Semisubmersible Designs Compared According to RAO Criterion

IONUT CRISTIAN SCURTU, DUMITRU DINU
Constanta Maritime University
104, Mircea cel Batran Street
Constanta, cod 900663
ROMANIA
scurtucristian@yahoo.com; dinud@imc.ro; http://www.cmu-edu.eu/

Abstract: - Renewable energy extraction is extended to deep waters and more and more projects related to this field are developed, so semisubmersible projects, like WindFloat, requires safe, reliable and good sea keeping characteristics. Different designs of semisubmersibles will affect the sea keeping characteristics and the hydrodynamic response in different incident regular waves. The numerical results denote that the heave motion RAO of semisubmersibles is optimized using the heave plate for a wide range of frequencies. The semisubmersible heave response can be suppressed by installing heave plates in any submersible design. The work compares five different strengthening configurations realized with Solidworks software. Investigations of semisubmersible designs according to RAO criterion may provide guidance to heave motion control of semisubmersibles.

Key-Words: Semisubmersibles, RAO Criterion, Solidworks design, heave plate.

1 Introduction

Since now the renewable energy domain has been focused to fixed platforms (which are limited to depths of 300 m); recently the renewable energy domain started going into deeper waters and the fixed platforms are not suitable. The semisubmersibles are suitable for great depths and can load big amount of equipment onboard. Because the semisubmersible structure will deal with great hydrodynamic and operational forces, the structural design must be well studied before implementing a project from sketch.

On design of semisubmersible structures we can a response amplitude operator (RAO) which is an engineering statistic and a tool for hydrodynamic studies [1]. This statistic is used to determine the behavior of any floating structure when affected by waves. Response amplitude operators (RAO) are usually computed and studied to determine the transfer function from waves to floating body movements and rotations. RAOs are usually calculated for all motions and for all wave headings. For this we will assume that the response of a semisubmersible to the individual component wave regular is a linear function, we can consider that the answer is linear and it will be proportional to the amplitude of the incident wave.

Semisubmersible structures are used in more and more projects related to renewable energy and this is the way to unlock the lost potential of wind and waves [7], now accessible to new projects in this field, like WindFloat. A Windfloat structure is equal to a semisubmersible platform with added wind turbine. This type of project will combine wind forces and wave forces and the result will impact the normal function of the equipment loaded or operating onboard. In other words, choosing the best design will help engineers improve reliability for all projects developed onboard semisubmersibles. The technical literature is mostly referring to four columns semisubmersible designs and the three columns semisubmersibles are a point of interest in developing future renewable energy related projects.

2 Problem Formulation

All semisubmersibles are subjected to different sea states and each design has its characteristics, so small changes in design can make a huge difference in hydrodynamic response of the structure and in service intervals for the equipment loaded onboard semisubmersibles.

Semisubmersibles can be strengthened in various ways: D shape, K shape, V shape, Y shape or Z shape and can have a heave plate (HP) or not. The problem is to choose the most suitable for offshore operation based on RAO criterion deriving from Windfloat main particulars.

All forces acting on semisubmersibles will be also applied to the structure fixings and to the equipment loaded. That is why we must study RAO criterion for each type of design in order to obtain a
minimum RAO function with respect to small loads. The idea to compare and analyze different three columns semisubmersibles according to RAO criterion is an original one.

3 Problem Solution

The body-bound coordinate system is drawn below for a three column semisubmersible (Fig. 1). Motions and rotations of the semisubmersible platform are:

\[
\text{Surge: } x = x_0 \cos (\omega t + \epsilon x \xi) \quad (1)
\]

\[
\text{Sway: } y = y_0 \cos (\omega t + \epsilon y \zeta) \quad (2)
\]

\[
\text{Heave: } z = z_0 \cos (\omega t + \epsilon z \zeta) \quad (3)
\]

\[
\text{Roll: } \Phi = \Phi_0 \cos (\omega t + \epsilon \Phi \zeta) \quad (4)
\]

\[
\text{Pitch: } \Theta = \Theta_0 \cos (\omega t + \epsilon \Theta \zeta) \quad (5)
\]

\[
\text{Yaw: } \Psi = \Psi_0 \cos (\omega t + \epsilon \Psi \zeta) \quad (6)
\]

For any design the RAO criterion will be established considering [5]:

- \( \xi \) the amplitude of the wave in metres,
- \( \omega \) the frequency of the wave in Hz,
- \( t \) the time in seconds,
- \( q \) one of the movement of the semisubmersible in metres (heave is the most important to this study).

