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TECHNICAL MEMORANDUM

title: DYNAMIC VERTICAL FORCES ON A CRANE LOADING (UNLOADING) A FLOATING PLATFORM, by

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PREFACE

Operational Requirement (OR-YSL03) for the Container Off-Loading and Transfer System (COTS) addresses the need for an integrated cargo handling system for discharging non-self-sustaining container-capable ships and other ships and barges at open beach sites and identifies the Navy's responsibility for developing certain elements of the required overall cargo handling system. DOD policy is documented in the DOD Project Master Plan for Surface Container Supported Distribution and the DOD system definition paper "Over-the-Shore Discharge of Containerships (OSDOC) System."

The Navy's version of the container distribution elements constitute the Container Off-Loading and Transfer System (COTS). The COTS advanced development program includes (a) the ship unloading subsystem, (b) the ship-to-shore subsystem, and (c) system level elements. The ship unloading subsystem includes: (a) ship/barge candidates, (b) cranes, (c) crane integration with ships/barges and (d) moorings. This report addresses the progress and accomplishments associated with the crane element of the ship unloading subsystem.

CONTENTS

page

INTRODUCTION 1

ANALYSIS 1

Derivation of Separation Conditions 3

Solution of the Equation of Motion 5

Calculation of Dynamic Forces 8

Special Cases 9

Case 1. Setting the Load on the Deck 9
Case 2. Harmonic Wave Motion 11
Case 3. Random Wave Motion 11

CONCLUSIONS 11

REFERENCES 12

LIST OF SYMBOLS 13

LIST OF ILLUSTRATIONS

Figure 1. Dynamic system 2

Figure 2. Load separating from the deck at t = 0 4

Figure 3. Step force due to transferring the weight, W, from the deck to the crane, f(w) 6

Figure 4. Phase relationship between oscillating components of F 10

INTRODUCTION

Marine cranes operate in the demanding and ever changing dynamic environment imposed by the sea. Some of the most severe loads occur when the crane is ship mounted and is on/off loading an adjacent barge or ship. The wave induced relative motion between the crane and the load, as the load leaves the barge platform, can produce severe dynamic stresses in the crane boom. The lifting line can become slack and then suddenly taut. But even with a continuous load in the hoist line, just the transfer of load from the moving platform to the crane will produce oscillations in the load. It is these oscillations which are treated in this paper.

The dynamic forces on marine cranes have been computed in Ref (1,2). In these references, forces produced by the initial relative velocity between the hook and the load are computed, but the force due to the weight of the load is assumed to be static or constant. Using this assumption the static and dynamic loads were added to find the derating factor. Unfortunately the load is not static. In operation the load is transferred from the deck to the crane and the force on the crane due to the weight of the load varies with time.

In the following analysis the response caused by the application of the load weight is determined. The effects of deck and hoist relative velocity are also included. Then using vector addition the combined dynamic force is computed. Finally, the results are related to wave characteristics so that derating charts can be developed similar to those in Reference (1).

ANALYSIS

The objective of this study is to find the dynamic forces on a marine crane caused by lifting a load from, or setting a load on, a moving deck.

Although the crane support and load platform are rotating in inertial space the effect of rotation will be neglected in order to simplify the equations. The concept being presented is difficult to grasp and needs to be presented in its simplest form. The rotational effect can and should be added eventually by rewriting the equations in three dimensions and using transformation matrices to convert to the crane coordinate system. However in this preliminary study, the crane and platform are assumed to be moving the load only in the vertical direction (refer to Figure 1).

