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Mooring Model for Barge Tows in Lock Chamber

by Richard L. Stockstill

BACKGROUND: Extensive research has been conducted in the area of modeling mooring systems in sea environments where the forcing function is in the form of periodic waves. A general summary of this is provided by the Society of Naval Architects and Marine Engineers (1983). Recently, a model of hawser forces in a lock chamber was published (Natale and Savi 2000), but this work does not provide values of system coefficients. Kalkwijk (1975) developed model equations for a mooring system within a lock chamber, but did not attempt to reproduce the flow resulting from any particular filling and emptying system, and did not address the issue of model coefficients. Information on such parameters as the hawser spring constant is available (e.g., Naval Facilities Engineering Command 1986a, 1986b), but the added mass and hydrodynamic damping coefficients have never been documented for a tow moored in a lock chamber. This study has developed a mooring system model for tows in a lock chamber (damped vibration system with nonharmonic excitation) and has implemented it in a computer code. The program reads LOCKSIM (Schohl 1999) output from a lock filling and emptying operation model and computes the resulting time-varying hawser forces.

VESSEL INFLUENCE: The presence of a displacement vessel in a lock chamber influences the flow field produced during locking operations. The beam width and draft establish an area restriction of flow along the vessel (blockage area). The vessel also applies a pressure field at the water surface that must be accounted for in a hydrodynamic simulation. The presence of a vessel will affect the pressure gradient term in the momentum equation. The modified momentum equation for free-surface flow, which accounts for the presence of a tow, is:

$$\frac{\partial Q}{\partial t}+\frac{Q}{A}\left(2\beta\frac{\partial Q}{\partial x}+q\right)-\beta\frac{Q^2}{A^2}\frac{\partial A}{\partial x}+\frac{A}{\rho}\left(\frac{\partial p}{\partial x}+\frac{\partial p_s}{\partial x}\right)+gA\frac{\partial Z_0}{\partial x}+4\frac{A\tau_0}{\rho D_h}=0 \tag{1}$$

Here, Q = discharge, q = lateral inflow, p = pressure, D_h = hydraulic diameter, β = momentum correction factor, ρ = fluid density, Z_0 = bed elevation, t = time, and x = spatial coordinate. Under the vessel, A = total available area minus the blockage area and $p_s = \rho g d$ where g = gravitational acceleration and d = vessel draft. At stations not under the vessel $p_s = 0$ and A = total flow area. The shear stress, τ_0, includes shear on the vessel surface, and the fourth term of the equation accounts for free-surface pressure gradients created by the vessel.

MOORING SYSTEM MODEL: If the buoyant force balances the barge weight, then the dynamic equation for the moored system is:

$$(1+C_a)\; m_v\, \ddot{s} \;+\; C_h\, \dot{s} \;+\; (k_0 + k\;\; s) = F \tag{2}$$

where the overscript dot indicates differentiation with respect to time, s = surge displacement of the barge, C_a = added mass coefficient, m_v = mass of the barge tow, C_h = hydrodynamic damping coefficient, (k_0 + ks) = restoring force, k_0 = initial tension in the hawser, k = hawser spring constant, and $F = F_s + F_\tau + F_p$. The right-hand side of Equation 2 is the sum of the external forces acting on the system with F_s = difference in hydrostatic force between the bow and stern, F_τ = force due to shear stress, and F_p = hydrodynamic response (force required to accelerate the fluid). In equation form

$$F_s = \rho g \ b \ d \ l \ S_s \tag{3}$$

$$F_\tau = \tfrac{1}{2} C_f \rho \ AV|V| \tag{4}$$

$$F_p = \tfrac{1}{2} \rho \ b \ dC_p \ V \ |V| \tag{5}$$

Here, b = beam width of barge, d = barge draft, l = barge length, S_s = slope of the water surface, g = acceleration due to gravity, C_f = friction coefficient, A = wetted area of the hull, C_p = pressure coefficient, and V = mean velocity of fluid relative to the vessel.

