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DESIGN OF A STABLE FLOATING PLATFORM FOR AIR-SEA INTERACTION MEASUREMENTS

by

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Abstract

The design of an oceanographic platform can be defined as the rational specification of the platform dimensions and geometry. This specification is usually the result of an iterative process which compares the platform performance with the objectives to be reached and the logistic constraints to be met. This report describes such an exercise.

The scientific objectives - measurements of heat flux at the ocean surface - are first outlined. The limits of heave and roll motion compatible with the desired measurement accuracy are then established. Given the stochastic nature of platform response, these limits are stipulated in terms of expected means.

A review is then made, in some detail, of the analytical approach followed and of the computer programs used to compute the statistical expectations of buoy heave and roll response to random sea excitation.

The next section of the report describes the comprehensive parametric study performed on some twenty different buoy configurations. The purpose of this study was first to investigate the dynamic response of a plausible base line design and of modified versions of the base line. A comparison of the dynamic response of these configurations could then be made, and the good features that this comparison would reveal could be used to design the buoy prototype. Following this approach a final configuration was specified which would meet the rather severe motion requirements (0.2 feet RMS in heave and 5.0 degrees RMS in roll in sea state 3).

The final section describes the techniques recommended to deploy and recover the 60 feet long buoy prototype.

Acknowledgements

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1. Platform Purpose and Design Constraints. Conceptual Spar Buoy.

1.1. Scientific Objectives

The objective of the project that is summarized in this report was to design a stable platform from which the following measurements could be made:

1. dry- and wet-bulb temperature
2. wind speed
3. ocean water temperature
4. net radiation
5. wave height

Items 1, 2 and 3 can be used to calculate the sensible and evaporative heat loss of the ocean by the profile method. These heat losses and Item 4 can be combined to obtain the total heat loss of the ocean, which is the scientific objective of the measurements.

Temperature and wind speed measurements were to be made at 6 logarithmically spaced stations located between 3 and 10 meters above the buoy's waterline (Figure 1). Wave height was to be measured by a wave gauge mounted at the waterline. The water temperature was to be measured at various depths.

The wave height measurements document the wave conditions. The water temperature measurements may be used to calculate temperature gradients caused by heat loss to the air.

1.2. Heave and Roll Stability Requirements

Acceptable limits on the buoy's motion were set by considering the errors that the motion would produce in calculated heat fluxes.

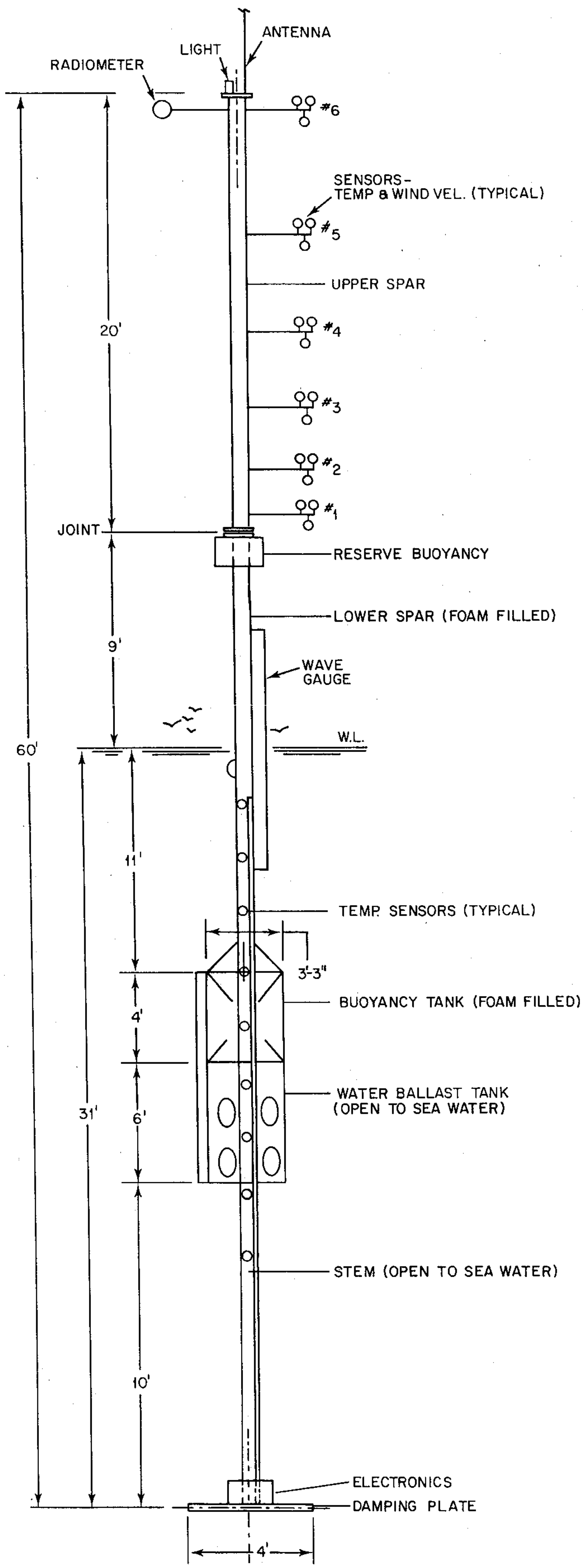

ANTENNA
LIGHT
RADIOMETER
#6
SENSORS-
TEMP & WIND VEL. (TYPICAL)
#5
UPPER SPAR
#4
20'
#3
#2
#1
JOINT
RESERVE BUOYANCY
LOWER SPAR (FOAM FILLED)
9'
WAVE
GAUGE
W.L.
60'
11'
TEMP. SENSORS (TYPICAL)
3'-3"
BUOYANCY TANK (FOAM FILLED)
4'
WATER BALLAST TANK
(OPEN TO SEA WATER)
31'
6'
STEM (OPEN TO SEA WATER)
10'
ELECTRONICS
DAMPING PLATE
4'

Figure 1

The RMS heave and RMS roll of the buoy were picked to describe its motion. The general consensus was that it would be unwise to attempt to launch or recover the buoy in greater than sea state 3. Consequently, the RMS motion limits were arbitrarily specified for sea state 3.

Some description of profiles and turbulent transport in the 10m above the sea is necessary to understand the analyses by which the RMS motion limits were calculated. This will be given next, and then the RMS motion limits will be derived.

Momentum and heat are transported away from the ocean's surface by turbulence. As a result of this transport, the wind speed U (associated with momentum transport), and temperature T and specific humidity q of the air (associated with heat transport) are not constant with respect to time or height above mean sea level (MSL). A time series of either U, T, or q comprises fluctuations about an average value. Thirty minute averages of a series are typically used in the profile method for describing heat and momentum transport. (The data from the buoy will be analyzed by application of the profile method.) The averages are functions of height Z above MSL that are described by

$$V = V_* \left(\ell n \frac{Z}{Z_o} - \Psi \left(\frac{Z}{L} \right) \right)$$

where: V is a 30 min average of either U, T, or q,

V_* and Z_o are constants, and

Ψ is a function of Z and of the stability of the atmosphere (which is described by L, the Monin-Obukhov length)

As Table 1 shows, if V represents T, then V_* is proportional to the sensible heat flow in the air Q_S, which is the heat transported by dry air in turbulent motion. Sensible heat is a manifestation of the heat capacity of the air. Similarly, if V represents q, then V_* is proportional to the evaporative heat flow in the air Q_E, which is the heat transported by water vapor. Evaporative heat flow is a manifestation of the latent heat of vaporization of water.

If averages of V are computed for two different heights Z_a and Z_b above MSL, their difference is described by

$$V_a - V_b = V_* \left(\ln \frac{Z_a}{Z_b} - \left(\psi(Z_a) - \psi(Z_b) \right) \right) \tag{2}$$

For the analysis described below, the difference of ψ is assumed to be small compared to $\ln Z_a/Z_b$.

$$\psi(Z_a) - \psi(Z_b) << \ln \frac{Z_a}{Z_b} \tag{3}$$

The terms involving ψ are then ignored and

$$V_a - V_b \cong V_* \ln \frac{Z_a}{Z_b} \tag{4}$$

As mentioned above, the profile method will be applied to measurements at a number of heights Z of U, T, and q (represented by V in Equations (2) and (4)) to obtain Q_S and Q_E (represented by V_* in Equations (2) and (4).

This can be done by using the method of least squares on Equation (4). The fitting parameter would be V_* and the data would

Table 1

Profile Variables and Constants

Profile	Variable, V	Constant, V_*
Momentum Flux	Wind Speed, U	$U_* = 0.0373\ U_{10}$ [1.]
Sensible Heat Flux, Q_S	Temperature, T	$T_* = Q_S/(0.4 \rho C_P U_*)$ [2.]
Evaporative Heat Flux, Q_E	Specific Humidity, q	$q_* = Q_E/(0.4 \rho \lambda\ U_*)$ [3.]

1. Subscript of U_{10} indicates measurement height (in meters) above MSL

2. ρ = density of air
   C_P = specific heat of dry air

3. λ = latent heat of vaporization of water

Table 2

Buoy Design Specifications
(Sea State 3)

Motion	Symbol	Specification	Period
Heave	h	6.0 cm	25 sec
Roll	θ_o	4.9°	25 sec

would be pairs of averages (V_a and V_b) and pairs of heights (Z_a and Z_b). When the value of each V_* (one for U, T, and q (Table 1)) is known, then Q_S and Q_E can be calculated.

For the analysis described here, the least squares procedure will be simulated by choosing Z_a and Z_b as follows:

1. Z_a will be the height (10m above MSL) of the top sensor
2. Z_b will be a geometric average of the heights of the top and bottom (3m above MSL) sensor

$$Z_b = \sqrt{30\ \text{m}} = 5.48\ \text{m} \tag{5}$$

The choice of Z_b is an attempt to simulate the averaging of a number of heights that would occur in the method of least squares. The calculation of V_* will be simulated by the solution of Equation (4) (for V_*).

$$V_* = \frac{(V_a - V_b)}{\ell n \dfrac{Z_a}{Z_b}} \tag{6}$$

All of the above discussion presumes that measurements are made at fixed heights above MSL.

The effects of the buoy's motion will be considered next. Its motion will be separated into heave and roll. These will be modeled by simple sinusoidal motions that are described by the following equations:

1. heave:

$$Z = Z_o + h \sin \omega_h t \tag{7}$$

2. roll:

$$Z = Z_c(\cos \theta - 1) + Z_o \cong Z_o - Z_c \frac{\theta^2}{2} \tag{8}$$

where

$$\theta = \theta_o \quad \sin \omega_r t \tag{9}$$

The buoy is assumed to roll about its center of mass CM. In these equations,

h = amplitude of heave motion

θ = roll angle

θ_o = amplitude of roll angle

ω_i = frequency of heave ($i = h$) or roll ($i = r$), and

Z_c = distance from the center of mass of the buoy to a point that is Z_o meters above MSL (Figure 2).

Note that sensors that would be Z_a and Z_b meters above MSL when the buoy is motionless, will occasionally be located $Z_a + Z_{ra}$ and $Z_b + Z_{rb}$ meters above MSL when the buoy is moving (as described by Equations (7), (8), and (9)). Here Z_{ra} and Z_{rb} are the RMS excursions of points that respectively are Z_a and Z_b meters above MSL. The equations for Z_r are

1. heave:

$$Z_r = \frac{\omega_n}{2\pi} \left[\int_o^{2\pi/\omega_h} (Z_o + h \sin \omega_h t)^2 \, dt - Z_o^2 \right]^{1/2} = \frac{h}{\sqrt{2}} \tag{10}$$

2. roll:

$$Z_{ri} = Z_{ci} \quad \frac{\theta_o^2}{2\sqrt{2}} \qquad (i = a, b) \tag{11}$$

where

$$Z_{ci} = Z_i + d \qquad (i = a, b) \tag{12}$$

In the last equation, Z_{ci} (Figure 2) is the distance of a point from the buoy's CM, and d is the distance from MSL to the CM (here $d \simeq 5.7$m). (Note that rolling motion always decreases the height of a sensor above MSL (Figure 2).)

If the buoy's motion were taken into account in the estimate of V_* (Equation (6)), a second estimate V'_* could be made

$$V'_* = \frac{V_a - V_b}{\ln\left|\frac{Z_a + Z_{ra}}{Z_b + Z_{rb}}\right|} \tag{13}$$

Since the buoy is moving, either estimate V_*, or V'_*, is likely to be valid, and the percent difference between these represents a measurement error that cannot be avoided. Thus, the percent uncertainty P in the estimate of V_* is

$$P = \left|\frac{V_* - V'_*}{V_*}\right| \simeq \left|\frac{V_* - V'_*}{V'_*}\right| \tag{14}$$

where

$$P \simeq \frac{\left|\frac{Z_{ra}}{Z_a} - \frac{Z_{rb}}{Z_b}\right|}{\ln\left|\frac{Z_a}{Z_b}\right|} \tag{15}$$

Note, for example, that V_* is proportional to Q_S if V = T. As a result, the percent uncertainty in Q_s is also P

$$\left|\frac{Q_S - Q'_S}{Q_S}\right| = P \tag{16}$$

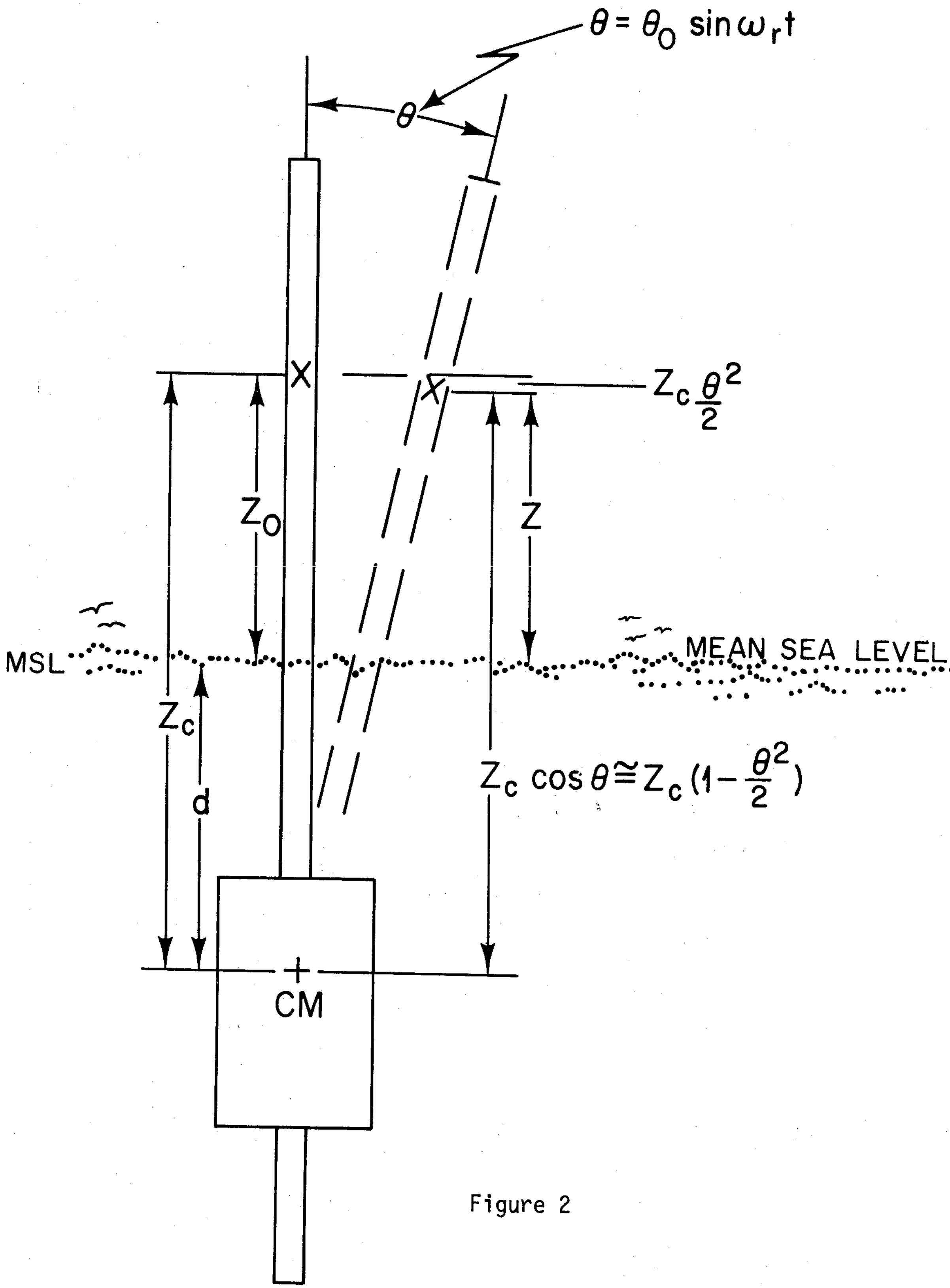

θ = θ0 sin ωr t
θ
Zc θ²/2
Zo
Z
MSL
MEAN SEA LEVEL
Zc
d
Zc cos θ ≅ Zc (1 − θ²/2)
CM

Figure 2

(Q_S' is the estimate of sensible heat obtained from V_*'.) A similar situation applies to q and to Q_E.

