Development of a Motion Stabilizer for a Shallow-Sea-Area Spar Buoy in Wind, Tidal Current and Waves

Toru Katayama and Kazuki Hashimoto
Graduate School of Engineering, Osaka Prefecture University
Osaka, Japan

Hiroshi Asou
Zeni Lite Buoy Co., Ltd.
Okayama, Japan

Shigenori Komori
Zeni Lite Buoy Co., Ltd.
Tokyo, Japan

In this study, the performance of a spar buoy with a motion stabilizer and an airfoil as a platform of wind state observation and with a Doppler Lidar for a bottom-mounted offshore wind farm project in the shallow sea area of less than 50 m in depth is investigated. Model tests in steady flow and in waves demonstrate the effectiveness of the motion stabilizer. The effectiveness of the airfoil is also confirmed by model tests in wind. In order to understand the mechanisms of the model-test stabilizer results, a time-domain motion simulation program is developed. Finally, the particulars of the stabilizer and shape of the airfoil are optimized based on the simulation results.

INTRODUCTION

Renewable energy technology is developed to create a sustainable society. Offshore wind farms are generally viewed as one of the most important energy supply resources.

Before construction of an offshore wind farm, a continuous measurement of upper wind field (wind direction and speed) for one year at the planned construction location is required. For measurement in past investigations, an upper wind field observation tower or platform for a Doppler Lidar or a Doppler Sodar as a remote sensing technique on the sea bottom was usually built. If a moored floating structure can be used as its platform, its foundation construction is lighter than these structures, and its environmental impact is smaller. However, in the case of a floating structure, it will oscillate in waves, and this oscillation affects the measurement accuracy.

In order to achieve accurate measurements, motion reduction of the buoy is important. Therefore, a motion stabilizer composed of four disk-fins and struts (they are called arms here) is proposed to reduce the motion of the buoy in waves and keep it upright in tidal current by using the hydrodynamic forces acting on it. Moreover, to reduce inclination of the buoy in wind, an airfoil is attached to the top of the buoy.

To understand the oscillation reduction, the authors used model tests in steady flow and in waves. The motion stabilizer effectiveness is confirmed from comparisons of the measured motions with and without the motion stabilizer. It is observed that the buoy without the motion stabilizer causes large-amplitude pitching motion when the incident wave period is half of the natural pitch period of the buoy.

In order to understand the mechanisms of motion reduction and of the large-amplitude pitching motion, a time-domain motion simulation is developed. From the calculated results in steady flow, it is understood that the lift forces acting on the fins of the motion stabilizer cause an inclining moment on the upstream side, and the drag forces acting on the fins cause an inclining moment on the downstream side when the fins are located above the mooring point of the buoy. When the fins are located below the mooring point, the drag forces cause an inclining moment to the upstream side. From the calculated results in waves, it is also understood that when the direction of a relative flow of water to the surface of the fins is normal, the effects of motion reduction are maximum by the drag force caused by the fins.

The simulation shows the occurrence of the above-mentioned large-amplitude pitching motion. Namely, the analysis of the calculated moments in the simulation shows that the large-amplitude pitching is caused by the variation of the pitch-restoring moment caused by the change in draft of the buoy at every time step. From these calculated results, the particulars of the stabilizer and shape of the airfoil are optimized.

Since the tidal current and wave directions are not always the same, the hydrodynamic forces to reduce the motion of the buoy cannot be very effective when they come from different directions. Therefore, an improved device, a motion stabilizer composed of a ring-fin and arms, is proposed, and the effects of the motion stabilizer are confirmed by model tests. Finally, in order to calculate the motion of the buoy with the motion stabilizer, the hydrodynamic forces acting on the motion stabilizer in steady flow are accurately measured.

MODEL AND COORDINATE SYSTEM

A spar buoy with a motion stabilizer is designed for 18 m water depth. Figure 1 shows schematic views of the buoy with the motion...
Fig. 1 Schematic views of the buoy with the motion stabilizer and coordinate system

The earth-fixed coordinate system is defined as O-X0Y0Z0, and the body-fixed coordinate system is defined as O-x0y0z0. H is water depth, h0 is the distance from the sea bottom to O, U(Z0) and Uwinds are the velocities of tidal current and wind, respectively, and Tw and Tw are period and amplitude of the regular wave, respectively.

