Assessing the dynamic stability of a floating tidal energy platform during ballast operations

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Key words: Renewables, mooring lines, lift force, drag force, changing waterline area, changing mass, 6 DOF, large amplitude rotations, MATLAB, Bluewater.

Abstract: A method is developed to assess the dynamic stability of a floating tidal energy platform during ballast operations. This method is applied to a tidal energy platform designed by Bluewater Energy Services B.V., showing the sensitivity of this platform's dynamic stability during ballast operations to tidal current velocity, changes in lightship centre of gravity and changes in the rate of ballasting. The developed method includes dynamic effects, tidal currents and mooring lines. Part of the developed method is a numeric model, written in the MATLAB environment, that simulates the platform motions, in 6 DOF, in time, during ballast operations. The model allows for large amplitude translations and rotations and for a changing mass and waterline area in time. Gravity, buoyancy, mooring line forces and tidal current lift and drag forces are taken into account. The model is analytically verified.

1. INTRODUCTION

The growing demand for renewable energy sources has stimulated the design of unconventional floating platforms. One of these designs is the floating tidal energy platform developed by Bluewater Energy Services, illustrated in Figure 1.

This tidal energy platform supports two tidal turbines with a rated power of 1 MW each. The tidal currents provide a predictable, renewable source of energy. The floating concept enables a quick installation and good accessibility for maintenance.

For the feasibility and safety of a floating design, its stability should be proven to be sufficient. Existing stability assessment methods are aimed towards conventional ships and platforms. A review of these methods shows that they are not sufficient for a complete stability assessment of the Bluewater design. Therefore a new method is developed to assess the dynamic stability of a floating tidal energy platform during ballast operations. This method is used to investigate sensitivities in the stability
of the Bluewater platform during ballast operations.

The contents of this paper are a summary of the public results of a graduation thesis research for the master degree Marine Technology at the Delft University of Technology. The research is performed in cooperation with Bluewater Energy Services B.V.

2. DEFINITION OF STABILITY

Stability is a term widely used in the engineering of floating marine structures and ships. Various definitions can be found in literature [1][2][3]. For a systematic assessment a clear definition is chosen.

Stability is a system property that categorizes the response of a system to external disturbances. The definition of stability can be split into three levels, as illustrated in Figure 2. First, an object's position or condition can be an equilibrium or not an equilibrium. At an equilibrium, the object will stay in this position or condition when external disturbances are absent. Secondly, an equilibrium condition can be stable, unstable or indifferent. When the condition is stable, the object will return to this condition after encountering an external disturbance. Another formulation is that a stable condition is a condition of minimum energy. Thirdly, a stable equilibrium position is only stable for external disturbance up to a certain magnitude (which can differ per direction when multiple degrees of freedom are considered). In case of a ship, this can mean that the ship is stable for a small wave, but unstable for a larger one. The ship can return to its equilibrium position after encountering a small wave, but capsize for a larger one.

This principle is referred to as 'stability margin'.

Floating platforms are generally designed to be in a stable equilibrium position. Therefore the relevant stability property to assess is the stability margin. In a static analysis the stability margin can be quantified by the potential energy present in the system, per direction of rotation. When the order of events in time or when inertial effects are considered relevant for the system response, a dynamic analysis is required. In a dynamic analysis the stability margin cannot be measured with a single quantity. It can however be quantified by determining the range of design and environmental parameters for which the system response, being the platform motions and loads, remains within accepted limits.

3. EXISTING METHODS

Existing methods for stability assessment are reviewed for relevance. The conventional stability assessment methods for floating structures [2] and the stability regulations [4][5][6] are primarily based on the static and quasi-static approach of the righting moment or GZ curve of a vessel. This approach focuses on predicting the failure mechanism 'roll induced by a heeling
moment’, which can be predicted using a combination of equilibrium of moments (the GZ value at each angle) and potential energy (the area below a GZ curve). Safety buffers compensate for dynamic effects. The magnitude of these buffers is based on practical experience with conventional ships and platforms.

Guidelines for the assessment of the stability of floating wind, wave and tidal platforms use methods similar to the conventional ones or refer to these conventional methods [7][8][9].

