ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Laboratory Modelling of Waves

7.5	Process Control
7.5-02	Testing and Extrapolation Methods
7.5-02-07	Loads and Responses
7.5-02-07-01	Environmental Modelling
7.5-02-07-01.2	Laboratory Modelling of Waves

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Table of Contents

Laboratory Modelling of Waves

1. PURPOSE OF GUIDELINE

The purpose of this recommended guideline is to help laboratories in conducting tests on waves. The guideline addresses, among other things, nonlinear effects, extreme events and wave breaking, wave generation and control, and interaction with wind and currents.

2. WAVE MODELLING

2.1 Regular waves

Ideally, regular waves are periodic unidirectional progressive wave trains, with a single (monochromatic) basic harmonic.

2.1.1 Linear waves

For most regular wave applications, the average wave height H and the average period T are of main interest. Amplitudes A, defined by $H/2$ or by crests A_C and troughs A_T, and the average steepness kA, are also used, where k is the angular wave number.

Theoretically, properties should be constant throughout time and in space, but in physical generation in a wave basin, there is always a certain level of variation. Time windows for analysis of the generated wave field are selected based on criteria such as minimum variations, minimum transient effects in the model test set-up, or minimum reflections from the beach or from the side walls. Normally a minimum of 10 wave cycles are selected. Parameters are defined by a time-domain (zero crossing) approach or by a frequency domain (Fourier or harmonic) approach, mainly with focus on the basic harmonic. Simple root-mean-squared (RMS) analysis of elevation records is also applied.

2.1.2 Non-linear effects – analysis, control

Real water waves are not exactly linear. They are influenced by nonlinear effects which are of higher order with respect to the wave amplitude. Higher-order solutions may be derived by using the Stokes's expansion as shown in Newman (1977) or Dean and Dalrymple (2000), or they may be derived by using fully nonlinear methods, as e.g. presented in Rienecker and Fenton, (1981). In a non-dimensional form, the wave amplitude is better represented by the wave steepness $\varepsilon = kA$. With increasing wave steepness ε, the wave profile progressively deviates from a pure sinusoidal wave form and are characterised by higher crests and shallower troughs, Toffoli et al. (2005). The asymmetry with respect to the horizontal axis (in this case a vertical asymmetry) is generally referred to as skewness, which is defined as (e.g. Babanin (2011))

$$S_k = \frac{A_C}{A_T} - 1$$

and is positive, unless some other phenomena, such as wave breaking, occurs. In the above equation A_C and A_T denote the crest height and the trough depth, respectively.

Nonlinear effects on wave height distributions are discussed in Tayfun and Fedele (2007). The nonlinear effects in the water waves and, in particular, the vertical asymmetry are also responsible for wave drift.

Non-linear regular wave characteristics are defined by the significant components at higher harmonics. The asymmetric wave geometry, with increased crests (and decreased troughs) and associated local steepness, may have important consequences in practice, for instance in the case of stability tests. Recent studies also show that the bound harmonics are also responsible for the generation of rogue waves, Fedele et al. (2016).

To distinguish these 'real' non-linear effects in open-sea wave fields from 'parasitic' laboratory-induced ones, comparisons of laboratory generated wave profiles with theoretical/numerical nonlinear reference models are helpful. In this regard, although referring to a two-dimensional wave system, Henderson et al. (2006) showed the relevance of accounting for nonlinear effects in wave generation in order to achieve a wave pattern that propagates with a time independent form.

For second-order nonlinear regular (periodic) wave generation for intermediate water depth and deep water conditions, the method presented by Schäffer (1993) can be used by selecting a single frequency component only. The numerical algorithm will automatically generate a "clean" second-order Stokes wave containing the fundamental component plus its phase-locked second-order frequency component only. The unintended and undesirable second-order free wave induced by incompatible geometry of the wave board will be removed from the wave field by a potential wave equal in amplitude but with a 180-degree phase shift, thus having a cancelling effect on the second-order free wave (see Schäffer, 1996).

Another approach, which is more general and can accurately generate nonlinear Stokes waves of arbitrary order, is the higher-order spectral (HOS) method developed by the LHEEA-ECN (Hydrodynamics, Energetics and Atmospheric Environment Laboratory of Ecole Centrale de Nantes) group. Their High-Order Spectral method (HOSM) includes two packages, namely HOS-NWT, a numerical wave tank model with wavemaking and absorption capabilities, and HOS-Ocean, an open boundary solver to approximate wave field transformation from an initial state. The HOS method owes its accuracy and efficiency to the pseudo-spectral approach in solution procedure and has been proven to be more efficient than finite-base discretization models, Ducrozet et al. (2012 and 2016). The solution procedure details and formulation of the problem can be found in the original works of Dommermuth et al. (1987), and West et al. (1987). As in the Schäffer (1996) case, nonlinear regular waves of arbitrary order can be generated using the HOS method by selecting a single wave component. High degree of accuracy can be achieved using the HOS model, Ducrozet et al. (2007).

Over the past three decades, significant progress has been made on the developed of a nonlinear Fourier analysis methodology (NLFA) to characterize nonlinear ocean waves in arbitrary water depth. The work by researchers on this topic was documented comprehensively in a full-length text by Osborne (2010). For waves in coastal regions, the Korteweg-de Vries (KdV) equation governing shallow water wave behaviour was used. For waves further offshore, the nonlinear Schrodinger (NLS) equations governing intermediate to deep water was applied (Osborne, 2010). Both the KdV and NLS equations admit both regular waves as well as irregular wave solutions, and thus are applicable to analysis and simulation of nonlinear waves in both categories (Bruhl and Oumeraci, 2016; Mohtat et al. 2018b)). For regular waves, the nonlinear periodic waves are cnoidal waves (in the shallow water case) and Stokes waves (in the intermediate to deep water case) (Mohtat et al., 2020).

A note of caution is in order here. Regular plane waves are stable only up to a limited steepness ratio. For long-duration regular wave generation, as the wave steepness increases, stability of the one spatial-dimension plane waves will deteriorate with time and the wave field may become two dimensional and converge to a stable wave surface consisting of rectangular cells. This nonlinear phenomenon was explained in Henderson et al. (2006) via the stability of the one spatial dimension (third-order) nonlinear Schrodinger equation.

