can be analyzed, as well as different loading conditions.

Two principal disadvantages are associated with this technique:

1. The programs are dependent on the quality of the data provided. Determining hydrodynamic coefficients and resistance data requires tow tank experiments and analysis, and are not obtained for most vessels;
2. The programs require large amounts of computer time and memory to run, which may not be available or too costly for potential users, especially to run extensive "what-if" scenarios. This problem may be alleviated as more inexpensive, high speed, high capacity micro- and personal computers become available.

B. RECOMMENDATIONS

This study was done for only one set of conditions. Further research can be done in determining the effect of varying conditions, such as different speeds or maneuvering by the towing vessel, on the stability of the tow. External forces are modelled by the bias in the data file. A systematized method of introducing biases into the data would enable the analysis of the effect of environmental conditions on the towing system.

Further work should be conducted to improve the "user-friendliness" of the programs. As currently configured, the programs must be run instructively, and graphics produced offline. This is a time consuming process which does not use the full capabilities of either the programs or the graphics capabilities of the mainframe. Program

improvements should focus on streamlining computations and user interaction, and incorporating graphics, with the goal of making it available as a ship design tool.

APPENDIX

Driver programs used in this thesis are shown here.
Subroutines can be obtained by contacting:

Prof. F.A. Papoulias
Department of Mechanical Engineering
Naval Postgraduate School
Monterey, CA 93943

FILE: TOWBIF1 FORTRAN A1

	PROGRAM TOWB11	TOW00010
C		TOW00020
C	BIFURCATION ANALYSIS OF TOWING SYSTEMS	TOW00030
C	PARAMETER DEPENDS ON IPAR	TOW00040
C	IPAR = 1 : XP	TOW00050
C	2 : YP	TOW00060
C	3 : LW	TOW00070
C	IT NEEDS SUBROUTINES FROM TOWING.FTN	TOW00080
C		TOW00090
	IMPLICIT DOUBLE PRECISION (A-H,O-Z)	TOW00100
	DOUBLE PRECISION MAGSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW,	TOW00110
1	NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV,	TOW00120
2	NRDD,NRU,NRUU,ND,NDD,NDVV,NDRR,NDU,NDUU,NVRD	TOW00130
		TOW00140
C	DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6)	TOW00150
C		TOW00160
	COMMON/INTGR/ISKEG,NREDP,ITYS,ID,IFDS,ISTAB,IPROP	TOW00170
	COMMON/SPAR/MAGSP,LW,XPP,YPP,LB	TOW00180
	COMMON/SURGE/SU(7)	TOW00190
	COMMON/XSURG/XU,XUU,XUUU	TOW00200
	COMMON/SWAY/SW(15)	TOW00210
	COMMON/YAW/YA(16)	TOW00220
	COMMON/MTR/VCAR,RHO,ABS,CON1,CON2	TOW00230
	COMMON/REGIST/VEL(40),RESI(40)	TOW00240
	COMMON/VELE/VEL(100)	TOW00250
	COMMON/POSTH/X1,V1,Z1	TOW00260
	COMMON/GEOM/AL,RW,G,AET,MW,HW1	TOW00270
	COMMON/PROP/ALE,P,EY,DIA,ANIU	TOW00280
	COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99)	TOW00290
	COMMON/INT1/IC	TOW00300
	COMMON/DOC/UC,ALPHA	TOW00310
	COMMON/UEPT/RLX,RLY,RLZ	TOW00320
	COMMON/GLOPE/PDRXX,PDRXY,PDRYX,PDRYY	TOW00330
	COMMON/CLAN/RXX6,RYY6,RXX,RYY	TOW00340
C		TOW00350
	OPEN (UNIT=35,FILE='BARGE2',STATUS='OLD')	TOW00360
	OPEN (UNIT=1,FILE='RES0',STATUS='NEW')	TOW00370
C		TOW00380
	OPEN (UNIT=11,FILE='RES1R',STATUS='NEW')	TOW00390
	OPEN (UNIT=12,FILE='RES2R',STATUS='NEW')	TOW00400
	OPEN (UNIT=13,FILE='RES3R',STATUS='NEW')	TOW00410
	OPEN (UNIT=14,FILE='RES4R',STATUS='NEW')	TOW00420
	OPEN (UNIT=15,FILE='RES5R',STATUS='NEW')	TOW00430
	OPEN (UNIT=16,FILE='RES6R',STATUS='NEW')	TOW00440

