ABSTRACT

Heave, pitch and roll motions as well as airgap are key characteristics of semisubmersibles in extreme seas which are defined by Ultimate Limit State design conditions (ULS) with a specified 100-year design wave height $H_s$ and peak period $T_p$. The increasing number of reported rogue waves with unexpected large wave heights ($H_{max}/H_s > 2$), crest heights ($\zeta_{max}/H_{max} > 0.6$), wave steepness and group pattern (e.g. Three Sisters) may suggest a reconsideration of design codes by implementing an Accidental Limit State (ALS) with a return period of $10^4$ years. For investigating the consequences of specific extreme sea conditions this paper analyses the seakeeping behaviour of a semisubmersible in a reported rogue wave, the Draupner New Year Wave embedded in irregular sea states.

The numerical time-domain investigation using a panel method and potential theory is compared to frequency-domain results. In particular, the characteristics of the embedded rogue wave is varied to analyse the dynamic response of the semisubmersible in extreme wave sequences. For validation, the selected sea condition is generated in a physical wave tank, and the seakeeping behaviour of the semisubmersible is evaluated at model scale. In conclusion, the results demonstrate the consequences of rogue wave impacts, with respect to the relevance of present design methods and safety standards.
only, results show surprisingly good agreement with model tests if one considers magnitude and phase of structure response, even in rogue waves.

In this case study the impact of rogue waves in a severe sea state is investigated for the semisubmersible of the type GVA 4000 which is characterized by favorable seakeeping behaviour. This offshore structure is designed for worldwide operations, especially for the harsh conditions in the North Sea.

**NUMERICAL SIMULATION**

For our numerical simulations we use the program TiMIT (Time-domain investigations, developed at the Massachusetts Institute of Technology), a panel-method program for transient wave-body interactions [3] to evaluate the motions of the semisubmersible. TiMIT performs linear seakeeping analysis for bodies with or without forward speed. In a first module the transient radiation and diffraction problem is solved. The second module provides results like the steady force and moment, frequency-domain coefficients, response amplitude operators, time histories of body response in a prescribed sea of arbitrary frequency content on the basis of impulse-response functions. In the following section an overview of the fundamentals of TiMIT is presented. Terms which consider forward speed are maintained to give an idea of the capability of TiMIT.

**Theoretical background**

The motion equation balances the exciting forces due to incident waves which stimulate motions of a freely floating body with forward speed in its six degrees of freedom, and the body forces which arise from these motions [4]:

\[
\sum_{k=1}^{6} (M_{jk} + a_{jk})\ddot{s}_k + b_{jk}\dot{s}_k + (C_{jk} + c_{jk})s_k + \int_{-\infty}^{t} K_{jk}(t - \tau) \dot{s}_k(\tau) d\tau = F_j(t, \beta)
\]  

(1)

The body inertia matrix is expressed by \( M_{jk} \), the added mass coefficients by \( a_{jk} \), the potential damping coefficients by \( b_{jk} \) and the hydrostatic restoring force coefficients by \( C_{jk} \). The restoring coefficient \( c_{jk} \) accounts for restoring forces due to dynamic restoring forces resulting from forward speed. The memory function \( K_{jk}(t) \) considers free-surface effects which follow from body motions. The translatory and angular displacements of the body are designated by \( s_k \), its velocities and accelerations are derivatives of \( s_k \) with respect to time. The terms \( F_j \) on the right hand side are the components of the exciting force due to the incident wave elevation \( \zeta(t) \) (force is understood in the generalized sense, including the exciting moments for \( j = 4, 5, 6 \)).

With the assumptions that fluid is incompressible and inviscid, and flow is irrotational, the flow can be described by velocity potentials, which are assigned to

- \( v_b \) steady basis flow
- \( \phi_b \) steady perturbation due to forward speed
- \( \phi_0 \) incident wave potential
- \( \phi_v \) potential of the scatter wave field
- \( \phi_k \) potential of the radiation wave field

evoked by a motion in mode \( k \)

Assuming linear theory the total velocity potential \( \phi \) is given as superposition of the individual potentials due to the incoming plane waves and the wave systems which arise from the motions of the body:

\[
\phi(x, t) = v_b \Psi + \phi_b + \phi_0 + \phi_v + \sum_{k=1}^{6} \phi_k
\]  

(2)