2.1.3 Confinement effects

Wave generation in water of finite depths introduces additional effects relative to that in deep water. Dispersion is depth-dependent, with shorter wavelengths and reduced speed in decreased depths, Newman, (1977), Toffoli et al. (2005). This may lead to spatial variations due to refraction effects unless the bottom is perfectly horizontal and flat. Fully nonlinear solutions for wave propagation over topography are provided in Kennedy and Fenton (1997).

Non-linear wave-wave interactions increase with reduced depth, with sharper peaks but also larger set down effects and corresponding return currents.

In a wave basin, reflections on side walls and wave generator are present, resulting in undesired influence on the required wave field. Waves reflected by the wave absorber at the opposite end of the tank limit the total duration of the test. Once the residual energy reflected by the (imperfect) absorbers and accumulated in tank becomes unacceptably high compared to the wave energy of the spectrum, the experiment shall be terminated. In computing the accumulated energy, the effects of the side wall also have to be accounted for.

Passive wave absorbers suppress the reflections and presents a cost effective feasibility for a wide range of wave tanks. The physical wave absorption mechanism is related to wave breaking and viscous dissipation. These issues were generally addressed by Chakrabarti (1994) and USACE (2002).

An important aspect to improve the efficiency of the wave absorption device is porosity on the surface and inner layers of the devices. Usually, sloped and parabolic beach with porous layers can have good absorption properties for long waves and a wide range of wave steepness by an optimization of the shape and porosity. Studies on this topic are provided by Straub et al. (2011) and Lean (1967).

Most existing wave tanks are of rectangular shaped with straight corners. In case of wave tanks with wave generators on multiple sides, two adjacent sides of wave paddles are used to generate oblique waves for a wide range of incidence angles. The combined movement of the paddles changes the wave crests directions for a continuum wave field generation. However, in the corner there is at least one paddle with restricted movements or blocked to prevent collisions. This discontinuous surface (or singularity) at the corner creates a border effect on the wave field that propagates to the test section of the wave tank. The simplest solution to prevent a discontinuity of the wave field is adopting a gradual movement fader in the paddles corner but this results in an incorrect wave amplitude propagating to the test section. A more complex solution is provided by Matsumoto & Hanzawa (2001) who modified the paddle movement to maintain the wave field stability. An optimization of paddle movements is obtained numerically before the test execution in the tank.

Another option to overcome a discontinuity at the corner is to use a circular layout of wave paddles. In this case, the paddle angle changes gradually connecting the two adjacent sides of the tank. In order to prevent collision between paddles during movements, a gap between paddles is introduced. Normally, a mechanism made by metal strips and fabric connection is used to cover the gap between the paddles.

It is also important to make the transition from the wave generator to the wave absorption parts as smooth as possible, regardless if the wave absorption is active or passive.

2.1.4 Wave frequency and low frequency reflections

In order to limit the effects of confinement on wave generation, wave absorbers are usually employed to suppress or substantially reduce the reflections for the side walls of the tank. As already discussed, sloped and parabolic beaches with porous layers are generally used but their effectiveness in absorbing the incoming wave changes with frequency and steepness.

Theoretical approaches for the design of wave absorption devices in shallow water are provided in Lean (1967) for different bottom shapes. Laboratory tests to measure the absorber performances for different wave absorption solutions when varying wave frequencies and steepness are shown in Straub et al. (2011).

Different techniques to measure the reflection coefficients based on two or three wave probe signals are provided in Isaacson (1991). A technique to separate incoming and reflected waves in a deep water towing tank based on the Doppler shift in frequency domain from a known velocity of a single measuring probe is presented in Drzewiecki and Sulisz (2019).

Particularly for long wave tanks, long and very low frequency oscillations may occur. Such long waves cannot be effectively damped out neither by passive nor active absorbers. Besides the seiche waves, in long wave tanks, circulation may develop. In such cases, the only solution is to wait enough time before starting a new test. The time interval depends on the specifications by the client as well as on the specific test and dimensions of the facility.

2.1.5 Radiation and reflection from model, beaches, etc.

As anticipated, wave reflected from the side walls and/or waves radiated or reflected by the model and subsequently reflected by either the side walls and/or the damping beaches may enter the measuring field.

For instance, in a two-dimensional wave tank, three-dimensional waves, albeit of small amplitude, can be generated due to the interaction with the structure and/or tank walls. The phenomenon is noticeable for single flap wavemakers: in such cases the effect can be suppressed, or at least significantly reduced in a given range of wavelength, by using straighteners in the upstream portion of the tank. Multi-segmented wavemakers, with paddles of small size compared to the tank width, can be properly controlled to suppress the phenomenon. The use of control system also allows suppression of other disturbances (e.g. reflection from the beach, transverse standing wave and reflections from the model test).

Active absorption by the wave generator contributes to reduce these effects. When the model reflects or irradiates waves, it creates standing waves between the wave generator and the model. The interaction of incidence and reflected waves changes the wave field by nonlinear effects, even induces wave breaking. Thus, active absorption in the wave generator is often used to decrease the resonance of standings waves, as presented in a study by de Mello et al. (2013). Similarly, cross–tank waves could occur as standing waves. To prevent such transverse waves, one of the tank sides could be used for passive or active wave absorbers.

The time interval of 20 minutes between subsequent repeats is suggested in ITTC (2014) as acceptable for a typical facility. However, the time interval can be tank specific and it has to be long enough to pitch down the residuary tank disturbance beneath 1% of the next target wave height, as pointed out in the document.

In Van Essen et al. (2014 and 2016) methods to avoid/suppress long standing waves in test facilities are described.

2.1.6 Deviations from ideal conditions

Ideally, a regular wave model would require a unidirectional periodic wave field with amplitude, period and direction constant throughout time and space. In practice, deviations from the ideal situation are observed, for various reasons, which are associated with wavemaker, basin and wave absorbing devices.

