EVALUATION OF THE DYNAMIC-RESPONSE-BASED INTACT STABILITY CRITERION FOR FLOATING WIND TURBINES

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ABSTRACT

As an alternative to the conventional intact stability criterion for floating offshore structures, known as the area-ratio-based criterion, the dynamic-response-based intact stability criteria was initially developed in the 1980s for column-stabilized drilling units and later extended to the design of floating production installations (FPIs). Both the area-ratio-based and dynamic-response-based intact stability criteria have recently been adopted for floating offshore wind turbines (FOWTs).

In the traditional area-ratio-based criterion, the stability calculation is quasi-static in nature, with the contribution from external forces other than steady wind loads and FOWT dynamic responses captured through a safety factor. Furthermore, the peak wind overturning moment of FOWTs may not coincide with the extreme storm wind speed normally prescribed in the area-ratio-based criterion, but rather at the much smaller rated wind speed in the power production mode. With these two factors considered, the dynamic-response-based intact stability criterion is desirable for FOWTs to account for their unique dynamic responses and the impact of various operating conditions.

This paper demonstrates the implementation of a FOWT intact stability assessment using the dynamic-response-based criterion. Performance-based criteria require observed behavior or quantifiable metrics as input for the method to be applied. This is demonstrated by defining the governing load cases for two conceptual FOWT semisubmersible designs at two sites. This work introduces benchmarks comparing the area-ratio-based and dynamic-response-based criteria, gaps with current methodologies, and frontier areas related to the wind overturning moment definition.

NOMENCLATURE

B 6x6 quadratic damping matrix  
B_ϕ Center of buoyancy at heel angle ϕ  
G Center of gravity  
GM Metacenter height above the center of gravity  
GZ Restoring moment arm  
K Keel position  
KG Center of gravity height from the keel  
ME Total wind overturning moment  
MP Platform wind overturning moment  
MR Hydrostatic restoring moment  
MT RNA aerodynamic overturning moment  
Mϕ Metacenter of heel angle ϕ  
q 6x1 generalized platform transitional/rotation vector  
z_b,z_0 Buoyant/gravity position below the reference origin  
ρGV Vessel displacement  
ϕ_C Rotor shutdown heel angle  
ϕ_1 First intercept angle; static heel offset  
ϕ_2 Second intercept angle  
ϕMAX Maximum dynamic heel offset

INTRODUCTION

Intact stability is the process to assess the resistance of an undamaged vessel to capsize. Historical assessment methods are based on prescriptive rules, though performance-based methods are on the rise, commensurate with improved simulation capabilities [1]. Although ship stability concepts span several decades, application of these codes to FOWTs is in an early stage. There are many unique accommodations needed for the wind turbine. Unlike ships and offshore platforms, where the wind overturning moment scales proportional to wind speed-squared, FOWTs are designed to maximize energy capture at low wind speeds. The result is a wind overturning moment that does not behave monotonically.

Prescriptive intact stability requirements entail meeting a minimum ratio between the buoyancy restoring energy and environmental overturning energy. The assessment is quasi-static in nature, ignoring interaction between the vessel and waves, though effects from waves are captured through a safety
factor. The traditional area-ratio-based criterion is considered to be a prescriptive rule [2]. Performance-based criteria, on the other hand, factor vessel motion in waves and wind. Column-stabilized units used as mobile offshore drilling units (MODUs) have adopted the dynamic-response-based criterion as a performance-based metric [3]. Because the inputs vary according to quantifiable, observable, and vessel-specific motions, the required reserve energy ratio (RER) is lower.

Two intact stability criteria are assessed in this paper, the dynamic-response-based criterion and traditional area-ratio-based criterion. The merits of both methods are assessed using the OC4 semisubmersible [4, 5] and NREL 5-MW reference wind turbine [6] as surrogates, Fig. 1. This paper includes two variations of the OC4 semisubmersible with different stability characteristics. One OC4 variant is left unmodified from the definition in [4] with $KG = 10.11 \text{ m}$. The second variant reduces the metacenter and increases the roll/pitch period by raising the center of gravity to $KG = 15.00 \text{ m}$ in order to highlight differences between the two approaches, Tab. 1. Definitions of the design load cases (DLC) leading to the largest heel angles are necessary for successful application of the dynamic-response-based criterion. To begin this study, the history of events that led to modern stability codes is discussed.