The first term of the right-hand side of Eq. (2), \( v_b \Psi \), describes the steady flow neglecting free surface effects. Commonly, uniform flow, i.e. \( \Psi = -x \), or double-body flow is applied. If the body is travelling at the calm free surface a wave system is generated, designated by \( \phi_b \). Combined, \( v_b \Psi + \phi_b \) represents the steady potential due to the forward speed of the body in calm water. The three remaining terms denote the potentials of a body with zero speed, but free to perform unsteady motions due to incident waves: \( \phi_0 \) and \( \phi_v \) are assigned to the initial wave and its diffraction wave field of the fixed body. The last term is the sum of the six radiation potentials \( \phi_k = \delta_k \phi_k \) (for six degrees of freedom), which define the wave systems arising from the unsteady motions of the body at a calm free surface. They are related to the body velocity vector \( \dot{x} = (\dot{x}_1, \dot{x}_2, ..., \dot{x}_6)^T \), and are expressed in the body-fixed coordinate system \( (x, y, z) \). The local potential functions \( \phi_k \) depend only on the body geometry. The origin of the body-fixed coordinate system lies in the undisturbed free surface above the center of buoyancy with the \( x \)-axis pointing to the bow and the \( z \)-axis pointing upwards.

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The mathematical formulation of a rigid body in plane waves leads to a boundary value problem (see e.g. [5]) with the Laplace equation as governing equation:

$$\Delta \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0. \quad (3)$$

Each of the above defined potentials has to satisfy the Laplace equation as well as all boundary conditions on the surrounding boundaries:

- free surface: \( \left( \frac{\partial}{\partial t} - v_s \frac{\partial}{\partial x} \right)^2 \phi + g \frac{\partial \phi}{\partial z} = 0 \) for \( z = 0 \) \quad (4)
- ocean bottom: \( \frac{\partial \phi}{\partial z} = 0 \) for \( z = -d \) \quad (5)
- body surface: \( \delta V (\phi_t + \phi_\tau) = 0 \)
- \( \delta V_k = n_k s_k + v_s m_s s_k \)

in the farfield: \( \lim_{r \to \infty} \sqrt{r} \left( \frac{\partial \phi_j}{\partial r} - ik \phi_j \right) = 0, \quad j = 1, 2, \ldots \) \quad (7)

The generalized normal unit vector \( n = (n_1, n_2, n_3, n_4, n_5, n_6) \) is given by \((\hat{n} \times \hat{r})\) with \( \hat{n} = (n_1, n_2, n_3) \). The \( m \)-terms describe the coupling between the steady and the unsteady potentials.

By applying Green’s second theorem the initial boundary-value problem for the velocity potential \( \phi \) is transformed into the following integral equation [6]:

$$2 \pi \phi + \iint_{S_b} \left( G_{n}^{(0)} - G_{t}^{(0)} \right) dS + \int_{-\infty}^{t} \iint_{S_b} (\phi G_{tn} - G_{tn} \phi) dS d\tau$$

$$- \frac{V_s}{g} \int_{-\infty}^{t} n_1 \left( \phi (G_{tt} + v_s G_{t6}) + G_{t6} (\phi_t - v_s \phi_6) \right) dld\tau = 0 \quad (8)$$

\( S \) is the waterline contour and \( G(x, \xi, z, t) \) the transient, free-surface Green function, considering also forward speed \( [7] \). Equation (8) is valid for each point \( x \) on the body surface, and solved for each perturbation potential of Eq. (2) [8].

The solution of the integral equation (8) is implemented in the panel-method TiMIT for transient wave-body interactions of bodies with forward speed by discretizing the body surface into \( N \) quadrilateral (or triangular) panels (see Fig. 2). With the potential kept constant on the panels, a system of \( N \) linear equations is developed, and solved by common numerical methods.

From the calculated diffraction and radiation potentials the first order dynamic pressure and the hydrodynamic coefficients are determined. The equation of motion is solved for the unknown displacements \( x_e \) with respect to the mean body position.

**APPLICATION**

The drilling semisubmersible GVA 4000 has been selected as a typical harsh weather offshore structure to investigate the seakeeping behaviour in rogue waves in time-domain. The wetted surface of the body is discretized into 760 panels (Fig. 2). The number of panels is sufficient to simulate accurate results. To proof this accuracy a TiMIT run with 2456 panels on the wetted surface has been performed for comparison, confirming the results.