Equation (15) applies to either heave or roll motion. If P for roll is to be calculated, then $-Z_{ra}$ and $-Z_{rb}$ for roll (Equations (11) and (12)) must be substituted into Equation (13). (The minus signs are explained in the paragraph that contains Equation (12)). Similarly, if P for heave is to be calculated, the Z_{ra} and Z_{rb} for heave must be substituted.

If the errors for both heave and roll are specified as 0.5%, or

$$P = .005 \tag{17}$$

then the amplitudes of motion h or θ_o can be calculated from Equation (15) by substitution of either Equation (10) or Equations (11) and (12), respectively. The results of this calculation are tabulated in Table 2. These were used as the design specifications for the amplitude of the buoy's motion.

The design specifications for the buoy's natural periods of heave and roll were obtained by requiring that both be five times larger than a reasonable data sampling period of five seconds. This allows a sensor to sample three different elevations during one natural period of the buoy's motion and produces some spatial averaging. Hopefully, the spatial average of many samples will approach the average that would be obtained if the buoy were motionless.

1.3. Logistic Constraints

The type of measurements described above and the desire to launch and recover the buoy from as small a boat as possible create a number of problems. One problem is launch and recovery of the buoy. The sensors are delicate; they stick out from the buoy's centerline; they are placed on all sides of the buoy. These complicate the handling and storage under the best of conditions. And in moderate seas, once the buoy is partially in the water, the boat and the buoy can move independently, which increases the chance that the sensor arms or the wave gauge will be damaged by unavoidable collisions with the boat. For these reasons, the launch and recovery procedures were considered as part of the buoy design project (Section 5).

Another problem relates to the size of the boat required to safely handle the buoy. A large, heavy buoy requires large deck space for storage. It also requires large, heavy duty cranes for handling and a long, unobstructed expanse of rail for launching. A design philosophy that was used was that the frequency of use of a buoy is related to its ease of handling, and hence, to its size and weight. Thus, a large, heavy buoy would be used less frequently than a short, light one.

But the ease of handling conflicts directly with the need to minimize motion of the buoy. The motion of the buoy in the sea states for which it was intended is its most important design specification. This occurs because the magnitude of the buoy's motion determines the size of the systematic errors in the calculation of heat flux by the profile method. (Large motions introduce large errors.) A long, heavy buoy is more stable than a shorter, lighter one. Thus, a compromise had to be effected between the conflicting requirements of measurement accuracy and a large, stable buoy on one hand and the requirements of handling ease and a small light buoy on the other.

1.4. Tentative Buoy Design

A spar buoy of approximate dimensions to accomodate the scientific requirements and logistic constraints was designed by A.P.L. and W.H.O.I. This tentative design would serve as the base line for subsequent computer analysis and comparative study of base line modifications. This base line buoy was 60 feet long and weighed approximately 2,900 pounds (without water in the ballast tank). Solid ballast was adjusted for the water line to be 31 feet from the lower end of the buoy. The main components of the buoy were:

- A spar mast made of two sections of aluminum 6061T6 pipe. The upper section was made of 8'' schedule 10 pipe (8.625'' O.D. with 0.148'' wall thickness). The lower section was made of 8'' schedule 40 pipe (8.625'' O.D. with 0.322'' wall thickness). Both sections were 20 feet long. The two sections were flange bolted.
- A cylindrical buoyancy tank, made of aluminum, dimensions 3.25 feet diameter by 4.0 feet length. The buoyancy tank was

filled with 2 lbs/cu. ft foam. The top and bottom plates were 3/8" thick, the wall plate 3/16".

- A cylindrical water ballast tank also made of aluminum, same diameter as the buoyancy tank but with a length of 6.0 feet. Wall thickness 1/8". Holes in the wall permit free flooding of the tank.
- A circular damping plate, 4.0 feet in diameter, made of 1/2 inch thick aluminum. The damping plate supports the solid ballast and the electronic package.
- A stem, 20 feet long, made of 8 inch schedule 40 aluminum pipe, passing through the buoyancy and ballast tanks, and connecting the damping plate to the rest of the buoy.
- The instrumentation which included a net radiometer, 6 meteorological sensors, 9 water temperature sensors, and a wave gauge. The base line buoy design is depicted in Figure No. 1.

2. Description of Heave and Roll Response Analysis

2.1. Analytical Approach

2.1.1. Heave and Roll Response to Single Harmonic Wave

2.1.1.1. Assumptions

The mathematical models used in this study to investigate the heave and roll response of spar buoys to single harmonic waves are based on the following assumptions.

- The water particles move in circular orbits of exponentially decreasing amplitude, the parametric equations of their motion being:

$$\xi = A e^{-kz} \sin\omega t \tag{18}$$

$$\eta = A e^{-kz} \cos\omega t \tag{19}$$

  In these expressions A is the wave amplitude, ω the wave angular frequency, k the wave number ($k = \omega^2 / g$, g being the gravity acceleration) and z the depth below the mean water level.

- The diameter of the buoy is small compared to the wave length, and it is assumed that the presence of the buoy does not alter the shape of the wave.

- Drag and damping forces are linearly proportional to water particle and buoy velocity. Values for the linearized drag and damping coefficients are obtained by making the assumption that the actual nonlinear drag force and the equivalent linear damping force dissipate the same amount of energy per cycle.

- The center of roll is at the buoy center of gravity.
- Coupling between roll and heave is neglected, a fair assumption when dealing with axisymmetric buoys. (Reference No. 4)
- The buoy can be represented, for modeling at least, by a collection of hollow or solid cylinders of appropriate dimensions.

2.1.1.2 Equations of Heave and Roll Motion

a. Heave Motion

The differential equation of motion in heave is obtained from Newton's law

$$\sum_i F_i = (m + m')\ddot{x} = m_v \ddot{x} \tag{20}$$

where $\sum_i F_i$ is the sum of the vertical forces applied to the buoy, m is the buoy mass, m' is the added mass of the buoy due to the water entrained in the vertical direction, and $m_v = m + m'$ is the buoy virtual mass when moving in the vertical direction.

To illustrate the derivation of the equation of heave motion, let us consider a spar buoy with shape and dimensions as shown on Fig. 3 . The forces acting on this buoy are:

- Its weight "W"
- The resultant "P" of the pressure forces exerted by water particles on the top and bottom plates of the watertight compartments of the buoy. The pressure p at a depth z is given by

$$p = \rho g\,(z + Ae^{-kz} \cos\omega t) \tag{21}$$

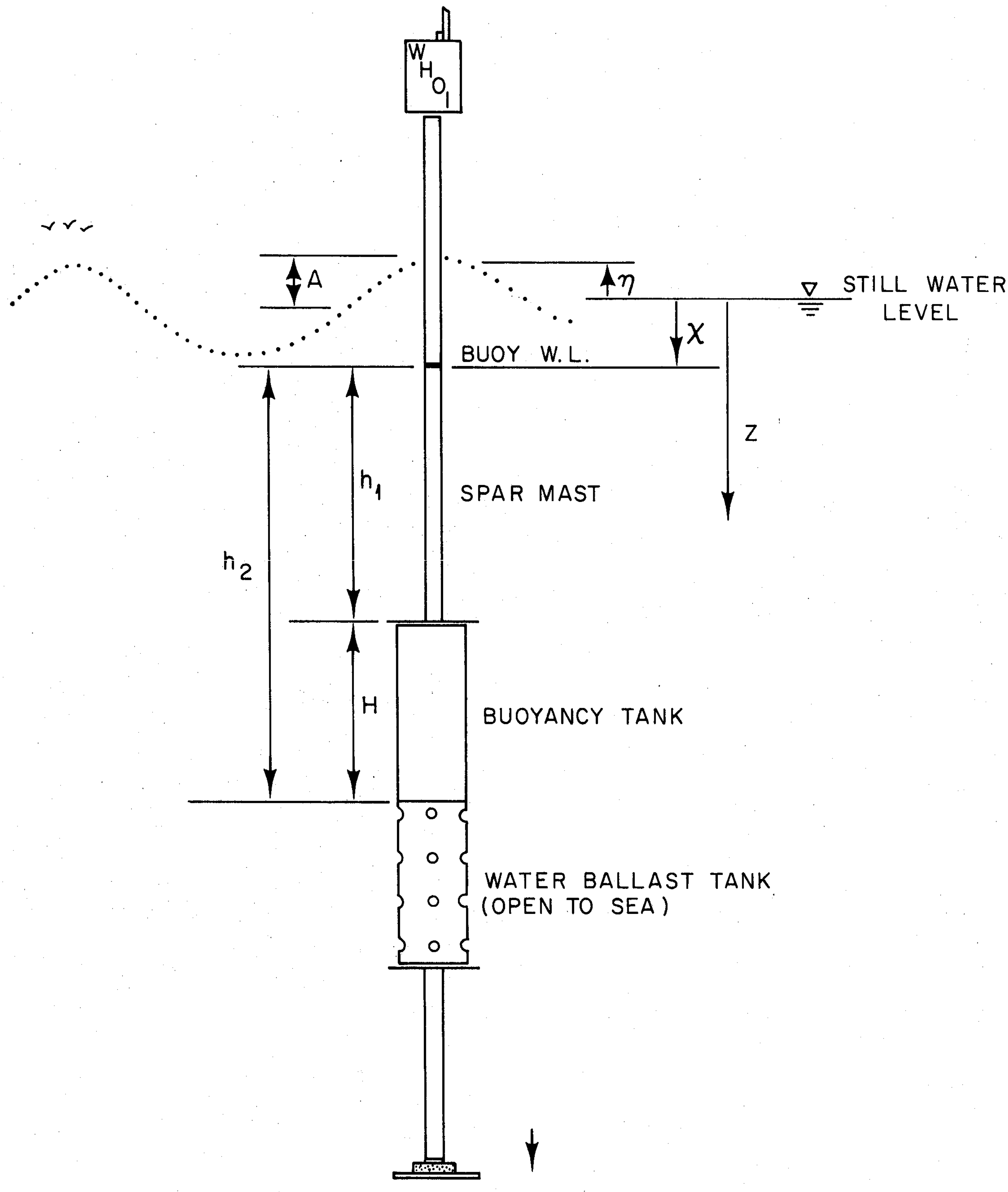

WHOI
A
η
STILL WATER LEVEL
χ
BUOY W.L.
Z
h_1
SPAR MAST
h_2
H
BUOYANCY TANK
WATER BALLAST TANK
(OPEN TO SEA)

Figure 3

At the bottom of the buoyancy tank

$$Z = x + h_2$$

where h_2 = depth of the bottom plate below buoy water line. Assuming $x \ll h_2$, the upwards pressure force P_B on the tank bottom is thus given by

$$P_B = \rho g \{ x + h_2 + Ae^{-kh_2} \cos \omega t \} S_B$$

where S_B = area of bottom plate subjected to water pressure (the entire area of the plate in this case).

Similarly the pressure force P_T on the top plate of the buoyancy tank is given by

$$P_T = \rho g \{x + h_1 + Ae^{-kh_1} \cos \omega t\} S_T$$

where S_T = area of top plate subjected to water pressure.

If the spar mast has a cross section S_M and is watertight, then obviously $S_T = S_B - S_M$. The resultant $\underline{P}$ will be the difference between the bottom pressure force and top pressure force. Being in the upwards direction, $\underline{P} = -(P_B - P_T)$ i.e.

$$\underline{P} = -\rho g \left\{ (S_B - S_T)\, x + (h_2 S_B - h_1 S_T) - A \cos\omega t \, (S_B e^{-kh_2} - S_T e^{-kh_1}) \right\}$$

The constant terms in the expression of the pressure force must equal the buoy static weight W. This can be easily established. Noting that

$$h_2 = h_1 + H$$

where H = length of the buoyancy tank, the constant terms

$$\rho g \,(S_B h_2 - S_T h_1)$$

can be written:

$$\rho\, g \left[S_B\,(h_1 + H) - S_T h_1 \right] = \rho\, g \left[(S_B - S_T)\, h_1 + S_B H \right]$$

which obviously is the sum of the weight of the water displaced by the immersed portion of the mast and by the buoyancy tank under equilibrium conditions, and therefore is equal to the buoy weight.

The sum of the weight force and the pressure force can then be in general expressed by:

$$P + W = -\rho g \; (S_B - S_T) \; x + (\rho g \sum_i e^{-kh_i} S_i) \; A \cos\omega t \qquad (22)$$

where S_i is the surface at a depth h_i subjected to the pressure. S_i is positive if the pressure exerted upon it is in the upwards direction, and vice versa S_i is negative if the pressure exerted upon it is in the downwards direction.

This expression can further be simplified and written:

$$P + W = - Cx + MA \cos \omega t \qquad (23)$$

where

$$C = \rho g \; (S_B - S_T) = \rho g \; S_M \qquad (24)$$

is the heave restoring force constant and

$$M = \rho g \sum_i S_i e^{-kh_i} = \rho g \sum_i S_i e^{-\frac{\omega^2}{g} h_i} \qquad (25)$$

The damping force "D", which is the sum of the individual damping forces exerted by the water which resists buoy vertical motion, i.e.

$$D = \sum_i \; D_i . \qquad (26)$$

The damping force D_i on a buoy component is assumed to be directly proportional to the buoy speed $\dot{x}$. It will therefore be of the form

$$D_i = -b_i \dot{x} \tag{27}$$

where b_i is the linearized coefficient of damping associated with buoy heave motion.

It can be shown (Reference No. 1) that the general expression of linearized damping coefficients "d" for periodic motion of amplitude X and frequency ω is of the form

$$d = \frac{4}{3\pi} \rho C_D SX\omega$$

where ρ = water mass density = 2 slugs/ft^3

C_D = conventional drag coefficient

S = area normal to the flow.

In order to keep the differential equation of heave motion linear, an arbitrary constant value $\overline{X}_b$ of average heave motion must be selected to compute the linearized damping coefficients b_i . The value of $\overline{X}_b$ selected is left as an input for the program users. One can use, for example, a reasonable fraction of the average wave amplitude for the sea state considered in a given study.

The expression of b_i then becomes

$$b_i = \frac{4}{3\pi} \rho C_{D_i} S_i \overline{X_b} \omega = \omega b_i'$$

The total damping force is thus finally

$$D = \sum_i D_i = -\omega\dot{x} \sum_i \frac{4}{3\pi} \rho C_{D_i} S_i \overline{X_b} \tag{28}$$

or simply

$$D = -B\dot{x} \tag{29}$$

with

$$B = \omega \sum_i \frac{4}{3\pi} \rho C_{D_i} S_i \overline{X}_b = \omega \sum_i b_i' \tag{30}$$

The induced drag force "G" which is the sum of the individual drag forces resulting from water particles impinging with a vertical velocity $\dot{\eta}$, i.e.

$$G = \sum_i G_i \tag{31}$$

The drag force G_i exerted on the buoy component "i" is again assumed to be linear and expressed by

$$G_i = C_i \dot{\eta} \tag{32}$$

where C_i is the linearized coefficient of drag associated with particle velocity.