**Origin of the Intact Stability Requirement**

Archimedes’ Principle establishes the relationship between the vessel mass and proportionality to fluid displacement to resist sinking. Upright stability through a balance of moments was discovered 1,900 years later by S. Stevin [7, 8]. Stevin’s Law marked a paradigm shift in naval architecture and changed how new designs came to fruition. Mathematical principles were developed in these formative years to judge the fitness of a design, later leading to the discovery of a ship’s metacenter [7, 9, 10].

Modern ship stability criteria can trace its roots to the ‘energy balance’ criteria credited to Mosely [7, 11]:

$$ W = \int_{Environment \ work} M_g \, d\phi = \int_{Ship \ heeling \ work} \rho g V(GZ) \, d\phi $$

(1)

International acceptance of intact stability requirements emerged shortly after the introduction of Eqn. 1. In 1939, Rahola expanded Mosely’s Principle and applied it to ships deemed as safe, and compared the restoring energy with capsizing’s [12]. Rahola’s criterion specifies minimum $GM$ and $GZ$ values, where $M_R = \rho g V(GZ)$.

It wasn’t until the mid-20th century when modern intact stability adaptations began to appear on the basis of prescribed wind conditions [13, 14], thus codifying the properties of $M_R$. The current prescriptive stability requirements closely emulate the principles established in Yamagata [13] and Sarchin and Goldberg [14], with variations depending on vessel type.

**Intact Stability for Column-Stabilized Units**

Column-stabilized units and ships must satisfy similar stability requirements. With column-stabilized units, however, a bulk of the buoyancy is below the sea surface, and application of ship area ratio requirements would lead to overly conservative designs. Area-ratio-based criteria for ships require a larger $RER$ compared to MODUs. This is reflected as a 30% minimum reserve buoyant energy requirement for MODUs. Ships, in contrast, require 40% reserve energy. The area-ratio-based criterion is defined as:

$$ RER = \frac{\text{Buoyant Moment Energy}}{\text{Wind Overturning moment}} \geq \frac{\text{Area}(A+B)}{\text{Area}(B+C)} \geq C $$

(2)

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**Table 1: Vessel hydrostatic and natural frequency properties at equilibrium for different $KG$ locations.**

<table>
<thead>
<tr>
<th>$KG$ [m]</th>
<th>$KB$ [m]</th>
<th>$GM_c$ [m]</th>
<th>Natural Period [s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>OC4 semisubmersible</td>
<td>10.11</td>
<td>6.85</td>
<td>7.45</td>
</tr>
<tr>
<td>Modified OC4 semisubmersible</td>
<td>15.00</td>
<td>6.85</td>
<td>2.51</td>
</tr>
</tbody>
</table>

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**Figure 1:** The OC4 semisubmersible with hydrostatic definitions. Position of hydrostatic definitions $(M_g, B_g, Z_g)$ are not to scale.
where the energy is integrated to the second intercept angle $\phi_2$ or downflooding angle, whichever is less, Fig 2(a). The safety factor $C$ is 1.3 for column-stabilized units and 1.4 for monohull ships.

An increase in the reserve energy can be sought by raising the metacenter $GM$. Although a large $GM$ would promote stability, Chen, et al. [15] justifies an upper limit to $GM$. As $GM$ is raised, the vessel resonant frequency increases to eventually coincide with wave energy frequency ranges, leading to larger dynamic heel motion amplitudes. Chen, et al, argued that a method balancing static needs with dynamic characteristics could ease the conservative nature of traditional area-ratio-based methods. As a result, dynamic-response-based criterion was developed [16, 17] for column-stabilized units as an alternative to the area-ratio-based criterion. The dynamic-response-based criterion is defined as:

$$ RER = \frac{\text{Area}(B)}{\text{Area}(A)} \geq 0.10 $$

where the area regions are defined in Fig 2(b). The dynamic-response-based criterion integration range is between $\phi_1$ to $\phi_2$, where $\phi_1$ is the static heel angle and the range beyond $\phi_1$ is treated as the dynamic motion. The ratio is regulated by the area-dividing maximum heel angle $\phi_{MAX}$, which is subject to change based on site-specific conditions or changes in KG.