C		TCW00450
	OPEN (UNIT=21,FILE='REC11',STATUS='NEW')	TCW00460
	OPEN (UNIT=22,FILE='REC21',STATUS='NEW')	TCW00470
	OPEN (UNIT=23,FILE='REC31',STATUS='NEW')	TCW00480
	OPEN (UNIT=24,FILE='REC41',STATUS='NEW')	TCW00490
	OPEN (UNIT=25,FILE='REC51',STATUS='NEW')	TCW00500
	OPEN (UNIT=26,FILE='REC61',STATUS='NEW')	TCW00510
C		TCW00520
	CALL INPUTD(10)	TCW00530
	VCAR =VCAR*1.689D0	TCW00540
	MATZ =0	TCW00550
	IFLOW=1	TCW00560
C		TCW00570
	WRITE (N,1001)	TCW00580
	READ (N,*) IPAR	TCW00590
	WRITE (N,1002)	TCW00600
	READ (N,*) A1,A2	TCW00610
	WRITE (N,1003)	TCW00620
	READ (N,*) JM1	TCW00630
	WRITE (N,1005)	TCW00640
	READ (N,*) IKB	TCW00650
	WRITE (N,1006)	TCW00660
	READ (N,*) NEQL	TCW00670
	IF (IKB.GT.NEQL) GO TO 500	TCW00680
	DO 1 I=1,NUM1	TCW00690
	WRITE (N,2001) I,NUM1	TCW00700
	AA=A1*(A2-A1)**(I-1)/(NUM1-1)	TCW00710
	IF (IPAR.EQ.1) XPP=AA	TCW00720
	IF (IPAR.EQ.2) YPP=AA	TCW00730
	IF (IPAR.EQ.3) LW =AA	TCW00740
	AL =L*LB*0.3048D0	TCW00750
	ALE=AL	TCW00760
	CALL STABIL(IVV,VV,ISOL)	TCW00770
C		TCW00780
C	SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM	TCW00790
C		TCW00800
	IF (IVV.NE.NEQL) GO TO 1	TCW00810
	V=VV(IKB)	TCW00820
	IF (DABS(V).GT.1.D0) STOP 1111	TCW00830
	CALL EQUILB(V,X,RES,RX,RY)	TCW00840
	CALL LINEAR(X,RES,A,RX,RY)	TCW00850
	CALL RG(6.6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TCW00860
	IF (IER1.NE.0) STOP 2222	TCW00870
	CALL DEGSTB(DEQS,WR)	TCW00880
	WRITE (1,10) AA,DEQS	TCW00890
	DO 11 J=1,6	TCW00900
	JR=10+J	TCW00910
	WRITE (JR,10) AA,WR(J)	TCW00920
	JI=20+J	TCW00930
	WRITE (JI,10) AA,WI(J)	TCW00940
	11 CONTINUE	TCW00950
	1 CONTINUE	TCW00960
	500 STOP	TCW00970
	10 FORMAT (2D20.10)	TCW00980
	1001 FORMAT (' ENTER 1 : XP VARIATION',/,	TCW00990
	1 ' 2 : YP VARIATION',/,	TCW01000
	2 ' 3 : LW VARIATION')	TCW01010
	1002 FORMAT (' ENTER PARAMETER RANGE')	TCW01020
	1003 FORMAT (' ENTER NUMBER OF INCREMENTS')	TCW01030
	1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')	TCW01040
	1006 FORMAT (' ENTER ESTIMATED NO. OF EQUILIBRIA')	TCW01050
	2001 FORMAT (2I5)	TCW01060
	END	TCW01070

