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ON THE EVOLUTION OF TECHNIQUES USED FOR REALISTIC SIMULATION OF WAVES IN LABORATORIES

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ABSTRACT

Wave simulation techniques have evolved significantly over the last three decades that it is now possible to simulate realistic sea states inside laboratory facilities for testing purposes. This capability has led to improved designs of coastal and ocean structures. A review of the evolution of these wave simulation techniques is presented in this paper.

KEWORDS: WAVE SIMULATION, MULTIDIRECTIONAL WAVES, NON-LINEAR WAVES, WAVE REFLECTIONS, ACTIVE WAVE ABSORPTION

1 INTRODUCTION

For some time now, experts have been predicting that physical models will disappear with the growth of numerical modelling techniques. However, in spite of the impressive advances achieved in the field of numerical models, physical modelling still remains as the preferred technique for optimizing designs of coastal and ocean structures. It can also be claimed that many marine structures are being constructed in locations where more and more complex sea state environments exist. For such locations, the use of numerical modelling capabilities still remains limited. In some cases even if the numerical models provide more or less reliable designs, physical models are also used to validate or to calibrate them.

With advances made in wave theory, coupled with advances in control and electronic systems, it is now possible to simulate most of the well known features of the natural waves within the laboratory facilities. This type of simulation is necessitated by the fact that there is now a requirement for the waves reproduced within a laboratory facility to correspond as much as possible to the waves encountered in nature. In other words there is a now an expectation to simulate what is called as "realistic sea states". This expectation has in turn led to requirements to achieve a better understanding of the natural sea sates by using appropriate wave parameters that can provide a comprehensive description of those sea states. In parallel, advances in wave analysis techniques have also been achieved in order to make sure that the desired sea states are indeed well simulated.

Some of the developments in wave generation and analysis techniques have been made possible by international collaboration between members of some of the leading testing laboratories, either on an individual basis or sponsored by organisations such as ASCE (American Society of Civil Engineers), COASTLAB network, COPRI (Coasts, Oceans, Ports, and Rivers Institute) of the ASCE, IAHR (International Association for Hydro-Environment Engineering and Research, *(formerly known as International Association for Hydraulic Research*), ITTC (International Towing Tank Conference) etc. Since the early eighties, the Maritime Hydraulics Section of IAHR has been quite active in promoting collaborations between leading laboratories and in publicising some of the pioneering work that resulted from them in large international conferences (e.g. IAHR (1987, 1997) , Goda et al (1993)).

Prototype wave measurements have also seen significant advances because of this evolution in wave simulations. Sophisticated wave sensors such as directional wave buoys (e.g. TRIAXYS Buoy, GPS buoys etc), coupled with a substantial increase in prototype measurement programs in different parts of the world, are now helping to achieve the ultimate goal of realistic wave generation in laboratory wave basins. This paper briefly describes the evolution of some of the key developments that have been achieved to replicate the natural waves in laboratory facilities. The readers are also asked to refer to Mansard and Miles (2010) for more details on some of the key achievements made in this field. Some of the illustrations and descriptions presented in this paper were extracted from that publication.

2 ADVANCES IN SIMULATION OF WAVES

Laboratory testing of marine structures started initially using regular waves of different periods and heights. Numerous research and practical studies were successfully carried out using regular waves, which led to design criteria for many types of structures. Subsequently, with advances made in control system theory and in computer resources, it was possible to simulate the irregular nature of the ocean waves, for testing purposes. This development was then followed by the incorporation of the directional characteristics of the ocean waves in the simulations. Also, in order to account for situations where wave heights are large or where the depth of water is shallow (i.e. where waves are non-linear), second order wave generation techniques have been developed. A review of the advances achieved in this field of wave simulation is briefly described below.

3 SIMULATION OF UNIDIRECTIONAL WAVES

3.1 Wave Generation

Generally, the sea state to be simulated in a physical model investigation is characterised by its significant wave height, peak period and a parametric spectrum. Some of the commonly used parametric spectra include: Bretschneider spectrum, Pierson Moskowitz spectrum, JONSWAP spectrum, Scott Spectrum, Ochi and Hubble spectrum and TMA spectrum. Mansard and Miles (2010) briefly describe the situations for which each of these spectra is appropriate.

