ABSTRACT: During the design process of floating structures, different boundary conditions have to be taken into account. Besides the basic determination of the type of vessel, the range of application and the main dimensions at the initial stage, the reliability and the warranty of economical efficiency are an inevitable integral part of the design process. Model tests to evaluate the characteristics and the performance of the floating structure are an important milestone within this process. Therefore it is necessary to determine an adequate test procedure which covers all essential areas of interest. The focus lies on the limiting criteria of the design such as maximum global loads, maximum motions or relative motions between two or more vessels or maximum accelerations, at which the floating structure has to operate or to survive. These criteria are typically combined with a limiting characteristic sea state (\(H_s, T_p\)) or a rogue wave. However, the important question remains: What is the worst case scenario for each design parameter - the highest rogue wave or a wave group of certain frequency? And which sea states have to be taken into account for the experimental evaluation of the limiting criteria? As an approach to these questions, several critical wave sequences are characterized and analysed for different scenarios in order to identify the most important characteristics and to improve the efficiency of model tests.

1 INTRODUCTION

Productivity and survivability are critical parameters for offshore construction design. Modern computer-based analysis techniques allow calculation and simulation of these parameters in the design stage, but nevertheless model tests are indispensable for validating the respective approaches. The central problem that has to be solved in the design process of maritime structures is the choice of environmental design conditions to be considered:

- What are the maximum wave heights?
- What is the worst case scenario - the highest wave or a wave group with certain frequency characteristics?

Of course, this issue cannot be solved globally, i.e. different operating conditions (transit, operation, survival) and characteristics (body motions, local and global loads) will lead to individual results. In order to verify the calculated parameters sought, sophisticated model tests are required. Since complex sea states as wave groups have to be generated as exact as possible but with the least amount of time and money, only experienced test facilities are capable of conducting such experimental series.

Linear frequency-domain analysis, i.e. the calculation of RAOs (Response Amplitude Operators), is a basic but fast and elegant approach to investigate the motion characteristics of floating structures prior to model tests (Clauss et al. 1992), which is provided by various numerical tools available. By stochastic analysis procedures, the annual downtime of offshore production facilities can be calculated on basis of this method. Clauss and Birk (1996) proposed a procedure for optimizing buoyancy bodies of floating structures based on linear theory, where the geometry is generated automatically and subsequently analysed linearly and modified to find the minimum of a certain target function (annual downtime).

Extreme sea states and their consequences on body motions and loads can be investigated by transferring the linear RAOs into time-domain. Jacobsen and Clauss (2006) applied this method to analyse the sea-keeping behaviour of multi-body systems. Motions and global loads of a FPSO in extreme sea states were numerically simulated and successfully validated by model tests (Clauss et al. 2004).

Impact loads and motions in severe seas and rogue waves are investigated with special emphasis on the influence of bow shape (Watanabe et al. 1989). Fonseca and Guedes Soares (2002) compared numerical and experimental results of wave-induced vertical ship motions and loads, revealing that the geometry
of the bow flare in combination with wave steepness significantly influences the global loads and leads to higher sagging than hogging moments. This nonlinearity is mostly associated with the "nonlinear geometry" of the hull and increases with decreasing block coefficient. Furthermore, these nonlinear effects were approved and enhanced by Clauss et al. (2010, a) for different ship types in high, steep, regular waves as well as in irregular waves, confirming the influence of block coefficient, bow flare and freeboard height.

Besides the analysis of motion behaviour and global loads, the assessment of the maximum number of responses during a structure’s lifetime also has to include local loads. Stansberg (2008) determined a parameter to assess the risks of slamming at a ship’s bow due to waves and wave groups. As already mentioned above, the exact generation and reproduction, respectively, of sea states in a wave tank is an important component of the analysis of floating structures. An experimental optimization procedure for tailor-made wave sequence generation in a wave tank has been proposed by Clauss and Schmittner (2005), which enables the exact reproduction of wave or wave groups of desired characteristics.

This paper presents a new optimization approach for the determination of critical situations (i.e. wave sequences) combining with extreme wave heights. The method for generating linear wave groups is based on the wave focussing technique of Davis and Zarnick (1964), and its significant development by Takezawa and Hirayama (1976).