Following previous reasoning the expression of C_i will be given by

$$C_i = \frac{4}{3\pi} \rho C_{D_i} S_i \overline{X_c} \omega = \omega C_i'$$

where $\overline{X}_c$ is now the arbitrary average value of wave amplitudes retained for the particular study.

A comment should also now be made regarding the water particle velocity $\dot{\eta}$. It will be recalled that the expression of $\dot{\eta}$ is

$$\dot{\eta} = - A\omega e^{-kz} \sin \omega t$$

In the case of a plate or a cylinder of small height placed at a distance h below the buoy W.L. and if $x \ll \eta$, then $z \doteq h$ and the speed of the water particles acting on this plate is well established. On the other hand, if the cylinder is one of considerable height, as for example the buoyancy tank shown in

Fig. No. 2 then the speeds at the top and at the bottom must be somehow averaged and replaced by a unique equivalent speed.

For simplicity, one could consider this averaged speed to be the speed at the depth of the cylinder midpoint. For the buoyancy tank previously mentioned this speed would then be:

$$A\omega e^{-k(h_1 + \frac{H}{2})} \sin\omega t$$

More appropriate values of equivalent depths could also be devised.

With these remarks in mind, the expression of the friction force becomes

$$G = \sum_i G_i = -A\omega \sin\omega t \rho \frac{4}{3\pi} \sum_i C_{D_i} S_i \overline{X}_c \omega e^{-kz_i} \tag{33}$$

z_i being the true or the equivalent depth of the component "i".

More simply written,

$$G = -NA\omega \sin\omega t \tag{34}$$

with

$$N = \omega \sum_i \frac{4}{3\pi} \rho C_{D_i} S_i \overline{X}_c e^{-kz_i} = \omega \sum_i C_i' e^{-\frac{\omega^2}{g} z_i}$$

The inertial force "I" which is the sum of the individual inertial forces produced by the water particles vertical acceleration $\ddot{\eta}$, i.e.

$$I = \sum_i I_i \tag{35}$$

The inertial force I_i exerted on the buoy component "i" is of the form:

$$I_i = m_i' \ddot{\eta} \tag{36}$$

where m_i' is the added mass of the component "i" and is given by:

$$m_i' = \rho C_{m_i} V_i \tag{37}$$

with C_{m_i} = added mass coefficient of component "i"

V_i = volume of the ith component (ft^3).

The values of C_{m_i} and V_i depending of course on the dimensions and shape of the component "i", are left as an input for the program users.

The remarks on the averaged value of the water particle speed also apply for the water particle acceleration.

The expression of the inertial force "I" is therefore given by

$$I = \sum_i I_i = -A\omega^2 \cos \omega t \sum_i m'_i \, e^{-kz_i} \tag{38}$$

or simply,

$$I = -QA\,\omega^2 \cos \omega t \tag{39}$$

with

$$Q = \sum_i m'_i e^{-kz_i} = \rho \sum_i C_{m_i} V_i \, e^{-\frac{\omega^2}{g} z_i} \tag{40}$$

Using the force expression yields the differential equation of heave motion of the buoy, namely:

$$-C_x + MA\cos\omega t - B\dot{x} - NA\omega \sin\omega t - QA\omega^2 \cos\omega t = m_v \ddot{x} \tag{41}$$

or,

$$Cx + B\dot{x} + m_v\ddot{x} = A\{(M - \omega^2 Q)\cos\omega t - N\omega \sin\omega t\} \tag{42}$$

This expression can be further reduced to:

$$Cx + B\dot{x} + m_v\ddot{x} = F_o \cos(\omega t + \sigma) \tag{43}$$

where F_o, the exciting force is given by

$$F_o = A\sqrt{(M - Q\omega^2)^2 + (N\omega)^2} \tag{44}$$

and σ , the phase angle between the wave and the force is given by

$$\sigma = \tan^{-1} \frac{N\omega}{M - \omega^2 Q} \tag{45}$$

The integration of this differential equation yields the heave response of the buoy to a simple harmonic wave (Reference No. 2). The heave expression is then:

$$x = \frac{A\sqrt{(M - \omega^2 Q)^2 + (N\omega)^2}}{\sqrt{(C - m_v\,\omega^2)^2 + (\omega B)^2}} \cos(\omega t + \sigma + \psi) \qquad (46)$$

where ψ, the phase angle between the exciting force and the heave response is in turn given by:

$$\psi = \tan^{-1} \frac{-\omega^2 \sum_i b_i}{\rho g S_M - m_v\,\omega^2} \qquad (47)$$

Finally the phase angle ϕ between wave and heave response is the sum of the phase angles σ and ψ, that is

$$\phi = \sigma + \psi \qquad (48)$$

b. Roll Motion

The differential equation of roll motion is obtained with the help of Newton's law for rotating bodies, namely:

$$\sum_i M_i = (I + I_F)\,\ddot{\theta} = I_v\,\ddot{\theta} \qquad (49)$$

where $\sum_i M_i$ = sum of the moments applied to the buoy

I = moment of inertia with respect to the buoy center of gravity (c.g.)

I_F = added moment of inertia due to entrained water, also with respect to buoy c.g.

I_v = virtual moment of inertia = $I + I_F$

The moments applied to the buoy are:

- The righting moment "M_r", which opposes roll motion. Its value is given by:

$$M_r = - W\overline{gm}\,(\theta - \phi) \tag{50}$$

where θ is the angle of roll measured from the vertical, ϕ is the wave slope, and $\overline{gm}$ is the distance from the buoy c.g. to the buoy metacenter.

Thus,

$$M_r = - W\overline{gm}\,(\theta - kA \sin \omega t) \tag{51}$$

- The damping moment "M_D", produced by the damping forces resisting the buoy roll motion. Its expression is derived as follows.

Let us consider an elementary buoy section at a distance r from the buoy c.g. (see Fig. No. 4).

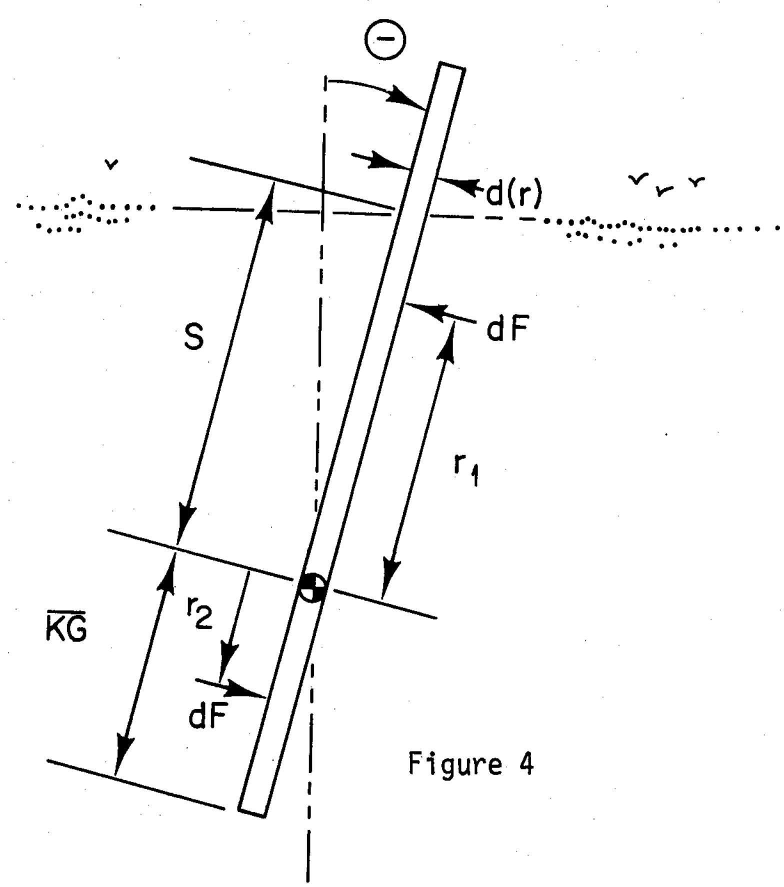


Figure 4

The elementary damping force on this element will be assumed to be of the form:

$$dF_D = b(r)\, r\, \dot{\theta} \cos\theta$$

or, for small angles of roll

$$dF_D = b(r)\, r\, \dot{\theta}$$

where b (r) is a linearized damping coefficient again given by:

$$b(r) = \frac{4}{3\pi}\, \rho\, C_D\, S(r)\, X(r)\, \omega$$

with

ρ = fluid density = 2 slugs/ft^3

C_D = drag coefficient for cylinders, normal flow

$S(r)$ = area across the flow = $d(r)\,dr$ with $d(r)$ the cylinder diameter at distance r

$X(r)$ = amplitude of cyclic motion at distance r

$X(r)$ = $r\,\theta$ (in order to keep the equation of motion linear an arbitrary constant value of θ must be selected, say $\theta = \bar{\theta}$).

ω = angular frequency of cyclic motion, which under steady state conditions should equal the frequency of the exciting wave.

The expression of the damping force thus becomes:

$$dF_D = \left(\frac{4}{3\pi}\, \rho\, C_D\, \bar{\theta}\, \omega\, d(r)\, r\, dr \right) r\, \dot{\theta}$$

or

$$dF_D = \alpha\omega\, d(r)\, r^2\, dr\, \dot{\theta}$$

where

$$\alpha = \frac{4}{3\pi}\, \rho C_D\, \bar{\theta}$$

The moment of this elementary force is:

$$dM_D = -r F_D = -\alpha \omega \dot{\theta} d(r) r^3 dr$$

and the total damping moment is found from

$$M_D = -\alpha \dot{\theta} \omega \left\{ \int_{r_1 = o}^{r_1 = s} d(r_1) r_1^3 dr_1 + \int_{r_2 = o}^{r_2 = \overline{kg}} d(r_2) r_2^3 dr_2 \right\} \quad (52)$$

or

$$M_D = -B \dot{\theta} \quad (53)$$

where

$$B = -\alpha \omega \left\{ \int_{r_1 = o}^{r_1 = s} d(r_1) r_1^3 dr_1 + \int_{r_2 = o}^{r_2 = \overline{kg}} d(r_2) r_2^3 dr_2 \right\} \quad (54)$$

The wave drag moment M_F due to drag forces produced by the water particles' horizontal velocity impinging on the different buoy sections. Above the c.g. these forces will tend to capsize the buoy. Below the c.g. these forces will tend to upright the buoy. The expression of the wave drag moment is derived as follows.

Consider again an elementary buoy section of area $d(r) dr$ at a distance r from the buoy center of gravity (Fig. 5). The elementary drag force due to the water horizontal velocity on this elementary section will be assumed to be of the form:

$$dF_F = c(r) \dot{\xi}$$

where $c(r)$ the linearized damping coefficient, will be expressed by:

$$c(r) = \frac{4}{3\pi} \rho C_D S(r) X(r) \omega$$

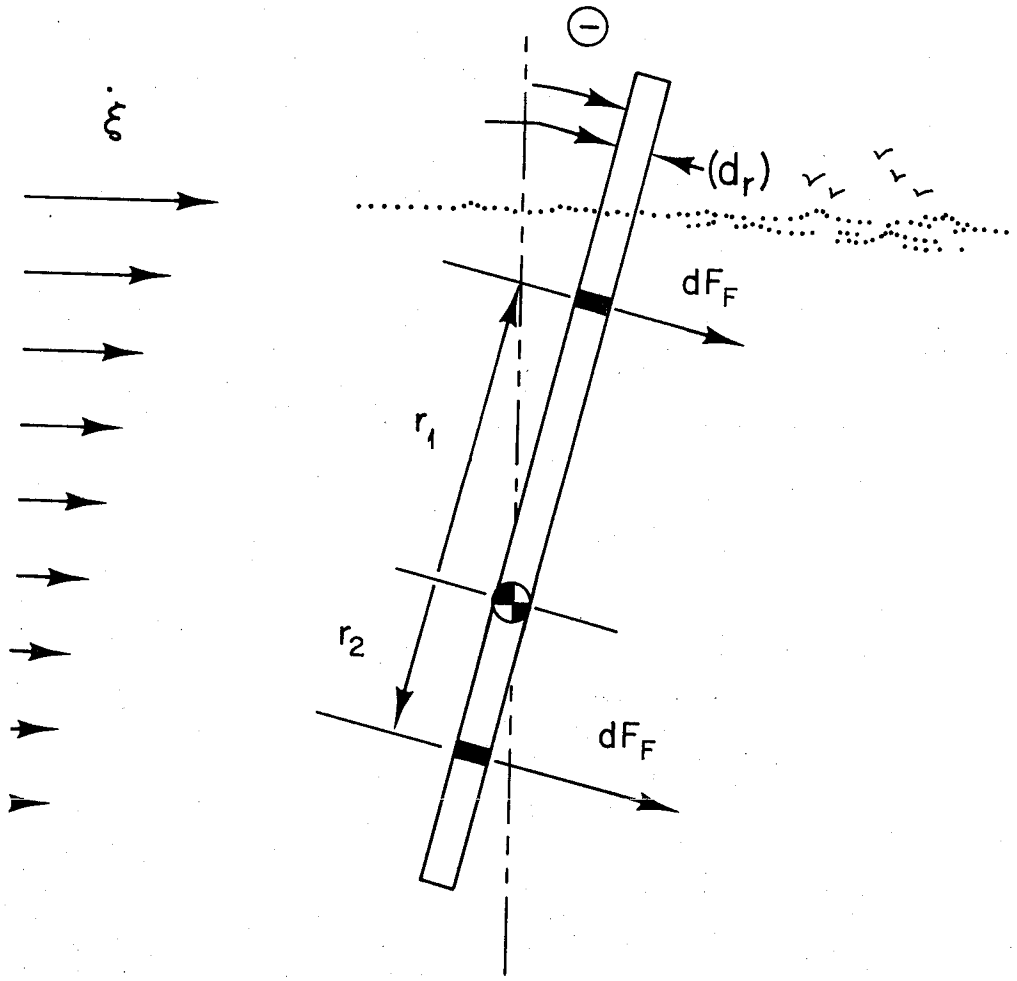


Figure 5

X(r) in this case is the amplitude of the water particle cyclic motion and is therefore given by

$$X(r) = Ae^{-kz}$$

Here again, in order to maintain linearity, an arbitrary constant amplitude $\overline{A}_F$ must be selected. One could for example, select the average amplitude $\overline{A}$ of the waves in the particular sea state.

With these remarks in mind, the expression of c(r) can be written:

$$c(r) = \frac{4}{3\pi} \rho C_D d(r)\, dr\, \overline{A}_F \omega e^{-kz}$$

or

$$c(r) = \beta d(r) e^{-kz} dr$$

where

$$\beta = \omega \frac{4}{3\pi} \rho C_D \overline{A}_F$$

The expression of the elementary drag force dF_F thus becomes

$$dF_F = \beta A \omega \cos\omega t\, e^{-2kz} d(r)\, dr$$

The moment of this elementary force is in turn:

$$dM_F = r dF_F = \beta A \omega \cos \omega t\, d(r)\, r e^{-2kz} dr$$

The expression of the wave drag moment is thus given by:

$$M_F = \omega \beta A \cos\omega t \left\{ \int_{r_1 = o}^{r_1 = s} d(r_1) r_1 e^{-2kz} dr_1 - \int_{r_2 = o}^{r_2 = \overline{kg}} d(r_2) r_2 e^{-2kz} dr_2 \right\} \quad (55)$$

or

$$M_F = DA\omega \cos \omega t \quad (56)$$

where

$$D = \beta \left\{ \int_{r_1 = o}^{r_1 = s} d(r_1) r_1 e^{-2kz} dr_1 - \int_{r_2 = o}^{r_2 = \overline{kg}} d(r_2) r_2 e^{-2kz} dr_2 \right\} \quad (57)$$

The wave inertia moment M_I induced by the water particle horizontal acceleration acting on the different buoy sections. The elementary inertia force dI acting on an elementary buoy volume

$$dV = \frac{\pi}{4} d(r)^2 dr$$

is of the form:

$$dI = C_m \rho dV \ddot{\xi} \cos\theta$$

or, for small angles θ ,

$$dI = C_m \rho \frac{\pi}{4} d(r)^2 \ddot{\xi} \, dr$$

where C_m = coefficient of added mass for cylinders. This elementary force can be more simply written:

$$dI = \gamma \ddot{\xi} d(r)^2 \, dr$$

with

$$\gamma = \frac{\pi}{4} \rho C_m$$

The moment with respect to the c.g. of this elementary force is in turn given by

$$dM_I = \gamma \, d(r)^2 \, r \, \ddot{\xi} \, dr$$

$$= \gamma\omega^2 A \sin \omega t \, d(r)^2 \, r e^{-kz} dr$$

Noting again (Fig. 6) that inertia forces due to the wave action have a tendency to upright the buoy above the c.g. and to capsize it below the c.g., the expression of the total moment will be given by:

$$M_I = \gamma\omega^2 A \sin\omega t \left\{ \int_{r_1 = o}^{r_1 = s} d(r_1)^2 r e^{-kz} dr_1 + \int_{r_2 = o}^{r_2 = \overline{kg}} d(r_2)^2 r_2 e^{-kz} dr_2 \right\} \quad (56)$$

or,

$$M_I = PA\omega^2 \sin\omega t \quad (57)$$

Before the equation of roll can be written, the expression for the added moment of inertia I_F must also be established.

