SECOND-ORDER STEADY DRIFT
OF A
FLOATING TRIANGULAR PLATFORM:
THEORY AND EXPERIMENT

BY


A thesis submitted to the School of Graduate Studies in partial fulfillment of the requirements for the degree of Master of Engineering

Faculty of Engineering and Applied Science
Memorial University of Newfoundland
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Newfoundland
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ABSTRACT

As ocean industries have grown to demand larger offshore vessels achieving ever increasing levels of performance, the need for a better understanding of the phenomena which govern motions and loading of these structures has been recognized. These motions and forces are a result of complex environmental conditions including ice, wind, current and waves. A significant part of the environmental loading is due to waves.

In general wave loading on a structure is a complex non-linear process of which the first- and second-order (in wave amplitude) components are of main interest. The steady second-order component of drift force may cause large excursions of the structure and therefore must be seriously considered in the design considerations of mooring and dynamic positioning systems.

In this thesis second-order mean drift forces on a triangular floating structure in regular waves are calculated utilizing far field potential theory. These computed forces are compared to those measured during testing of a 1:200 scale model of a moored triangular body. This is done in an attempt to decide whether mooring forces can be reasonably estimated for such a structure.
It was concluded that the mean drift forces can be reasonably well predicted using the method presented. Therefore this method can be used as an aid in the design process.
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NOMENCLATURE

A non-dimensional table of offsets describing the geometry of the structure nondimensionalized with characteristic length

$A_D = \frac{A}{\rho D}$

$A_I = \frac{\rho n D^2}{4}$

$A_{jk}$ added mass coefficient

$A_{wp}$ water plane area

$B_{jk}$ damping coefficients

$C$ restoring coefficients

$C_A$ added mass coefficient

$C_d$ drag coefficient

$C_{d'}$ drag coefficient for oscillating body in still water

$C_m$ inertia coefficient

$D$ body characteristic length

$d$ depth of water

$ds$ differential of surface area

$F$ total force on body

$F$ nondimensional force

$F_d$ horizontal drift force

$F_{d,x}$ drift force in x-direction

$F_{d,y}$ drift force in y-direction

$F_g$ force due to gravity

$F_j$ generalized force

$f_{ex}$ external forces acting on the body

$f$ frequency
\( f_{o2}, f_{o3} \) \( \text{natural frequency of moorings 2 and 3 respectively} \)

\( g \) \( \text{acceleration due to gravity} \)

\( G(\vec{x}, \vec{z}) \) \( \text{Green's function} \)

\( H \) \( \text{wave height} \)

\( \text{Im} \) \( \text{imaginary part of complex term} \)

\( K \) \( \text{spring constant} \)

\( \text{kg} \) \( \text{kilogram mass} \)

\( \text{kg} \) \( \text{kilogram force} \)

\( \text{K-C} \) \( \text{Keulegan-Carpenter number} \)

\( k_R \) \( \text{structure relative roughness coefficient} \)

\( k \) \( \frac{\omega^2}{g}, \text{wave number} \)

\( L \) \( \text{linear momentum} \)

\( M \) \( \text{mass of body} \)

\( M_{jk} \) \( \text{body mass matrix (6 x 6)} \)

\( M_v \) \( \text{virtual mass of body} \)

\( m,p \) \( \text{subscripts representing model and prototype, respectively} \)

\( \hat{n} \) \( \text{unit normal vector (into the fluid)} \)

\( n \quad = \begin{cases} (\hat{n})_j, & \text{for } j=1,2,3 \\ (\hat{r} \times \hat{n})_{j-3}, & \text{for } j=4,5,6 \end{cases} \)

\( p \) \( \text{pressure} \)

\( Q(\xi) \) \( \text{source density function} \)

\( Q_j \) \( \text{source densities, } j=1,\ldots,7 \)

\( R \) \( \text{reflection coefficient (ratio of reflected wave height to incident wave height)} \)

\( \text{Re} \) \( \text{real part of complex term} \)

\( R_n \) \( \text{Reynolds number} \)

\( r \) \( \text{radius of cylindrical control surface} \)
\[ r_{xx} \] radii of gyration
\[ r_{yy} \] 
\[ r_{zz} \] 
\[ S \] surface of control volume
\[ S_b \] mean wetted body surface area
\[ S_b(t) \] instantaneous wetted body surface area
\[ S_f \] free surface area
\[ S_h \] sea bed surface area
\[ S_m \] fixed control surface
\[ S_L \] wave elevation spectral density
\[ T \] wave period
\[ T_r \] relative period; wave period as observed from the floating vessel
\[ T(\theta)e^{i\tau(\theta)} \] Kotchin function
\[ t \] time
\[ u \]
\[ v \]
\[ w \] velocity components in \( x, y, z \) directions
\[ u_o \] amplitude of horizontal water particle velocity
\[ \bar{U}, \bar{\dot{U}} \] rigid body velocities and accelerations
\[ U_n \] velocity of the surface normal to itself
\[ \bar{u} = u\bar{i} + w\bar{j} + z\bar{k} \] fluid velocity vector
\[ \dot{u} \] acceleration of fluid
\[ u_r \] relative velocity
\[ u_R \] radial component of fluid velocity
\[ u_\theta \] tangential component of fluid velocity
\[ u_{ro} \] amplitude of relative velocity
X response of wave-structure system used in dimensional analysis

\[ \mathbf{xyz} \] coordinates, \( z \) positive up

\[ \mathbf{x} = x\mathbf{i} + y\mathbf{j} + z\mathbf{k} \], position vector

\[ \mathbf{v}, \mathbf{a} \] velocity and acceleration of body

\[ \mathbf{x}_{cg} \] vector defining center of gravity

\( z_b \) \( z \) coordinate of center of bouyancy

\( z_c \) \( z \) coordinate of center of gravity

\( \alpha \) wave elevation

\( \beta \) incident angle of wave system, measured from positive \( x \) axis to the direction of wave propagation.

\( \zeta_a \) wave amplitude of incident wave

\( \delta \) diameter of fluid particle orbits

\( \eta \) wave amplitude

\( \eta^*(t) \) time-dependent first-order linear and angular motions

\( \mathbf{\eta} \) complex amplitude of body motion

\( \theta \) angle

\( \lambda \) wave length

\( \mu \) dynamic viscosity of fluid

\( \nu \) kinematic viscosity of fluid

\( \mathbf{\xi} = (\xi, \eta, \zeta) \), position vector of a point

\( \pi \) 3.14159

\( \rho \) density of fluid

\( \phi \) represents a functional relationship

\( \phi \) velocity potential
\( \Phi_I \)  incident wave potential

\( \Phi_S \)  scattered wave potential

\( \omega \)  circular frequency

\( \tilde{\omega} \)  nondimensional frequency

\( \omega_0 \)  natural circular frequency

\( \omega_{0,2}, \omega_{0,3} \)  natural frequency, mooring 2 and 3 respectively

\( \delta \omega \)  frequency bandwidth

\( \nabla \)  \( \frac{\partial}{\partial x} \frac{\partial}{\partial y} + \frac{\partial}{\partial z} \frac{\partial}{\partial z} \)

\( \Lambda \)  displaced volume of fluid

\( \langle \rangle \)  time average over one period
CHAPTER I

INTRODUCTION

A floating vessel with zero forward speed acted upon by ocean waves will experience forces which produce vessel motions in six degrees of freedom. These forces are generally the result of a complex, non-linear process of which the first- and second-order components are of main interest. The first-order forces are proportional to wave amplitude and oscillate at a frequency equal to the wave frequency. The mean and low frequency components of the second-order forces are commonly referred to as "wave drift forces". These second-order forces are proportional to the square of the wave amplitude, and are generally small compared to first-order forces. The mean, or "steady", component is recognized (Standing et al 1981) as a second-order consequence of the first-order waves interacting with the structure. This force results in a mean horizontal excursion of the moored vessel. The slow-oscillating second-order component is due to non-linear interactions with the wave field. As the name indicates, these forces cause the vessel to oscillate slowly about the mean position. These second-order forces are often the cause of low frequency, large amplitude
motions of moored vessels, and are, therefore, of great importance in the design considerations of mooring and dynamic positioning systems.

It is the purpose of this work to compare computational and experimental estimations of mean drift forces on a large floating triangular structure in regular waves. Experiments were conducted at the National Research Council's Institute for Marine Dynamics in St. John's. Mooring force data collected by IMD were used to evaluate the validity of the computational estimations, and therefore of their influences in the design process. Such a structure is being considered for operation as a support base in the Hibernia region. It is known as the Deltaport. Experiments were carried out on the 1:200 scale model at IMD. However, they were not designed for the research purposes of interest here. Although it is felt that sufficient data was obtained for the purpose of the present study, more test information would have been an asset.

Chapter II of this report reviews the historical progress of work in the field of wave force prediction. Theory governing wave-structure interaction is presented in Chapter III. Experimental results and numerical evaluations of steady drift forces are discussed in Chapter IV. Chapter V compares computations with experiments. Conclusions from this comparison are drawn in Chapter VI.
CHAPTER II

LITERATURE REVIEW

One of the earliest studies of drift forces on floating bodies in waves was the experimental study by Suyehiro (1924). He measured the steady drift force experienced by a ship model in beam seas. He believed the drift force was a result of the model rolling motion causing the waves to be reflected. In 1938 Watanabe derived an expression for lateral drift force acting on a ship subject to beam waves based on the product of the first-order roll motion and the Froude-Krylov component of the roll moment. This expression indicated that the force was a second-order phenomenon. Havelock (1940, 1942) later made use of Watanabe's theory to develop formulae to predict the mean drift force acting on a ship heaving and pitching in regular head waves.

Dean (1948) concluded that if there is no reflection from a restrained submerged circular cylinder the incident wave only changes by a shift in phase. Ursell (1950) developed a procedure to resolve forces on a
submerged cylinder based on Dean's findings. Ogilvie (1963) developed expressions for and calculated the first- and second-order forces on a submerged cylinder based on Ursell's procedure. A body subject to forced oscillations in an otherwise calm fluid was analysed by Kotchin (1937, translation 1951) while considering the problem of wave radiation. He developed expressions for the steady forces through the use of body surface integrals which are now known as Kotchin functions.

After examining Watanabe's and Havelock's progress the "far field" approach was taken by Maruo (1960) to develop expressions for steady second-order forces on a fixed body in regular waves. In this approach the wave field far from the structure is used to evaluate the loads on the structure. He included both radiation and diffraction effects. Newman (1967) extended this theory and used it with slender body and strip theory to calculate mean forces on ships. Mei and Black (1969) calculated the mean drift force on a moored barge of infinite breadth utilizing the waves travelling outward from the body. Kim and Chou (1970) developed an expression for the two dimensional case of a ship in oblique waves by extending Maruo's expression. They applied their theory using the strip method.
Hsu and Blenkarn (1970) and Remery and Hermans (1971) showed that the low frequency components of drift force in irregular waves could excite large amplitude, low frequency horizontal motions. Remery and Hermans established that these low frequency components are associated with group effects. Faltinsen and Michelsen (1974) worked with the theory presented by Maruo and Newman and utilized three-dimensional source singularities on body surface panels to obtain their results. Experimental and theoretical results for the mean horizontal force showed good agreement for the case of a rectangular barge in regular waves. Faltinsen and Loken (1978) developed a procedure to calculate slow drift oscillations of a ship in irregular beam seas using a boundary integral technique combined with Newman's method. Molin (1979) also modified Maruo's expression for the horizontal drift force by changing the surface of integration. His theoretical results compared well with experiments.

An added resistance formula was developed by Gerritma and Beukelman (1972) by assuming that the energy in waves progressing outward from the vessel is equal to the work done by incoming waves. Results for a ship travelling in head waves showed good agreement between theory and experiment. A significant conclusion from their
work was the dependency of drift force on the square of the wave amplitude. The energy-work theory was also employed by Salvesen (1974,1978) and Lin and Reed (1976). Kaplan and Sargent (1976) used it to research the drift forces on a semi-submersed barge in regular oblique seas.

Pinkster et al (1976,1977,1979) initiated the near field approach to study first- and second-order wave forces on bodies floating in waves. Their work included methods based on direct integration of pressure and included the force components presented by Boese (1970). Pinkster and Hooft (1978) and Pinkster (1979) extended the method of direct pressure integration to include the low frequency components of the second-order wave forces set up by regular wave groups. Karppinen (1979) developed a method to estimate mean second-order wave forces and moments based on an assumption that the structure can be subdivided into noninteractive slender elements. The mean forces on the elements were summed to get total mean forces on the structure.

Pinkster (1981) and Standing et al (1981) presented insight into theory and experiment for predicting mean and slowly-varying second order forces. Kaplan (1983) utilized an approximate 3-D method to predict the steady drift force on a floating ship model. He applied Maruo's far field theory for drift forces but used a modified
Kotchin function. He professed that the forces could be resolved numerically in relatively short CPU time. Marthinsen (1983) studied the effect of short crested seas on second-order slowly varying drift forces and motions. He developed a method to predict these forces, which is shown to agree very well with Newman's method. Isaacson (1984) presented a useful review of nonlinear wave effects on offshore structures. Murray (1984) discussed the effects of wave grouping on slow drift oscillations of floating moored structures. Rahman (1987) presented a method to predict second-order wave diffraction caused by large offshore structures. He has extended Lighthill's (1979) deep water theory to shallow water waves. Chakrabarti (1987) has also reviewed this subject.

In summary, there are two basic approaches that can be used to analyse drift forces on a floating structure: the "near field" method and the "far field" method. The near field approach involves direct integration of pressure over the wetted surface of the body and can be used to predict mean and low-frequency second-order forces. The far field method can be used to predict mean second-order forces on the basis of conservation of momentum and energy. The potential far from the structure is used to describe fluid motions. In general the near field method is more cumbersome to
utilize. Therefore many researchers have attempted to develop simple methods for prediction of the low-frequency second-order forces to use in conjunction with the far field approach of predicting the mean second-order forces.

The present work is a study of the mean second-order forces on a floating triangular platform utilizing the far field method.

The following section outlines the theory which governs wave-structure interactions.
3.1 Governing Equations

The equations describing the flow of fluid around a marine structure are the Navier-Stokes equations and the conservation of mass (continuity) equation, supplemented with appropriate boundary conditions. For a constant density Newtonian fluid they are, in primitive variable form:

\[
\begin{align*}
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} &= - \frac{1}{\rho} \frac{\partial P}{\partial x} + \nu \nabla^2 u \\
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} &= - \frac{1}{\rho} \frac{\partial P}{\partial y} + \nu \nabla^2 v \\
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} &= - \frac{1}{\rho} \frac{\partial P}{\partial z} + \nu \nabla^2 w + \frac{1}{\rho} F_g \\
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} &= 0
\end{align*}
\]

where \( u, v, \) and \( w \) are velocity components in the \( x, y, \) and \( z \) directions respectively, \( t \) is time, \( \rho \) is density of fluid, \( \nu \) is kinematic viscosity of fluid, \( F_g \) is force due to gravity, \( P \) is pressure and \( \nabla \) indicates the gradient such
that:

\[ \mathbf{v} = \frac{\partial}{\partial x} \mathbf{i} + \frac{\partial}{\partial y} \mathbf{j} + \frac{\partial}{\partial z} \mathbf{k} \]  

(3.2)

A right hand cartesian coordinate system \((x, y, z)\) is fixed with respect to the mean position of the body with \(z\) positive upwards through the center of gravity and the origin in the plane of the undisturbed free surface. (see Figure 1*)

The governing equations are comprised of these four partial differential equations along with pertinent boundary conditions. In practice it has not been possible to obtain exact solutions for flows about complex geometric bodies.

Many theories have been developed to predict the motion of and hydrodynamic loading on floating bodies. It has been determined that the theory to be utilized in any particular case depends on the ratio of body characteristic length to wavelength, \(D/\lambda\). It is generally accepted that two flow regimes can be distinguished as presented by Standing (1981) and shown in Figure 2:

(i) wave diffraction around large structures:

for \(D/\lambda > 0.2\) the influence of viscosity is negligible and potential flow theory applies:

\[ \mathbf{U} = \nabla \phi \]  

(3.3)

* For convenience all figures are contained in Appendix A and reproduced when directly referred to in the main text.
Figure 1
Coordinate System
where \( \mathbf{u} \) is the velocity vector and \( \phi \) is the velocity potential.

(ii) Flow separation around slender structures:

for \( D/\lambda < 0.2 \) viscous stresses are important and vorticity is not neglected.

These two regimes are also acceptable for floating structures.

The following section develops the scaling equations corresponding to each of these flow regimes.

Figure 2
Regions of Validity of Force Prediction Methods
for a Fixed Pile (Standing 1981)
3.2 Modelling Theory

Dimensionless functional equations can provide the laws whereby phenomena such as those presently being discussed may be successfully modelled. These equations are important in the design of model tests and in the interpretation of the results.

One approach of analysing the basic functional equations of a system was developed by Rayleigh (Sharp 1981) and is known as the indicial approach. In this method the basic functional equations are rewritten in terms of the dimensions involved. The exponents of the dimensions are equated to ensure that the equation is dimensionally homogeneous. Buckingham utilized this method and developed the $\pi$ theorem which relates the number of parameters in a correct functional equation to the number of variables necessary to specify the phenomenon and the number of dimensions involved. He concluded that, in general, if $m$ variables describe the system with $n$ dimensions, there will be $(m-1)$ exponents to be determined from $n$ simultaneous equations and $(m-n)$ dimensionless parameters will correctly describe the system. He refers to the dimensionless parameters as $\pi$-terms.

The functional relationship is written:

$$\phi(b_1, b_2, \ldots, b_n) = 0$$  \hspace{1cm} (3.4)
where $\phi$ represents a functional relationship, $b_1, b_2, ..., b_n$ are the variables describing the system in which $b_1, b_2, ..., b_k$ (k<n) are dimensionally independent physical quantities. In the present case these quantities are length, $l$, mass, $m$, and time, $t$. (ie. $k=3$)

Now the functional relationship may be written for the general case:

$$b_1 b_2 \cdots b_k \phi(\beta_{k+1}, \beta_{k+2}, \ldots \beta_n) = 0$$  \hspace{1cm} (3.5)

where $\phi$ is nondimensional and:

$$\beta_{k+i} = b_1 b_2 \cdots b_k, \hspace{0.5cm} i = 1, 2, \ldots n-k$$  \hspace{1cm} (3.6)

where $\beta_{k+i}$ are nondimensional.

For the case of a body floating in waves with no forward speed the variables which correctly describe the system can be written in functional form as:

$$\phi(X, \rho, \mu, g, d, H, T, M, x_{cg}, r, D, A, k) = 0$$  \hspace{1cm} (3.7)

where:

- $X$ represents a response of the wave-structure system in terms of force [N], motion [m], or velocity [m/s]
- $\rho, \mu$ are physical properties of water; density [kg/m$^3$] and dynamic viscosity [kg/ms], respectively
\( g, d \) are environmental properties affecting wave propagation; acceleration due to gravity \([\text{m/s}^2]\) and water depth \([\text{m}]\) respectively

\( H, T \) are wave parameters; wave height \([\text{m}]\) and period \([\text{s}]\) respectively (wavelength, \( \lambda \) \([\text{m}]\) or frequency, \( \omega \) \([\text{rads/s}]\), or \( f \) \([\text{Hz}]\) could replace \( T \))

\( M, \bar{x}_{cg}, r, D, A, k_R \) parameters of the structure; mass \([\text{kg}]\), center of gravity \([\text{m}]\), radii of gyration \([\text{m}]\), characteristic length \([\text{m}]\), nondimensional table of offsets, and relative roughness, respectively.

Taking \( \rho, g, \) and \( D \) as dimensionally independent parameters and resolving the functional equation for \( X \), equation 3.7 can be rewritten:

\[
\phi_X(\rho, \mu, g, d, H, T, M, \bar{x}_{cg}, r, D, A, k_R) = X
\]

(3.8)

Now \( n \)-terms are formed by combining all other terms, separately, with these three relevant variables which cannot form a \( n \)-term on their own, but contain all three dimensions involved in the problem. Now one can write:

\[
\rho a_1^2 g a_2^2 \bar{D} a_3^2 (X - \phi_X(\frac{\bar{v}}{\sqrt{\rho D}}, \frac{d}{\bar{D}}, \frac{H}{\sqrt{g/D}}, \frac{M}{\rho D}, \frac{\bar{x}_{cg}}{\bar{D}}, \frac{r}{\bar{D}}, A, k_R)) = 0
\]

(3.9)
or,
\[ \hat{x} = \hat{x}_X \left( \frac{v}{\sqrt{gD}}, \frac{d}{D}, \frac{H}{D}, \frac{T}{g/D}, \frac{M}{\rho D^3}, \frac{c_g}{D}, \frac{\alpha}{D}, \kappa_R \right) \]  

(3.10)

where \( \hat{x}_X \) is nondimensional and \( \hat{x} \) represents \( x \) normalized with respect to \( \rho, g, \) and \( D, \) depending on the definition of \( x \) as a force, velocity or motion. If \( x \) is taken as a force \( F, \) then \( \hat{x} \) can be written:

\[ \hat{x} = \frac{F}{\rho g D^3} \]  

(3.11)

The first term on the right hand side, \( \frac{v}{\sqrt{gD}} \), represents Reynolds number \( \frac{uD}{v} \), where \( u \) is a characteristic wave speed. Let \( x = u \) in equations 3.9 and 3.10 such that nondimensional \( \hat{x} \) is the Froude number:

\[ \hat{x} = \frac{u}{\sqrt{gD}} = \hat{x}_u \left( \frac{v}{\sqrt{gD}}, \frac{d}{D}, \frac{H}{D}, \frac{T}{g/D}, \frac{M}{\rho D^3}, \frac{c_g}{D}, \frac{\alpha}{D}, \kappa_R \right) \]  

(3.12)

Compounding dimensionless terms one can write the Reynolds number:

\[ \frac{v}{\sqrt{gD}} = \left( \frac{v}{\sqrt{gD}} \right)^{-2} \cdot \frac{u}{\sqrt{gD}} = 2 \]  

(3.13)

Substituting this into equation 3.12:

\[ \frac{uD}{v} = \frac{v}{\sqrt{gD}} \hat{x}_u \left( \frac{v}{\sqrt{gD}}, \frac{d}{D}, \frac{H}{D}, \frac{T}{g/D}, \frac{M}{\rho D^3}, \frac{c_g}{D}, \frac{\alpha}{D}, \kappa_R \right) \]  

(3.14)

Therefore the Reynolds number, \( Rn = \frac{uD}{v} \), can be substituted for \( \frac{v}{\sqrt{gD}} \) in equation 3.10. This also shows that the Froude number, \( \frac{u}{\sqrt{gD}} \), cannot in general be modelled between

* Personal notes of Dr. J. S. Pawlowski, NRC/IMD
the scale model and prototype unless viscous scale effects can be neglected.

In a similar way the parameter \( T\sqrt{g/D} \) represents the Keulegan-Carpenter number, \( K-C = \frac{uT}{D} \), since:

\[
T\sqrt{g/D} \cdot \frac{u}{\sqrt{gD}} = \frac{uT}{D}
\]

(3.15)

Now equation 3.10 can be written in terms of well known parameters:

\[
X = \bar{X} \left( \frac{ud}{D}, \frac{uT}{D}, \frac{M}{D^3}, \frac{cg}{D}, \frac{r}{D}, A, k_R \right)
\]

(3.16)

This is the most convenient representation when both wave and viscous effects, such as flow separation, are of primary importance.

Now if viscous scale effects are negligible and, therefore the dependence on \( Rn \) can be neglected, it is common to replace \( T\sqrt{g/D} \) in equation 3.16 by nondimensional frequency, \( \tilde{\omega} \):

\[
2\pi \left( \frac{T\sqrt{g/D}}{D} \right)^2 = \frac{\omega \sqrt{D/g}}{\tilde{\omega}} = \tilde{\omega}
\]

(3.17)

If \( \lambda \) had been used in the basic functional equation 3.7 in place of \( T \), the resulting \( \pi \)-term would be \( \lambda/D \). Equation 3.10 can be written for Froudian similarity:
\[ \chi = \phi_X \left( \frac{d}{D}, \omega, \frac{M}{\rho D^3}, \frac{x}{D}, \frac{r}{D}, A, k_R \right) \]  

(3.18)

Now considering first- and second-order quantities \( X \) with respect to the wave height, \( H \):

\[ \dot{\chi} = \chi^{(1)} + \chi^{(2)} = \left( \frac{H}{D} \right)^2 \phi_X^{(1)} + \left( \frac{H}{D} \right)^2 \phi_X^{(2)} \]  

(3.19)

Therefore it follows that:

\[ \chi^{(1)} \left( \frac{H}{D} \right) = \phi_X^{(1)} \left( \frac{d}{D}, \omega, \frac{M}{\rho D^3}, \frac{x}{D}, \frac{r}{D}, A, k_R \right) \]  

(3.20)

\[ \chi^{(2)} \left( \frac{H}{D} \right)^2 = \phi_X^{(2)} \left( \frac{d}{D}, \omega, \frac{M}{\rho D^3}, \frac{x}{D}, \frac{r}{D}, A, k_R \right) \]  

(3.21)

for Reynolds modelling, or:

\[ \chi^{(1)} \left( \frac{H}{D} \right) = \phi_X^{(1)} \left( \frac{d}{D}, \omega, \frac{M}{\rho D^3}, \frac{x}{D}, \frac{r}{D}, A, k_R \right) \]  

(3.22)

\[ \chi^{(2)} \left( \frac{H}{D} \right)^2 = \phi_X^{(2)} \left( \frac{d}{D}, \omega, \frac{M}{\rho D^3}, \frac{x}{D}, \frac{r}{D}, A, k_R \right) \]  

(3.23)

for Frouadian scaling.

Therefore one can write nondimensional force as:

\[ \tilde{F} = \tilde{\chi} = \frac{F}{\rho g D^3} \]  

(3.24)

consisting of first- and second-order components:

\[ \tilde{F} = \tilde{F}^{(1)} + \tilde{F}^{(2)} \]  

(3.25)

The first-order component is written:

\[ \tilde{F}^{(1)} = \chi^{(1)} \left( \frac{H}{D} \right) = \frac{F^{(1)}}{\rho g D^3 H} \]  

(3.26)

indicating that the first-order force is proportional to the waveheight. The second-order component is written:

\[ \tilde{F}^{(2)} = \chi^{(2)} \left( \frac{H}{D} \right)^2 = \frac{F^{(2)}}{\rho g D H^2} \]  

(3.27)
indicating that the second-order forces are proportional to the square of the waveheight.

