中国造船工程学会

第一届船舶耐波性会议

论文集

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一九七九年

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中国造船工程学会

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本会议于1979年7月30日至31日在哈尔滨召开

《中国造船》编辑部

1979年7月

中国造船工程学会
编 辑 者：《中国造船》编辑部
主 编：方文均 顾懋祥
出版发行者：《中国造船》编辑部
上海市 4116 信箱
印 校 者：力学委员会耐波性学组
印 刷 者：哈尔滨船舶工程学院印刷厂

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目　录

HYDRODYNAMIC CHARACTERISTICS OF THE SPAR BUOY TYPE FLOATING STATION DEVELOPED BY THE RESEARCH INSTITUTE FOR APPLIED MECHANICS OF KYUSHU UNIVERSITY

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1. Buoys for the oceanographic research

Two kinds of buoys are usually used for the oceanographic research. The one is the wave rider buoy which follows correctly on the wave surface and the other one is a spar buoy of which oscillations in waves are very small in the range of small wave periods. Concerning the former type of buoys, we can find the discus buoy developed in the United States of America and used also in Japan(for example, diameter $d=10$m, displacement $w \doteqdot 43$ ton[1]) and the cloverleaf buoy[2] (the one developed by the Research Institute for Applied Mechanics of Kyushu University is composed of three floaters with diameter of 1.0m).
The representative buoy which belongs to the latter type is the FLIP[3] *. This was developed by the Scrips Institute of Oceanography and used for the research of underwater acoustics.Its principal dimensions are follows: over all length = 355 ft, draft at upright condition = 300 ft, waterplane area = 125 square ft, displacement = 2,200 ton.In addition to the above spar buoy type station, we know the following several stations, for example, the Telecommunication Relay Float developed in Japan[4] (draft = 100m, displacement $w=2{,}000$ ton), SPAR**

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* FLIP: abbreviation of the Floating Instrument Platform

**SPAR: abbreviation of the Seagoing Platform for Acoustic Research

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(w = 1,700 ton), POP*** (w = 115 ton) and Bouee Laboratoire**** (w = 250 ton).

In 1975 we also developed the single point mooring spar buoy type station of displacement approximately 11 ton[5],[6] (mean water depth of the experimental site is 16 m and underwater length of the station is 13 m).

Using the wave data measured by the cloverleaf buoy we have determined the directional spectrum of ocean waves[2]. From the research of developing the single point mooring spar buoy type station with small displacement following results were obtained.

The influence of the buoy motion on the wave data was so small that the amount of correcting the motion was negligible. Wave data obtained at the buoy were compared with those obtained at the fixed type platform, which was built in 1974 to get the reference data of wind, waves and currents. The agreement was found to be good. Thus, it was shown that the buoy so for developed could be used as the platform for oceanographic research such as measuring wind and waves with higher precision[6].

2. Dynamic characteristics of a spar buoy

2.1 Natural frequency of heave

According to the "Webster" (Third New International Dictionary), it is defined that a spar buoy is a buoy consisting of a spar anchored to one end.

We show a floating buoy with circular section and coordinate systems in Fig.1, where o_1YZ is fixed in space, while oyz is attached to the buoy.

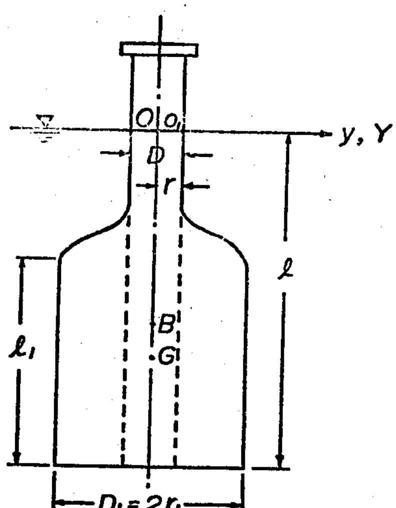

Fig.1 Spar buoy and coordinate axes

The equation of the free heaving motion of the buoy can be written in the following form:

$$(M + M_Z)\ddot{Z} + N_Z\dot{Z} + \rho g A_w Z = 0 \qquad (1)$$

where

Z = heaving displacement

M = mass of the buoy

***POP: abbreviation of Perpendicular Ocean Platform

****Bouee Laboratoire: belongs to the centre National pour Exploitation dês Oceans

M_Z = added mass of heaving

N_Z = damping coefficient of heaving

A_w = water plane area

ρ = density of the fluid

g = acceleration of gravity.

