Accordingly, for a steady current speed in knots, Eqs. (4-2) through (4-4) become in foot pound units

$$F_{cx} = 2.85 C_{cx} U_c^2 A_x \tag{4-8}$$

$$F_{cy} = 2.85 C_{cy} U_c^2 A_y \tag{4-9}$$

$$M_{cym} = F_{cym} C_{cym} \mathrm{LBP} \tag{4-10}$$

In these equations, U_c is the average current over the vessel's draft and the coefficients are a function of the water depth to draft (d/T) ratio. Force and moment coefficients for currents are less certain than for wind because, although generally still within the turbulent flow regime, the Reynolds number is near the transition zone, especially for the largest vessels at low current velocities, resulting in a wider scatter in the experimental data. In deep water the longitudinal force coefficient, C_{cx}, ranges from 0.1 to 0.6 with 0.15–0.4 being more typical. The lateral force coefficient, C_{cy}, is typically in the range of 0.8 to 1.0 with an extreme range of 0.5–1.5. The yaw moment coefficient, C_{cym}, is typically within the range of 0.05–0.10. Typical deep water ranges of the current force and moment coefficients are similar in shape to the wind coefficients shown in Fig. 4-3; however, the effects of d/T are highly variable and in some cases extreme so that relying on generic data or an assumed curve shape is generally not advisable. Fig. 4-8 shows an example current force on the moored FDD shown in Fig. 4-5 and used in the wind force example. Note that, as for wind, the maximum longitudinal and lateral force may not occur exactly for currents directly from ahead, from astern, or from abeam. In fact, the maximum longitudinal force typically occurs with currents from around 25° from the bow. Current forces are also affected by the vessel's trim and load condition. Yaw moments in particular increase for tankers in ballast condition, typically with a large amount of trim. OCIMF 1994 are based on model tests at 0.8 deg trim and may need correction if actual trim exceeds around 1°. These tests were also conducted with models having length to beam ratios, LBP/B, of 6.3 to 6.5 and may need correction for vessels much outside this range. Note that some contemporary tankers may have an LBP/B as low as 5.0, which may result in an increase of longitudinal force of 25 to 30% at angles of attack up to 15° or more. For a fully loaded tanker with a bulbous bow in shallow water, $d/T = 1.1$, and currents between 10 to 33° from the bow, the OCIMF 1994 show a forward-directed component of longitudinal force, due to low pressure in the vicinity of the bulbous bow.

The lateral force is especially sensitive to d/T, ranging from a minimum value of $d/T \geq 6$ for "deep water" to approximately five times the minimum value at $d/T = 1.1$. Figure 4-9 illustrates this effect. It is very important to note from these curves the very steep rise in lateral force, even with the current nearly end on, which is especially acute at low d/T. For this reason the designer should never assume that the current is

