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THE EFFECT OF PASSING SHIPS ON MOORED SHIPS

(*revised*)

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INTRODUCTION

As a moving ship passes another ship, it exerts forces and moments on that ship. This passing ship phenomenon is of particular concern in the design and analysis of ship mooring facilities alongside shipping fairways and channels.

This paper presents a set of equations to calculate the peak forces and moments produced by the passing ship. It provides a method to develop time histories of these forces and moments. It discusses the possible consequences of these effects on the moored ship and gives advice on how to reduce these effects.

BACKGROUND

In the early 1970s Esso Research and Engineering Co. (ER&E), now Exxon Mobil Research and Engineering Co., conducted several studies of the effects of passing ships on moored ships. Those studies were conducted by others; I advised and vetted the studies and thus am familiar with the methods and the results. Papers published by others give some of the results of those studies. Recently I used those published results to develop the method of predicting passing ship effects which is presented in this paper.

Remery

ER&E conducted a model test program at the Netherlands Ship Model Basin (NSMB) in Wageningen, the Netherlands. NSMB is now the Maritime Research Institute Netherlands (MARIN). Some of the results of that program were later published by Remery.(1)

Remery concluded, "... the forces and moments on the captive ship were proportional to the square of the speed of the passing tanker." Remery also observed, "... the lowest mooring forces occurred when the ship was fully restrained. Lower mooring forces could only be attained for a very soft mooring system, but very large motions would have then have to be accepted."

Remery's paper provided plots of forces and moments on the moored ship against the position of the passing ship. He observed that, "plotting the measured forces and moments to a base of the position of the passing ship relative to the moored ship shows that the character of the curves is similar for the various sizes and passing distances of the sailing {passing} ship". These data plots are the basis for most of the equations given in this paper.

Muga and Fang

The NSMB model test results provided ER&E with some data for predicting passing ship effects. But a more general method of predicting passing ship forces and moments for various ship sizes and other parameters was needed. ER&E then developed a method for calculating passing ship forces and moments. A paper describing that method was published by Muga and Fang.(2)

The Muga and Fang calculation method gave good agreement with the results of the NSMB model tests. However, the method required a special computer program, and thus it is not suitable for general use.

Like Remery, Muga and Fang observed, "... the time pattern (or phase relations) of the occurrence of the peaks and the sequences of the loadings are very similar. This suggests that each loading function can be described by a single value of the ordinate, perhaps the maximum." They also observed "... the time pattern of the loading functions as predicted by theory are all very similar to each other and to their corresponding experimental cases."

Development of Equations

A full explanation of the background and development of the equations given in this paper is provided in my earlier paper presented at the ASCE Ports 2001 Conference.(3) A brief explanation for the equations is given here.

Remery's paper presented plots of the forces and moments exerted on a moored vessel by ships of three sizes passing at various velocities with various separations. Using those plots, I developed a set of non-dimensional equations which calculate the peak forces and moments as functions of vessel separation distance and passing ship velocity. These equations give good correlation, within 5%, of the results published by Remery.

The moored vessel used in the model tests was a 100,000 dwt tanker with a length between perpendiculars of 257 m. Using Froude law scaling, I developed scale factors to adjust the forces and moments to other moored vessel sizes. In this paper, these scale factors are calculated separately and then incorporated into the force and moment equations.

The model tests were all conducted with an underkeel-clearance to draft ratio (UKCDR) of 0.15. I used the computed results given in the Muga-Fang paper to develop equations to extrapolate the forces and moment to other underkeel-clearance to draft ratios.

Conventions Used in This Paper

The nomenclature and conventions used in this paper are illustrated in Figure 1. These conventions are the same as used by Remery.

The separation distance is measured between the sides of the two ships as they pass.

The passing ship position is related to the distance between the two ships' transverse centerlines, measured along the path of the passing ship at a particular time. This position is expressed as a ratio of that distance to the characteristic length, which is the average of the two ship's lengths. That is:

$$L_c = \frac{L_m + L_p}{2} \qquad \text{(eq. 1)}$$

where:

L_c = Characteristic Length

L_m = Length of Moored Ship

L_p = Length of Passing Ship

The ships' lengths used should be length between perpendiculars. Using overall length will result in a distortion of the position graph and thus the time scale, but it will have little effect on the calculated maximum forces.

The sign conventions for the forces and moments are shown in Figure 1. Positive longitudinal force is toward the approaching passing ship (and thus opposite to its direction of travel). Positive lateral force is toward the passing ship (and away from the pier). Positive moment tends to turn the end of the moored ship which is closest to the approaching ship away from that approaching ship.