Clauss and Bergmann (1986) recommended a special type of transient waves, i.e. Gaussian wave packets, which have the advantage that their propagation behaviour can be predicted analytically, later on completely performed numerically (Clauss and Kühnein 1995). The generated wave trains are predictable at any instant and at any stationary or moving location. According to its high accuracy the technique is capable of generating special purpose transient waves.

In general, "rogue" waves or critical wave groups are rare events embedded in a random seaway. As long as linear wave theory is applied, the sea state can be regarded as superposition of independent harmonic "component" waves, each having a particular direction, amplitude, frequency and phase. 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.

Extreme wave conditions in a 100-year design storm arise from unfavourable superpositions of component waves which represent the severe sea spectrum. Freak waves have been registered in standard irregular seas when component waves accidentally superimpose in phase. Extensive random time-domain simulation of the ocean surface for obtaining statistics of the extremes, however, is very time consuming. Generally, when generating irregular seas in a wave tank the phase shift is supposed to be random, however, it can be fixed by the control program on the basis of a pseudo-random process: Consequently, the phase spectrum is also given as a deterministic quantity and can be optimized. Why should we wait for rare events if we can achieve freak wave conditions by intentionally selecting a suitable phase shift, and generate a deterministic sequence of waves converging at a preset concentration point? At this position all waves are superimposed without phase shift resulting in a single high wave peak. Assuming linear wave theory, the synthesis and up-stream transformation of appropriate wave packets is developed from this concentration point, and the Fourier transform of the wave train (phase spectrum) is transformed back to the upstream position at the wave board.

2.2 Nonlinear transient wave description

The generation of higher and steeper wave sequences requires a more sophisticated approach as propagation velocity increases with height. Kühnein (1997) developed a semi-empirical procedure for the evolution of extremely high wave groups which is based on linear wave theory: The propagation of high and steep wave trains is calculated by iterative integration of coupled equations of particle positions. With this deterministic technique "freak" waves up to 3.2m high have been generated in a wave tank (Clauss and
For the simulation of the nonlinear wave propagation a potential theory solver has been developed at Technical University Berlin (WAVETUB) (Clauss and Steinhagen 1999; Steinhagen 2001). Therefor, the twodimensional nonlinear free surface flow problem is solved in time domain - a complete description of this numerical wave tank is published by Steinhagen (2001). Tailored wave groups can be integrated into irregular seas using a Sequential Quadratic Programming (SQP) method and nonlinear wave theory (Hennig 2005).

Summarizing the achievements of the numerical wave tank we can generate deterministic high and steep wave sequences at a selected position, and integrate them into irregular seas with defined significant wave height and period.

2.3 Self-validating procedure for optimizing tailored design wave sequences

To further improve the process of the deterministic evolution of tailored wave sequences, a fully automated optimization technique with integrated validation has been developed. As shown in Figure 1 the wave tank is combined with a computer system representing a hybrid control loop for optimizing the selected wave train at a target position. Nonlinear free surface effects are automatically considered in the fitting process since the wave train propagates in the real wave tank, and thus the objective function is automatically validated (Clauss 2002). Based on deviations between the measured wave sequence and the design wave group at target location the control signal for generating the seaway is iteratively optimized in the fully automatic computer-controlled model test procedure (Fig. 1).

As an example, Figure 2(a) presents the evolution of the famous Draupner New Year Wave (Haver and Anderson 2000) (full scale data deduced from model tests at a scale of 1:70). The registrations show how the extremely high wave develops on its way to the target position: Two kilometers ahead of the concentration point we observe a wave group with three high waves between 700s and 730s. The slightly longer waves (right hand side waves of the registration) are travelling faster catching up with the leading wave of the group. Just 500m ahead of the concentration point only two higher waves are visible, superimposing to the single New Year Wave at target. The registrations at 500m and 1000m behind the target document the dissipation of the wave sequence. Figure 2(b) presents the measured registration of the New Year Wave at target position. As compared to the registered New Year Wave the experimental simulation is quite satisfactory. Finally, Figure 2(c) shows a snapshot of the freak wave at target time.

3 STEP 2 : WAVE-STRUCTURE INTERACTION

3.1 Modeling System Behavior

The performance assessment of offshore structures starts with computation of selected response amplitude operators of forces and motions. For hydrodynamically compact structures the well established 3D diffraction-radiation software package WAMIT (Wave Analysis Massachusetts Institute of Technology) is used (Department of Ocean Engineering, MIT 1994).