Here the pressure coefficient, C_p, is taken as 0.15 (Maynord 2000). Applications to tows moored in a lock chamber must make shallow-water corrections when computing the hull drag. The friction coefficient for shallow-water applications is (Maynord 2000)

$$C_f = \left[1.55 - 0.105\left(\frac{h}{d}\right)\right] \left[0.075\left(\log\frac{Vl}{\nu} - 2\right)^2 + \Delta C_f\right] \tag{6}$$

where h = depth, ν = kinematic viscosity of water, and ΔC_f = a roughness allowance for the barge surface.

The single-degree-of-freedom equation of motion (Equation 2) is a second-order, nonhomogeneous, ordinary differential equation for a damped system with external forcing. In mooring applications, the system is generally underdamped and the displacement of the moored vessel oscillates with an exponential decay in amplitude.

DETERMINATION OF COEFFICIENTS: Laboratory data for hawser forces has been used to quantify the model coefficients. These data provided the hydrostatic force from the water-surface slope and the corresponding longitudinal hawser force, both as a function of time. The laboratory setup differed from prototype mooring in that a single semicircular aluminum ring was used to moor the laboratory barge train as shown in Figures 1 and 2; whereas, in the field, bow and stern hawsers (manila, steel, or synthetic material) are tied from the barge train to one of the lock walls. The spring constant for the model hawser ring was determined prior to use. The added mass and hydrodynamic damping coefficients were obtained from the record of oscillations of the moored tow in a chamber of still water. The barge tow was displaced from the rest position and the oscillating hawser forces were recorded from the time the barge was released until the

Figure 1. Barge train moored in laboratory model

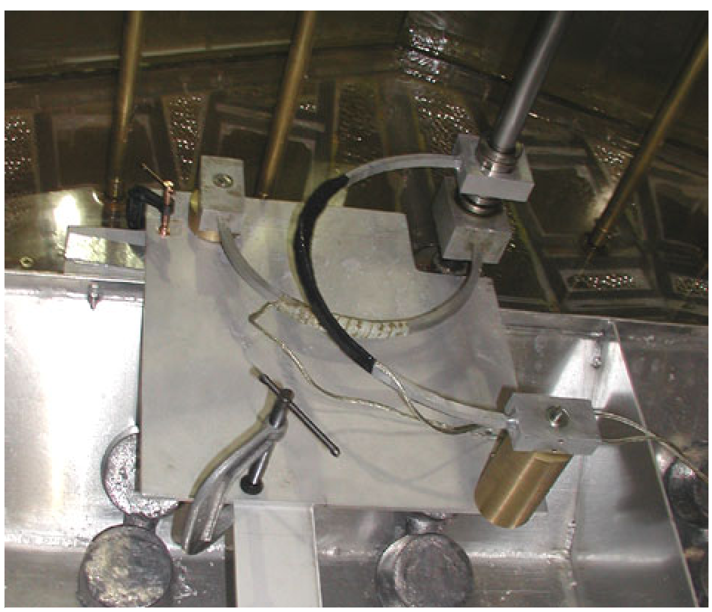

Figure 2. Detail of hawser ring mooring the laboratory barge train

barge returned to rest. The damping coefficient was then deduced from the oscillating hawser data as the barge tow returned to the rest position.

Quantifying Coefficients. Experiments were conducted in four laboratory flumes containing scaled models of navigation lock filling and emptying systems. These projects each have different lock chamber dimensions thereby providing data from a range of geometries appropriate for navigation locks. Barge tow and chamber model dimensions are provided in the following tabulation.