Naval architects rely on numerical simulations, tank-tests or analytical models to extract $\phi_{MAX}$ estimates. Analytical models are derived for column-stabilized units under specific geometric constraints [3], but are not appropriate for the three-column units assessed in this paper. Simulation tools have a large bearing on the successful application of the dynamic-response-based criterion, and it is crucial to apply these tools within the framework to which they are designed. Three simulation programs will be included as part of the dynamic-response-based intact stability assessment in this paper.

Unique Features of Floating Wind Turbines

The established convention for ships, MODUs and FPIs is to specify a wind overturning moment based on prescribed conditions or an n-year maximum wind speed [18]. Horizontal axis FOWT systems may experience larger wind overturning moments at lower wind while operating than at the maximum wind speeds. This paradox is rectified in [19, 20] and in the forthcoming IEC-61400-3-2 international standard on horizontal axis FOWTs to permit overturning moments to be derived based the wind speed where aerodynamic loads peak. As a result, the largest wind moment may exist at the rated wind speed, even when tower and vessel exposed area are included, Fig. 3. As described in [20], the aerodynamic thrust loads are based on the global FOWT response.

An additional consideration not addressed with conventional floating systems is the control logic influence on the FOWT wind overturning moment. A poorly designed or faulty controller can incite negative damping and exacerbate heel offsets, though this is less likely when good control design strategy is practiced [21]. Power generation is regulated through blade pitch. Rotor thrust force is often largest when the turbine is operating. The operational wind speed range varies depending on wind turbine manufacturer, but maximum power for the NREL 5-MW wind turbine is generated in the range of 11.4 m/s – 25 m/s, with 11.4 m/s being the rated wind speed. Rated wind speed generally produces the largest thrust load.

The governing load cases defining $\phi_{MAX}$ can be isolated during the global performance exercise. This process also captures transient behaviors, such as emergency shutdown. Wind turbines are certified for safe operation within a given heel angle range to maintain clearance between the blade-tip and tower. When the vessel heel offset exceeds $\phi_C$, the wind overturning moment can be discontinuous. The subject of this discontinuity and implications of FOWT design will be discussed.
DEFINITIONS

The intact stability studies begin with definitions of the environment, wind turbine and support vessel hydrostatic properties. Two sites are assessed, the Gulf of Mexico (GoM) and Oregon (OR). The OR region is characterized by larger wave heights, but higher wind speed in storm conditions belong to the GoM. The NREL 5-MW baseline wind turbine accompanies each platform. Site-specific wind conditions must be considered for the purpose of defining the wind overturning moment.

Vessel

The floating vessel is described as a three-column stabilized unit with a volumetric displacement of 13,985 m$^3$ at equilibrium deployed in 200 m water depth, Fig. 1 [4]. The tower height is 87.6 m above the still water line (SWL), with a final hub-height of 90.0 m. The floating vessel itself has a center of mass located at 13.46 m below the reference origin, with the reference origin defined at the equilibrium still water line (SWL). Depending on the simulation tool used, a hydrostatic correction is necessary to modify the gravitational restoring moment at different $K_G$ locations. The premise of this correction will be discussed in a subsequent section.

The $M_R$ Restoring Moment

Intact stability is assessed along the least stable axis, also referred to as the critical heel axis. The critical axis is interpreted as the heel direction leading to the smallest area under the $M_R$ restoring moment, as shown in Fig. 4. A different interpretation of the weakest axis follows from Eqn. 1, implying the critical axis expends the least energy to reach a desired heel angle [22]. As with most vessels exhibiting large transverse and longitudinal displacements, the OC4 semisubmersible is susceptible to orthogonal tipping [22, 23]. This behavior arises from uneven waterplane area distribution [22] to provoke a trim/yaw offset to balance the moments. Orthogonal tipping is observed with the OC4 semisubmersible when an outer column completely submerges below the SWL (as depicted in Fig. 1).