The Response Amplitude Operators (RAOs) of the body motions $s_{la}/\zeta$ follow from Newton’s motion equation which constitute a system of linear equations if small harmonic motions $s_{l} = s_{la}e^{-i\omega t}$ are assumed:

$$[-\omega^2(M + A) + i\omega B + C] \frac{s}{\zeta} = f.$$

Figure 1: Computer controlled experimental optimization of tailored design wave sequences.

Figure 2: New Year Wave: (a) Evolution of the New Year Wave (scale 1:70), (b) Experimental simulation in comparison to the registered New Year Wave (full scale wave data) and (c) Snapshot of the experimental simulation at target time.
Hydrodynamic analysis of the structure has to provide the system matrices for added masses $A$, potential damping $B$ and hydrostatic restoring coefficients $C$ as well as the exciting wave forces $f$.

Considering the well known boundary value problem of a rigid body in plane harmonic waves, the total velocity potential $\Phi$ has to satisfy the Laplace equation

$$\Delta \Phi = 0 \quad (2)$$

and can be separated into a superposition of

- the potential $\Phi_0$ of the incident plane waves,
- the diffraction potential $\Phi_\tau$, which expresses the interaction of the incident wave and the fixed body, and
- the six radiation potentials $\Phi_l = \mathbf{s}_l\phi_l$ which characterize the impact of body motions on the fluid.

The local potential functions $\phi_l (l = 1, 2...6)$ are due to body motions

Summation yields

$$\Phi = \Phi_0 + \Phi_\tau + \sum_{l=1}^{6} \mathbf{s}_l\phi_l. \quad (3)$$

In addition to the Laplace equation (2), the solution must also satisfy the linearized boundary conditions on the ocean bottom ($z = -d$), on the free surface ($z = 0$), on the wetted body surface (mean position) and in the far field (radiation condition).

The diffraction-radiation program WAMIT solves the linear Fredholm integral equations for the six local potential functions $\phi_l$ and for the total diffraction potential $\phi_d = \phi_0 + \phi_\tau$. As a result, the integral equations are reduced to a set of seven systems of linear equations - the number of unknowns equals the number of panels $N$. The WAMIT algorithms for evaluating the coefficients of the linear equations with the Green function $G(X, \xi)$ are presented by Newman (1986). The accuracy of the solution of the linear systems is controlled by an iterative equation solver (Newman 1977). Once the system matrices and the exciting force are known, the response amplitude operators can be calculated from Equation 1.

### 3.2 Modeling Environmental Conditions

In reality, the elevation of the ocean surface is irregular and of random nature. Hence, rational seakeeping criteria have to be based on a probabilistic description of random seas. Gaussian distribution of wave elevations and Rayleigh distribution of wave heights are assumed. The relevant parameters are significant wave height $H_s$ and mean zero-upcrossing period $T_0$.

The significant wave height is linked to the variance $\sigma^2$ of the random process by $H_s^2 = 4\sqrt{\sigma^2}$ (Newland 1975). The probabilities of sea states are recorded in wave scatter diagrams (Hogben and Lumb 1967) which may be subdivided according to the region, season and direction of wave origin. For computing purposes the discrete data are approximated by an analytical joint probability density function $p(T_0, H_s)$ (Mathisen and Bitter-Gregerson 1990). Nonlinear regression yields the corresponding function parameters.

### 3.3 Downtime Prediction

The application of spectral analysis in ship dynamics started with the fundamental publication of (Devis and Pierson 1953). Natural seaway is interpreted as a random superposition of a great number of harmonic long-crested waves of different amplitudes $\zeta_{an}$ and frequencies $\omega_n$ (Clauss et al. 1992).

Assuming linear behaviour of the system, the harmonic excitation of a structure due to a wave of frequency $\omega_n$ yields a phase shifted harmonic response of the same frequency. The seaway (input signal) as well as the response (output signal) are a superposition of an infinite number of harmonic elementary components. The complex ratio of output and input signals $s(\omega)$ and $\zeta(\omega)$ for each wave frequency $\omega$ constitutes the transfer function or response amplitude operator (RAO) which gives a complete description of the corresponding hydrodynamic characteristics.

$$H(\omega) = \frac{s(\omega)}{\zeta(\omega)} = \frac{s_n(\omega)}{\zeta_n(\omega)} e^{i\epsilon_n}. \quad (6)$$