As preparatory step the response amplitude operators are calculated in frequency-domain using the well-known panel-method WAMIT (Wave Analysis developed at Massachusetts Institute of Technology, 1994 [9, 10, 11] for wave/structure interactions. Since results from WAMIT have been validated by numerous model tests and CFD-simulations they will serve as control for TiMIT results. Fig. 3 presents response amplitude operators for heave, pitch and roll motion (wave headings \( \beta = 0^\circ \) and \( 90^\circ \)) comparing TiMIT and WAMIT results. The RAOs agree quite well, though values obtained from TiMIT seem to be slightly underestimated. Important characteristics like resonance or cancellation frequencies and the trend of the curves correspond accurately. Resonance peaks of pitch and roll motion at very long waves are detected much more distinctly by TiMIT calculations. These peaks have also been confirmed in experimental tests, however at slightly different frequencies due to a variation of the radii of gyration.
Experimental investigations

Model tests in seas from astern ($\beta = 0^\circ$) have been carried out to validate TiMIT and WAMIT results of wave/structure interactions. Fig. 4 presents the general set-up. The semisubmersible GVA 4000 has been modelled at a scale of 1:81. The tank is 80m long, 4m wide and has a water depth of 1.5m. Model motions are registered with a dedicated video system. The air-gap is measured using wave gauges at different locations of the platform deck. The registrations of the wave probe in midship position are compared to the airgap from numerical results. Regular waves, irregular seas and transient wave groups are used to validate the calculated RAOs. For details on wave generation techniques and seakeeping tests using wave packets see [12, 13, 14, 15, 16]. Fig. 5 proofs that numerical and experimental results agree quite well. Note that the measured heave resonance peak gives maximum values of $s_3a/\zeta_n = 2$. A profound study of semisubmersible motion behaviour at heave resonance (and at cancellation period) reveals that this value is typical in high seas [17] as viscous effects are quite significant. Generally, viscous damping forces are overestimated in model tests, and neglected in WAMIT and TiMIT calculations (considering only potential damping). This fact allows the conclusion, that full scale
motions at heave resonance in severe sea states are expected to be between experimental and numerical data.

After successfully completing these preparation steps the investigations in extreme seas with embedded irregular rogue waves start with the experimental modelling of the Draupner New Year Wave (see Fig. 1) at the selected scale of 1:81. Based on dedicated techniques for generating tailored wave sequences in extreme model sea states [12, 13, 14, 15, 16] the wave board control signal is calculated from the target wave sequence at the selected wave tank location. Fig. 6 presents the modelled wave train at target location. For comparison the exact New Year Wave is also shown to illustrate that we have not reached an accurate agreement so far. However, this is not detrimental since the associated numerical analysis is based on the modelled wave train, registered at target position.

Fig. 7 presents the modelled wave train as well as the heave and pitch motions of the semisubmersible comparing numerical results and experimental data. The air gap as function of time is also shown. Note that this airgap is quite sufficient, even if the rogue wave passes the structure. However, wave run-up at the columns (observed in model tests) is quite dramatic, with the consequence that green water will splash up to the platform deck.

As a general observation, the rogue wave is not dramatically boosting the motion response. The semisubmersible is rather oscillating at a period of about 14s with moderate amplitudes.

Related to the (modelled) maximum wave height of $H_{\text{max}} = 23m$ we observe a maximum measured double heave amplitude of 7m. The corresponding peak value from numerical simulation is 8.6m. As a consequence, the measured airgap is slightly smaller than the one from numerical simulation. The associated maximum double pitch amplitudes compare quite well. Note that the impact results in a sudden inclination of about $3^\circ$. Considering the complete registration it can be stated that the numerical approach gives reliable results. At rogue events the associated response is overestimated due to the disregard of viscous effects in TiMIT calculations.

As agreement is quite satisfactory the numerical procedure is now applied to analyse the impact of the exact New Year Wave on the semisubmersible GVA 4000. The results in Fig. 8 and 9 show the wave registration as well as heave (with air gap), pitch and roll of the semisubmersible at the two wave headings of $\beta = 0^\circ$ and $90^\circ$, respectively. Water depth is adjusted to 70m, the depth of the North Sea at Draupner platform [1]. (Note that the comparison of experimental and numerical data in the previous section is related to a water depth of 120m, according to the modelled wave tank depth).

By definition the maximum wave height $H_{\text{max}} = 25.63m$, and the entire registration is identical to the registered rogue wave sequence in Fig. 1. Maximum heave and pitch (double amplitude) results in 10.1m and 8.0m ($\beta = 0^\circ$) as well as in 7.5m and 12.1m ($\beta = 90^\circ$), respectively. The semisubmersible oscillates moderately at a nearly constant period of $T = 14s$ ($\omega = 0.45rad/s$) where heave and pitch RAOs are characterized.
by higher values. The remaining airgap is well above 10m for \( \beta = 0^\circ \) and 7m for \( \beta = 90^\circ \). In conclusion, for these investigated cases the semisubmersible seems not to much impressed by the extraordinary single rogue wave.