Miller and McGregor (1978) recommended that, despite which modelling technique is employed, model tests should not be carried out in a flow regime that is different than that of the prototype, as indicated in Figure 3 (Miller and McGregor 1978). This is often impossible to achieve. It is useful to look at the Reynolds number and Keulegan-Carpenter number in more detail.

The usual form of the Reynolds number is:

\[
Rn = \frac{u_o D}{v} \quad (3.28)
\]

where \(u_o\) is the amplitude of \(u\), the horizontal water particle velocity.

The Keulegan-Carpenter number is generally of the form:

\[
K-C = \frac{u_o T}{D} \quad (3.29)
\]

The horizontal water particle velocity, at an elevation \(s\) above the seabed, is given by:

\[
u = \frac{\pi H \cosh ks}{T \sinh kd} \cos \theta \quad (3.30)
\]

where \(s = a + d\), \(a\) is wave amplitude, \(k\) is the wave number, \(T\) is the wave period and \(\theta = (kx - \omega t)\).

Now the amplitude of this velocity, at \(a = 0\), is:

\[
u_o = \frac{\pi H \cosh kd}{\sinh kd} \quad (3.31)
\]
Substituting equation (3.31) into equations (3.28) and (3.29), the Reynolds number and the Keulegan-Carpenter number can be rewritten as:

$$ R_n = \frac{\eta H \cosh k d}{T \sinh k d} \frac{D}{v} $$  

or,

$$ R_n = \frac{\eta H D \cosh k d}{v \sinh k d} $$  

(3.32)

(3.33)

$$ K-C = \frac{\eta H \cosh k d}{T \sinh k d} \frac{T}{D} $$  

or,

$$ K-C = \frac{\eta H \cosh k d}{D \sinh k d} $$  

(3.34)

(3.35)

![Figure 3](image)

**Figure 3**

Wave Force Regimes (Miller and McGregor 1978)
Assuming deep water, the wave number is:

\[ k = \frac{2\pi}{\lambda} = \frac{\omega^2}{g} = 4\frac{n^2}{T^2g} \]  

(3.36)

and the wavelength is:

\[ \lambda = \frac{c}{2\pi f^2} \]  

(3.37)

\[ \text{Rn and K-C can be more accurately evaluated for the dynamic response of offshore platforms by utilizing relative velocity terms:} \]

\[ K-C = \frac{\text{u}_{ro} T_r}{D} \]  

(3.38)

\[ \text{Rn} = \frac{\text{u}_{ro} D}{v} \]  

(3.39)

where \( \text{u}_{ro} \) is amplitude of relative velocity, \( u_r = (u - \lambda) \), and \( T_r \) is relative period of encounter.

It is necessary to choose which scaling laws should be used for any particular case. In general when viscous forces are dominant due to structural detail Reynolds scaling is utilized, which is represented by equation 3.16. In this case the second flow regime described in section 3.1 exists. When gravity forces are dominant, as in the present case where the body appears to act as a fully solid structure, Froudian scaling best describes the system. This is represented by equation 3.18 and the first flow regime of section 3.1 is presumed to exist.
These scaling equations are important in the design of model tests and in the interpretation of the results of the tests. They are utilized in section 4.1.6 for analyzing the data generated in present work.

The following section presents theory used for predicting forces on slender bodies in waves.

3.3 Slender Structures

The oscillatory flow about a slender structure is depicted by the second regime of section 3.1 in which drag is significant. In this case there is little disturbance to the incident wave, but a vortex wake forms behind the body as the flow separates from its surface. Figure 4 (Chakrabarti 1981) illustrates the shedding of vortices around a vertical circular cylinder in waves for various K-C values. In practice this type of wave-structure interaction is dealt with by neglecting free surface effects, accounting for viscous effects semi-emperically and adopting Morison's equation. This equation has been developed to estimate hydrodynamic loads and motions in this case and is reported in many sources (Morison et al 1950, Sarpkaya and Isaacson 1981, and Lovaas 1983).

The Morison Equation is a formula which was developed by Morison, Johnson, O'Brien and Schaaf (1950) to predict the hydrodynamic force acting on a section of pile
and is comprised of two components: an inertial force and a drag force. It is assumed that the body is small relative to the wave length so that the incident flow is uniform near the body and diffraction effects are negligible. For the common case of a vertical circular section of diameter $D$ and sufficiently small length $dL$:

$$\frac{dF}{dL} = 0.5 \rho D C_d |u| + 0.25 \rho \pi D^2 C_m \frac{du}{dt} \quad (3.40)$$

where $F$ is hydrodynamic force and $u$ is velocity of fluid.

Figure 4
Vortex Shedding Patterns Around a Vertical Cylinder in Waves as Functions of $K$–$\zeta$ (Chakrabarti 1987)
The first term on the right hand side represents the force required to overcome the drag due to vortex separation and skin friction effects. $C_d$ is the drag coefficient.

The second or potential flow term involves momentum (scattering) effects. $C_m$ is the inertia coefficient. Data for $C_m$ and $C_d$ have been determined experimentally for a variety of bodies (Sarpkaya and Isaacson 1981). These show that $C_m$ and $C_d$ are functions of the Keulegan-Carpenter number, the Reynolds's number and the body surface roughness.

Note that the drag force is a nonlinear function of the flow velocity while the inertia term is linear. For the latter, the total horizontal acceleration is:

$$\frac{du}{dt} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \nu \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z}$$

Equation (3.40) has been modified to describe a floating rigid structure in waves. Two independent flow fields are superimposed: the field due to wave motion alone:

$$F = C_m A \ddot{u} + C_d A_d |u| \dot{u}$$

and the field due to structure motion alone:

$$F = -C_A \dddot{x} - C_d A_d |x| \dot{x}$$

where $\dot{x}$ and $\dddot{x}$ are velocity and acceleration of the structure, $C_A$ is the added mass coefficient and $C_d$ is the
drag coefficient. The resulting form is known as the independent flow fields model (Chakrabarti 1987):

\[ F = C_m A_I \ddot{u} - C_A A_I \dot{u} + C_d A_d |u|u - C_d A_d |\dot{u}| \dot{x} \]  
(3.44)

With the following relations:

\[ C_m = 1 + C_A \]  
(3.45)

\[ A_I = \frac{\rho \pi D^2}{d} \]  
(3.46)

\[ A_d = \frac{\rho \pi D}{3} \]  
(3.47)

\[ C_d = C_d' \]  
(3.48)

When forces are written in terms of relative motion, single coefficients are assumed to apply and the force can be written:

\[ F = C_m A_I (\ddot{u} - \ddot{x}) + A_I \dot{x} + C_d A_d |u - x| (u - x) \]  
(3.49)

\[ F = \frac{2}{3} \rho \pi D^2 C_m (\ddot{u} - \ddot{x}) + \rho \pi D^2 \ddot{x} + \rho D C_d |u - x| (u - x) \]  
(3.50)

The final section of this chapter describes the potential flow theory for predicting wave forces on large bodies.

3.4 Large Structures

When a structure is large compared to the wavelength the first flow regime is assumed in which the incident wave undergoes significant scattering in the region of the body and free surface effects cannot be neglected. The motions and forces on the structure are affected by this phenomenon and must be calculated
accordingly. Linear diffraction theory is well developed (Faltinsen and Michelsen 1974, Morison et al 1950, Garrison 1975) and widely used to predict motions and hydrodynamic loading on offshore structures.

This theory assumes ideal or potential fluid flow (i.e. acyclic, irrotational flow). See Milne-Thomson 1968. It describes the scattering of small-amplitude waves by large objects in the ocean and predicts the wave loads associated with both the local accelerating flow field and the wave scattering process.

The governing equations are:

(i) continuity (in fluid domain):
\[ \nabla^2 \Phi = \frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \] (3.51)

(ii) impermeability:
\[ \frac{\partial \Phi}{\partial n} = 0 \quad \text{on solid submerged boundaries} \quad (3.52) \]
\[ \frac{\partial \Phi}{\partial z} = 0 \quad \text{on bottom surface} \quad (3.53) \]

(iii) free surface conditions (z=0):
\[ \frac{\partial \Phi}{\partial z} = \frac{\partial n}{\partial t} \quad \text{kinematic condition} \quad (3.54) \]
\[ \frac{\partial \Phi}{\partial t} + gn = 0 \quad \text{dynamic condition} \quad (3.55) \]

which together give:
\[ \frac{\partial^2 \Phi}{\partial t^2} + \frac{\partial \Phi}{\partial z} = 0 \] (3.56)
(iv) radiation condition

Together with the appropriate initial conditions for the time domain problem are the radiation conditions for the steady frequency domain problem. In this latter case the radiation condition demands that the waves scattered by the structure represent a wave field propagating away from the structure. In the panel method utilized in this study the radiation condition is implicitly satisfied by the use of an appropriate Green's function.

In the fluid domain, pressure, $P$, is defined by the linearized Bernoulli equation:

$$P = -p g z - \rho \frac{\partial \Phi}{\partial t} \quad (3.57)$$

Now the force on the body may be expressed in terms of the pressure on the body surface:

$$F_j = \int_{S_b} P \, ds = \int_{S_b} (p g z + \rho \frac{\partial \Phi}{\partial t}) n_j \, ds \quad (3.58)$$

where $n_j$ is the generalized normal, positive into the fluid, $S_b$ is the mean wetted body surface area and $F_j$ is the generalized force:

$$n_j = (\vec{n})_j, \quad j=1,2,3$$

$$(\vec{x} \times \vec{n})_{j-3}, \quad j=4,5,6$$

$$F_j = \int_{S_b} \rho g z n_j \, ds + \int_{S_b} \rho \frac{\partial \Phi}{\partial t} n_j \, ds \quad (3.60)$$
The problem at hand is to solve for the velocity potential, \( \Phi \), which, because the problem is linear, can be represented by the superposition of the "incident" and "scattered" wave potentials:

\[
\Phi = \Phi_I + \Phi_S
\]  

(3.61)

Equation (3.50) becomes:

\[
F_j = \left( \rho \int g z n_j dS + \rho \int \frac{\partial}{\partial t} \Phi_I n_j dS \right) + \rho \int \frac{\partial}{\partial t} \Phi_S n_j dS \quad (3.62)
\]

\[
= \text{Froude-Krylov} + \text{scattering}
\]

The scattering force consists of radiation and diffraction components.

The potential may be represented by a continuous distribution of complex sources on the surface of the body. This method is discussed in more depth in section 4.2.

The next chapter presents a study of drift forces on a triangular shaped floating structure in regular waves. An experimental study is first given, and this is followed by a numerical simulation.
CHAPTER IV

THE STUDY OF DRIFT FORCES

4.1 Experimental Study

4.1.1 Purpose of Model Tests

In general wave loading on a structure is a complex non-linear process of which the first- and second-order components are of primary interest. The first-order wave force oscillates at the wave frequency and has zero mean. This is responsible for the vessel motions with wave frequencies. The mean and low-frequency components of the second-order force are known collectively as "wave drift forces". The mean second-order force, or "steady drift" component, is recognized as a second-order consequence of first-order waves interacting with the structure. The slowly oscillating second-order force component is due to wave group effects which are non-linear interactions in the wave field. Although the second-order forces are usually substantially smaller than first-order forces, they may excite large resonant response motions if damping is low. This response can cause severe loads in mooring systems
and, therefore, must be seriously considered in the design of mooring and dynamic positioning systems.

A structure floating in regular waves will be subject to first-order forces and second-order steady drift as shown in Figure 5. A structure floating in irregular or beating waves will be additionally acted upon by second-order slow drift oscillatory forces as shown in Figure 6.

The model tests described herein were initially intended to estimate mooring forces only, in a series of regular waves, to assist in the design analysis of the offshore structure. Models of at least 1:25 scale are recommended for accurate predictions of prototype motions and forces. The results of the 1:200 scale model tests conducted here were expected to be useful in the design of the 1:25 scale model. The tests were exploratory in nature and motions were not measured. Only tension in the mooring line was measured, and the incident wave was recorded.

4.1.2 The Model

A 1:200 scale model of a proposed delta-shaped offshore service and supply base was constructed of tetrahedron space-frames and buoyancy tubes, as shown in Figures 7a and 7b. Model dimensions are shown in Figure
Figure 5
Measured Forces in Regular Waves
Figure 6
Measured Forces in Beating Waves
Figure 7a: Model Space Frame and Buoyancy Tubes

Figure 7b: 1:200 Scale Model Used in Testing
8. The main particulars of the model are calculated in Appendix B and are summarized below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>150 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>0.30 m³</td>
</tr>
<tr>
<td>Mooring stiffness #2</td>
<td>4.6 kG/m = 45.1 N/m</td>
</tr>
<tr>
<td>Mooring stiffness #3</td>
<td>9.2 kG/m = 90.3 N/m</td>
</tr>
<tr>
<td>Natural surge frequency</td>
<td>$\omega_2 = 0.4477 \text{ rps}$ $f_{o_2} = 0.0713 \text{ Hz}$</td>
</tr>
<tr>
<td></td>
<td>$\omega_3 = 0.6335 \text{ rps}$ $f_{o_3} = 0.1008 \text{ Hz}$</td>
</tr>
<tr>
<td>Center of gravity</td>
<td>(0,0,0.0381m)</td>
</tr>
<tr>
<td>Center of buoyancy</td>
<td>(0,0,-0.0235m)</td>
</tr>
<tr>
<td>Radii of gyration</td>
<td>rxx = 0.91m</td>
</tr>
<tr>
<td></td>
<td>ryy = 0.88m</td>
</tr>
<tr>
<td></td>
<td>rzz = 1.26m</td>
</tr>
<tr>
<td>Virtual Mass</td>
<td>225 kg</td>
</tr>
</tbody>
</table>

Note that the virtual mass, $M_v = (1+C_A)M = C_mM$, is frequency dependent since the added mass coefficient is frequency dependent. $C_A = 0.5$ is used for the calculations in Appendix A.

4.1.3 Test Facility

Tests were carried out at the National Research Council's Institute for Marine Dynamics in St. John's. The towing tank is 200m long and 12m wide with a water depth of 7m. The towing carriage spans the full width of the tank and has a maximum speed of 10.0 m/s, with
Figure 8
Model Dimensions
possible acceleration ranging from 0.2 to 1.2 m/s². The wavemaker is a hydraulically driven dual flap type which provides for the modelling of regular and irregular seas. A conventional parabolic beach is located at the opposite end of the tank to prevent waves from reflecting back down the tank (see Figure 9).

4.1.4 Test Set-Up

The model was held in place at the carriage by a model mooring system consisting of linear springs, nylon line, and a counter weight, as shown in Figure 10. Mooring line tension was read with a hoop strain gauge. Tests were carried out in regular waves ranging in frequency from 0.4 to 1.4 Hertz. Two different mooring line stiffnesses were used, \( K_2 = 4.60 \) kG/m and \( K_3 = 9.20 \) kG/m. (Mooring system #1 was not used in these tests). Since the model was constructed of densely distributed elements the permeability of the structure to waves was of interest. In order to determine the extent of this the model's outer surface was covered by a plastic sheet for a test sequence in order to make the model appear solid to the wave field. The two model configurations are referred to as the covered and uncovercd models throughout this text.
Figure 9
IMD Towing Tank Facility
Figure 10
Test Set-Up
4.1.5 Data Acquisition

Wave data were measured by a wave probe on the carriage. Mooring line tension data were measured by the strain gauge. The data acquisition system at IMD uses a DEC microVAX II computer running on the VAX/VMS operating system. Analog data was digitized using a NEFF 620 A/D converter-multiplexer interfaced to the microVAX Q-bus. Fortran-77 acquisition software controlled the sampling of data, which was then stored on a hard disk.

4.1.6 Data Analysis

Model tests were carried out in regular head waves ranging in frequency from 0.4 to 1.4 Hz, corresponding to $\lambda/D$ equal to 3.02 and 0.25 respectively for $D=3.23$ m. The analysis was carried out for the covered and uncovered models. In some test cases the incident wave lacked consistency, so the time series were truncated to include only a uniform portion for analysis. The mean mooring line tension for each test was determined using NRC's time series analysis (TSA) software. Power spectral density plots for both wave amplitude and mooring force were generated for all tests and are given in Appendix C. As can be seen, not all of the waves were of a pure sinusoidal nature. In fact, most of them showed group effects to some degree. Wave amplitudes, $\eta$, were
determined by a statistical analysis of the peaks and troughs of each time series. The wave amplitude power spectrum can be represented by (Abkowitz et al 1965):

$$\eta_n = (S_{\zeta n} \delta \omega_n)^{1/2}$$

(4.1)

where $S_{\zeta}$ is the wave elevation spectral density, $n$ the number of representative frequencies in the power spectra and $\delta \omega$ is the frequency bandwidth.

For the case of regular waves, the mooring line tension time series indicates two components of force; a high frequency first-order component which oscillates at the wave frequency and a second-order steady drift component.

When wave group effects are apparent, the mooring line tension time series shows three force components; the two mentioned above along with a second-order slowly oscillating force. The frequency of this force is equivalent to the frequency difference of the wave components contributing to the group effects.

The steady horizontal drift force in the x-direction, $F_{d,x}$, is being analysed herein. It may be written for regular waves:

$$F_{d,x} = \frac{1}{2} \rho g \eta^2 DR^2$$

(4.2)

where $R$ is the reflection coefficient, the ratio of the reflected wave height to the incident wave height, in two dimensional flow. $R^2$ becomes a nondimensional drift force in three (or two) dimensional flow.
When two wave frequencies are present, according to Remery and Hermans (1971), this equation for steady drift force becomes:

$$F_{d,x} = \frac{1}{2} \rho g (\eta_1^2 + \eta_2^2) DR^2$$  \hspace{1cm} (4.3)

where $\eta_1$ and $\eta_2$ are the amplitudes of the waves corresponding to frequencies 1 and 2.

Now we can rewrite equation 4.2:

$$R^2 = \frac{F_{d,x}}{\frac{1}{2} \rho g \eta^2 D}$$  \hspace{1cm} (4.4)

A similar form of this equation was previously derived in section 3.2 on modelling laws (see equation 3.27). With proper modelling this term, which is the nondimensional drift force, should be equal for model and prototype structures if previously discussed modelling laws are obeyed.

In order to keep consistent with literature on this subject, we substitute the following relation into equation 4.4:

$$D = \Lambda^{1/3}$$  \hspace{1cm} (4.5)

where $\Lambda$ is the displaced volume of fluid. Thus, equation 4.4 becomes:

$$R^2 = \frac{F_{d,x}}{\frac{1}{2} \rho g \eta^2 \Lambda^{1/3}}$$  \hspace{1cm} (4.6)

Similarly, equation 4.3 can be rewritten:

$$R^2 = \frac{F_{d,x}}{\frac{1}{2} \rho g (\eta_1^2 + \eta_2^2) \Lambda^{1/3}}$$  \hspace{1cm} (4.7)
In either case this term is known as the nondimensional steady drift force, and is plotted against nondimensional frequency:

\[ \tilde{w} = w(\lambda^{1/2}/g)^{1/2} \]  

(4.8)

Table 1 shows test frequencies for model and prototype, with corresponding nondimensional frequency and wave lengths. The wave lengths at lower frequencies are not common in real sea states and are considerably longer than the body.

<table>
<thead>
<tr>
<th>( f_m ) (Hz)</th>
<th>( f_p ) (Hz)</th>
<th>( f_{\text{non-dim.}} )</th>
<th>( \lambda_m ) (m)</th>
<th>( \lambda_p ) (m)</th>
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</thead>
<tbody>
<tr>
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<td>0.578</td>
<td>9.76</td>
<td>1952</td>
</tr>
<tr>
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<td>0.731</td>
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<tr>
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<td>3.19</td>
<td>638</td>
</tr>
<tr>
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<td>1.17</td>
<td>2.44</td>
<td>488</td>
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<tr>
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<td>0.092</td>
<td>1.90</td>
<td>0.92</td>
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</tr>
<tr>
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<td>0.099</td>
<td>2.05</td>
<td>0.80</td>
<td>160</td>
</tr>
</tbody>
</table>

Results of the model tests are recorded in Tables 2 and 3 for the uncovered and covered model, respectively. The drift forces are noted negative due to the direction of the incoming wave with respect to the x-axis. Plots of the measured steady drift force against frequency are given in Figures 11 and 12. An interactive
graphics program was used to fit elastic splines through the data points.

In Tables 2 and 3 the wave number and wavelength estimates are based on deep water theory. The mean drift force recorded in the time series is reduced by the 10N counterweight used in experiments. This is based on an assumption that the spring elongation is due to surge motion only. Reynolds number and Keulegan-Carpenter number are calculated according to equations 3.33 and 3.35, respectively. Since the model is fabricated of small tubular members of two different sizes in a near-solid matrix, Reynolds numbers and Keulegan-Carpenter numbers are calculated for cases of three characteristic dimensions of the body (see figures 7 and 8):

(i) the linear space frame component diameter, 0.007m
(ii) the buoyancy tube diameter, 0.04m
(iii) the width of one side leg of the triangular structure, based on a near-solid hull assumption, 0.625m

Test results, judged from power spectra, were grouped in four categories: (i) regular waves, (ii) waves with some group characteristics (vague groups) (iii) fully developed (distinct) groups and (iv) discarded results due to many wave frequencies. In general, the
Table 2
Input Data and Test Results: Uncovered Model

<table>
<thead>
<tr>
<th>TEST NUMBER</th>
<th>FREQ (Hz)</th>
<th>WAVE NUMBER (rad/m)</th>
<th>WAVE LENGTH (m)</th>
<th>MEAN DRIFT FORCE (N)</th>
<th>WAVE AMPL.</th>
<th>REYNOLDS NUMBER</th>
<th>KEULEGAN-CARPENTER NO.</th>
</tr>
</thead>
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<td>9.76</td>
<td>1.11</td>
<td>0.0345</td>
<td>388.6</td>
<td>2220.7</td>
</tr>
<tr>
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<td>2</td>
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<td>428.8</td>
<td>2450.1</td>
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<td>2796.8</td>
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<tr>
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<td>0.6</td>
<td>4.34</td>
<td>2.23</td>
<td>0.0376</td>
<td>640.8</td>
<td>3651.6</td>
</tr>
<tr>
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<td>0.6</td>
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<td>2.28</td>
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</tr>
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</tr>
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</tr>
<tr>
<td>TEST NUMBER</td>
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<td>FREQ. (Hz)</td>
<td>WAVE NUMBER (rad/m)</td>
<td>WAVE LENGTH (m)</td>
<td>MEAN DRIFT FORCE (N)</td>
<td>WAVE AMPL. (m)</td>
<td>REYNOLDS NUMBER</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
<td>------------</td>
<td>---------------------</td>
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<td>----------------------</td>
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<td>------------------</td>
</tr>
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<td>input</td>
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<td>λ = θ</td>
<td>meas'd-10N wt.</td>
<td>Rn=2πfπnD cosh kd</td>
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</table>
lower frequency waves were most regular, while the group phenomena increased with increasing frequency. Table 4 indicates the status of each test and the significant frequencies and frequency differences. In the case of beating waves (i.e., two or more waves of small frequency differences contributing to the incident wave) the frequency difference can be of great importance. If this frequency of the slow drift oscillations coincides with the natural frequency of the mooring system, resonance may occur. In model tests this can be controlled by varying the stiffness of the mooring. From observing Table 4 one can see that many of the frequency differences are near the calculated natural frequency of the moored structure. Therefore these test results are questionable, and they are indicated as such on the plots. At higher frequencies some of the test results were discarded due to the number of wave frequencies present in the test.

Drift force plots, Figures 11 and 12, indicate that drift forces were near zero for low frequencies. For the covered model the drift forces were considerably higher than those of the uncovered model as frequency increased. No significant difference due to mooring systems is obvious.

The nondimensionalized plots of Figures 13 and 14, with higher frequency results discarded (see Table 4), should be a better interpretation of test results.
<table>
<thead>
<tr>
<th>RUN NUMBER</th>
<th>MAIN FREQ (Hz)</th>
<th>OTHER FREQ (Hz)</th>
<th>DELTA FREQ</th>
<th>STATUS</th>
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<tr>
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<tr>
<td>13</td>
<td>0.8</td>
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<tr>
<td>14</td>
<td>0.9</td>
<td>1.0</td>
<td>0.1</td>
<td>ii(i) distinct</td>
</tr>
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<td>ii(i) distinct</td>
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<td>0.1</td>
<td>ii(i) distinct</td>
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<td>?</td>
<td>discarded</td>
</tr>
<tr>
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<td>1.3</td>
<td>many</td>
<td>?</td>
<td>discarded</td>
</tr>
<tr>
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<td>many</td>
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<td>discarded</td>
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<td>0.2</td>
<td>ii(i) vague</td>
</tr>
<tr>
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<td>0.8</td>
<td></td>
<td></td>
<td>ii(i) vague</td>
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<td>66</td>
<td>1.0</td>
<td>0.8, 1.2</td>
<td>0.2</td>
<td>ii(i) distinct</td>
</tr>
<tr>
<td>67</td>
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<td>0.8, 1.2</td>
<td>0.2</td>
<td>ii(i) distinct</td>
</tr>
<tr>
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<td>1.2</td>
<td>many</td>
<td>?</td>
<td>discarded</td>
</tr>
<tr>
<td>69</td>
<td>1.2</td>
<td>many</td>
<td>?</td>
<td>discarded</td>
</tr>
<tr>
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<td>1.4</td>
<td>many</td>
<td>?</td>
<td>discarded</td>
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<td>71</td>
<td>1.4</td>
<td>many</td>
<td>?</td>
<td>discarded</td>
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</table>
Figure 11
Plot of Experimental Results: Uncovered Model; Drift Force vs. Frequency
Figure 12
Plot of Experimental Results: Covered Model; Drift Force vs. Frequency
Figure 13
Plot of Experimental Results: Uncovered Model;
Nondimensional Drift Force vs. Nondimensional Frequency

\[ \hat{\omega} = \frac{\omega}{\omega_0} \]
Figure 14
Plot of Experimental Results: Covered Model; Nondimensional Drift Force vs. Nondimensional Frequency
\( A_m = 0.15 m^3 \) was used in the nondimensionalization. Figure 15 displays the nondimensional forces for both models for comparison. The differences relative to the variations displayed in forces observed for individual cases appear to be not significant. More covered model data would be necessary to pick up significant differences, if any. It is apparent from the analysis that in the uncovered model case the structural members blocked the flow paths such that the model acted as a near solid structure in the wave field. From the present work it is concluded that both models react similarly in regular waves. Of course, the higher frequency results are questionable due to group effects.

