Abstract
For the design and operation of offshore structures, heave motion, airgap, splitting forces as well as bending moments are key parameters to reduce down time and ensure safe operations. The increasing number of reported rogue waves with unexpected large wave height ($H_{\text{max}}/H_s > 2.0$), crest height ($\eta_c/H_{\text{max}} > 0.6$), wave steepness and group pattern (e.g. Three Sisters) suggests a reconsideration of design codes by implementing an Accidental Limit State with a return period of 10000 years. For investigating the consequences of specific extreme sea conditions numerical simulations of the seakeeping behavior, including motions and structural forces, as well as model tests have been carried out with FPSOs and semisubmersibles in a reported rogue wave, the Draupner New Year Wave. Both, frequency and time-domain results are presented. With frequency-domain analysis the profound data for the standard assessment of structures, concerning seakeeping behavior, operational limitations and fatigue are obtained. In addition, time-domain analysis in real rogue waves gives indispensable data on extremes, i.e. motions and structural forces. As the wave/structure interaction is analyzed in deterministic (freak) wave sequences the most critical position is evaluated by systematic simulations, and the causes of (nonlinear) structure response are revealed.

Introduction
Surviving a freak wave - what an experience. However, only scarce observations are available of such mystic disasters.

Reports on individual extreme waves in deep water mention either single high waves or several successive high waves.

Fig. 1—Rogue wave observations - Bay of Biscay (top) and Atlantic Ocean South (bottom)
succeeding waves have steepness values around half the significant values while their heights are around the significant height. Regressions of rogue waves are shown in Fig. 2 and 3:

- a giant wave \( (H_{\text{max}} = 25.63m) \) with the crest height \( \eta_c = 18.5m \) hit the Draupner jacket platform on January 1, 1995.

- off Yura harbor in the Japanese Sea a 13.6m wave with \( \eta_c = 8.2m \) has been recorded in a sea state of \( H_s = 5.09m \).

Exceptional waves have also been reported from the Norwegian Frigg field\(^6\): \( H_s = 8.49m, \; H_{\text{max}} = 19.98m, \; \eta_c = 12.24m, \) water depth \( d = 99.4m, \) as well as from the Danish Gorm field\(^7\): \( H_s = 6.9m, \; H_{\text{max}} = 17.8m, \; \eta_c \approx 13m, \) water depth \( d = 40m. \) All these wave data, with \( H_{\text{max}} / H_s > 2.15 \) and \( \eta_c / H_{\text{max}} > 0.6, \) prove that rogue waves are serious events which should be considered in the design process. Although their probability is very low they are physically possible. It is a challenging question which maximum wave and crest heights can develop in a certain sea-state characterized by \( H_s \) and \( T_p. \)

In addition to the global parameters \( H_s \) and \( T_p \) the individual wave height and shape as well as its effects on a structure depend on superpositions and the interaction of wave components, i.e. on local wave characteristics. Phase relations and nonlinear interactions are key parameters to specify the relevant surface profile at the structure as well as the associated wave kinematics and dynamics.

Time-domain analysis yields the response of an offshore structure to individual wave sequences including freak waves. The procedure allows the analysis of wave/structure interaction and the determination of extreme motions and structural forces in sea states with integrated freak waves. If deterministic wave sequences or even real registrations like the New Year Wave (Fig. 2) or the Yura Wave (Fig. 3) are selected as input data, the genesis of the propagating wave train up to the culmination point can be analyzed. Depending on the position of the wave/structure interaction the maximum impact is determined.

This paper presents the evaluation of rogue wave impacts on FPSOs and semisubmersibles comparing frequency and time-domain results. The numerical investigations are backed up by experimental validation. The seakeeping tests allow the precise (deterministic) generation of design wave groups or even the Draupner New Year Wave sequence at a selected target position. Consequently, it is suited for investigating the mechanism of arbitrary wave/structure interactions, including slamming, green water and capsizing as well as other survivability design aspects because cause-reaction chains can be traced. In conclusion, you can observe your structure in a real freak wave - and survive.

**Wave generation and experimental setup**

To simulate rogue wave sequences experimentally a fast and precise method is required which can be adopted to the test purpose easily.