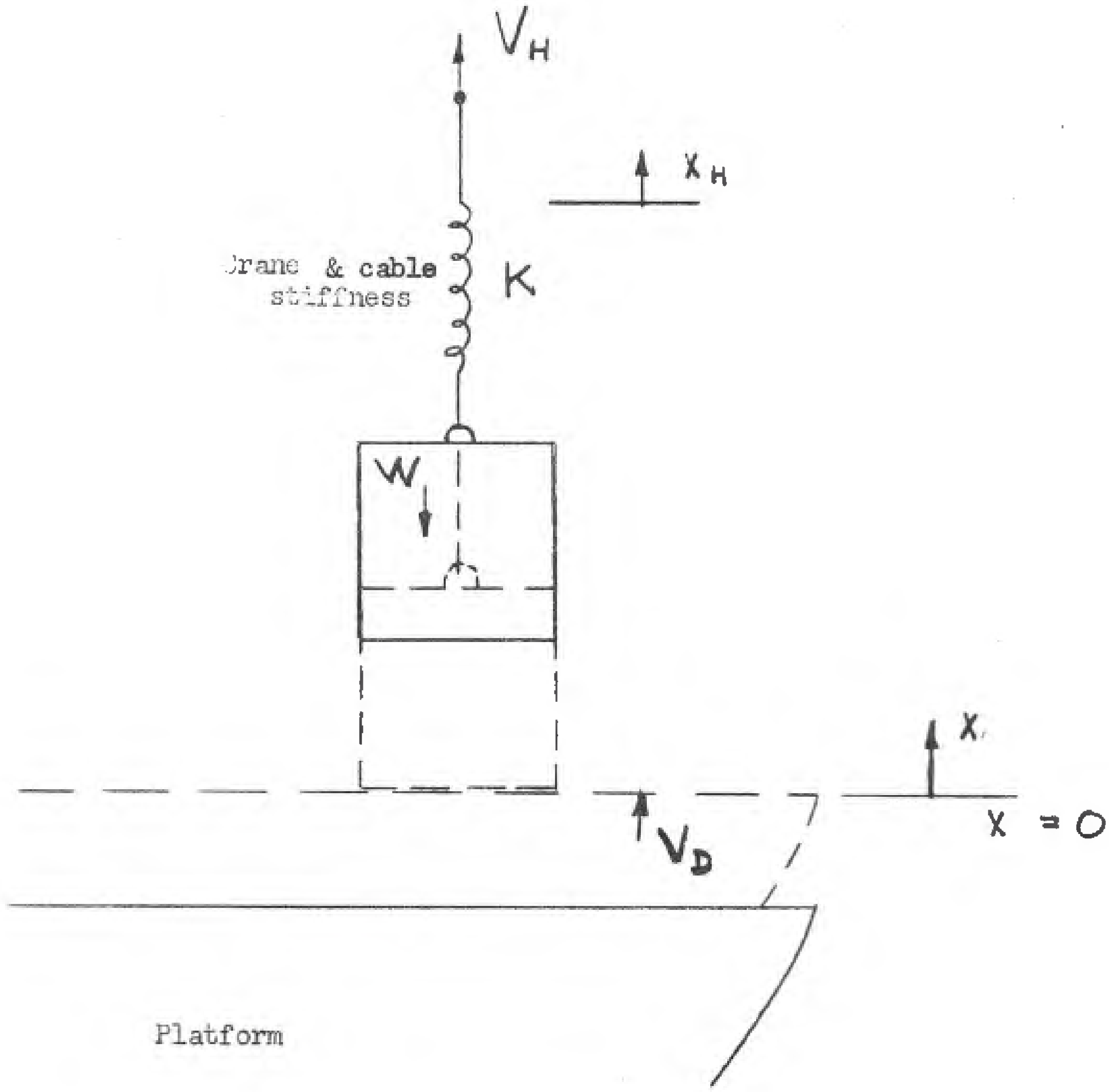


Figure 1 . Dynamic System.

The other simplifying assumptions are the following: (a) stiffness of the combined structural system (crane boom, suspension lines and hoisting line) is represented by a single vertical spring stiffness. The mass of the lines and boom are neglected using this assumption. (b) This structural stiffness does not change in the short time interval being studied. (c) The vertical motion of the platform follows the wave. (d) Damping is neglected. (e) The system is linear.

The solution separates into three parts: (1) The determination of the conditions when the load leaves the deck, (2) The solution of the dynamic equation of motion, and (3) the calculation of dynamic forces. The Laplace transform method is used to solve the differential equation of motion.

Derivation of Separation Conditions

Before the crane hook contacts the load, the weight of the load and the inertia force due to deck acceleration are reacted only by the deck or load platform. Refer to Figure 2. If the load is being accelerated up by the wave action, the equation for the deck force F_D is

$$F_D = -MA_D - W \qquad (1)$$

where A_D is the acceleration of the deck. When the crane hook is attached to the weight but before the load leaves the deck the equation becomes

$$F_D = -W - MA_D + F_C \qquad (2)$$

These conditions are shown in Figure 2. The load supported by the crane is equal to the elastic deformation of the structure, u, multiplied by its stiffness K

$$F_C = -Ku \qquad (3)$$

(for a positive F_C, u is negative according to the sign convention in Figure 2),