Putting $N_Z = 0$ in the equation (1) the natural period of heaving T_Z is given by the following equation

$$T_Z = 2\pi\sqrt{(M + M_Z)/\rho g A_w}\ . \qquad (2)$$

a) Cylindrical buoy

In case of the cylindrical buoy with radius r and draft l, which is shown by the dotted line in Fig.1,we have

$$M = \rho\pi r^2 l, \quad A_w = \pi r^2 \text{ and } M_Z \doteqdot \frac{4}{3}\rho r^3. \qquad (3)$$

The approximate value of M_Z is obtained by neglecting the effect of free surface and assuming the half of the submerged circular disc with radius r. Then the natural heaving period T_Z of the cylindrical buoy is given by

$$T_Z = 2\pi\sqrt{\rho\pi r^2 l\left(1 + \frac{4r}{3\pi l}\right)/\rho\pi r^2 g} = 2\pi\sqrt{\frac{l}{g}\left(1 + \frac{4r}{3l}\right)} \qquad (4)$$

From the equation (4), in the case of $l \gg r$ we obtain

$$T_Z = 2\pi\sqrt{\frac{l}{g}}. \qquad (5)$$

and the values of T_Z for various values of draft l are shown in the Table 1.

Table 1

l (M)	0.26	3	10	100
T_Z (sec)	1.0	3.4	6.3	20

As seen from the equation (5) and the Table 1, the cylindrical buoy with larger draft than 100 m has the natural heaving period T_Z longer than 20 sec.

b) Bottle type buoy

In case of the bottle type buoy which is shown by the solid line in Fig.1, T_Z is given by the following equation

$$T_Z = 2\pi\sqrt{\frac{l}{g}\alpha}. \qquad (6)$$

where

$$a = \left(\nabla + \frac{4}{3} r_1^3 \right) / \pi r^2 l \qquad (7)$$

and ∇ = volume of displacement.
Since the volume of displacement of cylindrical buoy $\pi r^2 l$ is much smaller than $\nabla + \frac{4}{3} r_1^3$, it results $a > 1.0$. As mentioned above, the bottle type buoy with large underwater volume has longer natural heaving period than the one of the cylindrical buoy with the same draft. The FLIP and the Telecommunication Relay Float are the bottle type spar buoys.

2.2 Wavelessp eriod andc haracteristics of heaving response amplitude

We show the profile of the FLIP in Fig.2. As seen from this figure the waterplane area is smaller than the horizontal sectional area of the underwater part. Such a buoy as the underwater sectional area is larger than the waterplane area has a waveless period in the heaving motion. That is to say, the heaving motion of the buoy is extremely small in the wave with the same period as the waveless period. According to the potential wave theory, heaving amplitude in the waveless period becomes zero.

The characteristics of heaving amplitude of a spar buoy with waveless period is shown in Fig.3.

Fig.2 Profile of the FLIP

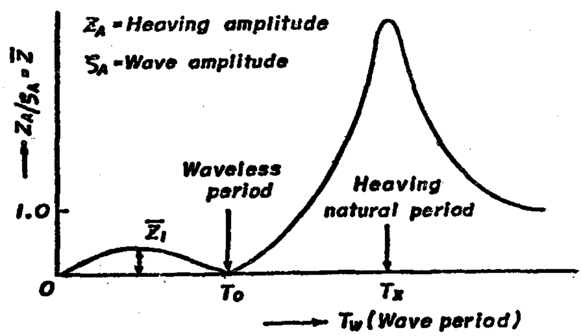

Fig.3 Characteristics of heaving response amplitude

In Fig.4 we show the characteristics of heaving amplitude Z_A/ζ_A (trasfer functions) and response spectra of heaving for the cloverleaf buoy and the FLIP. In this calculation, power spectral density of heaving S_{ZZ} is calculated by using the linear spectral analysis method. As seen from this figure, variance σ_Z of the cloverleaf buoy is nearly equal to that of wave spectrum $S_{\zeta\zeta}$ and the σ_Z of the FLIP is small.