As a first step, the design spectrum and a target position \( x_{\text{target}} \) is selected. At this location, the target wave train is either designed or given as an existing wave registration like the New Year Wave.

This wave train is transformed upstream to the position of the wave maker which requires an adequate wave propagation model. On the basis of linear wave theory the specified amplitude distribution of the target wave train is given as Fourier transform \( F(\omega, x_{\text{target}}) \) with circular frequency \( \omega \) as a function of wave number \( k. \) Adaptation of the phase spectrum to the wave maker location \( x_0 \) gives the Fourier transform in \( x_0: \)

\[
F(\omega, x_0) = |F(\omega, x_{\text{target}})|e^{i(\omega-(x_{\text{target}}-x_0))} \quad \cdots \cdots \cdots \cdots \cdots (1)
\]

As the process is strictly linear and deterministic, wave groups as well as arbitrary wave sequences can be analyzed back and forth in time and space.

For a given design variance spectrum of an unidirectional wave train, the phase spectrum is responsible for all local characteristics, e.g. the wave height and period distribution as well as the location of the highest wave crest in time and space. For this reason, an initially random phase spectrum \( \arg F(\omega) \) is optimized to generate the desired design wave train with specified local properties.

The set-up of the optimization problem is illustrated for a transient design wave within a tailored group of three successive waves in random sea. The target zero-upcrossing wave...
heights of the leading, the design and the trailing wave are defined by \( H_l, H_d \) and \( H_t \). The target locations in space and time of the design wave crest height \( \zeta_{\text{d target}} \) and \( \zeta_{\text{t target}} \). These data define equality constraints. The maximum values of stroke, velocity and acceleration of the wave board motion define inequality constraints to be taken into account \(^{10}\).

The heights of the leading and the trailing waves adjoining the design wave are set to be \( H_l = H_t = H_s \). Note that this wave sequence is quite representative for rogue wave groups as has been proved by Wolfram et al. \(^{3}\) who classified 114 extremely high waves with their immediate neighbors out of 345245 waves collected between 1994 and 1998 at North Alwyn.

The surface elevation is described by \( N = 512 \) data points with time step of \( dt = 0.2s \) resulting in a time window of 102.2 s. The design variance spectrum remains unchanged and 70 components in the frequency range of \( \omega/\omega_p = 0.5 \) to \( \omega/\omega_p = 3.5 \) are considered.

As illustrated in Fig. 4, the optimization process finds local minima, i.e. a number of different wave trains which depend on the initial phase values. Hence the random character of the optimized sea state is not completely lost.

For generating higher waves, i.e. the extremely high Draupner New Year Wave train, the linear approach is expanded by a semi-empirical nonlinear procedure which is based on the fact that short and high wave groups with strong nonlinear characteristics evolve from long and low wave groups which are characterized by linear principles. As the total energy of the wave is invariant during its metamorphosis, the initial Fourier transform of the linear wave train is introduced as “wave information” and selected as the backbone of wave propagation \(^{11}\).

This wave information along with the adequate celerity at each time step give the nonlinear phase characteristics of the wave train \(^{12}\). The detailed shape of the resulting wave train is developed at each time step considering the temporary steepness of the wave. This iteration principle can be used either for backward transformation (wave generation) as well as for forward transformation (calculation of the moving reference frame wave train at cruising ships \(^{13}\)).

From the wave train at the position of the wave maker the corresponding control signals are calculated using the hydrodynamic transfer function (relating wave board motion to wave elevation), the geometrical RAO (which considers the flap type), and the electric-hydraulic RAO. This control signal is used to generate the specified wave train which is measured at the target position in the tank. Model test results are presented in Fig. 5. As compared to the target wave sequence of the New Year Wave (in full scale data), wave heights and phase relations are satisfactorily modeled.

The seakeeping tests with semisubmersibles and FPSOs are carried out in a 80m long wave flume, see Fig. 6. Water depth is 1.5m. A computer controlled piston-type wave paddle gen-
erates the selected wave sequences within a given band of frequencies, including regular and irregular waves as well as wave packets and deterministic wave trains.