Figure 2 shows a schematic view of the motion stabilizer (arm and fin). The angles of the arms and fins (θarm [°] and θfin [°]) can be changed. The zero values of the angles are defined as the condition where they are perpendicular to the center pipe of the spar buoy. Table 1 shows the principal particulars of the model (θarm = 20° and θfin = 15°).

MODEL TEST

In order to investigate the effectiveness of the motion stabilizer, model tests of the buoy with and without the motion stabilizer are carried out in steady flow (tidal current) and waves. The motion is recorded by a video camera (Power Shot G1X, Canon) and analyzed with motion capture software (TEMA, Photron).

Motion Measurement in Steady Flow

The motion measurement in steady flow is carried out in the circulating water channel of Osaka Prefecture University (size of observation section: length = 6 m, breadth = 1.5 m, depth = 1.09 m). Table 2 shows the measurement conditions in steady flow. The flow velocities are 1, 2, and 3 kts in real scale. For each flow velocity, the measurements for the buoy with and without the motion stabilizer are carried out.

In the measurements, the buoy without the motion stabilizer inclines to the downstream ward and causes periodic pitching and rolling. In contrast, the buoy with the motion stabilizer does not cause pitching and rolling.

Figure 3 shows the measured results of the buoy with the motion stabilizer in steady flow. In the same figure, the result of the buoy without the motion stabilizer, which is the time average value of the measured pitching motion, is also shown as a dotted line. Figure 3 shows that the increase in angle of the arm makes the angle of inclination smaller for the buoy having the same angle of fins. The figure also shows that the increase in angle of the fin makes the angle of inclination smaller for the buoy having the same angle of arms. When the angles of arms and fins are adjusted, the buoy is upright for any test velocities.

The reason that the inclination of the buoy is decreased by the motion stabilizer is as follows: Fig. 4 shows the schematic view of the position of the fins. The same figure also shows the drag and lift forces acting on the fins and the pitching moment caused by these forces in steady flow. In the left figure, the mounting angle of the arms is zero (= horizontal) and the fins are located above the mooring point of the buoy. On the other hand, in the right figure, the mounting angle of the arms is 20° and the fins are located below the mooring point. It can be understood that the lift forces cause an upstream pitching moment and the drag forces cause a downstream pitching moment in the left side of the

<table>
<thead>
<tr>
<th>Flow velocity [m/s]</th>
<th>With the motion stabilizer</th>
<th>W/o motion stabilizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11, 0.23, 0.34</td>
<td>0, 5</td>
<td>0, 5, 10, 15, 20, 25</td>
</tr>
<tr>
<td>0.34</td>
<td>0, 5, 10, 15</td>
<td>0, 5, 10, 15, 20, 25</td>
</tr>
<tr>
<td></td>
<td>0, 5, 10, 15, 20, 25</td>
<td>0, 5, 10, 15, 20, 25</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 2 Conditions of the experiment in steady flow
Development of a Motion Stabilizer for a Shallow-Sea-Area Spar Buoy in Wind, Tidal Current and Waves

Fig. 3 Measured angle of inclination in pitching in steady flow figure. On the other hand, the drag forces also cause an upstream pitching moment in the right side of the figure. When the mounting angle of the arms increases, the lever of the upstream pitching moment caused by lift forces decrease, the direction of the pitching moment caused by drag forces is changed from downstream to upstream, and the total upstream pitching moment increases. It can be understood that the inclination of the buoy decreases. In the right side of Fig. 4, the larger attack angles of the fins to steady flow result in larger drag and lift forces, which reduce the buoy inclination. If the upstream ward pitching moment caused by drag and lift forces acting on the fin equals the downstream ward pitching moment caused by drag forces acting on the buoy, then the buoy can be upright. Moreover, if the hydrodynamic coefficients acting on the fin and the buoy are constant regardless of Reynolds number, then the buoy can be upright regardless of flow velocity.