Due to the geometry of the model, any wave reflection via the sides of the model off the wave tank walls would be directed behind the model. Therefore contamination of results due to wave reflection is not considered a problem.

In the following section a numerical scheme corresponding to the tests previously described is developed and implemented.
Comparison of Covered and Uncovered Model Test Results
4.2 Numerical Evaluation of Steady Drift Forces Using Linear Diffraction Theory

4.2.1 A Model for Steady Drift Forces

The two main components of the model, linears and buoyancy cells, are small compared to the wavelength and fall into the slender structure category. Typically Morison's equation would be used in such a case, but that theory does not allow for the interactions due to the proximity of the structural elements of the model. Thus, the most obvious alternative was to use the well developed linear diffraction theory, assuming a solid hull construction for calculation purposes. It is also possible to assume that due to the dense distribution of the structural elements the blockage effects significantly the permeability of the structure in waves, thus bringing it close to the diffraction model. A numerical scheme developed by Faltinsen and Michelsen (1974) and presented by Tse (1984) is used.

The numerical model presented is based on linear diffraction theory using the 3-D source distribution method. The software Tse presents calculates the first-order wave forces, response motions, second-order steady horizontal drift forces and vertical drift moment for a floating body in regular waves. The steady drift
forces, which are of main interest here, are evaluated by the far field (wave momentum) approach (Standing et al 1981, Murray 1984). This method utilizes potential flow theory and conservation of momentum and energy. Changes in momentum in the fluid surrounding the body are equated to the steady force acting on the vessel in regular waves.

The equations of motion of the body may be written in the following form:

\[
M_{jk} \ddot{U}_k = \int S_b(t) \left( \frac{\partial \Phi}{\partial t} + \frac{\partial}{\partial x} \nabla \Phi \right) n_j dS + (f_{ex})_j \quad (4.9)
\]

\[
j, k = 1, \ldots, 6
\]

where \( \dot{U} \) is the acceleration of the structure, \( S_b(t) \) is the instantaneous wetted surface of the body. The integral term on the right hand side represents the forces due to the integration of pressure distribution over the instantaneous wetted surface. \( (f_{ex})_j \) are external forces which are assumed to be known.

When one assumes that the external forces balance the sum of all second or higher-order hydrodynamic forces, equation 4.9 can be reduced to:

\[
\int S_b(t) \frac{\partial \Phi}{\partial t} n_j dS - C_{jk} n^*_k(t) = M_{jk} \ddot{U}_k \quad (4.10)
\]

\[
j, k = 1, \ldots, 6
\]

where,

\[
\dot{U}_k = \frac{d^2}{dt^2} (n^*_k(t)) \quad (4.11)
\]
\( \eta_k^*(t) \) are the time-dependent first-order linear \((k=1,2,3)\) and angular \((k=4,5,6)\) rigid body motions. \( C_{jk} \) are the restoring coefficients. Since the body is symmetric with respect to the x-z plane the restoring coefficients can be written (Tse 1984, Paltinsen and Michelsen 1974):

\[
C_{2,3} = \rho g A_{wp} \\
C_{2,5} = C_{5,2} = -\rho g \int x \, ds \\
C_{4,4} = \rho g A(z_b - z_c) + \rho g \int y^2 \, ds \\
C_{5,5} = \rho g A(z_b - z_c) + \rho g \int x^2 \, ds
\]

where \( A_{wp} \) is the water plane area, \( A \) is the displaced volume of fluid, \( z_b \) and \( z_c \) are the z-coordinates of the center of buoyancy and center of gravity of the body.

For steady harmonic excitations and motions it is more convenient to represent the potential, \( \Phi \), and motion, \( \eta^* \), by the real part of the complex function such that:

\[
\eta^*_j(t) = \text{Re}[\eta_j e^{-i\omega t}] \\
\Phi(\vec{x},t) = \text{Re}[\Phi(\vec{x}) e^{-i\omega t}]
\]

Now \( \Phi(\vec{x}) \) can be broken down into three parts for this linear case:

\[
\Phi = \varphi_0 + \Phi_+ (-i\omega \eta_j) \Phi_j \\
\text{where } j,k=1,\ldots,6
\]

Now, \( \varphi_0 = \varphi_I \), the incident wave potential, can be obtained from small amplitude wave theory:
\[
\phi_0 = g_w \frac{\zeta_a \cosh k(z+h)}{\cosh kh} e^{i(kx \cos \beta + ky \sin \beta)} \quad (4.18)
\]

where \( \zeta_a \) is the amplitude of the incident wave, \( \beta \) is the incident angle of the incident wave, and \( \phi_0 \) is known as the solution of the wave diffraction problem. \( \phi_j, j = 1 \ldots 6 \) are the solutions to the radiation problem.

Using the following definitions (Faltinsen and Michelsen 1974):

added mass coefficients:

\[
A_{jk} = -\rho \text{Re} \left[ \int_{S_b} \phi_j \mathbf{n}_k \, dS \right] \quad (4.19)
\]

damping coefficients:

\[
B_{jk} = -\rho \omega \text{Im} \left[ \int_{S_b} \phi_j \mathbf{n}_k \, dS \right] \quad (4.20)
\]

generalized exciting force:

\[
F_j = (-i\omega) \rho \int_{S_b} (\phi_0 + \phi_j^n) \mathbf{n}_j \, dS \quad (4.21)
\]

the equation of motion can be written:

\[
(-\omega^2(A_{jk} + M_{jk}) - i\omega B_{jk} + C_{jk}) \mathbf{\eta}_k = F_j \quad (4.22)
\]

\( j, k = 1 \ldots 6 \)

The velocity potential associated with the flow about a body, \( \phi_j, j = 1 \ldots 7 \), for the infinite fluid case, can be described by either a complex source or doublet distribution over the body surface through the application of Green's Theorem. For the region bounded by the body surface, the free surface and the sea bed, the velocity potential, based on a distribution of complex sources, can be written:
\[
\Phi_j(\vec{x}) = \int_{S_b} Q_j(\vec{z}) G(\vec{x}, \vec{z}) \, dS(\vec{z}) \quad (4.23)
\]

where \(Q_j(\vec{z})\) is the source density function and \(G(\vec{x}, \vec{z})\) is the Green's function which satisfies the free surface and radiation conditions. The Green's function and its derivative are evaluated by either the series form or the integral form (see Tse 1984), depending on Bessel function criteria. The integral form is used when the maximum value of the Bessel function of the first kind is greater than 1000, otherwise the series form is used. Tse states some cases where these criteria do not work well in the evaluation of the Green's function.

\(Q_j, j=1, \ldots, 7\) is solved by a surface discretization panel method (Tse 1984, Faltinsen and Michelsen 1974), and \(A_{jk}, B_{jk}, F_j\) are computed from equations 4.19, 4.20, and 4.21. \(\Phi_j\) is obtained from equation 4.23. The complex amplitudes of body motions, \(\tilde{v}_k\), are then calculated from equation 4.22.

The steady horizontal drift forces can be expressed as:

\[
(F_d)_{j} = \langle \int_{S_b(t)} P n_j \, dS \rangle \quad (4.24)
\]

where \(\langle \rangle\) denotes the time average over one period. \((F_d)_{j}\) is the drift force in the \(x\) and \(y\) directions. \(P\) is the hydrodynamic pressure. \(n_j\) denotes the unit normal positive into the fluid.

The direct evaluation of expression 4.24
involves the second-order effect due to the instantaneous wetted surface $S_b(t)$ and is known as the near field approach. It can be used to predict mean forces as well as low frequency components, but is cumbersome and extensive in terms of CPU time. The second-order mean forces can also be calculated by implementing conservation of momentum over some cylindrical control surface requiring little computational effort beyond that required for the first-order solution.

Conservation of momentum over a control volume of the fluid domain which is bounded by the body surface $S_b(t)$, the free surface $S_f$, the sea bed $S_h$, and a chosen fixed control surface at infinity $S_\infty$, can be written:

$$
\frac{dL_j}{dt} = -\rho \int \left( \frac{\partial}{\partial t} + g x_j \right) n_j + v_j \left( u_n - U_n \right) dS \quad (4.25)
$$

where:

$$
S = S_b(t) + S_\infty + S_f + S_h
$$

and $L_j (j=1, 2, 3)$ is the linear momentum in $x, y, z$ directions, $v_j$ is the fluid velocity vector, $u_n$ is the normal velocity component of fluid particles on $S$, $U_n$ is the normal velocity component of the surface $S$.

If contributions in the horizontal plane only are considered this equation reduces to:

$$
\frac{dL_j}{dt} = -\int \left( P_n + \rho v_j (u_n - U_n) \right) dS \quad (4.27)
$$

where $j=1, 2$.

Applying the corresponding boundary conditions on $S$:

- on $S_f$: $p=0$, $u_n = U_n$
on $S_n$: \( \vec{n} = (0,0,n_z), u_n = U_n = 0 \)
on $S_b(t)$: \( u_n = U_n \)
on $S_\infty$: \( U_n = 0 \)
the equation becomes:
\[
\int_{S_b(t)} P_{nj} dS - \int_{S_\infty} (P_{nj} + \rho u_j u_n) dS - \frac{dL_j}{dt} = 0 \quad (4.28)
\]
j=1,2
Taking the time average over one period and choosing the control volume to have a vertical cylindrical surface of large radius, \( r \), extending from the free surface down to the sea bed, the horizontal mean drift forces can be written using polar coordinates:
\[
(F_d)_x = -\iint_{S_\infty} (P \cos \theta + \rho u_r (u_r \cos \theta - u_\theta \sin \theta)) r d\theta dz \quad (4.29)
\]
\[
(F_d)_y = -\iint_{S_\infty} (P \sin \theta + \rho u_r (u_r \sin \theta + u_\theta \cos \theta)) r d\theta dz \quad (4.30)
\]
where \( u_r \) and \( u_\theta \) are the radial and tangential velocity components and \( x = r \cos \theta \), and \( y = r \sin \theta \).

Using expanded versions of equations 4.17 and 4.23 as given in Tse (1984) (see also Faltinsen and Michelsen 1974) the far field expression for the first-order potential is:
\[
\phi \sim q_u \frac{L_c}{w} \cosh \frac{k(z+h)}{\cosh k\theta} e^{i(k \cos \beta + k \sin \beta \cdot \omega t)} \\
+ T(\theta) e^{i\tau(\theta)} \cosh(k(z+h)) \sqrt{\frac{1}{r}} \cos k \cdot \omega t \quad (4.31)
\]
where \( T(\theta) \) and \( \tau(\theta) \) are real functions of \( \theta \) and \( T(\theta)e^{i\tau(\theta)} \) is in the form of a Kotchin function:
\[ T(\theta) \ e^{i\tau(\theta)} = \frac{2\pi (w^2-k^2)}{k^2h-w^2h^2} \sqrt{\frac{2}{\pi\kappa}} e^{-i\kappa \pi} \int_{S_B(t)} (Q(\xi) \cosh[k(\xi+h)] - i(k\xi \cos \theta + k\eta \sin \theta)) \, dS \]

where \( Q(\xi) \) is the total source density.

\[ Q(\xi) = Q + (-i\omega \eta_j) Q_j \quad j=1,\ldots,6 \]

Substituting relations:

\[ v_r = \text{Re} \left[ \frac{\partial \Phi}{\partial r} e^{-i\omega t} \right] \quad \text{(4.34)} \]
\[ v_\theta = \text{Re} \left[ \frac{1}{r} \frac{\partial \Phi}{\partial \theta} e^{-i\omega t} \right] \quad \text{(4.35)} \]

and retaining terms up to second-order in \( \Phi \), the mean horizontal forces can be written:

\[ (F_d)_x = \]
\[ = \frac{\rho}{2} \frac{w\ell_a}{\sinh(kh)} \sqrt{\frac{2\pi}{k}} \left( \frac{4}{2} \sinh(2kh) + \frac{kh}{2} \right) \cdot 2T(\beta) \cdot \cos(\tau(\beta) + \frac{\pi}{4}) \cdot \cos \beta \]
\[ - \frac{\rho k}{2} \left( \frac{4}{2} \sinh(2kh) + \frac{kh}{2} \right) \cdot \int_0^{2\pi} T^2(\theta) \cdot \cos \theta \, d\theta \]

\[ (F_d)_y = \]
\[ = \frac{\rho}{2} \frac{w\ell_a}{\sinh(kh)} \sqrt{\frac{2\pi}{k}} \left( \frac{4}{2} \sinh(2kh) + \frac{kh}{2} \right) \cdot 2T(\beta) \cdot \cos(\tau(\beta) + \frac{\pi}{4}) \cdot \sin \beta \]
\[ - \frac{\rho k}{2} \left( \frac{4}{2} \sinh(2kh) + \frac{kh}{2} \right) \cdot \int_0^{2\pi} T^2(\theta) \cdot \sin \theta \, d\theta \]

It is documented (John 1949, 1950) that there are particular 'irregular' wave frequencies at which the numerical scheme presented breaks down. These frequencies are dependent on body shape, and in the present case are
not easy to predict. They are generally associated with wave lengths in the order of, or less than, the characteristic dimension of the body, but not always. Murphy (1978) found that for a circular cylinder irregular frequencies existed at wavelengths considerably longer than the characteristic dimension of the body.

4.2.2 Numerical Application

Tse's programs were designed for a body symmetrical about both the x and y axes. His programs were modified to handle a body symmetrical about the x axis only. Before proceeding it was necessary to confirm that the program, with modification, was executing properly. The new version was tested thoroughly by executing it for Tse's rectangular box in 500m of water and wave heading zero degrees, with consistent results. The program was also successfully executed for Pinkster's (1981) barge model in head waves. Thus, it was concluded that the newly modified program is working correctly in comparison with other available results. The new versions of the programs are called DPORT2.FOR and OUTPORT2.FOR and are listed in Appendix D. A list of main subroutines in DPORT2.FOR with their functions and pertinent equations is found in Appendix H. Program DPORT2 computes first-order wave forces, response motions, steady horizontal drift forces and vertical drift moment. Program OUTPORT2
is a simple program which formats this information and creates output files. Programs DPORT2 and OUTPORT2 were executed with the triangular shaped platform input as a full scale solid hull structure. The body wetted surface was partitioned into 230 panels, as shown in Figure 16, utilizing program SHAPE.FOR in Appendix E. The panels are small relative to the wavelength. The inputs to the program, as determined by the geometry of the model, are: panel centroids, areas, and unit normal vectors (as given in Appendix F); center of gravity; water depth; a characteristic dimension of the structure; and radii of gyration (as estimated in Appendix B). In addition to the geometric inputs, various water depths and wave headings can be input. The program was run with 500m water depth, and wave periods ranging from 10.5 to 34.4 (\(\lambda/D\) equal to 0.266 to 2.86 for \(D = 646m\)) seconds, which correspond to the wave frequencies used in model tests. Inputs specific to this model are listed in Table 5.

Four computational schemes were investigated to determine which is best suited to the model tests previously described. The basic differences in the schemes was in the representation of the space in between the structural elements of the model.

**CASE 1:** Center of gravity, radii of gyration and displaced volume were estimated for the model
Figure 16: Model Panels Used in Numerical Analysis
### TABLE 5
Particulars of the Model

<table>
<thead>
<tr>
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<th>MODEL</th>
<th>PROTOTYPE</th>
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<tr>
<td>mass (kg)</td>
<td>150</td>
<td>1.2 x 10^9</td>
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<tr>
<td>volume (m³)</td>
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<td>2.4 x 10^6</td>
</tr>
<tr>
<td>submerged volume</td>
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<td>1.2 x 10^6</td>
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<tr>
<td>draft (m)</td>
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<td>11.9</td>
</tr>
<tr>
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<td>(0, 0, 7.62)</td>
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<tr>
<td>c of b (m)</td>
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<td>(0, 0, -4.7)</td>
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<td>0.0317</td>
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<tr>
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</table>

### CONSIDERING ENTRAPPED WATER PART OF MODEL

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<tr>
<td>volume (m³)</td>
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<td>2.8 x 10^6</td>
</tr>
<tr>
<td>draft (m)</td>
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<td>11.9</td>
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<tr>
<td>c of g (m)</td>
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<td>(0, 0, -1.26)</td>
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<tr>
<td>c of b (m)</td>
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<td>0.0207</td>
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<td>radii of rₓₓ</td>
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<tr>
<td>gyration rᵧᵧ</td>
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<td>1.18</td>
<td>236</td>
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</table>
in air. Other particulars of the model, center of buoyancy and water plane area, were calculated by the program which assumes a solid hull structure.

CASE 2: The center of gravity, radii of gyration and submerged volume were estimated for the model including entrapped water in the space between the structural components. Water plane area and center of buoyancy were calculated in the programs.

CASE 3: Water plane area, radii of gyration and center of buoyancy were estimated for the model in air. The submerged volume and center of gravity were calculated with entrapped water.

CASE 4: The radii of gyration, submerged volume, center of gravity, center of buoyancy, and water plane area were all estimated for air entrapped.

The program thus took on four versions DPORT1 through DPORT4. The results of each version were analysed for the full range of frequencies and version 2, DPORT2, was best suited to the experimental results. This version represents the structure and entrapped water acting together as a dynamic body. As is mentioned in section
4.1.6 The covered model tests did in fact have water entrapped in the structure and showed little difference in uncovered model tests. This also suggests that case 2 is the most suitable version of the program.

Initially the program was executed for the model free floating with six degrees of freedom in head seas. Results of this run are listed in Appendix G. Errors in Green's function calculations due to Bessel function restrictions were noted at several wave periods: 10.8, 11.7, 11.9, 12.7, 13.5, 16.0, 23.4. The program failed to execute at periods in the neighbourhood of 11, 12, 15, 18, and 20 secs, so no results are available in these areas. Note that drift forces are generally negative due to the orientation of the body in the waves.

The program was then executed for head seas with motions of the body restricted in seven combinations in an attempt to determine the influence of first-order motions on the body:

(i) Surge motion only;
(ii) Heave only;
(iii) Pitch only;
(iv) Surge and heave only;
(v) Surge and pitch only;
(vi) Heave and pitch only;
(vii) Zero motions (fixed structure).

The numerical scheme for surge only was extended to include the two mooring systems. These stiffnesses were impressed upon the numerical model by equating the stiffness in surge, \( C(1,1) \), to each mooring spring stiffness separately.

The program was finally run for the free floating model in quartering seas of 240°. In this case the waves are head long into the side of the model.

4.2.3 Computational Results

Results of the numerical evaluation of drift force in the x-direction have been nondimensionalized as previously discussed in section 4.1.6 and plotted against nondimensional frequency for comparison to experimental results. \( \Lambda_p = 1.2 \times 10^6 \text{ m}^3 \) was used for nondimensionalization. A discussion of these numerical results follows.

Figure 17 shows the nondimensional results of the free floating model in head seas. Figures 18a to 18f, shown in Appendix A, are plots of the calculated first-order surge, heave and pitch RAO's and phases. Added mass and damping coefficients are given in Figures 19a to 19h for surge, heave, pitch and yaw and are also shown in Appendix A.
From Figure 17 it is seen that at low frequencies, \( \omega < 0.7 \), the nondimensional mean drift force is near zero. As frequency increases, drift force increases in the direction opposite to wave propagation. In this frequency range, the first-order heave motion transfer function is not quite equal to 1 while phase is near zero. Therefore the body is not exactly following the wave motion completely. As frequency increases heave motion decreases, and surge motion increases.

In the nondimensional frequency range of 0.7 to 1.0, the drift force varies considerably. The order of magnitude of these variations is close to 50% of the maximum mean second-order force calculated. Similar trends in drift force can be seen in Pinkster's (1981) results for a semisubmersible in head waves, and for a barge in bow quartering seas, as shown in Figure 20. Similarities are also shown in Hearn and Tong (1987) in the plot of mean drift forces computed by the near field method for a semisubmersible displayed in Figure 21. In the lower frequency range both semisubmersibles show oscillations of a much smaller order of magnitude when compared to the maximum force. The barge in quartering seas shows results at lower frequencies in the order of magnitude of 50% of the maximum, as in the present case. Head waves on the
Mean longitudinal drift forces in head waves.

Mean longitudinal and transverse drift forces and yawing moment in bow quartering waves.

Figure 20
Pinkster's Results for Head Seas and Quartering Seas
Comparison of predicted and measured zero forward-speed added resistance (drift force).

Figure 21
Hearn's Results For a Semisubmersible
triangular model are comparable to quartering seas on a barge.

The plot of first-order surge force (Figure 22) displays a maximum force in the nondimensional frequency range 0.7-0.8. Inspection of corresponding Froude-Krylov (Figure 23) and scattering (Figure 24) forces indicate that the scattering force is the main contributor to this maximum surge force.

First-order motions, particularly surge, show considerable variations in this frequency range. Superimposing Figures 17 and 18a it is seen that an increase in surge motion corresponds to an increase in mean horizontal drift force. Alternately, a decrease in surge motion matches a decrease in drift force. (Note that a higher negative number indicates an increase in drift force in the direction of wave propagation). Pitch angle follows the same trend.

Also in this frequency range, surge added mass (Figure 19a) peaks at $\ddot{\omega}=0.7$ and goes negative at $\ddot{\omega}=0.8$ while surge damping (Figure 19b) peaks at 0.8. Added mass and damping in heave (Figures 19c and 19d) dip negative at $\ddot{\omega}=0.77$ while added mass peaks at $\ddot{\omega}=0.8$. Pitch damping (Figure 19f) also shows a distinct negative dip at 0.77.

Negative added mass is expected, on the basis of two dimensional calculations, in such a structure with outwardly sloping sides, but negative damping is not
Figure 22
Calculated First-Order Surge Force
Figure 23
Calculated Froude-Krylov Force - Surge
Figure 24
Calculated Scattering Force - Surge
physically justified when considering pure (uncoupled) motions. In order to investigate this, NRC's program for the solution of generalized two dimensional scattering problems was implemented to compute added mass and damping in heave for a solid cross-sectional area of one leg of the model. The model scale was used in the program and results are plotted in Figures 25a and 25b. Added mass shows a pronounced trough at $\hat{\omega} = 0.7$ where damping shows a distinct peak. It is noted that in general for two dimensional problems a zero crossing in added mass corresponds to a peak in damping. If this is extended to the three dimensional problem of Figures 19 it is seen by superimposing Figures 19c and 19d that the actual damping peak in heave is at $\hat{\omega} = 0.7$ as expected. It is then suspected that the negative damping in heave and pitch is due to accumulative errors causing an overshoot in calculations. After this frequency range, the added mass and damping tend to quickly level off again.

It is noted that at low frequencies the corresponding wavelengths based on deep water theory (ie. $(\lambda/d) \geq 2$) exceed the limits based on 500 m water depth used in computations. Therefore the program was executed for 1000 m water depth to represent deep water for all ranges of frequency. The results were not significantly different from those for 500 m.
2-DIMENSIONAL PROGRAM RESULTS

Figure 25a
2-D Numerical Results: Added Mass
In the nondimensional frequency range 0.8 to 1.1 the drift forces increase to a small peak close to 0.9 and level off for a narrow band of frequencies. Surge amplitude shows a minimum at 0.9, peaks sharply at 1.0, and decreases again. Heave amplitude exhibits a small dip between 0.8 and 1.0. The pitch angle increases sharply in this range. Damping increases in heave and pitch and decreases slightly in surge.

It is interesting to note that at \( \tilde{\omega} < 0.9 \) the corresponding wavelengths are longer than the structure, which in prototype is 646 m along the x-axis and approximately 745 m along each leg. The inside dimensions of the prototype are approximately 225 m along the x-axis and 260 m along the leg.

The maximum mean drift force occurs in the nondimensional frequency range 1.1-1.5, peaking at 1.3. This area looks conspicuous with few datapoints due to the unexplained failure of the numerical scheme. This failure might be due to irregular frequencies causing the numerical method to breakdown as discussed in section 4.2.1. The magnitude of this maximum is large compared to other computed forces. This "surge" in force corresponds closely to a distinct low point in first-order surge force and subsequent peak in heave and surge amplitudes as well as pitch angle at \( \tilde{\omega} \approx 1.5 \). Added mass and damping coefficients
have levelled off in this range.

At nondimensional frequency 1.4 the drift force decreases to a steady level for the higher frequencies. The heave and surge amplitudes and pitch angle tend to zero after nondimensional frequency of 1.6.

Inspection of drift force plots with model motions restricted, Figures 26a-26f (in Appendix A) shows the significance of the effect of surge motion on the mean horizontal force in the lower half of the frequency range. Heave and pitch motions appear to play a stronger role in the mid-frequency range where the force increases greatly and decreases again.

The computed drift force on the fixed body is depicted in Figure 27. As expected the forces are not as erratic, since the body is not dynamically interacting with the wave field. At the lowest frequencies the forces are somewhat higher than when the body was free to move. Near \( \hat{\omega} = 0.8 \) the force peaks and then drops off again. At the higher frequencies the plot is virtually the same as the others in this group.

When the stiffness of the mooring systems was introduced in the program for the body free to move in surge only, the results were uneffected (see Figures 28a and 28b in Appendix A). This indicates that the moorings were too soft to restrict to body's motions in surge.
Figure 27
Plot of Computed Steady Drift Forces:
Fixed Body
Finally the numerical procedure was repeated for a free floating and fixed structure in quartering seas. Figures 29a and 29b (in Appendix A) show that the results do not vary a lot from those of head seas. For the floating structure the forces are generally somewhat lower in the first half of the frequency range, but the same tendencies are obvious. Similarly, for the fixed structure, the results are not significantly different. In the lower frequency range the forces are lower, tending to zero at the lowest frequencies.

It is known that the Green's function fails for bodies with voids, such as a donut shaped structure. It was thought that the inner configuration of the structure may have caused problems in this computation. Therefore the program was executed for a similar shape with two legs but no semi-enclosed back. The results were not significantly different.

In Chapter V the theoretical results are compared to the experimental results.
CHAPTER V

COMPARISON OF EXPERIMENTAL AND NUMERICAL RESULTS

In order to determine the validity of the numerical scheme presented it is necessary to compare the theoretical results with physical reality. First, model test results are compared to the theoretical results (numerical model version 2 as described in section 4.2.2) of the free floating structure in head waves, Figures 30 and 31. In these figures it can be seen that the theoretical results closely match the model test results. Not enough experimental data were obtained to show any fluctuations in mean drift force with respect to nondimensional frequency in the lower frequency ranges as was displayed in the computed results. The experimental datapoints do correspond closely to the computed results and there is no evidence to conclude that these fluctuations do not occur. Judging from other documented cases mentioned previously and the speculated error in the damping coefficients, it is questionable if these fluctuations would be as large in reality.