Each component wave contributes an amount of energy to the seaway proportional to its squared wave amplitude. The spectral density $S$ represents the energy distribution as a function of wave frequency $\omega$. Evidently two characteristic parameters define the shape of the energy distribution. The significant wave height

$$H_s = 4\sqrt{m_0} \quad (7)$$
and the zero-up-crossing period

$$T_0 = 2\pi \sqrt{m_0/m_2}$$

(8)

with

$$m_n = \int_0^\infty \omega^n S_{zz}(\omega) d\omega.$$  

Corresponding to the wave spectrum $S_{zz}(w)$ of the seaway, the response spectrum $S_{ss}(w)$ represents the energy distribution of the output signal. Wave and response spectra are related by

$$S_{ss}(\omega) = |H_s(\omega)|^2 S_{zz}(\omega).$$

(9)

Similarly to the significant wave height $H_s$, a significant force or motion double amplitude $(2s)_s$ follows from the response spectrum:

$$(2s)_s = 4 \sqrt{\int_0^\infty S_{ss}(\omega) d\omega}.$$  

(10)

These significant double amplitudes characterize the behaviour of offshore structures in stationary sea states, and are appropriate hydrodynamic 'measure of merit' criteria for the evaluation procedure. Of course, any combination of significant double amplitudes of forces, motions, or other hydrodynamic parameters of interest may be used as objective functions. If limiting values of significant double amplitudes of forces and motions $(2s)a,s,lim$ are known, the objective function (Eq. 10) defined above may be extended to include long term wave statistics.

4 STEP 3 : RESPONSE BASED EVALUATION OF WAVE/STRUCTURE INTERACTIONS

In the previous sections the accurate generation of arbitrary extreme wave sequences embedded in irregular seas has been presented. Concerning wave/structure interactions, with respect to response based design the crucial question has to be answered: Is the highest wave with the steepest crest the most relevant design condition or should we identify wave sequences with critical frequency characteristics embedded in an irregular wave train? In addition to the global parameters $H_s$ and $T_p$ the wave effects on a structure depend on its dynamic behaviour as well as on superposition and interaction of wave components, i.e. on local wave characteristics.

If a cruising vessel is investigated the wave characteristics must be transformed to the moving reference frame, i.e. the characteristics of the encountering wave are relevant. Phase relations and nonlinear interactions are key parameters to specify the relevant surface profile at the (moving) structure. Only if wave kinematics and dynamics are known, cause-effect relationships can be detected.

The aiming target is the response of the structure which follows from the associated response amplitude operators (in frequency-domain) or impulse response functions (in time-domain)

$$M \cdot \ddot{s} + (\omega_n^2 + \omega^2\zeta)\cdot \dot{s} + \omega_n^2 s = F_{error}.$$  

(11)

By assuming harmonic forces as well as motions due to harmonic waves the equation of motion becomes time-independent

$$\{-\omega^2(M + A) - \omega B + C\} \frac{\zeta a}{\zeta a} e^{i\omega} = \frac{F_{error,a}}{{\zeta a}} e^{i\gamma}.$$  

(12)

and the associated response amplitude operator (Eq. 6) is obtained by relating motions and forces.

4.1 Offshore lift-off operation

The first case study is a typical offshore problem, i.e. the lift-off operation of a heavy load from a barge by a semisubmersible crane vessel (Jacobsen and Clauss 2006). Figure 3 illustrates the proposed lift-off operation of such a multi-body system, i.e. the crane vessel Thialf and a barge.

Three stationary states of the transfer of a 10000t load are discussed.

- transport barge carrying the load, no mechanical connection, structures are coupled hydrodynamically only
- load is fastened, rope is pretensioned up to 80%, structures are coupled mechanically also
- load is hanging, fast lift up by usage of rapid ballast water system, hydrodynamically coupling again

The most critical parameter of this process is the vertical relative motion between barge and load shortly after lift-off since this is the limiting criterion (Lift state 3). As the seaway excites both vessels the resulting motion depends on the incoming wave field as well as on the scattered and radiated wave fields of both structures, which are hydrodynamically coupled (Newman 2001). The hydrodynamic analysis in frequency-domain is performed by using the diffraction code WAMIT. The body surface is discretised to solve the system of integral equations numerically.