Flume	Test Number	Barge Tow Dimensions			Lock Chamber Dimensions		
		Draft, m	Beam, m	Length, m	Width, m	Length, m	Depth, m
McAlpine	1Mc	0.110	1.280	14.265	1.341	15.484	0.335
Intermediate System	1I	0.110	1.280	14.265	1.341	16.337	0.305
	2I	0.110	1.280	14.265			0.549
	3I	0.110	1.280	14.265			0.183
Monongahela No. 4	1Mon	0.110	0.951	8.778	1.026	9.632	0.277
	2Mon	0.110	0.951	8.778			0.518
JT Myers	1JTM	0.110	1.280	14.265	1.341	16.093	0.256

The purpose of these experiments was to quantify the mooring system model coefficients. The laboratory data includes barge-tow dimensions (length, beam width, and draft), hawser ring spring constant, and loads measured with the strain gages mounted on the hawser rings. Model coefficients were determined from experiments with no flow in the lock chamber.

Coefficient values were derived from the experiments using the following procedure. The laboratory spring constant, k, is known, so the added mass can be determined from the frequency of oscillation records using the vibration equation for a spring

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m_{eff}}} \tag{7}$$

The hydrodynamic effects on the moored system can be determined by computing the effective mass, m_{eff}, of the system from the measurements of frequency, f_n. That is

$$m_{eff} = \frac{k}{4\pi^2 f_n^{\,2}} = m_v + m_a \tag{8}$$

m_v = mass of the tow and m_a = added mass. The dominant frequency of the system is determined using Fourier transformation of the data from the time domain to the frequency domain. With the vessel mass known, the added mass can be calculated. The added mass is typically expressed as a coefficient relative to the vessel's mass

$$m_{eff} = (1 + C_a)m_v \tag{9}$$

where C_a = added mass coefficient.

The damping coefficient is determined using laboratory experiments of a tow moored with a hawser ring mounted along the longitudinal axis of the lock chamber. The rate of peak amplitude reduction on subsequent cycles defines the damping. The peak amplitudes are related as

$$F/F_0 = ae^{-b^* t} \tag{10}$$

Here, F = measured force, F_0 = initial force, t = time, the exponent $b^* = C_h / (2m_v)$, and C_h = hydrodynamic damping coefficient. System damping is shown on the plot of time-series force data for a representative example from the experiments (Figure 3).