Motions are registered by a video camera, observing LEDs fixed on the deck of the models. For measuring splitting forces the cross bracing of the semisubmersible is equipped with strain gauges. Vertical bending moments are registered similarly by connecting the two elements of the model by steel profiles equipped with strain gauges.

### Numerical simulation

The evaluation of motions, splitting forces and bending moments is carried out with the program systems WAMIT (Wave Analysis, developed at Massachusetts Institute of Technology) for wave/structure interaction at zero-speed and TiMIT (Time-domain investigations, developed at Massachusetts Institute of Technology), a program for transient wave/body interactions at arbitrary speed. Three-dimensional panel methods using potential theory are implemented in both programs. WAMIT solves the equation of motion in frequency-domain, and is therefore applicable only for zero-speed problems. Results of motions and forces are given uniquely as response amplitude operators (RAO) by amplitude and phase. Re-calculations and - combined with wave scatter diagrams - motions are deduced, and the down-time of the structure can be evaluated.

### Hydrodynamic analysis

This section presents a short introduction to mathematical background. For details see [16,20–22]. The analysis of a compact rigid body with six degrees of freedom is described by a boundary value problem. The total velocity potential \( \phi(x,t) \) for an inviscid, incompressible fluid and irrotational flow follows from Laplace equation

\[
\Delta \phi(x,t) = 0 \quad \text{.......................................................... (2)}
\]

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

\[
\phi(x,t) = \phi_0 + \phi_7 + \sum_{k=1}^{6} \phi_k \quad \text{.......................................................... (3)}
\]

with \( \phi_0 \) incident wave potential 
\( \phi_7 \) potential of scatter wave field 
\( \phi_k \) potential of the radiation wave field evoked by a motion in mode \( k \)

These potentials describe the initial wave field \( \phi_0 \) and its reflection on the body surface resulting in the scatter wave field \( \phi_7 \). The last term in Eq. (3) describes the radiation wave fields \( \phi_k \) which follow from body motions in 6 degrees of freedom.

On the wetted body surface normal velocity is zero. For a moving body this condition results into:

\[
\frac{\partial \phi_i}{\partial n} = \hat{z} \cdot \mathbf{u}^* \quad \text{on } S_b \quad \text{................................. (4)}
\]

The linearized kinematic and dynamic boundary condition on the free surface are merged into the generalized free surface condition:

\[
\frac{\partial \phi_i}{\partial n} = 0 \quad \text{for } z = -d \quad \text{................................. (5)}
\]

On the ocean bottom normal velocities are zero:

\[
\frac{\partial \phi_i}{\partial n} = 0 \quad \text{for } z = -d \quad \text{................................. (6)}
\]

\( \phi_i \) \( i = 0, 1, ..., 7 \) holds for any potential, which are superimposed to form the complete solution. Finally in the farfield the Sommerfeld radiation condition for the scatter and radiation wave field must be satisfied:

\[
\lim_{R \to \infty} \sqrt{R} (\frac{\partial \phi_j}{\partial R} - ik \phi_j) = 0 \quad j = 1, ..., 7 \quad \text{................................. (7)}
\]

The initial boundary value problem, defined by Laplace equation (2) and the above boundary conditions, is transformed into an integral equation by applying Green’s second theorem and, after some manipulation, we obtain:

\[
2\pi \phi(x,t) = \int \left( \phi(x,t) G_0(\hat{x}, \hat{z}) - G_0(\hat{x}, \hat{z}) \phi_0(x,t) \right) dS + \int \int \int \left( \phi(x,t) G_n(\hat{x}, \hat{z}, \mathbf{t}) - G_n(\hat{x}, \hat{z}, \mathbf{t}) \phi_n(x,t) \right) dS d\tau = 0 
\]

(8)