FILE: TOWBIF2 FORTRAN A1

```
PROGRAM TOWB12                                TOW00010
C PROGRAM TOWBIF.FTN                          TOW00020
C                                              TOW00030
C BIFURCATION ANALYSIS OF TOWING SYSTEMS     TOW00040
C PARAMETERS ARE: Xp, Yp                      TOW00050
C IT NEEDS SUBROUTINES FROM TOWING.FTN       TOW00060
C                                              TOW00070
C USER DEPENDENT SUBROUTINES:                TOW00080
C   DEGSTB = CURVES ENCLOSING REGION II OF FIGURE 13 TOW00090
C   (SUBROUTINE DEGSTB IS IN TOWING.FTN)      TOW00100
C   DS1   = CURVES ENCLOSING REGION V OF FIGURE 13 TOW00110
C   (SUBROUTINE DS1 IS IN SPMBIF)            TOW00120
C                                              TOW00130
C IMPLICIT DOUBLE PRECISION (A-H,O-Z)        TOW00140
C DOUBLE PRECISION MASSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW, TOW00150
1 NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV, TOW00160
2 NRDD,NRU,NRUU,ND,NDDD,NDVV,NDRR,NDU,NDUU,NVRD TOW00170
C                                              TOW00180
C DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6) TOW00190
C                                              TOW00200
C COMMON/INTGR/ISKEG,NRECP,ITYS,ID,IFDS,ISTAB,IPROP TOW00210
C COMMON/SPAR/MACSP,LW,XPP,YPP,LB           TOW00220
C COMMON/SURGE/SU(7)                       TOW00230
C COMMON/XSURG/XU,XUU,XUUU                 TOW00240
C COMMON/SWAY/SW(15)                       TOW00250
C COMMON/YAW/YA(16)                        TOW00260
C COMMON/MTER/VCAR,RHO,ABS,CON1,CON2       TOW00270
C COMMON/RESIST/VEL(40),RESI(40)           TOW00280
C COMMON/VELE/VEL(100)                    TOW00290
C COMMON/POSTN/X1,Y1,Z1                    TOW00300
C COMMON/GEOM/AL,RW,G,AET,HW,HW1          TOW00310
C COMMON/PROP/ALE,P,EY,DIA,ANTI           TOW00320
C COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99) TOW00330
C COMMON/INT1/IC                           TOW00340
C COMMON/DCC/UC,ALPHA                      TOW00350
C COMMON/UEPT/RLX,RLY,RLZ                 TOW00360
C COMMON/SLOPE/PDRXX,PDRXY,PDRYX,PDRYY    TOW00370
C COMMON/SLAN/RXX6,RYY6,RXX,RYY           TOW00380
C                                              TOW00390
C OPEN (UNIT=35,FILE='BGKEG2',STATUS='OLD') TOW00400
C OPEN (UNIT=11,FILE='RES1R',STATUS='NEW') TOW00410
C OPEN (UNIT=12,FILE='RES2R',STATUS='NEW') TOW00420
C OPEN (UNIT=13,FILE='RES3R',STATUS='NEW') TOW00430
C OPEN (UNIT=14,FILE='RES4R',STATUS='NEW') TOW00440
C OPEN (UNIT=15,FILE='RES5R',STATUS='NEW') TOW00450
C OPEN (UNIT=16,FILE='RES6R',STATUS='NEW') TOW00460
C                                              TOW00470
C CALL INPUTD(10)                           TOW00480
C VCAR =VCAR=1.689D0                        TOW00490
C AL =LW*LB=0.3048D0                       TOW00500
C ALE =AL                                    TOW00510
C MATZ =0                                    TOW00520
C IFLOW=1                                    TOW00530
C EPS =1.D-5                                TOW00540
C ILMAX=1500                                TOW00550
C                                              TOW00560
C WRITE (*,1001)                             TOW00570
C READ (*,*) A1,A2                           TOW00580
C WRITE (*,1002)                             TOW00590
C READ (*,*) NUM1                            TOW00600
C WRITE (*,1003)                             TOW00610
C READ (*,*) B1,B2                           TOW00620
C WRITE (*,1004)                             TOW00630
C READ (*,*) NUM2                            TOW00640
```