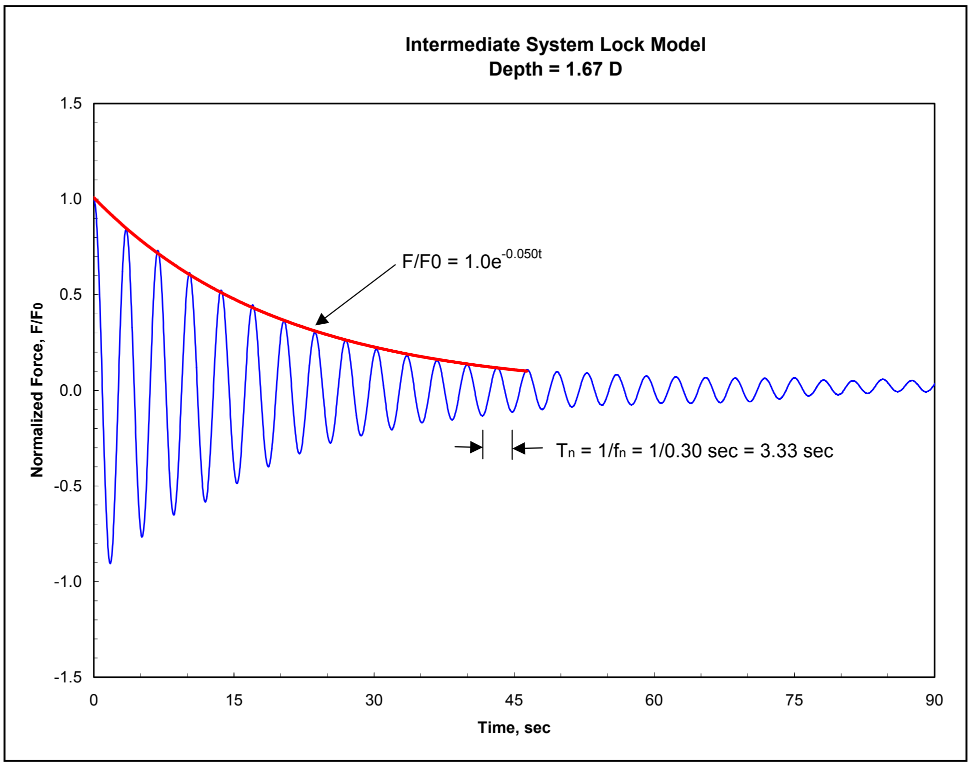

Figure 3. Time series of laboratory data of hawser forces for still-water tests

Scaling. The added mass coefficient, which is dimensionless, is primarily dependent on geometry, and so field values can be scaled from laboratory values by using geometric similarity. The damping coefficient is also dependent on the geometry of the vessel and the fluid container's boundaries (lock chamber walls and floor and upper and lower miter gates), but it has units of mass per time. The hydrodynamic damping coefficient associated with surging is made nondimensional with the vessel mass and beam width.

$$C_h^* = \frac{C_h}{m_v}\sqrt{\frac{b}{g}} \tag{11}$$

Over the range of geometric and hydraulic conditions tested, neither coefficient was found to vary significantly. An average value of 0.5 was found for the added mass coefficient and the nondimensional hydrodynamic damping coefficient, C_h^*, was determined to be 0.045 for the 33.53-m-wide (110-ft-wide) locks and 0.050 for the 25.60-m-wide (84-ft-wide) lock.

Once these coefficients are scaled to field values, then only the hawser spring constant will be needed for prototype applications of the model. Hawser properties are available from the literature for various rope sizes and materials (e.g., Naval Facilities Engineering Command 1986a, 1986b; PIANC 1995; O'Brien 1954).

NUMERICAL SOLUTION OF MODEL EQUATIONS: There are several numerical techniques that lend themselves to solution of the second-order differential equation of vessel motion, when it is linear. A basic algorithm is the Euler method which is second-order accurate. Higher order methods include multistep methods such as Hamming's method, which is a fourth-order predictor-corrector scheme. The choice of appropriate numerical schemes is significantly reduced if nonlinearities are present in the equation. The equation will be nonlinear if either the added mass or the damping coefficient is a function of vessel displacement or velocity. The fourth-order Runge-Kutta (RK4) scheme is very general in that it will numerically solve nonlinear forms of the governing equation. The RK4 scheme is a single-step method that provides fourth-order accuracy and is quite stable. For these reasons, the RK4 scheme was chosen as the numerical scheme employed in the computer code constructed for the simulation of time-varying hawser forces.

The hawser force model was evaluated by comparing model results with laboratory data. The particular experiment configuration is a still-water test similar to those used to quantify model coefficients. Figure 4 shows that the hawser force model accurately reproduces the laboratory data.

SIGNIFICANCE OF EQUATION OF MOTION: Currently, the hawser forces during lock operations are calculated from water-surface slopes computed by LOCKSIM. This assumption ignores the inertial effects of acceleration of the vessel and water. The equation of motion (Equation 2) accounts for the added mass and hydrodynamic damping effects and includes forces produced by shear stresses and end pressures. Evaluation of the differences produced by these calculation techniques was made using the results from a LOCKSIM model of the Intermediate Lock System. The tow configuration used in the calculations was a 3-wide by 5-long train drafted at 2.74 m (9 ft). Hawser forces were computed using the LOCKSIM model results in two different ways. First, the water-surface slope was used to compute the hawser forces as simply the hydrostatic force component of (Equation 2) as defined in (Equation 3).

