A study on an experiment of behavior of a SPAR type offshore wind turbine considering rotation of wind turbine blades

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***Abstract*-Many From environmental problem such as the global warming, the time to utilize renewable energy is ripe in substitution for fossil fuel now. The marine space is a treasure house of renewable energy of various forms. In Japan holding EEZ more than 10 times of the national land, the inflection of the renewable energy is extremely important from the viewpoint of self-supply of the energy. Above all, wind-generated electricity is success of the large-scale industrialization in Europe, and the introduction is examined positively in Japan. However, in the sea near Japan and Japanese EEZ, there is little shallow for a good distance from the shore sea area where large-scale industrialization was made in Europe. Therefore, in the expansion of the offshore wind-generated electricity in Japan, expansion of the offshore wind-generated electricity facility which is available for the very deep waters is necessary**

In this paper, we examine a SPAR type wind-generated electricity facility as the wind-generated electricity system which we can install in the very deep sea area.

Because the SPAR type wind-generated electricity facility is a slim institution, it is thought that the moorings which are necessary for setting relatively decrease. In addition, in the windmill, that an inclination vibrates is expected gently in actual sea area by the characteristic of the shape because the stability for the inclination is relatively small.

It is thought that the Yaw motion of windmill surface is caused by this inclination oscillation and gyro moment by the rotation of the windmill. Therefore, by this research, we show a water tank experiment and numerical computation about interaction between the rotary motion of the windmill blade and the dynamic motion of the SPAR type wind-generated electricity system in waves. In addition, we perform examination about the safety based on those results.

I. INTRODUCTION

An emission gas from the fossil fuel which continues having been used after the Industrial Revolution becomes the factor of one of the environmental problems such as the global warming. Therefore, we have motion of a breakaway from dependence to fossil fuel and positive practical use of the renewable energy worldwide. As the energy that is renewable, photovoltaic power generation, wind-generated electricity or the hydraulic power generation have already reached the practical use stage in the land. Because there are the successful results for large-scale industrialization as for the wind-generated electricity in particular in Europe and U.S.A., in late years high interest is put to even Japan. The wind-generated electricity is means a wind-force turns a windmill, and the rotary motion of the windmill is handed down to a dynamo, and to generate electricity. In late years the introduction advances steadily, and the quantity of the introduction has reached 1,850,000 KW in Japan as of the end of March, 2009 to show it in figure 1.

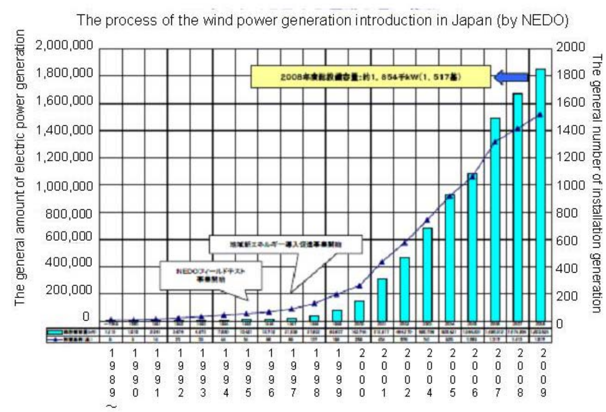

Figure.1 A change of the quantity of wind-generated electricity in Japan (NEDO)

The wind-generated electricity business developed rapidly in this way in Japan, but various problems occur recently. As for one of those, Japanese wind conditions is caused by disturbance being bigger than the wind conditions of American and European countries. In other words, for disturbance of this wind, a utilization rate of the wind-generated electricity facility lowers, and generation cost relatively becomes higher. For means to lower generation cost, making a windmill large size and doing a wind-generated electricity farm on a large scale be thought about. However, the land of Japan has little construction sites suitable for the large-scale wind-generated electricity facility originally. In the construction site where the wind conditions is suitable for, there are many cases that considerable consideration is necessary for problems of a scene and the noise by building it, besides. An argument to look for a construction site as solution to these many problems on the ocean space not the land space becomes active like Europe in Japan. It has generally the following merits to develop wind-generated electricity facility on the ocean.

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- Wind velocity is bigger than the land, and a utilization rate is high because disturbance of the wind is small.
- There are few obstacles at the time of transportation and installation
- It is easy to clear a problem about a scene and the noise.

On the other hand, it has generally the following demerits to build the large-scale generation institution.

- Operative cost in the ocean is more expensive than use it in the land.
- There is worry of influence on marine environment and the interference of the course.