The OC4 semisubmersible with $K_G = 10.11$ m remains upright at large heel angles. In contrast, the OC4 semisubmersible with a raised $K_G = 15.00$ m position encounters the vanishing stability angle at $\phi_v = 33^\circ$. Another characteristic of the $M_R$ curve is that the metacentric height can be derived from the slope at zero heel: $G_M = \frac{dGZ}{d\phi}$ evaluated at $\phi = 0^\circ$. The $GZ$ slope at $\phi = 0^\circ$ in Fig. 4 matches the estimated $G_M$ calculations in Tab. 1. An inflection point is present for both $M_R$ curves in Fig. 4 at approximately $\phi = 23^\circ$. This inflection point corresponds to submergence of the 12 m diameter main column in Fig. 1. Increasing the height of this main column would delay this inflection, but a change in $K_G$ does not diminish its onset.
Environment
Extensive reporting of the Gulf of Mexico (GoM) and Oregon (OR) site conditions can be found in [24]. The report provides an assessment of the sea state, wind speed, methodology to extrapolate 50-year and 500-year extremes, and buoy measurement locations. A subset of the environment properties is summarized in Tab. 2 with a description of the DLC conditions provided in section ‘Global Performance Analysis’. The 3-hour significant wave height is recorded along with the 10-minute average wind speed at a 10.0 m reference height. A reference height of 10.0 m is reported, though these wind speeds must be extrapolated to the hub-height [25] using a wind shear law. The semisubmersible systems defined in Tab. 1 encompass roll and pitch natural frequencies outside the waveband range (typically 5–25 seconds), although the heave period lies within this range.

Simulation Toolset
Two programs are utilized to disseminate the FOWT heel response. The time-domain simulation tools are FAST and a coupled variant of it, FAST+Charm3D. FAST is an aero-elastic program developed to capture the performance of both onshore and offshore wind turbines subjected to atmospheric disturbances [26]. Wind turbine control logic is included for the operational case in turbulence. Model fidelity is extended by coupling FAST to Charm3D to replace the quasi-static mooring system with a finite-element model. Hydrodynamic capabilities are also expanded with FAST+Charm3D by including second order effects and discrete Morison elements for the columns and cross-braces.

A third program, denoted as FAST (NH)¹, is derived from an unmodified FAST program to omit the roll/pitch mooring stiffness, done in accordance with intact stability rules and regulations [20, 27]. Mooring contribution from the remaining degrees-of-freedom is preserved to restrain the system and prevent drift outside the simulation domain.

A hydrostatic roll/pitch stiffness correction may be required to account for changes in the gravity restoring force as KG changes. Both FAST and Charm3D operate within the domain of linearized hydrodynamic constraints, with the heel restoring stiffness commonly expressed as:

\[ K_{\phi} = \rho g \iiint_{S_p} dS + \rho g \int z_p \quad - m g z_g \]

where \( \iiint_{S_p} dS \) represents the distribution of area at the water line (or second moment of area). In FAST, the gravity restoring stiffness is not included in the hydrostatic stiffness, as it is calculated implicitly based on discrete mass distribution. Another way to see this is the hydrostatic heel stiffness between the two simulation programs are related by:

\[ K_{\phi}^{\text{Charm3D}} = K_{\phi}^{\text{FAST}} - m g z_g \]  \hspace{1cm} (5)

Another difference between the FAST program and the coupled FAST+Charm3D variant is the viscous damping representation. The FAST model uses a linearized damping matrix to capture flow separation effect [5]:

\[ F_{\text{viscous}} = -B|q|q \]  \hspace{1cm} (6)

Note that Eqn. 6 considers the absolute platform velocity, whereas the Morison element representation adopted in Charm3D uses the relative fluid velocity between the wave kinematics and platform absolute velocity to model each column/cross-brace entity.

GLOBAL PERFORMANCE ANALYSIS
Governing load cases are defined by two criteria. The first condition is to find the load cases with the largest heel angle to quantify \( \phi_{\text{MAX}} \). The second criterion isolates the load cases leading to the largest aerodynamic thrust and defines the overturning wind moment properties. In accordance with [20], the wind overturning moment is based on worst-case site-specific conditions. Although the focus of this paper is on the procurement of \( \phi_{\text{MAX}} \) and application of stability rules, the importance of extrapolating an accurate \( M_E \) representation is not to be diminished. The effort required to produce \( M_E \) is outside the scope of this paper, but it is a crucial ingredient to evaluate safety margins.