Once the spectrum is chosen, a time series of the water surface elevation is synthesised from it, by using techniques known as random phase spectrum method or random complex spectrum method. The most commonly used technique amongst these two is the random phase spectrum method which consists of pairing the amplitude spectrum derived from the parametric spectrum with a phase spectrum created by a random number generator. A time series of water surface elevation of desired length is then obtained by Inverse Fourier Transform. In the random complex spectrum method of synthesis, first a Gaussian distributed white noise complex spectrum with a standard deviation of 1 is created, and then filtered using the amplitude spectrum derived for the chosen parametric spectrum. Subsequent inverse Fourier transform results in a time series of desired length. Each of these methods has its own proponents and the rationale associated with these methods is discussed in Funke and Mansard (1987).

One of the requirements during the synthesis of a time series of the water surface elevation is the choice of the length of time series, which in turn is linked to the number of waves contained in that time series. Ideally, one would like to have an optimal length of time series that provides a good statistical distribution of wave heights and at the same time keeps the aggregate testing time in the model reasonable.

In some situations, instead of using a parametric spectrum in the synthesis procedure, wave spectrum measured in nature can also used. But in this case, a reasonably large amount of prototype data is desirable in order to produce an average spectrum that is representative of the site. Alternatively, time series of water surface elevation measured in nature could also be used directly, provided that there is again enough data to provide a representative input for testing purposes. Reproduction of prototype of wave trains is also a preferred methodology if there is a requirement to recreate a specific situation, such as damage incurred by a structure.

The next step in the wave generation process is the preparation of a command signal to drive the wave machine in order to produce the desired time series of water surface elevation. The correct reproduction of this time series depends on the accuracy of transfer functions used for converting a time series of the water surface elevation into a time series of wave machine control signal. While the classical hydrodynamic transfer function, known as Biésel relationship, is well known for computing the wave board displacement required to produce a desired wave height, the transfer function of the associated components within the wave generator system such as the servo controller and digital to analog filter have to be established correctly. The NRC (National Research Council of Canada) uses a dynamic calibration procedure to establish and compensate for the dynamic response of the wave machine. More details on this calibration procedure could be found in Mansard and Miles (2010). Once the wave machine control signal is created, real time control and data acquisition systems are used to generate the waves and to sample the data measured by the wave sensors.

3.2 Wave Analysis

Figure 1 shows a classical wave analysis output of NRC from the data measured by one of the water level gauges deployed in a test program. It displays the time series of the measured waves, its spectrum and the probability distribution of the measured wave heights along with some relevant parameters derived by spectral and zero crossing analyses. In the same figure, the target JONSWAP spectrum and the theoretical Rayleigh distribution of wave heights are also overlaid for comparison purposes. The notations of these parameters and their definitions can be found in IAHR/PIANC (1986). They follow the recommendations of an International Working Group sponsored by the IAHR (see IAHR (1987)). Many other parameters considered to be relevant to provide a comprehensive description of sea states are also included in that publication.