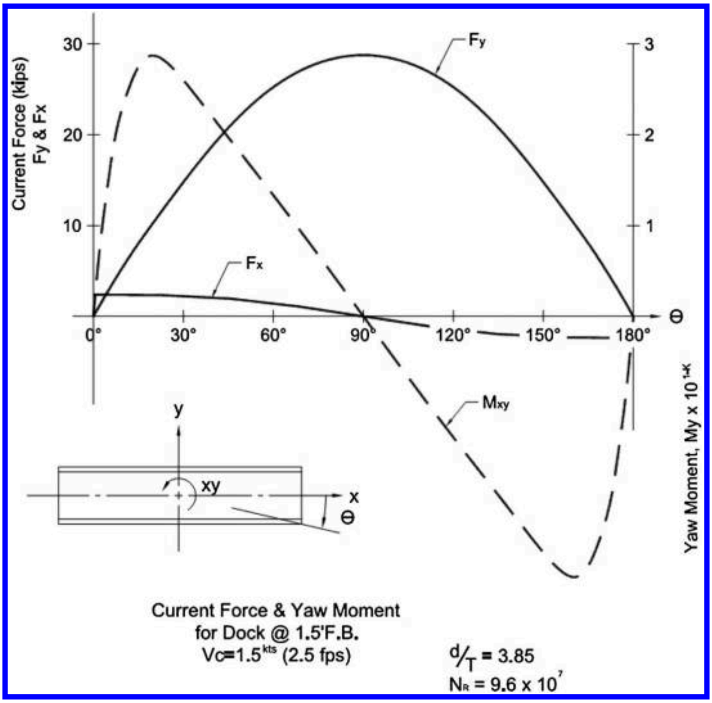

Fig. 4-8. Example current forces and moment on moored floating dry dock

exactly end on and that the lateral component is zero. A margin of at least 15° is generally recommended to allow for current variability and uncertainty. The curves in this figure were based in part on model tests conducted under the auspices of the OCIMF between 1968 and 1977 and later drawn and published by NAVSEA (1987). Full-scale measurements conducted on a moored tanker and destroyer as reported by Palo (1983) showed that lateral force coefficients are somewhat insensitive to hull shape but show a significant dependence on the vertical distribution of current velocity or "current shear." Seelig et al. (1992) provide a simplified method for calculating the lateral force coefficient based on model test data from the U.S. Naval Academy and adopted by the *UFC 4-159*.

Tidal currents generally exhibit a typical boundary layer-type flow profile, and assuming a 1/7 law, vertical velocity profile similar to wind is common practice so that the current velocity at any depth is given by

$$U_{(z)} = U_s \left(\frac{z}{d}\right)^{1/7} \tag{4-11}$$

where z is measured upward from the bottom and U_s = the maximum current at the surface. Therefore, assuming the maximum value of the

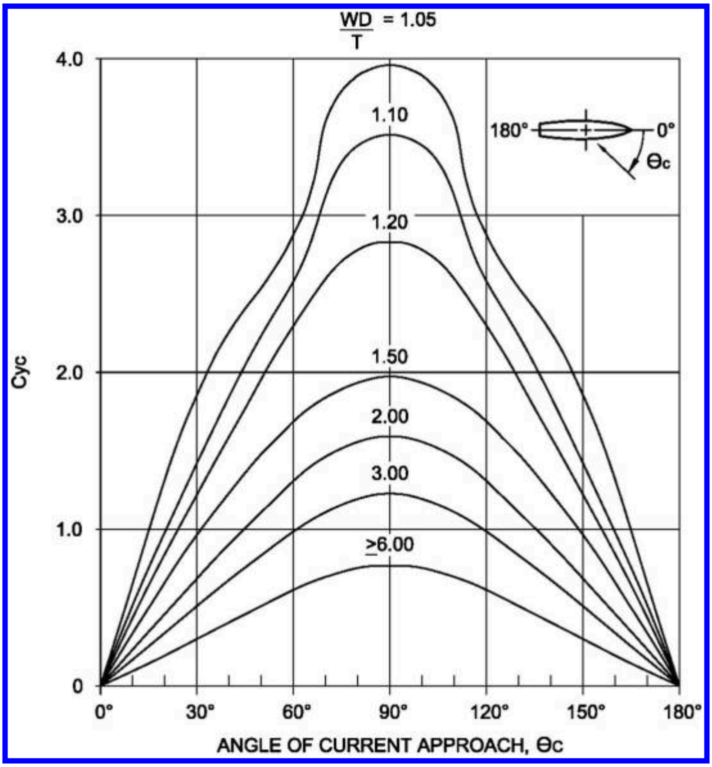

Fig. 4-9. Lateral current force coefficient for varying d/T
Source: NAVSEA (1987)

current is uniformly distributed over the vessel's draft is generally conservative, if the current is confirmed as the surface/maximum value. The actual vertical and horizontal distribution may vary at a given site and among sites. The velocity can be affected by wind, and in general it varies in strength in rough proportion to the tide range.

The averaged squared velocity of the current over a vessel's draft can be found from

$$U_c^2 = \frac{1}{T}\int_o^T (U_z^2) d_z \tag{4-12}$$

where U_z is the current velocity at depth z. In this case, z is measured upward from the ship's keel. Refer to Fig. 4-10.