The added mass of an elementary buoy section of volume dV,

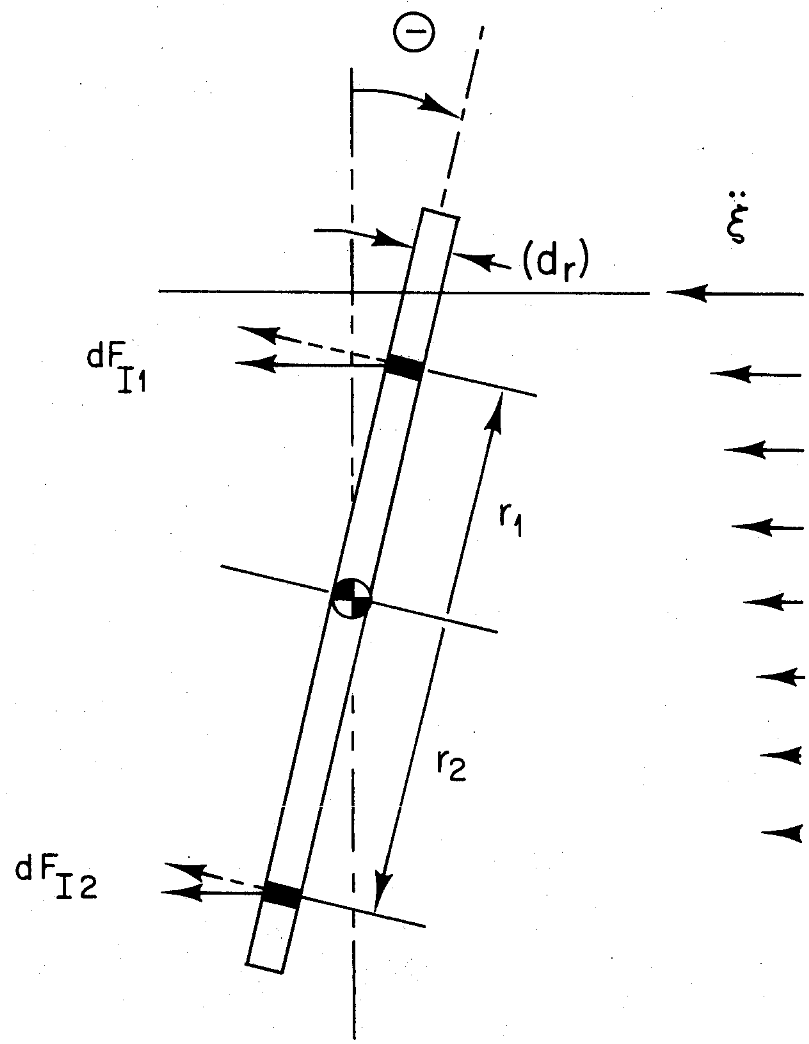


Figure 6

located at a distance r from the buoy c.g. is given by

$$dm' = C_m \rho \; dV$$

C_m = added mass coefficient = 1 for cylinders.

The moment of inertia of this elementary mass with respect to the c.g. is:

$$dI_F = r^2 \, dm' = r^2 \rho \, dV$$

and the total moment of inertia is

$$I_F = \int dI_F = \rho \iiint r^2 \, dV \qquad (58)$$

Thus I_F is simply the moment of inertia of the water displaced by the buoy with respect to the buoy c.g.

Summing the moments and applying the angular form of Newton's law yield:

$$-W\overline{gm}(\theta - \frac{\omega^2}{g} A\sin\omega t) - B\dot{\theta} + DA\omega\cos\omega t + PA\omega^2\sin\omega t = (I + I_F)\ddot{\theta} \quad (59)$$

The resulting equation of motion is then:

$$I_v\ddot{\theta} + B\dot{\theta} + C\theta = A\left\{ (\frac{\omega^2 C}{g} + P\omega^2) \sin\omega t + D\omega\cos\omega t \right\} \quad (60)$$

where $C = W\overline{gm}$ is the roll restoring constant.

The equation of roll motion can be further reduced to:

$$C\theta + B\dot{\theta} + I_v\ddot{\theta} = M\cos(\omega t + \sigma) \quad (61)$$

where M , the exciting torque due to wave action is given by

$$M = A\sqrt{(\frac{C\omega^2}{g} + P\omega^2)^2 + (D\omega)^2} \quad (62)$$

and σ the phase angle between wave and resulting torque is in turn given by:

$$\sigma = -\tan^{-1}\frac{\frac{C\omega^2}{g} + P\omega^2}{D\omega} \quad (63)$$

The expression of the roll response to single harmonic waves is obtained by integration of the roll equation. The result of this integration is

$$\theta = \frac{A\sqrt{(\frac{C\omega^2}{g} + P\omega^2)^2 + (D\omega)^2}}{\sqrt{(C - I_v\omega^2)^2 + (\omega B)^2}} \cos(\omega t + \sigma + \psi) \quad (64)$$

The phase angle ψ between the exciting torque and the roll response is in turn given by:

$$\psi = \tan^{-1}\frac{\omega B}{C - I_v\omega^2} \quad (65)$$

Finally the phase angle Φ between wave and roll response will be the sum of the two, i.e.

$$\Phi = \sigma + \psi \quad (66)$$

2.1.2. Heave and Roll Response to Random Sea

Readers unfamiliar with the probabilistic theory of ship and buoy dynamics should consult References 1, 3, and 5 for a theoretical review of the subject.

Regular swells of the kind represented by simple harmonic waves are exceptional seaways. Randomness of the sea surface prevails most of the time. Confronted with this irregularity, one must resort to statistical analysis to describe the buoy dynamic response in terms of means and maxima which are likely to occur.

If the probability density function p(x) of the wave amplitudes "x" for a given seaway can be explicitly expressed, then the expectation of certain values of wave amplitudes can be directly computed.

For example:

- The most probable amplitude x_m is the value of x for which

$$\frac{d}{dx} p(x) = 0$$

- The average amplitude x is given by

$$x = \int_0^{\infty} x p(x) \, dx$$

- The average of a fraction f ($o \leq f \leq 1$) of wave amplitudes larger than a given amplitude x_o can be obtained

$$x_f = \frac{\int_{x_o}^{\infty} x \, p(x) \, dx}{\int_{x_o}^{\infty} p(x) \, dx} = \frac{1}{f} \int_{x_o}^{\infty} x \, p(x) \, dx$$

When certain restrictive conditions prevail, wave amplitudes have been found to follow a Rayleigh distribution given by:

$$p(x) = \frac{2x}{\overline{x^2}} e^{-\frac{x^2}{\overline{x^2}}} \tag{67}$$

where $\overline{x^2}$ is the mean square value of the wave amplitudes.

When this probability function is used to compute the expectation of wave amplitudes means and maxima, the results are found to be proportional to the root mean square (RMS) value of the wave amplitudes (see Tables 3 and 4).

Table 3

Wave Amplitude Means

Fraction, f , of Largest Amplitudes Considered	Mean Values $x_f \div \sqrt{\overline{x^2}}$ or $x_f \div$ RMS
0.01	2.359
0.10	1.800
0.333	1.416
0.50	1,256
1.00	0.886

Table 4

Expected Maximum Amplitudes

Number of Waves	Maximum Wave Amplitudes $x_{max} \div \sqrt{\overline{x^2}}$ or $x_{max} \div$ RMS
50	2.12
100	2.28
500	2.61
1,000	2.78
10,000	3.13
100,000	3.47

When wave measurements are available, the RMS can be directly obtained from the record. On the other hand, if no measurements are available, and if the expected values of wave amplitude are to be predicted for a certain seaway, then the RMS must be derived by computation. This is done with the help of the spectral density $S(\omega)$ which best characterizes the particular seaway. Assuming the seaway to be stationary, then the integral over all positive frequency ranges of $S(\omega)$ is equal to the mean square value of the wave amplitudes, i.e.

$$\overline{x^2} = \int_0^\infty S(\omega)\, d\omega$$

Therefore this result can be used to compute $\overline{x^2}$ and $\sqrt{\overline{x^2}}$. The value of $\sqrt{\overline{x^2}}$ thus obtained can in turn be used to compute the expected wave amplitude means and maxima listed in Tables 1 and 2.

The empirical wave spectrum formula used in this study is:

$$S(\omega) = \frac{16.875\, e^{-\frac{9.7 \times 10^4}{v^4\, \omega^4}}}{\omega^5} \quad \text{ft}^2 - \text{sec} \tag{68}$$

where v is the wind speed (knots). (Pierson-Moskowitz)

The approach followed to investigate the response of the buoy to random seaways is based on the linearization of the buoy response to single harmonic waves. This response being linear, the assumption can safely be made that the buoy response to a sum of sinusoids describing the seaway equals the sum of the responses to the individual sinusoids.

The amplitude $Y(\omega)$ of the buoy response to a simple harmonic wave of unit amplitude and frequency ω is usually called the Response Amplitude Operator (RAO). Thus, based on our previous derivation, the RAO's of heave and roll are respectively given by:

$$\text{HEAVE RAO} = \sqrt{\frac{(M - \omega^2 Q)^2 + (N\omega)^2}{(C - m_v\omega^2)^2 + (\omega B)^2}} \tag{69}$$

$$\text{ROLL RAO} = \sqrt{\frac{\left(\frac{C\omega^2}{g} + P\omega^2\right)^2 + (D\omega)^2}{(C - I_v\omega^2)^2 + (\omega B)^2}} \tag{70}$$

The response of the buoy to a component wave of the spectrum is given by

$$\lim_{d\omega \to 0} Y(\omega)\sqrt{S(\omega)\, d\omega}$$

The quantity

$$Y^2(\omega)\, S(\omega)\, d\omega \tag{71}$$

thus represents the mean square value of the response in the frequency band $d\omega$.

The mean square value of the response to all component waves will therefore be

$$\overline{r^2} = \int_0^\infty Y^2(\omega) \; S(\omega)\, d\omega = \int_0^\infty R(\omega)\, d\omega = R \tag{72}$$

from which the response RMS can be simply computed, i.e.

$$RMS = \sqrt{R} \tag{73}$$

The response $Y(\omega)$ of the body being linear, the probability density function of the response will also follow the probability density function of the wave amplitudes. Thus the results tabulated in Tables 3 and 4 can be used again, together with the computed response RMS to derive the statistical means and maxima of body response amplitude.

For example, the average of the one third highest response amplitudes will be given by

$$r_{1/3} = 1.416 \sqrt{\overline{r^2}}$$

with

$$\sqrt{\overline{r^2}} = \sqrt{\int_0^\infty Y^2(\omega) \; S(\omega) \; d\omega}$$

2.2. Computer Solution

The computer programs which implement the analytical approach just reviewed are fully described in Reference No. 2.

2.2.1. Computation of Response Amplitude Operators and Statistical Expectations

The operations performed by the heave and roll analysis computer programs are hereafter briefly reviewed.

HEAVE

- The program computes the heave RAO using formula (69) for decreasing values of the wave angular frequency ω.

  The recurrence formula used to change the value of the angular frequency between two consecutive computations of the RAO is

$$\omega_n = \frac{2\pi}{T_{n-1} + \Delta T}$$

  where ΔT, the change in wave period is constant. The value of ΔT to use for a particular set of computations is left as a program input, and so is the range of variation of wave periods to be considered.

- It computes the phase angles between force and wave, heave and force, and heave and wave using formulas (45, 47, 48) for the same set of angular frequencies $\{\omega_n\}$.

- It computes the wave amplitudes spectral density using formula (68) for the same set of $\{\omega_n\}$.

- It computes the heave response spectral density $R(\omega)$ using formula (71) and the computed values of the RAO for the selected set $\{\omega_n\}$.

- It computes the root mean square values of the wave amplitudes and of the heave response amplitudes by taking, as suggested by formulas (72) and (73), the square root of the area under the wave and heave amplitudes spectral density curves established for the set $\{\omega_n\}$.
- It uses the statistical results of Tables 3 and 4 and the two root mean square values of wave amplitudes and heave response to compute the corresponding expectations of wave and heave means and maxima.

ROLL

The operations performed by the roll computer program are similar to those performed by the heave program. They include:

- Computation of the roll RAO, using formula (70) over the set $\{\omega_n\}$. previously defined. The roll RAO is expressed in units of degrees of roll per foot of wave amplitude.
- Computation of the phase angles between external torque and wave, roll response and torque, and roll and wave using formulas (63, 65, 66) for the same set $\{\omega_n\}$.
- Computation of the wave amplitude and roll response spectral densities $S(\omega)$ and $R(\omega)$ and of the root mean square values of wave amplitudes and roll amplitudes.
- Finally, computations of expectations of means and maxima of wave and roll amplitudes with the help of the statistical parameters shown in Tables 3 and 4.

2.2.2. Programs Output

The outputs of the heave and roll programs include:

1. Summary of the input parameters and physical properties of the buoy.

2. Listing of RAO's values, phase angles, amplitude spectrum as a function of wave period increments.

3. Tabular summaries of wave and roll response statistical properties.

4. Plot of the RAO (optional).

As an example of typical computer outputs, the heave and roll output data for the tentative (APL first cut) buoy design described in section 1.4 are presented in Appendix I. These data include:

- The summary of input parameters furnished for the heave and roll programs.
- A complete listing of the heave and roll RAO's and phase angles by period intervals of 1 second.
- The summary of the wave amplitudes and heave and roll statistical properties for winds of 16 knots.
- The printer plots of the heave and roll RAO's.

2.2.3. Interpretation of Computer Results

The immediate usefulness of RAO's is that they permit easy prediction of the buoy response to a wave of known amplitude and frequency. For example, if the roll response - as can be seen from the buoy roll RAO listing - of the buoy to a wave of one foot amplitude and with a period 7.0 seconds is 1.277 degree/foot, then the roll response of this buoy to a 4 feet amplitude wave of the same period should be 5.108 degrees. Another very useful feature provided by inspection of the RAO listings or graph, is the resonant period and the amplitude of the response to a unit wave at resonance (maximum heave/roll RAO).

The listing of the sea spectrum yields the wave period with maximum energy content. This information can then be used to investigate how close the buoy response resonant period is to this wave period and to determine the response amplitude of the buoy to waves with maximum energy content. This investigation can be very useful when considering survival conditions.

The listing of the statistical properties include:

- The most probable and the RMS values of the wave and heave/roll amplitudes.
- The means of the wave and heave/roll amplitudes. For example, the average of the one tenth highest waves, with 16 knots wind, will be found to be 4.087 feet, the significant angle of roll (the average of the one third highest angles of roll) to be 2.173 degrees, and the mean of all heave amplitudes to be .629 feet.
- Certain values of expected wave and heave/roll maximum amplitudes. For example, in 1,000 waves one wave amplitude may be expected to be as large as 4.816 feet, and the buoy may be expected to roll as much as 4.265 degrees.