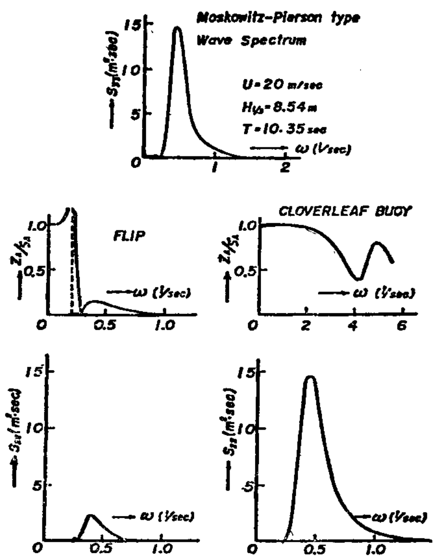

Fig.4 Comparison of heaving response ofthe FLIP and the cloverleaf buoy in irregular waves

This means that the cloverleaf buoy follows well on the wave surface and heaving motion of the FLIP is extremely small.

2.3 Natural rolling period and GM

Let J_ϕ be the mass moment of inertia of roll about G, I_ϕ the added mass moment of inertia, GM the metacentric height and W the displacement. Then the natural rolling period T_ϕ is given by the following equation

$$T_\phi = 2\pi\sqrt{(J_\phi + I_\phi)/W\cdot GM}. \tag{8}$$

In order to decrease the steady heel due to wind, waves and current, it is necessary to have a large value of $W\cdot GM$. In case of the spar buoy with a small W, the buoy must have large GM. On the other hand, when the value of T_ϕ is large the rolling amplitude of a buoy in waves will be generally small. Then, after all, it is necessary to make $J_\phi + I_\phi$ as large as possible and let down the position of G.

3. Dynamic characteristics of spar buoy station RIAM

At our experimental site[5], it was estimated that the maximum values of tidal current velocity is 1 knot, the wind velocity 40 m/sec, the wave height 5 m, and the energy of waves for long period greater than 10 sec will be extremely small. In order to develop a small floating type sea observation platform exhibiting excellent performance under these condition, we performed theoretical investigations and tank tests.

3.1 Shape of the main body

The main body of the station RIAM was consisted of a column with footing and three fins (discus fin perforated with circular holes, bottom vertical fin and vertical fin) (see Figs.5 and 6). We can increase the