Since computational and experimental results both show a pronounced maximum mean drift force of the same order of magnitude in the range of $\tilde{\omega}=1.3$, it is deduced
COMPARISON OF THEORY AND EXPERIMENT

Figure 30
Plot of Comparison of Steady Drift Forces:
Computed Free Floating Structure vs. Experimental Uncovered Model
COMPARISON OF THEORY AND EXPERIMENT

Figure 31
Plot of Comparison of Steady Drift Forces:
Computed Free Floating Structure vs. Experimental Covered Model
that this frequency range is of major concern in the design process. The maximum mooring force is expected to occur in this range. It is noted earlier that the experimental results at high frequencies were doubtful due to group effects and the risk of resonance. This does not seem to have caused any great error in the vessels mean drift force, even though the vessel may have oscillated about this mean.

The theoretical results for a fixed structure are compared to model test results in Figures 32 and 33. The comparison of uncovered model experiments to the linear diffraction theory for the fixed model (Figure 32) indicates that model motions were, in fact, playing a role in the intermediate frequency range where this theory flattens out. At the higher and lower frequencies the theory is similar in both cases, and the experimental results compare well.

Although motions of the experimentally tested model were not measured, spring forces do indicate surge motion of the structure.
Figure 32
Plot of Comparison of Steady Drift Forces:
Computed Fixed Structure vs. Experimental Uncovered Model
Figure 33
Plot of Comparison of Steady Drift Forces: Computed Fixed Structure vs. Experimental Covered Model
CHAPTER VI

CONCLUSIONS

This thesis considered, both experimentally and theoretically the mean wave-induced drift forces acting on a large moored porous-like floating structure. The following conclusions were drawn:

1. No significant difference was noted in the results for the two modelled mooring systems (which can be considered a means to measure drift forces on the otherwise free-floating structure). A softer mooring would have reduced the natural frequency of the system to better ensure that the effect of the mooring system on the first-order motions was negligible. This is necessary to avoid adverse effects due to distorted first-order motions. The fact that no significant difference is apparent indicates that no more-adverse effects were present using the stiffer mooring.

2. Covered model tests were conducted in which a plastic sheet was used to eliminate any porosity of the structure. It was found that the drift force on the covered model was basically the same as that of the uncovered model. Both were represented closely by the far field theory for a solid structure. Apparently in
model tests the structural members blocked the flow paths in the uncovered case such that the model acted as a solid structure in the wave field. Therefore it may be concluded that viscous effects did not play a major role in the wave forces on the model. Froudian scaling, in which viscous effects are ignored, proved to be accurate verifying that diffraction effects were dominant. An investigation of first-order forces also verified this.

3. For a prototype the data suggests that the peak force due to regular 5m waves would be in the order of $10^8$ N. For a 1m/s current without waves the drift force would be approximately $0.05 \times 10^8$ N. Therefore, according to this study the drift forces due to waves appear to be dominant for the structure. This is an indication of the practical significance of the present study.

4. Calculated added mass and damping coefficients are questionable, particularly in the nondimensional frequency range 0.7-0.9, probably due to accuracy of Bessel function calculations. This accuracy can be adjusted. The Green's function algorithm should be investigated for this case.

5. The far field theory using a panel method showed considerable variations in the mean drift force at low frequencies. A review of literature showed that this
had been seen earlier in data and theoretical formulations. Investigation of forces and calculated pure uncoupled motions indicated that these variations are due mainly to surge motions. The maximum drift force, which occurred at a higher frequency, was determined to be mainly a result of heave and pitch motions.

6. The mean horizontal drift forces on this particular model can be computed with reasonable accuracy using the numerical model for a free floating structure presented in which the structure includes entrapped water. The frequency range in which the maximum mooring force occurs was identified. Therefore the results presented can be utilized with confidence in the design process.

7. Model motions were not measured during testing since the tests were not designed for research purposes. Observations indicated that some wave attenuation was occurring, particularly at high frequencies. It would be useful, in future work, to determine experimentally and theoretically the extent to which waves are absorbed and reflected, etc. Also the possibility of standing waves occurring in the inner triangular area of water should be investigated.
Although wave group effects were present in second-order slow drift oscillations of the vessel forces, they did not appear to significantly affect the steady drift offset of the model. These group effects may have caused the vessel to oscillate about the mean position which results in an additional second-order low frequency drift force. When the group frequency is near the natural frequency of the system, resonance may occur. The complexity of this, both experimentally and theoretically, is well beyond the scope of the present work. In future work an attempt should be made to study this in relation to mooring design.
REFERENCES


42. PINKSTER, J.A. (1979), "Wave Drifting Forces", Proceedings of WEGEMT.


APPENDIX A

FIGURES
Figure 1
Coordinate System
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Regions of Validity of Force Prediction Methods for a Fixed Pile (Standing 1981)
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Nondimensional Drift Force vs. Nondimensional Frequency
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Nondimensional Drift Force vs. Nondimensional Frequency
Comparison of Covered and Uncovered Model Test Results

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Nondimensional Force

Nondimensional Frequency
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Plot of Computed Results:
First-Order Motions; Surge Phase
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Plot of Computed Results:
First-Order Motions; Heave Amplitude Operator
Figure 18d
Plot of Computed Results:
First-Order Motions; Heave Phase
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Mean longitudinal drift forces in head waves.

Mean longitudinal and transverse drift forces and yawing moment in bow quartering waves.

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Hearn's Results For a Semisubmersible
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Calculated Froude-Krylov Force

$$\hat{f} = u \left( \frac{L}{g} \right)^{\frac{1}{2}}$$
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THEORY / WATER ENTRAPPED / SURGE

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Plot of Comparison of Steady Drift Forces:
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Figure 33

Plot of Comparison of Steady Drift Forces:
Computed Fixed Structure vs. Experimental Covered Model
APPENDIX B

CALCULATIONS OF PARTICULARS OF THE MODEL
About x-x

$e + f = d + b$

SECTION A-A

About y-y
DETERMINATION OF RADII OF GYRATION

1:200 SCALE MODEL

**Table A1**

<table>
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<td>B</td>
<td>C</td>
</tr>
<tr>
<td>a</td>
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<td>116</td>
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<td>b</td>
<td>55</td>
<td>70</td>
<td>83</td>
</tr>
<tr>
<td>c</td>
<td>132</td>
<td>122</td>
<td>112</td>
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<tr>
<td>d</td>
<td>80</td>
<td>72</td>
<td>66</td>
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<td>e</td>
<td>20</td>
<td>20</td>
<td>20</td>
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<tr>
<td>f</td>
<td>108</td>
<td>116</td>
<td>126</td>
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<td>g</td>
<td>28</td>
<td>34</td>
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<td>h</td>
<td>45</td>
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<td>70</td>
</tr>
<tr>
<td>q</td>
<td>90</td>
<td>82</td>
<td>75</td>
</tr>
<tr>
<td>r</td>
<td>52</td>
<td>47</td>
<td>43</td>
</tr>
<tr>
<td>s</td>
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<td>41</td>
<td>43</td>
</tr>
<tr>
<td>t</td>
<td>26</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td>u</td>
<td>57</td>
<td>50</td>
<td>44</td>
</tr>
<tr>
<td>v</td>
<td>27</td>
<td>29</td>
<td>31</td>
</tr>
<tr>
<td>Δz</td>
<td>14</td>
<td>14</td>
<td>14</td>
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</table>
Calculation of Area for 1:200 scale model:

About \( x-x \)

<table>
<thead>
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<th>AREA ((\text{cm}^2))</th>
<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 = \frac{1}{2}ab )</td>
<td>2557.5</td>
<td>4060</td>
<td>5893</td>
</tr>
<tr>
<td>( R_2 = b \cdot c )</td>
<td>7260</td>
<td>8540</td>
<td>9296</td>
</tr>
<tr>
<td>( R_3 = \frac{1}{2}gh )</td>
<td>630</td>
<td>977.5</td>
<td>1400</td>
</tr>
<tr>
<td>( R_4 = f \cdot h )</td>
<td>4860</td>
<td>6670</td>
<td>8820</td>
</tr>
<tr>
<td>( A_T= \sum_{i=1}^{4} R_i )</td>
<td>15307.5</td>
<td>20247.5</td>
<td>25409</td>
</tr>
</tbody>
</table>

About \( y-y \)

<table>
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<th>( A )</th>
<th>( B )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_1 = \frac{1}{2}ab )</td>
<td>2557.5</td>
<td>4060</td>
<td>5893</td>
</tr>
<tr>
<td>( R_2 = b \cdot q )</td>
<td>4950</td>
<td>5740</td>
<td>6225</td>
</tr>
<tr>
<td>( R_3 = b \cdot (s+h) )</td>
<td>4895</td>
<td>6895</td>
<td>8964</td>
</tr>
<tr>
<td>( R_4 = \frac{1}{2}hv )</td>
<td>607.5</td>
<td>833.75</td>
<td>1085</td>
</tr>
<tr>
<td>( R_5 = hu )</td>
<td>2565</td>
<td>2875</td>
<td>3080</td>
</tr>
<tr>
<td>( A_T= \sum_{i=1}^{5} R_i )</td>
<td>15575</td>
<td>20403.75</td>
<td>25247</td>
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</table>
### TOTAL VOLUME AND MASS OF THE MODEL (without weights)

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<tr>
<th>Deck and Layer</th>
<th>Volume (l)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st deck (bottom)</td>
<td>7.1064</td>
<td>7.20</td>
</tr>
<tr>
<td>2nd deck</td>
<td>5.4804</td>
<td>5.56</td>
</tr>
<tr>
<td>3rd deck</td>
<td>4.6104</td>
<td>4.67</td>
</tr>
<tr>
<td>4th deck (top)</td>
<td>3.8016</td>
<td>3.86</td>
</tr>
<tr>
<td>1st web (bottom)</td>
<td>4.9320</td>
<td>5.01</td>
</tr>
<tr>
<td>2nd web</td>
<td>4.212</td>
<td>4.28</td>
</tr>
<tr>
<td>3rd web (top)</td>
<td>3.528</td>
<td>3.59</td>
</tr>
<tr>
<td>Bottom buoyancy layer</td>
<td>89.0728</td>
<td>18.86</td>
</tr>
<tr>
<td>Middle buoyancy layer</td>
<td>76.3481</td>
<td>16.17</td>
</tr>
<tr>
<td>Top buoyancy layer</td>
<td>76.3481</td>
<td>16.17</td>
</tr>
<tr>
<td><strong>Subtotals</strong></td>
<td><strong>275.44 l</strong></td>
<td><strong>85.37 kg</strong></td>
</tr>
<tr>
<td><strong>Total Volume</strong></td>
<td><strong>0.275 m³</strong></td>
<td></td>
</tr>
</tbody>
</table>

Adding on for additional materials (ie. plexiglass, plastic reinforcing, wood)
- Caps: 4.17 kg
- Harbour: 10.0 kg
- Other: 16.5 kg

**Total Volume = 0.30 m³**

**Total mass = 116.0 kg**

The model was weighed down such that the waterline was halfway up the second buoyancy layer. Steel bars were used for weights; total = 34 kgs (75 lbs)

### VOLUME OF SUBMERGED PORTION

<table>
<thead>
<tr>
<th>Component</th>
<th>Volume (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom layer of buoyancy cells</td>
<td>89.0728</td>
</tr>
<tr>
<td>50% of middle layer of buoyancy cells</td>
<td>38.175</td>
</tr>
<tr>
<td>72.9% of bottom deck</td>
<td>3.595</td>
</tr>
<tr>
<td>Bottom deck</td>
<td>7.1064</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>137.95 l</strong></td>
</tr>
<tr>
<td>Plastic reinforcing</td>
<td>2.0 l</td>
</tr>
<tr>
<td>Harbour entrance reinforcing</td>
<td>10.0 l</td>
</tr>
</tbody>
</table>

**Total submerged volume = 150 l**

### TOTAL MASS OF THE MODEL WITH WEIGHTS

Mass of the structure with weights = 150 kg
### CENTER OF GRAVITY OF THE MODEL WITH WEIGHTS

Grouping weights as shown:

![Diagram showing weight grouping](image)

#### TABLE A4

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>wt. (kg)</th>
<th>dist. from bottom (cm)</th>
<th>moment f x d (Nm)</th>
<th>dist. from c.g. (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUP 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 decks</td>
<td>7.2 + 5.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 web</td>
<td>5.01</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 layers of tubes</td>
<td>18.86 + 16.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>harbour etc.</td>
<td>15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>caps</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 layer tubes</td>
<td>16.17</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>caps</td>
<td>1.2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>GROUP 3</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 web</td>
<td>4.28</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 decks</td>
<td>4.67 + 3.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 web</td>
<td>3.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plexiglass</td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GROUP 6</td>
<td></td>
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<tr>
<td>steel bars</td>
<td>34.0</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

**TOTALS**

|             | 149.1   | 142.7   |

---

*Note: The moments are calculated by multiplying the weight (moment of inertia) by the distance from the center of gravity.*
CENTER OF GRAVITY OF THE MODEL

c.g. = \frac{\text{moment}}{\text{force}} = \frac{142.7 \text{ Nm}}{149.1 \text{kg} \times 9.81 \text{m/s}^2} = 9.76 \text{cm from the bottom}

Using the waterline as the reference line...

9.76 - 5.95 = 3.81 \text{ cm} = 0.0381 \text{ m}

the coordinates of the center of gravity for the model are;

\((0, 0, +0.0381)\)

For the prototype they are;

\((0, 0, +7.62)\)

RADII OF GYRATION

\[ I = \int y^2 \, dm = r^2 \, M \]

\[ M = m_1 + m_2 + m_3 + \ldots \]

\[ r = \sqrt{\frac{I}{M}} \]

\[ I_{xx} = m_1 x_1^2 + m_2 x_2^2 + m_3 x_3^2 + \ldots \]

\[ I_{yy} = m_1 y_1^2 + m_2 y_2^2 + m_3 y_3^2 + \ldots \]

\[ I_{zz} = m_1 z_1^2 + m_2 z_2^2 + m_3 z_3^2 + \ldots \]
About x-x:

<table>
<thead>
<tr>
<th>GROUP</th>
<th>R₁</th>
<th>R₂</th>
<th>R₃</th>
<th>R₄</th>
<th>z</th>
<th>Iₓₓ</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>m₁x</td>
<td>Y₁</td>
<td>m₂x</td>
<td>Y₂</td>
<td>m₃x</td>
<td>Y₃</td>
</tr>
<tr>
<td>2</td>
<td>1.75</td>
<td>.387</td>
<td>3.67</td>
<td>.702</td>
<td>0.42</td>
<td>1.53</td>
</tr>
<tr>
<td>3</td>
<td>0.36</td>
<td>.387</td>
<td>0.76</td>
<td>.702</td>
<td>0.09</td>
<td>1.53</td>
</tr>
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<td>4</td>
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<td>.473</td>
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<td>.735</td>
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<td>.656</td>
<td>0.22</td>
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<td>15</td>
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<td></td>
<td></td>
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<td></td>
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<tr>
<td>water</td>
<td>46.4</td>
<td>73.2</td>
<td></td>
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<td></td>
</tr>
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</table>

About y-y:

<table>
<thead>
<tr>
<th>GROUP</th>
<th>R₁</th>
<th>R₂</th>
<th>R₃</th>
<th>R₄</th>
<th>Rₛ</th>
</tr>
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<tr>
<td></td>
<td>m₁y</td>
<td>X₁</td>
<td>m₂y</td>
<td>X₂</td>
<td>m₃y</td>
</tr>
<tr>
<td>1</td>
<td>6.15</td>
<td>1.22</td>
<td>6.52</td>
<td>.375</td>
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</tr>
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<td>2</td>
<td>1.73</td>
<td>1.21</td>
<td>2.44</td>
<td>.410</td>
<td>2.94</td>
</tr>
<tr>
<td>3</td>
<td>0.36</td>
<td>1.21</td>
<td>0.51</td>
<td>.410</td>
<td>0.61</td>
</tr>
<tr>
<td>4</td>
<td>1.05</td>
<td>1.21</td>
<td>2.04</td>
<td>.450</td>
<td>2.01</td>
</tr>
<tr>
<td>5</td>
<td>0.86</td>
<td>1.21</td>
<td>1.67</td>
<td>.450</td>
<td>1.65</td>
</tr>
<tr>
<td>6</td>
<td>5.68</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>15</td>
<td>.70</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE A7

<table>
<thead>
<tr>
<th>GROUP</th>
<th>z</th>
<th>I_{yy}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.0145</td>
<td>15.99</td>
</tr>
<tr>
<td>2</td>
<td>.0705</td>
<td>4.51</td>
</tr>
<tr>
<td>3</td>
<td>.0755</td>
<td>0.93</td>
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<td>4</td>
<td>.1655</td>
<td>3.13</td>
</tr>
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<td>5</td>
<td>.2105</td>
<td>2.65</td>
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<tr>
<td>6</td>
<td>.0755</td>
<td>27.71</td>
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<tr>
<td>7</td>
<td>.1045</td>
<td>3.76</td>
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</table>

58.68

About z-z; using TABLE A5 and:

### TABLE A8

<table>
<thead>
<tr>
<th>GROUP</th>
<th>x₁</th>
<th>x₂</th>
<th>x₃</th>
<th>x₄</th>
<th>I_{zz}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.223</td>
<td>0.19</td>
<td>0.8967</td>
<td>0.78</td>
<td>32.96</td>
</tr>
<tr>
<td>2</td>
<td>1.207</td>
<td>0.21</td>
<td>0.7933</td>
<td>0.6975</td>
<td>9.16</td>
</tr>
<tr>
<td>3</td>
<td>1.207</td>
<td>0.21</td>
<td>0.7933</td>
<td>0.6975</td>
<td>2.16</td>
</tr>
<tr>
<td>4</td>
<td>1.21</td>
<td>0.24</td>
<td>0.74</td>
<td>0.665</td>
<td>5.84</td>
</tr>
<tr>
<td>5</td>
<td>1.21</td>
<td>0.24</td>
<td>0.74</td>
<td>0.665</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>1.80</td>
<td></td>
<td>0.9ⁿ</td>
<td></td>
<td>60.49</td>
</tr>
<tr>
<td>7</td>
<td>0.70</td>
<td></td>
<td></td>
<td></td>
<td>4.49</td>
</tr>
</tbody>
</table>

119.9
RADIi OF GYRATiON OF MODEL WITHOUT WATER ENTRAPPED

\[ I_{xx} = 2(62.45) = 124.9 \quad I_{yy} = 2(58.68) = 117.36 \]

\[ M = 150 \text{ kg} \]

\[ r_{xx}^2 = \frac{I_{xx}}{M} = \frac{124.9}{150} \]

\[ r_{xx} = 0.91 \text{ m} \]

\[ r_{yy}^2 = \frac{I_{yy}}{M} = \frac{117.36}{150} \]

\[ r_{yy} = 0.88 \text{ m} \]

\[ I_{zz} = 2(119.9) = 239.8 \]

\[ r_{zz}^2 = \frac{I_{zz}}{M} = \frac{239.8}{150} \]

\[ r_{zz} = 1.26 \]

<table>
<thead>
<tr>
<th></th>
<th>model</th>
<th>prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r_{xx}</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>r_{yy}</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>r_{zz}</td>
<td>1.26</td>
</tr>
</tbody>
</table>
Taking moments about the bottom of the submerged portion;

wt. of group 1 = 70.8 kg  \hspace{1cm} \text{moment} = 27.78 \text{ Nm}

subtracting half a layer of tubes above the waterline;

-5.12 \text{ Nm}

and subtracting 27.1% of the web above the waterline;

-1.15 \text{ Nm}

\text{moment} = 27.78 - 5.12 - 1.15 = 21.5 \text{ Nm}

Total mass of submerged part is \((70.8 - 8.7 - 0.976)\text{kg}\)
\hspace{1cm} = 61.1 \text{ kg}

\[d = \frac{M}{f} = \frac{21.5 \text{ Nm}}{61.1 \text{ kg} \cdot 9.81 \text{ m/s}^2} = 0.036 \text{ m} = 3.6 \text{ cm from bottom}\]

z-coordinate is;

\(-5.95 + 3.6 = -2.35 \text{ cm} \hspace{1cm} \text{(model)}\)

\[-\frac{2.35 \text{ cm}}{100 \text{ cm/m}(200)} = -4.7 \text{ m} \hspace{1cm} \text{(prototype)}\]
NATURAL FREQUENCY

spring stiffness' #2 4.6 kg/m = 45.1 N/m
#3 9.2 kg/m = 90.3 N/m

\[
\omega_2 = \sqrt{\frac{K}{M}} \quad M_v = (1+0.5)150 \text{ kg} = 225 \text{ kg}
\]

\[
\omega_2 = \sqrt{\frac{45.1}{225}} = 0.448 \text{ rads/sec (model)}
\]
\[= 0.0317 \text{ rads/sec (prototype)}
\]

\[f_2 = 0.0713 \text{ Hz (model)}
\]
\[= 0.005 \text{ Hz (prototype)}
\]

\[
\omega_3 = \sqrt{\frac{90.2}{225}} = 0.633 \text{ rads/sec (model)}
\]
\[= 0.0448 \text{ rads/sec (prototype)}
\]
\[f_3 = 0.101 \text{ Hz (model)}
\]
\[= 0.007 \text{ Hz (prototype)}
\]

WATER PLANE AREA

The waterline is halfway up the second layer of buoyancy tubes. So the ratio of cross sectional area to total area is;

\[
\frac{4.5}{8.5} = 0.529
\]

Thus, the buoyancy tubes take up approximately 52.9% of the water plane area. The linears also break the surface, so say approximately 55% of the total area is actually water plane area.
CALCULATIONS WITH WATER ENTRAPPED IN THE MODEL

VOLUME OF ENTRAPPED WATER

The volume estimated for the prototype of the submerged portion with water entrapped is 2,800,000 m³. In model scale this is 0.35 m³ which corresponds to 350 kg. The model weighs 150 kg so the entrapped water weighs 200 kg.

The volume of the submerged portion of the body is 150 l and the volume of entrapped water is 200 l. Therefore the ratio of body to water volume is:

\[
\frac{\text{Volume of body}}{\text{Volume of water}} = \frac{150}{200} = 0.75
\]

\[
\frac{\text{volume of body}}{\text{Volume of water}} = \frac{150}{350} = 0.43
\]
CENTER OF GRAVITY WITH WATER ENTRAPPED

Taking the centroid of mass of water at -4.0 cm on the z-axis, the moment about the bottom is:

\[ \text{Moment} = f \times d = (200 \text{kg})(9.81 \text{m/s}^2)(0.02 \text{m}) = 39.24 \text{ Nm} \]

The total moment is;

\[ 143.3 + 39.24 = 182.5 \text{ Nm} \]

The z centroid is located at 5.95 from the bottom so;

\[ 5.32 - 5.95 = -0.68 \text{ cm (model)} \]
\[ -0.0063 \times (200) = -1.26 \text{ m (prototype)} \]

CENTER OF BUOYANCY WITH WATER ENTRAPPED

\[ \text{Moment} = 21.5 + 39.24 = 60.74 \text{ Nm} \]

\[ d = \frac{M}{f} = \frac{60.74 \text{ Nm}}{(200 \text{kg} + 61.1 \text{kg})(9.81 \text{m/s}^2)} = 0.0237 \text{ m from bottom} \]

z-coordinate is:

\[ 2.37 \text{ cm} - 5.95 \text{ cm} = -3.58 \text{ cm} = -0.0358 \text{ m (model)} \]
\[ -0.0358 \times (200) = -7.16 \text{ m (prototype)} \]
NATURAL FREQUENCY WITH WATER ENTRAPPED

spring stiffness' #2 = 4.6 kg/m = 45.1 N/m
#3 = 9.2 kg/m = 90.3 N/m

\[ w_0 = \sqrt{\frac{K}{M_v}} \quad M_v = (1+0.5)(150\text{kg} + 200\text{kg}) \]
\[ = 525 \text{ kg} \]

\[ w_{o2} = \sqrt{\frac{45.1}{525}} = 0.293 \text{ rads/sec (model)} \]
\[ = 0.0207 \text{ rads/sec (prototype)} \]

\[ f_{o2} = 0.047 \text{ Hz (model)} \]
\[ = 0.003 \text{ Hz (prototype)} \]

\[ w_{o3} = \sqrt{\frac{90.2}{525}} = 0.414 \text{ rads/sec (model)} \]
\[ = 0.0293 \text{ rads/sec (prototype)} \]

\[ f_{o3} = 0.066 \text{ Hz (model)} \]
\[ = 0.005 \text{ Hz (prototype)} \]

RADIUS OF GYRATION WITH WATER ENTRAPPED

**TABLE A9**

<table>
<thead>
<tr>
<th>M from A5</th>
<th>x</th>
<th>y</th>
<th>z</th>
<th>I_{xx}</th>
<th>I_{yy}</th>
<th>I_{zz}</th>
</tr>
</thead>
<tbody>
<tr>
<td>46.4</td>
<td>1.223</td>
<td>0.473</td>
<td>0.03</td>
<td>10.42</td>
<td>69.44</td>
<td>79.78</td>
</tr>
<tr>
<td>73.2</td>
<td>0.19</td>
<td>0.735</td>
<td>0.03</td>
<td>39.61</td>
<td>2.71</td>
<td>42.19</td>
</tr>
<tr>
<td>11.0</td>
<td>0.8967</td>
<td>1.623</td>
<td>0.03</td>
<td>28.99</td>
<td>8.85</td>
<td>37.82</td>
</tr>
<tr>
<td>69.4</td>
<td>0.78</td>
<td>0.83</td>
<td>0.03</td>
<td>47.87</td>
<td>42.29</td>
<td>90.03</td>
</tr>
<tr>
<td></td>
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<tr>
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<td>124.9</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTALS</td>
<td>251.79</td>
<td>240.65</td>
</tr>
</tbody>
</table>
\[ r_{xx} = \frac{I_{xx}}{M} = \frac{251.79}{350} = 0.72 \text{ m}^2 \]

\[ r_{yy} = \frac{I_{yy}}{M} = \frac{240.65}{350} = 0.69 \text{ m}^2 \]

\[ r_{zz} = \frac{I_{zz}}{M} = \frac{489.62}{350} = 1.40 \text{ m}^2 \]

\[ r_{xx} = 0.85 \text{ m} \]

\[ r_{yy} = 0.83 \text{ m} \]

\[ r_{zz} = 1.18 \text{ m} \]

<table>
<thead>
<tr>
<th></th>
<th>model</th>
<th>prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{xx} )</td>
<td>0.85 m</td>
<td>170 m</td>
</tr>
<tr>
<td>( r_{yy} )</td>
<td>0.83 m</td>
<td>166 m</td>
</tr>
<tr>
<td>( r_{zz} )</td>
<td>1.18 m</td>
<td>236 m</td>
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</tbody>
</table>
APPENDIX C

POWER SPECTRA OF WAVE AMPLITUDE AND MOORING FORCE
MOORING LINE TENSION
SPRING 3, F=0.40 HZ, POT. DISPL. RECALIBRATED.