Computer results used to compare the different buoy configurations for this parametric study did at least include:

- The natural period of heave.
- The maximum heave RAO.
- The heave RAO at periods T = 7 sec. and 16 seconds which are the periods of maximum wave energy for winds of 16 knots (design) and 40 knots (survival).
- The average heave for winds of 16 and 40 knots.
- The RMS value of heave for winds of 16 and 40 knots.
- The natural period of roll.
- The maximum roll RAO.
- The roll RAO at periods of 7 and 16 seconds.
- The average roll for winds of 16 and 40 knots.
- The RMS value of roll for winds of 16 and 40 knots.

3. Design Steps

For the scope of this study, buoy design meant specifying the buoy external dimensions, the weight and buoyancy distribution, and the location of vertical and horizontal dampers which, on one hand, would accomodate the scientific payload requirements, and on the other hand, would insure that the buoy heave and roll motions would fall within the prescribed limits. These limits, as previously mentioned, were rather severe, namely:

1. The buoy's heave amplitudes were to be less than 6.0 centimeters (or 0.196 foot) in and up to including sea state 3 (winds of 16 knots).
2. The buoy roll amplitudes were to be less than 4.9 degrees for the same sea conditions.

A study of buoy survival under more severe conditions (sea state 8, winds up to 40 knots) was also made.

3.1. First Parametric Study

The objective of this first parametric study was to establish the dynamic response of the APL first cut buoy design, hereafter called the base line, and of a number of other buoy shapes obtained by plausible alterations of the base line. A comparison of the dynamic response of these buoys would show trends and the good features could thus be kept and incorporated in an improved design.

Fourteen buoy configurations, numbered 01 to 14, were investigated in this first design iteration. The buoys were modeled with the help of hollow and solid cylinders of such dimensions and density as to reproduce the weight and the weight distribution of the actual buoys. Damping plates, however, are treated as actual plates by the program. The computer equivalent of the base line is depicted in Fig. 7. The configurations of the 14 cases studied are shown in Fig. 8.

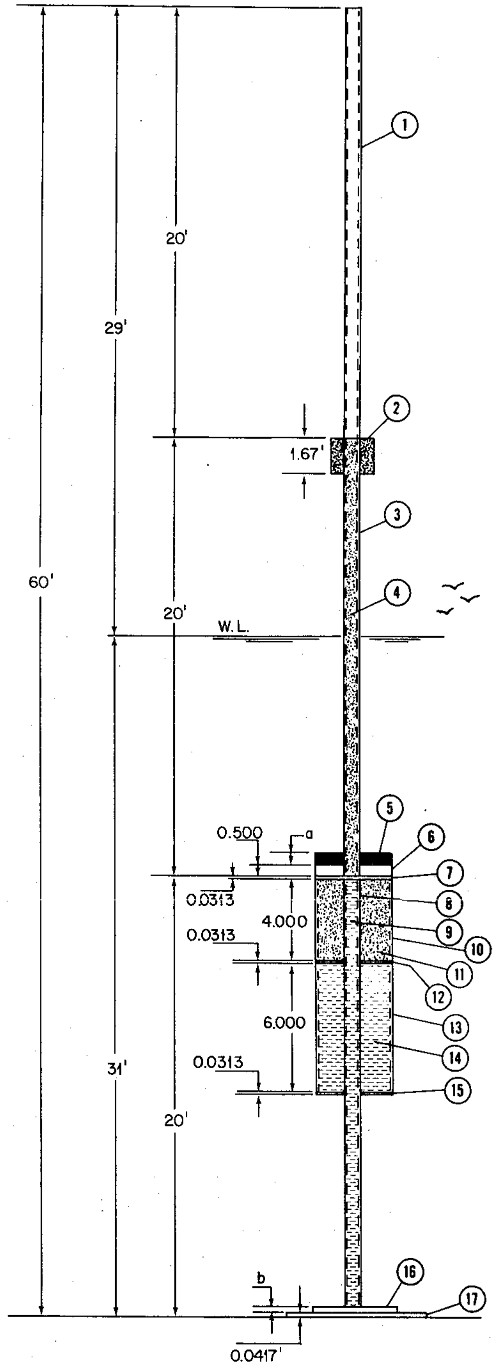
Alterations made to the base line included relocation of the water ballast tank, increase in the water ballast tank, and relocation of the solid ballast.

A brief description of these changes, of the rationales used, and of the results obtained hereafter follows.

Case #01. Base line, as previously described.

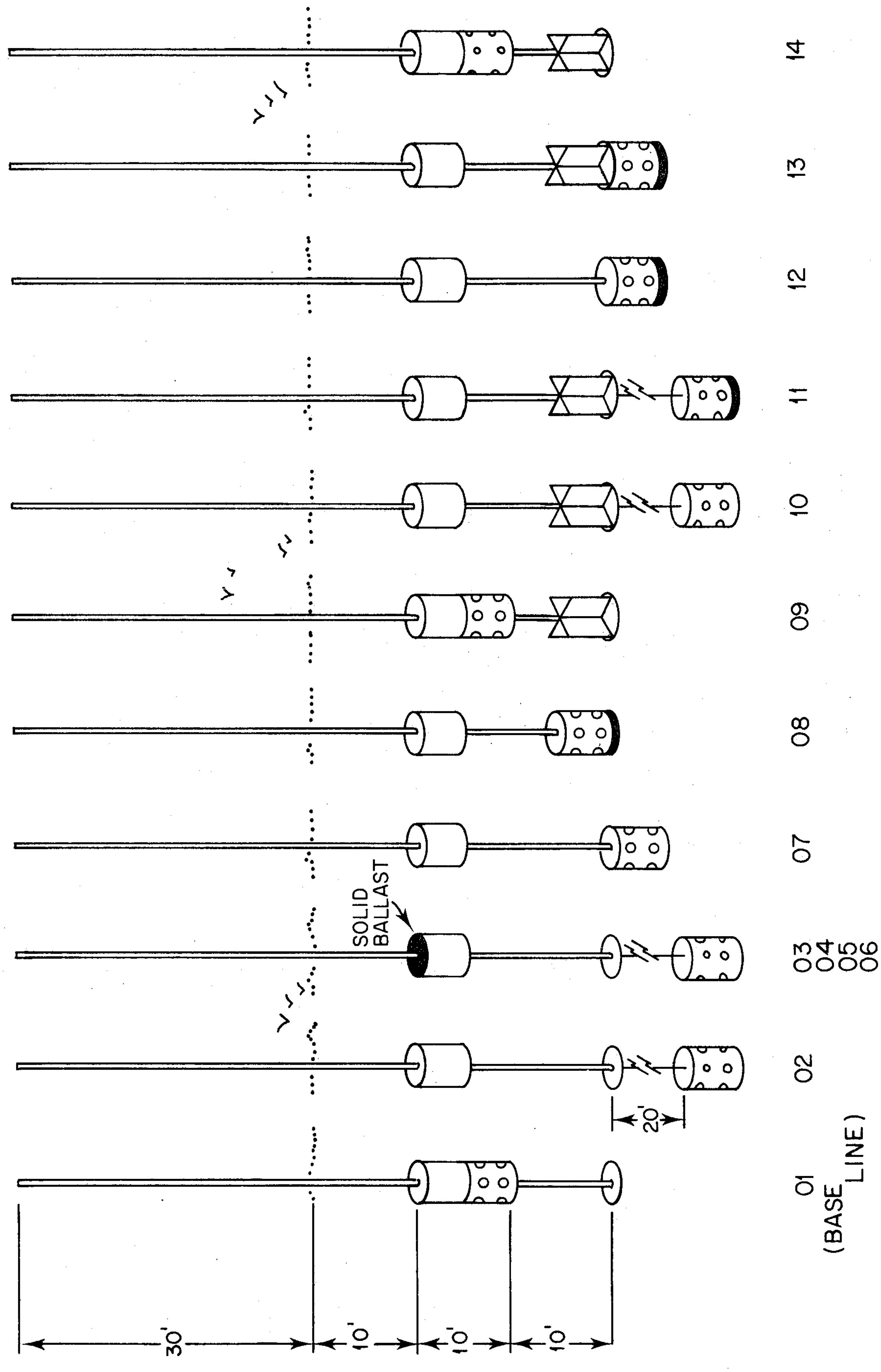
Case #02. Same as #01, except place water ballast tank at end of wire rope 20 feet below damping plate. This change provides more added mass and damping areas in heave motion and slightly increases the righting moment. As a result, the heave period is slightly increased and the heave response is appreciably reduced. On the other hand, the effect on the roll response is found to be small.

Cases #03, #04, #05, and #06. In these four cases, 25, 50, 75, and 100 percent of the buoy solid ballast was placed on top of the buoyancy tank. All other parameters are as in case #02. This was done to investigate the effect that a reduction in the meta-centric height would have on the roll response. Only case #03 gave positive results, the buoy being unstable in roll in the three other cases. Case #03 indicated an improvement of the roll response over case #02.



PART NO.	NAME	CYLINDER TYPE	WIDTH (O.D.) (FT.)	HEIGHT (FT.)	WALL THICKNESS (IN.)	DENSITY (LB./FT^3)	DISTANCE FROM REEL TO PART C.G. (FT.)	WEIGHT (LB.)
1	UPPER SPAR	HOLLOW	0.719	20.0	0.148	430.22	50.0	231.4
2	RES. BUOYANCY	HOLLOW	2.17	1.67	8.688	10.564	39.165	58.0
3	LOWER SPAR - WALL	HOLLOW	0.718	20.0	0.322	231.040	30.0	259.0
4	LOWER SPAR - FOAM	SOLID	0.665	20.0	—	6.996	30.0	48.6
5	UP BALLAST - SOLID	HOLLOW	3.250	a = 0	15.188	500	*	
6	ELECTRONIC PACKAGE	HOLLOW	3.250	0.5	15.188	87.455	20.25	345
7	BUOYANCY TANK TOP PL	SOLID	3.250	0.03125	—	173.582	20.016	45
8	STEM - WALL	HOLLOW	0.719	19.927	0.322	163.0	9.984	196.9
9	STEM - WATER	SOLID	0.665	19.927	—	64.0	9.984	442.9
10	BUOYANCY TANK WALL	HOLLOW	3.250	4.0	0.1875	264.22	19.969	167.0
11	BUOYANCY TANK FOAM	HOLLOW	3.219	4.0	15.0	4.16	17.969	128.7
12	BUOYANCY TANK - BOTTOM PL	HOLLOW	3.250	0.03125	15.188	173.582	15.958	42.8
13	WATER BALLAST TANK WALL	HOLLOW	3.250	6.0	0.125	201.88	12.937	128.0
14	WATER BALLAST	HOLLOW	3.229	6.0	15.063	64.0	12.937	2988.6
15	WATER BALLAST TANK BOTTOM PL	HOLLOW	3.250	0.03125	15.188	173.582	9.921	42.8
16	LOW BALLAST SOLID	HOLLOW	3.250	b = 0.282	15.188	500.	0.1827	1113
17	DAMPER PLATE	SOLID	4.0	0.0417	—	173.582	0.0208	90.9

Figure 7



14
13
12
11
10
09
08
07
SOLID BALLAST
03
04
05
06
02
20'
01
(BASE LINE)
30'
10'
10'
10'

Figure 8

Case #07. Same as case #01, except place the water ballast tank just below damping plate. This configuration has the advantage of having the buoy in one part (no cable). It also retains some desirable features, such as a large roll period and a reduced roll excitation, the water ballast tank being deeper than in case #01. The loss of added mass and damping is reflected on the heave response which is not as good as in case #02. On the other hand, the roll response is found to be far better than in either case #01 or #02.

Case #08. Same as case #01, except place the water ballast tank just above the damping plate. This configuration has the advantage of having the buoy in one part, and to be shorter than case #07. Placing the ballast tank closer to the surface does not affect the heave as much as the roll response which is not as good as in case #07.

Case #09. Four (4) plates, dimension 4 feet by 2 feet, are added to case #01, in order to further reduce the average and the RMS of roll.

Case #10. Here again, 4 roll damping plates are added to case #02. In both cases these antiroll plates are found to effectively reduce the roll.

Cases #11 and #12. In these cases, the righting moment is in-increased by placing the solid ballast at the lowest point of buoy configurations #10 and #07, that is just under the water tank. The resulting reduction in roll is more pronounced in case #11.

Case #13. Same as #12, except now antiroll plates are added which improves the roll response of #12 - as expected.

Case #14. In this case the water ballast tank of configuration #09 is increased from 6 feet long to 9 feet long. This considerably increases the buoy mass and therefore its natural heave period. On the other hand, the heave and roll responses are found to be almost the same as in case #09.

Figure 9 is a summary of the results obtained in this first parametric study. The salient points of the study were:

- All configurations met the roll specifications.
- None of the configurations met the heave specifications, some however being much better than others.
- The lowest RMS heave was achieved with configuration #02. Yet configuration #14 has more mass. This shows that damping effects predominate inertial effects to reduce heave motion.
- The addition of antiroll plates reduces roll considerably, and more so at the higher sea state.

From all configurations studied, configuration #09 appeared as the best candidate for further studies. It met the roll specifications, and it was felt that its heave response could be improved by the addition of damping plates or by profiling. Furthermore, being relatively short and built in one piece, it had the desirable features of compactness, ease of fabrication, and ease of handling.

3.2. Second Parametric Study

Six buoy configurations, numbered 091 to 096 were investigated in the second parametric study. These configurations are shown in Figure 10. Alterations made to the case #09 included the addition of

W.H.O.I.

Date: 5/15/77 By: H.O. Berteaux

APL HEAT FLUX SPAR BUOY - FIRST PARAMETRIC STUDY

SUMMARY OF RESULTS (HEAVE & ROLL)

		HEAVE									ROLL									
Case No.	Description	Virtual Mass (slugs)	Natural Period of Heave (secs)	Max. Heave RAO	Heave RAO FOR T= 7 sec	Heave RAO FOR T=16 sec	Average Heave (ft.) At 16 knots wind	Average Heave (ft.) At 40 knots wind	Heave RMS (ft.) At 16 knots wind	Heave RMS (ft.) At 40 knots wind	Natural Period of Roll (secs)	C.G. from Keel (ft.)	C.B from Keel (ft)	Max Roll RAO (degree/ft.)	Roll RAO T=7 sec (degree/ft.)	Roll RAO T=16 sec (degree/ft.)	Average Roll (Degrees) At 16 knots wind	Average Roll (Degrees) At 40 knots wind	Roll R.M.S. (Degrees) At 16 knots wind	Roll R.M.S. (Degrees) At 40 knots wind
01	Base Line	257.2	20	3.847	.577	.764	.629	7.134	.710	8.052	11.030	13.38	14.82	6.765	1.277	.783	1.359	104.319	1.534	117.741
02	Same as #01 except place water ballast tank 20' below damping plate	275.2	21	6.377	.338	.305	.377	6.269	.425	7.076	10.323	13.33	16.51	6.444	1.446	.678	1.513	102.137	1.708	115.279
03	Same as #02 except place 25% solid ballast on top buoyancy tank	"	"	"	"	"	"	"	"	"	14.162	15.22	16.75	4.545	.789	1.839	.927	74.257	1.047	83.812
04	Same as #02 except place 50% solid ballast on top buoyancy tank	"	"	"	"	"	"	"	"	"										
07	Same as #01 except place water ballast tank below damping Pl.	232.6	19	4.857	.501	.525	.539	6.937	.608	7.83	14.794	11.46	13.19	2.782	.898	.393	1.228	75.41	1.386	85.121
08	Same as #01 except place water ballast tank above damping Pl.	232.6	19	5.283	.519	.503	.565	7.01	.638	7.912	12.781	8.62	10.21	4.095	1.188	1.392	1.352	97.821	1.526	110.408
09	Same as #01 except add roll damping Pls	257.2	20	3.901	.560	.664	.617	7.134	.696	8.052	11.091	13.37	14.80	4.810	.989	.591	1.085	36.170	1.225	40.823
10	Same as #02 except add roll damping Pls	275.2	21	6.377	.338	.305	.377	6.269	.425	7.076	10.354	13.29	16.45	4.775	1.140	.521	1.215	41.306	1.371	46.621
11	Same as #10 except place solid ballast below water tank	"	"	"	"	"	"	"	"	"	12.570	13.83	16.62	4.082	.635	.796	.710	24.846	.802	28.043
12	Same as #07 except place solid ballast below water tank	232.6	19	4.857	.501	.525	.539	6.269	.608	7.076	12.299	10.63	13.35	3.044	1.168	1.171	1.283	74.44	1.448	84.02
13	Same as #12 except add roll damping Pls	"	"	"	"	"	"	"	"	"	12.382	10.66	13.31	2.904	1.13	1.14	1.258	70.615	1.420	79.701
14	Same as #09 except increase water ballast tank from 6' to 9'	303.6	22	2.567	.898	.393	.620	9.33	.7	8.22	11.802	12.48	13.58	4.262	.974	.693	1.107	47.809	1.249	53.961