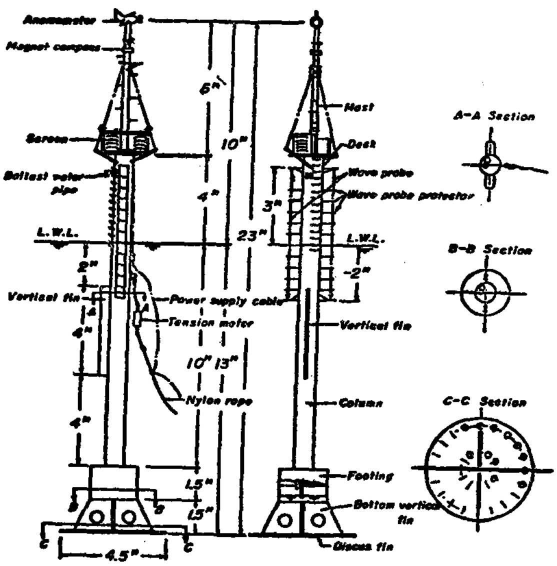

Fig.5 Spar buoy station RIAM

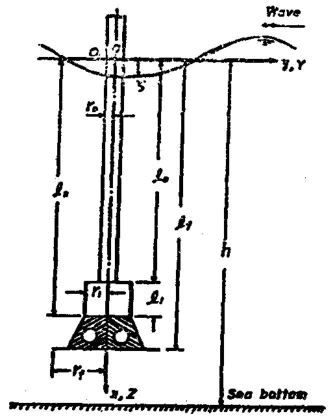

Fig.6 Profile of the station RIAM and coordinate systems

draft of the station by pouring sea water into the footing. By equipping the large discus fin, the heaving added mass and damping force increase and the station has a large waveless period for heaving. The bottom vertical fin increases both the added mass moment of inertias and damping forces for the rolling and pitching. The vertical fin is a resistance plate for the rotating motion around the vertical axis of the station.

Let r_0 = radius of the column
l_0 = length of the column
r_1 = radius of the footing
l_1 = length of the footing
and r_f = radius of the discus fin.

3.2 Natural heaving period and GM

The natural heaving period of the station RIAM T_Z is given by

$$T_Z = 2\pi\sqrt{(M + \Delta M + \Delta M_f)/\rho g A_w}, \quad (9)$$

where M: mass of the station
ΔM: added mass of the footing

ΔM_f: added mass of the discus fin.

Put
$$M=\rho\pi(r_0^2 l_0+r_1^2 l_1)+m, \qquad (10)$$
where m is the sum of masses of discus fin, bottom vertical fin and vertical fin.

Assuming that the effect of the free surface is negligibly small and considering $r_1>r_0$, we obtain
$$\Delta M \doteqdot \rho\frac{8}{3}r_1^3. \qquad (11)$$
Furthermore, supposing that the effects of free surface and sea bottom are negligibly small, and the heaving displacement is also small, we obtain
$$\Delta M_f \doteqdot \rho\frac{8}{3}r_f^3. \qquad (12)$$
Using the equations (9), (10), (11) and (12) we get
$$T_Z \doteqdot \frac{2\pi}{\sqrt{g}}\sqrt{l_0+\left(\frac{r_1}{r_0}\right)^2 l_1+\frac{m}{\rho\pi r_0^2}+\frac{8}{3}\,\frac{r_1^3+r_f^3}{\pi r_0^2}}. \qquad (13)$$
Putting
$$T_Z=2\pi\sqrt{l_0(1+a_1)/g} \qquad (14)$$
we obtain
$$a_1=\left(\frac{r_1}{r_0}\right)^2\left(\frac{l_1}{l_0}\right)+\frac{m}{\rho\pi r_0^2 l_0}+\frac{8}{3\pi}\left(\frac{r_1^3+r_f^3}{r_0^2 l_0}\right). \qquad (15)$$
As seen from the equations (14) and (15), the larger the radius of discus fin is the larger T_Z is.

In the cylindrical buoy with a column of length 10 m, we obtain $T_Z=2\pi\sqrt{l_0/g}=6.3$ sec. On the other hand, we obtain $T_Z \doteqdot 19$ sec for the station RIAM which has following dimensions: $\Delta \doteqdot 11$ ton, $l_0=10$ m, $r_0=0.4$ m, $l_1=1.5$ m, $r_1=1.0$ m and $r_f=2.25$ m. The value of T_Z measured by the field experiment was about 21 sec.

In order to let down the center of gravity G we increased the weight of the discus fin (about 4.5 ton). Then we obtained $GM \doteqdot 1.0$m. Furthermore, the actual rolling period became about 19 sec. This large period is due to the added mass moment of inertia of bottom vertical fin.

3.3 Heaving response in regular waves

As seen from Fig.3, in order to design the spar buoy with excellent performance it is necessary to increase the values of T_Z and T_0 and decrease the local maximum value $\overline{Z}_1$.

a) Equation of motion

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We show the coordinate systems in Fig.6, where the one represented by the capital letter O_1YZ is fixed in space, while the other written by the little letter oyz is attached to the spar buoy. Regular waves propagating to $-Y$ direction are given by

$$\zeta_A \cos(m_0 Y + \omega t), \tag{16}$$

where

ζ_A: wave amplitude

ω: circular frequency

m_0: wave number in finite depth and the real root of the equation $\omega^2/g = m_0 \tanh m_0 h$

h: water depth.