We’ll have the next expressions:

If the excitatory component is [4]

\[
\xi = \xi_0 \cdot \cos (w \cdot t), \quad (7)
\]

the answer component will be:

\[
q = q_0 \cdot \cos (w \cdot t) \quad (8)
\]

At the domain of frequency, the amplitudes are related with the transference function \( H(w) \), understanding that the wave spectrum (wave input), with the frequency characteristics, will determine the motion spectrum (Motions output) (Fig.2):

\[
E(w) \xrightarrow{\text{Entry}} [H(w)] \xrightarrow{\text{exit}} q(w) \quad (9)
\]

\[
q(w) = H(w) \cdot \xi(w) \quad (10)
\]

The wave spectrum being a random process, we do not use the amplitudes values, but the power spectral density related with the amplitude squared.

\[
S_\xi(w) \cdot \Delta w = \frac{1}{2} \cdot \sum_{i=1}^{n} \xi_i^2 \quad (11)
\]

\[
S_q(w) \cdot \Delta w = \frac{1}{2} \cdot \sum_{i=1}^{n} q_i^2 \quad (12)
\]

Considering the spectrum of waves as entry and the power spectral density of semisubmersible movement as exit, related with the encounter frequency \( (w_e) \), we’ll have:

\[
E(we) \xrightarrow{\text{Entry}} [H(we)] \xrightarrow{\text{exit}} q(we) \quad (13)
\]

\[
H^2(we) = \frac{S_q(we)}{S_\xi(we)} = \frac{\frac{1}{2} \cdot \sum_{i=1}^{n} q_i^2(we)}{\frac{1}{2} \cdot \sum_{i=1}^{n} \xi_i^2(we)} = \frac{q_i^2(we)}{\xi_i^2(we)} = RAO_q \quad (14)
\]
The RAO for our case will be on z axis:

\[
RAO = \frac{z_3^2(w_e)}{\xi_3(w_e)}. \tag{15}
\]

### 3.1. Semisubmersible designs used in study

All three columns semisubmersibles (D shape, K shape, V shape, Y shape or Z shape) are designed with Solidworks software and can have a heave plate or not and all structures are built from steel with \(E=200\,\text{GPa}\) and \(\rho=7850\,\text{kg/m}^3\). All geometrical dimensions in structures from Fig. 3 to fig.12 are according to the actual dimensions of construction of the project Windfloat [2] presented in Table 1 and Table 2.

#### Table 1. WindFloat geometrical specifications [6]

<table>
<thead>
<tr>
<th>Geometrical specifications</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column diameter</td>
<td>m</td>
<td>10</td>
</tr>
<tr>
<td>Heave plate radius</td>
<td>m</td>
<td>15</td>
</tr>
<tr>
<td>Draft</td>
<td>m</td>
<td>17</td>
</tr>
<tr>
<td>Column center to center</td>
<td>m</td>
<td>46</td>
</tr>
<tr>
<td>Thickness of heave plate</td>
<td>m</td>
<td>0,1</td>
</tr>
<tr>
<td>Operating depth</td>
<td>m</td>
<td>&gt;40m</td>
</tr>
</tbody>
</table>

#### Table 2. Mass distribution for WindFloat [2]

<table>
<thead>
<tr>
<th></th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Displacement</td>
<td>t</td>
<td>4640</td>
</tr>
<tr>
<td>Coordinate of the center of gravity</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>(x_G)</td>
<td>34.28</td>
<td></td>
</tr>
<tr>
<td>(y_G)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>(z_G)</td>
<td>4.70</td>
<td></td>
</tr>
<tr>
<td>Radius of gyration</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>(R_x)</td>
<td>34.9</td>
<td></td>
</tr>
<tr>
<td>(R_y)</td>
<td>34.7</td>
<td></td>
</tr>
<tr>
<td>(R_z)</td>
<td>26.5</td>
<td></td>
</tr>
</tbody>
</table>
3.2. Semisubmersible designs comparison

Based on the designs in Solidworks software, the mass of each structure, momentum of inertia of the semisubmersible about its center of mass and the vertical center of gravity (VCG) is computed. Different structural mass will determine different inertial mass of the structure and the heave plate will have an effect of increasing the added mass [2]. Values computed with Solidworks are compared in Table 3.

Table 3. Compared structures mass and VCG

<table>
<thead>
<tr>
<th>Semisubmersibles type</th>
<th>Total structure mass [m]</th>
<th>( I_{xx} ) ([10^7 \text{m}^2])</th>
<th>( I_{yy} ) ([10^7 \text{m}^2])</th>
<th>( I_{zz} ) ([10^7 \text{m}^2])</th>
<th>VCG [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>D shape</td>
<td>4620.0</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.70</td>
</tr>
<tr>
<td>D shape with HP</td>
<td>4620.2</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.69</td>
</tr>
<tr>
<td>K shape</td>
<td>4632.0</td>
<td>1.11</td>
<td>0.86</td>
<td>1.51</td>
<td>4.75</td>
</tr>
<tr>
<td>K shape with HP</td>
<td>4632.2</td>
<td>1.11</td>
<td>0.86</td>
<td>1.51</td>
<td>4.74</td>
</tr>
<tr>
<td>V shape</td>
<td>4640.0</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.70</td>
</tr>
<tr>
<td>V shape with HP</td>
<td>4640.2</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.69</td>
</tr>
<tr>
<td>Y shape</td>
<td>4690.0</td>
<td>1.12</td>
<td>0.88</td>
<td>1.55</td>
<td>4.75</td>
</tr>
<tr>
<td>Y shape with HP</td>
<td>4690.2</td>
<td>1.12</td>
<td>0.88</td>
<td>1.55</td>
<td>4.74</td>
</tr>
<tr>
<td>Z shape</td>
<td>4620.0</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.70</td>
</tr>
<tr>
<td>Z shape with HP</td>
<td>4620.2</td>
<td>1.10</td>
<td>0.87</td>
<td>1.52</td>
<td>4.69</td>
</tr>
</tbody>
</table>