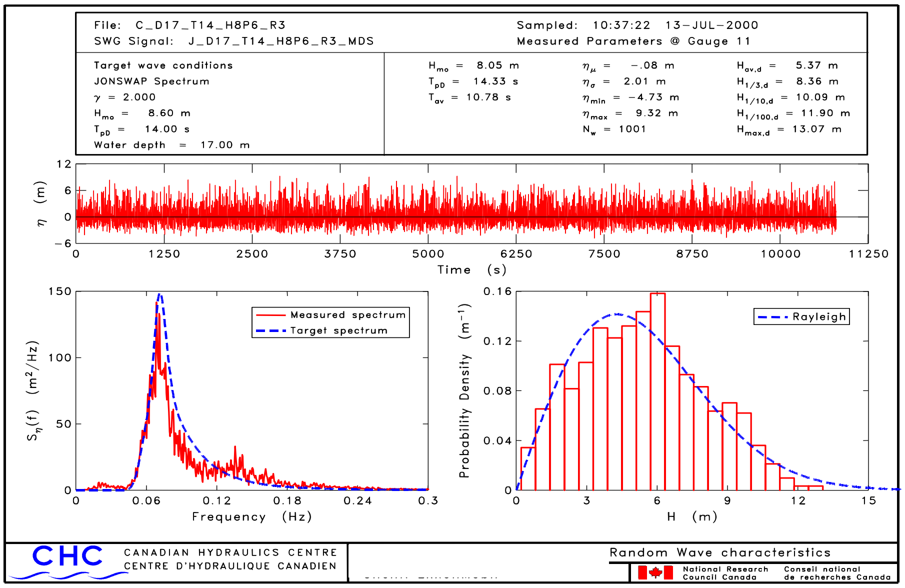

Figure 1. Sample analysis output of unidirectional waves

The comparison between the desired JONSWAP spectrum and the measured spectrum shown in this figure displays some non-linear components in the high and low frequency domains. These are called super-and sub-harmonics respectively. Correct simulation of these harmonics requires a second order wave generation technique. This technique will be discussed in one of the subsequent sections.

3.3 Reflection Analysis of Waves

In order to ensure a good simulation of sea states, it is also essential that the reflections emanating from the wave absorbers installed in the facility be kept minimal. Therefore reflection analysis technique is one of important tools used in laboratories to design an efficient of wave absorber that can dissipate the wave energy produced by the generator. This analysis is also useful to estimate waves reflected by test structures.

This analysis technique has also seen improvements over the years. One of the first methods of reflection analysis for irregular waves was proposed by Goda and Suzuki (1976). This method was based on simultaneous measurements of the co-existing waves (sum of incident and reflected waves) at two known positions in the flume along the length of the flume. In 1980, a least squares technique that uses simultaneous measurements of the co-existing waves in three positions was proposed to estimate the reflected wave components (see Mansard and Funke (1980)), through cross-spectral analysis. This technique validated extensively through numerical simulations and physical model tests, provided a more accurate estimation of the incident and reflected components. However, since this technique was based on frequency domain analysis, it was later extended to estimate the time domain characteristics of the incident and reflected wave components as well. Numerical and physical model investigations have confirmed that this least squares technique could reliably be used to estimate the time domain parameters of the incident waves, such as the statistics of the wave heights and the degree of grouping (see Mansard (1994)).

3.4 Active Wave Absorption

As indicated above, it is now possible to estimate the incident and reflected wave components of unidirectional waves in an accurate fashion. However, the wave components reflected by the test structures and/or by the wave absorbers would propagate back to the wave generator and get re-reflected by it, thus superimposing themselves onto the sea state that is being simulated. This process will greatly reduce the accuracy of the test results and cause a build-up of energy within the facility. In order to overcome this limitation, designs of wave generator, that can simultaneously generate the desired waves as well as absorb any reflected components that propagate back towards the wave generator, have been conceived. The technique used for this purpose is called Active Wave Absorption (AWA).

Some early examples of active wave absorption systems are described in Hirakuchi et al (1990) and Schäffer et al (1994). The methodology adopted in these systems uses a water surface elevation gauge mounted on or near the wave board. The measured wave elevation is used as a feedback in the main servo control loop to produce appropriate wave board motion. Another system uses dynamic force on the wave board for the feedback signal instead of the water surface elevation (see

Salter 1984). One of NRC's flumes was also equipped with active wave absorption, based on a wave elevation sensor mounted on the wave paddle. However, there are several limitations with the methods that use wave elevation or wave force sensors. Some of these limitations include: necessity to maintain adequate stability in the main servo control loop, phase errors that may occur because the wave board actuator may not have enough time to react to the incoming waves and limitation on the accuracy because of simplified assumptions on certain hydrodynamic effects such as evanescent waves.

In order to overcome these limitations, the NRC developed a new technique that is based on the reflection analysis method described in the earlier section. It estimates in real time the wave train propagating towards the paddle. The set of three gauges required by the least squares reflection analysis is installed a few metres in front of the wave generator. A special set up consisting of a wave flume with wave generators at both extremities of the flume was used for validating this technique over a large range of sea state parameters. Figure 2 shows the layout of his special wave flume.

Instead of using a test structure for generating reflection, Wave machine A was installed at the left end of the flume. Wave machine B acted as the wave generator as well as active wave absorber. The wave train propagating towards the wave machine B, computed by the real-time reflection analysis is propagated to the wave board position and converted to the corresponding wave board motion drive signal required to absorb it. This conversion is similar to the calculation of the wave board motion required to generate the desired waves, but the resulting signal is of opposite sign. The two drive signals are then added to so that the desired waves are generated while the reflected wave components are absorbed simultaneously. This particular system provides an easy and convenient way to add active wave absorption to an existing wave machine since the original servo controller incorporated in that wave machine control system could still be used.