The equation of heaving motion of a freely floating spar buoy in regular waves with small amplitudes can be written in the following form:

$$(M + \Delta M + \Delta M_f)\ddot{Z} + n_1 \dot{Z} + \rho g A_w Z = F_{ZE} + n_2 (\dot{\bar{\zeta}}_{w2} - \dot{Z})|\dot{\bar{\zeta}}_{w2} - \dot{Z}|, \tag{17}$$

where Z: heaving displacement $\doteqdot Z_A \cos(\omega t + \varepsilon)$

Z_A: heaving amplitude

ε: phase difference

n_1: coefficient of the linear damping which is due to wave making

F_{ZE}: wave exciting force for heave

n_2: coefficient of non-linear damping which is due to viscous drag $= \frac{1}{2}\rho C_D \pi r_f^2$

C_D: drag coefficient

$\dot{\bar{\zeta}}_{w2}$: vertical component of the wave orbital velocity at the center of the discus fin

b) Wave exciting force

The linear wave exciting force for heaving is given by

$$F_{ZE} = F_Z^{FK} + F_Z^D, \tag{18}$$

where F_Z^{FK} is the wave force due to the Froude-Kriloff's theory and F_Z^D is the one due to the diffraction wave by the buoy restrained in incident waves.

The velocity potential Φ_W is given by

$$\Phi_W = \zeta_A \frac{g}{\omega} H_1(h, Z) \sin(m_0 Y + \omega t), \tag{19}$$

where $$H_1(h, Z) = \cosh m_0(h - Z)/\cosh m_0 h. \tag{20}$$

The subsurface ζ and the fluctuating water pressure P are given by the following equations:

$$\zeta = \frac{1}{g} \frac{\partial \Phi_W}{\partial t} = \zeta_A H_1(h, Z)\cos(m_0 Y + \omega t) \tag{21}$$

$$P = -\rho \frac{\partial \Phi_W}{\partial t} = -\rho g \zeta = -\rho g \zeta_A H_1(h, Z)\cos(m_0 Y + \omega t). \tag{22}$$

Using the equation (22) F_Z^{FK} is given by

$$\begin{aligned} F_Z^{FK} &= -P(Z = l_2)\pi r_1^2 + P(Z = l_0)\pi(r_1^2 - r_0^2) \\ &= \rho g \zeta_A \pi r_0^2 H_1(h, l_0)\{1 - \gamma^2(1 - \beta)\}\cos \omega t. \end{aligned} \tag{23}$$

where $\gamma = r_1/r_0, \qquad \beta = H_1(h, l_2)/H_1(h, l_0).$ (24)

In the next place, the vertical component of wave orbital velocity $\dot{\zeta}_W$ and the acceleration $\ddot{\zeta}_W$ are

$$\left.\begin{aligned} \dot{\zeta}_W &= -\omega \zeta_A H_2(h, Z)\sin(m_0 Y + \omega t) \\ \ddot{\zeta}_W &= -\omega^2 \zeta_A H_2(h, Z)\cos(m_0 Y + \omega t), \end{aligned}\right\} \tag{25}$$

where $H_2(h, Z) = \sinh\, m_0(h - Z)/\sinh\, m_0 h.$ (26)

Let

$$\begin{aligned} \overline{\dot{\zeta}}_{W1} &= \dot{\zeta}_W \text{ at } Z = l_0 + l_1/2 \text{ and } Y = 0 \\ \overline{\dot{\zeta}}_{W2} &= \dot{\zeta}_W \text{ at } Z = l_f \text{ and } Y = 0 \\ \overline{\ddot{\zeta}}_{W1} &= \ddot{\zeta}_W \text{ at } Z = l_0 + l_1/2 \text{ and } Y = 0 \\ \overline{\ddot{\zeta}}_{W2} &= \ddot{\zeta}_W \text{ at } Z = l_f \text{ and } Y = 0 \end{aligned}$$