T1 = 100.38 SEC
T2 = 200.10 SEC
DT = 0.050 SEC
W1 = 0.0000 RPS
W2 = 10.0010 RPS
ADW = 0.0014 RPS
RMS = 2.2072
EPSILON = 0.2245
DWE = 0.001 RPS
EDF = 3.0
MOORING LINE TENSION
SPRING 2, F=8.48 HZ.

MOORING LINE TENSION (NEUTIONS)

T1 = 34.65 SEC
T2 = 188.30 SEC
DT = 0.0060 SEC
W1 = 0.0049 RPS
W2 = 10.9915 RPS
ADW = 0.0014 RPS
RMS = 0.4764
EPSILON = 0.1668
DUE = 9.122 RPS
EDF = 3.8
<table>
<thead>
<tr>
<th>RUN</th>
<th>CH.</th>
<th>WAVE HEIGHT Φθ (CM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

MOORING LINE TENSION
SPRING 2, F=0.00 Hz.

T1 = 0.10 SEC
T2 = 100.15 SEC
DT = 0.050 SEC
W1 = 0.000 RPS
W2 = 10.0016 RPS
ADV = 0.0014 RPS
RMS = 2.4128
EPSILON = 0.1028
DUE = 0.000 RPS
EDF = 3.0
MOORING LINE TENSION
SPRING S, F=1.0 Hz.

WAVELENGTH #3 (CM)

T1 = 0.25 SEC
T2 = 78.10 SEC
DT = 0.050 SEC
W1 = 0.0008 RPS
W2 = 10.0010 RPS
ACW = 0.0014 RPS
RMS = 0.1638
EPSILON = 0.0862
DWE = 0.115 RPS
EDF = 3.0
MOORING LINE TENSION
SPRING 2, F=1.1 Hz.

MOORING LINE TENSION (NEWTONS)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>T1</td>
<td>62.40 s</td>
</tr>
<tr>
<td>T2</td>
<td>149.40 s</td>
</tr>
<tr>
<td>DT</td>
<td>0.050 s</td>
</tr>
<tr>
<td>W1</td>
<td>0.0000 RPS</td>
</tr>
<tr>
<td>W2</td>
<td>19.9916 RPS</td>
</tr>
<tr>
<td>ADV</td>
<td>9.0614 RPS</td>
</tr>
<tr>
<td>RMS</td>
<td>0.0319</td>
</tr>
<tr>
<td>EPSILON</td>
<td>0.8144</td>
</tr>
<tr>
<td>DWI</td>
<td>0.063 RPS</td>
</tr>
<tr>
<td>EDF</td>
<td>3.0</td>
</tr>
</tbody>
</table>
MOORING LINE TENSION
COVERED MODEL, F=0.4 HZ, SPRING 2.

WAVEHEIGHT #9 (CH)

T1 = 0.20 SEC
T2 = 100.00 SEC
DT = 0.050 SEC
W1 = 0.0000 RPS
W2 = 10.0010 RPS
ADV = 0.0614 RPS
RMS = 2.6000
EPSILON = 0.3161
DME = 0.001 RPS
EDF = 3.0

RUN #9 CH. 3
MOORING LINE TENSION
COVERED MODEL, F=0.4 Hz, SPRING 9.

T1 = 0.15 SEC
T2 = 100.00 SEC
DT = 0.050 SEC
W1 = 0.0000 RPS
K2 = 10.0000 RPS
ADN = 0.0014 RPS
RMS = 2.7111
EPSILON = 0.3866
DUE = 0.000 RPS
EDF = 3.0
MOORING LINE TENSION

COVERED MODEL, F=1.0 Hz, SPRING 9.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>25.15 SEC</td>
</tr>
<tr>
<td>T2</td>
<td>100.10 SEC</td>
</tr>
<tr>
<td>DT</td>
<td>0.050 SEC</td>
</tr>
<tr>
<td>W1</td>
<td>0.000 RPS</td>
</tr>
<tr>
<td>W2</td>
<td>10.00 RPS</td>
</tr>
<tr>
<td>ADW</td>
<td>0.0014 RPS</td>
</tr>
<tr>
<td>RMS</td>
<td>2.5010</td>
</tr>
<tr>
<td>EPSILON</td>
<td>0.1562</td>
</tr>
<tr>
<td>DVE</td>
<td>0.187 RPS</td>
</tr>
<tr>
<td>EDF</td>
<td>3.6</td>
</tr>
</tbody>
</table>
Moorline Tension
Covered Model, F=1.2 Hz, Spring 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>50.10 sec</td>
</tr>
<tr>
<td>T2</td>
<td>100.20 sec</td>
</tr>
<tr>
<td>DT</td>
<td>0.050 sec</td>
</tr>
<tr>
<td>U1</td>
<td>0.0000 RPS</td>
</tr>
<tr>
<td>W2</td>
<td>10.8316 RPS</td>
</tr>
<tr>
<td>ADW</td>
<td>0.8614 RPS</td>
</tr>
<tr>
<td>RMS</td>
<td>0.4620</td>
</tr>
<tr>
<td>EPSILON</td>
<td>0.0874</td>
</tr>
<tr>
<td>DWE</td>
<td>0.160 RPS</td>
</tr>
<tr>
<td>EDF</td>
<td>3.6</td>
</tr>
</tbody>
</table>
MOORING LINE TENSION
COVERED MODEL, F=1.4 HZ, SPRING 2.

WAVELENGTH 93 (CM)

T1 = 40.18 SEC
T2 = 99.85 SEC
DT = 0.050 SEC
W1 = 0.8060 RPS
W2 = 10.8018 RPS
ADW = 0.8014 RPS
RMS = 1.5884
EPSILON = 0.2781
DWE = 0.181 RPS
EDF = 0.6
APPENDIX D

PROGRAM LISTINGS: DPORT2.FOR AND OUTPORT2.FOR
DATA NSP/115/.
DIMENSION PAN(115,3),UN(115,3),UNN(115,3),SUR(115),
1 DG11R(115,115),DG11I(115,115),DG12R(115,115),DG12I(115,115),
2 G11R(115,115),G11I(115,115),G12R(115,115),G12I(115,115),
3 PHI7R(115),PHI7I(115),PHI8R(115),PHI8I(115),QDF1(230),
4 QDF2(230),PT(100),
5 FO135(230,4),POT246(230,4),Q135(230,4),Q246(230,4),
6 AM(6,6),DEMP(6,6),RM(6,6),C(6,6),FOR(12),AMP(12)
DIMENSION DA(230,230),DN(230,4),TUUN(115,6),P01R(115),P01I(115),
1 P02R(115),P02I(115),TPR(115,6),TPI(115,6),
2 VA(3),VB(3),VC(3),VD(3),VE(3),VF(3)

COMMON /C2/ GRAV,DEN,FREQ,DEPTH,WNUM,ANU,HEAD
COMMON /C3/ VOL,XB,YB,ZB,AREA,AREAWP,XG,YG,ZG
COMMON /CC/ RI44,RI55,RI66
COMMON /SER/ UK(1000),GAMMA(1000),ALPHA
DATA GRAV,DEN/9.8,1000.0/
DATA XG,YG,ZG/0.0,0.0,-1.26/
DATA RI44,RI55,RI66/170.0,166.0,236.0/
DATA DEPTH,HEAD/500.0,240.0/

CALL ASSIGN1,'PRNT 1,2.DAT'
CALL ASSIGN2,'COM 2,2.DAT'
OPEN(UNIT=4,FILE='DEBUG1.OUT',STATUS='NEW')
HEAD=HEAD/180.0*3.14159
CALL CHART(NSP,PAN,UN,UNN,SUR,C,RM)
PT(1)=10.5
PT(2)=10.8
PT(3)=11.7
PT(4)=11.9
PT(5)=12.7
PT(6)=12.9
PT(7)=13.5
PT(8)=13.6
PT(9)=14.1
PT(10)=14.25
PT(11)=16.0
PT(12)=16.5
PT(13)=17.25
PT(14)=17.5
PT(15)=19.0
PT(16)=21.25
PT(17)=22.0
PT(18)=22.5
PT(19)=23.0
PT(20)=23.4
PT(21)=23.6
PT(22)=24.0
PT(23)=24.6
PT(24)=25.0
PT(25)=25.6
PT(26)=26.2
PT(27)=26.4
PT(28)=26.6
PT(29)=27.0
PT(30)=27.4
PT(31)=27.6
PT(32)=28.0
PT(33)=28.5
SUBROUTINE CHART(NSP, PAN, UN, UNN, SUR, C, RM)
C...COMPUTE THE CHARACTERISTICS OF THE FLOATING BODY
C...OUTPUT: PAN, UN, UNN, SUR, C; ALSO VOL, XB, AREA, AREAMP IN /C3/

DIMENSION PAN(NSP, 3), UN(NSP, 3), UNN(NSP, 3), SUR(NSP),
C(6,6), RM(6,6)
DIMENSION VA(3), VB(3), VC(3), VE(3), VF(3)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /C3/ VOL, XB, YB, ZB, AREA, AREAMP, XG, YG, ZG
COMMON /CC/ R144, R155, R166
CALL ASSIGN(5, 'DELTA1_2.DAT')
N=NSP
DO 10 J=1,N
READ(5,*)X, Y, Z, UN1, UN2, UN3, S
TYPE*, X, Y, Z, UN1, UN2, UN3, S, J
PAN(J, 1)=X
PAN(J, 2)=Y
PAN(J, 3)=Z
UN(J, 1)=UN1
UN(J, 2)=UN2
UN(J, 3)=UN3
SUR(J)=S
10 CONTINUE
XB=0.0
YB=0.0
ZB=0.0
AREA=0.0
STOP
END
AREAWP=0.0
VOL=0.0
TEMP2=0.0
TEMP3=0.0
TEMP4=0.0
DO 40 I=1,NSP
  VA(1)=PAN(I,1)
  VA(2)=PAN(I,2)
  VA(3)=PAN(I,3)
  UNN(I,1)=VA(2)*UN(I,3)-VA(3)*UN(I,2)
  UNN(I,2)=VA(3)*UN(I,1)-VA(1)*UN(I,3)
  UNN(I,3)=VA(1)*UN(I,2)-VA(2)*UN(I,1)
  VB(1)=UN(I,1)
  VB(2)=UN(I,2)
  VB(3)=UN(I,3)
  CALL VDOT(VA,VB,TEMP1)
  VOL=VOL+TEMP1*SUR(I)
  XB=XB+VA(1)*VA(1)*VB(1)*SUR(I)
  ZB=ZB+VA(3)*VA(3)*VB(3)*SUR(I)
  AREA=AREA+SUR(I)
  TEMP=VB(3)*SUR(I)
AREAWP=(AREAWP+TEMP)
TEMP2=TEMP2+VA(1)*TEMP
TEMP3=TEMP3+VA(1)*VA(1)*TEMP
TEMP4=TEMP4+VA(2)*VA(2)*TEMP
40 CONTINUE

DO 45 I=1,6
45 CONTINUE

VOL=2.0*(VOL/3.0)
C VOL=1200000.0
C TYPE*, 'VOLUME', VOL
  XB=XB/VOL
  ZB=ZB/VOL
C XB=0.0
C ZB=4.7
C AREA=2.0*AREA
C TYPE*, 'AREA', AREA
C AREAWP=2.0*AREAWP*0.55
C AREAWP=2.0*AREAWP
C TYPE*, 'AREAWP', AREAWP
C TEMP=DEN*GRAV
C C (1,1)=1804000
C C (3,3)=TEMP*AREAWP
C C (3,5)=0.55*(TEMP*2.0*TEMP2)
C C (5,3)=C(3,5)
C C (4,4)=TEMP*(VOL*(ZG-ZG)-2.0*TEMP4*0.55)
C C (5,5)=TEMP*(VOL*(ZG-ZG)-2.0*TEMP3*0.55)
C C (3,3)=TEMP*AREAWP
C C (3,5)=TEMP*2.0*TEMP2
C C (5,3)=C(3,5)
C C (4,4)=TEMP*(VOL*(ZG-ZG)-2.0*TEMP4)
C C (5,5)=TEMP*(VOL*(ZG-ZG)-2.0*TEMP3)
C RM(1,1)=DEN*VOL
C RM(2,2)=DEN*VOL
C RM(3,3)=DEN*VOL
C RM(4,4)=DEN*VOL*RI44*RI44
C RM(5,5)=DEN*VOL*RI55*RI55
C RM(6,6)=DEN*VOL*RI66*RI66
SUBROUTINE PRNT1(NSP,PAN,UN,UNN,SUR,C,RM)

DIMENSION PAN(NSP,3),UN(NSP,3),UNN(NSP,3),SUR(NSP),
       C(6,6),RM(6,6)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /C3/ VOL, XB, YB, ZB, AREA, AREA_W, XG, YG, ZG

WRITE(1,*)'DATA FOR TRIANGULAR MODEL'
WRITE(1,*)'VOLUME ',VOL
WRITE(1,*)'AREA ',AREA
WRITE(1,*)'CENTROID XB,YB,ZB: ',XB,YB,ZB
WRITE(1,*)'CENTER OF GRAVITY XG,YG,ZG: ',XG,YG,ZG
WRITE(1,*)'AREA_W=',AREA_W
WRITE(1,*)'C(3,3)=',C(3,3)
WRITE (1,*)'PAN(I,K)'
DO 40 I=1,NSP
     WRITE (1,100)I,(PAN(I,K),K=1,3)
40 CONTINUE
WRITE (1,*)'UN(I,K)'
DO 50 I=1,NSP
     WRITE (1,500)I,(UN(I,K),K=1,3)
50 CONTINUE
WRITE (1,*)'UNN(I,K)'
DO 51 I=1,NSP
     WRITE (1,500)I,(UNN(I,K),K=1,3)
51 CONTINUE
WRITE (1,*)'SUR(I)'
DO 60 I=1,NSP
     WRITE (1,600)I,SUR(I)
60 CONTINUE
100 FORMAT(1X,'(',I3,')',3F13.6)
500 FORMAT(1X,'(',I3,')',3F13.6)
600 FORMAT(1X,'(',I3,')',F13.6)
700 FORMAT(1X,6E14.5)
WRITE(1,*)'RESTORING COEFFICIENT'
DO 21 I=1,6
     WRITE(1,700) (C(I,J),J=1,6)
21 CONTINUE
WRITE(1,*)'
WRITE(1,*)'REAL MASS MATRIX'
DO 22 I=1,6
     WRITE(1,700) (RM(I,J),J=1,6)
22 CONTINUE
CALL CLOSE (1)
RETURN
END

SUBROUTINE LINK1(N,PAN,UN,SUR,DG11R,DG11I,DG12R,DG12I,
       DG11R,DG11I,DG12R,DG12I)
C...THIS PROGRAM COMPUTES THE ELEMENTS OF GREEN'S FUNCTION MATRIX
C...INPUT:N,PAN,UN,SUR
DIMENSION PAN(N,3), UN(N,3), SUR(N)  
DIM... DG11R(N,N), DG11I(N,N), DG12R(N,N), DG12I(N,N)  
DIMENSION G(2), DGX(2), DGY(2), DGZ1(2), DGZ2(2), VA(3), VB(3), VC(3)  
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD  
COMMON /SER/ UK(1000), GAMMA(1000), ALPHA  

ANU=WNUM*TANH(WNUM*DEPTH)  
FREQ=SQRTr(GRAV*ANU)  
CALL ROOTUK(1000)  
ALPHA=6.283185/(4.0*DEPTH*EXP(-2.0*WNUM*DEPTH)+ANU*  
1 ((1.0+EXP(-2.0*WNUM*DEPTH))/WNUM)**2.0)  
DO 10 I=1,N  
  VA(I)=PAN(I,1)  
  VA(I)=PAN(I,2)  
  VA(I)=PAN(I,3)  
  DO 20 J=1,N  
  VB(J)=PAN(J,1)  
  VB(J)=PAN(J,2)  
  VB(J)=PAN(J,3)  
  CALL VSUB(VA, VB, VC)  
  IF(I.EQ. J) GO TO 11  
  RL=SQRTr(VC(1)+VC(2)+VC(2))  
  IF(R1 .EQ. 0.0) GO TO 11  
  TEMP=2.0+10.0*DEPTH/(3.1416*R1)  
  IF(TEMP .GT. 1000.) GO TO 11  
  NTERM=TEMP  

CALL GS2(VA, VB, G, DGX, DGY, DGZ1, DGZ2, NTERM)  
GO TO 12  

11 UMAX=-10.0/(VA(3)+VB(3))  
CALL GI2(VA, VB, G, DGX, DGY, DGZ1, DGZ2, UMAX)  
CONTINUE  

12 G11R(I, J)=G(1)  
  G11R(I, J)=G(2)  
  DG11R(I, J)=DGX(I)*UN(I,1)+DGY(I)*UN(I,2)+(DGZ1(I)+DGZ2(I))  
  *UN(I,  
  DG11I(I, J)=DGY(I)*UN(I,1)+DGY(I)*UN(I,2)+(DGZ2(I)+DGZ2(I))  
  *UN(I,  
  IF (I .EQ. J) GO TO 20  
  G11R(J, I)=G(1)  
  G11R(J, I)=G(2)  
  DG11R(J, I)=DGX(I)*UN(J,1)-DGY(I)*UN(J,2)+(DGZ1(I)-DGZ2(I))  
  *UN(J,  
  DG11I(J, I)=DGY(I)*UN(J,1)-DGY(I)*UN(J,2)+(DGZ1(I)-DGZ2(I))  
  *UN(J,  

20 CONTINUE  
  DO 30 J=1,N  
  VB(J)=PAN(J,1)  
  VB(J)=PAN(J,2)  
  VB(J)=PAN(J,3)  
  CALL VSUB(VA, VB, VC)  
  RL=SQRTr(VC(1)+VC(2)+VC(2))  
  TEMP=2.0+10.0*DEPTH/(3.1416*R1)  
  IF(TEMP .GT. 1000.) GO TO 31  
  NTERM=TEMP  
  NSER=NSER+1
CALL GS2(VA, VB, G, DGX, DGY, DGZ1, DGZ2, NTERM)
GO TO 32
31 UMAX=-10.0/(VA(3)+VB(3))
NINTEG=NINTEG+1
CALL GI2(VA, VB, G, DGX, DGY, DGZ1, DGZ2, UMAX)
32 CONTINUE
G12R(I,J)=G(I)
G12I(I,J)=G(2)
DG12R(I,J)=DGX(I)*UN(I,1)+DGY(I)*UN(I,2)+(DGZ1(I)+DGZ2(I))
1 *UN(I,3)
DG12I(I,J)=DGY(I)*UN(I,1)+DGY(I)*UN(I,2)+(DGZ1(I)+DGZ2(I))
1 *UN(I,3)
IF(I.EQ. J)GO TO 30
G12R(J,I)=G(I)
G12I(J,I)=G(2)
DG12R(J,I)=-DGX(I)*UN(J,1)+DGY(I)*UN(J,2)+(DGZ1(I)-DGZ2(I))
1 *UN(J,3)
DG12I(J,I)=-DGY(I)*UN(J,1)+DGY(I)*UN(J,2)+(DGZ1(I)-DGZ2(I))
1 *UN(J,3)
30 CONTINUE
10 CONTINUE
C...COMBINE DG11 AND DG12 TO BE DG11 FOR DG135 MODE,
C...AND DG12 FOR DG246 MODE
DO 40 I=1,N
DO 40 J=1,N
TEMP1=DG11R(I,J)+DG12R(I,J)
TEMP2=DG11I(I,J)+DG12I(I,J)
TEMP3=DG11R(I,J)-DG12R(I,J)
TEMP4=DG11I(I,J)-DG12I(I,J)
DG11R(I,J)=TEMP1*SUR(J)
DG11I(I,J)=TEMP2*SUR(J)
DG12R(I,J)=TEMP3*SUR(J)
DG12I(I,J)=TEMP4*SUR(J)
40 CONTINUE
C...ADDING THE DIAGONAL TERM OF DG MATRIX
DO 50 I=1,N
DG11R(I,I)=DG11R(I,I)-6.28318
DG12R(I,I)=DG12R(I,I)-6.28318
50 CONTINUE
C...COMBINE G11 AND G12 TO BE G11 FOR G135 MODE, AND G12 FOR G246 MODE
DO 60 I=1,N
DO 60 J=1,N
TEMP1=G11R(I,J)+G12R(I,J)
TEMP2=G11I(I,J)+G12I(I,J)
TEMP3=G11R(I,J)-G12R(I,J)
TEMP4=G11I(I,J)-G12I(I,J)
G11R(I,J)=TEMP1*SUR(J)
G11I(I,J)=TEMP2*SUR(J)
G12R(I,J)=TEMP3*SUR(J)
G12I(I,J)=TEMP4*SUR(J)
60 CONTINUE
C...ADDING THE DIAGONAL TERM OF G MATRIX
DO 70 I=1,N
TEMP=2.0*SQRT(SUR(I)*3.14159)
G11R(I,I)=G11R(I,I)+TEMP
G12R(I,I)=G12R(I,I)+TEMP
70 CONTINUE
RETURN
SUBROUTINE PHI8(N, PAN, UN, PHI7R, PHI7I, PHI8R, PHI8I)

C...THIS PROGRAM CALCULATE THE PHI7: SYMMETRIC PART, PHI8: ANTI-SYM PART

DIMENSION PAN(N,3), UN(N,3)
DIMENSION PHI7R(N), PHI7I(N), PHI8R(N), PHI8I(N)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD

APHI=GRAV/(FREQ*(1.0+EXP(-2.0*WNUM*DEPTH)))
AK1=WNUM*COS(HEAD)
AK2=WNUM*SIN(HEAD)

DO 10 I=1,N
   V1=PAN(I,1)
   V2=PAN(I,2)
   V3=PAN(I,3)
   XK1=V1*AK1
   YK2=V2*AK2
   ZH=V3+DEPTH
   XN=UN(I,1)
   YN=UN(I,2)
   ZN=UN(I,3)
   TEMP=APHI*EXP(WNUM*V3)*(1.0+EXP(-2.0*WNUM*ZH))
   TEMPB=APHI*EXP(WNUM*V3)*(1.0-EXP(-2.0*WNUM*ZH))
   AKNX=TEMPA*AK1*XN
   AKNY=TEMPA*AK2*YN
   AKNZ=TEMPSB*WNUM*ZN
   CY2=COS(YK2)
   SY2=SIN(YK2)
   CX1=COS(XK1)
   SX1=SIN(XK1)

   PHI7R(I)=-(-AKNX*CY2*SX1-AKNY*SY2*CIX1+AKNZ*CY2*CIX1)
   PHI7I(I)=-(-AKNX*CY2*CIX1-AKNY*SY2*SX1+AKNZ*CY2*SX1)
   PHI8R(I)=-(-AKNX*SY2*CIX1-AKNY*CY2*SX1+AKNZ*SY2*SX1)
   PHI8I(I)=-(-AKNX*SY2*SX1-AKNY*CY2*CIX1+AKNZ*SY2*CIX1)

10 CONTINUE
RETURN
END

SUBROUTINE GINVER(N, NN, UN, UNN, PHI7R, PHI7I, PHI8R, PHI8I, DA, DN)

DIMENSION UN(N,3), UNN(N,3), PHI7R(N), PHI7I(N), PHI8R(N), PHI8I(N),
       DG135R, DG135I, DG246R, DG246I, Q135, Q246)

C...THIS PROGRAM COMPUTES THE INVERSE OF MATRIX DG AND SOURCE Q

C...INPUT:N, NN, UN, UNN, PHI, DG135, DG246
C...OUTPUT:Q135, Q246
C...DA AND DN IS FOR TEMPERARY USE, NN=2*N=2*NSP

DIMENSION Q135(NN,4), Q246(NN,4)

C...FORMATION OF THE REAL MATRIX DA*Q=UN FOR THE SYMMETRIC PHI7R

DO 10 I=1,N
   DN(I,1)=UN(I,1)
   DN(I,2)=UN(I,2)
   DN(I,3)=UNN(I,2)
   DN(I,4)=PHI7R(I)
   DN(I+N,1)=0.0
   DN(I+N,2)=0.0
   DN(I+N,3)=0.0
   DN(I+N,4)=PHI7I(I)

10 CONTINUE
DO 10 J=1,N
DA(I,J)=DG135R(I,J)
DA(I+N,J)=DG135I(I,J)
DA(I,J+N)=DG135I(I,J)
DA(I+N,J+N)=DG135R(I,J)
10 CONTINUE

C...SOLVING Q BY INVERSION A*X=R, A:(M*M), R:(M*N), X:(M*N) STORED IN R
CALL INV(DN,DA,NN,4)
DO 20 I=1,NN
DO 20 J=1,4
Q135(I,J)=DN(I,J)
20 CONTINUE

C...SOLVING Q246 (ANTISYMMETRIC PART) BY THE SIMILAR PROCESS AS ABOVE
DO 30 I=1,N
DN(I,1)=UN(1,2)
DN(I,2)=UNN(I,1)
DN(I,3)=UNN(I,3)
DN(I,4)=PHI8R(I)
DN(I+N,1)=0.0
DN(I+N,2)=0.0
DN(I+N,3)=0.0
DN(I+N,4)=PHI8I(I)
30 CONTINUE
CALL INV(DN,DA,NN,4)
DO 40 I=1,NN
DO 40 J=1,4
Q246(I,J)=DN(I,J)
40 CONTINUE
RETURN
END

SUBROUTINE POTEN(N,NN,G135R,G135I,G246R,G246I,Q135,Q246,DA,
POT135,POT246)