NRC also developed a new digital active wave absorption system which is applicable for segmented wave generators as well. It uses a wave gauge mounted on the wave paddle. This system uses two drive signals which define the paddle motion for wave generation and the expected elevation at the gauge including the evanescent component. The controller subtracts the expected wave elevation from the measured wave elevation to obtain the elevation of the incoming wave to be absorbed. This digital servo control system is carefully designed and tuned so that there is very little phase lag over the full frequency range because the paddle motion must respond immediately to the measured incoming field. The control system compensates also for the amplitude and phases of the evanescent waves. This method was also tested in the special flume described above. Some of the results of the validation tests for both these methodologies can be seen in Mansard and Miles (2010).

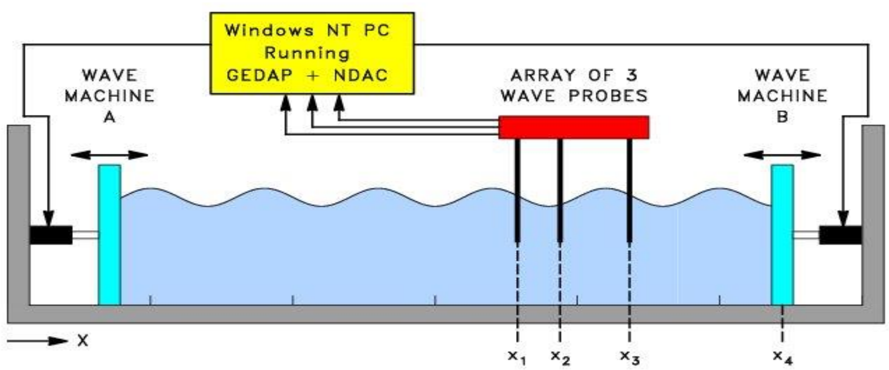

Figure 2. Layout of the special wave flume for validation of active wave absorption techniques

This capability of active wave absorption also helps to still the basin oscillations in between the tests. Figure 3 presents an example of the influence of Active Wave Absorption in terms of stilling a flume**.** The time series shown here is a part of the wave train synthesized form a JONSWAP spectrum.

The two curves show the elevations measured by a gauge when the active absorption was turned off and also when it was turned on. During these tests, the wave generation was stopped at t = 100s. Data was sampled for another 260 seconds. The two measured wave trains are almost identical for this first 100s, which means that the AWA has accurately identified that there is virtually no incoming waves to absorb during that period. The periods from 100 to 160s consists mainly the first reflection of waves by the generator A (see Figure 1). During this period, the AWA ON wave height is approximately half as large as the AWA OFF, indicating the good absorption when AWA is on. Finally a comparison of the results for the period 160 to 360s shows that the AWA system has very effectively reduced the residual wave energy in the flume.