THE PASSING SHIP PHENOMENON

As a ship moving through a waterway passes a moored ship, it exerts time-varying forces and moments on the moored ship. These forces and moments are caused in part by the waves produced by the moving ship. But the principal cause is the movement of water around the passing ship which exerts a Bernoulli suction effect on the moored ship.

Passing Ship Force and Moment Diagrams

Figure 2 shows plots of typical patterns of longitudinal force, lateral force, and moment exerted on the moored ship. The horizontal axis marks the position of the passing ship relative to the moored ship, expressed as a ratio to the characteristic length, explained above. In each plot, the vertical axis is scaled relative to the peak value respective force or moment, thus making the values dimensionless.

These force and moment vs. position graphs were derived from Remery's published figures. When Remery's longitudinal force, lateral force, and moment figures are nondimensionallized in this manner, the respective plots for the various tanker sizes and separation differences become essentially the same, allowing one set of graphs to represent all cases.

Later I present empirical formulae for calculating the peak longitudinal force, lateral force, and moment which are based on separation distance, relative tanker size, and underkeel clearance. These peak values can be used with the respective nondimensionallized graphs in Figure 2 to produce graphs of forces and moment against passing ship position.

Then, with knowledge of the ship's lengths, and the speed of the passing ship, graphs of respective forces and moment against time can be created.

Narration of the Passing Ship Phenomena

Figure 3 illustrates successive positions of a passing ship relative to a moored ship and indicates the respective force and moment directions. In the following narration, the bow of the moored ship points toward the approaching passing ship. Thus positive moment pushes the bow away from the passing ship.

The influence of the passing ship is first felt when it is about –2 characteristic lengths away. Small negative longitudinal and lateral forces are first felt at about that relative position. When the passing ship is about –1 characteristic length away, there is a peak negative lateral force. In this position, the passing ship's bow comes in line with the bow of the moored ship.

The bow of the passing ship reaches the midpoint of the moored ship at –0.5 characteristic length. At about this position, the longitudinal force reaches a positive peak, and the moment reaches a negative peak, as shown in Figure 2. There is a strong tendency to pull the moored ship along the pier toward the approach direction and to pull its bow away from the pier. The lateral force is essentially zero at this position.

When the two ships are side-by-side, the longitudinal force and the moment both drop essentially to zero. This is fortunate, because the peak positive lateral force occurs at this position, tending to pull the ship away from the pier. This may seem counterintuitive, but the flow of water flowing from ahead to behind the passing ship produces a Bernoulli suction effect.

As the passing ship moves on, essentially a mirror image of the above effects takes place. At about +0.5 characteristic length, the longitudinal force reaches a negative peak and the moment reaches a positive peak. These tend to pull the moored ship's stern off the pier and to push the moored ship in the direction along which the passing ship is traveling. Fortunately, the lateral force drops almost to zero by this point. However, because ship response lags behind the applied force, the ship may still be pulled away from the pier at this time, permitting it to surge along the pier without the restraining frictional effects of the fenders.

When the passing ship's stern is in line with the moored ship's stern, there is a small negative lateral force and a small negative moment tending to push the moored ship against the pier. By the time the passing ship has traveled one ship length beyond the moored ship, the applied forces and moment drop to zero. However, because of the ship response lags the applied force, and also because of mooring system dynamics, the moored ship may still be moving at this time.

Principal Features of the Passing Ship Phenomena

Typical graphs of passing-ship-induced surge and sway force and yaw moment vs. position show the following:

Longitudinal Force (surge) –

- maximum positive longitudinal force occurs at a position of about -0.5
- maximum negative longitudinal force occurs at about 0.4
- magnitudes of positive and negative longitudinal forces are about equal
- zero longitudinal force occurs at about 0

Lateral Force (sway) –

- maximum positive lateral force occurs at about 0
- maximum negative lateral force occurs at about -0.8
- the zero lateral forces occur essentially coincidentally with the maximum longitudinal forces

Moment (yaw) –

- maximum negative moment occurs at about same time as maximum positive longitudinal force
- maximum positive moment occurs at about same time as maximum negative longitudinal force
- magnitude of maximum negative moment is greater than that of maximum positive moment
- moment at time of maximum lateral force is nearly zero.

CALCULATING THE PASSING SHIP LOADS

The Passing Ship Force and Moment Equations

Following are the empirical formulae for the passing ship loads.