Motion Measurement in Waves

The motion measurement in irregular waves is carried out at the towing tank of Osaka Prefecture University (length = 70 m, breadth = 3 m, depth = 1.5 m). The Bretschneider-Mitsuyasu spectrum, as shown in Eq. 1, is used (Mitsuyasu, 1970). For the wave making, this spectrum is divided into 100 equally, from 0.2 to 2.0 Hz. The sinusoidal waves at each frequency are then superposed. The phase difference at each frequency component is given as random numbers, and motion measurement is then carried out for more than 200 encounter waves.

\[
S(f) = 0.257H_2^{1/3}T_{1/3}(T_{1/3}f)^{-5} \exp\left\{ -1.03(T_{1/3}f)^{-1} \right\}
\]

(1)

Table 3 summarizes the measurement conditions in irregular waves. The full-scale significant wave height is 2 m and the average wave period is 12 s. Similar to the measurement in steady flow, the measurements in irregular waves for the buoy with and without the motion stabilizer are carried out. The data sampling is started before the wavemaker waves reach the position of the buoy. The data sampling is finished before the reflected wave from the wall of the tank end reaches the buoy.

Table 4 shows the significant peak-to-peak values of measured pitching in irregular waves, which are obtained by the zero-downcross method. First, from Table 4, the effect of the motion stabilizer is confirmed. Second, when the mounting angle of the arms is 20°, the amplitude is the smallest at 15° of the mounting angle of the fins; when the mounting angle of the fins is 15°, the amplitude is the smallest at 10° of the mounting angle of the arms.

It is supposed that the main factor of motion reduction by the motion stabilizer is the damping moment caused by the drag force acting on the fins as a result of motion of the buoy. It can be understood that the red line through the surface of the fin, as shown in Fig. 5, means the direction of a relative flow of water to the surface is normal and the motion reduction is maximum.

| Significant wave height in model scale [mm] | 98.4 |
| Significant wave period in model scale [s] | 2.7 |
| \( \theta_{Arm} \) [°] | \( \theta_{Fin} \) [°] |
| 10 | 15 |
| 20 | 5, 15, 25 |
| 30 | 15 |

Table 3 Conditions of the experiment in irregular waves

| W/o motion stabilizer | 28.40° |
| With motion stabilizer | \( \theta_{Arm} = 10° \) | 20° | 30° |
| \( \theta_{Fin} = 5° \) | — | 10.22 | — |
| 15° | 9.55 | 9.58 | 10.15 |
| 25° | — | 10.17 | — |

Table 4 Significant peak-to-peak value of measured pitching in irregular waves
Figure 6 shows the relative position of the fins to the mooring point in the conditions given in Table 3. In the same figure, the red dotted line through the surface of the fin is also shown. When the mounting angle of the arms is 20°, the distance between the red line and the mooring point is the nearest at 15° of the mounting angle of the fins. When the mounting angle of the fins is 15°, the distance between the red line and the mooring point is the nearest at 20° of the mounting angle of the arms. But when the mounting angle of the arms is 10°, the effect of motion reduction is the maximum because the distance between the fin and the mooring point is at its greatest. Consequently, for each mounting angle of the arm, an optimized mounting angle of the fin ($\theta_{\text{DMAX}}$) can be estimated that results in maximum motion reduction. Table 5 presents an example of this optimized mounting angle.

**Motion Measurement in Wind**

The motion measurement in wind is carried out by using the wind fan at the towing tank of Osaka Prefecture University. For the model tests in wind, the upper structure of the buoy is changed and an airfoil (circular-arc airfoil) is attached to its top, as shown in Fig. 7. By using the lift force acting on the airfoil, the inclination of the buoy in wind is reduced. Figure 8 shows a schematic side view of the measurement and coordinate systems. Table 6 shows the conditions of the measurement in wind. The model tests for the buoy without the motion stabilizer are carried out in order to compare the measured motions with and without the airfoil. The wind velocities are 10, 20, 30, and 40 m/s in real scale.

Figure 9 shows the measured results in wind. In the same figure, the pitch angles of the buoy with and without the airfoil are shown by a red triangle and a black circle, respectively. It is noted that the buoy without the airfoil can be upright without wind. The buoy with the airfoil has an initial incline caused by the weight of the airfoil. Therefore, the subtraction of the initial angle of inclination from the results for the vertical axis is shown as a blue quadrangle. Through comparison of the tests denoted by the blue quadrangle and the black circle, the effect of the airfoil is confirmed.