This equation allows to solve for the unknown scatter and radiation potentials on the mean position of the body surface \( \mathcal{S}_b \). The wetted body surface has to be discretized into \( N \) panels (see e.g. Fig. 7 or 13) where the boundary conditions are satisfied on the collocation point. Based on this potential the instationary Bernoulli equation gives the (linearized) dynamic pressure:

\[
p_{dy} = -\rho \frac{\partial \phi}{\partial t} \quad \text{................................. (9)}
\]

which defines the forces and moments acting on the body:

\[
F = \int p_{dyn} \mathbf{n}^* dS = -\rho \int \int \frac{\partial \phi}{\partial t} \mathbf{n}^* dS \quad \text{................................. (10)}
\]
With Newton’s second law and assuming the body and its forcing comprise a stable linear system, the equation of motion is obtained:

\[
(M + a)\ddot{s}_i + B\dot{s}_i + C_s + \int_{-\infty}^{t} K(t-\tau)\ddot{s}_i d\tau = F(t) \quad \ldots \quad (11)
\]

From equation (11) the unknown motions in 6 degrees of freedom are calculated in time-domain. Note that the resulting motions are given as impulse-response function which are the reaction of the body on an impulsive forcing (see right side of the equation). The motions of the body in arbitrary wave trains are calculated in a subsequent step by convolution of the impulse response functions with the wave train.

In the following applications the wave trains measured during experiments are used to carry out the simulations and allow therefore direct comparison between simulation and experiment.

In frequency-domain, Eq. (11) is solved for harmonic excitation. Divided by the wave amplitude \( \zeta_r \), the equation is reduced to:

\[
(-\omega^2(M + a) - i\omega B + C)H(\omega) = \frac{F_r}{\zeta_r} e^{i\gamma} \quad \ldots \quad (12)
\]

with the unknown response amplitude operator \( H(\omega) = \frac{F_r}{\zeta_r} e^{i\epsilon} \), representing amplitude \( \zeta_r \) and phase shift \( \epsilon \) of the motion in frequency-domain. \( \gamma \) is the phase of forcing.

**Hydroelastic analysis** The program WAMIT allows the analysis of generalized modes of body motions, in addition to the usual six degrees of rigid-body motions. By defining the ship bending modes the associated structural deformations can be calculated. Legendre polynomials \( P_i(x), i = 2, 3, \ldots \) are found to approximate very well the bending modes of a ship.\(^{25}\) The deflection line for each bending mode is given by the product of the calculated amplitude and the corresponding Legendre polynomial.

\[
w_i(x) = s_{ia} \cdot P_i(x), \quad i = 7, 8, \ldots \quad \ldots \quad (13)
\]

The indexing takes into account, that the first 6 indices are reserved for the conventional rigid body motions. For several bending modes, the total deflection results from complex addition of the individual deflection lines. Twice differentiation of the deflection line, multiplied with the flexural stiffness results in the bending moment of the ship:

\[
M_b(x) = -w_i(x) \cdot EI_i(x) \quad \ldots \quad (14)
\]

**Applications**

For the investigation of the impact of freak waves on offshore structures two typical types of offshore structures are selected:

- Drilling semisubmersible of type GVA 4000 especially designed for operations in harsh environment, Fig. 7. Pontoon length is 80.56m, pontoon beam 16m, column spacing (longitudinal and transverse) 54.72m, column diameter 12.9m, and operation draught 20.5m. The wetted surface of the body is discretized into 760 panels.

- FPSO (Floating Production Storage Offloading) with a length of \( L_{pp} = 194.4m \), beam 37.8m, draught 10.09m, and a displacement of 65250t. The wetted surface is discretized with 336 panels for the numerical simulations, see Fig. 13.

Model tests have been carried out for both structures at a scale of 1:81.

Numerical simulations of the seakeeping behavior include six (coupled) rigid body motions, however the presentation is restricted to heave as critical parameter during operation. In addition, the airgap and the splitting forces of the semisubmersible are determined.

Vertical bending moments are measured by strain gauges at the intersection of the fore and aft body of the model (see Fig. 13). The amplitudes of the bending modes calculated with WAMIT are transformed into the vertical bending moment (Eqn. (13) and (14)).

**Semisubmersible - Heave, Airgap and Splitting forces**

For operation of semisubmersible heave motion, airgap and splitting forces are key parameters.