After evaluating the total potential the pressure is derived from the linearised, instationary Bernoulli equation. The forces and moments acting on the body are determined by integrating the pressure over the body surface, including hydrostatic as well as hydrodynamic forces and moments. Related to Newton’s second law, the equation of motion for a stable, linear system is obtained:

Figure 3: Sketch of the investigated multi-body systems — three states of the lift-off operation (load 10000t).
to the wave amplitude $\zeta$. The decision, however, whether an operation is feasible needs information about the behaviour in natural seaways.

The motion behaviour in a natural seaway is obtained by spectral analysis. For engineering purposes standard spectra as the Pierson-Moskowitz spectrum are formulated. By multiplying the sea spectrum with the squared RAO the response spectrum is obtained (Fig. 4). Relevant characteristics, as significant double amplitude $(2s_0)_s$ and zero-upcrossing period $T_{0,s}$ of the response are derived from the associated response spectrum. The procedure is similar to the determination of significant wave height $H_S$ and Zero-upcrossing period $T_0$ from the sea spectrum. To derive assessment criteria in arbitrary seaways the procedure is repeated for several sea states with varied zero-upcrossing periods $T_0$. The resulting significant double amplitudes are normalized by the significant wave height. This leads to the significant response amplitude operator as a function of the zero-upcrossing period

$$\frac{(2s_0)_s}{H_S} = f(T_0), \quad \text{(13)}$$

which allows the comparison of different structures or configurations and serves as basis for operation decisions.

With frequency-domain results the motion behaviour of multi-body systems in waves are investigated very fast and efficiently, but the results can only be interpreted statistically. If cause-reaction effects are of interest and wave/structure interactions are evaluated in detail a time-domain analysis in deterministic wave trains is required. A sophisticated method of transforming frequency-domain results into time-domain enables the investigation of hydrodynamically coupled structures including memory effects. For this the response amplitude operators (calculated by WAMIT) are transformed into impulse response functions by Fourier transformation (Cummins 1962):

$$K_i(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} H_i(\omega) e^{i\omega t} \, d\omega \quad \text{(14)}$$

For this purpose a Fortran routine F2T by J.N. Newman has been provided to the authors and enhanced to an improved F2T+ procedure (Jacobsen 2005). With known impulse-response functions of the motions $K_i(t)$ the time dependent response in arbitrary wave trains $\zeta(t)$ is calculated by convolution (Fig. 4):

$$s_i(t) = \int_{t=\infty}^{\infty} K_i(t - \tau)\zeta(\tau)\, d\tau \quad \text{(15)}$$

The improved F2T+ procedure combines the

- Transformation of the complex frequency-domain RAOS into time-domain impulse-response functions
- Convolution of the impulse response function with arbitrary wave sequences to determine the behaviour of a structure in time-domain.

From the rigid body motions, i.e. heave and pitch of the semisubmersible as well as heave of the barge, the response amplitude operator of the relative motion between the crane hook and the barge is determined by complex addition in order to include the phase angles correctly. For the barge positioned at the lee side of the floating crane the relative motion between the 1000t-load and the barge is analysed for a sea state with a significant wave height of $2\text{m}$ and a zero-upcrossing period of $T_0 = 5\text{s}$. Three wave sequences are chosen from an entire 1000 waves registration and compared in time- and frequency-domain. In the first sequence from 2650-2750s the smallest relative motion is observed. The third includes the maximum wave height. The three ranges with the associated relative motions are shown in Figure 5. They illustrate the different motion behaviour:

- In the first sequence very small motions are observed. The zero-upcrossing period $(T_{0,\text{rel}} = 6.4\text{s})$ of the relative motion is very low. The basis of a safe lift is to start the operation in such a sequence with low motion.
- The second sequence is characterised by the maximum double amplitude of the relative motion. Though the exciting wave heights are quite similar to the waves of the first sequence (most of them are smaller than the significant wave height) the response is quite different. The associated zero-upcrossing period of the relative motions at $8.2\text{s}$ is high. Such events should be avoided during lifting operations.

![Figure 4: Response of structures in the sea — evaluation in frequency and in time-domain (relative motion between elevated load and barge during a lift-off operation with the crane semisubmersible Thialf).](image-url)
During the third sequence, containing the highest wave, the response is something between the first and the second sequence. The zero-upcrossing period is \( T_{0,\text{rel}} = 7.13s \), located between the two others.

Apparently, the maximum wave exites a rather un-spectacular reaction, while wave of medium height may lead to heavy responses.

If the analysis is focused on wave height only we cannot detect the effect of resonance-dominated wave sequences which excite temporally significant responses (Fig. 5 - detail 2).