**TIME DOMAIN SIMULATION**

To further clarify the motion reduction mechanisms measured in the experiments, a time-domain motion simulation program is developed. In this section, the calculation results are presented in model scale.
Equation 2 is the single-degree-of-freedom motion equation of the buoy in tidal current and waves:

\[
(I + i + I_D + i_D) \ddot{\theta} = M_R + M_{D1} + M_{D2} + M_D \\
+ M_{DD1} + M_{LD1} + M_{DD2} + M_{MD} + M_{DWING} + M_{LWING}
\]  

(2)

where \( I \) and \( i \) are the moment of inertia and added moment of inertia of the center column, respectively. \( I_D \) and \( i_D \) are the moment of inertia and added moment of inertia, respectively, of the arms and fins. \( M_R, M_{D1}, M_{D2}, \) and \( M_D \) are the forces acting on the center column, and they are restoring moments, steady and unsteady drag force, and body force in waves. \( M_{DD1}, M_{LD1}, M_{DD2}, \) and \( M_{MD} \) are the moments acting on the fins, and they are caused by steady drag and lift force, unsteady drag force, and body force in waves. \( M_{DWING} \) and \( M_{LWING} \) are the moments caused by steady drag and lift force in wind acting on the airfoil.

The moment of inertia and restoring moment are obtained from calculation, and the other moments are obtained from experiments.
and existing data (Otsuka et al., 1997; Sarpkaya, 2010). Equation 2 is calculated by the fourth-order Runge-Kutta method.

In addition, free decay tests of the model are carried out. In the simulation for the buoy without the motion stabilizer, the moment of inertia and unsteady drag force acting on the center column are adjusted by the results. On the other hand, in the simulation for the buoy with the motion stabilizer, the moment of inertia and unsteady drag force acting on the fins are adjusted by the results.

Motion Calculation in Steady Flow

Figure 10 shows the measured and calculated inclinations in steady flow for the buoy with and without the motion stabilizer. This figure shows that the calculated results for the buoy without the motion stabilizer agree with the measured results. On the other hand, the calculated results for the buoy with the motion stabilizer are larger than the measured results. In order to get better agreement with the measured results, as shown in Fig. 11, the lift coefficient of the fin of the motion stabilizer is multiplied by 1.17.

Figure 12 shows the calculated inclination in steady flow for the same conditions as in Fig. 3. From the results, it is confirmed that the buoy can be upright at any velocity when the mounting angle of the arms is $20^\circ$ or $30^\circ$ and one of the fins is $15^\circ$ to $25^\circ$.

Motion Calculation in Waves

Table 7 shows the calculated pitch amplitudes in regular waves at $T_w = 2.66$ s and $H_w = 98.4$ mm ($T_w = 12$ s and $H_w = 2.0$ m in real scale). The results show the effect of the motion stabilizer. It qualitatively agrees with the measured results in irregular waves given in Table 4.

Figure 13 shows the calculated and the measured pitch amplitudes in regular waves for the conditions shown in Table 8. From this figure, it is confirmed that the calculated results agree with the measured results. The results without the motion stabilizer in Fig. 13 indicate that pitch amplitude becomes large at $T_w = 2.00$ s. In the following part, the reason for the high rolling occurrence is discussed.

Figure 14 shows the time history of the calculated pitch angle in regular waves at $H_w = 123.0$ mm and $T_w = 2.00, 2.44$ s. From this figure, it is found that the motion period is the same as the wave period at $T_w = 2.44$ s. On the other hand, the motion period is twice the wave period at $T_w = 2.00$ s.

In addition, the natural pitch period of the buoy without the motion stabilizer is 4.00 s, and the encounter wave period is half of the natural pitch period. Therefore, it is supposed that this motion is a form of parametric excitation motion (e.g., Nayfeh and Mook, 1979). This is written in Mathieu’s equation as:

$$\ddot{x} + (a - 2q \cos 2t)x = 0$$

where $a$ and $q$ are arbitrary constants.

Figure 15 shows the time history of the calculated buoyancy of the buoy in regular waves at $H_w = 123.0$ mm and $T_w = 2.0$ s. It is confirmed that the buoyancy changes in the encounter wave period, and this causes the change in the pitch-restoring coefficient. If the encounter period is half of the natural pitch period, the buoy experiences the upstream or downstream pitching moment with each wave.