The area of the exclusive economic zone of Japan is 4,510,000 km^2, and the area is the sixth place in the world. That there is enormous wind power energy only in an area of the near seas in the economic zone is already reported. However, the results of the wind-generated electricity in the ocean in Japan are only one place managing in Hokkaido from April, 2004. One of the causes that wind-generated electricity facility in the ocean is not readily introduced into in Japan is that Japanese sea is not shallow for a good distance from the shore than European sea. In other words, in the Japanese sea that the depth of the water is suddenly deep in the near sea, it is difficult to introduce grounding-type wind-generated electricity facility like Europe. As the technique that such a problem is settled, a floating structure-type wind-generated electricity institution becomes the candidate, and it is studied lively at various universities and research institutes.

It is assumed that there are two types of floating offshore wind-generated electricity system. One is that has one windmill on the floating structure and the other is that has multi windmills on the floating structure. We show a simple conception sketch in Figure.2.

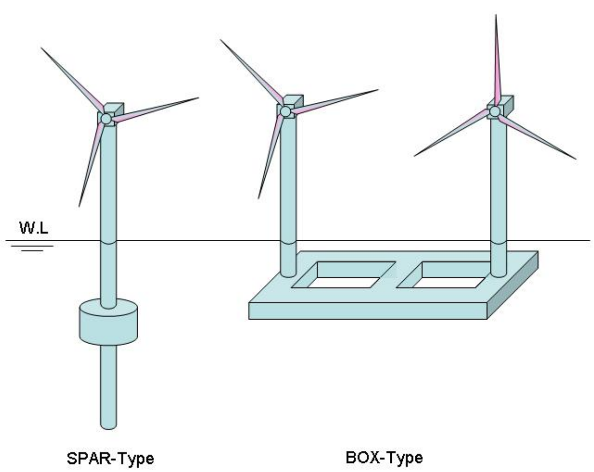


Figure.2 Rough sketch of concepts of the offshore floating wind-generated electricity systems

There are a lot of problems that must be settled so that such a floating structure-type wind-generated electricity system becomes the practical use. The one is the dynamic motion of the windmill. Generally, about the dynamic motion of the floating structure, the motion by the ocean waves becomes the large problem. It is, however, the important problem that not only the influence of the ocean waves but also the influence of the gyro moment by the rotation of the windmill should examine in the floating-type wind-generated electricity facility.

Because the tower of the windmill is fixed in the case of grounding-type wind-generated electricity facility, the change of the rotor surface of revolution of the windmill is extremely small. In contrast, in the case of a floating type, the whole floating structure is upset by ocean waves. Therefore, rotor surfaces of revolution of the windmills always vibrate. When a rigid body turning like a top and a gyro caught the force to change a surface of revolution, it is known by the rigid body that stability force occurs. In the floating structure-type wind-generated electricity facility, we can imagine that the influence appears easily. When the influence on oscillation of the floating structure by the rotation of the windmill is not so big, it is reported by the existing research, but there are extremely few examples which really confirmed those influence experimentally. In this report, we experiment on the water tank using the model of the SPAR type offshore floating wind-generated electricity facility and examine the influence that the rotation of the windmill in the waves gives to motion of the floating structure.

II. Formulation

The motion of floating structure in the waves is written down as follows.

$$\sum_{j=1}^{6}\{(M_{ij}+m_{ij})\ddot{\xi}_j+N_{ij}\dot{\xi}_j+C_{ij}\xi_j\}=F_i \qquad (1)$$

Here, M_{ij} , m_{ij} and N_{ij} are the coefficient of the mass of the structure or the moment of inertia, the added mass coefficient, and the damping coefficient respectively. The added mass coefficient and the damping coefficient are related the hydrodynamic radiation force which is proportional to the acceleration of the motion and that is proportional to the velocity of the motion respectively. C_{ij} is the restoring force coefficient, and F_i is wave exciting force. Subscript ij shows the coefficient of j-th motion by i-th motion as defined in Figure 3. We should add the equation of a moment occurring by the rotation of the windmill to this expression. The additional coordinate system for express the rotational motion of a disk is shown in Figure 4. The rotational disk whose angular velocity is ω_1 (=const) is in original point O_r. The rotary shaft of the disk at the original position is made the x axis direction in Figure 3.