Rewriting Equation 2

$$F_D = -W - MA_D - Ku \qquad (4)$$

When $F_D = 0$

$$Ku = -W - MA_D \qquad (5)$$

the load lifts off the deck. Note that at lift off the load in the crane line is NOT equal to W but equal to W plus another quantity which is a function of sea state. The force in the cable would only be equal to W if the load were stationary. The force necessary to lift the weight off the deck is analogous to picking an object in

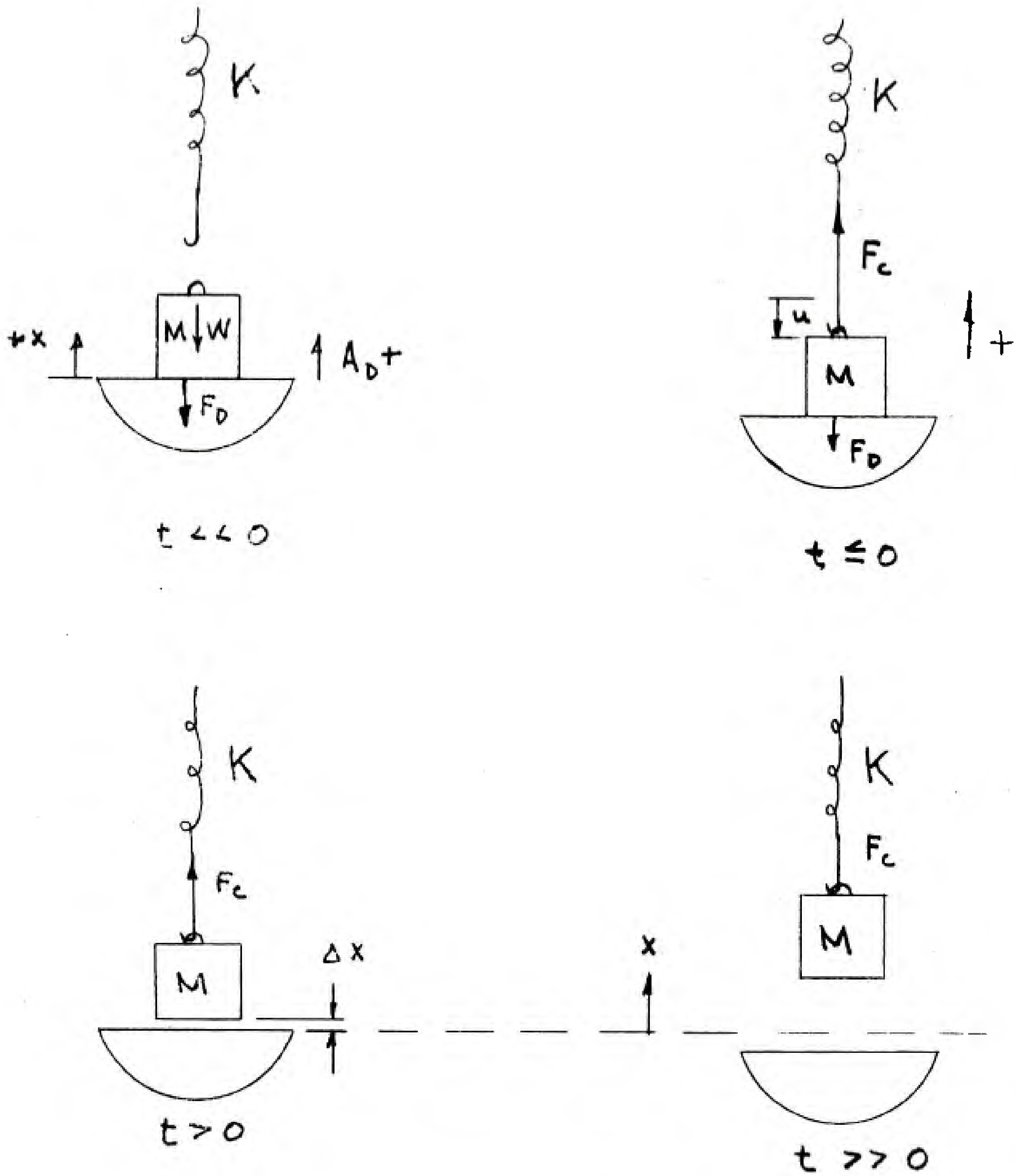


Figure 2 . Load separating from the deck at t=0.