![Fig. 13 Calculated and measured pitch amplitudes in regular waves](image1)

**Table 8 Conditions of the experiment in regular waves**

| Wave height: $H_w$ [mm] | 49.2, 123.0 |
| Wave period: $T_w$ [s] | 1.11, 1.33, 1.55, 1.77, 2.00, 2.22, 2.44 |
| With motion stabilizer | $\theta_{Arm} = 20^\circ$, $\theta_{Fin} = 15^\circ$ |
| Without motion stabilizer | |
Development of a Motion Stabilizer for a Shallow-Sea-Area Spar Buoy in Wind, Tidal Current and Waves

**Fig. 15** Time history of calculated buoyancy in regular waves at $H_w = 123.0$ mm, $T_w = 2.0$ [sec]

**Motion Calculation in Wind**

Figure 16 shows the measured and calculated angles of inclination in pitching in wind for the buoy without and with the airfoil. In the same figure, the calculated and measured results are shown with open marks and filled marks, respectively. Figure 16 shows good agreement between the calculated and measured results, except for the calculated result at wind velocity $U = 8.87$ m/s.

The airfoil is attached to the top of the upper structure of the buoy, and the drag force acting on the airfoil causes an inclining moment to the downstream side. When the airfoil is located on the downstream side, the lift force acting on the airfoil causes an inclining moment to the upstream side. Therefore, it is necessary to select the airfoil whose lift-drag ratio is large enough to reduce the angle of inclination in wind.

Figure 17 shows the calculated angles of inclination in pitching in wind of the buoy with the NACA 6409 airfoil, whose lift-drag ratio is larger than the circular-arc airfoil. The upper figure of Fig. 17 shows the angle of inclination in pitching with the earth-fixed coordinate system; the lower figure shows the displacement angles from initial inclination. In the lower figure, it is confirmed that the inclination of the buoy can be made smaller by attaching NACA 6409, whose lift-drag ratio is large.

**OPTIMIZATION OF MOTION STABILIZER**

If the length of the arm and diameter of the fin are decided for steady flow, the mounting angle of the arm and the fin to make the buoy upright can be determined. Also, in waves, the mounting angle of the arm and the fin can be optimized to minimize pitch amplitude.

Figure 18 shows the optimized mounting angle of the fin and the arm for a certain arm length and fin area at the current velocity = 0.34 m/s, $H_w = 148$ mm, and $T_w = 2.66$ s in regular waves. It is found that the optimum mounting angle of the fins in steady flow monotonously decreases and the optimum mounting angle of the fins in waves increases according to the increase in the mounting angle of the arms. Consequently, we found that the intersection point indicates the optimum mounting angles of the arm and the fin in both steady flow and waves.

The length of the arm and diameter of the fin are optimized as follows: The optimum mounting angle of the arms and the fins are first calculated using the time-domain motion simulation for each parameter shown in Table 9. When the length of the arm becomes longer or the diameter of the fin becomes larger, the effect of motion reduction becomes large. However, the bending moment acting on

![Graphs and diagrams here]

Table 9  Conditions of motion stabilizer

<table>
<thead>
<tr>
<th>Diameter of fin [mm]</th>
<th>123, 140, 155</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of arm [mm]</td>
<td>344, 394, 443, 492, 541, 591</td>
</tr>
</tbody>
</table>
the joint between the arms and the center column also becomes large, and the results of moment become a design constraint. If the length of the arm becomes long, the limit of inclination angle, defined by when the end of the motion stabilizer of the buoy reaches the sea bottom, is decreased. This angle is a limit on design. With consideration of the above-mentioned limits, the optimized length of the arms and diameter of the fins are shown in Fig. 19.

Fig. 21 Schematic side view of the buoy with the motion stabilizer and coordinate system (top), and photo of the side view of the buoy in real seas (bottom)

**IMPROVED MOTION STABILIZER**

Figure 20 shows two schematic top views of the buoy with the motion stabilizer and coordinate system. In the upper figure of Fig. 20, the motion stabilizer, which is composed of four disk-fins and arms, is shown. The hydrodynamic forces acting on the disk-fins to reduce the motion of the buoy can be gained effectively when the angle between the arm and the tidal current or wave (ψ) equals 45°, as shown in the figure. When the incident directions of the tidal current and wave are not the same, it is difficult to realize the maximum effects of the stabilizer for both of them. Therefore, an improved motion stabilizer is developed. It is composed of a ring-fin and arms, as shown in the lower figure of Fig. 20. In addition, the airfoil is attached to the top of the buoy, and the buoy is under yaw-free condition. As a result, the buoy is redirected toward the incident direction of the wind. It can be maintained in an upright position in any incident direction of tidal current. This allows for the maximum effects of the stabilizer in any incident direction of wave. In order to confirm the effect, the 1/2.5 scale model of the buoy with the motion stabilizer is tested. The motion
measurement in real seas was also carried out at Sagami Bay in Japan from January 2015 to February 2015, as shown in the bottom photo of Fig. 21.