Figure 9

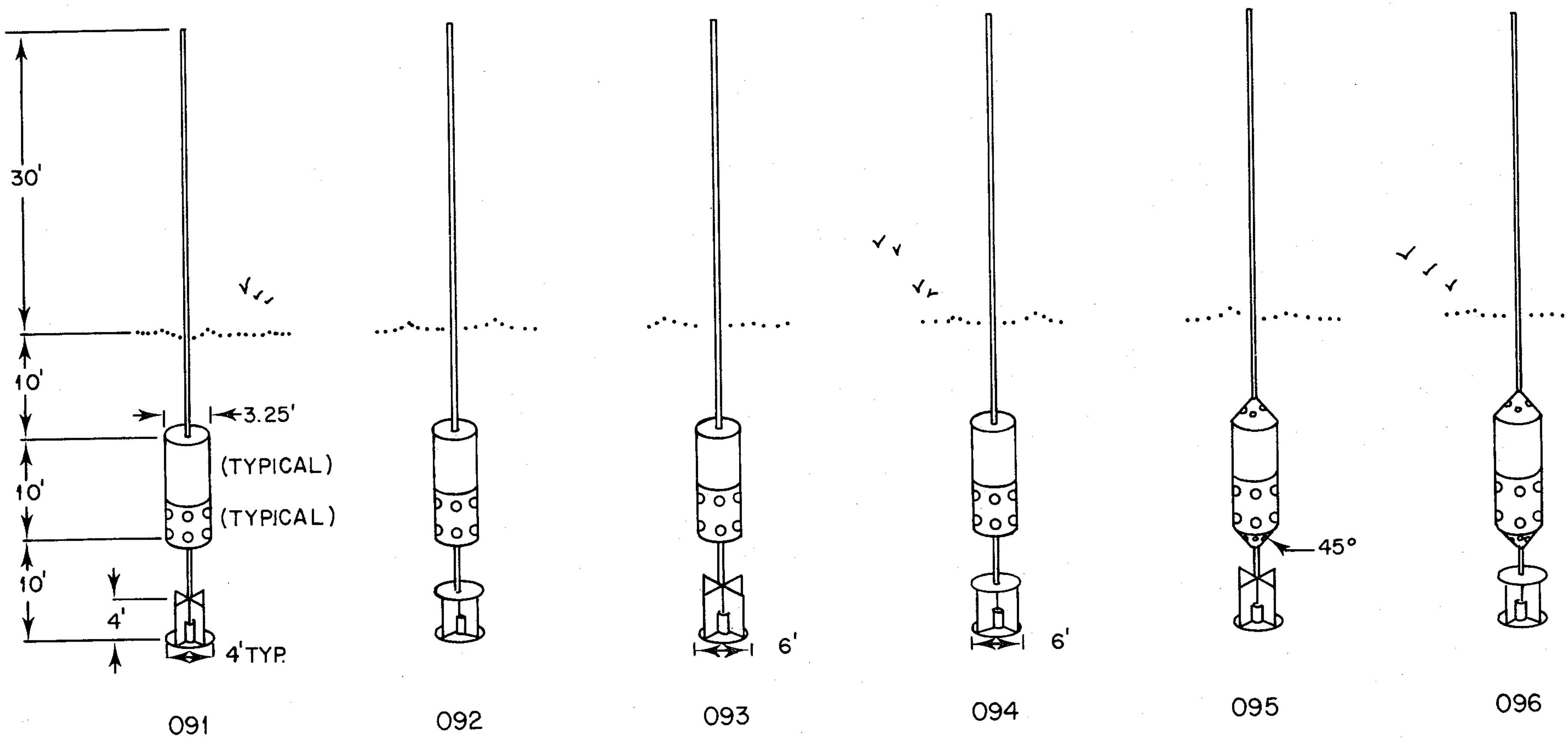

30'
10'
10'
10'
3.25'
(TYPICAL)
(TYPICAL)
4'
4'TYP.
6'
6'
45°
091
092
093
094
095
096

Figure 10

a second heave damping plate, the increase of the damping plates diameter, and the addition of profiling cones, one on top of the buoyancy tank, the other on the bottom of the water ballast tank. Rationales for these changes and results obtained are hereafter briefly reviewed.

Case #091. Same as #09, except relocate electronic package on top of damping plate. This case serves as a new base line for this second parametric study.

Case #097. Same as #091, except place one additional heave damping plate on top of the roll damping plates. This damping plate would increase the buoy virtual mass and its damping. As a result, the natural period of heave was increased and the heave at resonance reduced. On the other hand, because of the increase in the wave drag force, the RMS and the average heave response were found to be larger than in case #091. Adding a horizontal damping plate had little effect on the roll response.

Case #093. Same as #091, except the diameter of the bottom damping plate is increased from 4 feet to 6 feet. This would again increase the buoy virtual mass and damping. It was found that this change resulted in a virtual mass larger and a natural heave period longer than the ones of both #091 and #092 cases. On the other hand, the RMS and average heave response were even larger than found in the two preceding cases, a somewhat surprising result, probably due to the increase in wave drag force caused by the considerable increase in the plate area. Effects on roll were negligible.

Case #094. In this case, an additional heave damping plate, six feet in diameter, is located at the top of the roll damping plates. This change resulted in the largest virtual mass, the longest natural heave period, and the smallest heave response at resonance of all six cases studied. The average and RMS heave response were not improved for winds of 16 knots. The heave response for survival was, however, slightly better. Effects on roll were again negligible.

Case #095. Same as #091, except two profiling cones are added, one on top of the buoyancy tank, one on the bottom of the ballast tank. This change would increase the virtual mass and reduce both the damping and the wave drag of the blunt ends of the cylindrical tanks. Results from this addition were very noticeable. Heave at resonance due to less damping was increased. On the other hand, the natural heave period being 24 seconds, the chances of exciting the buoy at that period remain very small. The average and RMS values of heave were considerably smaller than in case #091.

Case #096. Same as #092, except add two profiling cones. This configuration provides additional virtual mass and damping. As a result, the natural period of heave is further increased (25 seconds), and the heave at resonance is reduced. Average and RMS heave are found to be somewhat higher than in case #095, but certainly better than in case #092.

Figure 11 is a summary of the results obtained in the second parametric study. Important points of this study were:

- All cases studied met the roll specifications.
- Only two cases (#095 and #096) met the heave specifications.
- An increase in virtual mass results, as it should, in an increased natural period of heave.
- Increasing the plate area normal to heave motion results in increased damping and drag effects. Damping, being a function of the buoy heave velocity, is not a function of depth. Drag however, being a function of the water particle velocity is depth dependent. This means that the lower the damping plate, the better the buoy design. Increased damping results in lesser response at periods close to the natural heave period. Increased drag results in larger RMS and average heave response.
- These changes were introduced in order to improve heave motion, and they had little effect on the roll response.

From the six configurations studied, it appeared that configuration #095 was the best candidate to build. It satisfied the heave and roll specifications. Made of one piece, of reasonable dimensions, it retained the desirable features of ease of fabrication and handling.

WHOI

Date: 10/1/77 By: H.O. Berteaux

APL HEAT FLUX SPAR BUOY – SECOND PARAMETRIC STUDY
SUMMARY OF RESULTS (HEAVE & ROLL)

CASE NO.	DESCRIPTION	HEAVE: VIRTUAL MASS (slugs)	HEAVE: NATURAL PERIOD of HEAVE (secs)	HEAVE RAO FOR: MAX	HEAVE RAO FOR: T=7 SEC	HEAVE RAO FOR: T=16 SEC	AVERAGE HEAVE (ft.): AT 16 KNOTS WIND	AVERAGE HEAVE (ft.): AT 25 KNOTS WIND	AVERAGE HEAVE (ft.): AT 40 KNOTS WIND	HEAVE RMS (ft.): AT 16 KNOTS WIND	HEAVE RMS (ft.): AT 25 KNOTS WIND	HEAVE RMS (ft.): AT 40 KNOTS WIND	ROLL: NATURAL PERIOD of ROLL (secs)	C.G. FROM KEEL (ft.)	C.B. FROM KEEL (ft.)	ROLL RAO: MAX	ROLL RAO: T=7 SEC	ROLL RAO: T=16 SEC	AVERAGE ROLL (DEGREES): AT 16 KNOTS WIND	AVERAGE ROLL (DEGREES): AT 25 KNOTS WIND	AVERAGE ROLL (DEGREES): AT 40 KNOTS WIND	ROLL RMS (DEGREES): AT 16 KNOTS WIND	ROLL RMS (DEGREES): AT 25 KNOTS WIND	ROLL RMS (DEGREES): AT 40 KNOTS WIND
091	Same as 09 except place electronics package on top of bottom damping plate	257.2	20	20.64	.227	1.974	.279	1.116	14.897	.315	1.259	16.813	10.47	11.77	13.46	10.87	1.62	.888	1.69	9.82	25.76	1.91	11.08	29.07
092	Same as 091 except add damping plate on top of roll damping plates	299.9	22	13.02	.285	1.087	.326	1.429	12.333	.368	1.613	13.920	11.05	11.88	13.44	13.82	1.54	.992	1.62	9.32	25.13	1.83	10.52	28.36
093	Same as 091 except increase diameter of bottom damping plate from 4'0" to 6'0"	358.5	23	13.72	.305	.529	.333	1.390	10.434	.375	1.569	11.777	10.92	11.79	13.41	13.93	1.58	.964	1.54	9.63	25.98	1.73	10.87	29.32
094	Same as 093 except add 6'0" diameter damping plate on top of roll damping plates	502.6	28	11.17	.382	.296	.401	1.811	10.455	.452	2.045	11.801	11.14	11.78	13.32	12.44	1.45	.982	1.53	7.17	13.80	1.72	8.1	15.58
095	Same as 091 but add 45° water filled cones on top and bottom of buoyancy/ballast tanks	382.2	24	47.67	.116	.883	.151	.542	9.470	.170	.612	10.688	11.11	11.93	13.49	16.13	1.88	1.25	1.97	10.70	28.37	2.22	12.08	32.02
096	Same as 092 but add 45° water filled cones on top and bottom of tanks	424.8	25	23.37	.168	.604	.196	.804	8.336	.221	.907	9.408	10.89	11.83	13.44	16.27	1.94	1.18	2.03	11.09	29.01	2.29	12.52	32.74

Figure 11

4. Final Buoy Design

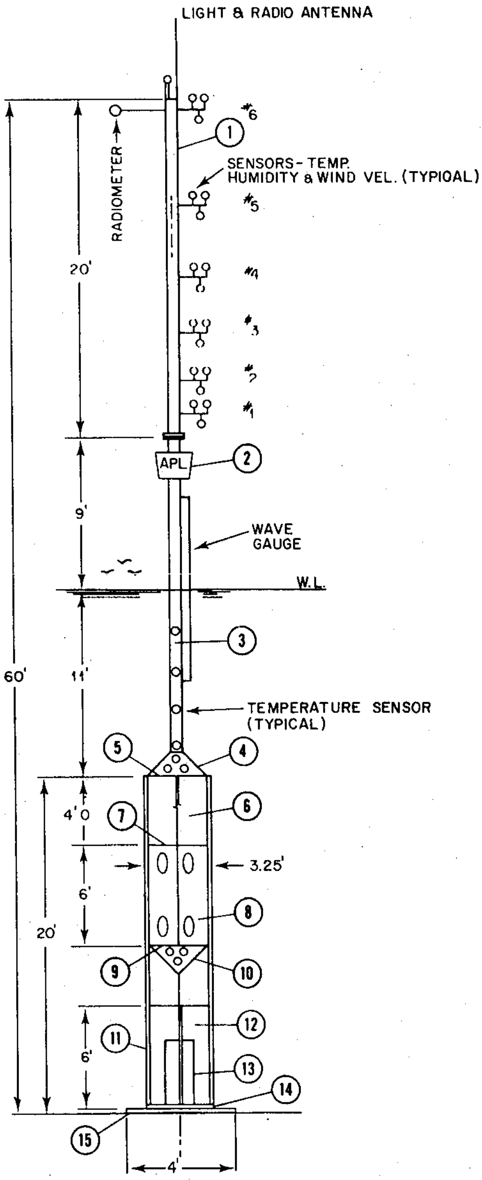
Based on the results of the parametric study, a final buoy design was made at A.P.L. As shown in Figure 12, the main features of this design included:

- The 40 feet spar mast, made of two sections, supporting the light, the antenna, the meteorological sensors, the wave gauge, the temperature sensors, and the reserve buoyancy.
- The 3.25 feet diameter by 4.0 feet long buoyancy tank, filled with foam, and the 3.25 feet diameter by 6.0 feet long free flooding water ballast tank.
- A bottom damping plate supporting the electronic package and the solid ballast.
- Two profiling cones, one on top of the buoyancy tank, one at the bottom of the ballast tank.
- Four equally spaced struts 20 feet long securing the bottom damping plate to the buoyancy and ballast tanks.
- Four equally spaced roll damping plates, 2 feet wide by 6 feet high.

5. Suggested Deployment and Recovery Procedure

5.1. General

A buoy of dimensions and weight of this spar will require special considerations for the successful launch and recovery. Sensors attached to the buoy are fragile and will be damaged if allowed to come in contact with the vessel or handling lines. Likewise, meteorological



PART	DESCRIPTION	MATERIAL	REMARKS
1	UPPER SPAR - 8" SCH. 10 PIPE	6061-T6-AL	
2	RESERVE BUOYANCY	FOAM	
3	LOWER SPAR - 8" SCH. 40 PIPE	6061-T6-AL	FOAM FILLED
4	PROFILING CONE - 3/16" THICK	6061-T6-AL	OPEN TO WATER
5	BUOYANCY TANK TOP PL. 3/16" THICK	6061-T6-AL	
6	BUOYANCY TANK - SHELL PL. 3/16" THICK	6061-T6-AL	FOAM FILLED REINFORCED W/RINGS
7	BUOYANCY TANK - BOTTOM PL. 3/8" THICK	6061-T6-AL	
8	WATER BALLAST TANK - SHELL PL. 1/8" THICK	6061-T6-AL	OPEN TO WATER
9	WATER BALLAST TANK - BOTTOM PL. 3/8" THICK	6061-T6-AL	
10	PROFILING CONE - 3/16" THICK	6061-T6-AL	OPEN TO WATER
11	STRUTS (4 AROUND) 20' LONG	6061-T6-AL	CHANNEL, 4" x 1.72" x 2.5 LBS./FT.
12	ROLL DAMPING PL., 2' x 4' x 1/8" THICK	6061-T6-AL	
13	ELECTRONICS		
14	BALLAST SOLID, 3'-3" x 3-1/2" THICK	STEEL	
15	BOTTOM DAMPING PL. 4' O.D. x 1/2"	6061-T6-AL	

Figure 12

sensors must not be allowed to contact the water. The weight seen by the handling equipment will be less during deployment than on recovery due to the entrapped water in the ballast tank. The effect of waves and dynamic forces must be carefully considered in both operations.

The vessel must be maneuverable and be capable of maintaining a heading at dead slow speed or stopped. The vessel size must be of adequate size to permit an unrestricted area for assembly and stowage of the complete spar on deck or on the bulwarks. There must be adequate handling gear and trained personnel to run it.