![Fig. 7—Main dimensions and discretization with 760 panels on the mean position of the semisubmersible GVA 4000](image_url)
Fig. 8—Semisubmersible GVA 4000 in (modelled) New Year Wave ($H_{\text{max}} = 23\text{m}$) - Results of numerical simulation (TiMIT) and model tests of semisubmersible GVA 4000: Heave and airgap (measured at a scale 1:81, presented as full scale data)

Year Wave. Fig. 10 presents the splitting forces of the semisubmersible GVA 4000 in the (modelled) New Year Wave comparing numerical and experimental results.

Table 1—Maximum motions and structural forces of GVA 4000 comparing time- and frequency-domain results

<table>
<thead>
<tr>
<th>Semisubmersible GVA 4000</th>
<th>Time-domain</th>
<th>Frequency-domain</th>
</tr>
</thead>
</table>
| maximum double amplitudes of | New Year Wave $H_{\text{max}} = 23.13\text{m}$ | $H_s = 11.92\text{m}$ $T_0 = 10.8s$
| heave | Exp. 7.0m Sim. 8.6m | PM 10.5m JONSWAP 9.88m |
| airgap | 7.62m 9.87m | - - |
| split force | 71.5MN 63.6MN | 76.7MN 76.1MN |

In frequency-domain the 20-min New Year Wave registration gives the sea spectrum in Fig. 9 (top) with $H_s = 11.92\text{m}$ and $T_0 = 10.8s$. The corresponding JONSWAP spectrum ($\gamma = 3.3$) and the Pierson-Moskowitz spectrum are shown for comparison. Note that the New Year Wave registration coincides well with the PM spectrum. Thus, the New Year Wave sequence represents a quite exotic sample of a conventional PM spectrum. Consequently, the significant and maximum motions and forces can also be determined by spectral analysis. From the area under the response spectrum $m_i$ the significant double amplitude

$$2s_{i\text{ia}} = 4\sqrt{m_i} \tag{15}$$

and the maximum double amplitude

$$2s_{i\text{ia}} = 1.86 \cdot (2s_{i\text{ia}}) \tag{16}$$

is derived.

Results are presented in Table 1. Evidently, the maximum values of motions and forces (double amplitudes) as predicted from frequency-domain evaluations are quite higher as compared to measured data and time-domain numerical results in a freak wave. Consequently, the prognosis based on the standard frequency-domain procedure proves to be reliable and is sufficient to cover even freak wave effects. Note that maximum double amplitudes based on JONSWAP-spectra give comparable results (see Fig. 9 and Table 1).

So far, the hydrodynamic analysis of the semisubmersible GVA 4000 is related to the (modelled) New Year Wave with a maximum height of 23.1m only. Comparison of WAMIT, TiMIT and wave tank results proof that TiMIT is a reliable tool for predicting time-domain impacts, even in extremely high
waves. On this basis a sensitivity study has been launched to investigate the effect of increase of freak wave height (and steepness), integrated in the New Year Wave sequence.

Fig. 11 presents illustrative (focused) results. With increasing freak wave height we observe higher direct response and a slight deviation of the subsequent motions. The semisubmersible is following the exciting wave elevation with little phase shift. Concerning the maximum values, Fig. 12 illustrates that the heave motion is non-linearly increasing with freak wave height.

**FPSO - Heave, Pitch and Bending Moment** FPSOs are widely used in deep and harsh offshore areas. Therefore, a ship-type structure has also been selected for our rogue wave investigation. Regarding structural loads bending moments are probably one of the most critical values. In Fig. 13 the model (scale 1:81) as well as the discretized wetted hull of the FPSO are presented.

Again, the (modelled) New Year Wave has been used for comparative studies. Fig. 15 presents the associated heave and pitch motion as well as the bending moment. Note that the time series of the bending moment is calculated from the RAO obtained by WAMIT, see Fig. 14, in the same manner as the splitting forces of the semisubmersible. As has been stated in equations (13) and (14): Legendre polynomials describe the geometry of the deflection line and their second derivatives the curvature of the deflection line. The product with the curvature and the calculated amplitudes is proportional to the bending moment. The total curvature derived from the three bending
Fig. 14—RAO of bending moment, comparison of experimental and numerical results.