4. METHOD REQUIREMENTS

The axis of lowest stability of the Bluewater tidal energy platform is not obvious and can change during ballasting operations. Therefore all 6 degrees of freedom (DOF) need to be taken into account in a stability assessment. The GZ curve approach can only account for a single rotation direction at once. A quasi-static method is available to determine GZ curves for platforms with unknown lowest axis of stability [10].

The ballast operations of the tidal platform may induce significant velocities and accelerations. No practical experience with the platform is present, which means the magnitude of required safety buffers to compensate for these dynamic effects is unknown. The dynamic effects need to be taken into account in order to predict all failure mechanisms that can occur. A static and quasi-static approach is not able to truly capture dynamic effects.

Tidal current forces are estimated to be of significant order of magnitude so need to be taken into account. Since mooring lines are installed to keep the platform in place in currents, the mooring line forces should also be taken into account. These forces are not included in existing methods for ship and floating platform stability assessment.

Ballast water changes result into a changing mass, a changing draught and waterline area and into large amplitude rotations. This is relevant for stability so should be taken into account. Existing methods and models are not capable of predicting dynamic processes of irregular platforms with changing mass in time domain.

Wind and wave forces are not expected to be significant for the platform at its design location, so do not need to be taken into account.

These requirements show that the relevant effects for a complete stability assessment of a tidal energy platform during ballast operations are dynamics, 6 degrees of freedom, tidal currents, mooring lines and changing system properties due to ballast operations and large amplitude motions. Since existing methods do not take all these effects into account, they are not sufficient. A new method needs to be developed.

5. DEFINED METHOD

The dynamic stability margin is of interest. A single quantity is not available to define this margin in a dynamic analysis, so the dynamic stability margin is defined as the range of design and environmental parameters for which the platform displacements, velocities and accelerations remain within the accepted maxima.
This results into a dynamic stability assessment method consisting of three steps:
1. Determine acceptable output and required input. The output consists of the platform motions and loads during ballast operations. The accepted output is referred to as the set of stability criteria. The input is the range of relevant design and environmental parameters.
2. Predict the platform motions and loads during the ballast procedure (output) for this range of parameters (input).
3. Compare the predicted motions and loads with the set maxima. This shows weather or not the platform is sufficiently stable.

For the Bluewater tidal energy platform, the stability criteria are shown in Table 1, at page 8.

In order to test the developed method, several sensitivities in the Bluewater platform stability are investigated. For this, the varied parameters are the tidal current velocity, the position of the lightship centre of gravity and the rate of ballasting and de-ballasting.

Step 2 of the method requires a numeric model that connects the input to the output, so is able to simulate large amplitude platform motions in 6 DOF, during a designed ballast operations, due to the buoyancy, gravity, tidal current forces and mooring line forces. Such a model was not yet available so is written and analytically verified.

6. NUMERIC MODEL

A numeric model is written which solves the Newton-Euler equations of motion [11][12] in time in 6 DOF. The equations of motion for a rigid body with its centre of gravity outside the body origin are used. The model is written in the MATLAB environment. The MATLAB numeric solver ode45 is used to solve the equations of motion. This solver is based on the 4th order Runge-Kutta numeric integration scheme for time integration and uses a variable time step to reduce computation time [13].

The model input is the platform geometry and mass distribution, the designed ballast procedure, the initial platform position and the tidal current velocity. The model output consists of the platform motions in time and the buoyancy, gravity, mooring line, lift and drag force in time.

Reference frames and transformation
The Newton-Euler equations of motion describe the motions of a rigid body in a body-fixed reference frame. The platform motions are required in earth-fixed reference frame. Since the platform during ballasting rotates over large angles, Euler angle theory is used to transform motions between these two reference frames [12]. For the rotation matrices, the sequence yaw-pitch-roll is maintained when transforming from earth-fixed to body-fixed.

The origin of the earth-fixed reference frame is located at the water surface, centred between mooring points, with an upward pointing positive z-direction. The origin of the body-fixed reference frame can be chosen at any point.

Geometry description
The geometry of the platform is approximated by a set of rigidly connected rectangular and cylindrical
parts. This geometry is variable model input, so any desired combination and size of parts can be chosen in order to approximate any irregular geometry. Each platform part and each ballast water tank can be given a shape, mass and relative location to the body origin.