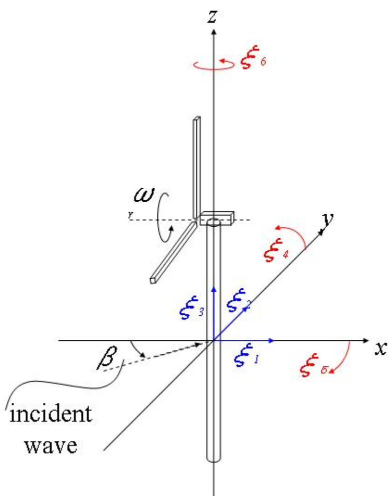


Figure.3 Coordinate system of the whole of floating structure

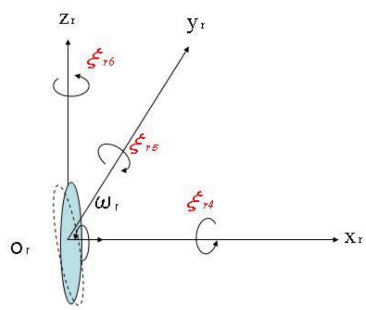


Figure.4 Coordinate system for the rotational motion of the disk

It's supposed that the vibration angle of the disk around x axis is $\xi_{r4} = \xi_4$, that around y axis is $\xi_{r5} = \xi_5$ and that around z axis is $\xi_{r6} = \xi_6$. Because the angular velocity of those angle is depend on the angular velocity of the waves ω_0, those angles are defined as follows:

$$\begin{aligned} \xi_4 &= \xi_4^0 e^{-i\omega_0 t} \\ \xi_5 &= \xi_5^0 e^{-i\omega_0 t} \\ \xi_6 &= \xi_6^0 e^{-i\omega_0 t} \end{aligned} \tag{2}$$

Here, $\xi_4^0, \xi_5^0, \xi_6^0$ of right side of the above equation show the amplitudes of the rotation angle of the motion. Therefore angular speeds $\omega_1, \omega_2, \omega_3$ around the respective axis are shown by,

$$\begin{aligned} \omega_1 &= \omega_1 - i\omega_0 \xi_4^0 e^{-i\omega_0 t} \\ \omega_2 &= -i\omega_0 \xi_5^0 e^{-i\omega_0 t} \\ \omega_3 &= -i\omega_0 \xi_6^0 e^{-i\omega_0 t} \end{aligned} \tag{3}$$

We differentiate this equation by time and obtain the next equation.

$$\begin{aligned} \dot{\omega}_1 &= -\omega_0^2 \xi_4^0 e^{-i\omega_0 t} \\ \dot{\omega}_2 &= -\omega_0^2 \xi_5^0 e^{-i\omega_0 t} \\ \omega_3 &= -\omega_0^2 \xi_6^0 e^{-i\omega_0 t} \end{aligned} \tag{4}$$

We can demand moments for each axis by substituting these equations for motions of Euler equation. Euler equation is represented by using the moments M_1, M_2 and M_3, and shown by,

$$\begin{aligned} M_1 &= I_1 \dot{\omega}_1 - (I_2 - I_3)\omega_2\omega_3 \\ M_2 &= I_2 \dot{\omega}_2 - (I_3 - I_1)\omega_3\omega_1 \\ M_3 &= I_3 \dot{\omega}_3 - (I_1 - I_2)\omega_1\omega_2 \end{aligned} \tag{5}$$

I_1, I_2 and I_3 are the inertia moment of the disk around the each axis. We can obtain the following equations when we substitute Equations (2), (3) into Equation (5).

$$\begin{aligned} M_1 &= I_1\omega_0^2\xi_4^0 e^{-i\omega_0 t} - (I_2 - I_3)\omega_0^2\xi_5^0\xi_6^0 e^{-2i\omega_0 t} \\ M_2 &= -I_2\omega_0^2\xi_5^0 e^{-i\omega_0 t} + (I_3 - I_2) i\omega_0\xi_6^0 e^{-i\omega_0 t}(\omega_1 - i\omega_0\xi_4^0 e^{-i\omega_0 t}) \\ M_3 &= -I_3\omega_0^2\xi_6^0 e^{-i\omega_0 t} + (I_1 - I_2) i\omega_0\xi_5^0 e^{-i\omega_0 t}(\omega_1 - i\omega_0\xi_4^0 e^{-i\omega_0 t}) \end{aligned} \tag{6}$$

When we suppose the oscillation of the Equation (6) to be small here and decide to ignore square of the oscillation, we can renew Equation (6) like Equation (7).

$$\begin{aligned} M_1 &= -I_1\omega_0^2\xi_4^0 e^{-i\omega_0 t} \\ M_2 &= -I_2\omega_0^2\xi_5^0 e^{-i\omega_0 t} + (I_3 - I_2) i\omega_1\omega_0\xi_6^0 e^{-i\omega_0 t} \\ M_3 &= -I_3\omega_0^2\xi_6^0 e^{-i\omega_0 t} + (I_1 - I_2) i\omega_1\omega_0\xi_5^0 e^{-i\omega_0 t} \end{aligned} \tag{7}$$

The terms of the gyro moment of the disk rotation are appeared as 2nd term of the right hand side in Equation(7) for M_2 and M_3. Therefore, the gyro moment M_{gyro} is as shown in the following separately.、

$$M_{gyro} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & (I_3 - I_1) i\omega_1\omega_0 \\ 0 & (I_1 - I_2) i\omega_1\omega_0 & 0 \end{bmatrix} \begin{bmatrix} \xi_{r4} \\ \xi_{r5} \\ \xi_{r6} \end{bmatrix} \tag{8}$$