Then we obtain

$$\left.\begin{aligned} \overline{\dot{\zeta}}_{W1} &= -\omega \zeta_A H_2\left(h, l_0 + \frac{l_1}{2}\right)\sin \omega t \\ \overline{\dot{\zeta}}_{W2} &= -\omega \zeta_A H_2(h, l_f)\sin \omega t \\ \overline{\ddot{\zeta}}_{W1} &= -\omega^2 \zeta_A H_2\left(h, l_0 + \frac{l_1}{2}\right)\cos \omega t \\ \overline{\ddot{\zeta}}_{W2} &= -\omega^2 \zeta_A H_2(h, l_f)\cos \omega t \end{aligned}\right\} \tag{27}$$

The diffraction force F_Z^D can de expressed by the sum of the forces proportional to $\overline{\dot{\zeta}}_W$ and $\overline{\ddot{\zeta}}_W$. When the wave making damping coefficient n_1 is small, however, the former force will be neglected. Thus, F_Z^D is approximately given by

$$\begin{aligned} F_Z^D &\doteqdot \Delta M \cdot \overline{\ddot{\zeta}}_{W1} + \Delta M_f \cdot \overline{\ddot{\zeta}}_{W2} \\ &= -\frac{8}{3}\rho \omega^2 \zeta_A \left\{ r_1^3 H_2\left(h, l_0 + \frac{l_1}{2}\right) + r_f^3 H_2(h, l_f) \right\} \cos \omega t. \end{aligned} \tag{28}$$

Using the equations (18), (23) and (28) we obtain

$$F_{ZE} = F_Z{}^{FK} + F_Z{}^{D}$$
$$= \rho g \zeta_A \pi r_0^2 H_1(h, l_0) A \cos \omega t = F_A \cos \omega t, \tag{29}$$

where

$$A = A_1 + A_2 + A_3,$$
$$A_1 = 1 - \gamma^2(1-\beta),$$
$$A_2 = -\frac{8}{3\pi}\,\frac{\omega^2 r_1}{g}\left(\frac{r_1}{r_0}\right)^2 \overline{H}_2\left(\frac{l_1}{2}\right), \tag{30}$$
$$A_3 = -\frac{8}{3\pi}\,\frac{\omega^2 r_f}{g}\left(\frac{r_f}{r_0}\right)^2 \overline{H}_2(l_f),$$
$$\overline{H}_2\left(\frac{l_1}{2}\right) = H_2\left(h, l_0 + \frac{l_1}{2}\right) / H_1(h, l_0)$$

and

$$\overline{H}_2(l_f) = H_2(h, l_f) / H_1(h, l_0).$$

In the equation (29), $\rho g \zeta_A \pi r_0^2 H_1(h, l_0)$ is the amplitude of heaving exciting force for the column with draft of l_0.

Then, A_1 is the Froude-Kriloff's effect by the footing, A_2 the diffraction effect by the footing and A_3 the diffraction effect by the discus fin.

Shown in Fig.7 are the frequency characteristics of A_1, A_2, A_3 and A. These are the calculation results for the two RIAM stations with $l_f = 12$ m and $l_f = 13$ m. In these calculations we assumed that water depth $h \doteqdot 16$m and dimensions of the main body are $r_0 = 0.4$ m, $l_0 = 10$m, $r_1 = 1.0$m, $l_1 = 1.5$ m and $r_f = 2.25$ m.