The Bluewater tidal energy platform geometry is not public, so another shape is shown in Figure 3, to illustrate how a irregular floating moored platform can be defined and visualized in the numeric model.

![Figure 3 - Geometry in numeric model](image)

**Hydrodynamic effects**

The hydrodynamic force due to accelerations is modelled as added mass. This is included in the added mass matrix in the equations of motion. The added mass matrix of the Bluewater platform is unknown and expected to change during ballast operations. Since the accelerations are expected to be low, the added mass is not expected to be critical so is set to zero in the simulations.

The lift and drag forces on the platform are modelled per platform part and dependent on the tidal current velocity and the rotational position of the platform. They are based on the formula:

\[ F_{\text{drag/ift}} = \frac{1}{2} \rho U^2 C_{DS/L} S \]  

In which \( \rho \) is the water density and 1025 [kg/m\(^3\)], \( U \) is the velocity of the platform, relative to the water, in [m/s], \( C_{DS} \) is the drag coefficient in steady flow, \( C_L \) is the lift coefficient in steady flow and \( S \) is the projected area in normal flow direction in [m\(^2\)]. The drag coefficients are based on coefficients for rectangular and cylindrical shapes and the lift coefficient on the coefficient for flat plates under large angles of attack [14].

The buoyancy force is a function of the submerged platform geometry at each time step. For increased accuracy, the discretization of the platform geometry in cylindrical and rectangular parts is refined by meshing each part into cubic elements. The mesh size of these elements is variable input. For the tidal platform simulations 0.1 m is used. For each element it is determined whether it is fully, partly or not submerged. Each submerged element or element portion contributes towards the total buoyancy force and the buoyancy moments about the local axes. The translational rotation matrix [12] is used to transform the forces and moment between local and global reference frames.

**Gravity**

The gravity force equals the mass of the platform and ballast water, multiplied by the gravitational acceleration. It acts in negative global z-direction. The moments induced by the gravity force about the local axes depend on the platform mass properties and the platform position at that time step.

**Linear damping**

For numeric stability, linear damping is included in the model. The damping is a function of platform and tidal
velocity. The magnitude of this force is set to be approximately 1% of critical damping and depends on the absolute translational velocities of each platform part.

**Mooring lines**
The mooring lines are modelled as linear springs with a pre-tension and constant stiffness. The mooring point of each mooring line at the seabed is fixed. The mooring point of each mooring line at the platform is fixed to the platform. This means that the length and direction of each mooring line changes when the platform moves.

7. **MODEL VERIFICATION**

In order to test the numeric model for errors, it is verified using analytical calculations for several simple cases. The buoyancy, gravity, lift, drag, linear damping and mooring line forces are checked for several simple shapes at various translated and rotated positions. The natural frequency and amplitude of free heave and pitch vibrations of a free floating and moored barge are compared to analytical results for the same cases.

The linear damping is expected to vary between 1 and 20% of the critical damping. This variation is caused by the high nonlinearity of the model. The numeric error in the simulations of the Bluewater tidal platform is expected to remain well below 5%, which is sufficiently accurate for the purpose of the model.

8. **RESULTS**

The sensitivity of the Bluewater tidal energy platform stability during ballast operations to tidal current velocity, lightship COG position and rate of ballasting is investigated. This is done by simulating the ballasting and de-ballasting procedure, varying the magnitude of these parameters in the model input and comparing the simulated results to the stability criteria. The simulated platform positions before, during and after ballasting as designed, are shown in Figure 4. The input variations are shown in Table 2. The cases, for which all criteria are met, are marked green. The cases, for which one or more stability criteria are not met, are marked red. This overview in Table 2 shows the sensitivity of the dynamic platform stability during ballast operations for the varied input parameters.

Stability failure for all red marked cases is caused by exceeding the maximum roll angle after ballasting. Accelerations and mooring loads remain well below the accepted values for all simulated procedures.

A selection of results is shown in more detail to illustrate the insights that can be gained from the numeric simulations. The platform motions for various ballasting rates are shown in Figure 5. This shows that motions in all DOF are simulated in the model, for large angle rotations. It also shows that, when the rate of ballasting is increased, the platform accelerations and final positions remain acceptable.