C	WRITE (*,1005)	TOW00650
	READ (*,*) IKB	TOW00660
	WRITE (*,1006)	TOW00670
	READ (*,*) IDC	TOW00680
	DO 1 I=1,NUM1	TOW00690
	WRITE (*,2001) I,NUM1	TOW00700
	YPP=A1*(A2-A1)*(I-1)/(NUM1-1)	TOW00710
		TOW00720
	XPP=B1	TOW00730
	CALL STABIL(IVV,VV,ISOL)	TOW00740
C		TOW00750
C	SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM	TOW00760
C		TOW00770
	V=VV(IKB)	TOW00780
	IF (DABG(V).GT.1.D0) STOP 1111	TOW00790
	CALL EQUILB(V,X,RES,RX,RY)	TOW00800
	CALL LINEAR(X,RES,A,RX,RY)	TOW00810
	CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW00820
	IF (IER1.NE.0) STOP 2222	TOW00830
	IF (IDG.EQ.1) CALL DEGSTB(DEOS,WR)	TOW00840
	IF (IDG.EQ.2) CALL DSI(DEOS,WR)	TOW00850
	DEOSCO=DEOS	TOW00860
	XPCO =XPP	TOW00870
	L =0	TOW00880
	DO 2 J=2,NUM2	TOW00890
C	WRITE (*,*) J	TOW00900
	XPP=B1+(B2-B1)*(J-1)/(NUM2-1)	TOW00910
	CALL STABIL(IVV,VV,ISOL)	TOW00920
		TOW00930
C		TOW00940
C	SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM	TOW00950
C		TOW00960
	V=VV(IKB)	TOW00970
	IF (DABG(V).GT.1.D0) STOP 1111	TOW00980
	CALL EQUILB(V,X,RES,RX,RY)	TOW00990
	CALL LINEAR(X,RES,A,RX,RY)	TOW01000
	CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW01010
	IF (IER1.NE.0) STOP 2222	TOW01020
	IF (IDG.EQ.1) CALL DEGSTB(DEOS,WR)	TOW01030
	IF (IDG.EQ.2) CALL DSI(DEOS,WR)	TOW01040
	DEOSNN=DEOS	TOW01050
	XPNN=XPP	TOW01060
	PR=DEOSCO=DEOSNN	TOW01070
	IF (PR.GT.0.D0) GO TO 3	TOW01080
	L=L+1	TOW01090
	IF (L.GT.6) STOP 1000	TOW01100
	IL=0	TOW01110
	XPO=XPCO	TOW01120
	XPN=XPNN	TOW01130
	DEOSO=DEOSCO	TOW01140
	DEOSN=DEOSNN	TOW01150
6	XPL=XPO	TOW01160
	XPR=XPN	TOW01170
	DEOSL=DEOSO	TOW01180
	DEOSR=DEOSN	TOW01190
	XPP=(XPL+XPR)/2.D0	TOW01200
	CALL STABIL(IVV,VV,ISOL)	TOW01210
	V=VV(IKB)	TOW01220
	IF (DABG(V).GT.1.D0) STOP 1111	TOW01230
	CALL EQUILB(V,X,RES,RX,RY)	TOW01240
	CALL LINEAR(X,RES,A,RX,RY)	TOW01250
	CALL RG(6,6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW01260
	IF (IER1.NE.0) STOP 2222	TOW01270
	CALL DEGSTB(DEOS,WR)	TOW01280
	DEOSH=DEOS	TOW01290

XPM=XPP	TOW01290
PRL=DEOGL*DEOSM	TOW01300
PRR=DEOSR*DEOSM	TOW01310
IF (PRL.GT.0.D0) GO TO 5	TOW01320
XPO=XPL	TOW01330
XPN=XPM	TOW01340
DEOSO=DEOSL	TOW01350
DEOSN=DEOSM	TOW01360
IL=IL+1	TOW01370
IF (IL.GT.ILMAX) STOP 3100	TOW01380
DIF=DABS(XPL-XPM)	TOW01390
IF (DIF.GT.EPS) GO TO 6	TOW01400
XP=XPM	TOW01410
GO TO 4	TOW01420
5 IF (PRR.GT.0.D0) STOP 3200	TOW01430
XPO=XPM	TOW01440
XPN=XPR	TOW01450
DEOSO=DEOSM	TOW01460
DEOSN=DEOSR	TOW01470
IL=IL+1	TOW01480
IF (IL.GT.ILMAX) STOP 3100	TOW01490
DIF=DABS(XPM-XPR)	TOW01500
IF (DIF.GT.EPS) GO TO 6	TOW01510
XP=XPM	TOW01520
4 LLL=10*L	TOW01530
WRITE (LLL,10) XP,YPP	TOW01540
3 XPO=XPN	TOW01550
DEOSO=DEOSN	TOW01560
2 CONTINUE	TOW01570
1 CONTINUE	TOW01580
STOP	TOW01590
10 FORMAT (2D20.10)	TOW01600
1001 FORMAT (' ENTER RANGE OF Yp VARIATION')	TOW01610
1002 FORMAT (' ENTER NUMBER OF INCREMENTS IN Yp')	TOW01620
1003 FORMAT (' ENTER RANGE OF Xp VARIATION')	TOW01630
1004 FORMAT (' ENTER NUMBER OF INCREMENTS IN Xp')	TOW01640
1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')	TOW01650
1006 FORMAT (' ENTER DEGREE OF STABILITY CONTROL')	TOW01660
2001 FORMAT (2I5)	TOW01670
END	TOW01680
C	TOW01690
SUBROUTINE DSI(DEOS,WR)	TOW01700
IMPLICIT DOUBLE PRECISION (A-H,O-Z)	TOW01710
DIMENSION WR(6)	TOW01720
DEOS1=-1.D30	TOW01730
DO 1 I=1,6	TOW01740
IF (WR(I).LT.DEOS1) GO TO 1	TOW01750
DEOS1=WR(I)	TOW01760
IJJ=I	TOW01770
1 CONTINUE	TOW01780
DEOS2=-1.D30	TOW01790
DO 2 I=1,6	TOW01800
IF (IJ.EQ.I) GO TO 2	TOW01810
IF (WR(I).LT.DEOS2) GO TO 2	TOW01820
DEOS2=WR(I)	TOW01830
IJJ=I	TOW01840
2 CONTINUE	TOW01850
DEOS=-1.D30	TOW01860
DO 3 I=1,6	TOW01870
IF (I.EQ.IJ.OR.I.EQ.IJJ) GO TO 3	TOW01880
IF (WR(I).GE.DEOS) DEOS=WR(I)	TOW01890
3 CONTINUE	TOW01900
RETURN	TOW01910
END	TOW01920