In consideration of these, we can express the motion equation of floating wind-generated electricity facility in waves as follows:

$$\sum_{i=1}^{6} [-\omega_0^2 (M_{ij} + m_{ij}) - i\omega_0 (N_{ij} + M_{gyroij}) + C_{ij}][\xi_i] = [F_j] \tag{9}$$

Here, we define matrix $\left[COE_{ij}\right]$ as follow,

$$\left[COE_{ij}\right] = \left[-\omega_0^2 (M_{ij} + m_{ij}) - i\omega_0 N_{ij} + C_{ij} + M_{gyroij}\right] \tag{10}$$

we can obtain the relations among external force of regular waves, angular velocity of the disk and the amplitude of each motion as shown in Equation (11)

$$\sum_{i=1}^{6} \left[COE_{ij}\right]\left[\xi_i\right] = \left[F_j\right] \tag{11}$$

Finally, when we multiple the inverse matrix of $\left[COE_{ij}\right]$ to both sides of the equation, we obtain the dynamic equation as follow:

$$[\xi_i] = \sum_{j=1}^{6} [COE_{ij}]^{-1} [F_j] \tag{12}$$

III. EXPERIMENTS

In this research, we experimented on the effect of the gyro moment of the disk to the motion of the floating body. There are two experiment types in this paper. One is the experiment that how the natural periods of various motions change, and the other one is that how the harmonic motions in regular waves affected by the disk rotation.

(1) Natural period

For the natural period of the floating structure, it is an important index about the motion. In addition, GM and radius gyration of the floating structure have close relation to its natural period. Therefore we carried out next experiment.

i) Experiment method

The experiment model of the SPAR-type floating structure and the disk are shown in Figure 5 and Table 1.

Table.1 Particular of the rotational disk

Radius of the disk	95[mm]
Thickness of the disk	1.0[mm]
Weight of the disk	84[g]
Inertia moment of the disk	$3.8*10^5$ [g* mm^2]
Material	Aluminum

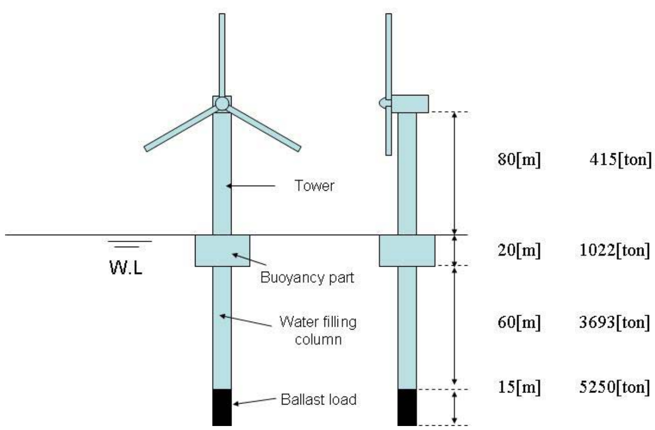


Figure.5 Sketch of the assumed actual SPAR model which is proposed by Suzuki et al

The assumed model is proposed by Suzuki et al. The windmill part used an aluminum disk to examine the influence that the gyro moment of the windmill gave to floating structure experimentally, and the wind did not generate it. The tower part is made by it chloroethylene, and the buoyancy body part is made by styrofoam. The actual experimental model is made by chloroethylene. And we used the thing which put lead in a polyethylene container for ballast. It is hereby changed weight and a center of gravity position. The sketch and picture of the experimental model are shown in Figure 6.

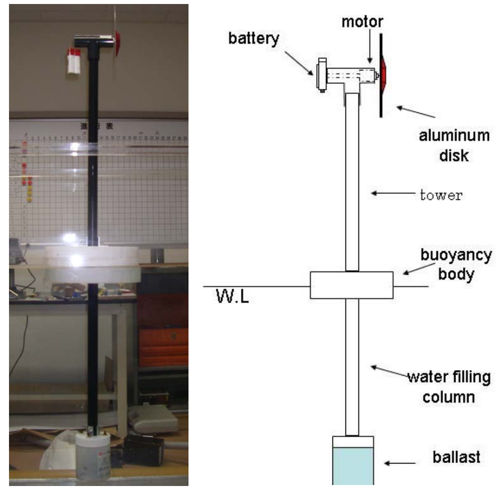


Figure.6 Picture (left) and sketch (right) of the experimental model

In the experiment, we measured the natural frequency of pitch motion and roll motion in the case of no rotation and in the case of disk rotation. The angular velocity of the disk ω_1 is 178[rad/s]. Table 2 is shown the detail value of the experimental model.