The longitudinal force component is primarily due to surface friction drag, and although many sources still apply, a single overall form drag coefficient the surface drag or "skin friction" can be calculated separately as well. The U.S. Navy per *UFC 4-159* adds the form drag and friction drag

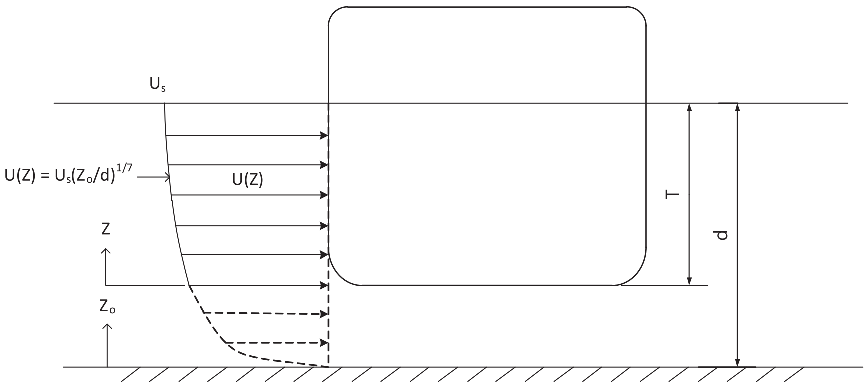

Fig. 4-10. Vertical distribution of current velocity (U_c) over vessel's draft

components and an additional term for appendages and propeller drag to the longitudinal force component, separately. The drag of locked propellers on military vessels can exceed the longitudinal drag force on the hull itself. The longitudinal force due to skin friction alone (F_{cst}) is calculated from

$$F_{cst} = \frac{\rho}{2} Ccsf U_c^2 A_{ws} \tag{4-13}$$

where C_{csf} is the skin friction coefficient, which is a function of R, and A_{ws} is the immersed wetted surface area, which is a function of the vessel's geometry. The skin friction coefficient is normally within the range of 0.001–0.006 for laminar to turbulent flow conditions. *UFC 4-159* provides formulas for estimating C_{csf} and A_{ws}.

The added drag due to fixed propellers (F_{cp}) is determined from

$$F_{cp} = \frac{\rho}{2} C_{cp} U_c^2 A_{cp} \tag{4-14}$$

where C_{cp} is the propeller coefficient, usually taken as equal to 1.0, and A_{cp} is the expanded propeller blade area, which is a function of the total projected blade area and the propeller pitch. Again, *UFC 4-159* provides a methodology for calculating C_{cp} and A_{cp}.

4.3.2 Local Current Effects

For vessels moored alongside in rivers and narrow channels, the presence of the vessel may obstruct enough water flow to accelerate the flow around the vessel and within the channel in general, thus increasing the forces on the moored vessel. This effect, greatest in shallow water, normally needs to be taken into account when the channel width (W) to vessel beam ratio $W/B < 5$. A blockage coefficient can be defined as BT/Wd

where d is the average water depth. Also, in somewhat shallow water, the current flow below the vessel may increase, causing the vessel to sink slightly due to higher pressure at the bow and stern resulting in a wave trough below most of the vessel's mid length. The resulting sinkage is known as "squat" and is generally small, less than 1 ft, for a moored vessel, but can be much greater for vessels underway at speed in constricted channels. Squat effects increase with the square of the current velocity, with decreasing d/T and W/B, and with a vessel's block coefficient.

Tidal flows typically exhibit changes in speed and direction over a period of hours with minor fluctuations on the time scale of minutes. In certain stratified estuaries and river mouths where fresh water and sea water mix, a current shear may be created with pronounced changes in speed and direction with depth such that at some locations surface and bottom currents may flow in opposite directions at certain stages of the tide. Wind stress and peaks in river discharge may significantly alter the normal flow profile. Downstream of islands or obstructions and/or along irregular shorelines turbulent eddies may be formed that result in more dramatic changes of speed and direction over shorter time scales. In such situations dynamic analysis may be required, especially if the eddies are on the order of the vessel size.