Model testing procedures must take these effects into account, in one or several of the following ways: a) avoiding them, b) reducing them, c) documenting them and interpreting their effect on vessel and offshore structure responses.

If the disturbances cannot be suppressed, their effects on the measurements can be reduced by choosing a proper combination of location and time windows. In all cases, reflections or other disturbances have to be measured and documented.

Another important aspect concerns the model scale. When reducing the scale of the problem, and thus the wavelength, the waves are keener to develop natural modulational instability, e.g. Tulin and Waseda (1999). The phenomenon is partly reduced by the increased role played by the viscous dissipation, Ma et al. (2012) but a careful check of accuracy and repeatability of the wave quality is needed when using relatively small scales.

2.2 Irregular waves

2.2.1 Wave spectra

Sea states are generally specified by the short-term variance spectrum *S(f)* or *S(ω)*, where *f* and *ω* are the frequency and the angular frequency respectively. Primary spectral parameters are the significant wave height H_s, defined as $H_s = H_{m0} = 4\sqrt{M_0}$ and a characteristic wave period, e.g. the peak period T_p or the zero-crossing period T_z defined from the spectrum as $T_z = T_{m02} 2\pi\sqrt{M_0/M_2}$, the mean wave period $T_1 = T_{m01} 2\pi\, M_0/M_1$ where M_i is the *i*-th spectral moment (DNV, 2011) defined as

$$M_n = \int_0^\infty \varpi^n\, S(\varpi) d\varpi \qquad (1)$$

$S(\varpi)$ being the power spectral density.

Many widely-used models for the spectrum of waves measured at a point (without regard to wave direction) are of the Bretschneider (1959) form

$$S(f) = \frac{A}{f^5} \exp(-\mathrm{B}/f^4) \qquad (2)$$

where *f* is the frequency and *A* and *B* are constants. Among this class are those referred to as Pierson & Moskowitz (one- and two-parameter forms), see ITTC (1999, 2002, 2017a, and 2017b) and Liu et al. (2018). These presentations differ only with respect to the parameters that are used in determining *A* and *B*.

Other spectra include those related to the basic Bretschneider form, for cases where there is a limited fetch (JONSWAP), a finite water depth (TMA), or a combination of a known wind speed and limited fetch, Mitsuyasu (1972). A specified duration of random simulations is important to achieve stationary irregular wave conditions: typically, a duration of 1 hour (full scale) for seakeeping and 3 hours (full scale) in offshore engineering is applied.

2.2.2 Bi-modal or multi-modal spectra

In some cases the spectrum is characterized by two (or more) energy peaks occurring at different frequencies and/or directions. This is the case when a swell generated remotely, combines with a wind sea generated by a local storm close to the observation point.

Bi-modal spectra, that is, wind-sea plus swell, are recently more frequently specified thanks to improved field data documentation. Bi-modal spectra are generally built by combining different solutions for wind sea and swell. It is typically specified as the sum of two unimodal spectra, or by an integrated formula, with a given set of parameters. Bi-modal spectra commonly used in laboratories include those by Ochi and Hubble (1976) and Torsethaugen (1993). Each component is often modelled unidirectionally, collinear or in different directions, while directional spreading is sometimes included.

2.2.3 Nonlinear effects - analysis and control

Generally, for waves of very low steepness, nonlinear effects are of secondary importance and can be neglected. However, the importance of nonlinear effects increases with increasing wave steepness, in particular for irregular waves, and as a result affect the measured wave spectrum in the wave basin.

In case the wave theory in use is not able to capture all non-linear phenomena and basin effects and the wave spectrum is not correctly reproduced with the required accuracy, a Black-Box approach can be used to account for the effects of nonlinearities. The Black-Box approach is based on calibration of the control signal in the frequency domain using the ratio between the required and realized wave energy spectrum as presented in Drzewiecki (2018).

For second-order nonlinear irregular (random) waves generation for intermediate water depth to deep water conditions, as in the regular wave cases, the method presented by Schäffer (1993) can be used by selecting multiple frequency components. The numerical algorithm will automatically generate a superposition of “clean” second-order Stokes waves containing the fundamental components plus their phase-locked second-order frequency components, Schäffer (1993). Sulisz and Hudspeth (1993) have also developed a complete second-order solution to wave generation in unidimensional wave flumes. A stream function solution approach was developed by Zhang and Schäffer (2007).

The more general higher-order spectral (HOS) method developed by the LHEEA-ECN group, as in the Schäffer case, nonlinear irregular waves of arbitrary order can be generated using the HOS method by selecting multiple wave components. A high degree of accuracy can be achieved using the HOS model, Ducrozet et al. (2016).

As mentioned earlier in the regular wave section, a nonlinear Fourier analysis methodology (NLFA) has been developed to characterize nonlinear irregular waves in arbitrary water depth using the KdV equation for shallow water and the NLS equations for intermediate to deep water. Applications of NLFA to irregular ocean waves are documented in Osborne (2010). In this case, the irregular waves for the shallow water case are a superposition of cnoidal waves plus their nonlinear interaction terms, and the irregular waves for the intermediate to deep water case are a superposition of Stokes waves plus their nonlinear interaction terms (Osborne, 2010).

2.2.4 Distribution of extremes

From linear wave theory under an ideal random sea state, for a narrow-banded wave spectrum, the wave crests follow the Rayleigh distribution (see Longuett-Higgins, 1952). However, because of the nonlinearity of real waves, higher-order effects should be accounted for and thus the Tayfun distribution is more representative for wave heights, Tayfun and Fedele (2007). A probability distribution based on second-order wave simulations was proposed by Forristall (2000), which represents the wave crest distributions of moderately steep short-crested waves quite well.

However, there may be cases in which effects of third and higher order are relevant. It is shown in Buchner et al. (2011) that the tail of the distribution rises substantially when increasing the wave steepness. This result confirms what was found by Onorato et al. (2006 and 2009) who observed that for long-crested, steep and narrow banded waves, the probability of finding an extreme wave can be underestimated by more than one order of magnitude if only second-order theory is considered.