FILE: TOWBIF3 FORTRAN A1

```
C PROGRAM TOWBIF3.FTN TOW00010
C TCW00020
C BIFURCATION ANALYSIS OF TOWING SYSTEMS TCW00030
C PARAMETERS ARE: Xp, Lw TCW00040
C IT NEEDS SUBROUTINES FROM TOWING.FTN TCW00050
C TCW00060
C USER DEPENDENT SUBROUTINES: TCW00070
C DEGSTB = CURVES ENCLOSING REGION II OF FIGURE 13 TCW00080
C (SUBROUTINE DEGSTB IS IN TOWING.FTN) TCW00090
C DS1 = CURVES ENCLOSING REGION V OF FIGURE 13 TCW00100
C (SUBROUTINE DS1 IS IN SPMBIF) TCW00110
C TCW00120
C IMPLICIT DOUBLE PRECISION (A-H,O-Z) TCW00130
C DOUBLE PRECISION MASSP,NVD,NV,NRD,IZZ,NR,LB,LEN,LW, TCW00140
1 NO,NOU,NOUU,NVVV,NVRR,NVDD,NVU,NVUU,NRRR,NRVV, TCW00150
2 NRDD,NRU,NRUU,ND,NDD,NDVV,NDRR,NDU,NDUU,NVRD TCW00160
C TCW00170
C DIMENSION IV1(6),A(6,6),VV(3),X(6),WR(6),WI(6),Z(6,6),SV2(6) TCW00180
C TCW00190
C COMMON/INTGR/ISKEG,NREDP,ITYS,ID,IFDS,ISTAB,IPROP TCW00200
C COMMON/SPAR/MASSP,LW,XPP,YPP,LB TCW00210
C COMMON/SURGE/SU(7) TCW00220
C COMMON/XSURG/XU,XUU,XUUU TCW00230
C COMMON/SWAY/SW(15) TCW00240
C COMMON/YAW/YA(16) TCW00250
C COMMON/MTER/VCAR,RHO,ABS,CON1,CON2 TCW00260
C COMMON/RESIST/VEL(40),RESI(40) TCW00270
C COMMON/VELE/UEL(100) TCW00280
C COMMON/POSTN/XI,YJ,Z1 TCW00290
C COMMON/GECH/AL,RH,G,AET,HW,HW1 TCW00300
C COMMON/PRCP/ALE,P,EY,DIA,ANIU TCW00310
C COMMON/CTNR/XC(99),YC(99),ZC(99),TC(99) TCW00320
C COMMON/INT1/IC TCW00330
C COMMON/DOC/UC,ALPHA TCW00340
C COMMON/UEPT/RLX,RLY,RLZ TCW00350
C COMMON/SLOPE/PDRXX,PDRXY,PDRYX,PDRYY TCW00360
C COMMON/SLAN/RXX6,RYX6,RXX,RYY TCW00370
C TCW00380
C OPEN (UNIT=35,FILE='TANKER2',STATUS='OLD') TCW00390
C OPEN (UNIT=1,FILE='RES1R',STATUS='NEW') TCW00400
C OPEN (UNIT=2,FILE='RES2R',STATUS='NEW') TCW00410
C OPEN (UNIT=3,FILE='RES3R',STATUS='NEW') TCW00420
C OPEN (UNIT=4,FILE='RES4R',STATUS='NEW') TCW00430
C TCW00440
C CALL INPUTD(10) TCW00450
C VCAR =VCAR*1.689D0 TCW00460
C AL =LW*LB*0.3048D0 TCW00470
C ALE =AL TCW00480
C MATZ =0 TCW00490
C IFLOW=1 TCW00500
C ILMAX=1500 TCW00510
C EPS =1.D-5 TCW00520
C TCW00530
C WRITE (*,1001) TCW00540
C READ (*,*) A1,A2 TCW00550
C WRITE (*,1002) TCW00560
C READ (*,*) NUM1 TCW00570
C WRITE (*,1003) TCW00580
C READ (*,*) B1,B2 TCW00590
C WRITE (*,1004) TCW00600
C READ (*,*) NUM2 TCW00610
C TCW00620
C WRITE (*,1005) TCW00630