In Table 3 we can observe that the Z shape is the lightest way of construction of semisubmersible platforms and the Y shape is the heaviest form our models. Also the value from VCG are different but the differences are not noticeable and all of the values are close to 4.70 m.

To compute and plot different RAO for each structure studied (D shape, K shape, V shape, Y shape or Z shape) in 3 different cases (incident regular wave 90°, 150°, 180°) in saltwater (\( \rho = 1.024 \))
A Matlab code was developed. The results are shown below in Table 4.

The smallest values in RAOz 90 plotted in Fig. 13 are observed for V shape (maximum value of 2.47) strengthening design and the order in increasing RAO criterion is V, K, Z, Y and D. The difference is also shown in Table 4 in the corresponding column to the 90 angle of the incident wave.

Table 4. Compared semisubmersibles design with RAO criterion

<table>
<thead>
<tr>
<th>Semisubmersible type</th>
<th>Maximum RAOz 90°</th>
<th>Maximum RAOz 150°</th>
<th>Maximum RAOz 180°</th>
</tr>
</thead>
<tbody>
<tr>
<td>D shape</td>
<td>3.02</td>
<td>3.11</td>
<td>3.08</td>
</tr>
<tr>
<td>D shape with HP</td>
<td>2.94</td>
<td>2.88</td>
<td>2.78</td>
</tr>
<tr>
<td>K shape</td>
<td>2.57</td>
<td>2.42</td>
<td>2.08</td>
</tr>
<tr>
<td>K shape with HP</td>
<td>2.45</td>
<td>2.38</td>
<td>2.01</td>
</tr>
<tr>
<td>V shape</td>
<td>2.47</td>
<td>2.41</td>
<td>2.09</td>
</tr>
<tr>
<td>V shape with HP</td>
<td>2.45</td>
<td>2.38</td>
<td>2.01</td>
</tr>
<tr>
<td>Y shape</td>
<td>2.83</td>
<td>2.76</td>
<td>2.87</td>
</tr>
<tr>
<td>Y shape with HP</td>
<td>2.52</td>
<td>2.43</td>
<td>2.54</td>
</tr>
<tr>
<td>Z shape</td>
<td>2.49</td>
<td>2.42</td>
<td>2.12</td>
</tr>
<tr>
<td>Z shape with HP</td>
<td>2.43</td>
<td>2.42</td>
<td>2.21</td>
</tr>
</tbody>
</table>

Values in RAOz 150 are plotted in Fig. 14. We observe that for Z shape strengthening design we have the smallest value of RAO criterion (maximum value of 2.42) and the order in increasing RAO criterion is Z, V, K, Y and D. Differences are small and we will not study further RAO related to waves with 150 angle of the incident wave.

Values in RAOz 180 are plotted in Fig. 15. We observe that for V shape strengthening design we have the smallest value of RAO criterion and the order in increasing RAO criterion is Y, K, Z, V, and D. Differences are small and we will not study further RAO related to waves with 180 angle of the incident wave.
As shown before the V shape strengthening design is one of the best in obtaining the smallest values in RAOz 90, RAOz 150 and RAOz 180. Using heave plates the RAOz is reduced and the variation is plotted in Fig.16. This heave plate is improving semisubmersible response in vertical direction in almost any sea state. There is also a frequency range (0.10-0.172Hz) that should be avoided in construction of semisubmersibles with heave plates. The results shown in RAO response are applicable to three column semisubmersible and comparing with results reported by Ghajar [3] the heave plate has a positive effect on sea keeping of the semisubmersible studied.

![Fig.16. Graphic of RAOz 90 for V shape design](image)

### 4 Conclusion

This paper is intended to compare designs of semisubmersibles used in offshore renewable energy based on the RAO criterion. The results of RAO criterion suggest that small changes in VCG and mass will have a significant effect on submersible motion characteristics. Each type of structure was designed with Solidworks software. The response of each type of design was plotted with Mathlab and compared in order to obtain a small heave response in different incident waves. Extensive data presented are available for choosing the best design in semisubmersible projects and is helpful in estimating different responses from the developed structures. This study was developed only to choose the design of semisubmersibles according to RAO criterion. The stress analyses in operating conditions should be studied to find a safe and with good sea keeping characteristic. So the design in a three column semisubmersible is required to be compared based on RAO criterion before building the structure in shipyards.

**References:**