C...COMPUTE THE POTENTIAL
C...INPUT:N,NN,G135,G246,Q135,Q246
C...OUTPUT:POT135,POT246
C...DA IS FOR TEMPORARY USE
DIMENSION G135R(N,N),G135I(N,N),G246R(N,N),G246I(N,N),Q135(NN,4),
Q246(NN,4),DA(NN,NN)
DIMENSION POT135(NN,4),POT246(NN,4)

DO 10 I=1,N
DO 10 J=1,N
DA(I,J)=G135R(I,J)
DA(I+N,J)=G135I(I,J)
DA(I,J+N)=G135I(I,J)
DA(I+N,J+N)=G135R(I,J)
10 CONTINUE
CALL MPRD(DA,Q135,POT135,NN,NN,4)
DO 20 I=1,N
DO 20 J=1,N
DA(I,J)=G246R(I,J)
DA(I+N,J)=G246I(I,J)
DA(I,J+N)=G246I(I,J)
DA(I+N,J+N)=G246R(I,J)
20 CONTINUE
20 CONTINUE
CALL MPRD(DA,Q246,POT246,NN,NN,4)
RETURN
END

SUBROUTINE MASS(N,NN,UN,UNN,SUR,POT135,POT246,TPR,TPI,TTUN,AM,DEMP)
C...COMPUTE THE ADDED MASS AND DEMPING COEFFICIENT
C...INPUT:N,NN,UN,UNN,SUR,POT135,POT246
C...OUTPUT:AM,DEMP
C...TPR,TPI,TTUN IS FOR TEMPORARY USE
DIMENSION UN(N,3),UNN(N,3),SUR(N),POT135(NN,4),POT246(NN,4),
      TPR(N,6),TPI(N,6),TTUN(N,6),AM(6,6),DEMP(6,6)
COMMON /C2/ GRAV,DEN,FREQ,DEPTH,WNUM,ANU,HEAD

DO 5 I=1,N
  DO 5 K=1,3
    TTUN(I,K)=UN(I,K)
  CONTINUE
  DO 5 J=1,N
    JJ=J+N
    TTUN(I,K+3)=UNN(I,K)
  CONTINUE
5 CONTINUE
DO 10 J=1,N
  JJ=J+N
  DO 10 K=1,3
    TPR(J,2*K-1)=POT135(J,K)
    TPR(J,2*K)=POT246(J,K)
    TPI(J,2*K-1)=POT135(JJ,K)
    TPI(J,2*K)=POT246(JJ,K)
  CONTINUE
10 CONTINUE
DO 20 J=1,5,2
  JJ=J+1
  DO 20 K=1,5,2
    KK=K+1
    S1R=0.0
    S1I=0.0
    S2R=0.0
    S2I=0.0
    DO 25 I=1,N
      S1R=S1R+TPR(I,J)*TTUN(I,K)*SUR(I)
      S1I=S1I+TPI(I,J)*TTUN(I,K)*SUR(I)
      S2R=S2R+TPR(I,JJ)*TTUN(I, KK)*SUR(I)
      S2I=S2I+TPI(I,JJ)*TTUN(I, KK)*SUR(I)
  CONTINUE
25 CONTINUE
  AM(J,K)=-2.0*DEN*S1R
  AM(JJ,KK)=-2.0*DEN*S2R
  DEMP(J,K)=-2.0*DEN*FREQ*S1I
  DEMP(JJ,KK)=-2.0*DEN*FREQ*S2I
20 CONTINUE
RETURN
END

SUBROUTINE EXFOR(N,NN,PAN,UN,UNN,SUR,POT135,POT246,TTUN,P01R,P01I,
P02R,P02I,FOR)
C...COMPUTE THE EXCITING FORCE
C...INPUT:N,UN,UNN,SUR,POT135,POT246
C...OUTPUT:FOR
C...TTUN,PO1R,PO1I,PO2R,PO2I IS FOR TEMPORARY USE
DIMENSION PAN(N,3),UN(N,3),UNN(N,3),SUR(N),POT135(NN,4),POT246(NN,4),
      TTUN(N,6),PO1R(N),PO1I(N),PO2R(N),PO2I(N),FOR(12)
COMMON /C2/ GRAV,DEN,FREQ,DEPTH,WNUM,ANU,HEAD

DO 5 I=1,N
  DO 5 K=1,3
    TTUN(I,K)=UN(I,K)
  CONTINUE
  DO 5 J=1,N
    JJ=J+N
    TTUN(I,K+3)=UNN(I,K)
  CONTINUE
5 CONTINUE
DO 10 J=1,N
  JJ=J+N
  DO 10 K=1,3
    TPR(J,2*K-1)=POT135(J,K)
    TPR(J,2*K)=POT246(J,K)
    TPI(J,2*K-1)=POT135(JJ,K)
    TPI(J,2*K)=POT246(JJ,K)
  CONTINUE
10 CONTINUE
DO 20 J=1,5,2
  JJ=J+1
  DO 20 K=1,5,2
    KK=K+1
    S1R=0.0
    S1I=0.0
    S2R=0.0
    S2I=0.0
    DO 25 I=1,N
      S1R=S1R+TPR(I,J)*TTUN(I,K)*SUR(I)
      S1I=S1I+TPI(I,J)*TTUN(I,K)*SUR(I)
      S2R=S2R+TPR(I,JJ)*TTUN(I, KK)*SUR(I)
      S2I=S2I+TPI(I,JJ)*TTUN(I, KK)*SUR(I)
  CONTINUE
25 CONTINUE
  AM(J,K)=-2.0*DEN*S1R
  AM(JJ,KK)=-2.0*DEN*S2R
  DEMP(J,K)=-2.0*DEN*FREQ*S1I
  DEMP(JJ,KK)=-2.0*DEN*FREQ*S2I
20 CONTINUE
RETURN
END
DO 5 I=1,N
DO 5 K=1,3
TTUN(I,K)=UN(I,K)
TTUN(I,K+3)=UNN(I,K)
5 CONTINUE
DO 10 I=1,5,2
II=I+1
SR=0.0
SI=0.0
SB=0.0
SB=0.0
DO 20 J=1,N
JJ=J+N
SR=SR+POT135(J,4)*TTUN(J,I)*SUR(J)
SI=SI+POT135(JJ,4)*TTUN(J,J)*SUR(J)
SB=SB+POT246(J,4)*TTUN(J,J)*SUR(J)
SB=SB+POT246(JJ,4)*TTUN(J,J)*SUR(J)
20 CONTINUE
DEL=2.0*FREQ*DEN
F(I)=DEL*S7R
F(I+1)=DEL*S8R
F(I+6)=DEL*S7I
F(I+6)=DEL*S8I
10 CONTINUE
APHI=GRAV/(FREQ*(1.0+EXP(-2.0*WNUM*DEPTH)))
AK=1=WNUM*COS(HEAD)
AK=2=WNUM*SIN(HEAD)
DO 30 J=1,N
X=PAN(J,1)
Y=PAN(J,2)
Z=PAN(J,3)
T=APHI*EXP(WNUM*(Z+EXP(-2.0*WNUM*(Z+DEPTH))))*SUR(J)
T=AK*X+AK2*Y
T=AK*X-AK2*Y
P0R(J)=T*AK1*COS(T)
T=P01(J)=T*AK1*SIN(T)
P02R(J)=T*AK1*COS(T)
P021(J)=T*AK1*SIN(T)
30 CONTINUE
DO 40 I=1,6
II=I+6
SR=0.0
SI=0.0
TB=1.0
IF((I/2)*2.EQ.I) TB=-1.0
DO 50 J=1,N
SR=SR+P01(J)*TTUN(J,I)+TB*P02R(J)*TTUN(J,I)
SI=SI+P01(J)*TTUN(J,I)+TB*P02I(J)*TTUN(J,I)
50 CONTINUE
F(I)=FOR(I)+FREQ*DEN*SR
F(I)=FOR(I)+FREQ*DEN*SI
T=FOR(I)
F(I)=F(I)+FOR(I)
F(I)=T
40 CONTINUE
RETURN
END

SUBROUTINE AMPL(AM,DEMP,RM,C,FOR,AMP)
C...COMPUTE THE RESPONSE AMPLITUDE
C... INPUT: AM, DEMP, RM, C, FOR
C... OUTPUT: AMP
C... DC AND DF IS FOR TEMPORARY USE
DIMENSION AM(6,6), DEMP(6,6), RM(6,6), C(6,6), FOR(12), AMP(12),
1 DC(12,12), DF(12)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD

DO 10 I=1,6
II=I+6
DF(I)=FOR(I)
DF(II)=FOR(II)
DO 10 J=1,6
JJ=J+6
TEMP1=FREQ*FREQ*(AM(I,J)+RM(I,J))+C(I,J)
TEMP2=FREQ*DEMP(I,J)
DC(I,J)= TEMP1
DC(II,J)=TEMP1
DC(J,J)= TEMP2
DC(I,JJ)=-TEMP2
10 CONTINUE
CALL INV(DF, DC, 12, 1)
DO 20 I=1,12
IF ( (I.EQ.1).OR.(I.EQ.7) ) GOTO 15
IF ( (I.EQ.3).OR.(I.EQ.9) ) GOTO 15
IF ( (I.EQ.5).OR.(I.EQ.11) ) GOTO 15
AMP(I)=0.0
GOTO 20
15 AMP(I)=DF(I)
20 CONTINUE
RETURN
END
SUBROUTINE GI2(VX, VXX, G, DGX, DGY, DGZ1, DGZ2, UMAX)
EXTERNAL FG1, FG2, FGX1, FGX, FGZ11, FGZ1, FGZ2, FGZ2E
DIMENSION VX(3), VXX(3), G(2), DGX(2), DGY(2), DGZ1(2), DGZ2(2)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /SER/ UK(1000), GAMMA(1000), ALPHA
COMMON /GL/ ZH, ZZH, R1
C.... THIS PROGRAM CALCULATE THE GREEN'S FUNCTION BY INTEGRAL FORM
C... F1 IS THE INTEGRAND; FE IS THE SYMMETRIC PART OF THE INTEGRAND
FZ1(X)=X*(EXP(X*(ZH+ZZH-2.0*DEPTH))-EXP(-X*(ZH+ZZH+2.0*DEPTH))
FZ2(X)=X*(EXP(-X*(ZH-ZH+2.0*DEPTH)))-EXP(-X*(ZH-ZH+2.0*DEPTH))
TEMP1=VX(1)-VXX(1)
TEMP2=VX(2)-VXX(2)
TEMP3=VX(3)-VXX(3)
R1=SQR(T(TEMP1*TEMP1+TEMP2*TEMP2))
IF (R1 .LE. 1.0E-6) R1=0.0
TEMP4=R1*WNUM
ZH=VX(3)+DEPTH
ZZH=VXX(3)+DEPTH
R=SQR(TEMP1*R1+TEMP3*TEMP3)
IF (R .LE. 1.0E-6) R=0.0
R2H=SQR(TEMP1*R1+(ZH+ZZH)*(ZH+ZZH))
BJ0=BJ(TEMP4,0)
BJ1=BJ(TEMP4,1)
EZH=EXP(-2.0*WNUM*ZH)
EZZH=EXP(-2.0*WNUM*ZZH)
G(1)=1.0/R2H
IF (R .NE. 0.0) G(1)=G(1)+1.0/R
G(2)=ALPHA*(1.0+EZH)*(1.0+ZZH)*BJ0*EXP(WNUM*(VX(3)+VXX(3)))
DGX(1) = -1.0/R2H**3.0
IF(R .NE. 0.0)DGX(1)=DGX(1)-1.0/R**3.0
IF(R1 .EQ. 0.0) GO TO 1
DGX(2)=-ALPHA*(1.0+EZH)*(1.0+EZZH)*EXP(WNUM*(VX(3)+VXX(3)))
1
   *BJ(TEMP4,1)*WNUM/R1
GO TO 2
1
DGX(2)=-ALPHA*(1.0+EZH)*(1.0+EZZH)*EXP(WNUM*(VX(3)+VXX(3)))
1
   *0.5*WNUM*WNUM
2
DGZ1(1)=-(ZZH+ZH)/R2H**3.0
DGZ1(2)=ALPHA*FZ1(WNUM)*BJ0
DGZ2(1)=0.0
IF(R .NE. 0.0)DGZ2(1)=DGZ2(1)-(ZH-ZZH)/R**3.0
DGZ2(2)=ALPHA*FZ2(WNUM)*BJ0
UINT=0.01*WNUM
CALL DG16(UINT,WNUM,FGE,SMG1)
CALL DG16(2.0*WNUM,UMAX,FG1,SMG2)
G(1)=G(1)+SMG1+SMG2+UINT*FGE(UINT)
CALL DG16(UINT,WNUM,FGXE,SMG1)
CALL DG16(2.0*WNUM,UMAX,FGX1,SMG2)
DGX(1)=DGX(1)+SMG1+SMG2+UINT*FGXE(UINT)
CALL DG16(UINT,WNUM,FGZ1E,SMG1)
CALL DG16(2.0*WNUM,UMAX,FGZ21,SMG2)
DGZ1(1)=DGZ1(1)+SMG1+SMG2+UINT*FGZ1E(UINT)
CALL DG16(UINT,WNUM,FGZ2E,SMG1)
CALL DG16(2.0*WNUM,UMAX,FGZ21,SMG2)
DGZ2(1)=DGZ2(1)+SMG1+SMG2+UINT*FGZ2E(UINT)

DGY(1)=DGX(1)*TEMP2
DGX(2)=DGX(2)*TEMP2
DGX(1)=DGX(1)*TEMP1
DGX(2)=DGX(2)*TEMP1
RETURN
END

FUNCTION FGE(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
B=1.0/((X-ANU)/(X+ANU)-EXP(-2.0*X*DEPTH))
FGE=B*EXP(X*(ZH+ZZH-2.0*DEPTH))*(1.0+EXP(-2.0*X*ZH))
1
   (1.0+EXP(-2.0*X*ZZH))*BJ(X*R1,0)
RETURN
END

FUNCTION FGX1(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
B=-1.0/((X-ANU)/(X+ANU)-EXP(-2.0*X*DEPTH))
1
   *EXP(X*(ZH+ZZH-2.0*DEPTH))*(1.0+EXP(-2.0*X*ZH))
2
   (1.0+EXP(-2.0*X*ZZH))
IF (R1 .EQ. 0.0) GO TO 10
FGX1=B*BJ(X*R1,1)*X/R1
RETURN
10
   FGX1=B*0.5*X*X
RETURN
FUNCTION FGXE(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
FGXE = FGX1(X+WNUM) + FGX1(-X+WNUM)
RETURN
END

FUNCTION FGZ11(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
B = 1.0/(X-ANU)/(X+ANU) - EXP(-2.0*(X*DEPTH))
FGZ11 = B*X*(EXP(-(X*(ZH+ZZH-2.0*DEPTH)) - EXP(-X*(ZH+ZZH+2.0*DEPTH))))
1 *BJ(X*R1, 0)
RETURN
END

FUNCTION FGZ1E(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
FGZ1E = FGZ11(X+WNUM) + FGZ11(-X+WNUM)
RETURN
END

FUNCTION FGZ21(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
B = 1.0/(X-ANU)/(X+ANU) - EXP(-2.0*(X*DEPTH))
FGZ21 = B*X*(EXP(-(X*(ZH+ZZH-2.0*DEPTH)) - EXP(-X*(ZH+ZZH+2.0*DEPTH))))
1 *BJ(X*R1, 0)
RETURN
END

FUNCTION FGZ2E(X)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /G1/ ZH, ZZH, R1
FGZ2E = FGZ21(X+WNUM) + FGZ21(-X+WNUM)
RETURN
END

SUBROUTINE GS2(VX, VXX, G, DGX, DGY, DGZ1, DGZ2, NTERM)
DIMENSION VX(3), VXX(3), G(2), DGX(2), DGY(2), DGZ1(2), DGZ2(2)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /SER/ UK(1000), GAMMA(1000), ALPHA

C.... THIS PROGRAM CALCULATE THE GREEN'S FUNCTION BY SERIES FORM

TEMP1 = VX(1) - VXX(1)
TEMP2 = VX(2) - VXX(2)
TEMP3 = VX(3) - VXX(3)
R1 = SQRT(TEMP1*TEMP1 + TEMP2*TEMP2)
ZH = VX(3) + DEPTH
ZZH = VXX(3) + DEPTH
TEMP4 = ALPHA*(1.0 + EXP(-2.0*WNUM*ZH)) * (1.0 + EXP(-2.0*WNUM*ZBH))
1 * EXP(WNUM*(ZH+ZZH-2.0*DEPTH))
TEMP5 = WNUM*R1
TEMP6 = TEMP4*WNUM/R1
BY0 = BY0(TEMP5, 0)
BJ0 = BJ0(TEMP5, 0)
G(1) = TEMP4*BY0
G(2) = -TEMP4*BJ0
DGX(1) = -TEMP6 * BY(TEMP5, 1)
DGX(2) = TEMP6 * BJ(TEMP5, 1)
T21 = ALPHA * WNUM * EXP(WNUM * (ZH + ZZH - 2.0 * DEPTH)) *
(1.0 - EXP(-2.0 * WNUM * (ZH + ZZH)))
T22 = ALPHA * WNUM * (EXP(WNUM * (ZH + ZZH - 2.0 * DEPTH)) *
(1 - EXP(WNUM * (ZZH - ZH - 2.0 * DEPTH)))
DGZ1(1) = T21 * BY0
DGZ1(2) = T21 * BJ0
DGZ2(1) = T22 * BY0
DGZ2(2) = T22 * BJ0
SUMG = 0.0
SUMGX = 0.0
SUMGZ1 = 0.0
SUMGZ2 = 0.0
IF (NTERM .EQ. 0) GO TO 11
DO 10 I = 1, NTERM
  J = NTERM - I + 1
  TEMP7 = UK(J) * R1
  BK0 = BK(TEMP7, 0)
  S1 = GAMMA(J) * COS(UK(J) * ZH) * COS(UK(J) * ZZH)
  S2 = GAMMA(J) * UK(J) * BK0
  SG = S1 * BK0
  SGX = S1 * UK(J) * BK(TEMP7, 1)
  SGZ1 = S2 * 0.5 * SIN(UK(J) * (ZH + ZZH))
  SGZ2 = S2 * 0.5 * SIN(UK(J) * (ZH - ZZH))
  SUMG = SUMG + SG
  SUMGX = SUMGX + SGX
  SUMGZ1 = SUMGZ1 + SGZ1
  SUMGZ2 = SUMGZ2 + SGZ2
10 CONTINUE
11 CONTINUE
G(1) = G(1) + SUMG
DGX(1) = DGX(1) + SUMGX / R1
DGY(1) = DGX(1) + TEMP2
DGY(2) = DGX(2) + TEMP2
DGX(1) = DGX(1) + TEMP1
DGX(2) = DGX(2) + TEMP1
DGZ1(1) = DGZ1(1) + SUMGZ1
DGZ2(1) = DGZ2(1) + SUMGZ2
RETURN
END

SUBROUTINE ROOTUK(N)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /SER/ UK(1000), GAMMA(1000), ALPHA
F(X) = X * TAN(X * 1.570796327) + BETA
ERR = 1.0E-6
BETA = ANU * DEPTH / 1.570796327
DO 20 J = 1, N
  DELTA = 1.0E-2
  A2 = 2.0 * J
  A1 = 2 * J - 1 + DELTA
  Y1 = F(A1)
  Y2 = F(A2)
  IF (ABS(Y1) .LE. ERR) GO TO 100
  IF (ABS(Y2) .LE. ERR) GO TO 200
  IF (Y1) 13, 100, 12
20 CONTINUE
A2 = A1
GO TO 5
13 A3 = (A1 + A2) * 0.5
Y3 = f(A3)
IF (ABS(Y3) .LE. ERR) GO TO 101
IF (Y3 .LT. 0.0) A1 = A3
IF (Y3 .GT. 0.0) A2 = A3
RA = ABS((A2 - A1) / A3)
IF (RA .LE. ERR) GO TO 101
GO TO 13
100 UK(J) = A1
GO TO 10
200 UK(J) = A2
GO TO 10
101 UK(J) = A3
10 UK(J) = UK(J) * 1.570796327/DEPTH
20 CONTINUE
TEMP1 = ANU * ANU
TEMP2 = TEMP1 * DEPTH / ANU
DO 50 J = 1, N
TEMP3 = UK(J) * UK(J)
GAMMA(J) = 4.0 * (TEMP3 + TEMP1) / (TEMP3 * DEPTH + TEMP2)
50 CONTINUE
RETURN
END
FUNCTION B(J, N)
BJ = 0.0
IF (N .EQ. 1 .AND. X .EQ. 0.0) GO TO 1
IF (N .EQ. 0 .AND. X .EQ. 0.0) GO TO 2
D = 1.0E-4
IF (N) 10, 20, 20
10 IER = 1
TYPE *, 'SOMETHING WRONG IN BESJ IER = ', IER
RETURN
2 BJ = 1.0
RETURN
20 IF (X) 30, 30, 31
30 IER = 2
TYPE *, 'SOMETHING WRONG IN BESJ IER = ', IER
RETURN
31 IF (X-15.) 32, 32, 34
32 NTEST = 20. + 10. * X - X** 2/3
GO TO 36
34 NTEST = 90. + X/2.
36 IF (N-NTEST) 40, 38, 38
38 IER = 4
TYPE *, 'SOMETHING WRONG IN BESJ IER = ', IER
RETURN
40 IER = 0
N1 = N+1
BPREV = 0
C...COMPUTE STARTING VALUE OF M
IF (X-5.) 50, 60, 60
50 MA = X + 6.
GO TO 70
60 MA = 1.4 * X + 60 ./ X
70 MB = N + IFIX(X)/4 + 2
MZERO = MAXO(MA, MB)
C...SET UPPER LIMIT OF M
MMAX = NTEST
100 DO 190 M = MZERO, MMAX, 3
C. SET F(M), F(M-1)

FM = 1.0E-28
FM = 0.0
ALPHA = 0.0

IF(M-(N/2) * 2) 120, 110, 120
110 JT = -1
GO TO 130
120 JT = 1
130 M2 = M - 2
DO 160 K = 1, M2
MK = M - K
BMK = 2.0E-28 * FM1/X - FM
FM = FM1
FM = BMK
IF(MK-N1) 150, 140, 150
140 BJ = BMK
150 JT = JT
S = 1 + JT
160 ALPHA = ALPHA + BMK * S
BMK = 2.0E-28 * FM1/X - FM
IF(N) 180, 170, 180
170 BJ = BMK
180 ALPHA = ALPHA + BMK
BJ = BJ/ALPHA
190 BPREV = BJ
IER = 3
WRITE (4, *) 'ERROR = 3'
TYPE *, 'SOMETHING WRONG IN BESJ IER = ', IER
200 RETURN
END

FUNCTION BK(X, N)
DIMENSION T(12)
BK = 0.0
IF(N) 10, 11, 11
10 IER = 1
TYPE *, 'SOMETHING WRONG IN BESK IER = ', IER
RETURN
11 IF(X) 12, 12, 20
12 IER = 2
TYPE *, 'SOMETHING WRONG IN BESK IER = ', IER
RETURN
20 IF(X > 170.0) 22, 22, 21
21 IER = 3
C. . . . . . . . . . . . . . . TYPE *, 'SOMETHING WRONG IN BESK IER = ', IER
RETURN
22 IER = 0
IF(X < 1.0) 36, 36, 25
25 A = EXP(-X)
B = 1.0/X
C = SQRT(B)
T(1) = B
DO 26 L = 2, 12
26 T(L) = T(L-1) * B
IF(N) 27, 27, 27
C. . . . . . . . . . . . . . COMPUTE K0 USING POLYNOMIAL APPROXIMATION
27 G0 = A * (1.25333144 - 1.5666418 * T(1) + 0.088111278 * T(2) - 0.091390954 * T(3)
+ 2.13445962 * T(4) - 2.2998503 * T(5) + 3.7924097 * T(6) - 5.2247273 * T(7)
+ 3.55753684 * T(8) - 0.2626329 * T(9) + 2.1845181 * T(10))
4 - 0.66809767 \cdot T(11) + 0.009189383 \cdot T(12) \cdot C \\
\text{IF}(N) = 20, 28, 29 \\
28 \quad \text{BK} = \text{GO} \\
\text{RETURN} \\
\text{C... COMPUTE K1 USING POLYNOMIAL APPROXIMATION} \\
29 \quad G1 = A^* \cdot (1.2533141 + 0.65999270 \cdot T(1) - 1.4685830 \cdot T(2) + 0.12804226 \cdot T(3) \\
2.17364316 \cdot T(4) + 0.28476181 \cdot T(5) - 0.45943421 \cdot T(6) + 6.2833807 \cdot T(7) \\
3.66322954 \cdot T(8) + 0.50502386 \cdot T(9) - 2.5813038 \cdot T(10) + 0.07880012 \cdot T(11) \\
4 - 0.010824117 \cdot T(12) \cdot C \\
\text{IF}(N-1) = 20, 30, 31 \\
30 \quad \text{BK} = \text{G1} \\
\text{RETURN} \\
\text{C... FROM K0, K1 COMPUTE KN USING RECURRENCE RELATION} \\
31 \quad \text{DO } 35 \quad J = 2, N \\
32 \quad GJ = 2 \cdot (\text{FLOAT}(J) - 1.) \cdot G1 / X + G0 \\
33 \quad \text{IF}(GJ < 1.0E-38) \times 33, 33, 32 \\
34 \quad \text{IER} = 4 \\
35 \quad \text{TYPE}, 'SOMETHING WRONG IN BESK IER = ', IER \\
36 \quad \text{GO TO } 34 \\
37 \quad G0 = \text{G1} \\
38 \quad \text{G1 = GJ} \\
39 \quad \text{BK = GJ} \\
\text{RETURN} \\
40 \quad B = X / 2 \\
41 \quad A = 0.57721566 + \text{ALOG}(B) \\
42 \quad C = 8 \cdot B \\
43 \quad \text{IF}(N-1) = 37, 43, 37 \\
\text{C... COMPUTE K0 USING SERIES EXPANSION} \\
44 \quad G0 = -A \\
45 \quad X2J = 1 \\
46 \quad \text{FACT} = 1. \\
47 \quad HJ = 0.0 \\
48 \quad \text{DO } 40 \quad J = 1, 6 \\
49 \quad RJ = 1 \cdot \text{FLOAT}(J) \\
50 \quad X2J = X2J \cdot C \\
51 \quad \text{FACT} = \text{FACT} \cdot RJ \cdot RJ \\
52 \quad HJ = HJ + RJ \\
53 \quad G0 = G0 + X2J \cdot \text{FACT} \cdot (HJ - A) \\
\text{IF}(N) = 43, 42, 43 \\
54 \quad \text{BK = GO} \\
\text{RETURN} \\
\text{C... COMPUTE K1 USING SERIES EXPANSION} \\
55 \quad X2J = B \\
56 \quad \text{FACT} = 1. \\
57 \quad HJ = 1. \\
58 \quad G1 = 1 \cdot \text{FLOAT}(J) \cdot (A - HJ) \\
59 \quad \text{DO } 50 \quad J = 2, 8 \\
60 \quad X2J = X2J \cdot C \\
61 \quad RJ = 1 \cdot \text{FLOAT}(J) \\
62 \quad \text{FACT} = \text{FACT} \cdot RJ \cdot RJ \\
63 \quad HJ = HJ + RJ \\
64 \quad G1 = G1 + X2J \cdot \text{FACT} \cdot (A - HJ) \cdot \text{FLOAT}(J) \\
\text{IF}(N-1) = 31, 52, 31 \\
65 \quad \text{BK = G1} \\
\text{RETURN} \\
\text{END} \\
\text{FUNCTION BY(X,N) \\
\text{C... CHECK FOR ERRORS IN N AND X} \\
\text{IF}(N) = 180, 10, 10}
10 IER=0
   IF(X)190,190,20
C... BRANCH IF X LESS THAN OR EQUAL 4
20 IF(X<4.)40,40,30
C... COMPUTE Y1 AND Y0 FOR X greater THAN 4.0
30 T1=4.0/X
   T2=T1*T1
   P0=((X-.0000037043*T2+.00000173565)*T2-.0000487613)*T2
   1+.00017343)*T2+.001753062)*T2+.3989423
   Q0=((X-.0000032312*T2-.0000142078)*T2+.000342468)*T2
   1-.0000869791)*T2+.0004564324)*T2-.01246694
   P1=((X-.0000042414*T2-.0000200920)*T2+.0000580759)*T2
   1-.000223203)*T2+.00291826)*T2+.3989423
   Q1=((X-.0000036594*T2+.000016221)*T2-.000398708)*T2
   1+.0001064741)*T2-.0006390400)*T2+.03740884
   A=2.0/SQRT(X)
   B=A*T1
   C=X-.7853982
   Y0=A*P0*SIN(C)+B*Q0*COS(C)
   Y1=A*P1*COS(C)+B*Q1*SIN(C)
   GO TO 90