The heel angle is defined as:

\[ \text{heel} = \sqrt{\text{(roll)}^2 + \text{(pitch)}^2} \]  \hspace{1cm} (7)

The above equation is an acceptable estimate for the OC4 semisubmersible range of motion. The following load cases are surveyed in turbulent conditions to identify trends:

- DLC 1.3 – wind turbine operation at rated and cut-out wind speeds.
- DLC 1.6 – wind turbine operation at rated and cut-out wind speeds, associated with the severe sea-state (50-year) conditions.
- DLC 6.1 – parked turbine with 50-year extreme wind conditions and associated sea-state. The wind and RNA misalignment is 8° and wave misalignment is 0°, 30°, and 90°.

¹ NH is an acronym for ‘No Heel’ to imply the simulation is without roll/pitch mooring rotational stiffness.
• DLC 6.2 – parked turbine with 50-year extreme wind conditions and associated sea-state. Wind misalignment is 30° and wave misalignment is 0°, 30°, and 90°.

The simulation matrix and required simulation length follows the specifications in [20]. An outcome of this study reveals the largest aerodynamic RNA thrust and heel offsets congregate at similar load cases, with the largest aerodynamic thrust occurring at rated wind speed load cases. Numerous factors implicate the governing conditions, particularly:

• Center of gravity position.
• Load case condition and wave/wind misalignment.
• Simulation tool utilized to perform the analysis.

Performance: OC4 Semisubmersible with \( KG = 10.11 \text{ m} \)

The maximum heel offset for the OC4 semisubmersible with \( KG = 10.11 \text{ m} \) is provided in Tab. 3. The table arranges data according to region, load case and simulation tool. DLC 6.2 dominates the governing heel conditions for the GoM region. These GoM DLC 6.1 and DLC 6.2 conditions have a large wind speed and slightly lower wave height as compared to the OR region. In comparison, the OR region finds governing cases at three different load cases depending on the assumptions employed by the simulation program used: DLC 1.3, DLC 1.6, and DLC 6.2. The data shows an operational wind turbine experiences larger heel offsets at the rated wind speed than at the cut-out wind speed of 25.0 m/s despite the significant wave height being larger at the cut-out wind speed (see Tab. 1).

Larger waves are not guaranteed to lead to larger heel offsets. Instead, large heel offsets appear to be correlated to load cases with large wind speeds. The FAST (NH) model lacks mooring rotational stiffness and consistently yields larger heel offsets compared to the FAST variant (with intact moorings) in turbine operation mode, though this gap decreases as the wind speed moves away from the rated conditions. This observation is justified on the basis of Fig. 3, where the vessel must heel to a larger angle to counteract the large moment at reduced wind speeds close to the rated wind speed.

Aside from different mooring representations, the two simulations using FAST and FAST (NH) are implemented identically. FAST computes wave kinematics at the initial platform position, implying wave time series are identical. The wind time series (and hence the RNA relative velocity) are not guaranteed to be identical because FAST uses the instantaneous blade position.

Performance: OC4 Semisubmersible with \( KG = 15.00 \text{ m} \)

A similar comparison from the previous section is published in Tab. 4 for the OC4 variant with the raised \( KG = 15.00 \text{ m} \) position. Increasing the center of gravity position decreases the metacentric height, thereby decreasing hydrostatic stability. The vessel must also heel to a larger angle to maintain balance with the wind overturning moment. For all load cases, the platform in the new configuration yields larger heel offsets. However, the dominant governing case varies more with respect to the assumptions employed by the simulation programs. As established earlier, lowering the center of gravity raises the metacenter. This increases hydrostatic stiffness for the platform roll/pitch directions. Alternatively, a higher center of gravity softens the roll/pitch response, making the system susceptible to larger heel motion from external disturbances.

For both the GoM and OR region, the FAST (NH) model reports the largest heel offset for DLC 6.2. Both the FAST+Charm3D and FAST model report similar extremes in DLC 1.3 and DLC 1.6, although results vary by a wider margin when wind/wave misalignment cases are considered (DLC 6.1 and 6.2). In Tab. 5, the maximum heel offset is compared between the FAST model and the FAST (NH) model. The graphic displays a subset of simulations to illustrate evidence of wind thrust dominating the heel offsets during operational mode. Both DLC 1.3 and DLC 1.6 exhibit similar trends in peak heel offset because the same wind time series is used at each random seed, but the wave time history is different depending on site location. The OR site has lower 50-year wind speeds, and hence the maximum heel offsets are much lower – this is in spite of the OR region having a slightly elevated significant wave height.