Considering the effect on the wave height and particularly the crest height, a proper account for the higher order effects in large waves is essential for a correct estimate of air gaps, impact loads as well as green water conditions.

Results based on experiments or numerical simulations indicate that higher order effects on wave crests become less important when the directional spreading increases. For very large spreading the distribution of extremes approaches the second-order distribution, DNV-GL (2015) and Toffoli and Bitner-Gregersen (2011).

2.2.5 Short-crested wave modelling

Most likely, the multi-modal sea is also multidirectional. Generally, the swell component is unidirectional with very little directional spreading whereas the wind sea may be characterized by a more substantial directional spreading with the central (peak) direction oriented with a certain angle to the swell. A proper account for all the peaks of the frequency spectrum as well as of the directions of the different wave systems is fundamental for an accurate prediction of the ship response.

A more general and detailed discussion of the laboratory modelling of multi-modal and multi-directional wave spectra is provided in the Guideline 7.5-02-07-01.1, whereas a discussion on the methods generally employed for the measurement of directional seas are reported in the following.

For modelling purposes, the directional characteristics of waves are sometimes assumed to be uncoupled from their spectral properties, and then the spectrum of waves travelling within a given range of headings is taken to be some proportion of that measured at a point. On this basis, the directional spectrum is usually presented in the form

$$S(f,\theta) = S(f)\,G(\theta), \tag{3}$$

where the spreading function G depends only on the direction θ. Its most common form is

$$G(\theta) = F(s)\cos^{2s}[(\theta-\theta_1)/2], \tag{4}$$

where θ_1 is the predominant wave direction, and *s* is an index that determines the width of the directional spread. In other forms of $G(\theta)$, the power *2s* is replaced by *s*, or the argument of the cosine may omit the factor *1/2*. In another approach it can be expressed just in terms of its angular harmonics, see e.g. Frigaard et al., (1997) for further details. The function

$$F(s) = \frac{2^{2s-1}}{\pi}\frac{\Gamma^2(s+1)}{\Gamma(2s+1)}, \quad (5)$$

ensures that the total variance of the directional spectrum $S(f,\theta)$ is the same as that of the point spectrum $S(f)$.

Beside the changes in the distribution of extremes discussed in the previous section, the directional spreading also changes some statistical properties of the waves like skewness and kurtosis, Toffoli et al. (2010).

2.2.6 Wave breaking – influence on statistics and kinematics

In irregular seas, the occurrence of wave breaking limits the maximum steepness and reduces the probability of occurrence of extreme events, Buchner et al. (2011).

In some cases, the occurrence of breaking prevents the achievement of the specific spectrum. In order to overcome this problem, different seeds are used to generate the random phases until a reduction of the breaking occurrence is obtained. However, it can also indicate that the selected theoretical spectrum is not an appropriate representation of the actual wave spectrum at that steepness, i.e. the theoretical input spectrum might not be suitable to describe a very steep sea state with a lot of occurrence wave breaking, as also described in Huang et al. (2018). When performing tests in model scale the increased role played by surface tension changes some of the breaking feature and may affect both the breaking occurrence as well as bubble entrainment.

2.2.7 Geographical consistency of wave spectrum selection

In order to achieve an accurate prediction of the responses of ships or offshore structures to wave loading, it is important that wave spectrum characteristics are correctly reproduced in the laboratory. When performing tests for ships or offshore platforms and devices required to operate in certain regions, it is strongly recommended that the specific wave conditions are employed as long as they are producible.

There is evidence that some places in the world are characterized by specific wave conditions which may be seasonal. Examples of the inter-annual variability of the wind-sea and swell significant wave heights are presented in Semedo et al. (2011) for different Oceans and noticeable differences in Pacific and Atlantic Oceans have been observed. During winter in the Northern Hemisphere, a strong north–south swell propagation pattern is observed in the Atlantic Ocean.

Another very important example is represented by the West Africa region investigated in the WASP-JIP (West Africa Swell Project JIP). The wave spectra at sites off West Africa are dominated by the constant presence of one or more swell wave systems (Olagnon et al. 2013), with swell spectra exhibiting a strong narrowness, both in frequency and direction. Again concerning the seasonal variations Prevosto et al. (2013) show that during the austral winter swells approach the West Africa coast from south to south-westerly direction whereas during the austral summer north-westerly swells are observed.

Several examples are briefly summarized below:

Co-existence of wind seas and swells at different coastal regions in the Indian side of the Arabian Sea and how their relevance varies with the season is presented in Rashmi et al. (2013).

Similar information for the Bohai sea are provided in Wu et al. (1995). It is shown that the Mitsuyasu directional spectrum is the proper choice in fully developed conditions.

In the Yellow Sea, the wave spectrum is mostly unimodal and a specific wave spectrum is provided in Yang et al. (1984).

For the East China Sea, an analysis of the internal structure of waves is provided by Wu et al. (1998) who showed that the measured waves are well represented by the JONSWAP spectrum.

The Campos Basin wave climatology in Brazilian coast was presented in Parente et al. (2017). More general wave climatology for Brazilian coast was presented in Pianca et al. (2010).

For the South China Sea, a spectrum under typhoon is proposed in Lan (1984). Other spectra are proposed in different regions by Chen et al. (1990), Hong-Kong region, Li et al. (1992) for the Beibu Gulf, whereas Shu et al. (2012) recommended a JONSWAP spectra with γ=1.9205 for the coast of Yangxi, Guangdong.

For the North Sea, a bimodal wave spectrum was proposed by Torsethaugen (1993).

For the North Atlantic, a bimodal wave spectrum was proposed by Ochi and Hubble (1976).

The characteristics of the spectrum in the Western Pacific are provided in Fan et al. (1992) and Hemer et al. (2011).

For the Japan sea, a unimodal wave spectrum decaying as f^{-4} was measured by Mori et al. (2002).

For the Pacific Coast of the USA, an extensive data base of short-crested wave spectra is available from NOAA buoy measurements.