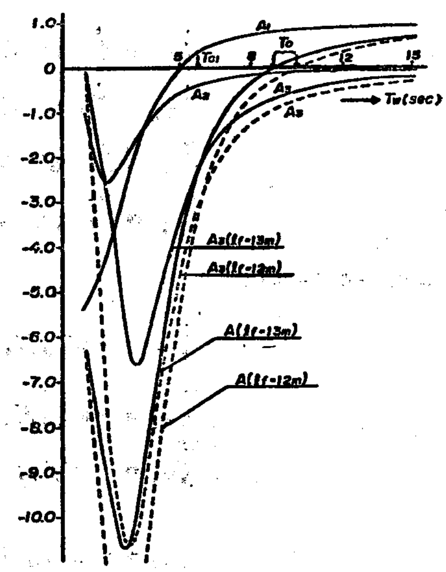

Fig.7 Frequency characteristics of A_1, A_2, A_3 and A

From the equations (29), (30) and the Fig.7 we can see the following.

(1) In case of the cylindrical buoy with a column only, it results that $\gamma = 1$ and $\beta = 1$. Then we obtain $A_1 = A = 1.0$ and F_A is always positive.

(2) In case of the buoy with a column and a footing, it results that $1-\beta > 0$ and $\gamma > 1.0$. Then we obtain a waveless period derived from the equation $A_1 = 0$.

(3) The values of A_2 and A_3 are negative for all wave periods T_w.

(4) Both T_{01} and T_0 are the waveless periods. T_{01} is obtained from the equation $A_1 + A_2 = 0$ and T_0 from the equation $A_1 + A_2 + A_3 = 0$. T_0 is usually larger than T_{01}.

(5) The larger r_f and the smaller l_f are the larger T_0 becomes.

As mentioned above, equipping the large discus fin is very effective to increase the periods T_Z and T_0. When the buoy is equiped with a too large discus fin of shallow draft, however, it results that the negative maximum value of A_3 in the Fig.7 and consequently the value of $\overline{Z}_1$ in the Fig.3 becomes large. Therefore, it is very important to decide the best dimensions of r_f and l_f in designing the station of RIAM type with small displacement.

c) Non-linear exciting force

When the station is restrained in waves, the non-linear viscous drag force F_{ZV} is given by the Morison's equation[7]. In case of the station RIAM, F_{ZV} is approximately given by

$$F_{ZV} = \frac{1}{2}\rho C_D \pi r_f^2 \,\overline{\dot{\zeta}_{w2}}|\overline{\dot{\zeta}_{w2}}|\,. \tag{31}$$

Using the equation (27) we obtain

$$\begin{aligned}\overline{\dot{\zeta}_{w2}}|\overline{\dot{\zeta}_{w2}}| &= -\omega^2\zeta^2{}_A H_2^2(h, l_f)\sin\,\omega t|\sin\,\omega t| \\ &= -\omega^2\zeta_A^2 H_2^2(h, l_f)\left(\frac{8}{3\pi}\sin\,\omega t + \frac{8}{15\pi}\sin 3\omega t + \cdots\cdots\right) \\ &\doteqdot -\omega^2\zeta_A^2 H_2{}^2\,(h, l_f)\frac{8}{3\pi}\sin\,\omega t.\end{aligned} \tag{32}$$

Therefore it results that

$$F_{ZV} \doteqdot -\frac{4}{3\pi}\rho C_D \pi r_f^2 \omega^2 \zeta_A^2 H_2^2(h, l_f)\,\sin\,\omega t. \tag{33}$$

On the other hand, in case of a floating station the nonlinear viscous drag force is given by

$$F_{ZV} = \frac{1}{2}\rho C_D \pi r_f^2\,(\overline{\dot{\zeta}_{w2}} - \dot{Z})|\overline{\dot{\zeta}_{w2}} - \dot{Z}|\,. \tag{34}$$

now put

$$\overline{\dot{\zeta}_{w2}} - \dot{Z} = U_0 \sin(\omega t + \delta), \tag{35}$$

then

$$(\overline{\dot{\zeta}_{w2}} - \dot{Z})|\overline{\dot{\zeta}_{w2}} - \dot{Z}| \doteqdot \frac{8}{3\pi}U_0(\overline{\dot{\zeta}_{w2}} - \dot{Z}). \tag{36}$$

Using the equations (34) and (35) we obtain

$$F_{ZV} \doteq \frac{1}{2}\rho C_D \pi r_f^2 \frac{8}{3\pi} U_0 (\overline{\dot{\zeta}_{w2}} - \dot{Z})$$

$$= N_Z U_0 (\overline{\dot{\zeta}_{w2}} - \dot{Z}), \tag{37}$$

where

$$N_Z = \frac{4}{3\pi}\rho C_D \pi r_f^2. \tag{38}$$

d) Damping coefficients

In case of the station RIAM, it is supposed that the wave making damping force is extremely small. This was also confirmed by Koterayama[8] .