This observation is confirmed by spectral analysis of the respective wave sequences and motion response (cf. Jacobsen (2005)). The spectrum of wave sequence 1 (Fig. 5 - top) contains relatively short waves, and hence the response remains low. In contrary, the wave sequence 2 (Fig. 5 - middle) shows higher energies at lower frequencies. As the RAO is quite high in this region, we obtain a significant responses, and the associated relative motions are significant.

### 4.2 Ships in encountering Freak Waves

The second case study presents investigations of a RoRo-vessel \( (L_{pp} = 195m, \Delta = 4483t, c_B = 0.71) \) encountering critical wave sequences with embedded freak waves such as there are:

- The "New Year Wave" (NYW), a giant single wave \( (H_{\text{max}} = 25.63 m) \) with a crest height of \( H_c = 18.5 m \) recorded during a storm on January 1, 1995 at the Draupner platform in the North Sea (Haver and Anderson 2000) in a surrounding sea state characterized by a significant wave height of \( H_s = 11.92 m \) (\( H_{\text{max}}/H_s = 2.15 \)) at a water depth of \( d = 70m \).

- The "North Alwyn Wave" (NAW), recorded in a 5 day storm at the North Alwyn platform (Wolfram et al. 2000) on November 19th, 1997, i.e. a giant single wave \( (H_{\text{max}} = 22.03 m) \) in a surrounding sea state of \( H_s = 8.64 m \) (\( H_{\text{max}}/H_s = 2.55 \)).

For the investigation of the influence of different wave characteristics on the vertical bending moment, the investigated vessel is chosen because it provides a pronounced horizontal asymmetry, due to its large flare at bow and stern. The wooden model is subdivided into three segments intersected at \( 1/2 L_{pp} \) and \( 3/4 L_{pp} \) (measured from the aft perpendicular) being connected with three force transducers at each cut. Based on the measured longitudinal forces and the given geometrical arrangement of the three force transducers, the resulting vertical wave bending moments and the longitudinal forces are obtained. On this basis, the superimposed vertical wave bending moment resulting from vertical and horizontal forces on the hull is determined.

For the investigations the model is fixed and towed with an elastic suspension system using a triangular towing arrangement pulling the model without inducing a moment. The longitudinal motions are restricted by a spring in front of and a counter weight behind the model. With this arrangement, heave and pitch motions as well as the measured forces and moments remain unrestrained.

The identification of the most critical wave sequence in an irregular sea state is not a single-edged problem. Loads and motions significantly depend on encountering speed and angle. To simplify this task the focus lays on long crested head seas as the worst case scenarios inducing the most critical vertical bending moments.

In the first part of the investigations, two target positions (at forward perpendicular and at midship) are analysed in the New Year Wave and compared to identify the more critical situation. The second part contains the investigations of two different time traces - a 20-minute time trace of the New Year Wave sequence and a 15-minute time trace of the North Alwyn Wave sequence, both at stationary condition.

### Target Position

The first investigations are made to compare different encounter positions of extreme waves to identify the most critical target position. Therefore, the RoRo vessel is investigated in the New Year Wave.
with target position at forward perpendicular as well as at midship. Figure 6 illustrates the vessel position in the freak wave and the surrounding surface elevation for both target positions. The spatial development of the New Year Wave was measured in the sea-keeping basin of the TU Berlin in a range from 2163 m (full scale) ahead of to 1470 m behind the target position by a total of 520 registrations (Clauss and Klein 2009). Figure 7 presents the vertical bending moments for both situations - the left column represents the target position at forward perpendicular, the right column shows the results of the target position midships. The first two rows compare the surface elevation at forward perpendicular and midships for both target positions. Due to minor local variations of the wave probes for the different test setups, the registrations at target location show some marginal differences, which can be neglected in the following. Row three and four provide the according vertical bending moments at $1/2 L_{pp}$ and $3/4 L_{pp}$. The last row shows the relative surface elevation, measured at the bow.