Table 3: Maximum heel offset (in degrees) for three simulation tools across all simulation realizations with \( KG = 10.11 \text{ m} \).

<table>
<thead>
<tr>
<th>DLC 1.3</th>
<th>DLC 1.6</th>
<th>DLC 6.1</th>
<th>DLC 6.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoM</td>
<td>FAST+Charm3D</td>
<td>6.05</td>
<td>4.38</td>
</tr>
<tr>
<td></td>
<td>FAST</td>
<td>5.75</td>
<td>3.92</td>
</tr>
<tr>
<td></td>
<td>FAST (NH)</td>
<td>8.63</td>
<td>4.59</td>
</tr>
<tr>
<td>OR</td>
<td>FAST+Charm3D</td>
<td>6.25</td>
<td>4.34</td>
</tr>
<tr>
<td></td>
<td>FAST</td>
<td>5.53</td>
<td>3.90</td>
</tr>
<tr>
<td></td>
<td>FAST (NH)</td>
<td>8.89</td>
<td>4.49</td>
</tr>
</tbody>
</table>

Table 4: Maximum heel offset (in degrees) for three simulation tools across all simulation realizations with \( KG = 15.00 \text{ m} \).

<table>
<thead>
<tr>
<th>DLC 1.3</th>
<th>DLC 1.6</th>
<th>DLC 6.1</th>
<th>DLC 6.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GoM</td>
<td>FAST+Charm3D</td>
<td>15.44</td>
<td>8.23</td>
</tr>
<tr>
<td></td>
<td>FAST</td>
<td>16.00</td>
<td>8.10</td>
</tr>
<tr>
<td></td>
<td>FAST (NH)</td>
<td>19.06</td>
<td>10.64</td>
</tr>
<tr>
<td>OR</td>
<td>FAST+Charm3D</td>
<td>15.47</td>
<td>8.14</td>
</tr>
<tr>
<td></td>
<td>FAST</td>
<td>16.00</td>
<td>8.14</td>
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<tr>
<td></td>
<td>FAST (NH)</td>
<td>18.75</td>
<td>10.52</td>
</tr>
</tbody>
</table>
INTACT STABILITY ASSESSMENT

The essence of a stability assessment is to ensure sufficient reserve energy exists to overcome environment forces to avert capsize. This is done by maintaining the prescriptive condition in Eqn. 2. On the other hand, the performance-based condition in Eqn. 3 can be met to satisfy the alternative intact stability requirement. Application of both stability rules are applied using the two OC4 systems studied in this paper.

Wind Overturning Moment

Following the procedure in [20], the ensuing wind overturning combines the worst-case wind turbine thrust, tower, and platform exposed area drag forces between 0° - ϕc based on the global performance analysis from the selected load cases, which are larger than the steady wind speed in Fig. 3. Beyond ϕc, the wind overturning moment is calculated at one wind speed – typically at the 50-year extreme wind condition with an idling turbine. For simplicity, the wind overturning moment is:

\[ M_E(\phi) = \begin{cases} 
\max[M_F(\phi, V)] + (M_f)^2 \cos^2 \phi & , \phi < \phi_c \\
M_T(\phi, V_{n-yr}) + (M_p)^2 \cos^2 \phi & , \text{else} \end{cases} \tag{8} \]

The quantity \( \max[M_F(\phi, V)] \) is the peak aerodynamic thrust at heel angle \( \phi \) with wind velocity \( V \). \( V \) is not necessarily at the rated speed, but is less than the cut-out wind speed. This wind velocity is then used to calculate \( M_F \). Once the critical heel angle \( \phi_c \) is exceeded, the wind overturning moment is calculated at the 50-year wind speed with the turbine idling. A \( \cos^2 \) scale factor is applied on all exposed platform and tower components as justified in the International Maritime Organization Intact Stability Code (IMO IS Code) [2]. A shutdown heel angle of \( \phi_c = 10^\circ \) is selected to define \( M_E \).