2.3 Extreme events

2.3.1 Deterministic generation of extreme waves

There is evidence that extreme events may be responsible for accidents on ships and offshore structures. Although there is not yet a consensus about the probability of occurrence and the extreme waves (also referred to as rogue or freak waves) are not included in the classification society rules and offshore standards, in the last decades there has been a growing interest towards the understanding of such events as well as in their reproduction in laboratories. A review of some research work done on the subject is provided in the DNV-GL position paper, DNV-GL (2015).

Although there is a debate about the physics behind the occurrence of rogue waves in Fedele et al. (2016), a rather reliable technique to generate rogue waves in a specific location and time in a wave basin is proposed in Chabchoub et al. (2012). The technique, developed for unidirectional waves only, is based on a weakly nonlinear formulation and exploits some solutions of the nonlinear Schrödinger equation to form a rogue wave. In particular, the so called Peregrine breather solution is considered. The local free surface elevation is expressed by

$$\eta(x,t) = Re\{\, q_p(x,t)\, \exp[i(k_0 x - \omega_0 t + \varphi]\} \tag{6}$$

where $q(x,t)$ is the equation of the envelope of the Peregrine breather:

$$q_p(x,t) = a_0 \exp\left(-\frac{i k_0^2 a_0^2 \omega_0}{2} t\right) \times \left(1 - \frac{4(1 - i k_0^2 a_0^2 \omega_0 t)}{1 + \left[2\sqrt{2}\, k_0^2 a_0 (x - c_g t)\right]^2 + k_0^4 a_0^4 \omega_0^2 t^2}\right) \tag{7}$$

In the above equations, a_0, ω_0 and k_0 are the amplitude, frequency and wave number, respectively, and c_g is the group velocity which can be estimated as half the phase velocity.

The above solution is valid for deep water. More recently, the solution has been generalized to finite water depth. The solution, which is provided in Onorato et al. (2013), is basically the same as above but the equation of the envelope is a little more complicated:

$$q_p(x,t) = a_0 \exp(-i\beta a_0^2 t) \times \left(\frac{4\alpha(1-i2\beta a_0^2 t)}{\alpha+\alpha(2\beta a_0^2 t)^2+2\beta a_0^2 x^2} - 1\right) \tag{8}$$

where:

$$\alpha = \frac{1}{2\omega_0}\left(c_g^2 - gh\,\mathrm{sech}^2[k_0 h](1 - k_0 h \tanh^2[k_0 h])\right)$$

and

$$\beta = \frac{\omega_0 k_0^2}{2}\left(\frac{8+\cosh[4k_0h]-2\tanh[k_0h]^2}{8\sinh[k_0h]^4} - \frac{\left(2\omega_0\cosh[k_0h]^2+k_0c_g\right)^2}{(k_0\sinh[2k_0h])^2\left(gh-c_g^2\right)}\right)$$

2.3.2 Wave groupness

Although extreme events are very important for estimation of the extreme loading, there is difficulty in using them for design as there is not much indication about the probability of occurrence in DNV-GL (2015). Moreover, not necessarily one single event, although extreme, represent the most critical situation. Considering the coupling of the wave system with the response of the ship for instance, the passage of a wave group with a sequence of a sufficient number of waves of critical height and length may be even more dangerous than a single wave, even if of higher amplitude.

Ocean waves often appear in sequences of wave groups. The response of marine structures on successive wave groups is quite different from regular waves and an isolated wave group.

An interesting study is under development at the University of Michigan in which a large database of field data has been analyzed with the aim of identifying the wave groups in Seyffert et al. (2016). These real time series could then be the basis for generating an ensemble of wave time series, all of which contain wave groups of known runs and probability of occurrence. The study is not yet mature and consolidated to be used as a practical approach for testing, but it seems to be a very interesting and promising direction to follow.

An envelope approach to simulate wave groups was proposed by Xu et al. (1993). Two parameters, i.e. the groupness factor height (GFH) and groupness factor length (GFL) were introduced to represent the group. An empirical wave envelope with given GFH and GFL is proposed in Liu et al. (2013) together with a generation procedure for random waves with determined wave groupness.

2.4 Measurement and analysis of long- and short-crested waves

For unidirectional waves with assigned direction, one wave probe is sufficient. If directional measurements are required, an array of wave probes is needed.

Several approaches can be used to estimate short-crested waves and directional spectrum, differing from each other by the minimum number of wave probes needed and the method of analysis employed. The Maximum Entropy Method (MEM) exploits the similarity between the directional distribution function and a probability density function. There are different versions developed which seem to reproduce multiple spectral peaks reasonably well, but as for parametric models (and all other methods as well), the estimates will be affected by the actual method and the way it is applied. Another widely used group of methods is based on the principle of Maximum Likelihood. It is normally easier to use and more computationally efficient than MEM.

Generally, MEM is more accurate but less robust: it does not always converge to an estimate and in some cases the estimate is far off. The MLM method is more robust (its estimates are never far off) and takes far less time to compute, Van den Berg (2011). The accuracy improves if wave slopes and elevation instead of the point elevation measurements are employed, particularly for a small footprint array.

Another method, based on a complex Morlet wavelet transform, which can be used with just three probes located arbitrarily, was proposed by Donelan et al. (1996). As the data are first resolved in time and frequencies by the wavelet transform, the stratification of the spectral content of the data in the time domain can simplify the directional estimation procedure. Compared with the estimation methods of maximum likelihood (MLM) and maximum entropy (MEM), the wavelet based method could give the best estimation of the directional spectra, Donelan et al. (2015).

Several types of probes can be used to measure the waves: resistive probe, capacitive probe, optical probe, ultrasonic probe, finger probe, as described in Payne (2008). Each of these probes has a different design and operation principle:

The resistive probe consists of two thin metal rods immersed in water in parallel, where the resistance measured between the rods is linearly dependent on the immersion, Clayson (1989).

The capacitive probe consists of two metal rods immersed in water in parallel, where at least one rod is covered with an electrical insulator and the capacitance measured between two mutually insulated rods is linearly dependent on the immersion depth, Clayson (1989).