4.3.3 Current Standoff Forces

A vessel moored alongside in a strong current such that the flow of water along the shore side is greatly reduced by the presence of a quay wall or even a densely spaced pile foundation may be subjected to a "standoff" force directed away from the shore. This is due to the Bernoulli effect of the higher water velocity along the outshore side of the vessel creating a pressure differential with resultant higher water elevation along the inshore side pushing the vessel away from the dock. This head difference (h_{so}) can be expressed as the velocity head times some empirical coefficient, C_{so}, and is thus given by

$$h_{so} = \frac{C_{so} U_c^2}{2g} \tag{4-15}$$

As the current velocity and associated head difference will likely vary along the vessel length the velocity head term must be integrated along the vessel's LBP. Also, as the pressure head applies over the vessel's draft this can result in very substantial forces on fully loaded/deep draft vessels even for somewhat low values of C_{so}. No generally accepted value for C_{so} exists. Early field measurements by Jackson (1973) indicated values of C_{so} as high as 0.42. Later studies based on model experiments of a design case history (Khanna and Sorenson 1980) for a scaled current velocity of 5 knots indicate C_{so} on the order of 0.10–0.15.

4.3.4 Combined Wind and Current Forces

Wind and current forces and moments calculated in accordance with the foregoing methods can be readily resolved into components about the vessel's cg and combined directly to obtain the resultant sum of forces. It is, however, important to note that a series of calculations may be required to obtain the worst case combinations with regard to water level, vessel draft, and relative wind and current directions. Although in most cases the current will ebb and flood in somewhat fixed directions, the peak current velocities usually occur at near mid tide and may differ considerably between flood and ebb. Typically the current is nearly still or "slack" at high and low tide so that at locations with somewhat large tide ranges applying the maximum design current may not be necessary at these times. Obviously, current forces are at maximum for loaded, deep draft conditions at low tide, whereas wind forces are higher in ballast condition, typically at high tide, for cases of offshore wind where pier shielding is less.

4.4 PASSING VESSEL FORCES

Moored vessels may be subjected to substantial dynamic forces due to the nearby passage of other vessels especially in narrow restricted waterways with large vessel traffic. Passing vessel forces have caused many mooring incidents, including some tragic breakaways as reported in Section 6.3.3. This section provides an overview of passing vessel forces and methods available to calculate them.

4.4.1 Force Generation Mechanism

Moving vessels in narrow waterways generate pressure differentials (pressure fields) in the surrounding body of water. High-pressure zones form at the bow and stern of the vessel, whereas low-pressure zones form along the sides of the vessel. The pressure differentials generate long-period waves typically known as drawdown, the Bernoulli effect, or the pressure field effect. For consistency with most recent technical publications, this effect is herein referred to as the "pressure field effect" or "pressure field wave." Fig. 4-11 shows a typical passing vessel situation in the Port of Oakland Inner Harbor Waterway. Fig. 4-12 shows a conceptual pressure field distribution surrounding a vessel entering a narrow waterway. Areas on the sides of the vessel represent zones of below-static pressure and areas in front and behind the vessel represent zones of above-static pressure.

In the case of high speeds and narrow channels, the hydrodynamic forces due to the pressure field are significant and may result in serious damage to port infrastructure and impose life safety risks. Pressure field waves and hydrodynamic forces generated by pressure fields should be