Intact Stability: OC4 Semisubmersible KG = 10.11 m

Figure 5(a) illustrates the application of the dynamic-response-based intact stability criterion for the OC4 semisubmersible at the original center of gravity position, \( KG = 10.11 \) m. Visibly absent is a second intercept angle and the vanishing stability angle without considering the downflooding limit. Although \( \phi_2 \) is needed by definition of the dynamic-response-based criterion, the assessment can proceed forward by seeking the minimum \( \phi_2 \) value where the ratio \( \frac{\text{Area}(B)}{\text{Area}(A)} \geq 0.10 \), is met. Defining \( \phi_1 = 6.51^\circ \) and \( \phi_{MAX} = 10.39^\circ \) (Tab. 3), the dynamic-response-based criterion is satisfied provided \( \phi_2 \geq 10.76^\circ \). A similar procedure is applied using the area-ratio-based criterion to yield a minimum second intercept...

![Figure 5: The dynamic-response-based intact stability assessment in (a) and the area-ratio-based criterion in (b).](image)
angle $\phi_2 \geq 14.04^\circ$, Fig 5(b). The dynamic-response-based criterion is satisfied with a lower heel margin. The vessel maximum heel angle $\phi_{\text{MAX}}$ heel angle does not exceed $\phi_c$ for all turbine operation cases (DLC 1.3 and DLC 1.6) in Tab. 3. This is the region where the rotor shutdown would occur. In the single case where $\phi_c$ is exceeded – DLC 6.2 for the FAST+Charm3D model – the wind turbine is idling and $\phi_c$ has no effect on simulation outcome.

The wind overturning moment specified by Eqn. 8 will influence the area-ratio-based RER based on a selected $\phi_c$. In contrast, the dynamic-response-based criterion exhibits no sensitivity to the shutdown heel angle provided it exists within the range $\phi_1 \leq \phi_c \leq \phi_2$. A designer may take advantage of RER requirements shifting $\phi_c$, but this is discouraged. The shutdown heel angle $\phi_c$ should be set according to turbine requirements specified by the manufacturer instead of stability needs.

Though the reserve buoyancy is excessive, FOWT designs are likely to adopt large initial metacentric heights to ensure the heel remains small during turbine operation and a small static heel is maintained. This observation will become apparent when the second OC4 variant is studied in the following section.

**Intact Stability: OC4 Semisubmersible $K_G = 15.00$ m**

A similar process is followed for the OC4 semisubmersible with the raised $K_G$ position. The dynamic-response-based criterion is applied in Fig. 6(a), and the area-ratio-based criterion in Fig. 6(b). Both criteria meet minimum RER requirements. Application of the criteria is straightforward because a second intercept angle $\phi_2$ is present. The dynamic-response-based criterion calculates $RER = 0.107$ in Fig. 6(a) for the OR region based on $\phi_{\text{MAX}} = 25.98^\circ$ in Tab. 4. In comparison, the GoM region records a maximum dynamic heel angle of $\phi_{\text{MAX}} = 25.89^\circ$ in Tab. 4, and the corresponding dynamic-response-based $RER$ is 0.119 (area-ratio illustration related to this result is not shown below).

Although the dynamic-response-based and area-ratio-based methods are consistent to show the system operates close to the minimum allowable requirements, the dynamic-response-based criterion is on the verge of not meeting safety margin thresholds. A design improvement with a marginal decrease in the heel offset would enhance the dynamic-response-based safety margins. For example, suppose a design improvement decreases in the maximum heel offset to $\phi_{\text{MAX}} = 20.65^\circ$ (which is the largest value in Tab. 4 for an intact mooring), this increases the $RER$ to $\frac{\text{Area}(B)}{\text{Area}(A)} = 1.085$. The area-ratio-based criterion, in comparison, would potentially remain unchanged at $\frac{\text{Area}(A+B)}{\text{Area}(B+C)} = 1.457$.