The ultrasonic probe emits the ultrasonic wave vertically downward, where the time elapsed from emission to the absorption of the ultrasonic wave reflected from the water elevation, is linearly dependent on the distance to water elevation, Payne (2008).

The optical probe consists of the camera and the laser, where the laser spot at the water elevation is captured by the camera and images are processed into a value of wave height based on the triangulation method, Payne (2009).

The finger probe, consist of the servo-drive mechanism tracking the water elevation, where the motions of the mechanism, that correspond to the water elevation, are measured using a servo-drive encoder, Payne (2008).

Each of the indicated solution, has certain advantages and disadvantages. The rods of the resistive and capacitive probes are immersed into water. Therefore, the rods can start vibrating under the wave loads and disturb the measured wave elevation, especially at forward speed. Direct contact with water causes the sediments to settle on the surface of the immersed rods which need to be cleaned regularly. The resistance and capacity between the rods are dependent on the temperature and chemical composition of water and thus it has to be included in the calibration of the wave probes. Consequently, it is recommended to calibrate the probes with cleaned rods in their operating environment and check the calibration regularly. The calibration determines the relation of the probe output signal to the height of the wave profile permeating the rods. The height of the wave profile for calibration is simulated by the vertical immersion of the rods into the water. The calibration has to be performed by measurement of the output signal of probe at enough points of reference immersion depth. The number of points should be large enough to determine a relationship based on a mathematical function with a satisfactory accuracy. The preferred relationship is given by a linear function. The scope of the calibration has to be determined in accordance with the measurement scope of the probes and generation scope of the wave profiles.

The tips of the ultrasonic and optical probes are not in contact with water. Thus, they are not exposed to the water and do not intrude the measured waves. However, the ultrasonic probes have a specified operating range of the wave steepness to be reliable, Payne (2008) and the speed of sound in the air at given temperature and humidity has to be included into calibration.

2.5 Non-stationary power spectrum (time and space)

In recent years, there have been an improved implementation of HOS packages that provide a large database of validation available and the code can be considered matured for engineering practices, Ducrozet et al. (2016). Some of the applications that could be more appealing to the energy industry and deep-water wave modelling are, but not limited to, modulational instabilities, Fernandez et al. (2014) and Toffoli et al. (2010) and freak waves, Ducrozet et al. (2007) and Xiao et al. (2013). It should be noted that HOSM is a strong nonlinear model can include the wave-wave interactions up to a defined order, which is called the order of HOSM. For instance with an order of 3 HOSM model, an accuracy equal to that of Zakharov equation in Zakharov (1968) can be achieved, Sergeeva et al. (2013). Further investigation revealed that an order 6 HOSM model with formulation of West et al. (1987) corresponds to a nearly fully nonlinear model, Clamond et al. (2006).

In the pseudo-spectral method of solution, computation of some of the equations, usually including products of variables, are performed in the physical domain and the rest, usually including the derivatives of the variables, in the Fourier space. This approach exhibits some amazing convergence properties. The addition of a second-order wave maker theory in the HOS-NWT makes this package even more suitable for validation and prediction of the wave conditions. Details of the additional wave maker boundary condition and the solution procedure is well defined in Ducrozet et al. (2012).

Nonlinear ocean wave governed by the KdV for shallow water and the NLS for intermediate to deep water will appear as non-stationary in the linear spectral sense as they contain Stokes waves and breathers (phase-locked Stokes wave modes), both of which contain phase-locked harmonic components. However, the wave modes are stationary when viewed from a nonlinear Fourier analysis perspective (Osborne, 2010).

2.6 Calibration

The wave environment needs to be calibrated prior to the test to ensure the correct environment modelling has been achieved. The effective duration of the wave field with transient part removed needs to be sufficiently long as specified. The required tolerances for wave calibration are usually ±5% for both significant wave height and peak wave period.

The shape of the wave spectrum can be calibrated comparing the measured wave spectrum with the theoretical wave spectrum at the target location in the basin. Correction factors that can be applied to the wavemaker steering signal can be calculated based on the frequency-by-frequency ratio between the measured and required spectrum.

DNV-RP-C205 (2010) recommends to use the Forristall distribution for stationary short-term storms noting that the distribution is based on second-order wave simulations and extremes predicted by this distribution may be on the low side. The criteria of the maximum wave crest for wave calibration test has not been established to date. Huang (2017) and Liu and Zhang (2018) adopted a CFD and a Higher-Order Spectral (HOS) method, respectively, to investigate this subject. They found that third-order nonlinearity should be taken into account when wave calibration is performed for long-crest waves in a wave basin with maximum wave crest being a key criterion. Liu and Zhang (2018) also proposed an empirical model to estimate the maximum wave crest height for wave calibration. It must be noted that the resulting crest height in a 3 hour realization is dependent on the randomly distributed phases. Especially, for very steep sea states the crest distribution of different 3 hour realizations can vary from one another and from theoretical distributions. However, this does not mean that a 3 hour realizations with large deviations from high order distributions can be neglected, but is the result of the random 3 hour realization of a certain sea state. A better representation of the crest distributions of a certain sea state can be achieved by running multiple 3 hour realizations, to fill in the tail of the distribution, see also Huang et al. (2018).

2.7 Interactions with and current and wind

2.7.1 Waves on currents

Theoretically, a perfectly steady current that is collinear with the waves slightly reduces the wave heights and increases the wavelength. Similarly, an opposing current increases the wave heights and reduces the wavelength. The problem becomes more complex in case of a depth-varying current (Ellingsen and Li (2017)) and in the open ocean the wave-current interaction can affect the modulation of the spectrum, the wave breaking rates, and wave statistics (Romero et al. (2017)).