Forced heaving tests for the submerged circular plate were performed by Koterayama[8] .

In the experiments the circular plate perforated with circular holes (see Fig.5) was also used. From the experimental results the added mass and damping force for heaving were analyzed. Main conclusion obtained from the above experiments is as follows:

1) The added mass of the circular plate perforated with circular holes is approximately given by the equation (12).

2) n_1 is negligibly small.

3) C_D of the circular plate perforated with circular holes is larger than C_D of the one without holes and can be expressed as following form:

$$C_D = 9.7 - 3.6\pi \frac{Z_A}{r_f}, \tag{39}$$

where $Z_A/r_f < 0.5$.

e) Heaving amplitudes in regular waves

Assuming that $Z = Z_A \cos(\omega t + \varepsilon)$, the water depth h is 16 m and the displacement is about 10 ton, and neglecting the term of $n_1 \dot{Z}$, we solved the equation (17) by use of the iteration method and obtained various results for combinations of dimensions of the column, the footing, and the discus fin. On the basis of the results we selected the final dimensinons as follows: $2r_0$ (diameter of the column) = 0.8 m, l_0 (length of the column) = 10 m, $2r_1$ (diameter of the footing) = 2.0 m, l_1 (length of the footing) = 1.5 m, $2r_f$ (diameter of the fin) = 4.5 m and l_f (draft of the discus fin) = 13 m.

The characteristics of the heaving response amplitude of the station

RIAM are that waveless period $T_0 = 9$ sec, the natural heaving period $T_Z = 21$ sec* and the local maximum response amplitude $\overline{Z}_1$ (in Fig. 3) $= 0.1$. In other words the heaving amplitude of the station at the experimental site is not exceeding 10 % of the incident wave amplitude, if the wave period is less than approximately 10 sec. This was also confirmed by the tank tests[5]. Fig.8 shows the comparison of the non-dimensional heaving amplitudes measured by model experiments and those obtained by theoretical calculations. The model experiments were carried out, by using the single point moored model with the scale 1/6, in the water tank ($L \times B \times D \times d = 80$ m $\times 8$ m $\times 3.5$ m $\times 3.0$ m) at the Research Institute for Applied Mechanics.

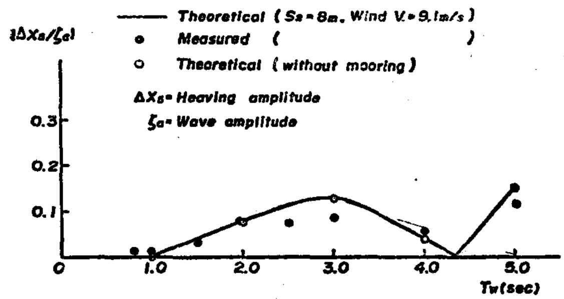

Fig.8 Comparison between the computations and model experiments of non-dimensional heaving amplitude

In the figure, the solid line shows the computation results for the single point moored condition in which s_2 is the length of mooring rope for the model. The calculation method of the buoy motion for the moored condition is described in the paper[5]. Both theoretical results (with mooring and without mooring) are in good agreement with the experimental ones. Since the natural heaving period T_Z is large, using the equation of motion (17) without n_1 and n_2 we can obtain sufficient correct values of heaving response amplitude for waves with short periods.

4. Concluding Remarks

We have derived the calculation method of heaving response in waves for the spar buoy with a large horizontal discus fin and developed the design method of the spar buoy of a new type with small displacement.

* The calculation result of T_Z was 19 sec and the measured value of T_Z for the actual station was 21 sec.

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