In contrast to expectations, global loads are higher in case of the midship target position (Fig. 7, right column). This becomes clearly apparent at the first sagging moment peak as well as at the maximum hogging moment. These higher loads at midship conditions are caused by the contour of the individual waves in the sequence, especially of the previous and following wave (cf. Fig. 7). Figure 6 illustrates that the wave trough in front of the rogue wave is much deeper than compared to the one in the forward perpendicular situation (Fig. 6, first row). Encountering the freak wave, the ship’s bow is completely submerged in both cases and lifted up. The preceding wave trough at about midships is significantly deeper for the situation with midship target position than for the forward perpendicular one. This results in higher sagging loads. At the following hogging situation, the fully developed freak wave - in case of midship target position - induces higher hogging loads than the already broken and propagated freak wave (target position forward perpendicular) with a thereby decreased wave height. Submerging in the next wave crest, the second sagging moments are nearly the same in both conditions.

Figure 6: Visualisation of the ship motions (full scale) and surface elevation for target position forward perpendicular (left column) and midship (right column).

Figure 7: Comparison of model test results in the New Year Wave at different target positions - target position at forward perpendicular (left column) and target position at midship (right column).

With the restriction of investigating only global loads, target position midship presents a more critical situation for the RoRo vessel, and is chosen for the following investigations.

**Wave Characteristics**

For further investigations, two different time traces including freak waves are analysed, starting with the registration of the New Year Wave ($F_n = 0$), presented in Figure 9. Beside the surface elevation, three other wave characteristics are chosen to identify the critical potential of the different investigated waves - the crest front steepness, the horizontal asymmetry and the relative wave length. The first row presents the surface elevation $\zeta_a$ at midship (target position midship), the next two show the crest front steepness $\epsilon$ and the horizontal asymmetry $\mu$, defined by Kjeldsen (1983) and illustrated in Figure 8. The fourth row presents the relative wavelength, the ratio of wave length ($L_w$) to ship length ($L_{pp} = \text{length between perpendiculars}$), which is an indicator for the critical wave length related to the bending moments. The last two rows show the ver-

$$\epsilon = \frac{\eta'}{2 \pi T \cdot T'} \quad \text{and} \quad \mu = \frac{\eta'}{H}, \quad (16)$$

both defined by Kjeldsen (1983) and illustrated in Figure 8. The fourth row presents the relative wavelength, the ratio of wave length ($L_w$) to ship length ($L_{pp} = \text{length between perpendiculars}$), which is an indicator for the critical wave length related to the bending moments. The last two rows show the ver-
tical bending moments at $1/2 \frac{L_{pp}}{H}$ and $3/4 \frac{L_{pp}}{H}$.

Previous investigations (Clauss et al. 2010) in regular waves revealed that the asymmetry of the vertical bending moment, induced by the horizontal asymmetry of the RoRo hull, increases for higher, steeper waves. This results in higher sagging and lower hogging moments, which was also observed by Guedes Soares and Schellin (Soares and Schellin 1998). The global maximum of the Response Amplitude Operator (RAO) as well as the maximum asymmetry is about $L_{w}/L_{pp} \approx 1.1$.

![Figure 8: Wave parameters for the definition of the wave front steepness and the horizontal asymmetry as proposed by Kjeldsen.](image)

New Year Wave

Figure 9 presents a 20 minute time trace of the New Year Wave in stationary condition, target position midship. Regarding the vertical bending moments, extreme values are observed at $t \approx 860$ s. Even though the wave length is not critical ($L_{w}/L_{pp} = 1.56$), the very deep preceding trough induces the first big sagging moment peak (cf. Fig. 6, right column). The extremely steep freak wave ($H_{\text{max}} = 25.63$ m, $H_{c} = 18.5$ m, $\epsilon = 0.44$, $\mu = 0.68$, $H_{\text{max}}/H_{s} = 2.15$) induces a maximum hogging moment at target position midship with large emerged parts at bow and stern (cf. Fig. 6). Protruding from the New Year Waves crest and submerging in the following wave trough, a second critical sagging moment is induced. Beside this highest wave, some other critical wave sequences exist at $t \approx 700$ s, $t \approx 1020$ s, $t \approx 1250$ s, $t \approx 1360$ s and $t \approx 1550$ s. These smaller waves - or better to say the according wave groups - have a similar level of relative wave length ($0.87 - 1.4$), which is about the maximum RAO region for the vertical bending moment ($L_{w}/L_{pp} \approx 1.1$). All wave groups show a distinct horizontal asymmetry ($0.61 - 0.71$) but no extraordinary crest front steepness, with exception of the fifth wave ($t \approx 1360$ s). This wave ($\epsilon = 0.41$, as well as the New Year Wave itself ($\epsilon = 0.44$), has a huge preceding wave trough. These troughs significantly increase the impact of the following giant wave and lead to a more critical vertical bending moment. The last critical wave sequence ($t \approx 1550$ s) shows a following deep wave trough which results in a huge second sagging moment.