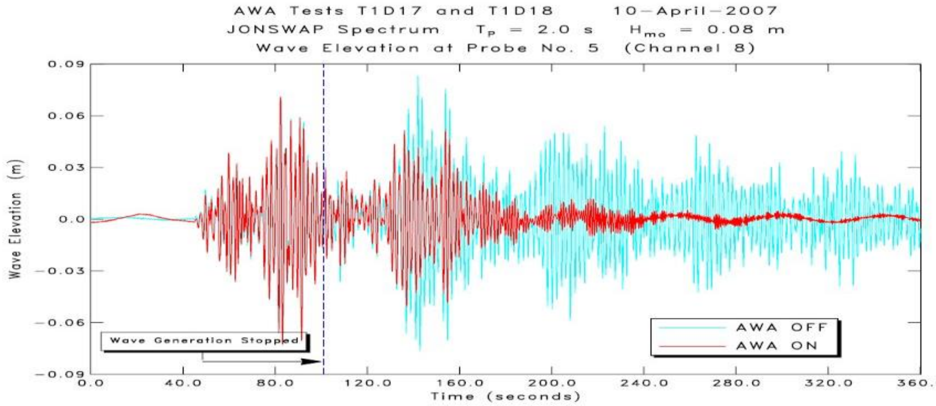

Figure 3. Validation of the active wave absorption technique

3.5 Simulations of Non-Linear Waves

For most engineering problems, the wave generation and analysis techniques based on first order (or linear theory) are often adequate. But when the wave heights are large or when the water depth is shallow, a 2^{nd} order theory would be required to ensure a correct simulation of sea states. By extending the Laplace Equation which is commonly used to describe waves up to 2^{nd} order, additional terms known as sub- and super-harmonics could be derived. These harmonies are characterized as bound harmonics since they travel locked to the 1^{st} order or primary components that created them through interaction process. The bound sub-harmonics (known also as bounded long waves) cause a set-down of the mean water level under wave groups and a set-up in between the groups. On the other hand, the super-harmonics cause a sharpening of wave crests and flattening of wave troughs. Researchers such as Mansard and Pratte (1982) and Mansard et al (1988) provide a convincing rationale to include these non-linear components in numerical and physical models in order to get reliable results. However, since these harmonics travel locked to the 1^{st} order components, it is not possible to generate them directly in the physical model facilities by using the classical 1^{st} order wave generation methods.

An international collaboration between the Danish Hydraulic Institute, the Delft Hydraulics and the National Research Council of Canada led to the formulation of an appropriate wave machine control signal to correctly reproduce a wave train with its bound sub-harmonics. Experimental validation was also carried out to ensure that the bounded long wave is correctly reproduced. Barthel et al (1983) gives an overview of the theoretical developments and the experimental validation.

Subsequently an international collaboration between the Danish Hydraulic Institute and the National Research Council of Canada led to the development of techniques for the description and correct reproduction of non-linear super- harmonics. Experimental validation was also carried to ensure the correct reproduction of these super-harmonics in laboratory flumes (Sand and Mansard (1986)).

Similar investigations on the correct reproduction of these harmonics were also undertaken by researchers such as Van Leeuwen & Klopman (1996) and Schäffer (1996). Schäffer derived a full second order wave maker theory in a unifying and compact form that includes both super-harmonics and sub-harmonics for rotational as well as translatory wave board motions. In addition to the well known transfer functions related to the generation of waves, some new terms were included by Schäffer. These are related to the first order local disturbances (evanescent modes) which become significant when the wave board motion makes a poor fit to the velocity profile of the desired progressive wave component This is typically the case for the high-frequency part of a primary wave spectrum when using a piston type wave maker The expressions given by Schäffer (1996) are in a relatively simple form and make the practical computation of second order wave maker control signals for irregular waves easy. The theoretical developments were verified experimentally using regular waves, wave groups and irregular waves generated by a piston type of wave generator.

4 SIMULATION OF MULTIDIRECTIONAL WAVES

4.1 Generation of Multidirectional Waves

Simulation of multidirectional waves (also known as 3D waves or short-crested seas) could be considered as the next major development in the realistic of simulation of sea states. One of the main reasons for the evolution of this capability is the evidence that laboratory testing of structures using 2D waves may result either in an over- or under-design of the structures, depending on the type of test structures. For instance, in studies of long structures, such as forces on storm surge barriers, the 2D waves produced overly conservative results, but for structures such as single point moorings, vessel motions and the resulting forces on various connecting links were found to be higher under 3D waves. An extensive comparison of test results obtained by both 2D and 3D waves can be found in Funke and Mansard (1992). These results led to the conclusion that testing under 3D waves would result in more accurate designs of structures from safety and economic points of view. Because of such conclusions, there has been a rapid increase in the number of 3D facilities around the world. An international survey conducted under the auspices of IAHR in 1993 showed that already more than 40 facilities were operational in nineteen different countries (see Mansard et al, 1997). A brief discussion of the advances made in the simulation of multidirectional seas is given below.

The multidirectional spectral density of a sea state is given by:

$$S(f,\theta) = S(f).D(f,\theta) \qquad (1)$$

Where *S(f)* is a spectral density and *D(f,θ)* is the directional spreading function satisfying the relationship.

$$\int_0^{2\pi} D(f,\theta)d\theta = 1 \qquad (2)$$

The main step involved in the generation of multidirectional seas is the choice of a directional spreading function, which describes the mean direction and the angular distribution of energy.