Table 2 Particular of the experimental model

Items	Actual model	Experiment model (1/158)
Height	175.0[m]	1108.0[mm]
Diameter of the buoyancy part	20.5[m]	120.0[mm]
Displacement	10380.0[ton]	2052.0～3452.0[g]
KB	68.0[m]	355.9～431.1[mm]
KG	37.0[m]	293.6～224.6[mm]
GM	32.0[m]	141.8～253.7[mm]
Draft	95.0[m]	523.3～556.2[mm]

ii) Experiment results

The results of the natural period are shown in Figure 7 (roll motion) and 8 (pitch motion). In these figures, the horizontal axis and vertical axis are GM[mm] and natural period[s] respectively. Blue lines and dots show the results without disk rotation and red lines and dots show the results with disk rotation. As shown these figures, the rotation of the aluminum disk decreases natural period of pitch and increases natural period of roll adversely. The change ratio is almost 1% of the value of the original which is in no rotation case. So we understand that the affect of the disk rotation to the natural period of the pitch and roll motion is not so large. But, when the GM becomes smaller, the influence of the gyro moment becomes larger. In this experiment, the water line crosses the fat buoyancy part. So, the GM becomes large. If the water line completely sets above the buoyancy part, the GM becomes quite smaller than the experiment model. To escape the natural frequency of the motions from the mean frequency range of the ocean waves, the GM of the facility sometimes set relatively small value.

By the way, the visible drifting yaw rotation appears in the experiment of the pitch oscillation. On the other hand, the few yaw rotation appears in the experiment of the roll oscillation.

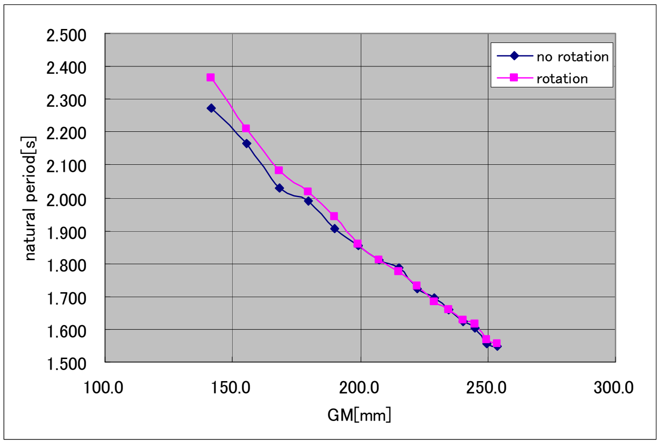


Figure 7 Relation between natural period of roll motion and GM

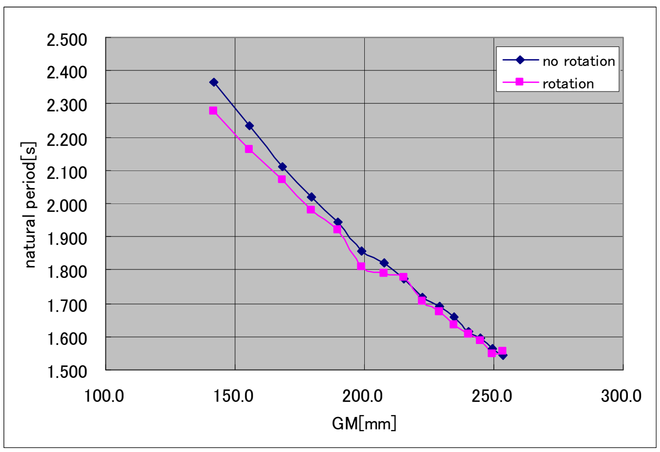
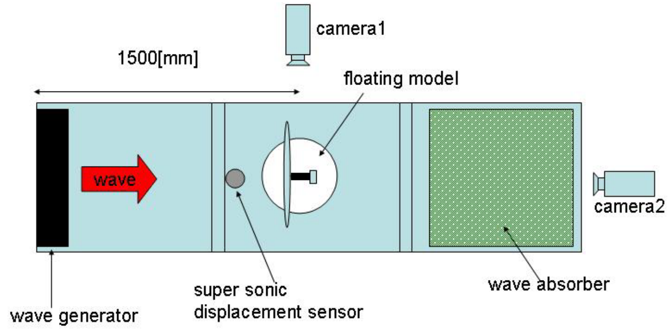