Longitudinal Force:

$$Fx_{max} = S_F\ Cx\ \ V^2\,[\ 0.171 + 0.134\ \ln(DR) - \{\ 0.71 + 0.28\ \ln(DR)\ \}\ \ln(SR - 0.06)\ ]$$

(eq. 2)

Lateral Force:

$$Fy_{max} = S_F\ Cy\ \ V^2\,[\ e^{(1.168\ DR - 2.25)} - \{\ 4.41 + 1.93\ \ln(DR)\ \}\ \ln(SR)\ ]$$

(eq. 3)

Moment:

$$M_{max} = S_M\ Cm\ \ V^2\,[\ e^{(-0.47\ DR + 2.651)} - \{\ 171.9 + 51.4\ \ln(DR)\}\ \ln(SR - 0.06)]$$

(eq. 4)

where:

Fx_{max} = Maximum Longitudinal Force, metric ton
Fy_{max} = Maximum Lateral Force, metric ton
M_{max} = Maximum Moment, metric ton meter
V = Passing Ship velocity, knots
DR = Displacement Ratio, Passing Ship / Moored Ship
SR = Separation Ratio, Distance Between Ships / Characteristic Vessel Length

The results of the equations may become negative at large separation distances, but negative values should be ignored. The equations are expressed in metric ton (1 metric ton = 9.8 kN, = 2204 pounds force) to preserve the relationship with Remery's data.

Scale Factors

The scale factors are calculated by

$$S_F = 1.5\text{x}10^{-5}\ \ L_m{}^2$$

(eq. 5)

$$S_M = 59\text{x}10^{-9}\ \ L_m{}^3$$

(eq. 6)

where:

L_m = Length of moored ship, meters

The constants in these scale factors account for the length of the modelled moored ship used in Remery's tests raised to the appropriate power. Thus the scale factors are nondimensional.

If the ship length is in units other than meter, then an appropriate conversion factor should be applied, for example, 1 ft = 0.304 m.

Effect of Underkeel Clearance

Remery's model test data is for an underkeel-clearance to draft ratio (UKCDR) of 0.15. Muga and Fang's paper presented graphs showing the variation of passing ship forces and moments with underkeel clearance. According to Muga and Fang, "the minimum water depth / draft ratio can be either that for the fixed vessel or the passing vessel ..."

I performed regression analyses on Muga and Fang's graphs to derive the following UKCDR coefficient equations:

$$Cx = e^{(0.0955 - 0.6367\ UKCDR)}$$

(eq. 7)

$$Cy = e^{(0.5157 - 3.438\ UKCDR)}$$

(eq. 8)

$$Cm = e^{(0.343 - 2.288\ UKCDR)}$$

(eq. 9)

where:

$UKCDR$ = ratio of underkeel clearance to draft of moored or passing vessel (which ever draft is greater).

C_X = adjustment to be applied to surge force , F_x

C_y = adjustment to be applied to sway force, F_y

C_m = adjustment to be applied to moments, M

For example, if the water depth is 20 m, the draft of the moored ship is 18 m and that of the passing ship is 15 m, then the underkeel clearance is 2 m and the UKCDR 2/20 = 0.10. For this case, $C_x = 1.032$, $C_y = 1.118$ and $C_m = 1.121$.

These coefficients are based on a UKCDR of 0.15. They should be used to adjust the results of the respective equations 2, 3 and 4 to other UKCDRs. They may be used with Remery's published data or with other appropriate data obtained at a UKCDR of 0.15. But they should not be used to adjust data or calculations based on other UKCDRs.

The relationsionship between water depth to draft ratio, WDDR, and UKCDR is:

$$UKCDR = 1 - 1 / WDDR$$

(eq 10)

where

$WDDR$ = ratio of water depth to draft of moored or passing vessel

This equation may be substituted for UKCDR in equations 7, 8 and 9. In the above example, the WDDR is 1.111.

Effect of Current

Several past papers gave contradictory advice on the effects of current on these forces and moments. Those papers generally indicated that the passing ship velocity through the water should be used if the ship was going against current but disagreed on the effect if the ship was going with current. Recently Seelig gave a reasoned explanation that the passing ship velocity with relation to the water should be used in both cases.(4)

Thus the velocity to be used in the above equations should be

$$V = V_E - V_C$$

(eq. 11)

where:

V_E = Passing ship velocity relative to earth

V_C = Velocity of current

Construction of Time Histories

After the maximum passing ship forces and moments are calculated time histories can be constructed from the curves given in Figure 2. The time for the passing ship to go one characteristic length is

$$T = L_C / (V_E \times UC)$$

where:
T = Characteristic Time, time for passing ship to go one characteristic length, sec
UC = Unit Conversion, 1.69 from knots to ft/sec or 0.515 from knots to m/sec.