The most commonly used spreading function is of the following form where Γ is the gamma function, θ_0 is the mean wave direction, and s is the spreading index. This function can either be the same for all frequencies or the parameters θ_0 and *s* may vary with frequency.

$$D(f,\theta) = \frac{\Gamma(s+1)}{\sqrt{\pi}\,\Gamma(s+1/2)} \cos^{2s}(\theta-\theta_0) \quad \text{for } |\theta-\theta_0| < \pi/2 \qquad (3)$$

Figure 4 shows an example of a directional spreading function, which is non-uniform over the different frequency ranges.

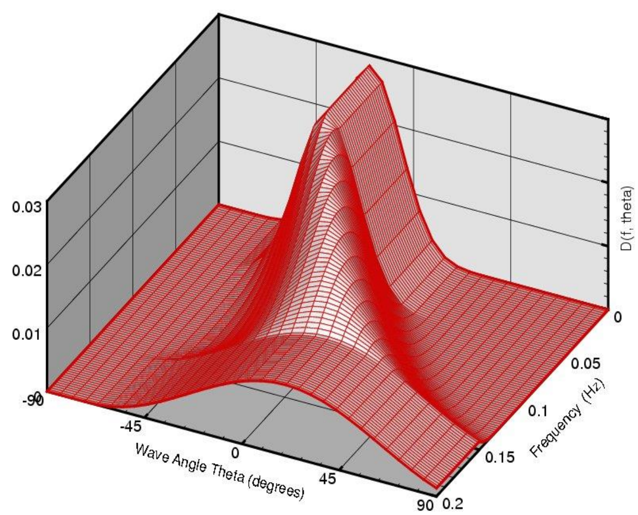

Figure 4 Example of a non-uniform spreading function

Several techniques can be used to synthesize a time series from the directional spectral density given by the equation 1. Amongst them, the most commonly used techniques are the Single Summation and Double Summation Models. In the Single Summation Model, each frequency component can only travel in one direction, thus ensuring a spatially homogeneous field in the basin for typical record lengths used in laboratory testing. On the other hand, in Double Summation Model multiple wave directions exist at each discrete frequency resulting in a non-homogeneous wave field in the test section. Details of these two models and an extensive discussion on their advantages and limitations can be found in publications such as Jefferys (1987) and Miles & Funke (1989). Amongst these two models, many laboratories prefer the use of the Single Summation Model, A multidirectional wave train could also be synthesized by combining a unidirectional wave record *η (t)* and a target spreading function. Alternatively, a time series of the water surface elevation *η (t)* and its associated orthogonal velocities *u (t)* & *v (t)* can also be used directly in the wave synthesis, since the values of *u (t)* & *v (t)* describe adequately the directional characteristics of the waves.

The water surface elevation generated by any of these methods is then used to compute the required paddle motions based on the snake principle method described in Sand & Mynett (1987). These paddle motions are then compensated for dynamic and static transfer functions to ensure the generation of multidirectional waves in the 3D basin.

It is however difficult to guarantee a homogeneous 3D surface in all parts of the basin because of local effects caused by processes such as wave reflection and wave diffraction. In fact for certain combination of wave periods and spreading function parameters, the homogeneous surface where reliable testing could be carried out may turn out to be quite limited. Because of this difficulty authors such as Funke and Miles (1987) and Dalrymple (1989) have advanced the concept of sidewall reflections to increase the potential area for testing (see Mansard et al (1992)).

Identification of test area where the sea state would be homogeneous is therefore a priority in every test program that uses 3D waves. NRC uses for this purpose a linear boundary element diffraction model that can predict the wave fields generated by a segmented wave generator in a basin of constant depth with fully or partially reflecting walls and end absorbers. This model called as WAGEN, was originally developed by Isaacson and Qu (1990) for the case of oblique unidirectional regular waves generated by one or more segmented wave machines in a basin of constant depth. This model was subsequently extended by NRC to cover the case of multidirectional irregular waves and wave machines with active wave absorption. It uses an iterative technique to compute the primary wave field and the secondary wave fields produced by partial reflection of the primary waves from the passive wave absorbers in the basin as well as the re-reflection of any incident waves from the segmented wave generators. One of the examples of the results obtained through this model is given below.