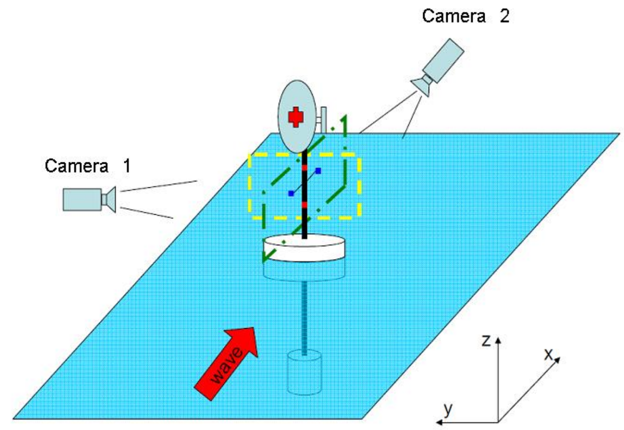
Figure 8 Relation between natural period of pitch motion and GM

(2) In regular waves

Next, we experimented how the gyro moment affects to the motion of SPAR type floating structure in regular waves. The experiment arrangement is shown in Figure 9. The floating model is moored by weak spring which only keeps from drifting. Wave periods are 0.3, 0.4, 0.5, 0.6 and 0.7. When we take the scale ratio of the model into consideration, the range of the period corresponds to the range from 4[s] to 9[s] in the actual sea. This range In each condition, we photograph the 6 motion modes of the floating structure with two digital cameras and analyze the image of the animation. We mark two points of red seals to the vertical tower part of the floating model and also mark two points of blue seals to horizontal light bar on the tower. We take pictures of these marks' motions on xy plane by using the one of the two cameras and analyze its surge, pitch and heave motion. And by using the other one, we take these marks' motion on yz plane and analyze sway, roll and heave motion. Then by using both cameras' data, we measure its yaw motion.

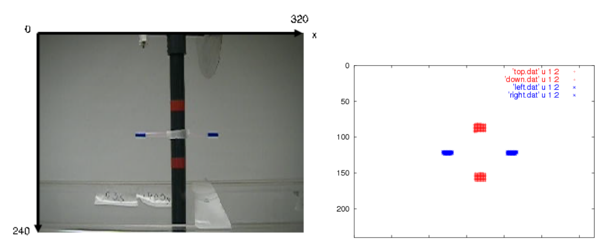


(a) A plan view

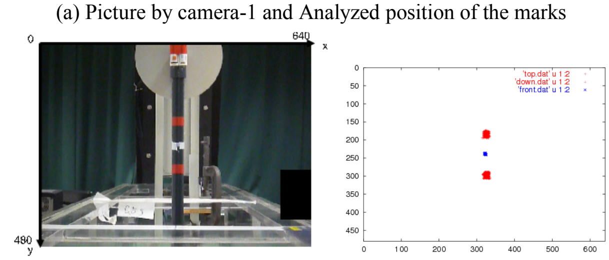


(b) A bird's-eye view

Figure 9 Arrangement of the experiment

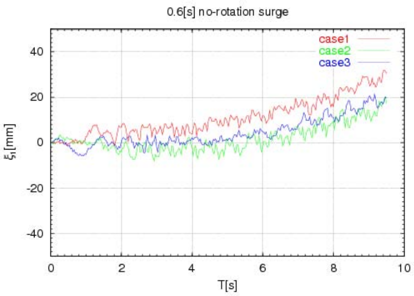


(a) Picture by camera-1 and Analyzed position of the marks

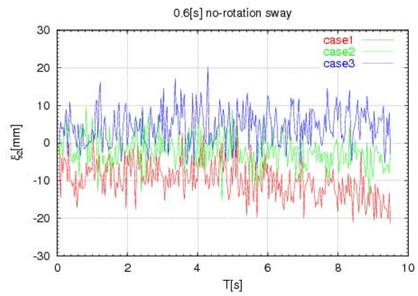


(b) Picture by camera-2 and Analyzed position of the marks

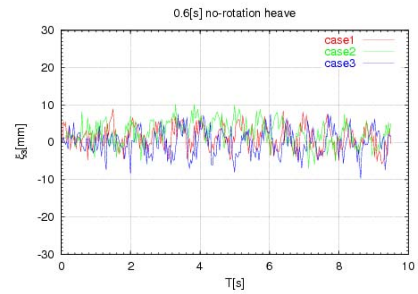
Figure 10 Sample results of the picture of the model which is in the still water and the analyses data; (a) :Camera-1 and (b):Camera-2