an accelerating elevation. If the elevator is accelerating in the upward direction the object feels heavier. When the elevator is accelerating down the reverse is true; the object is lighter. However, the crane motion is independent of the load acceleration and as the load clears the deck the load on the crane hook becomes W. Thus, a step change in force occurs as the load separates from the deck. The magnitude of the step being MA_D, the sign is defined by the direction of deck acceleration, A_D. The equation for the force at the hook is as follows:

$$\begin{aligned} f(w)_o &= +W + MA_D \quad && \text{at } t = 0 \\ f(w)_\Delta &= W && \text{at } t = \Delta t \end{aligned} \qquad (6)$$

Figure 3 shows step forces for several possible situations. Based on Equation 6 the worst condition would occur when the deck dropped out from under the load at an acceleration equal to the acceleration of gravity, g (i.e., $A_D = -g$). The resulting step force on the crane would go from 0 to W at lift off. Actually the deck could not drop with an acceleration equal to g. This is a ''worst-case'' condition, and is representiative of what would occur if the load slipped laterally off the ship deck before the hoist line elongated.

Solution of the Equation of Motion

At t = 0 the load lifts off the deck and a single differential equation can be used to describe the motion of the load.

$$M\ddot{x}_L + K(x_L - x_H) = -f(w) \qquad (7)$$

x_L and $\ddot{x}_L$ the load displacement and acceleration are measured relative to inertial space. $x_L - x_H$ is the elastic displacement of system after time t = 0. f(w) is the forcing function due to the weight. The displacement component due to line and crane motion, x_H, shown in Figure 1, is obtained by integrating

$$x_H = \int_0^t \dot{x}_H \, dt \qquad (8)$$

If $\dot{x}_H$ is not a constant it can be computed from $\ddot{x}_H$.