5.2. Vessel Requirements

An assumption is made that the same vessel will be used for both deployment and recovery even though the two capability requirements are not identical. The vessel should be capable of "holding her head up" into the predominant sea at very low speed to minimize roll. A bow thruster would permit this at zero forward speed which is to be desired. At least 70 feet of unrestricted deck or bulwark space will be required for assembly and storage of the buoy. Adequate tie-down points must be provided to secure the buoy for safe stowage in bad weather. A crane capable of lifting at least 10,000 pounds with an adequate reach to put the buoy over the side and retrieve it in a nearly horizontal position will be required. Ideally there should be no A-frames, stanchions or other structures between the buoy stowage area and outboard of the vessel beam. Air tuggers or capstans should be available for handling lines. A tagline to a suitable winch can also be used for this purpose.

5.3. Personnel Requirements

In addition to the technical personnel required to check out the electrical systems aboard the buoy, knowledgeable deck personnel will be required. The vessel should provide crane and winch operators and the bridge will provide the vessel maneuvering functions. Line handlers will be necessary to handle frapping lines controlled by air tuggers or capstans. A responsible person should be appointed to tend and operate the quick-release hook. One person, familiar with all aspects of the buoy and the deployment and recovery scenario, should supervise the overall operation. He should be in contact with the bridge to give orders concerning the vessel maneuvering while the operation is underway. He may be positioned near an intercom or use a walkie-talkie which will permit greater flexibility of movement. His orders to the launch or recovery crew should be directed to one man he has designated as the deck boss. The deck boss in turn should be the only one to give orders to the deck crew and the crane and winch operator. In most operations it is also useful to designate one person to keep a log of operations showing times of instrument turn-on and -offs and time in and out of the water and any other notes of future interest.

5.4. Weather Restrictions

A long spar of this type is awkward to handle from a relatively small vessel. The fragility of sensors, lights and antennas compounds the problems. Conservatism and prudence dictates that mild sea conditions prevail for both the deployment and retrieval phases. It goes without saying that a delay of a day or two in the operations, while waiting for the proper conditions, is far better than smashed sensors or other damage.

Swell is generally the most important consideration for any operation involving a spar buoy. During deployment the effect of swell is to cause roll of the vessel and during the critical moment of water entry while still attached to the crane hook will cause the buoy to be in and out of the water as the swells go by. Methods to minimize problems caused by this effect are discussed under <u>Deployment</u> (5.5). Swell is of concern during the retrieval operation because the spar with its inherently long natural period of heave essentially remains motionless in the seaway while the vessel is heaving at the swell period. The differential motion between the spar and the vessel makes it difficult to make preliminary contact and attachment and can cause large snap forces to the pickup gear.

Rain, poor visibility and moderate wind waves are of secondary importance to these operations. In general, both the deployment and retrieval operations should be conducted during periods of minimal swell and moderate wind waves. Operations should not be attempted where the swell amplitude is greater than 4 to 5 feet and wind waves greater than 2 to 3 feet.

5.5. Deployment

Prior to the operation the deck crew, ships captain and his designates, winch and crane operators and any others who will be involved should be thoroughly briefed on the detailed deployment scenario. At this time, the responsibilities as discussed in section 5.3 should be outlined.

The first operation should be to ready the sensors, radio and light systems aboard the spar. Electrical systems should be energized and checked out. Coincidentally, the deck crew should begin rigging the handling lines and blocks required to deploy. A minimum of two frapping lines should be used to steady and control the buoy while being lifted over the side. These should be 3/4" nylon lines, one end passed around the buoy, one near the upper end and another near the bottom and tied off on deck. The other ends should be fairleaded through a block inboard and opposite the buoy and lead to an air tugger or capstan for control. The crane can now be swung into position with the hook over the lifting eye of the lifting bridle on the buoy. A 6 foot, 1 inch nylon pennant should be attached to the crane hook to absorb shock and to separate the heavy block from the buoy. A quick-release hook rated for 10,000 pounds should be attached to the end of this pennant and connected to the lifting eye of the lifting bridle. A light quick-release trip line about 60 feet long should be attached to the quick-release hook and loosely coiled on deck. A short section of the frapping lines about a foot from where they are secured to the deck should be lightly taped to prevent the lines from unlaying when they are cut at the time of release.

When the sensors and electical systems are ready to go and all deck arrangements are completed, the deployment operation can begin. The vessel should head up into the predominant waves or swell at slow speed to minimize roll. If a bow thruster is available, the vessel way can be reduced to zero. Securing lines should be removed and personnel stationed according to the scenario. The crane must lift the buoy up and outboard while the buoy is being restrained by the frapping lines. The crane must be extended so that there is a fair angle from the tip of the boom to the buoy bridle. This will control the buoy in the presence of roll by holding back on the frapping lines. The buoy will assume a position in the air of approximately 20° off the horizontal, the top being high. This operation should be done slowly and deliberately. Alternately extending the crane boom, lifting the buoy and slowly paying out the frapping lines, always keeping tension in them. The buoy should be positioned about 10 feet outboard and kept high enough so that it does not touch the crests of the waves or swell. At this time, the bridge should be given orders to bring the wind onto the launch side. As the vessel slowly comes around, when the wind is just beginning to show on the launch side, the buoy should be lowered into the water. Personnel should be stationed at each frapping line deck tie-off point with sharp knives ready to cut the line at the taped section. At this point, deliberate speed in the operation should be made. The person in charge of the quick-release trip line, having tended the line making sure that it is clear at all times, should be given the signal to trip when the buoy first touches the water. At the same time the two frapping lines should be cut and the other ends swiftly brought aboard. Immediately upon tripping the quick-release hook, both the crane operator and the release person should concentrate upon getting the crane hook and boom out of the way of the buoy as it settles upright into the water. If the wind is kept on the launch side, the vessel and buoy will continue to separate.

5.6. Retrieval

The retrieval operation will require little or no sea and swell to reduce snap loadings due to the differential motion between the vessel and the buoy. The buoy should have a 1 inch nylon line fastened to the bridle lifting eye and led up alongside and taped off at intervals. This line should be made fast with light marlin at a point above the water line available to the pickup crew. The eye should contain a thimble and large steel ring to attach the pickup line to. Two pickup poles should be manned along the rail of the pickup side. The pickup poles should be at least 20 feet long with a large snap-hook with eye modified to slide into the end of the pole so that after the hook is snapped onto the ring of the pickup line, the pole can be jerked back leaving the hook connected to the buoy. A short 1 inch nylon lifting pennant is attached to the eye of the snap-hook. This pennant must be led to the crane hook by an additional length of small line attached to the end of the pennant. This light line is not a lifting line and is only used to pull the buoy close enough to the vessel to attach the lifting pennant to the crane hook.

The recovery scenario should generally follow these lines:

Position two men on each of the two pickup poles separated by 20 to 30 feet along the pickup rail. Station two people with 3/4 inch nylon lines near the rail so that they can attach these frapping lines as the buoy is brought in to steady it. The vessel should approach at dead slow speed from downwind. The buoy should pass close to the pickup side. It is imperative that the wind be ahead and on the pickup side of the bow. The vessel should be stopped as the buoy passes alongside the bow and the vessel allowed to fall off such that the wind is on the pickup side. It is generally poor practice to back-down during this maneuver, in fact, the screws should be all stopped when contact is made with the buoy with the pickup poles. After the snap-hook is attached to the pickup pennant ring, the pole should be retrieved and using the light line the buoy and pennant should be heaved in until the ring can be slipped over the crane hook. The crane should immediately start hauling up on the pennant which will part the marlin and tape seizing and the whole load will then be on the bridle. Any roll of the vessel at this time will cause the crane whip to alternately go slack and take up with large snap forces. This effect can be reduced by bringing the buoy up quickly but not completely out of the water. The spar weight is 2,900 pounds but in this condition it has an additional 3,430 pounds of water in it which must be allowed to drain. As the water drains out, the buoy will again assume its 20 degree angle to the horizontal. During the draining process the buoy should be gradually lifted higher and brought in closer to the vessel. The vessel should be brought up into the sea or swell immediately after the buoy is clear of the water to reduce rolling motion. It must be fended off by personnel and the frapping lines attached as soon as possible. Once the frapping lines are secured and fairleaded to tuggers or a capstan, the crane should boom out to provide an outboard component of tension working against the frapping lines which are holding it inboard. This will prevent swinging of the buoy and allow for a more deliberate operation of bringing the buoy aboard using the frapping lines and crane in concert. Additional steadying lines can be attached whenever possible during the retrieval operation.

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Appendix I

Typical Computer Program Outputs

```
HEAVE RESPONSE ANALYSIS PROGRAM
   ALL DEPTHS ARE POSITIVE

NUMBER OF PRESSURE SURFACES =     3

DEPTH (FT), AREA (SQ FT) (- AREA FOR DOWNWARD FORCE)
   10.500      -7.89
   21.100       7.89
   31.000        .41

NUMBER OF INERTIAL COMPONENTS =     2

 DEPTH (FT)  ADDED MASS COEFF   VOLUME (CU FT)
   16.050              .500            17.970
   31.000             1.000            21.330

NUMBER OF DRAG SURFACES =     2

 DEPTH (FT)  DAMPING COEFF  WAVE DRAG COEFF (LBF/(FT/SEC)/(RAD/SEC))
   16.050           2.315            9.260
   31.000           4.756           19.030

 CROSS SECTIONAL AREA AT SURFACE =      .4060 SQ FEET

 VIRTUAL MASS =      257.15 SLUGS

 PERIOD RANGE, IN SECONDS     START     END      DELTA
                              1.000   40.000     1.000

 PIERSON-MOSKOWITZ SEA SPECTRUM
    WIND SPEED =      16.000 KNOTS
```

PERIOD	ANG FREQ	RAO	W-F PHASE	F-H PHASE	W-H PHASE	AMP SPEC
1.000	.628E 01	.000	179.954	-178.421	1.533	.002
2.000	.314E 01	.008	178.122	-178.409	-.286	.054
3.000	.209E 01	.094	176.805	-178.388	-1.583	.388
4.000	.157E 01	.240	175.676	-178.358	-2.682	1.384
5.000	.126E 01	.381	174.765	-178.317	-3.552	2.975
6.000	.105E 01	.493	174.032	-178.265	-4.233	3.914
7.000	.898E 00	.577	173.391	-178.199	-4.808	2.962
8.000	.785E 00	.640	172.772	-178.116	-5.345	1.155
9.000	.698E 00	.685	172.117	-178.013	-5.896	.200
10.000	.628E 00	.718	171.376	-177.883	-6.507	.013
11.000	.571E 00	.742	170.488	-177.718	-7.231	.000
12.000	.524E 00	.757	169.373	-177.506	-8.133	.000
13.000	.483E 00	.766	167.909	-177.225	-9.315	.000
14.000	.449E 00	.769	165.886	-176.840	-10.954	.000
15.000	.419E 00	.765	162.906	-176.287	-13.381	.000
16.000	.393E 00	.754	158.113	-175.435	-17.322	.000
17.000	.370E 00	.739	149.345	-173.960	-24.615	.000
18.000	.349E 00	.757	130.172	-170.824	-40.652	.000
19.000	.331E 00	1.255	87.656	-159.980	-72.324	.000
20.000	.314E 00	3.847	45.898	-48.402	-2.503	.000
21.000	.299E 00	1.689	27.258	-11.996	15.262	.000
22.000	.286E 00	1.333	18.685	-6.549	12.136	.000
23.000	.273E 00	1.205	13.977	-4.432	9.545	.000
24.000	.262E 00	1.141	11.044	-3.312	7.732	.000
25.000	.251E 00	1.105	9.056	-2.621	6.435	.000
26.000	.242E 00	1.081	7.624	-2.153	5.471	.000
27.000	.233E 00	1.064	6.548	-1.817	4.731	.000
28.000	.224E 00	1.053	5.711	-1.563	4.148	.000
29.000	.217E 00	1.044	5.043	-1.365	3.677	.000
30.000	.209E 00	1.037	4.498	-1.207	3.291	.000
31.000	.203E 00	1.032	4.046	-1.078	2.968	.000
32.000	.196E 00	1.028	3.666	-.971	2.695	.000
33.000	.190E 00	1.024	3.342	-.881	2.461	.000
34.000	.185E 00	1.022	3.063	-.804	2.259	.000
35.000	.180E 00	1.019	2.820	-.737	2.083	.000
36.000	.175E 00	1.017	2.608	-.679	1.928	.000
37.000	.170E 00	1.015	2.420	-.629	1.792	.000
38.000	.165E 00	1.014	2.254	-.584	1.670	.000
39.000	.161E 00	1.013	2.105	-.544	1.561	.000
40.000	.157E 00	1.012	1.972	-.509	1.463	.000

RMS OF WAVE SPECTRUM = 1.732 FEET

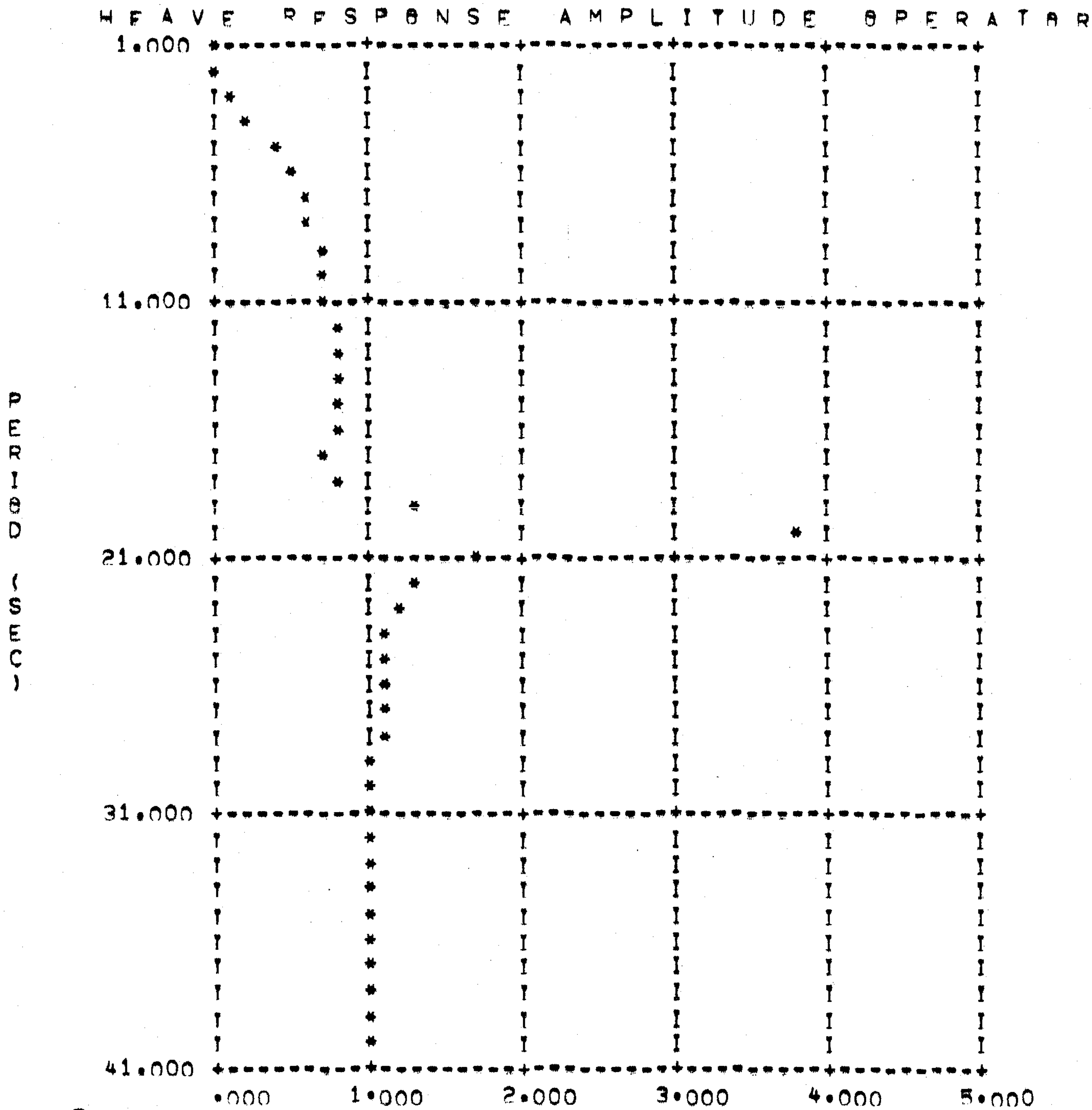
PROBABLE AMPLITUDE OF WAVE = 1.225 FEET

FRACTION OF LARGEST AMPLITUDES CONSIDERED	AVERAGE WAVE AMPLITUDE	NUMBER OF WAVES	EXPECTED WAVE MAXIMUM AMPLITUDE
.010	4.087	50	3.673
.100	3.118	100	3.950
.333	2.453	500	4.522
.500	2.176	1000	4.816
1.000	1.535	10000	5.423
		100000	6.012