**Model Test**

The effect of the motion initial stabilizer composed of the disk-fins is confirmed by model tests. In this section, the results of the ring-fin motion stabilizer tested in the same steady flow and waves are discussed.

Figure 22 shows a schematic side view of the motion stabilizer (arm and fin). The angles of the arms and fins ($\theta_{Arm}$ and $\theta_{Fin}$) can be changed. The zero values of the angles are defined as the condition where they are perpendicular to the center pipe of the spar buoy. The surface area ratio of the fin can be also changed to 100%, 125%, and 200% (the surface area ratio of the smallest fin is defined as 100%).

Table 10 shows the principal particulars of the model. Table 11 shows the principal particulars of the motion stabilizer (the surface area ratio of the fin is 100% and $\theta_{Arm} = 10^\circ$).

**Motion Measurement in Steady Flow**

Motion measurement in steady flow is carried out at the circulating water channel of Osaka Prefecture University (size of the observation section: length = 6 m, breadth = 1.5 m, depth = 1.09 m). Table 12 summarizes the measurement conditions in steady flow. For each flow velocity, the measurements for the buoy with and without the motion stabilizer are carried out.

---

**Table 10 Principal particulars of the model**

<table>
<thead>
<tr>
<th>$\theta_{Arm}$ [$^\circ$]</th>
<th>$\theta_{Fin}$ [$^\circ$]</th>
<th>Surface area ratio of the fin [%]</th>
<th>R [mm]</th>
<th>r [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.7</td>
<td>100</td>
<td>416.3</td>
<td>386.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td>420.0</td>
<td>382.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>431.2</td>
<td>371.6</td>
</tr>
<tr>
<td>20</td>
<td>13.8</td>
<td>100</td>
<td>396.7</td>
<td>366.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td>400.6</td>
<td>362.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>412.0</td>
<td>350.8</td>
</tr>
<tr>
<td>30</td>
<td>23.0</td>
<td>100</td>
<td>366.8</td>
<td>335.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td>370.8</td>
<td>331.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>382.5</td>
<td>319.6</td>
</tr>
</tbody>
</table>

**Table 11 Principal particulars of the motion stabilizer**

<table>
<thead>
<tr>
<th>With motion stabilizer</th>
<th>Surface area ratio of the fin [%]</th>
<th>Flow velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{Arm}$ [$^\circ$]</td>
<td>$\theta_{Fin}$ [$^\circ$]</td>
<td>100, 125, 200</td>
</tr>
<tr>
<td>10</td>
<td>4.7</td>
<td>0.11 [m/sec]</td>
</tr>
<tr>
<td>20</td>
<td>13.8</td>
<td>0.23 [m/sec]</td>
</tr>
<tr>
<td>30</td>
<td>23.0</td>
<td>0.34 [m/sec]</td>
</tr>
</tbody>
</table>

---

The measured results for the buoy with the motion stabilizer in steady flow are shown in Fig. 23. This figure shows the inclination is smaller when the surface area ratio of the fin increases. It also shows the inclination angle is smaller when the angle of the arms increases. When the angles of the arms and the surface area ratio of the fin are adjusted, the buoy can maintain upright condition for any velocity (for example, when the surface area ratio of the fin = 200% and $\theta_{Arm} = 16.36^\circ$ at 0.34 m/s).

**Motion Measurement in Waves**

Motion measurement in irregular waves is carried out in the towing tank of Osaka Prefecture University (length = 70 m, breadth = 3 m, depth = 1.5 m). The Bretschneider-Mitsuyasu spectrum
Table 13 Conditions of the experiment in irregular wave

<table>
<thead>
<tr>
<th>Arm angle (\theta_{\text{Arm}})</th>
<th>Surface area ratio of the fin (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.7</td>
</tr>
<tr>
<td>20</td>
<td>13.8</td>
</tr>
<tr>
<td>30</td>
<td>23.0</td>
</tr>
</tbody>
</table>