$$\dot{x}_H = \int_0^t \ddot{x}_H \, dt + \dot{x}_{Ho} \qquad (9)$$

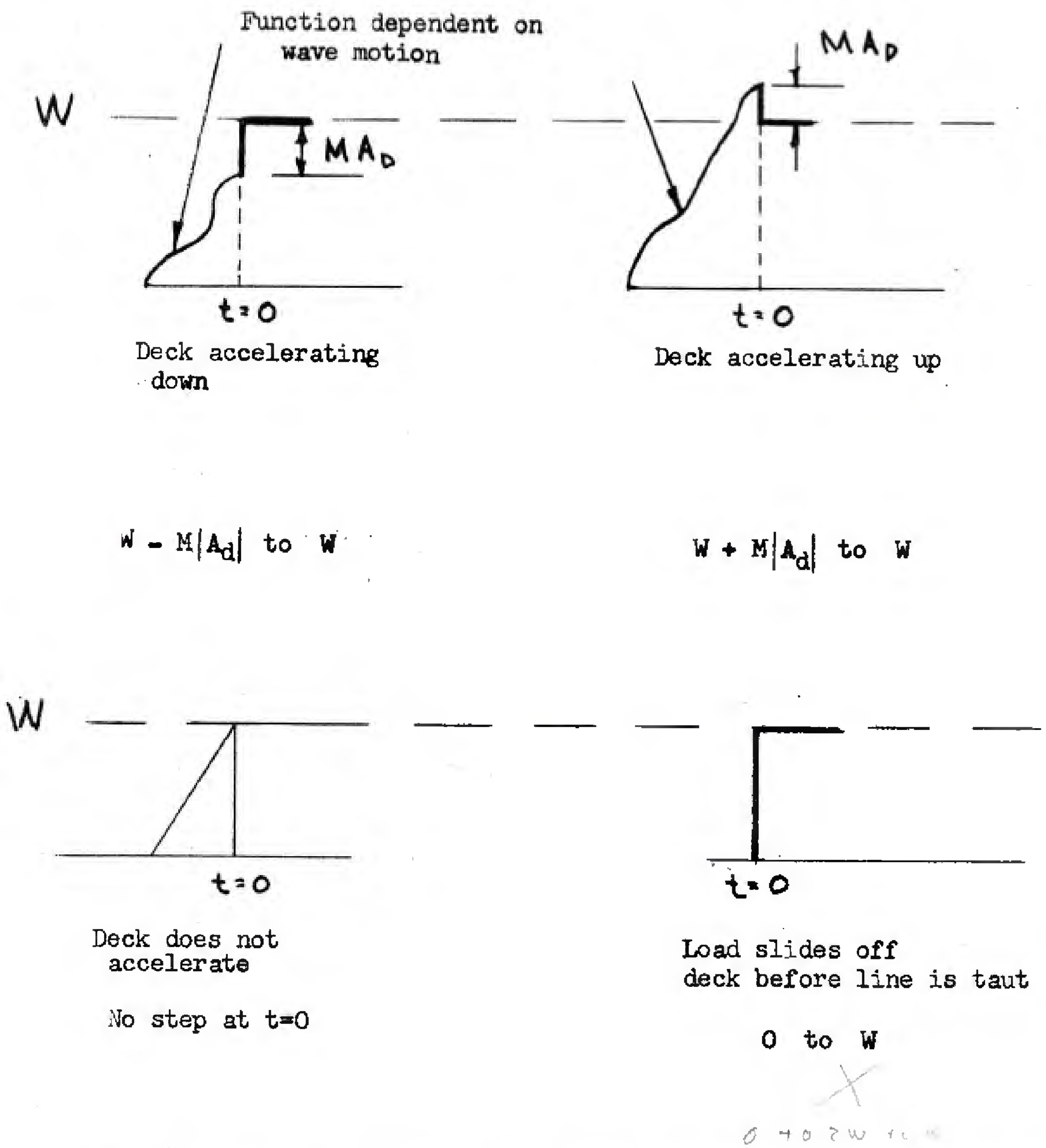


Figure 3 . Step force at the Crane hook due to transferring the weight, W, from the deck to the Crane, f(W).

The initial displacements are

$$x_o = x_L = u \qquad x_H = 0 \qquad \text{at } t = 0$$

Rewriting Equation 7 so that the known forces are on the right side

$$M\ddot{x}_L + Kx_L = +Kx_H - f(w) \tag{10}$$

To simplify the solution a new reference x is used for the load displacement.

$$x = x_L - u \tag{11}$$

By subtracting Equation 5 from Equation 10 the static force is subtracted out of the differential equation of motion.

$$M\ddot{x}_L + K(x_L - u) = Kx_H - f(w) + W + MA_D \tag{12}$$

Because $-W - MA_D = f(w)_o$ (the step value at $t < 0$), and x_L is independent of the coordinate reference change, Equation 12 can be written in terms of the new coordinate x as

$$M\ddot{x} + Kx = Kx_H - f(w) + f(w)_o \tag{13}$$

using Equation 6

$$-f(w) + f(w)_o = +MA_D \qquad \text{(step function)} \tag{14}$$

$-W + W + MA_D = MA_D$

the sign convention for A_D is
+ deck accelerating up
- deck accelerating down

The Laplace Transform of Equation 13 is

$$M[S^2\bar{X}(S) - SX(0) - X'(0)] + K\bar{X}(S) = \bar{F}_1(s) + \bar{F}_2(s) \tag{15}$$

where $X(0) = x_o = 0$

$X'(0) = \dot{x}_{L_o} = V_{D_o}$ the deck velocity at $t = 0$

$\bar{F}_1(s)$ = Laplace transform of $K \int \dot{x}_H \, dt$

$\bar{F}_2(s)$ = Laplace transform of step $+ MA_D$

The support velocity $\dot{x}_H$ depends on the main hoist line speed and the motion of the crane support. To simplify the solution the support velocity is assumed constant. That is, the crane support is not accelerating as the load is lifted from the deck. For this case

$$\bar{F}_1(s) = KV_H t = KV_H/S^2$$
$$\bar{F}_2(s) = (+MA_D) = +MA_D/S \quad (16)$$

Rewriting Equation 15

$$(MS^2 + K)\bar{X}(s) = MV_D - \frac{KV_H}{S^2} + \frac{MA_D}{S} \quad (17)$$

Dividing Equation 15 by $MS^2 + K$

$$x(s) = \frac{MV_D}{MS^2 + K} - \frac{KV_H}{S^2(MS^2 + K)} + \frac{MA_D}{S(MS^2 + K)} \quad (18)$$

Taking the inverse Laplace transform to find the displacement x and substituting β for $\sqrt{K/M}$

$$x = \frac{V_D \sin \beta t}{\beta} + \frac{V_H}{\beta}(\beta t - \sin \beta t) + \frac{A_D}{\beta^2}(1 - \cos \beta t) \quad (19)$$