The platform motions during the ballasting procedure in 0 and -3 m/s tidal current, and in -3 m/s tidal currents with the lift coefficient set to 0, are shown in Figure 6. This shows that a high negative tidal current results into stability failure: The final platform position contains a roll angle over 5
degrees. It also shows that this roll angle is created by lift force, since the angle disappears when the lift force is set to 0. The stability criterion that is failed in the cases '2% COG upwards' and '3 m/s tidal current' is also the final roll angle. This indicates a low stability margin of the platform in submerged condition. The designed and rolled platform positions are illustrated in Figure 7.

Since the model is verified, but not validated, these results show sensitivities, not exact values.

9. CONCLUSIONS

The developed method, consisting of simulating ballast procedures and comparing the predicted motions and loads with chosen criteria, provides a systematic approach to quantify the dynamic stability margin of a platform.

The relevant effects for the dynamic stability of a tidal energy platform are dynamics, 6 degrees of freedom, tidal currents, mooring lines and changing system properties due to ballast operations and large amplitude motions. A numeric model is written that calculates the platform motions and forces in time and takes these effects into account. The model is analytically verified to have a numeric error below 5% and provides plausible results. The model shows motions and forces in detail and enables a visualization of the platform motions, by images and by movies in time domain.

Four conclusions are reached for the Bluewater platform specifically. First, the stability of this platform is not sensitive to the rate of ballasting and de-ballasting. Secondly, it is sensitive to increasing the vertical position of the centre of gravity. Thirdly, the platform stability is sensitive to currents. This is caused by the lift forces, which are induced by the submerged geometry when the platform is pitched. When the lift force is sufficiently large, it causes large amplitude steady roll angles of the platform in submerged condition. Due to platform asymmetry, tidal currents coming in from the front of the platform are more critical than tidal currents from the aft. Finally, the platform stability margin is lowest when the platform is submerged. In this condition, the platform behaves non-stiff in roll direction, which results in large amplitude roll motions and positions.

The application of the developed method to the Bluewater platform results in several insights that were not available from static analyses. The method and numeric model are generic for other geometries, inertia properties and ballast procedures. This means that they are valuable tools for a qualitative investigation of the dynamic stability of other unconventional floating platforms, especially when large amplitude motions and significant waterline changes are expected.

REFERENCES

TABLES AND FIGURES

Table 1 - Stability criteria Bluewater tidal energy platform

<table>
<thead>
<tr>
<th>Property</th>
<th>Max. value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of translational accelerations</td>
<td>4.71</td>
<td>m/s²</td>
</tr>
<tr>
<td>Magnitude of rotational accelerations</td>
<td>10.75</td>
<td>degr/s²</td>
</tr>
<tr>
<td>Magnitude of mooring loads, x, y and z direction</td>
<td>2000</td>
<td>kN</td>
</tr>
<tr>
<td>Minimum value of z during ballasting</td>
<td>-20</td>
<td>m</td>
</tr>
<tr>
<td>Magnitude of roll, final position</td>
<td>5</td>
<td>degr.</td>
</tr>
<tr>
<td>Magnitude of pitch, final position</td>
<td>5</td>
<td>degr.</td>
</tr>
<tr>
<td>Magnitude of yaw, final position</td>
<td>5</td>
<td>degr.</td>
</tr>
</tbody>
</table>

Figure 4 - Simulated platform positions. Left to right: Before, during and after de-ballasting.
Table 2 - Input variations for results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base case</th>
<th>Variation 1</th>
<th>Variation 2</th>
<th>Variation 3</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rate of ballasting</td>
<td>As designed</td>
<td>2 times quicker</td>
<td>2.5 times slower</td>
<td></td>
<td>min.</td>
</tr>
<tr>
<td>Lightship COG</td>
<td>As designed</td>
<td>+0.3%</td>
<td>+0.5%</td>
<td>+2%</td>
<td>% of total height</td>
</tr>
<tr>
<td>Negative tidal current</td>
<td>0</td>
<td>-1</td>
<td>-2</td>
<td>-3</td>
<td>m/s</td>
</tr>
<tr>
<td>Positive tidal current</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>m/s</td>
</tr>
</tbody>
</table>

Figure 5 - Platform motions during ballast operations at various rates
Figure 6 - Platform motions during ballasting procedures in varied tidal currents

Figure 7 - Front view of platform position after ballasting with the lightship COG at design position (left) and moved 2% upwards (right).