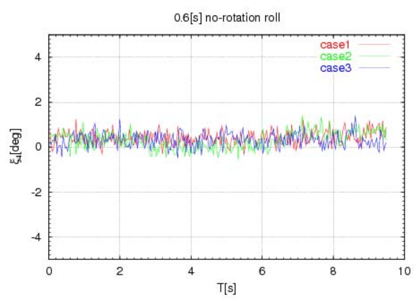
(a) Surge



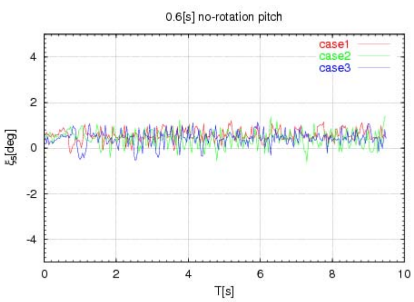
(b) Sway



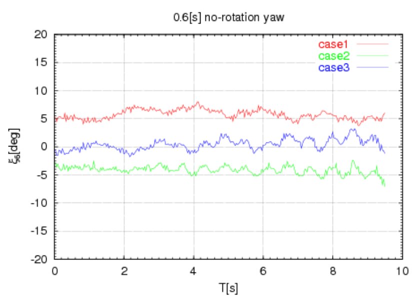
(c) Heave



(d) Roll

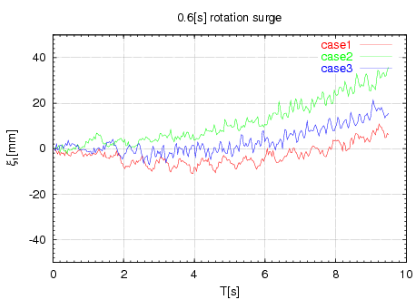


(e) Pitch

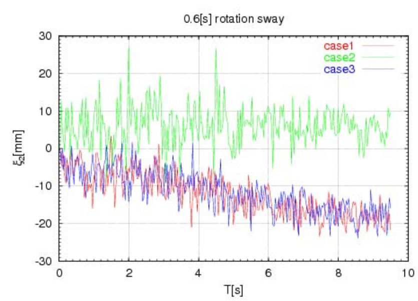


(f)Yaw

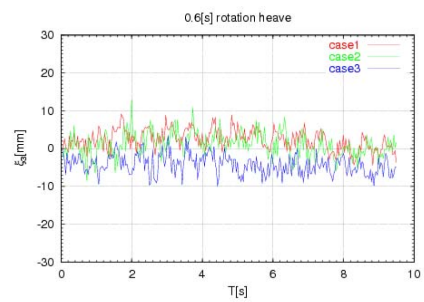
Figure 11 Time series experimental result of the behaviors of each motion mode in T=0.6s without disk rotation



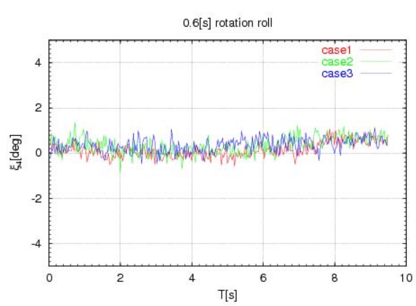
(a) Surge



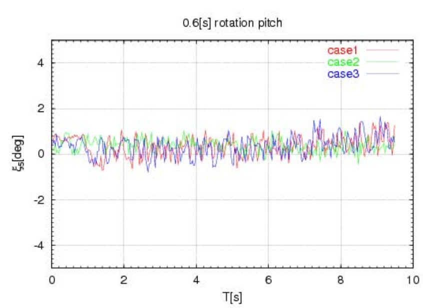
(b) Sway



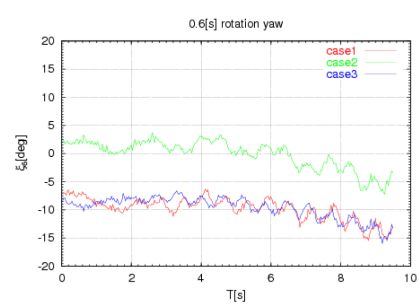
(c) Heave



(d) Roll



(e) Pitch



(f)Yaw

Figure 12 Time series experimental result of the behaviors of each motion mode in T=0.6s with disk rotation

We explain a concrete method of analysis. We separate the animation which we photographed with a digital camera to 30 pieces per second of still images. We read the position of each seal from the still image and read the time trajectory of the seal by unifying them. The sample result of the picture of the model which is in the still water and the analyses data are shown in Figure 10.

Figure 11 and Figure 12 show that the example of the experimental results. We carried out three times measurement in each condition; the case 1, 2 and 3 in these figures indicate the results in 1st, 2nd and 3rd time respectively.

About heave, roll and pitch with a little unevenness of the data every experiment, we show a stable and harmonic responses in both conditions. And we understand that the roll and pitch motions become quite small. On the other hand, surge motion shows the drift motion. A tendency has different impressions when we have a look at these results. However, the difference is an initial position and an initial phased difference, and the state of the surge drift understands that we show an about the same tendency all. When there is not the rotation of the disk, about sway, the motion of model vibrates around an initial position. In contrast, we understand that the model drifts slowly except one case when there is the rotation of the disk. As for the yaw motion, when there is not the rotation of the disk, the motion of model keep the position with little vibration. In contract, we understand that the yaw motion of the model in the case of disk rotation vibrates harmonically with drifting. This oscillation is regarded as the influence by the gyro moment by the rotation of the disk.