Fig. 15—FPSO: Heave, pitch motion and bending moment from experiment and TiMIT (with $H_{\text{max}} = 23.1\text{m}$).

The RAO of bending moment is obtained by complex addition, and the resulting RAO is presented in Fig. 14. The numerical results, calculated by TiMIT, are again satisfactorily validated by model test data.

To achieve detailed information of the freak wave impact we started a sensitivity study to investigate the worst position of the FPSO. Nine locations have been selected varying from $3/2L_{pp}$ to $3L_{pp}$. Registrations at 3 positions are presented in Fig. 16. In addition Table 2 gives all calculated and measured data. Before the seakeeping tests, the wave propagations at all 9 locations have been recorded separately without the ship to obtain undisturbed wave registrations as input for the numerical simulation. Comparing numerical and experimental results the excellency of TiMIT (based on linear theory) is confirmed again.

This is quite surprising, as nonlinear effects of wave/structure interactions seem to be insignificant in this case. It should be noted, however, that the highest waves in the wave train are very steep and thus the analysis considers (nonlinear) real sea conditions. The second surprise follows from the detailed study of the wave propagation: Our reference freak wave sequence, see Fig. 16 (middle column), is not the highest wave. Just one ship length before (at $x_1 - L_{pp}$) the maximum wave height is 25m, due to a very deep trough (Table 2).

A stochastic analysis based on Pierson-Moskowitz and JONSWAP spectra with significant wave height of $11.92\text{m}$ and zero-upcrossing period of $10.8\text{s}$ results in values for the maximum double amplitudes of heave and pitch, which are quite comparable:

<table>
<thead>
<tr>
<th>PM spectrum</th>
<th>JONSWAP spectrum</th>
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</thead>
<tbody>
<tr>
<td>$(2s_{3a})_{\text{max}}$</td>
<td>10.4m</td>
</tr>
<tr>
<td>$(2s_{5a})_{\text{max}}$</td>
<td>13.7$^\circ$</td>
</tr>
<tr>
<td>$(2M_{ba})_{\text{max}}$</td>
<td>4128.5MNm</td>
</tr>
</tbody>
</table>

Table 2—Maximum motions and structural forces of the FPSO located at different positions in the New Year Wave

Conclusions
What happens to a FPSO or a semisubmersible in a freak wave? Are motions and loads higher than predicted by standard stochastic evaluations? This paper presents a comprehensive study comparing time-domain and frequency-domain investigations of offshore structures in rogue waves, validated by seakeeping tests in irregular sea states with integrated modes, and thus the bending moment, is obtained by complex addition, and the resulting RAO is presented in Fig. 14. The numerical results, calculated by TiMIT, are again satisfactorily validated by model test data.
deterministic freak wave sequences. This model test technique allows the accurate simulation of the selected Draupner New Year Wave (with a slightly lower wave height of $H_{\text{max}} = 23.1 \text{m}$). Consequently, numerical time-domain results are directly compared to experimental data, and cause-reaction chains of wave/structure interactions can be detected and validated. As a result, the time-domain program TiMIT proves to be an excellent tool for the analysis of the selected structures i.e. a FPSO with a high block coefficient and a semisubmersible in freak waves. Motions, airgap, splitting forces and bending moments are predicted satisfactorily.

Systematic variation of the wave height of the rogue wave hidden in a normal storm sea reveals the sensitivity of structural response of the semisubmersible due to changed wave conditions. The results show a nonlinear increase of responses, fortunately significantly less than proportional.

A second systematic analysis tackles the question, what happens if the structure is exposed to the incoming freak wave further downstream or upstream. Surprisingly, the New Year Wave is even more severe at the position of one ship length upstream confirming the importance of time and phase information and the need for precise simulations and model test.

In conclusion, as numerical and experimental simulations can model impacts of extreme waves on offshore structures precisely, these tools are ideally suited to investigate cause-reaction chains of wave-structure interactions. Fortunately, the comparison of time and frequency-domain results point out that the frequency-domain standard approach for investigating sea keeping characteristics and operational limitations as well as wave scatter depending down-time evaluations are still sufficient even if rogue waves are hidden in the sea.

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References