Fig. 4-11. Inner harbor waterway, Port of Oakland, CA

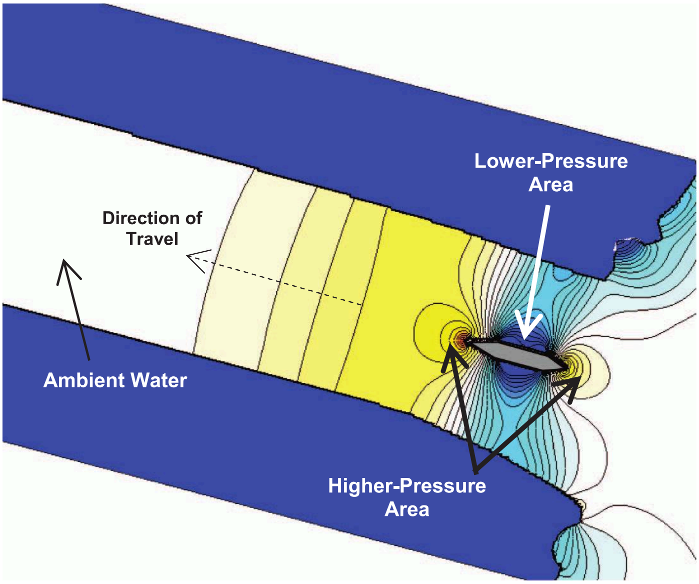

Fig. 4-12. Pressure field surrounding passing vessel entering narrow waterway

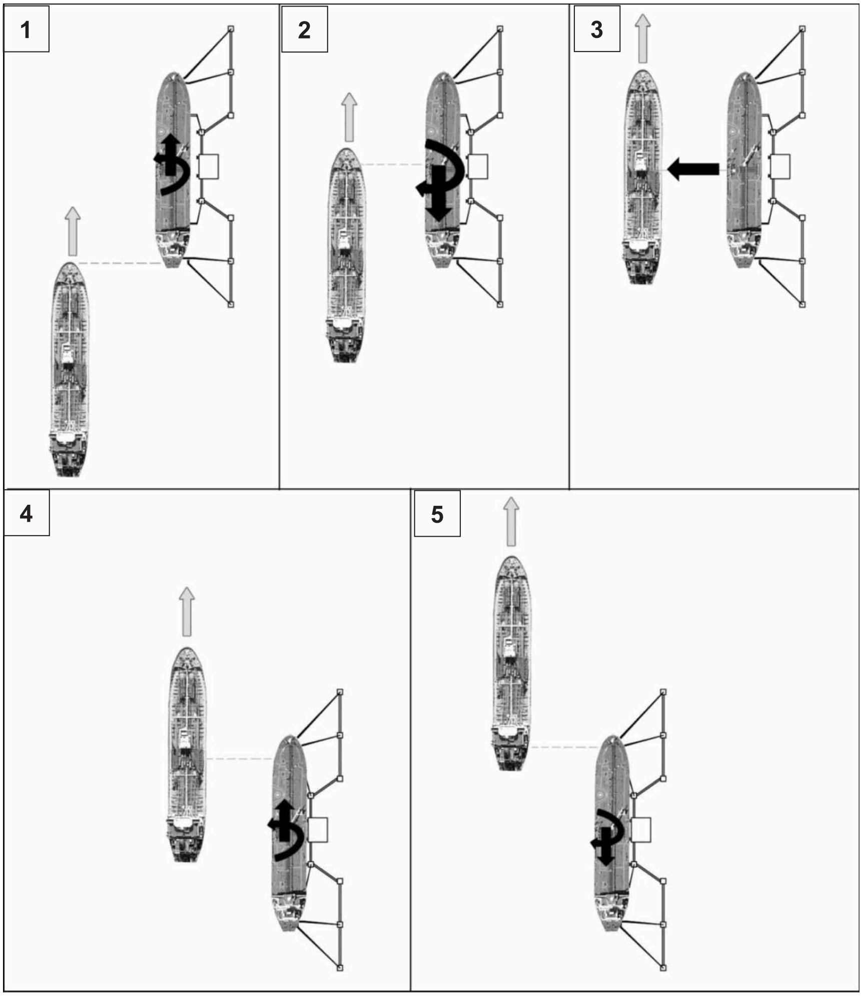

Fig. 4-13. Ship passing berthed ship moored alongside terminal

taken into consideration during design and operation in narrow waterways and navigation channels. Figure 4-13 shows a ship passing a berthed ship in a series of frames, during which the dynamic forces and moments evolve as follows:

1. Passing ship bow reaches stern of berthed ship, inducing primarily a small surge force in passing ship direction and small CCW yaw moment.
2. Passing ship bow reaches amidships of berthed ship, inducing primarily a large surge force counter to passing ship direction and large CW yaw moment.

3. Passing ship aligned amidships with berthed ship, inducing primarily a large sway force toward passing ship.
4. Passing ship stern reaches berthed ship amidships, inducing primarily a large surge force in passing ship direction and large CCW yaw moment.
5. Passing ship stern reaches berthed ship bow, inducing primarily a small surge force counter to passing ship direction and small CW yaw moment.