Multiply the abscissa of the force or moment plot by the characteristic time to convert it to time. Multiply the nondimensional ordinate of the force or moment by the respective maximum longitudinal or lateral force or moment to convert the values to units.

Discussion of Method

This paper presents a set of empirical equations for estimating the peak forces and moment produced by a passing ship and applied to a moored ship. These equations might appear to be complex, but they can be easily programmed on a computer. The values predicted by these equations agree closely with the results of model tests.

These equations may be used for the analysis of mooring systems. A static mooring analysis based on peak forces and moments can serve as a preliminary check. If a static analysis shows that the moored ship moves completely off the fenders or too far along the pier or if mooring line loads are too high, then passing ship effects may pose a problem at the mooring. A dynamic mooring analysis should then be conducted. With knowledge of the passing ship's speed, the force and moment vs. position graphs given in this paper can then be used to develop force and moment time histories for use in dynamic mooring analysis.

The equations for passing ship forces and moments given in this paper only apply to cases where the path of the passing ship is essentially parallel to the longitudinal axis of the moored ship. The model tests and analyses on which the equations are based represented an essentially infinite waterway. The effects may be different in a confined waterway or with the moored ship alongside a sloping or vertical wall. Further research is needed on this issue.

As the moored ship responds dynamically to time-varying passing ship loads, slack mooring lines can permit large vessel motions and result in very high mooring line loads. The ship should be held firm against the fenders so that friction prevents and controls longitudinal movement. Line pretensions should be accurately represented and not overestimated in the mooring analysis. If a static analysis shows high mooring line loads, the solution might appear to be to remove pretension from the lines, but this is the wrong thing to do.

Important Passing-Ship Factors Which Should be Controlled

The passing ship forces and moments vary with the square of the velocity of the passing ship. This has been demonstrated in model tests and analyses and is shown in these equations. The speed of passing ships should be strictly controlled in the vicinity of critical moorings.

The passing ship forces and moments vary with the natural logarithm of the separation distance. This effect does not have as much influence as velocity, but it still should be controlled. The passing ship should stay well clear of moored ships, especially if it is relatively large or must maintain high speed.

The mooring lines restrain the moored ship from moving off the pier in sway and thus being free to surge along the pier without the restraint of fender friction. Adequate tension should be maintained in all mooring lines to prevent excessive ship movements.

9/20/2002

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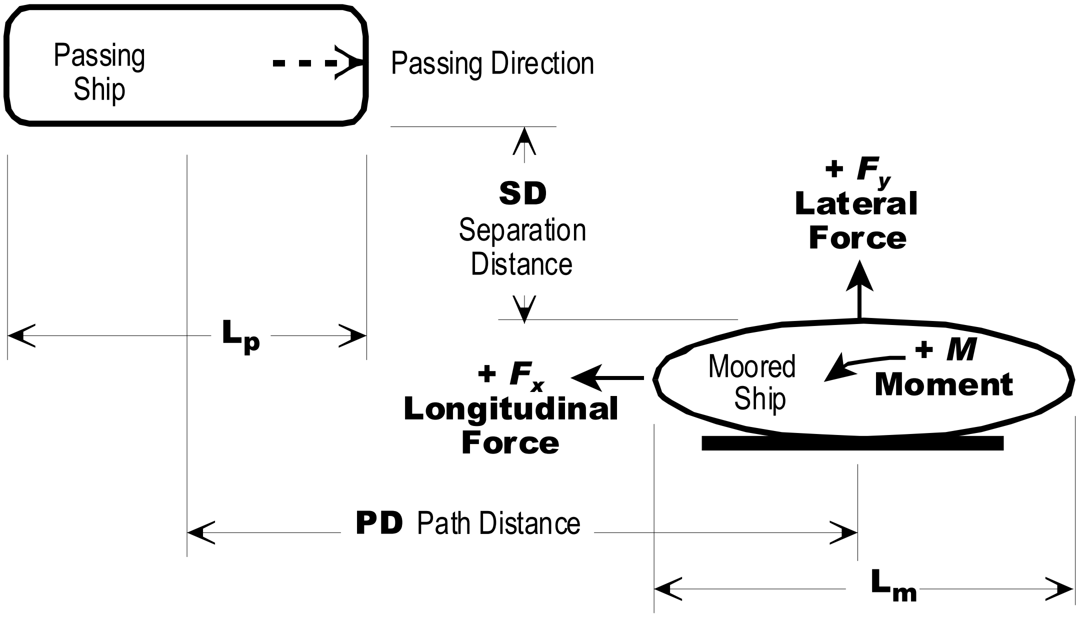
4. Seelig, W. N., *Passing Ship Effects on Moored Ships*, Technical Report TR-6027-OCN, Naval Facilities Engineering Command, East Coast Detachment, Washington, DC, 2001