C... COMPUTE Y0 AND Y1 FOR X LESS OR EQUAL TO 4.0
40 XX=X/2.
   X2=XX*XX
   T=Aalog(xx)+.5772157
   SUM=0.0
   TERM=T
   Y0=T
   DO 70 L=1,15
      IF(L-1)50,60,50
   50 SUM=SUM+1./FLOAT(L-1)
   60 FL=L
   TS=T-SUM
   TERM=(TERM*(-X2)/FL**2)*(1.-1./(FL*TS))
   70 Y0=Y0+TERM
   TERM=XX*(T-.5)
   SUM=0.0
   Y1=TERM
   DO 80 L=2,16
      SUM=SUM+1./FLOAT(L-1)
   80 FL=L
   FL1=FL-1
   TS=T-SUM
   TERM=(TERM*(-X2)/(FL1*FL)) *((TS-.5/FL)/(TS+.5/FL1))
   Y1=Y1+TERM
   Y1=PI2*.6366198
   Y0=PI2*Y0
   Y1=PI2/X+PI2*Y1
C... CHECK IF ONLY Y0 OR Y1 IS DESIRED
90 IF(N-1)100,100,130
C... RETURN EITHER Y0 OR Y1 AS REQUIRED
100 IF(N)110,120,110
110 BY=Y1
   GO TO 170
120 BY=Y0
   GO TO 170
C... PERFORM RECURRANCE OPERATIONS TO FIND YN(X)
130 YA=Y0
   YD=Y1
   K=1
SUBROUTINE DG16(XL,XU,FCT,SUM)
C....THIS PROGRAM COMPUTE INTEGRAL (FCT), SUMMED OVER X FROM
C....XL TO XU
C DOUBLE PRECISION XL,XU,Y,A,B,C,FCT
SUM=0.0
DO 10 I=1,10
DELTA=(XU-XL)/I
SUM=0.0
DO 20 J=1,I
X1=XL+(J-1)*DELTA
X2=X1+DELTA
A=.50*{(X2+X1)
B=DELTA
C=.9470046749582497E0*B
Y=1.3576229705877047E-1*(FCT(A+C)+FCT(A-C))
C=.7228751153661629E0*B
Y=Y+.31126761969323946E-1*(FCT(A+C)+FCT(A-C))
C=.3281560119391587E0*B
Y=Y+.47579255841246392E-1*(FCT(A+C)+FCT(A-C))
C=.7770220417750152E0*B
Y=Y+.62314485627766936E-1*(FCT(A+C)+FCT(A-C))
C=.3089381220132187E0*B
Y=Y+.74979799440828837E-1*(FCT(A+C)+FCT(A-C))
C=.22900838882861369E0*B
Y=Y+.8457825969750127E-1*(FCT(A+C)+FCT(A-C))
C=.14080177538962946E0*B
Y=Y+.9130170752246179E-1*(FCT(A+C)+FCT(A-C))
C=.47506254918818720E-1*B
Y=B*{Y+.472530522753425E-1*(FCT(A+C)+FCT(A-C))
SUM=SUM+Y
20 CONTINUE
IF(ABS(SUM-SUM0) .LE. ABS(SUM*1.0E-2)) GO TO 100
10 CONTINUE
RETURN
**FAIL TO CONVERGE IN DG16** NO = 10
100 CONTINUE
RETURN
END
SUBROUTINE MPRD(A,B,R,N,M,L)
C....THIS PROGRAM COMPUTES R=A*B, WHERE A(N*M), B(M*L)
DIMENSION A(1),B(1),R(1)
IR=0
IK=-M
DO 10 K=1,L
IK=IK+M
DO 10 J=1,N
IR=IR+1
JI=J-N
IB=IK
R(IR)=0.0
DO 10 I=1,M
JI=JI+N
IB=IB+1
10 R(IR)=R(IR)+A(JI)*B(IB)
RETURN
END

SUBROUTINE INV(R,A,M,N)
DIMENSION A(1),R(1)
EPS=1.0E-4
IF(M)23,23,1
C....SEARCH FOR GREATEST ELEMENT IN MATRIX A
1 IER=0
PIV=0.0E0
MM=M*M
NM=N*M
DO 3 L=1,MM
TB=ABS(A(L))
IF(TB-PIV)3,2,3
2 PIV=TB
I=L
3 CONTINUE
TOL=EPS*PIV
LST=1
DO 17 K=1,M
IF(PIV)23,23,4
4 IF(IER)7,5,7
5 IF(PIV-TOL)6,6,7
6 IER=K-1
7 PIVI=1.0E0/A(I)
J=(I-1)/M
I=I-J*M-K
J=J+1-K
DO 8 L=K,NM,M
LL=L+I
TB=PIVI*R(LL)
R(LL)=R(L)
8 R(L)=TB
IF(K-M)9,18,18
9 LEND=LST+M-K
IF(J)12,12,10
10 II=J*M
DO 11 L=1,LST,LEND
TB=A(L)
LL=L+II
A(L)=A(LL)
11 A(LL)=TB
12 DO 13 L=LST,MM,M

LL=L+1
TB=PIVI*A(LL)
A(LL)=A(L)

13 A(L)=TB
A(LST)=J
PIV=0.0E0
LST=LST+1
J=O
DO 16 II=LST,LEND
PIVI=-A(I)
IST=II+M
J=J+1
DO 15 L=IST,MM,M
LL=L-J
A(L)=A(L)+PIVI*A(LL)
TB=ABS(A(L))
IF(TB-PIV)15,15,14
14 PIV=TB
I=L
15 CONTINUE
DO 16 L=K,NM,M
LL=L+J
16 R(LL)=R(LL)+PIVI*R(L)
17 LST=LST+M
18 IF(M-I)23,22,19
19 IST=MM+M
LST=M+1
DO 21 I=I,3
II=LST-I
IST=IST-LST
L=IST-M
L=A(L)+0.5E0
DO 21 J=II,NM,M
TB=R(J)
LL=J
DO 20 K=IST,MM,M
LL=LL+1
20 TB=TB-A(K)*R(LL)
K=J+L
R(J)=R(K)
21 R(K)=TB
22 RETURN
23 IER=-1
TYPE *,??????SOMETHING WRONG IN INV.FTN****'
RETURN
END

SUBROUTINE VSUB(A,B,C)
DIMENSION A(3),B(3),C(3)
DO 10 I=1,3
10 C(I)=A(I)-B(I)
RETURN
END

SUBROUTINE VDOT(A,B,S)
DIMENSION A(3),B(3)
S=0.0
DO 10 I=1,3
10 S=S+A(I)*B(I)
RETURN
SUBROUTINE VCClO(A,B,C,SI
DIMENSION A(3),B(3),C(3)
C1=A(2)*B(3)-A(3)*B(2)
C2=A(3)*B(1)-A(1)*B(3)
C3=A(1)*B(2)-A(2)*B(1)
S=SQR1(C1*C1+C2*C2+C3*C3)
C(1)=C1
C(2)=C2
C(3)=C3
RETURN
END

SUBROUTINE VCOM(A,N1,N2,N3,C,I,J)
DIMENSION A(N1,N2,N3),C(N3)
DO 10 K=1,3
  C(K)=A(I,J,K)
RETURN
END

FUNCTION FTAN(AR,AL)
  D=ABS(AL/AR)
  D=ATAN(D)/3.1416*180.0
  IF(AL.GT.0.0 .AND. AR.LT.0.0) D=180.0-D
  IF(AL.LT.0.0 .AND. AR.GT.0.0) D=-D
  IF(AL.LT.0.0 .AND. AR.LT.0.0) D=-180.0+D
  FTAN=D
RETURN
END

SUBROUTINE QTOTAL(NSP,NN,Q135,Q246,AMP,QDF1,QDF2)
C...THIS PROGRAM CALCULATE THE TOTAL Q FOR DRIFTING FORCE
C...INPUT: NSP,NN,Q135,Q246,AMP
C...OUTPUT: QDF1(SIDE 1),QDF2(SIDE 2)
DIMENSION Q135(NN,4),Q246(NN,4),QDF1(NN),QDF2(NN),AMP(12)
COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
DO 10 I=1,NSP
  II=I+NSP
  T1=0.0
  T2=0.0
  T3=0.0
  T4=0.0
  DO 20 J=1,3
    J1=2*J-1
    J2=J1+1
    T1=T1+Q135(I,J)*AMP(J1+6)+Q135(I,J)*AMP(J1)
    T2=T2+Q246(I,J)*AMP(J2+6)+Q246(I,J)*AMP(J2)
    T3=T3+Q135(I,J)*AMP(J1)-Q135(I,J)*AMP(J1+6)
    T4=T4+Q246(I,J)*AMP(J2)-Q246(I,J)*AMP(J2+6)
  CONTINUE
QDF1(I)=Q135(I,4)+Q246(I,4)+FREQ*(T1+T2)
QDF2(I)=Q135(I,4)-Q246(I,4)+FREQ*(T1-T2)
QDF1(I)=Q135(I,4)+Q246(I,4)-FREQ*(T3+T4)
QDF2(I)=Q135(I,4)-Q246(I,4)-FREQ*(T3-T4)
C...TOTAL SOURCE STRENGTH WHICH MOTION IS NOT INCLUDED
C QDF(I)=Q135(I,4)+Q246(I,4)
C QDF2(I)=Q135(I,4)-Q246(I,4)
C QDF1(I)=Q135(I,4)+Q246(I,4)
SUBROUTINE DRIFT(NSP,NN,PAN,SUR,QDF1,QDF2,DRFX,DRFY,DRMZ)

C...CALCULATE THE DRIFTING FORCE
C...INPUT: NSP,NN,PAN,SUR,QDF1,QDF2
C...OUTPUT: DRFX,DRFY(DRIFTING FORCE IN X- AND Y-DIRECTION).

DIMENSION PAN(NSP,3),SUR(NSP),QDF1(NN),QDF2(NN)

COMMON /C2/ GRAV,DEN,FREQ,DEPTH,WNUM,ANU,HEAD

HK=WNUM*DEPTH

CONTINUE
RETURN
END

SUBROUTINE SR(N,NN,PAN,SUR,QDF1,QDF2,THETA,SR,SI,SCOS,SSIN,DSR,DSI,

C...THIS PROGRAM CALCULATE THE SR,SI...VALUES FOR DRIFTING FORCE
C...INPUT: N,NN,PAN,SUR,QDF1,QDF2,THETA
C...OUTPUT: SR,SI,SCOS,SSIN

DIMENSION PAN(N,3),SUR(N),QDF1(NN),QDF2(NN)

COMMON /C2/ GRAV,DEN,FREQ,DEPTH,WNUM,ANU,HEAD

SR=SI=SI=SI=SI

DO 10 I=1,N
II=I+N

CX=COS(THETA)*PAN(I,1)
SY=SIN(THETA)*PAN(I,2)
U1=WNUM*(CX+SY)+2.35619
U2=WNUM*(CX-SY)+2.35619
SX=SIN(THETA)*PAN(I,1)
CY=COS(THETA)*PAN(I,2)
DU1=WNUM*(SX-CY)
DU2=WNUM*(SX+CY)

Z=PAN(I,3)

T2=EXP(WNUM*Z)*(1.0+EXP(-2.0*WNUM*(Z+DEPTH)))*SUR(I)

S1=SI+QDF1(I)*COS(U1)+QDF2(I)*SIN(U1)*T2
S2=S2+QDF2(I)*COS(U2)+QDF2(I)*SIN(U2)*T2
S3=S3+QDF1(I)*COS(U1)-QDF1(I)*SIN(U1)*T2
S4=S4+QDF2(I)*COS(U2)-QDF2(I)*SIN(U2)*T2

DS1=DS1+QDF1(I)*SIN(U1)-QDF1(I)*COS(U1)*T2*DU1
DS2=DS2+QDF2(I)*SIN(U2)-QDF2(I)*COS(U2)*T2*DU2
DS3=DS3+QDF1(I)*COS(U1)+QDF1(I)*SIN(U1)*T2*DU1
DS4=DS4+QDF2(I)*COS(U2)+QDF2(I)*SIN(U2)*T2*DU2

10 CONTINUE

SR=SI+SI
SI=SI+SI

DSR=DS1+DS2
DSI=DS3+DS4

SCOS=SM*COS(THETA)
SSIN=SM*SIN(THETA)

RETURN
END
E2=EXP(-2.0*HK)
E4=EXP(-4.0*HK)
T1=(WNUM*WNUM-ANU*ANU)*DEPTH+ANU
T2=1.0+4.0*HK*E2/(1.0-E4)
TEMP1=4.44288*DEN*WNUM*FREQ*T2/(T1*(1.0+E2))
TEMP2=-6.28318*(1.0-E2)*DEN*(WNUM**4.0)*T2/(T1*T1*(1.0+E2)**3.0)

C...DRIFTING FORCE DUE TO THE INCOME WAVE EFFECT
CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,HEAD,SR,SI,SCOS,SSIN,DSR,DSI,TM)
DFRX=TEMP1*(SR-SI)*COS(HEAD)
DFRY=TEMP1*(SR-SI)*SIN(HEAD)
DRM2=TEMP1*(DSR+DSI)/WNUM

C...USING GAUSSIAN 16 POINTS FORMULAR TO INTEGRATE THE DRIFTING FORCE
C...DUE THE MOTION EFFECT
DELTA=6.28318/4.0
SUMX=0.0
SUMY=0.0
SUMME=0.0
DO 20 J=1,4
   X1=(J-1)*DELTA
   X2=X1+DELTA
   A=.5E0*(X2+X1)
   B=DELTA
   C=.49470046749582497E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.31576229705877047E-1*(APCC+AMCC)
   FY=1.31576229705877047E-1*(APCS+AMCS)
   FMEN=1.31576229705877047E-1*(DM1+DM2)
   C=.47228751153661629E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.47579255841246392E-1*(APCC+AMCC)
   FY=1.47579255841246392E-1*(APCS+AMCS)
   FMEN=FMEN+.475792555641246392E-1*(DM1+DM2)
   C=.43281560119391587E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.62314485627766936E-1*(APCC+AMCC)
   FY=1.62314485627766936E-1*(APCS+AMCS)
   FMEN=FMEN+.62314485627766936E-1*(DM1+DM2)
   C=.43770220417750152E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.7479799440828387E-1*(APCC+AMCC)
   FY=1.7479799440828387E-1*(APCS+AMCS)
   FMEN=FMEN+.7479799440828387E-1*(DM1+DM2)
   C=.3089381220132187E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.8457825969750127E-1*(APCC+AMCC)
   FY=1.8457825969750127E-1*(APCS+AMCS)
   FMEN=FMEN+.8457825969750127E-1*(DM1+DM2)
   C=.22900838882861369E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
   FX=1.9408017753862946E0*B
   CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,A-C,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
FX=FX+.9130170752246179E-1*(APCC+AMCC)
FY=FY+.9130170752246179E-1*(APCS+AMCS)
FMEN=FMEN+.9130170752246179E-1*(DM1+DM2)
C=.47506254918818720E-1*B
CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,A+C,SR,SI,APCC,APCS,TEM1,TEM2,DM1)
CALL SIR(NSP,2*NSP,PAN,SUR,QDF1,QDF2,A-C,SR,SI,AMCC,AMCS,TEM1,TEM2,DM2)
FX=B*(FX+.9472530522753425E-1*(APCC+AMCC))
FY=B*(FY+.9472530522753425E-1*(APCS+AMCS))
FMEN=B*(FMEN+.9472530522753425E-1*(DM1+DM2))
SUMX=SUMX+FX
SUMY=SUMY+FY
SUMMEN=SUMMEN+FMEN
20 CONTINUE
C...TOTAL DRIFTING FORCE AND MOMENT
DRFX=DRFX+TEMP2*SUMX
DRFY=DRFY+TEMP2*SUMY
DRMZ=DRMZ+TEMP2*SUMMEN
RETURN
END
PROGRAM OUT12
DIMENSION PAN(115,3), UN(115,3), UNN(115,3), SUR(115),
1 DG11R(115,115), DG11I(115,115), DG12R(115,115), DG12I(115,115),
2 G11R(115,115), G11I(115,115), G12R(115,115), G12I(115,115),
3 PHI1R(115), PHI1I(115), PHI2R(115), PHI2I(115), QDF1(230),
4 QDF2(230),
5 POT135(230,4), POT246(230,4), Q135(230,4), Q246(230,4),
6 AM(6,6), DEMP(6,6), RM(6,6), C(6,6), FOR(12), AMP(12)

COMMON /C2/ GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD
COMMON /C3/ VOL, XB, YB, ZB, AREA, AREA, WP, XG, YG, ZG
COMMON /SER/ UK(1000), GAMMA(1000), ALPHA
DATA DEN, GRAV/1000., 9.8/
DATA XB, YB, ZB/0.0, 0.0, -1.26/
DATA R144, R155, R166/170.0, 166.0, 236.0/
DATA DEPTH, HEAD/500.0, 240.0/
DATA NSP/115/

C**************************************************************
VOL=3054270.0
SLL=200.0
AA1=DEN*VOL
BB1=DEN*VOL*SQR(GRAV/SLL)
AA5=AA1*SLL*SLL
BB5=BB1*SLL*SLL
C**************************************************************
CALL ASSIGN (2, 'COM2.DAT')
CALL ASSIGN (3, 'PRN12.DAT')
OPEN (UNIT=7, TYPE='NEW', NAME='POINT2', FORM='FORMATTED')
OPEN (UNIT=8, TYPE='NEW', NAME='SURGE MOTION2', FORM='FORMATTED')
OPEN (UNIT=9, TYPE='NEW', NAME='HEAVE MOTION2', FORM='FORMATTED')
OPEN (UNIT=10, TYPE='NEW', NAME='PITCH MOTION2', FORM='FORMATTED')
OPEN (UNIT=11, TYPE='NEW', NAME='ADDED MASS', FORM='FORMATTED')
OPEN (UNIT=12, TYPE='NEW', NAME='DAMPING', FORM='FORMATTED')
WRITE(3,*)'**********************************************************'
WRITE(3,*)'RESULT OF 115 PANELS FOR DELTA SHAPE'
WRITE(3,*)'WATER ENTRAPPED IN MODEL IS CONSIDERED'
WRITE(3,*)'**********************************************************'
DO 17 KI=1,40
READ (2) PAN, SUR, FOR, AMP, AM, DEMP, C, RM,
1 GRAV, DEN, FREQ, DEPTH, WNUM, ANU, HEAD, DRIFX, DRIFY, DRMZ
C**************************************************************
WRITE (3,*) 'PERIOD = ', 2.0*3.14159/FREQ
WRITE (3,*) 'HEADING = ', HEAD*180./3.14159
WRITE (3,*)
WRITE (3,*) 'A(11) =', AM(1,1)/AA1, 'A(33) =', AM(3,3)/AA1
WRITE (3,*) 'A(55) =', AM(5,5)/AA5, 'A(66) =', AM(6,6)/AA5
WRITE (3,*) 'B(11) =', DEMP(1,1)/BB1, 'B(33) =', DEMP(3,3)/BB1
WRITE (3,*) 'B(55) =', DEMP(5,5)/BB5, 'B(66) =', DEMP(6,6)/BB5
FREQND=(FREQ)**(VOL**0.333/9.81)**0.5
PHASE=90.0-FTAN(AMP(1), AMP(7))
AMIG=SQR(AMP(1)+AMP(1)+AMP(7)*AMP(7))
WRITE (3,*) 'SURGE MOTION =', AMIG, 'PHASE =', PHASE
C
WRITE (8,*) AMIG, PHASE, FREQND
C
PHASE=90.0-FTAN(AMP(3), AMP(9))
AMIG = SQRT(AMP(3)*AMP(3)+AMP(9)*AMP(9))
WRITE (3,*) 'HEAVE MOTION = ', AMIG, ' PHASE = ', PHASE
WRITE (9,*) AMIG, PHASE, FREQND

PHASE=90.0-FTAN(AMP(5),AMP(11))
AMIG = SQRT(AMP(5)*AMP(5)+AMP(11)*AMP(11))
WRITE (3,*) 'PITCH MOTION = ', AMIG*SLL, ' PHASE = ', PHASE
WRITE (10,*) AMIG*SLL, PHASE, FREQND

PHASE=90.0-FTAN( FOR(1), FOR(7) )
AMIG = SQRT( FOR(1)*FOR(1)+FOR(7)*FOR(7) )
WRITE (3,*) 'SURGE EX.FORCE = ', AMIG/(GRAV*AAI/SLL), ' PHASE = ', PHASE

PHASE=90.0-FTAN( FOR(3), FOR(9) )
AMIG = SQRT( FOR(3)*FOR(3)+FOR(9)*FOR(9) )
WRITE (3,*) 'HEAVE EX.FORCE = ', AMIG/(GRAV*AAI/SLL), ' PHASE = ', PHASE

PHASE=90.0-FTAN( FOR(5), FOR(11) )
AMIG = SQRT( FOR(5)*FOR(5)+FOR(11)*FOR(11) )
WRITE (3,*) 'PITCH EX.FORCE = ', AMIG/(GRAV*AAI), ' PHASE = ', PHASE

WRITE (3,*) 'DRIFT FORCE(X) = ', DRIFX/(DEN*GRAV*SLL)
WRITE (3,*) 'DRIFT FORCE(Y) = ', DRIFY/(DEN*GRAV*SLL)
WRITE (3,*) 'DRIFT MOMENT(Z) = ', DRMZ/(DEN*GRAV*SLL*SLL)
WRITE (3,*) 'NONOM. DRIFT FORCE(X) = ', DRIFX/(0.5*DEN*GRAV*VOL**0.333)
WRITE (3,*) 'NONOM. DRIFT FORCE(Y) = ', DRIFY/(0.5*DEN*GRAV*VOL**0.333)
WRITE (3,*) 'DRIFT FORCE(X) = ', DRIFX
WRITE (12,*) 2*3.14159/FREQ,DEMP(1,1)/BB1,DEMP(3,3)/BB1 + ,DEMP(5,5)/BB5,DEMP(6,6)/BB5
WRITE (11,*) 2*3.14159/FREQ,AM(1,1)/AA1,AM(3,3)/AA1, + AM(5,5)/AA5,AM(6,6)/AA5
WRITE (7,*) 2*3.14159/FREQ,DRIFX
WRITE (3,*) 'DRIFT FORCE(Y) = ', DRIFY
WRITE (3,*) '******************************************************************'
WRITE (3,*) 'CONTINUE
CLOSE(UNIT=11)
CLOSE(UNIT=12)
CLOSE(UNIT=7)
STOP

FUNCTION FTAN(AR,AI)
C.............THIS FUNCTION COMPUTE THE ARGUMENT OF (AR,AI) IN THE RANGE
C.............FROM -90 DEG. TO +270 DEG.
D=ABS(AI/AR)
D=ATAN(D)/3.1416*180.0
IF(AI .GT. 0.0 .AND. AR .LT. 0.0) D=180.0-D
IF(AI .LT. 0.0 .AND. AR .GT. 0.0) D=-D
IF(AI .LT. 0.0 .AND. AR .LT. 0.0) D=+180.0+D
FTAN=D
RETURN
END
APPENDIX E

PROGRAM LISTING: SHAPE.FOR
**Program to Calculate Panels for DeltaPort Geometry**