RMS OF RESPONSE SPECTRUM = .710 FEET

PROBABLE AMPLITUDE OF HEAVE RESPONSE = .502 FEET

FRACTION OF LARGEST AMPLITUDES CONSIDERED	AVERAGE HEAVE AMPLITUDE RESPONSE	NUMBER OF WAVES	EXPECTED HEAVE MAXIMUM AMPLITUDE
.010	1.675	50	1.505
.100	1.278	100	1.619
.333	1.005	500	1.853
.500	.892	1000	1.974
1.000	.629	10000	2.222
		100000	2.464


HEAVE RESPØNSE AMPLITUDE ØPERATØR
1.000
11.000
21.000
31.000
41.000
.000
1.000
2.000
3.000
4.000
5.000
PERIØD (SEC)

STØP 0
EØD

ROLL RESPONSE ANNALYSIS PROGRAM
ALL DEPTHS ARE POSITIVE

PERIOD RANGE, IN SECONDS START 1.000 END 40.000 DELTA 1.000

PIERSON-MOSKOWITZ SEA SPECTRUM
WIND SPEED = 16.000 KNOTS

WATER PLANE RADIUS AT SURFACE = .36 FT

DEPTH TO THE KEEL = 31.00 FT

ESTIMATED AVERAGE AMPLITUDE = 1.50 FT

ESTIMATED AVERAGE ROLL = 4.00 DEG

NUMBER OF PARTS = 16

PART NO	SHAPE	WIDTH (FT)	HEIGHT (FT)	THICK (FT)	DENSITY (LBSM/ FT**3)	C.G. ABOVE KEEL (FT)	FRACT NORM	COMMENTS
1	H CYL	.72	20.00	.0123	430.2	50.00	1.00	UP SPAR
2	H CYL	2.17	1.67	.7240	10.6	39.16	1.00	RES BUOYANCY
3	H CYL	.72	20.00	.0268	231.0	30.00	1.00	LOW SPAR WALL
4	S CYL	.67	20.00	.3325	7.0	30.00	1.00	LOW SPAR FOAM
5	H CYL	3.25	.50	1.2657	87.5	20.25	1.00	ELECTRONICS
6	S CYL	3.25	.03	1.6250	173.6	20.02	1.00	BUOYANCY TANK
7	H CYL	.72	19.93	.0268	163.0	9.98	1.00	STEM WALL
8	S CYL	.67	19.93	.3325	64.0	9.98	1.00	STEM WATER
9	H CYL	3.25	4.00	.0156	264.2	17.97	1.00	BUOYANCY TANK
10	H CYL	3.22	4.00	1.2500	4.2	17.97	1.00	BUOYANCY TANK
11	H CYL	3.25	.03	1.2657	173.6	15.96	1.00	BUOYANCY TANK
12	H CYL	3.25	6.00	.0104	201.9	12.94	1.00	WATER BALLAST
13	H CYL	3.23	6.00	1.2552	64.0	12.94	1.00	WATER BALLAST
14	H CYL	3.25	.03	1.2657	173.6	9.92	1.00	WATER BALLAST
15	H CYL	3.25	.28	1.2657	500.0	.18	1.00	LOW SOLID BALL
16	S CYL	4.00	.04	2.0000	173.6	.02	1.00	DAMPER PL

CHECK FOR BUOYANCY BUOY WEIGHT = 6337.3 LBSM
WATER DISPLACED = 6333.0 LBSM

NATURAL PERIOD = 11.030 SECONDS

LOCATION OF BUOY CENTER OF GRAVITY = 13.38 FEET ABOVE KEEL
LOCATION OF BUOY CENTER OF BUOYANCY = 14.82 FEET ABOVE KEEL
LOCATION OF BUOY METACENTER = 14.82 FEET ABOVE KEEL

RAO IS IN DEGREES/FOOT OF WAVE AMPLITUDE

PERIOD	ANG FREQ	RAO	W-T PHASE	T-R PHASE	W-R PHASE	AMP SPEC
1.000	.628E 01	.537	93.195	-172.703	-79.508	.002
2.000	.314E 01	.430	105.409	-172.519	-67.110	.054
3.000	.209E 01	.271	156.680	-172.191	-15.511	.388
4.000	.157E 01	.471	-154.364	-171.681	-326.045	1.384
5.000	.126E 01	.744	-144.112	-170.919	-315.031	2.975
6.000	.105E 01	.997	-141.003	-169.775	-310.778	3.914
7.000	.898E 00	1.277	-139.481	-167.995	-307.476	2.962
8.000	.785E 00	1.666	-138.473	-164.999	-303.471	1.155
9.000	.698E 00	2.347	-137.698	-159.191	-296.890	.200
10.000	.628E 00	3.894	-137.081	-144.491	-281.572	.013
11.000	.571E 00	6.765	-136.486	-92.417	-228.903	.000
12.000	.524E 00	3.867	-136.093	-34.656	-170.750	.000
13.000	.483E 00	2.117	-135.662	-18.071	-153.733	.000
14.000	.449E 00	1.392	-135.310	-11.739	-147.049	.000
15.000	.419E 00	1.012	-135.076	-8.502	-143.578	.000
16.000	.393E 00	.783	-134.818	-6.560	-141.378	.000
17.000	.370E 00	.631	-134.512	-5.275	-139.787	.000
18.000	.349E 00	.520	-134.549	-4.366	-138.915	.000
19.000	.331E 00	.440	-134.362	-3.693	-138.055	.000
20.000	.314E 00	.378	-134.436	-3.177	-137.613	.000
21.000	.299E 00	.331	-133.990	-2.770	-136.760	.000
22.000	.286E 00	.293	-133.822	-2.441	-136.263	.000
23.000	.273E 00	.258	-134.176	-2.172	-136.348	.000
24.000	.262E 00	.231	-134.045	-1.947	-135.993	.000
25.000	.251E 00	.209	-133.962	-1.758	-135.720	.000
26.000	.242E 00	.190	-133.862	-1.596	-135.458	.000
27.000	.233E 00	.175	-133.065	-1.457	-134.522	.000
28.000	.224E 00	.161	-133.212	-1.336	-134.548	.000
29.000	.217E 00	.148	-133.087	-1.230	-134.318	.000
30.000	.209E 00	.139	-132.111	-1.137	-133.248	.000
31.000	.203E 00	.128	-132.651	-1.054	-133.706	.000
32.000	.196E 00	.113	-135.002	-.981	-135.982	.000
33.000	.190E 00	.112	-131.791	-.915	-132.706	.000
34.000	.185E 00	.103	-132.502	-.856	-133.357	.000
35.000	.180E 00	.096	-132.955	-.802	-133.757	.000
36.000	.175E 00	.088	-133.306	-.754	-134.060	.000
37.000	.170E 00	.081	-135.979	-.710	-136.689	.000
38.000	.165E 00	.077	-135.163	-.669	-135.832	.000
39.000	.161E 00	.074	-135.004	-.633	-135.636	.000
40.000	.157E 00	.067	-136.248	-.599	-136.847	.000

RMS ØF WAVE SPECTRUM = 1.732 FEET

PRØBABLE AMPLITUDE ØF WAVE = 1.225 FEET

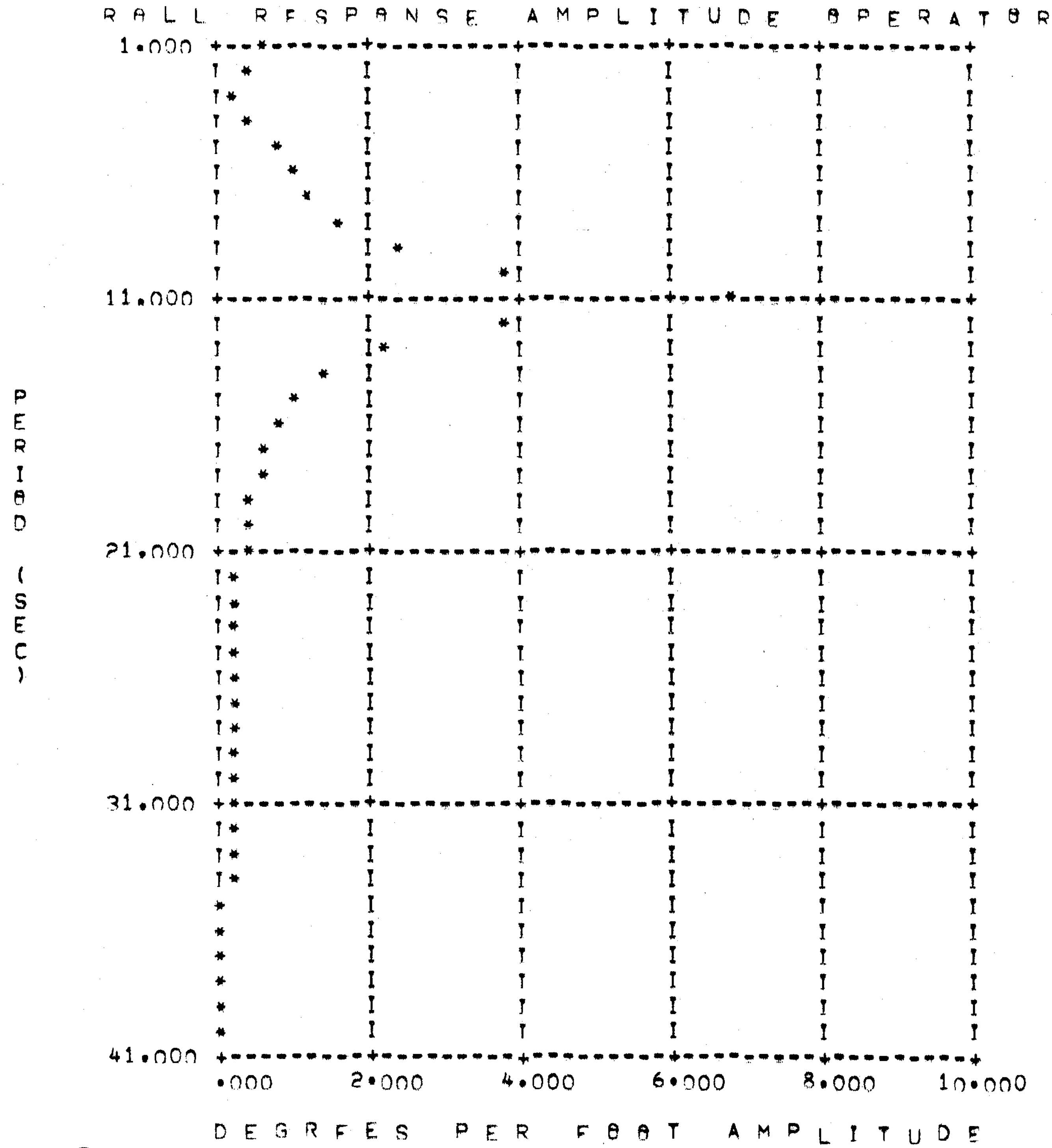
FRACTIØN ØF LARGEST AMPLITUDES CØNSIDERED	AVERAGE WAVE AMPLITUDE	NUMBER ØF WAVES	EXPECTED WAVE MAXIMUM AMPLITUDE
.010	4.087	50	3.673
.100	3.118	100	3.950
.333	2.453	500	4.522
.500	2.176	1000	4.816
1.000	1.535	10000	5.423
		100000	6.012

RMS ØF RESPØNSE SPECTRUM = 1.534 DEG

PRØBABLE AMPLITUDE ØF RØLL RESPØNSE = 1.085 DEG

AMPLITUDES ØF RØLL ARE IN DEGREES

FRACTIØN ØF LARGEST AMPLITUDES CØNSIDERED	AVERAGE RØLL AMPLITUDE RESPØNSE	NUMBER ØF WAVES	EXPECTED RØLL MAXIMUM AMPLITUDE
.010	3.619	50	3.253
.100	2.762	100	3.498
.333	2.173	500	4.004
.500	1.927	1000	4.265
1.000	1.359	10000	4.802
		100000	5.324


RØLL RESPØNSE AMPLITUDE ØPERATØR
1.000
11.000
21.000
31.000
41.000
PERIØD (SEC)
.000
2.000
4.000
6.000
8.000
10.000
DEGREES PER FØØT AMPLITUDE

STØP 0
EØD

Woods Hole Oceanographic Institution
WHOI-78-88

DESIGN OF A STABLE FLOATING PLATFORM FOR AIR-SEA INTERACTION MEASUREMENTS by H.O. Berteaux and R.G. Walden. 73 pages. December 1978. Prepared for the Johns Hopkins University, Applied Physics Laboratory, under Subcontract 600651.

The design of an oceanographic platform can be defined as the rational specification of the platform dimensions and geometry. This specification is usually the result of an iterative process which compares the platform performance with the objectives to be reached and the logistic constraints to be met. This report describes such an exercise.

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A review is then made, in some detail, of the analytical approach followed and of the computer programs used to compute the statistical expectations of buoy heave and roll response to random sea excitation.

The next section of the report describes the comprehensive parametric study performed on some twenty different buoy configurations. The purpose of this study was first to investigate the dynamic reponse of a plausible base line design and of modified (Cont. on back)

1. Spar Buoy Dynamics
2. Buoy Heave & Roll
3. Air-Sea Buoy

I. Berteaux, H.O.
II. Walden, R.G.
III. JHU/APL Subcontract 600651

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versions of the base line. A comparison of the dynamic response of these configurations could then be made, and the good features that this comparison would reveal could be used to design the buoy prototype. Following this approach, a final configuration was specified which would meet the rather severe motion requirements (0.2 feet RMS in heave and 5.0 degrees RMS in roll in sea state 3).

The final section describes the techniques recommended to deploy and recover the 60 feet long buoy prototype.

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BIBLIOGRAPHIC DATA SHEET	1. Report No. WHOI-78-88	2.	3. Recipient's Accession No.
4. Title and Subtitle DESIGN OF A STABLE FLOATING PLATFORM FOR AIR-SEA INTERACTION MEASUREMENTS			5. Report Date December 1978 6.
7. Author(s) H.O. Berteaux and R.G. Walden			8. Performing Organization Rept. No.
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, MA 02543			10. Project/Task/Work Unit No. 11. Contract/Grant No. 600651
12. Sponsoring Organization Name and Address Johns Hopkins University (Applied Physics Laboratory)			13. Type of Report & Period Covered Technical 14.

15. Supplementary Notes

16. Abstracts

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The scientific objectives - measurements of heat flux at the ocean surface - are first outlined. The limits of heave and roll motion compatible with the desired measurement accuracy are then established. Given the stochastic nature of platform response, these limits are stipulated in terms of expected means.

A review is then made, in some detail, of the analytical approach followed and of the computer programs used to compute the statistical expectations (Cont. ***)

17. Key Words and Document Analysis. 17a. Descriptors

1. Spar Buoy Dynamics
2. Buoy Heave & Roll
3. Air-Sea Buoy

*** of buoy heave and roll response to random sea excitation.

The next section of the report describes the comprehensive parametric study performed on some twenty different buoy configurations. The purpose of this study was first to investigate the dynamic response of a plausible base line design (Cont. ****)

17b. Identifiers/Open-Ended Terms

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17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 73
	20. Security Class (This Page UNCLASSIFIED	22. Price