The second method used (Equation 2) with a reasonable estimate for a hawser (spring) constant (k = 291,880 N/m) and the coefficient values determined from the laboratory study (C_a = 0.5 and C_h^* = 0.045) to compute the hawser forces. The LOCKSIM output was used as input defining the right-hand side of (Equation 2).

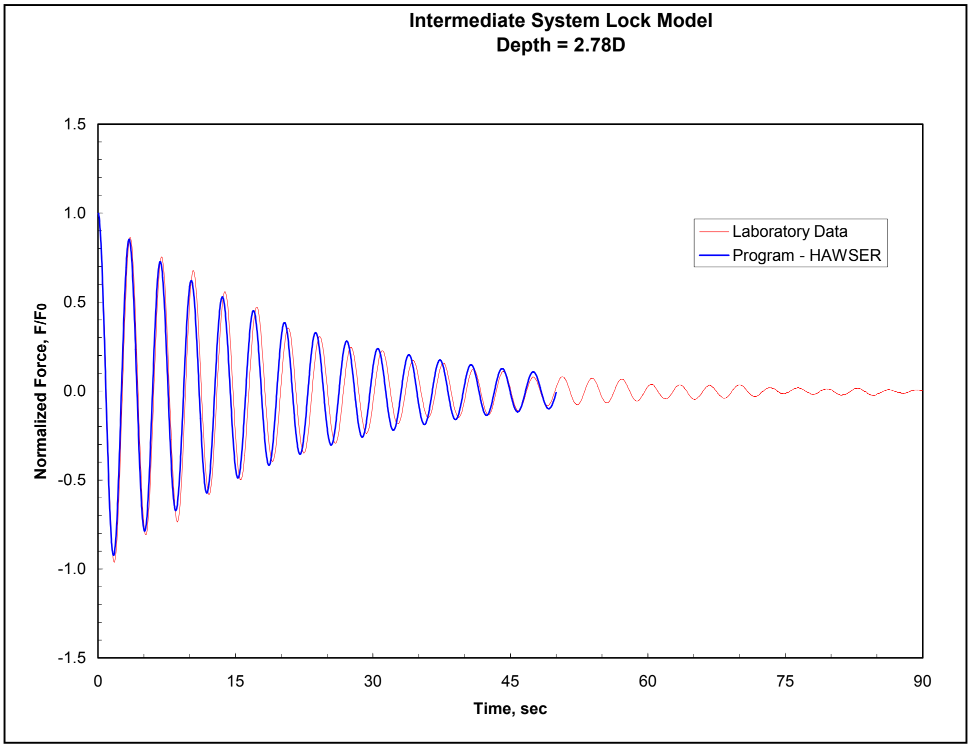

Figure 4. Observed and computed time series of hawser forces for still-water experiments

It is a common assumption that the slope method (hydrostatic method in Figure 5) is conservative in estimating hawser forces generated during filling. However, the results of Figure 5 show how in the case of the intermediate lock system model, the more complete description of the physics (Equation 2) predicts larger forces than does the hydrostatic method.

FUTURE WORK: Future efforts will be directed toward extending the LOCKSIM model to include the effects of vessel moored in a lock chamber. The LOCKSIM postprocessor, HAWSER, will then be evaluated as to its ability to reproduce hawser forces. This will consist of comparing HAWSER results with laboratory and field data for lock filling and emptying operations. This will also validate the coefficients employed when modeling hawser forces on tows in lock chambers.

Figure 5 Comparison of water-surface slope and equation of motion methods of computing hawser forces

ADDITIONAL INFORMATION: Questions about this technical note can be addressed to Dr. Richard L. Stockstill (601-634-4251; e-mail: *Richard.L.Stockstill@erdc.usace.army.mil*) This technical note should be cited as follows:

> Stockstill, R. L. (2002). "Mooring model for barge tows in lock chamber," ERDC/CHL CHETN-IX-9, U.S. Army Engineer Research and Development Center, Vicksburg, MS. *http://chl.wes.army.mil/library/publications/chetn*

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