The output file is Deltal.DAT.

```fortran
REAL I
DIMENSION X1(200),X2(200),Y1(200),Y2(200),XINT1(50),Z(200)
DIMENSION X(200),XX(200),Y(200),YY(200),XINT2(50)
OPEN(UNIT=6,FILE='DELTA1.DAT',STATUS='NEW')
OPEN(UNIT=7,FILE='DELTA2.DAT',STATUS='NEW')

*FIRST CALCULATE BOTTOM PANEL GEOMETRY (triangular panels)*

TYPE*, 'BOTTOM PANEL GEOMETRY'
TYPE*, '!
XL=430.0
YL=370.0
NX=6
NY=9
DY=YL/NY
DX=XL/NX

ROUTINE TO CALCULATE Y COORDINATE OF THE CENTROID

DO 20 I=1,NY
Y1(I)=370-(2*DY/3.0)-(I-1)*DY)
Y2(I)=370-(DY/3)-(I-1)*DY)
20 CONTINUE

CALCULATE THE EQUATION OF EACH CENTROID LINE

SLOPE=-1.726
DO 30 I=1,NX
XINT1(I)=(430.0-(DX/3.0)-(I-1)*DX)
XINT2(I)=430-(2*DX/3)-(I-1)*DX
30 CONTINUE

CALCULATE EACH PANEL AREA

AREA=DX*DY/2

CALCULATE X COORDINATE USING STRAIGHT EQUATION

X=mY + a

NOTE - Z=-11.9 m FOR ALL PANELS

THE FOLLOWING LOOP ALSO WRITES TO FILE DELTA1.DAT

DO 40 I=1,NX
DO 40 J=1,NY
X1(J)=SLOPE*Y1(J)+XINT1(I)
IF (X1(J).LT.-216.) GOTO 35
IF (((X1(J)).GT.-76).AND.(X1(J).LT.(SLOPE*Y1(J)+150))) GOTO 35
WRITE(6,* X1(J),Y1(J),-11.9,0.0,0.0,-1.0,AREA
WRITE(7,* X1(J),Y1(J)
PB=PB+1
35 X2(J)=SLOPE*Y2(J)+XINT2(I)
IF (X2(J).LT.-216) GOTO 40
IF (((X2(J)).GT.-76).AND.(X2(J).LT.(SLOPE*Y2(J)+150))) GOTO 40
WRITE(6,* X2(J),Y2(J),-11.9,0.0,0.0,-1.0,AREA
```

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WRITE(7,*) X2(J),Y2(J)
PB=PB+1
40 CONTINUE
C
PB=TOTAL NUMBER OF PANELS ON THE BOTTOM SIDE
C
******************************************************************************
C
GEOMETRY FOR OUTSIDE PANELS (RECTANGULAR + TWO TRIANGULAR END PANELS)
C
******************************************************************************
C
TAKING A RECTANGLE DOWN FROM THE WATER LINE...
NH=25
NZ=1
XL=615
YL=350
ZL=11.9
DZ=ZL/NZ
DX=XL/NH
DY=YL/NH
C
C CALCULATION OF X AND Y FOR VERTICAL SIDES
DO 100 I=1,NH
X(I)=(395.0-(DX/2.0))-(X(I-1)*DX)
XX(I)=X(I)
Y(I)=(DY/2.0)+(Y(I-1)*DY)
YY(I)=Y(I)
100 CONTINUE
C
C CALCULATION OF Z
C
DO 110 I=1,NZ
Z(I)=-(DZ/2.0)+(Z(I-1)*DZ)
110 CONTINUE
C
C CHANGE VERTICAL SIDES TO SLOPED SIDES
DO J=1,NZ
DO I=1,NH
IF (X(I).LT.395.) Y(I)=Y(I)-2.1
END DO
END DO
C
C CALCULATE PANEL AREA
C
TAREA=705*25
AREA=TAREA/(NH*NZ)
C
C WRITE PANELS TO FILE
C
DO 130 I=1,NZ
DO 130 J=1,NH
WRITE(6,*) X(J),Y(J),Z(I),.5,.866,0.3,AREA
130 CONTINUE
WRITE(6,*) 423.7,2.4,-7.93,0.5,0.866,0.3,45.4
WRITE(6,*) -215.3,365.9,-7.93,0.5,0.866,0.3,15.3
C
C PO=NUMBER OF OUTSIDE PANELS
C
PO=NH*NZ+2
C GEOMETRY FOR INSIDE PANELS (RECTANGULAR PANELS)
C
SIDE SECTION
C
**************************************************************************************
TYPE*,
DO 200 I=1,NH
200 CONTINUE
C WRITE TO FILE
C
DO 210 I=1,NZ
DO 210 J=1,NH
   IF (XX(J).LT.-216) GO TO 210
   IF (XX(J).GT.150) GO TO 210
WRITE(6,*) XX(J),Y(J),Z(I),-.5,.866,0.0,AREA
PI5=PI5+1
210 CONTINUE
C
**************************************************************************************
C INSIDE-BACK SECTION
C
NY=2
NZ=1
YL=80.0
ZL=11.9
DY=YL/NY
DZ=ZL/NZ
DO 250 I=1,NZ
   DO 250 J=1,NY
      Y(I)=130.-DY/2.-((I-1)*DY
      Z(I)=-(DZ/2.)+(I-1)*DZ)
      AREA=DY*DZ
      WRITE(6,*)-76.,Y(J),Z(I),1.0,0.0,0.0,AREA
250 CONTINUE
PIB=NY*NZ
NO. OF INSIDE-BACK PANELS=PIB
C
**************************************************************************************
C GEOMETRY FOR THE BACK PANELS (RECTANGULAR PANELS + ONE TRIANGULAR PANEL)
C
**************************************************************************************
NY=6
YL=225
DY=YL/NY
NZ=1
ZL=11.9
DZ=ZL/NZ
DO 300 I=1,NY
   Y(I)=(370.0-(DY/2.0))-((I-1)*DY)
300 CONTINUE
C
C CALCULATE PANEL AREA
C
TAREA=YL*ZL
AREA=AY*DZ
C
WRITE TO FILE
C
DO 310 I=1,NZ
DO 310 J=1,NY
WRITE(6,*),216.0,Y(J),Z(I),-1.0,0.0,0.0,AREA
310 CONTINUE
C
WRITE(6,*),-216.0,365.8,-7.93,-1.0,0.0,0.0,28.9
C
PS=NUMBER OF PANELS ON THE BACK SIDE
C
PS=NY*NZ+1
C
PRINT OUT PANEL DATA
C
TYPE*,
TYPE*, 'NUMBER OF BOTTOM PANELS',PB
TYPE*, 'NUMBER OF OUTSIDE PANELS',PO
TYPE*, 'NUMBER OF INSIDE-BACK PANELS',PIB
TYPE*, 'NUMBER OF INSIDE-SIDE PANELS',PIS
TYPE*, 'NUMBER OF BACKSIDE PANELS',PS
TYPE*,
TP=PB+PO+PIS+PS+PIB
TYPE*, 'TOTAL NUMBER OF PANELS',TP
END
APPENDIX F

INPUT PANEL DATA
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APPENDIX G

RESULTS OF PROGRAM OUTPORT2.FOR
RESULT OF 115 PANELS FOR DELTA SHAPE
WATER ENTRAPPED IN MODEL IS CONSIDERED

PERIOD = 10.50000
HEADING = 180.0000

A(11) = 0.1051111 A(33) = 3.264185
A(55) = 1.322998 A(66) = 7.0522197E-02
B(11) = 0.3095694 B(33) = 1.963395
B(55) = 0.9624655 B(66) = 0.6856030
SURGE MOTION = 3.0399682E-02 PHASE = 10.40342
HEAVE MOTION = 4.0052738E-02 PHASE = 109.7882
PITCH MOTION = 7.0765868E-02 PHASE = -127.6289
SURGE EX.FORCE = 0.1779432 PHASE = -161.1657
HEAVE EX.FORCE = 0.6456119 PHASE = -82.98737
PITCH EX.FORCE = 0.6801304 PHASE = 29.22635
DRIFT FORCE(X) = -0.7990930
DRIFT FORCE(Y) = 5.4137622E-06
DRIFT MOMENT(Z) = -3.8294975E-06

NONDIM.DRIFT FORCE(X) = -2.214028
NONDIM.DRIFT FORCE(Y) = 1.4999783E-05
DRIFT FORCE(X) = -1566222,
DRIFT FORCE(Y) = 10.61097

PERIOD = 10.80000
HEADING = 180.0000

A(11) = 7.5390019E-02 A(33) = 3.082586
A(55) = 1.280156 A(66) = 2.9582383E-02
B(11) = 0.3214764 B(33) = 2.048813
B(55) = 1.021827 B(66) = 0.6598853
SURGE MOTION = 4.4834834E-02 PHASE = 4.990059
HEAVE MOTION = 2.7377877E-02 PHASE = 105.6903
PITCH MOTION = 0.1025326 PHASE = -142.5691
SURGE EX.FORCE = 0.2593369 PHASE = -163.6033
HEAVE EX.FORCE = 0.2441363 PHASE = -87.04454
PITCH EX.FORCE = 0.8155283 PHASE = 15.49182
DRIFT FORCE(X) = -0.7740943
DRIFT FORCE(Y) = 5.2098894E-16
DRIFT MOMENT(Z) = -4.4709400E-06

NONDIM.DRIFT FORCE(X) = -2.144765
NONDIM.DRIFT FORCE(Y) = 1.4434917E-05
DRIFT FORCE(X) = -1517225.
DRIFT FORCE(Y) = 10.21138

PERIOD = 11.70000
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A(11) = 0.1275623 A(33) = 3.062597
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B(55) = 1.121208 B(66) = 0.9045595
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HEAVE MOTION = 3.2951895E-02 PHASE = -68.69910
PITCH MOTION = 0.1872946 PHASE = -157.9673
**SURGE EX. FORCE** = 0.2638972  PHASE = -140.4422
**HEAVE EX. FORCE** = 0.8396516  PHASE = 73.97691
**PITCH EX. FORCE** = 0.8002200  PHASE = -12.14268
**DRIFT FORCE(X)** = -0.7553183
**DRIFT FORCE(Y)** = 5.542232E-06
**DRIFT MOMENT(Z)** = -4.4382136E-06

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**NONDIM. DRIFT FORCE(X)** = -2.092743
**NONDIM. DRIFT FORCE(Y)** = 1.5355732E-05
**DRIFT FORCE(X)** = -14080424.
**DRIFT FORCE(Y)** = 10.86277

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A(55) &= 1.120250 & A(66) &= -6.7451335E-02 \\
B(11) &= 0.3043473 & B(33) &= 2.730379 \\
B(55) &= 1.194106 & B(66) &= 0.9537278 \\
\end{align*}
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**HEAVE MOTION** = 4.6865162E-02  PHASE = -76.86198
**PITCH MOTION** = 0.1839830  PHASE = -158.6190
**SURGE EX. FORCE** = 0.2564668  PHASE = -130.9018
**HEAVE EX. FORCE** = 1.029890  PHASE = 68.88496
**PITCH EX. FORCE** = 0.6901658  PHASE = -19.72369
**DRIFT FORCE(X)** = -0.7697544
**DRIFT FORCE(Y)** = 4.9107415E-06
**DRIFT MOMENT(Z)** = -4.5415172E-06

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**NONDIM. DRIFT FORCE(Y)** = 1.3628242E-05
**DRIFT FORCE(X)** = -1508719.
**DRIFT FORCE(Y)** = 9.640734

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A(55) &= 1.294403 & A(66) &= -7.8644283E-02 \\
B(11) &= 0.2824962 & B(33) &= 1.811906 \\
B(55) &= 1.5553260 & B(66) &= 1.150317 \\
\end{align*}
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**SURGE MOTION** = 4.9662489E-02  PHASE = 109.6301
**HEAVE MOTION** = 0.1341617  PHASE = -85.77682
**PITCH MOTION** = 9.8325081E-02  PHASE = 140.2582
**SURGE EX. FORCE** = 0.3125671  PHASE = -99.10809
**HEAVE EX. FORCE** = 1.528415  PHASE = 60.53459
**PITCH EX. FORCE** = 0.2145327  PHASE = -142.5464
**DRIFT FORCE(X)** = -0.7965198
**DRIFT FORCE(Y)** = 5.1752227E-06
**DRIFT MOMENT(Z)** = -3.7233426E-06

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DRIFT FORCE(Y) = 9.185428

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B(11) = 0.2993926 B(33) = 1.977532
B(55) = 1.270134 B(66) = 1.951465
SURGE MOTION = 0.2188288 PHASE = 151.8098
HEAVE MOTION = 0.2953013 PHASE = -81.64592
PITCH MOTION = 0.3624818 PHASE = 137.2020

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DRIFT FORCE(Y) = 4.3319069E-06
DRIFT MOMENT(Z) = -2.7723227E-06

NONDIM. DRIFT FORCE(X) = -2.822466
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DRIFT FORCE(Y) = 8.490538

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PITCH MOTION = 0.4339815 PHASE = 0.8754120

DRIFT FORCE(X) = -1.051563
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B(11) = 0.2024144 B(33) = 3.837221
B(55) = 1.256968 B(66) = 0.3480621
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PITCH MOTION = 1.167558 PHASE = -59.84427
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HEAVE EX. FORCE = 2.112711 PHASE = 96.65406
PITCH EX. FORCE = 4.053880 PHASE = -31.01726
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DRIFT MOMENT(Z) = -1.4671841E-06

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DRIFT MOMENT(Z) = -1.4671841E-06

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B(11) = 0.2093822 B(33) = 3.623490
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SURGE MOTION = 1.549247 PHASE = 85.13668
HEAVE MOTION = 0.4001127 PHASE = 70.91006
PITCH MOTION = 1.202109 PHASE = -61.32797
SURGE EX. FORCE = 0.6325737 PHASE = -87.03609
HEAVE EX. FORCE = 2.262950 PHASE = 93.94488
PITCH EX. FORCE = 4.074016 PHASE = -33.78485
DRIFT FORCE(X) = -0.6958893
DRIFT FORCE(Y) = 1.1538474E-06
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SURGE MOTION = 1.549247 PHASE = 85.13668
HEAVE MOTION = 0.4001127 PHASE = 70.91006
PITCH MOTION = 1.202109 PHASE = -61.32797
SURGE EX. FORCE = 0.6325737 PHASE = -87.03609
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DRIFT MOMENT(Z) = -1.9713486E-06

PERIOD = 23.01134
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**Non-Dimensional Drift Force (Y)**: 4.0133386E-06  
**Drift Force (X)**: -1662926  
**Drift Force (Y)**: 2.839070

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**Periode**: 23.41493  
**Heading**: 180.0000

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**A(11)**: -0.1084876  
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**Pitch Motion**: 1.330886  
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**Surge EX. Force**: 0.7860499  
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**Heave EX. Force**: 2.402791  
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**Pitch EX. Force**: 4.082338  
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**Drift Force (X)**: -0.9904994  
**Drift Force (Y)**: 2.3797968E-06

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**Non-Dimensional Drift Force (X)**: -2.744353  
**Non-Dimensional Drift Force (Y)**: 6.5936465E-06  
**Drift Force (X)**: -1941379  
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**Periode**: 23.61706  
**Heading**: 180.0000

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**Drift Moment (Z)**: -3.563846E-06
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**PERIOD = 24.02203**
**HEADING = 180.0000**

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**PITCH MOTION = 1.436704 PHASE = -54.92307**

**SURGE EX.FORCE = 0.8896191 PHASE = -93.01843**
**HEAVE EX.FORCE = 2.405713 PHASE = 87.55592**

**PITCH EX.FORCE = 4.064487 PHASE = -40.57574**

**DRIFT FORCE(X) = -1.006484**
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**DRIFT MOMENT(Z) = -3.7133782E-06**

**NONDIM. DRIFT FORCE(X) = -1.029692**
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**DRIFT FORCE(X) = -728412.8**
**DRIFT FORCE(Y) = 1.984792**

**PERIOD = 25.03972**
**HEADING = 180.0000**

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**SURGE MOTION = 2.981128 PHASE = 153.9076**
**HEAVE MOTION = 0.1731873 PHASE = -152.1879**

**PITCH MOTION = 1.339232 PHASE = -43.54454**

**SURGE EX.FORCE = 1.003944 PHASE = -94.25017**
**HEAVE EX.FORCE = 2.296605 PHASE = 87.08833**

**PITCH EX.FORCE = 4.014759 PHASE = -42.10704**

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**DRIFT MOMENT(Z) = -2.6656157E-06**

**NONDIM. DRIFT FORCE(X) = -1.029692**
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**DRIFT FORCE(Y) = 1.984792**

**PERIOD = 25.03972**
**HEADING = 180.0000**

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B(11) = 1.480782 B(33) = -1.622577
B(55) = -0.1925129 B(66) = 9.1763414E-02

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HEAVE MOTION = 0.2757234 PHASE = -57.32018
PITCH MOTION = 0.6220089 PHASE = -38.10844

SURGE EX.FORCE = 1.583952 PHASE = 33.08762
HEAVE EX.FORCE = 0.6359894 PHASE = -61.19234
PITCH EX.FORCE = 2.942208 PHASE = -42.70970

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DRIFT FORCE(Y) = 2.1762523E-06
DRIFT MOMENT(Z) = -3.5625231E-07

NONDIM.DRIFT FORCE(X) = -2.544373
NONDIM.DRIFT FORCE(Y) = 6.0296911E-06
DRIFT FORCE(X) = -179991.1
DRIFT FORCE(Y) = 4.265455

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B(11) = 1.670278 B(33) = -1.813437
B(55) = -0.4545512 B(66) = 8.7442666E-02

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B(11) = 1.722938 B(33) = -0.8090822
B(55) = -0.7562411 B(66) = 7.9631351E-02

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HEAVE MOTION = 0.4871.64 PHASE = -57.95239
PITCH MOTION = 0.4827384 PHASE = -67.56287

SURGE EX.FORCE = 1.599567 PHASE = -65.76749
HEAVE EX.FORCE = 3.497462 PHASE = -36.57304
PITCH EX. FORCE = 2.150258  PHASE = -59.36693
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DRIFT FORCE(Y) = 2.370474E-06
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NONDIM. DRIFT FORCE(X) = -2.271415
NONDIM. DRIFT FORCE(Y) = 6.5678182E-06
DRIFT FORCE(X) = -1606816.
DRIFT FORCE(Y) = 4.646131

PERIOD = 27.52836
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A(55) = 1.631363  A(66) = 0.8579154
B(11) = 1.297312  B(33) = 1.329930
B(55) = -0.5732459  B(66) = 7.2665038E-02
SURGE MOTION = 1.471505  PHASE = 87.89336
HEAVE MOTION = 0.6203058  PHASE = -46.53110
PITCH MOTION = 0.6079775  PHASE = -80.44890
SURGE EX. FORCE = 1.378362  PHASE = -56.52956
HEAVE EX. FORCE = 4.911064  PHASE = -16.6108
PITCH EX. FORCE = 2.445283  PHASE = -77.06796
DRIFT FORCE(X) = 5.299657E-02
DRIFT FORCE(Y) = -1.3831197E-08
DRIFT MOMENT(Z) = 5.630503E-07

NONDIM. DRIFT FORCE(X) = 0.1468364
NONDIM. DRIFT FORCE(Y) = -3.8321769E-08
DRIFT FORCE(X) = 103873.3
DRIFT FORCE(Y) = -2.7109146E-02

PERIOD = 27.73975
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B(11) = 1.048208  B(33) = 2.223159
B(55) = -0.3988609  B(66) = 6.9484539E-02
SURGE MOTION = 1.574234  PHASE = 95.99165
HEAVE MOTION = 0.6613620  PHASE = -40.98555
PITCH MOTION = 0.6692080  PHASE = -81.25737
SURGE EX. FORCE = 1.254201  PHASE = -54.38551
HEAVE EX. FORCE = 5.319924  PHASE = -8.910408
PITCH EX. FORCE = 2.698105  PHASE = -80.54503
DRIFT FORCE(X) = 0.2309085
DRIFT FORCE(Y) = -1.383197E-08
DRIFT MOMENT(Z) = -1.9270342E-07

NONDIM. DRIFT FORCE(X) = 0.6397728
NONDIM. DRIFT FORCE(Y) = -2.4147600E-06
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PERIOD = 28.16478
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**Non-dimensional quantities**

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**Non-dimensional drift forces**

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DRIFT FORCE(X) = \(-3050.776\)
DRIFT FORCE(Y) = \(-0.2535849\)

PERIOD = 30.34333
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A(11) = 0.7684965  A(33) = 2.703272
A(55) = 1.651726  A(66) = 0.8015384
B(11) = 0.1091132  B(33) = 3.942914
B(55) = 0.3721719  B(66) = 4.1833557E-02

SURGE MOTION = 1.462135  PHASE = 122.1273
HEAVE MOTION = 0.7772608  PHASE = -14.31600
PITCH MOTION = 0.7676228  PHASE = -74.72955
SURGE EX. FORCE = 0.7588099  PHASE = -71.34511
HEAVE EX. FORCE = 6.292231  PHASE = 17.97323
PITCH EX. FORCE = 3.639745  PHASE = -82.37506
DRIFT FORCE(X) = -0.8552436E-02
DRIFT FORCE(Y) = 1.2460151E-07
DRIFT MOMENT(Z) = -9.7919803E-07

NONDIM. DRIFT FORCE(X) = -0.1902137
NONDIM. DRIFT FORCE(Y) = 3.4523049E-07
DRIFT FORCE(X) = -134558.8
DRIFT FORCE(Y) = 0.2442190

PERIOD = 30.90411
HEADING = 180.0000

A(11) = 0.7086224  A(33) = 3.001352
A(55) = 1.704812  A(66) = 0.7928462
B(11) = 7.9429023E-02  B(33) = 3.852900
B(55) = 0.3802421  B(66) = 3.7824165E-02

SURGE MOTION = 1.427968  PHASE = 122.2878
HEAVE MOTION = 0.7886963  PHASE = -12.51565
PITCH MOTION = 0.7515257  PHASE = -74.57765
SURGE EX. FORCE = 0.7442636  PHASE = -75.03093
HEAVE EX. FORCE = 6.390761  PHASE = 18.53978
PITCH EX. FORCE = 3.648444  PHASE = -82.91093
DRIFT FORCE(X) = -7.7003114E-02
DRIFT FORCE(Y) = 1.5606898E-07
DRIFT MOMENT(Z) = -9.5850589E-07

NONDIM. DRIFT FORCE(X) = -0.2133507
NONDIM. DRIFT FORCE(Y) = 4.3241664E-07
DRIFT FORCE(X) = -150926.1
DRIFT FORCE(Y) = 0.3058952

PERIOD = 32.04819
HEADING = 180.0000

A(11) = 0.6220578  A(33) = 3.444352
A(55) = 1.784179  A(66) = 0.7769696
B(11) = 4.6159085E-02  B(33) = 3.660193
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SURGE MOTION = 1.379750  PHASE = 121.5456
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Non-dimensional Drift Force (Y) = 4.9364530E-07
Drift Force (X) = -151994.1
Drift Force (Y) = 0.3492089

Period = 32.63234
Heading = 180.0000

| A(11)   | 0.5901325 |
| A(33)   | 3.616407  |
| A(55)   | 1.813407  |
| A(66)   | 0.7697201 |
| B(11)   | 3.6412328E-02 |
| B(33)   | 3.565932  |
| B(55)   | 0.3537261 |
| B(66)   | 2.8125452E-02 |

Surge Motion = 1.363367
Heave Motion = 0.8204814
Pitch Motion = 0.6990978

Surge Ex. Force = 0.7175267
Heave Ex. Force = 6.711522
Pitch Ex. Force = 3.604810

Drift Force (X) = -7.4537806E-02
Drift Force (Y) = 1.7258093E-07
Drift Moment (Z) = -7.5108477E-07

Non-dimensional Drift Force (X) = -0.2065211
Non-dimensional Drift Force (Y) = 4.7816593E-07
Drift Force (X) = -146094.1
Drift Force (Y) = 0.3382586

Period = 33.22512
Heading = 180.0000

| A(11)   | 0.5632117 |
| A(33)   | 3.767319  |
| A(55)   | 1.837530  |
| A(66)   | 0.7628774 |
| B(11)   | 2.9180052E-02 |
| B(33)   | 3.475045  |
| B(55)   | 0.3379664 |
| B(66)   | 2.5524773E-02 |

Surge Motion = 1.350372
Heave Motion = 0.8204814
Pitch Motion = 0.6990978

Surge Ex. Force = 0.7099004
Heave Ex. Force = 6.823321
Pitch Ex. Force = 3.577482

Drift Force (X) = -7.0767097E-02
Drift Force (Y) = 1.6923470E-07
Drift Moment (Z) = -6.4887053E-07

Non-dimensional Drift Force (X) = -0.1960727
Non-dimensional Drift Force (Y) = 4.6889457E-07
Drift Force (X) = -138703.5
Drift Force (Y) = 0.3317000

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### PERIOD

PERIOD = 34.43806

### HEADING

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### SURGE MOTION

SURGE MOTION = 1.332985

### HEAVE MOTION

HEAVE MOTION = 0.8480464

### PITCH MOTION

PITCH MOTION = 0.6480946

### SURGE EX. FORCE

SURGE EX. FORCE = 0.6942537

### HEAVE EX. FORCE

HEAVE EX. FORCE = 7.049265

### PITCH EX. FORCE

PITCH EX. FORCE = 3.512018

### DRIFT FORCE (X)

DRIFT FORCE (X) = -6.2529884E-02

### DRIFT FORCE (Y)

DRIFT FORCE (Y) = 1.5289093E-07

### DRIFT MOMENT (Z)

DRIFT MOMENT (Z) = -5.2768371E-07

### NONDIM. DRIFT FORCE (X)

NONDIM. DRIFT FORCE (X) = -0.1732501

### NONDIM. DRIFT FORCE (Y)

NONDIM. DRIFT FORCE (Y) = 4.2361128E-07

### DRIFT FORCE (X)

DRIFT FORCE (X) = -122558.6

### DRIFT FORCE (Y)

DRIFT FORCE (Y) = 0.2996662
APPENDIX H

MAIN SUBROUTINES IN PROGRAM DPORT2.FOR
Brief Description of Main Subroutines
in
Program DPORT

(in order of occurrence and with pertinent equations referenced from the text)

CHART computes the characteristics of the floating body
- coordinates of the centroids of the panels
- normals
- panel surface area
- restoring coefficient
- volume
- x-coordinate of center of buoyancy
- wetted surface area
- water plane area
(reads input file and calls subroutine VDOT)

PRNT1 prints to a file the data of the characteristics of the floating body

LINK1 computes elements of the Green's function matrix
(calls ROOTK, VSUB, GS2, GI2)

PHI78 calculates the PHI7, symmetric part, and PHI8, the anti-symmetric part

GINVER computes inverse of matrix DG and source Q
(calls INV)

POTEN computes the potential
(calls MPRD)
equation 4.23

AMASS computes added mass and damping coefficients
equations 4.19 and 4.20

EXFOR computes the exciting force
equation 4.21

AMPL computes the response amplitude
(calls INV)
equation 4.22
QTOTAL calculates the total Q for drifting force
equation 4.33

DRIFT calculates drifting force
(calls SIR)
equations 4.36 and 4.37

GI2 calculates Green's function by integral form
(calls DG16)

GS2 calculates Green's function by series form

MPRD computes \( R = A \times B \) where \( A(N \times M) \), \( B(M \times L) \)