One trait appearing in Fig. 6, but not present in Fig. 5, is that rotor shutdown is engaged before the first intercept angle is reached. Recall that $\phi_1$ is often referred to as the static heel angle to represent vessel heel at the rated wind speed. The simulation tools, however, do not account for rotor shutdown once $\phi_c$ is surpassed. Both DLC 1.3 and DLC 1.6 in Tab. 4 result in peak heel angles larger than the shutdown angle value. If rotor shutdown were accounted for, values would potentially be lower. Since the governing case is DLC 6.2, which is for an idling turbine, omitting $\phi_c$ effects does not change the results for $\phi_{\text{MAX}}$ obtained using the FAST (NH) model. The dynamic-response-based intact stability evaluation for this particular example is not affected by model limitations.

**Estimated Minimum GM Requirements**

Should the critical heel angle occur before the first intercept angle (Fig. 6), this would imply the FOWT statically stable in a nonoperating configuration. Given that $\frac{dM_z(\phi)}{d\phi} = \frac{dM_y(\phi)}{d\phi} = GM$ at small heel angles, a first principles calculation can be carried out to ensure the metacentric height is sufficient:

$$\frac{M_y(\phi_c)}{pgy\phi_c} < GM$$

(9)
implying the initial $GZ(\phi)$ slope is large enough for $\phi_t$ to occur prior to $\phi_c$. The limiting condition $GM = M_p(\phi)/(\rho g \phi_c)$ suggests the static heel angle is reached at the critical heel offset $\phi_c$.

**DISCUSSION AND SUMMARY**

The adoption of a performance-based criterion for column-stabilized units can trace its roots to the early 1980’s [28]. The motivation for adopting a new criterion was based on relating the dynamic response of a vessel in random seas with reserve stability. The area-ratio-based criterion accounts for performance in waves through the safety factor. The dynamic-response-based criterion includes both wind and wave excitation through the maximum dynamic heel angle, which is normalized against the wind overturning moment.

As a performance-based metric, the dynamic-response-based intact stability criterion is suitable to measure safety margins and avert FOWT capsize. Column-stabilized FOWTs are comparable to modern column-stabilized MODUs and share similar vulnerabilities. Analysis procedures developed from decades of MODU research can be leveraged to help expand our understanding of FOWT systems. The area-ratio-based criterion can also be applied, but it is demonstrated through examples it could demand a more conservative design.

The assessment in this paper is performed using the public-domain OC4 semisubmersible design with two configurations. In conventional applications, stability analysis involves determining the maximum $KG$ threshold before safety margins are exceeded. In the absence of an analytical model, raising the center of gravity position requires new load cases to estimate the maximum heel angle. In comparison, the area-ratio-based criterion can be done independently of time-domain simulations. Research towards relating the environmental conditions to the maximum heel angle using analytical models is encouraged, as this would streamline stability calculations. A similar proposal was initiated for MODUs in [16], which evolved as part of the dynamic-response-based criterion adopted by ABS [18], followed by IMO [3]. Early indicators suggest wind conditions dominate the vessel heel performance during turbine operation. Although this is the region where the wind turbine operates for most of its life, a maximum heel angle can be experienced in storm conditions.

**Governing Load Cases**

The governing load case for maximum heel offset consistently centers around DLC 1.6 (at the rated wind speed), DLC 6.1 and DLC 6.2. Heel offset is dictated by wind conditions in low-to-moderate sea-states, though wave misalignment is recognized to be a critical component to converge on the largest heel offset values. The maximum aerodynamic thrust observed is at DLC 1.6 (rated wind speed). Larger sea-states seemingly lead to larger aerodynamic thrusts, potentially caused by greater in-flow wind velocity caused by greater platform motions.

**Heel Angle Limitations Imposed by Equipment**

The floating system must be designed to accommodate the wind turbine. The vessel should have sufficient metacentric height for the static heel angle to remain small. From a stability perspective, a smaller $\phi_c$ is desired since the wind overturning moment is reduced. Alternately, a larger shutdown heel angle $\phi_s$ allowed by the equipment is favored compared to the static heel angle $\phi_s$ since this would expand the FOWT operational window. While both designs assessed in this paper meet dynamic-response-based and area-ratio-based $RER$ requirements, the center of gravity configuration at $KG = 15.00$ m (Fig. 6) would prevent the wind turbine from operating due to insufficient roll/pitch hydrostatic stiffness.

**REFERENCES**