Calculation of Dynamic Forces

The force on the crane is the elastic deformation, $x_L - x_H$, multiplied by the stiffness. The crane force as a function of the variable x from equation (11) is

$$F_C = Kx - Kx_H + Ku \quad (20)$$

Substituting Equation 5 and 19 into Equation 20 yields

$$F_C = \frac{K}{\beta}\left[V_D \sin \beta t - V_H \sin \beta t + \frac{A_D}{\beta}(1 - \cos \beta t)\right] - W - MA_D \quad (21)$$

Simplifying Equation 21

$$F_C = \frac{K}{\beta}(V_D - V_H) \sin \beta t - MA_D \cos \beta t - W \quad (21a)$$

If the deck is accelerating downward A_D is negative changing the sign of the cos term, and Equation 21a becomes

$$F_C = \frac{K}{\beta}(V_D - V_H) \sin \beta t + M|A_D| \cos \beta t - W \quad (21b)$$

dividing by W, Equation 21a becomes

$$\frac{F_C}{W} = \frac{K}{W}\frac{(V_D - V_H)}{\beta} \sin \beta t - \frac{A_D}{g} \cos \beta t - 1 \qquad (22)$$

If separation occurs as the deck is moving down with a velocity $-V_D$ as in Reference 1, Equations 22a become

$$\frac{F_C}{W} = -\frac{K}{W}\frac{(V_D + V_H)}{\beta} \sin \beta t - \frac{A_D}{g} \cos \beta t - 1 \qquad (23)$$

If the A_D term were neglected the equation would be the same as that in References (1 and 2) except for a difference in sign convention. Vector addition can be used to combine the sin and cos terms and it can be shown that the maximum dynamic force is independent of the direction of the deck acceleration A_D. The deck acceleration only establishes a phase relationship (Refer to Figure 4). The load on the crane is obtained directly from Equation 23 by substituting in the values for V_D and A_D at $t = 0$, and the value for the hoist velocity, V_H. The maximum force on the crane is

$$F_C max = -W\left[\frac{1}{g}\frac{K}{W}(V_D + V_H)^2 + \frac{A_D^2}{g^2}\right]^{1/2} - W \qquad (24)$$

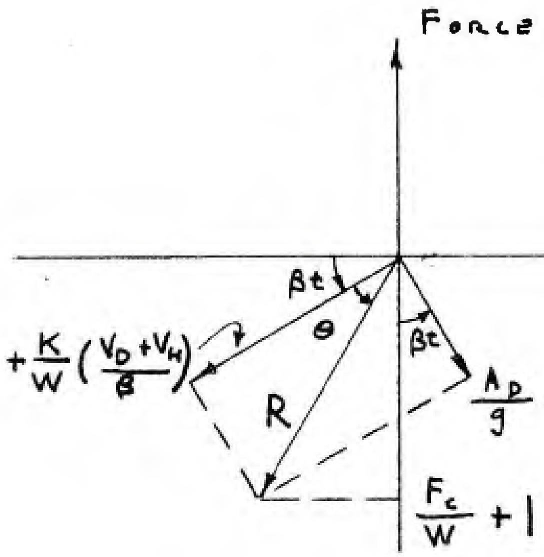
The terms within the square root parentheses are the dynamic force terms. In the first dynamic force term the quantity K/W appears. This term is directly related to the stiffness and if the crane were strengthened this term would increase. Actually

$$K/W = 1/\text{static displacement}$$

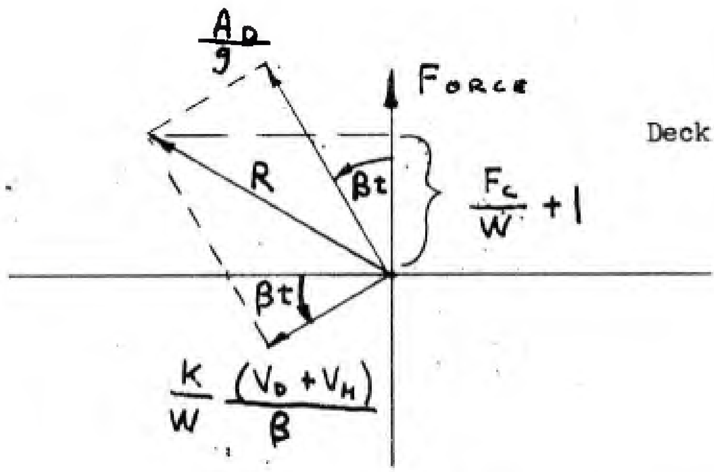
As the static deflection approaches 0 the dynamic loads become more severe. The second dynamic force term has the quantity A_D/g. The magnitude of this term may be easily established by comparing deck accelerations to the acceleration of gravity.