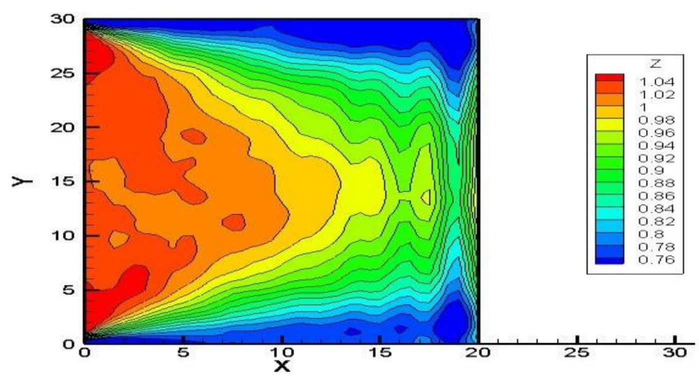

Figure 5 Normalized significant wave heights for irregular multidirectional waves

A contour plot of the normalized significant wave height computed by WAGEN for the case of a multidirectional JONSWAP spectrum with a spreading width of σ_θ = 30 degrees and a mean direction of 0 degrees is shown in Figure 5. The segmented wave generator is located on the left side of this basin and passive absorbers with a reflection coefficient of 0.1 are installed on the other three sides. These results show a useful working area about 5 m by 5 m at the centre of the basin where the wave height is quite homogeneous but there are large variations in other parts of the basin due primarily to diffraction.

4.2 Multidirectional Wave Analysis

Analysis of multidirectional waves has also seen significant advances in the last two decades. Some of the methods of wave analysis commonly used include: Fourier Decomposition Method, Fitting of Parametric Models, Maximum Likelihood Methods, Maximum Entropy Methods, Bayesian Directional Method, and Deterministic Analysis Methods. Amongst these methods, the Maximum Likelihood Method (MLM) and Maximum Entropy Method (MEM) are those that are commonly used. The instrumentation that best corresponds to these methods is either a wave gauge array or a *η-u-v* sensor.

An international working group was established by the IAHR in order to identify the various methods used for wave analysis and to assess the limits and advantages of these methods. The results of their findings are published in Benoit et al (1997). The NRC technique developed by Nwogu et al (1987), and based on MEM technique using *η-u-v* data, was found by Benoit et al (1997) to be superior to other methods. Therefore this method was extended by adapting it to work with data from an array of wave gauges, partly because of the fact the current meters used for estimation of u and v velocity components could be more expensive than wave gauges and also susceptible to errors caused by contamination of the current-turbulent fluctuations produced at the same frequencies as the wave induced kinematics. The wave gauge array consisted of five gauges arranged in a trapezoidal fashion and the water surface elevation data from the gauge array was used to resolve the directional characteristics of the sea state. More recently, this method was modified to use the wave slopes derived from the water surface elevation measured by these gauges in the MEM analysis rather than using directly the water surface elevations. This modification was triggered by the fact that the previous method was efficient only over a limited frequency range where the energy contained in the spectrum was substantial. Computational effort in terms of convergence of solution was also relatively high. It was also sensitive to some extent, to the spacing between gauges. The new method, is analogous to the *η-u-v* method since it uses the water surface elevation *η*, and the orthogonal surface slopes $\frac{d\eta}{dx}$ and $\frac{d\eta}{dy}$.

The layout of the 5 gauge array used for this purpose was such that 4 gauges known as gauges A, B, C and D were located on the circumference of a circle having a radius R, and the 5th gauge known as gauge E was located in the centre of the circle. The water surface elevation was obtained from Gauge E, while the orthogonal slopes $\frac{d\eta}{dx}$ and $\frac{d\eta}{dy}$ are derived from the wave elevation differences between gauges A & C and gauges B & D respectively. This method was validated through numerical simulations.

Following the good performance of *5-η MEM*, additional investigations were undertaken to establish the accuracy of the analysis if only 4 gauges were used instead of 5. In this case, the water surface elevations from gauges A, B, C & D were averaged rather than using the information from gauge E. Results of numerical validation showed that the 4-gauge array is quite adequate for resolving the directional characteristics of the sea states. Extensive investigations were carried out to validate the *4-η MEM* method through basin tests. It was concluded that this method performs well (see Cornett et al, 2005).