C READ (*,*) IKB TCW00640
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	WRITE (*-1006)	TOW00650
	READ (*-*) IDS	TOW00660
	DO 1 I=1,NUM1	TOW00670
	WRITE (*-2001) I,NUM1	TOW00680
	LW =A1*(A2-A1)/(I-1)/(NUM1-1)	TOW00690
	AL =LW*LB=0.304800	TOW00700
	ALE=AL	TOW00710
	XPP=B1	TOW00720
	CALL STABIL(IVV,VV,ISOL)	TOW00730
C		TOW00740
C	SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM	TOW00750
C		TOW00760
	V=VV(IKB)	TOW00770
	IF (DABS(V).GT.1.D0) STOP 1111	TOW00780
	CALL EQUILB(V,X.RES,RX,RV)	TOW00790
	CALL LINEAR(X.RES,A,RX,RV)	TOW00800
	CALL RG(6.6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW00810
	IF (IER1.NE.0) STOP 2222	TOW00820
	IF (IDS.EQ.1) CALL DEGSTB(DECS,WR)	TOW00830
	IF (IDS.EQ.2) CALL DS1(DEOS,WR)	TOW00840
	DEOSOO=DEOS	TOW00850
	XPOO =XPP	TOW00860
	L =0	TOW00870
	DO 2 J=2,NUM2	TOW00880
	XPP=B1*(B2-B1)*(J-1)/(NUM2-1)	TOW00890
	CALL STABIL(IVV,VV,ISOL)	TOW00900
C		TOW00910
C	SET V=VV(K) FOR BIFURCATION ANALYSIS OF K-TH EQUILIBRIUM	TOW00920
C		TOW00930
	V=VV(IKB)	TOW00940
	IF (DABS(V).GT.1.D0) STOP 1111	TOW00950
	CALL EQUILB(V,X.RES,RX,RV)	TOW00960
	CALL LINEAR(X.RES,A,RX,RV)	TOW00970
	CALL RG(6.6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW00980
	IF (IER1.NE.0) STOP 2222	TOW00990
	IF (IDS.EQ.1) CALL DEGSTB(DEOS,WR)	TOW01000
	IF (IDS.EQ.2) CALL DS1(DEOS,WR)	TOW01010
	DEOSNN=DEOS	TOW01020
	XPNN=XPP	TOW01030
	PR=DEOSOO+DEOSNN	TOW01040
	IF (PR.GT.0.D0) GO TO 3	TOW01050
	L=L+1	TOW01060
	IF (L.GT.4) STOP 1000	TOW01070
	IL=0	TOW01080
	XI=0+XPOO	TOW01090
	XPN=XPNN	TOW01100
	DEOSO=DEOSOO	TOW01110
	DEOSN=DEOSNN	TOW01120
6	XPL=XPO	TOW01130
	XPR=XPN	TOW01140
	DEOSL=DEOSO	TOW01150
	DEOSR=DEOSN	TOW01160
	XPP=(XPL+XPR)/2.D0	TOW01170
	CALL STABIL(IVV,VV,ISOL)	TOW01180
	V=VV(IKB)	TOW01190
	IF (DABS(V).GT.1.D0) STOP 1111	TOW01200
	CALL EQUILB(V,X.RES,RX,RV)	TOW01210
	CALL LINEAR(X.RES,A,RX,RV)	TOW01220
	CALL RG(6.6,A,WR,WI,MATZ,Z,IV1,SV2,IER1)	TOW01230
	IF (IER1.NE.0) STOP 2222	TOW01240
	CALL DEGSTB(DEOS,WR)	TOW01250
	DEOSM=DEOS	TOW01260
	XPM=XPP	TOW01270

PRL=DEOGL+DEOSM	TOW01280
PRR=DEOSR+DEOSM	TOW01290
IF (PRL.GT.0.D0) GO TO 5	TOW01300
XPO=XPL	TOW01310
XPN=XPM	TOW01320
DEOGO=DEOSL	TOW01330
DEOSN=DEOSM	TOW01340
IL=IL+1	TOW01350
IF (IL.GT.ILMAX) STOP 3100	TOW01360