North Alwyn Wave

After investigating the time trace of the New Year Wave, another freak wave embedded in a 15 minute time trace, recorded in a five day storm at North Alwyn platform, is analysed and presented in Figure 10. Similarly to Figure 9, the first row shows the surface elevation, followed by diagrams of the crest front steepness, horizontal asymmetry, relative wave length and the vertical bending moments at $1/2 \frac{L_{pp}}{H}$ and $3/4 \frac{L_{pp}}{H}$.

First of all, the maximum moments are observed in the vicinity of the highest North Alwyn Wave ($t \approx 860$ s). In relation to the New Year Wave and the surrounding sea state ($H_{s-N_{AW}} = 8.64$ m vs. $H_{s-N_{NYW}} = 11.92$ m), this wave ($H_{\text{max}} = 22.03$ m, $H_{c} = 16.38$ m, $\epsilon = 0.43$, $\mu = 0.72$, $H_{\text{max}}/H_{s} = 2.55$) is even more critical, in particular according to the relative wave length ($L_{w}/L_{pp} = 1.15$). This is obviously shown in similar bending moments - in comparison to the New Year Wave - which occur in this smaller freak wave. Regarding the whole time trace, there are a few other critical wave sequences, for example at $t \approx 550$ s, $t \approx 620$ s, $t \approx 1125$ s and $t \approx 1275$ s. Again, all sequences have a similar ratio of relative wave length ($0.85 - 1.26$), which is about the maximum RAO region for the vertical bending moment. However, neither a significant horizontal asymmetry nor an extraordinary crest front steepness are on hand, with an exception of the second wave group ($t \approx 620$ s).

Comparing the individual situations in both inves-
tigations, the most critical parameter is the relative wave length. Even with a smaller significant wave height \( H_s = 8.64 \) m, the time trace of the North Alwyn Wave provides comparable vertical bending moments in comparison to the New Year Wave \( H_s = 11.92 \) m. This fact is clearly caused by the smaller, more critical relative wave lengths. Another interesting result is the importance of the surrounding wave profile in terms of huge preceding or following wave troughs in combination with large crest front steepnesses. Situations like these can induce great sagging loads, which are comparatively big to those of the hogging condition. Nevertheless, freak waves like the New Year Wave can induce significant hogging moments and very critical situations while lifting the vessel up at the crest and emerging large areas at bow and stern. This effect is amplified by high, asymmetrically and steep crests. Examining the characteristics of the three different time traces, all discussed criteria can be found at target position.

Regarding the procedure of a passing giant wave, the vessel is going down in the preceding wave trough. By entering the steep, giant wave front, the bow section submerges completely and hence induces maximum sagging loads. Floating through the New Year Waves crest with large emerged areas at bow and stern, maximum hogging loads are the consequence. Submerging heavily into the following wave front, a second critical sagging moment is induced.

5 CONCLUSIONS
This paper presents two different case studies for the identification of critical offshore situations. Therefore, a multibody system, e.g. an offshore lift operation, and ship in severe sea state, e.g. a RoRo-vessel encountering freak waves, are analysed. For the investigation of critical situations, the relative vertical motions is chosen for the lift of operation and the vertical bending moment for the RoRo-vessel.

First of all, the classical design evaluation, using random phase distributions, is compared to a phase optimization procedure, which is applied for a straightforward identification of the worst case scenario with regard to a selected sea state. It is shown that serious responses depend on critical wave length more than on the highest wave.

Furthermore, the influence of several wave parameters - such as target position, wave height, crest front steepness, horizontal asymmetry and relative wave length - on the occurring vertical bending moments are analysed for a RoRo-vessel. As mentioned in previous investigations (Clauss et al. 2010, a), one of the key parameter is the relative wave length. In combination with an extraordinary wave height and steep crest front, maximum critical loads can appear.

Investigations for both cases have shown that only a few parameters are responsible for the maximum responses. With the help of numerical optimization (Clauss et al. 2010, b), these parameters can be used to define tailored worst case sea state scenarios to determine limiting criteria for offshore operations or structural reliability. This procedure, prior to the investigations in the test facilities, can reduce the model test duration and make the investigations more efficiently.

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