W/o motion stabilizer

Table 14 Significant peak-to-peak values of measured pitching in irregular wave

<table>
<thead>
<tr>
<th>Angle (\theta_{\text{Pitch}})</th>
<th>Flow velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>4.7</td>
</tr>
<tr>
<td>20</td>
<td>13.8</td>
</tr>
<tr>
<td>30</td>
<td>23.0</td>
</tr>
</tbody>
</table>

Table 15 Conditions of measurement of hydrodynamic forces of the motion stabilizer

The motion stabilizer is composed of a ring-fin and arms, and the hydrodynamic forces of the motion stabilizer measured by the three-component load cell are the total value of the hydrodynamic forces acting on the fin, arms, and strut. Therefore, measurement of the hydrodynamic forces of the strut and arms is also carried out. The hydrodynamic forces acting on the fin are obtained by subtracting the hydrodynamic forces acting on the strut and arms from the total value of the hydrodynamic forces. The measured moment is transformed from the center of the load cell to the mooring point of the buoy by using Eq. 6. The hydrodynamic coefficients are calculated with Eqs. 7 to 9.

\[ F_{\text{Ox}} = F_{\text{i}} \]  
\[ F_{\text{Oz}} = F_{\text{i}} \]  
\[ M_{\text{Oy}} = M_{\text{i}} - F_{\text{i}}(l_{1} + l_{2}\cos \alpha) + F_{\text{i}}l_{2}\sin \alpha \]  
\[ C_{D} = \frac{F_{\text{Ox}}}{0.5\rho SU^{2}} \]  

Hydrodynamic Coefficients Measurement in Steady Flow

It is necessary to clarify the characteristics of hydrodynamic coefficients of the motion stabilizer in order to calculate accurately the motion of the buoy with the motion stabilizer. These hydrodynamic forces acting on the motion stabilizer in steady flow are measured in the circulating water channel of Osaka Prefecture University.

The motion stabilizer is connected to a three-component load cell with a strut, as shown in Fig. 24. Table 15 summarizes the conditions of the measurements in steady flow. The angle of the motion stabilizer \(\alpha\) can be changed from -30 to 30°. The flow velocities are 2 and 3 kts in real scale. The drag force, lift force, and pitching moment of the motion stabilizer are measured for each angle and flow velocity.

Fig. 24 Schematic view of measurement of hydrodynamic forces of the motion stabilizer

Fig. 25 Measured hydrodynamic coefficients of the fin
Development of a Motion Stabilizer for a Shallow-Sea-Area Spar Buoy in Wind, Tidal Current and Waves

\[
C_L = \frac{F_{o_l}}{0.5\rho SU^2}
\]  

(8)

\[
C_M = \frac{F_{o_m}}{0.5\rho SU^2 l}
\]  

(9)

where \(\rho\) is the density of water, \(S\) is the surface area ratio of the fin, \(U\) is the flow velocity, and \(l\) is the length from the coordinate origin to the center of gravity of the fin. Figure 25 shows the hydrodynamic coefficients of the fin. These coefficients are used in the time domain simulation.

CONCLUSIONS

In this study, the development of a platform for wind state observation in a shallow sea area of less than 50 m depth is presented. The platform consists of a spar buoy with a motion stabilizer and a top-mounted airfoil. Using the measured and calculated results, the optimum conditions of the motion stabilizer and the airfoil are proposed. The following conclusions are obtained:

• The effects of the motion stabilizer in steady flow or waves and of the airfoil in wind on the motion reduction of the buoy have been clarified.
• In steady flow, lift forces acting on the fins of the motion stabilizer cause an upstreamward pitching moment, and when the fins are located below the mooring point, the drag forces also cause an upstreamward pitching moment.
• In waves, when the direction of a relative flow of water to the surface of the fin is normal, the effect of motion reduction is at its maximum by the maximum drag force caused by the fins.
• Based on the simulation results, the optimum condition of the motion stabilizer has been defined. It is found that the angle of inclination of the buoy caused by wind can be made smaller by attaching NACA 6409, whose lift-drag ratio is large. The result is confirmed by numerical simulation.
• As an improved device, the motion stabilizer composed of a ring-fin and arms is proposed, and the effectiveness of the motion stabilizer is demonstrated by model tests. Finally, the hydrodynamic forces acting on the motion stabilizer in steady flow are measured in order to determine accurate hydrodynamic forces for the calculations.

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