In the ocean, negative horizontal velocity gradients (i.e. an accelerating opposing current or a decelerating following current) make waves shorten and heighten which enhances wave steepness. As a result, a nonlinear mechanism known as modulational instability develops, leading to the formation of large amplitude waves (the so-called rogue waves), even if they would otherwise be unexpected. In Toffoli et al. (2019), laboratory experiments and numerical simulations with a current-modified version of the Euler equations are presented to assess the role of an opposing current in changing the statistical properties of unidirectional random wave fields. Results demonstrate in a consistent and robust manner that an opposing current induces a sharp and rapid transition from weakly to strongly non-Gaussian properties with a consequent increase of the probability of occurrence of rogue waves. The tests were conducted with irregular unidirectional waves in a wave flume and a directional wave basin at Plymouth University. The initial conditions at the wave maker were given in the form of an input JONSWAP-like wave spectrum to model waves in the frequency domain. As the wave field entered into a region of opposing current, the wave height was observed to increase. Evident breaking dissipation was observed for very strong current fields for $U/Cg > 0.3$ (breaking appeared with even less strong currents in the wave basin). The presence of the current also accelerated the downshift of the spectral peak, with energy migrating from high to low frequencies bands within scales of tens of wavelengths, in agreement with modulational instability effects, Onorato et al. (2009). The analysis of the statistical properties of extreme (rogue) waves with an aid of kurtosis, the fourth-order moment of the probability density function of the surface elevation. The kurtosis expresses the probability of extreme events in a record (this assumes the value of 3 for Gaussian sea states). The sea state rapidly transitioned from a weakly to a strongly non-Gaussian condition as current speed increased; maximum values of kurtosis were detected to reach 3.5 or higher, which are remarkably high for water waves. These features were evident in both facilities. However, the wave basin exhibited much higher kurtosis (> 4) than the wave flume. Agreement with numerical simulations confirms that this transformation can be attributed to quasi-resonant nonlinear interactions triggered by the background current.

Generally, the specified wave conditions are calibrated with the current, if current is required for the tested location. If waves are calibrated on current, changes in the wave height and wave length are accounted for and embedded in the resulting wave field. Nonlinear wave-current interaction effects influence the resulting hydrodynamic forces, such as wave drift damping (and corresponding modification in slow-drift excitation), wave-induced currents and wave kinematics.

2.7.2 Waves on wind

In most of the cases, waves are the ultimate effect of the action of the wind over the ocean surface. The wind modifies the kinematics and dynamics of the wave group. In the specific case of extreme waves evolving under the collinear wind, the focus point shifts downstream, Kharif et al. (2008). The airflow separation at the wave crest, beside contributing to the momentum transfer, sustains the steep waves, that subsequently breaks reaching larger steepnesses compared to the no-wind condition, Iafrati et al. (2019).

Aside from specific studies on wind generated waves, e.g. Buckley and Veron (2018), in the most practical applications the wind fetch in laboratory is too short to affect the wave dynamics substantially. In such a case, it is recommended that the wave spectrum has to be chosen to match the open ocean conditions, Babanin et al. (2019).

3. GENERATION TECHNIQUES

3.1 General aspects of wave generation techniques

Many different type of wave makers are in use, typically piston or flap type wave generators with hydraulic or electrical power units suitable for servo-controleld actuation of the wave boards. Through the motion of the wave board at prescribed amplitude and frequencies resulting in a displacement of the water in front of the wave board, progressive waves are generated.

The hydrodynamic transfer function required to calculate the required wave board motions has been deduced by Biesel (1951) and experimentally confirmed, for a piston type wave maker, by Ursell (1959). An overview of the application of the Biesel hydrodynamic transfer function is also given in Schmittner et al. (2013).

Piston type wave makers are typically used in water of finite depth, as the entire water column is moved by the wave maker. And flap type wave maker are typically used in intermediate to deep water. The hinge depth or underwater height of the wave board in combination with the maximum amplitude or angle determine the working range of the wave maker. Wave maker with large hinge depth can generate larger waves. On the other hand, when generating short waves, the mismatch between orbital motions and wave board geometry can become too large, resulting in spurious waves.

The water depth has to be considered accurately to determine the adequate transfer function. Depending on the particular frequency, a slight reduction of water depth of about 5 % might result in a wave height reduction up to 50 %.

Second order or higher order mitigation methods can be applied to reduce the effect of a mismatch between required orbital motions and flap motions. References describing these methods are given in the following sections.

Directional waves can be generated with multi-flap wave makers. For more details on directional wave generation refer to Section 3.3.3 of this guideline. A more general and detailed discussion of the laboratory modelling of multimodal and multi-directional wave spectra is provided in the Guideline 7.5-02-07-01.1

3.2 Regular wave generation

The quality of generated regular waves should be carefully monitored as quality degradation may occur quickly during propagation, Benjamin and Feir (1967) and Stansberg (1993). Also, attention has to be paid to the passive or active wave absorption of the beach and other boundaries. For the generation of regular waves, second-order generation techniques for irregular waves, Sulisz and Hudspeth (1993) and Schäffer (1996) can be used. Although second-order corrections are very important in the case of steep waves, the second-order correction of the flap motions compensate for waves generated due to a mismatch of the flap motion with the wave orbital velocity. This is particularly relevant for very long and shallow water waves.

Depending upon the application, documentation of possible deviations from ideal conditions such as reflections should be made available from the tests, see the 22nd ITTC Report on Environmental Modelling (1999). In the wave analysis, stability in time should also be documented, as well as stability in space whenever relevant.

When regular waves are generated in wave basins, some irregularities may appear due to discontinuities in the paddle distribution. This can be either due to the end of the wave maker or to the transition from the wave making to the wave absorbing paddles. A solution to suppress or mitigate the problem is provided by Matsumoto & Hanzawa (2001) who introduce a specific correction to each paddle movement in order to achieve a more uniform wave field in front of the wave maker. The method is well documented and can be used to different wave maker configurations.

Regular waves of arbitrary order can be generated using the HOS method as described in a series of papers by Ducroset and collaborators (see Ducroset et al. 2007, 2012 and 2016). For the NLS-based regular wave generation in intermediate to deep water conditions proposed by Mohtat et al. (2020) by restricting the total number of nonlinear modes to just one.

3.3 Irregular wave generation

3.3.1 Unidirectional wave generation

Unidirectional (or long-crested, 2D) irregular waves are frequently used in most model basins not only because they represent real seastates in a very simple form, but also because it is assumed that they result in conservative loadings and responses compared to short-crested (directional) seas. It is also easier to define a sea state in a unique manner.