The optimal gauge spacing required (i.e. value of R) as a function of the peak period wave length (Lp) in order to offer reliable results was also investigated through numerical simulations. The results of these investigations suggested that a value of $R/Lp \approx 0.02$ would be adequate to yield reliable results. More details on these investigations can be found in Cornett et al (2005).

4.3 Non-Linear Multidirectional Waves

A complete second-order wave maker theory for the generation of multidirectional waves with capabilities for correctly reproducing the non-linear wave components present in a 3D sea have been proposed by Schäffer and Steenberg (2003). The wave maker theory used for this purpose is a 3D extension of the full second order wave maker theory for wave flumes proposed in Schäffer (1996). This theoretical formulation, apart from being restricted by the usual limitations of the Stokes theory, uses no additional assumptions such as shallow water, small evanescent –mode interactions or narrow band spectra. The theory is valid for a rotational as well as translatory snake-type wave board motions. The primary goal was to obtain a prescribed multidirectional irregular wave held correct to second order, i.e. with no spurious free-wave generation. The theory could also be used to predict the spurring long waves that may exist in a 3D sea if only the first order wave generation is used.

4.4 Active Absorption of 3D Waves

Techniques are also available to perform active wave absorption of 3D seas. Under the auspices of IAHR, a review of multidirectional active wave absorption methods was undertaken, and a summary of the findings was summarised by Schäffer and Klopman (1997). In that review, Quasi 3D systems and Fully 3D systems used for performing multidirectional wave absorption are discussed. A brief description of these systems is given below.

Quasi 3D system is implemented by incorporating a prescribed wave angle to the waves propagating towards the wave generator without using a real time system that can detect the wave directionality. However, this quasi 3D system represents a tremendous improvement over traditional multidirectional wave generation with no absorption. The absorption characteristics are quite good even for angles with some deviation from the prescribed angle, since the amplitude varies as cos(θ).

In the fully 3D systems, the systems are able to discriminate waves from different directions, improving the absorption ability for oblique waves. The contributions to fully 3D systems have been published by several authors and a review of these contributions can be found in Schäffer and Klopman (1997).

In 2001, Schaffer outlined a theory for 2D and 3D active wave absorption in Fourier space and the principles of approximate time-space realisation were given. An analysis method by which the system checks its own performance was derived and the performance of the technique was demonstrated for a wave flume case. For AWA of oblique waves a qualitative test gave promising results (Schäffer, 2001).

NRC has successfully implemented Active Wave Absorption (AWA) for 2D irregular waves in its 3D facility. Each segment of the multidirectional wave generator is equipped with a wave gauge for measuring the water surface elevation required for this technique. The methodology used is the same as the digital active wave absorption system described earlier in Section 3.4. The system uses two drive signals for each segment which define the paddle motion for wave generation and the expected elevation at the gauge including the evanescent component. The controller subtracts the expected wave elevation from the measured wave elevation to obtain the elevation of the incoming wave to be absorbed.

The NRC program used for generating oblique unidirectional waves was modified to include AWA based on the snake principle. This modified version, tested in the multidirectional facility, works very well for small wave angles. However, the AWA feature does not work that well at larger wave angles due to diffraction effects which are not accounted for by the snake principle. Therefore a new and improved version of the program has been written to include diffraction effects when computing the expected wave elevation at each wave gauge for the generated waves. It first computes the paddle motions for each frequency component using the snake principle and then calls a subroutine version of WAGEN software to compute the resulting wave field at each wave gauge position including diffraction and reflection from the side walls. This results in a much better estimation of the expected wave elevation for the generated waves and consequently a more accurate measurement of the incoming waves to be absorbed. Numerical simulations indicate that this methodology works very well.

NRC has also recently implemented a truly 3D active wave absorption method by estimating the angle of the wave components propagating towards the wave paddles. This estimation is done by computing the angles for each frequency component by the use of simultaneous measurements of waves from neighbouring segments. Based on the difference in the elevations measured by the neighbouring segments (3 segments in total), the angle can be reliably estimated. This new technique is currently being implemented in the new multidirectional facility of NRC which is expected to be operational soon

5 CONCLUSIONS

This paper provides a brief review of improvements achieved over the years in the simulation of realistic sea states. These improvements combined with a significant increase in prototype wave measurements, make it possible to have a better reproduction of sea states in laboratory facilities thus contributing to improved designs of coastal and offshore structures.

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