DIF=DABS(XPL-XPM)	TOW01370
IF (DIF.GT.EPS) GO TO 6	TOW01380
XP=XPM	TOW01390
GO TO 4	TOW01400
5 IF (PPR.GT.0.D0) STOP 3200	TOW01410
XPO=XPM	TOW01420
XPN=XPR	TOW01430
DEOGO=DEOSM	TOW01440
DEOSN=DEOCR	TOW01450
IL=IL+1	TOW01460
IF (IL.GT.ILMAX) STOP 3100	TOW01470
DIF=DABS(XPM-XPR)	TOW01480
IF (DIF.GT.EPS) GO TO 6	TOW01490
XP=XPM	TOW01500
4 WRITE (L,10) XP,LW	TOW01510
3 XPOO=XPNM	TOW01520
DEOGOC=DEOSNM	TOW01530
2 CONTINUE	TOW01540
1 CONTINUE	TOW01550
STOP	TOW01560
10 FORMAT (2D20.10)	TOW01570
1001 FORMAT (' ENTER RANGE OF LW VARIATION')	TOW01580
1002 FORMAT (' ENTER NUMBER OF INCREMENTS IN LW')	TOW01590
1003 FORMAT (' ENTER RANGE OF Xp VARIATION')	TOW01600
1004 FORMAT (' ENTER NUMBER OF INCREMENTS IN Xp')	TOW01610
1005 FORMAT (' ENTER EQUILIBRIUM NUMBER')	TOW01620
1006 FORMAT (' ENTER DEGREE OF STABILITY CONTROL')	TOW01630
2001 FORMAT (2I5)	TOW01640
END	TOW01650
C	TOW01660
SUBROUTINE D01(DEOS,WR)	TOW01670
IMPLICIT DOUBLE PRECISION (A-H,O-Z)	TOW01680
DIMENSION WR(6)	TOW01690
DEOS1=-1.D30	TOW01700
DO 1 I=1,6	TOW01710
IF (WR(I).LT.DEOS1) GO TO 1	TOW01720
DEOS1=WR(I)	TOW01730
IJ=1	TOW01740
1 CONTINUE	TOW01750
DEOS2=-1.D30	TOW01760
DO 2 I=1,6	TOW01770
IF (IJ.EQ.1) GO TO 2	TOW01780
IF (WR(I).LT.DEOS2) GO TO 2	TOW01790
DEOS2=WR(I)	TOW01800
IJJ=I	TOW01810
2 CONTINUE	TOW01820
DEOS=-1.D30	TOW01830
DO 3 I=1,6	TOW01840
IF (I.EQ.IJ.OR.1.EQ.IJJ) GO TO 3	TOW01850
IF (WR(I).GE.DEOS) DEOS=WR(I)	TOW01860
3 CONTINUE	TOW01870
RETURN	TOW01880
END	TOW01890

LIST OF REFERENCES

1. Comstock, J.P., Editor, Principles of Naval Architecture, The Society of Naval Architects and Marine Engineers, 1967.
2. Department of Transportation, Report DOT/OST/P-34/86/046, Rational Method for Upgrading Towed Vessel Safety, by M.M. Bernitsas and F.A. Papoulias, May 1986
3. F.A. Papoulias, Dynamic Analysis of Mooring Systems, Doctoral Dissertation, The University of Michigan, Ann Arbor, Michigan, 1987.
4. M.M. Bernitsas and N.S. Kekridas, "Simulation and Stability of Ship Towing", International Shipbuilding Progress, v.32, 1985.
5. F.A. Papoulias, "A Qualitative and Quantitative Study of Steady-State Response of Towed Floating Bodies", Dynamics and Stability of Systems, v.3, 1988.

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