In the generation of 2D irregular waves, it is important to maintain “true” randomness that will prevent unrealistic repetition of the waves.

Also, careful attention should be given to the effects of the frequency range covered by the servo system. The test duration and the number of frequency components adopted are also important if proper natural statistics of the wave field are to be reproduced. Wave reflection from the beach and diffraction by the basin walls should be monitored carefully.

Linear irregular random waves can be modelled as a summation of sinusoidal wave components or as filtering of white noise.

The linear long-crested wave model with the summation of sinusoidal wave components is given by:

$$\eta(t) = \sum_{k=1}^{N} A_k \cos(\varpi_k t + \varepsilon_k) \quad (9)$$

where ε_k are random phases uniformly, identically and independently distributed between 0 and 2π, i.e., mutually independent of each other and of the random amplitudes A_k which can be given by

$$E[A_k^2] = 2S(\varpi_k)\Delta\varpi_k \quad (10)$$

where $S(\varpi_k)$ is the wave spectrum, and $\Delta\varpi_k = \varpi_k - \varpi_{k-1}$ is the difference between successive frequencies.

No recommended procedure for determining the upper and lower cut-off frequencies has been agreed. One has to minimize the effect of this truncation by carefully selecting the model scale for a given spectrum and wave machine. High frequency truncation lowers the mean period, reduces the bandwidth and is known to affect the slow drift motion due to wave-wave interaction (induced by difference frequency effects).

Increasing the number of frequency components increases the frequency resolution and improves the statistical representation of the waves. The longer the duration of wave generation (determined by the nature of the model tests), the more frequency components are needed. The specified duration of random simulations is important, normally 3 hours (full scale) for modelling a full storm, which is most often used in offshore engineering tests. It can be changed depending on the phenomena the test is focusing on, however it must be long enough to realize statistical properties if nonlinearities and extremes are to be studied. For seakeeping tests, at least 100~200 waves have traditionally been used (typically 0.5~1 hour, full scale), which is often defined as satisfactory if linear effects only are considered.

The lowest frequency interval $\Delta\varpi$ can be determined by $\Delta\varpi = \frac{2\pi}{T}$, where T is the duration. The number of frequencies to simulate for a typical short term sea state should be at least 1000 (DNV, 2010).

For second-order irregular wave generation, the methodology proposed by Schäffer (1996), and later enhanced by Schäffer and Jakobsen (2003), and the one proposed by Sulisz and Hudspeth (1993) can be used. For higher-order irregular wave generation, the HOS method by Ducrozet et al. (2007, 2016) is applicable. For nonlinear intermediate to deep-water waves generation governed by the NLS, the methodology proposed by Mohtat et al. (2020) is useful.

3.3.2 White noise approach

Another approach to generate irregular sea states is to use a digital white noise *w(t)*, characterized by a density content *W(f)*. By definition, the power spectral density of white noise is $S_w(f)$ = 1. An example is provided in Cuong et al. (1982) which is briefly summarized below.

Given the characteristic function of the wave generator, *H(f)*, the problem is to find a function *y(t)* to be used as input to the wave maker in order to obtain the desired spectral density function to be realized, $S_z(f)$. The idea behind the white noise generation approach is that the function *y(t)* can be obtained from *w(t)* through a specific filter *Q(f)*. The filter *Q(f)* may be viewed as the inverse of that needed for whitening the function *y(t)*.

Hence, if *Z*(f) is the desired frequency content of the wave system to be generated, it is obtained as:

$$Z(f) = H(f) \cdot Q(f) \cdot W(f)$$

and thus the frequency content of *y(t)* is

$$Y(f) = Q(f) \cdot W(f)$$

Correspondingly, the spectral density functions are related by:

$$S_z(f) = |H(f)|^2 |Q(f)|^2 S_w(f)$$

As already stated, $S_w(f)$ can be assumed to be unity and then:

$$S_z(f) = |H(f)|^2 |Q(f)|^2$$

which leads to:

$$|Q(f)|^2 = \frac{S_z(f)}{|H(f)|^2}$$

By introducing the additional constraint that *Q(f)* has to be a real function, the above equation finally provides

$$Q(f) = \frac{\sqrt{S_z(f)}}{|H(f)|}$$

and then:

$$Y(f) = \frac{\sqrt{S_z(f)}}{|H(f)|} W(f)$$

which represents the Fourier transform of the wave maker control time history.

The white noise approach has the advantage of generating non-repeating records.

3.3.3 Directional wave generation

Many basins now use multi-directional wave generators to achieve more realistic wave environments. Wave generators usually consist of many small wave boards, which can be controlled independently by electric or electric-hydraulic actuators.

Due to the effects of the Biesel limit on the size of the wave board, Biesel (1954) and reflection from the walls, wave characteristics in the test region need to be carefully determined. As a reference, the relation of the length of each element of wave makers and the angle of emission of waves is practically shown as follows:

$$l = \frac{\lambda}{\sqrt{2} + \sin\theta}$$

Here, l is the length of each element of wave makers, λ is the generated wave length and θ is the angle of emission of waves.

Modelling directional spectra in the laboratory is generally associated with a significant random scatter, especially in the finer features of the measurements. This reflects features of real sea data, reflecting natural statistical scatter, Stansberg (1998). Therefore, a robust description of the directional sea conditions is often restricted to a few parameters only, such as mean direction, directional spread, and a simple shape parameter that expresses the bimodality such as skewness and kurtosis, see Kuik et al. (1988) and Stansberg (2001), or simplified smooth parametric models such as the $\cos^{2s}(\theta)$ model.

For second-order directional wave generation the method by Schäffer and Steenberg (2003) can be used. Ducrozet et al. (2007, 2016) also have developed open-source HOS numerical codes for directional wave generation. Currently there are no known wavemaker theory for extensions of the NLS equation to directional wave generation, which is governed by the Davey-Stewartson equation (see Davey and Stewartson (1974) and Osborne (2010)).

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