To compare these data with results from standard evaluation methods the seakeeping behaviour of the semisubmersible is investigated in the sea state \( H_s = 11.92 \text{m} \) and \( T_0 = 10.8 \text{s} \) using conventional frequency-domain techniques. Fig. 10 shows the associated Pierson-Moskowitz as well as the JONSWAP-spectrum (\( \gamma = 3.3 \)) which has been introduced for comparison. In addition, the smoothed spectrum of the 20-minutes registration of the New Year Wave is also shown to proof that the PM-spectrum is quite representative for this evaluation. Multiplying the wave spectra by the squared RAOs of the semisubmersible we obtain the accompanying response spectra. The respective areas give the associated significant double amplitudes of heave, pitch and roll (see Table 1):

\[
(2s_{3a})_s = 4\sqrt{m_{30}} \quad \text{(9)}
\]

**Table 1.** Significant double amplitudes of GVA 4000: Heave, pitch and roll motions at two wave headings (sea state \( H_s = 11.92 \text{m}, T_0 = 10.8 \text{s}, \) water depth \( d = 70 \text{m} \))

<table>
<thead>
<tr>
<th>Wave heading ( \beta )</th>
<th>PM</th>
<th>JONSWAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heave 5.64m</td>
<td>5.31m</td>
<td>4.21m</td>
</tr>
<tr>
<td>Pitch 4.01(^\circ)</td>
<td>4.18(^\circ)</td>
<td>-</td>
</tr>
<tr>
<td>Roll -</td>
<td>-</td>
<td>6.07(^\circ) 6.3(^\circ)</td>
</tr>
</tbody>
</table>

From these data we expect a maximum double heave amplitude

\[
(2s_{3a})_{max} = 1.86 \cdot (2s_{3a})_s = 10.50 \text{m} \quad \text{for} \quad \beta = 0^\circ
\]

\[
(2s_{3a})_{max} = 1.86 \cdot (2s_{3a})_s = 7.83 \text{m} \quad \text{for} \quad \beta = 90^\circ \quad \text{(10)}
\]
considering the higher values given from the PM-Spectrum. The factor 1.86 relates the calculated significant and the most probable maximum double amplitudes in a narrow banded 3-hour sea state. As compared to time-domain results we observe that the maximum double heave amplitude in the extremely high rogue wave gives about the same maximum double amplitude for heave (10.1m at $\beta = 0^\circ$, and 8.0m at $\beta = 90^\circ$). For pitch and roll we would expect maximum double amplitudes of

\[
\begin{align*}
\text{pitch: } (2s_{\text{ha}})_{\text{max}} &= 1.86 \cdot 4.01^\circ = 7.5^\circ, \quad (\beta = 0^\circ) \\
\text{roll: } (2s_{\text{ra}})_{\text{max}} &= 1.86 \cdot 6.07^\circ = 11.3^\circ, \quad (\beta = 90^\circ)
\end{align*}
\]  

(11)

as compared to 7.5$^\circ$ (pitch) and 12$^\circ$ (roll) from time simulation.

In conclusion, time simulation and results of frequency-domain analysis correlate quite well for this semi-submersible. Considering heave, pitch and roll motions, as well as airgap variations, the standard procedure of predicting significant and maximum response are quite reliable even if the irregular sea hides a rogue wave. Of course, conclusions like this should be treated with caution, as the motion behaviour is depending on local wave characteristics. Continuing these investigations in near future we also will consider structural forces (splitting forces) as well as nonlinear phenomena in these extremely steep waves. In this context the steepness of the rogue wave will also be varied, and its consequences determined.

CONCLUSIONS

In this paper we present an investigation of the seakeeping behavior of the semi-submersible GVA 4000, which is a typical semi-submersible for world wide operations. In addition to frequency-domain analysis the motion behaviour is investigated
especially in the reported New Year Wave [1] in time-domain. Numerical results and the measurements at model scale agree quite well in frequency and time domain.

In particular, model tests in the extremely high Draupner New Year Wave prove that TiMIT simulations as well as standard procedures of predicting maximum response from frequency-domain analysis are quite reliable. This encouraging result relates just to the motion behaviour of a typical semisubmersible.

In future studies we plan to extend the scope investigating also the structural response as well as specific local phenomena related to wave grouping, wave steepness and wave breaking.

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References