Using the time series response curves of each motion, we make the graphs of the frequency response of heave, roll and pitch motion by Fourier analysis and compare these as results of numerical computation. The each dot in Figure 17-19 is the average value of the three experiments and each line in Figure 17-19 shows numerical result obtained by the formulation introduced in section 2. The results are normalized by 1mm amplitude of the incident waves. Because the natural frequencies of the motion except heave motion are from 1 sec. to 2 sec., the significant difference of the numerical results between those in the disk rotation case and those in the disk no-rotation case is not observed. As shown these figure, the heave motion affects to the yaw motion. It can be consider that the main reason of such influence is; the absolute value of the heave motion became large and directly affect to the rigid body motion and besides the model is relatively large to the water tank width and the radiation waves that is induced by the heave motion reflects and interacts to its' yaw motion and heave motion. But it is important that the yaw motion with disk rotation is almost twice of those with disk no-rotation despite the almost same heave motion. And also an interesting thing is that such influence appears conspicuously and only in the yaw motion. This fact indicates that the gyro moment is not so large but the motion without restoring force is affected much by it. In this model, the neck part of the disk is fixed to the tower. If the disk freely and independently oscillated from the tower part, it is expected that the larger oscillation is induced.

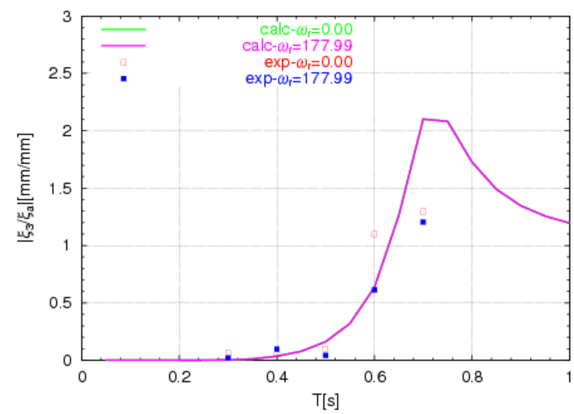


Figure.17 Response amplitude operator of heave motion of the model

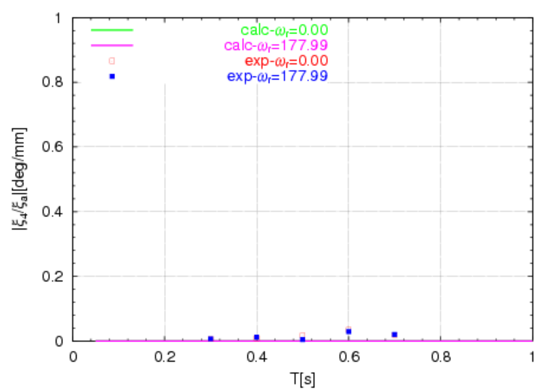


Figure.18 Response amplitude operator of roll motion of the model

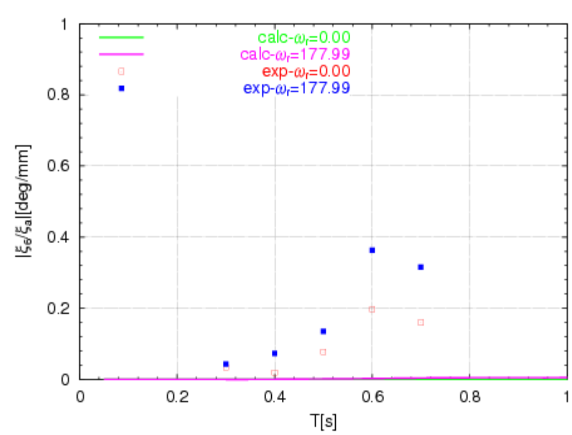


Figure.19 Response amplitude operator of yaw motion of the model

IV. Summaries

In this research, we got the following knowledge.

When we did free vibration in a water tank experiment while the disk part turned, we understood that natural period of the oscillation changed by a gyro moment of the rotation.

It was confirmed that roll and yaw which did not occur in the non-rotation disk occurred visually when we turned a disk. And that is indicated by the formulation. But the influence appears larger than the numerical expectation. The reason why is that the heave motion becomes quite large and affects directly and indirectly to the other rigid body motion. In addition, we understood that yaw motion appeared more conspicuously than roll motion. This is because that yaw motion doesn’t have restoring force.

We want to perform further inspection in the models that the neck of the disk turns freely in future.

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