Special Cases

Case 1. Setting the Load on the Deck. If the load is being set on the deck, and due to wave action the deck drops out from under the load before the load is off the crane, the force computations are the same as above. Equation 7 holds whether the load is moving up or down. The load is transferred to the crane as in Equation 5 when $F_D = 0$.



Deck accelerating up



Deck accelerating down

$$R = \sqrt{\left[\frac{K}{W}\,\frac{(V_D + V_H)}{\beta}\right]^2 + \left[\frac{A_D}{g}\right]^2}$$

$$\frac{F_c}{W} + 1 = -R\,\sin(\beta t + \theta)$$

Figure 4 . Phase relationship between oscillating components of F.

Case 2. Harmonic Wave Motion. Harmonic motion could be assumed as in Reference (1) to characterize a sea state. However in harmonic motion A_D is usually low and such an analysis would not be conservative. Using the quantities H and T, where H is peak to through amplitude and T is the period of the wave, the following relationships exist

$$V_D = \frac{\pi H}{T} \sin\left(\frac{2\pi}{T} t + \phi\right)$$

$$A_D = \frac{2\pi^2 H}{T^2} \cos\left(\frac{2\pi}{T} t + \phi\right)$$

to clear the wave $V_H = \frac{2}{3} \frac{H}{T}$

The above quantities can be substituted into Equation 24 to compute the force on the crane, F_C.

Case 3. Random Wave Motion. A better approach would be to substitute into Equation 24, measured accelerations and velocities. Some worst possible conditions should be selected. The vertical deck acceleration and velocity components obtained from the angular acceleration and velocity of the ship need to be included. A probability approach, that of selecting deck accelerations and velocities which would include a large percentage of situations, could also be used.

CONCLUSIONS

A systematic set of equations have been developed for on/off loading forces on a marine crane. The equations though simple in appearance can be easily expanded to include hoist accelerations and rotational effects. They can be combined with structural system equations to complete the crane dynamic analysis.

Dynamic forces develop because the load oscillates. These oscillations are caused by: (1) The initial relative velocity between the hook and the load and (2) the transfer of the load from the deck to the crane. The latter oscillations, those due to load transfer, have been overlooked in previous analysis (references 1 and 2).

The equations show that deck velocity and deck acceleration at load lift off influence the dynamic forces on the crane. Raising the crane stiffness factor by making it stronger would increase the dynamic load. Wave action such as sea chop which increases instantaneous deck accelerations can critically affect the dynamic forces.

A precise description of the acceleration and velocity of the deck is needed. Then using representative hoisting velocities, reliable estimates of the dynamic loads can be obtained. Eventually the dynamic characteristics of the boom and suspension line need to be simulated in three dimensions, so that out of plane loads can be investigated.

REFERENCES

1. K. Johnson, Theoretical Overload Factor Effect of Sea State on Marine Cranes, Offshore Technology Conference, Paper 2584.

2. D. E. Charrett, Dynamic Factors for Offshore Cranes, Offshore Technology Conference, Paper 2578.

LIST OF SYMBOLS

A_D	Acceleration of the deck at time $t = 0$
$\bar{F}(s)$	Laplace transform of forcing functions
F_D	Force on the deck
F_C	Force on crane
$f(w)$	Step forcing function due to the transfer of the load
g	Acceleration of gravity
H	Wave height peak to trough
K	Structural stiffness
$\mathcal{L}$	Laplace transform
M	Mass of load
S	Laplace operator
T	Wave period
t	Time
u	Elastic deformation of structure
V_H	Constant hoist velocity
V_D	Velocity of deck at $t = 0$
W	Weight of the load
$\bar{X}$	Laplace variable
$X(0)$, $X'(0)$	Initial position and velocity in Laplace Equation
x_L	Position of load in inertial space
x	$x_L - u$
x_H	Support position

$\ddot{x}_L$ Acceleration of load in inertial space

$\dot{x}_H$ Support velocity

$\ddot{x}_H$ Support acceleration

β $\sqrt{K/M}$

θ Phase angle

ϕ Wave phase angle

SUBSCRIPTS

o initial condition

Δ Condition at Δt