Characteristic Length, $L_C = (L_m + L_p) / 2$

Position $P = PD / L_c$

Length Ratio, $LR = L_p / L_m$

Separation Ratio, $SR = SD / L_C$

Figure 1 Nomenclature and Conventions Used in this Paper

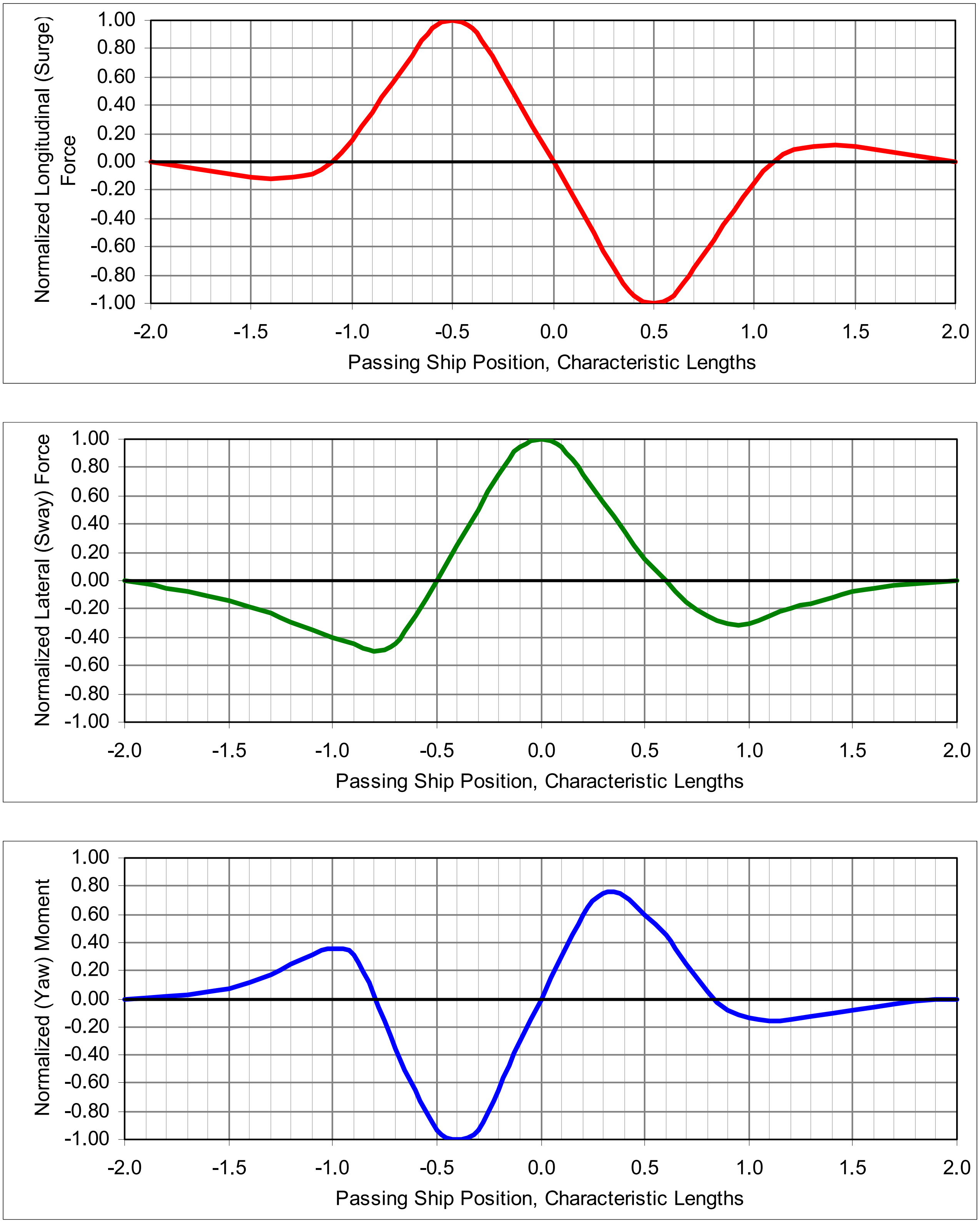
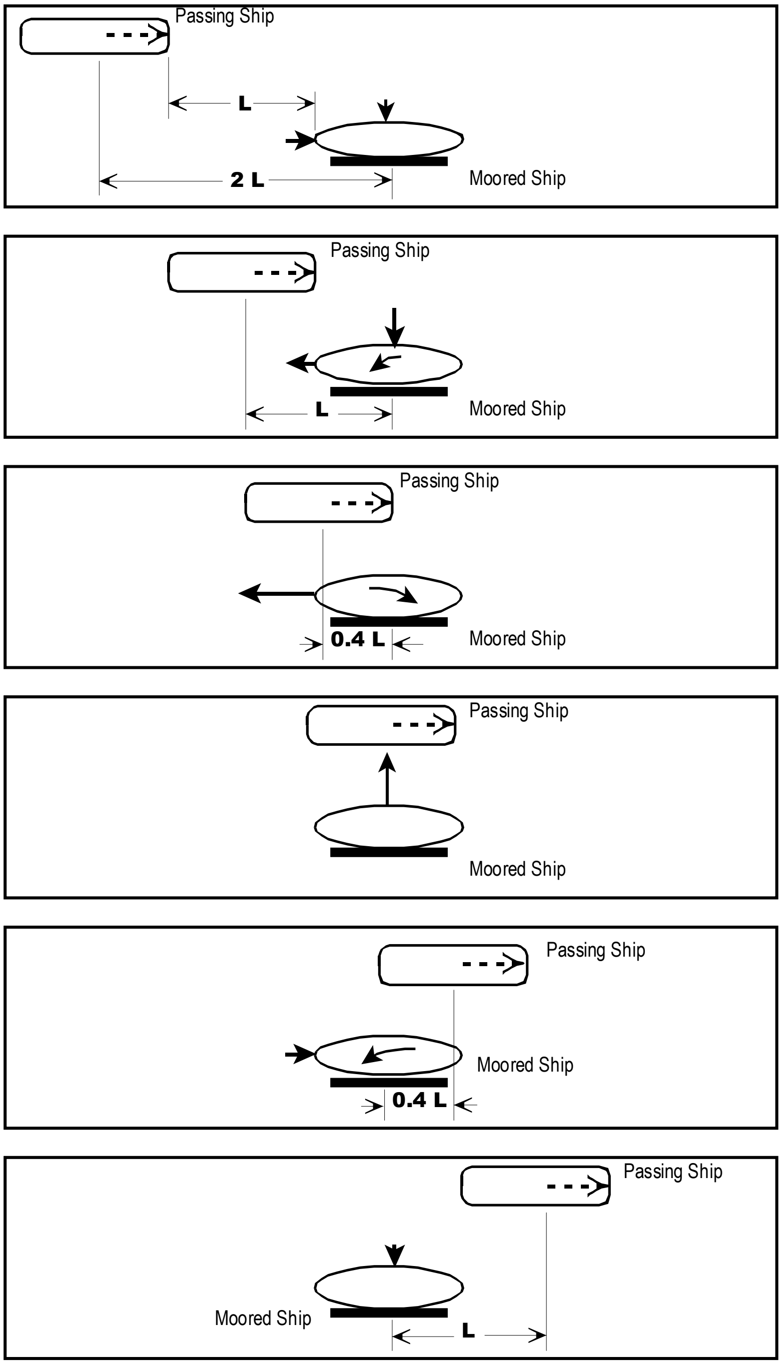


Figure 2 Nondimensional Passing Ship Position vs. Force and Moment Graphs



One-Ship Length Separation:
First influence.
Small negative longitudinal and lateral forces begin.

Bow-to-Bow:
Greatest negative lateral force.
Small positive longitudinal force.
Small positive moment.

Almost Bow-to-Midship:
Greatest positive longitudinal force.
Greatest negative moment.
Essentially zero lateral force

Side-by-Side:
Greatest positive lateral force.
Essentially zero longitudinal force.
Essentially zero moment.

Almost Stern-to-Midship:
Greatest negative longitudinal force.
Greatest positive moment.
Essentially zero lateral force.

Stern-to-Stern:
Small negative lateral force.
Longitudinal force and moment drop essentially to zero.

Figure 3 Narrative of Passing Ship Forces and Moments During Passage