4.4.2 Passing Vessel Force Analysis Techniques

4.4.2.1 Passing Vessel Hydrodynamics Pressure field effects should be evaluated to determine impacts to berthed vessels, passing vessels, waterfront structures, and protected (or unprotected) shorelines. Engineering practice has developed several levels of hydrodynamic analysis for evaluation of pressure field effects, including steady-state analytical methods, time-dependent two-dimensional (2-D) methods (depth-averaged finite difference or finite element), time-dependent three-dimensional (3-D) methods, and Reynolds Averaged Navier Stokes (RANS) panel methods. In design practice, the engineer may apply different levels of hydrodynamic evaluations depending on the complexity and scope of the project.

Steady-state vessel hydrodynamics models can be used to evaluate pressure field effects and water level fluctuations in narrow waterways as an initial approximation. The use of these types of methods and models can typically be justified only for waterways with simple geometry. Analysis approaches (Muga and Fang 1975, Shepsis et al. 2001) include the method of images, slender body theory approximations, and others. These methods can be used in some cases to determine the need for higher-level analysis with time-dependent numerical modeling tools. Several modeling tools have been developed recently based on finite-difference codes (Nwogu 2001, Fenical et al. 2006) and finite-element codes (Stockstill and Berger 1999) to simulate relevant hydrodynamic processes.

Deep-draft vessel hydrodynamic effects under consideration include water level fluctuations and velocities in the channel generated by the moving vessel's pressure field. The use of two-dimensional (depth-averaged) modeling tools typically is adequate as long as the hydrostatic pressure assumption is valid, and results of analysis using two–dimensional modeling tools have shown good correlation with laboratory and field measurements. Time-dependent two-dimensional (depth-averaged, hydrostatic) models can simulate vessels moving through modeling domains using finite–difference or mesh vessel hull shape approximations. Finite element models have also been used with similar shallow water equations to evaluate water level and velocity fluctuations.

Recent developments have also provided industry with fully three-dimensional hydrodynamic codes using RANS equations (Chen et al. 2002) and coupled codes with three-dimensional hydrodynamics in the near field and two-dimensional hydrodynamics in the far field (Kofoed-Hansen et al. 1999, Nwogu 2007). These codes are used to evaluate more detailed effects of moving vessels, particularly for vessels moving with high Froude numbers and for evaluation of high-frequency wakes. These types of studies require a high level of detail on vessel hull information and hydrodynamic predictions and are computationally expensive. Physical modeling (laboratory tests) can also be used for specific studies when the study scope requires the highest level of analysis, provided that the experiments are of sufficient scale. It should be noted that in practice the expense associated with most three-dimensional methods and physical modeling are rarely warranted for pressure field analysis on engineering projects.

4.4.2.2 Passing Vessel Force Calculations Passing vessel load calculations can typically be made using either of two methods: empirical load formulations or direct application of vessel hydrodynamic calculations from pressure field models.

Empirical Methods Several empirical methods have been developed for calculating passing vessel loads and moments using analysis of forces measured in the laboratory (Flory 2002, Seelig 2001, Kriebel 2005). Input to these methods includes channel and vessel dimensions, passing distance vessel locations, and passing speed. These methods represent a first approximation of loads and moments on passing vessels. However, only a few laboratory data sets were available for development of these methods (Remery 1974, Lean and Price 1977, Kriebel 2005), and the laboratory tests do not include significant geometric features such as channel banks and variable bathymetry; therefore, these methods should be used with caution and only as a first approximation.

In cases where vessel hull shapes, channels, or navigation conditions are more complex, passing vessel hydrodynamic forces and moments should be evaluated with time-dependent modeling tools. Passing vessel forces are strongly affected by the presence of confinement features such as channel side slopes and nearby wharf structures such as quaywalls. Within confined channels, passing vessel sway forces are likely to be less than in open water conditions, whereas surge forces are likely to be significantly greater than predicted by methods using the open sea condition. Passing vessel forces and moments are also strongly affected by the presence of ambient tidal/river currents. The simple approach of adding or subtracting ambient current speed and passing ship speed to