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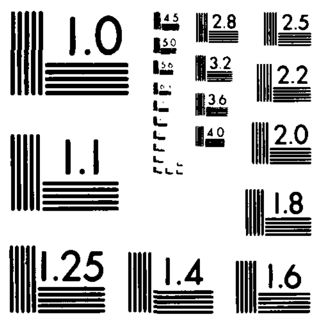


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DIVISION OF ENGINEERING AND WEAPONS
Hydromechanics Laboratory

Report EW-9-82

# A State-of-the-Art Review of Irregular Wave Generation and Analysis

by

Bruce Johnson

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A state-of-the-art review of deterministic and non-deterministic irregular wave generation and analysis. Extreme wave generation and wave group analysis are covered in the review. 38 references are included.

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# A STATE-OF-THE-ART REVIEW OF IRREGULAR WAVE GENERATION AND ANALYSIS

BY

Professor Bruce Johnson, U.S. Naval Academy
In collaboration with the Seakeeping Committee of the 16th ITTC

## INTRODUCTION

In 1979, a questionnaire on wave generation and analysis systems prepared by the Hydraulics Laboratory of the National Research Council of Canada was sent to member organizations of the ITTC as well as to hydraulics laboratories around the world. Replies were received from 98 of 184 Hydraulics Laboratories and from 44 of 74 institutions which have ship model towing basins. The results of this questionnaire were distributed to those institutions which responded and were summarized in a paper presented to the Coastal Engineering Conference in Sydney, Australia in March 1980 (1). Although a higher percentage of towing tanks reported irregular wave capabilities (67% to 41%), they also reported a very low utilization of those capabilities for ship model testing. This is most likely related to the nature of ship model testing as compared with the types of tests carried out in hydraulics laboratories and ocean engineering basins. It may also be related to discussions concerning the validity and applicability of deterministic vs. stocastic approaches to wave generation and analysis. Consequently, this review is organized according to the methods of irregular wave generation and analysis.

## I. NON-DETERMINISTIC GENERATION - STOCASTIC ANALYSIS

Non-deterministic wave generation is defined as the use of a non-repeating wave train derived by some method from a "true" random noise source such as thermal or cosmic noise. Stocastic analysis refers to the fact that probabilistic methods must be used to obtain the customary time series analysis functions such as spectral density functions, probability density functions, correlation functions, etc. This is because individual estimates of these functions for random phenomena show considerable variance with time. Averaging must be used to consider the analysis as approaching that of a stationary random process. A stationary random process is one for which the values of the time series analysis functions are independent of a shift in the time origin of the analysis (2).

Until recently, the most common methods of irregular wave generation involved the use of non-repeating wave trains derived from the use of a "true" random white noise source (3). The output from the noise generator can be shaped by analogue filters to compensate for the transfer function of the wavemaker and to shape the desired wave spectrum (4). The shaping filters can be set using trial and error procedures or can be programmed by computer to achieve the desired spectrum (4). The resulting wavemaker drive signal is generally stored on analogue or digital magnetic tape or on punched paper tape for use when desired. A digital computer can also be used to generate the non-repeating random numbers which could be converted into white noise, but it is more common to simulate true random waves by generating very long pseudo-random (repeating) sequences in the time domain using binary shift register techniques (5,6). A true continuous spectrum is non-repeating by definition since the frequency increment approaches zero. Pseudo-random techniques involving very long repetition periods can approach a nearly continuous spectrum but they still represent a discrete spectrum. The most frequently used pseudo-random time series are stationary random processes when their statistics are taken over the entire repetition period. This is because the component spectral density values average out to the constant coefficients in a Fourier series expansion. Wind generated waves in the actual ocean are quite unlikely to have constant spectral coefficients, however, since energy is being added by the time-varying wind fields, extracted by wavebreaking, and redistributed by non-linear wave interactions. Indeed, the resulting non-stationary, time-varying spectral density components present during a severe storm greatly increase the possibility of generating extreme waves as compared with artificial wave generation methods involving in-phase addition of constant amplitude components in pseudo-random waves. Thus, there is some question as to whether this type of pseudo-random sequence or even "true random Gaussian noise" should be considered adequate to simulate non-deterministic waves used in testing stationary models subject to extreme wave conditions.

Techniques utilizing actual sea records have also been developed (7). In this case, the component spectral density values generally vary with time and one has the problem of finding a record length long enough to approach a stationary random process if standard Gaussian statistical properties are to be assumed (2). If "wave grouping" effects are to be investigated, there is also the problem of determining whether or not a given prototype wave record contains the possibility of generating desired extreme waves at the model since the location of the wave height measuring device is frequently not at the site where the prototype structure is to be located. Therefore, the wave time histories which impact on the model may not represent what can be expected on the actual site, even though they may have the same spectrum. This problem is discussed further in section IV.

Since long term averaging of stocastic wave records is required to satisfy Chi-squared statistics for reasonable confidence intervals, this type of testing is more commonly used for stationary models. For tests involving moving models, Yamanouchi (8) advises that each run should be analyzed separately and the results averaged rather than attempting to splice together the records from short runs to make a long record. The latter introduces errors in the estimation of the spectrum as well as to the estimation of the response amplitude operator.

"Windowing" should also be used for the analysis of non-deterministic time series data since discrete Fourier analysis presumes that the sampled data repeats each frame. A "Hanning" or other type of window reduces the series to zero amplitude at the beginning and end of the analysis frame. A Fourier Integral may be used to describe the non-repeating series of data points which has no discontinuities at each end of the finite segment of the time history being analyzed (2).

Since any window (other than rectangular) effectively reduces the energy contained in an analysis frame, a correction to the appropriate time series function must be applied. There is some question on just how to apply this correction - whether to normalize the window time series to the original energy level or to apply a correction to each value of the spectral density estimates or their averages. The author was unable to find a satisfactory discussion of this problem in the typical books and literature on time series analysis.

## II. DETERMINISTIC GENERATION - STOCASTIC ANALYSIS

Deterministic wave generation is taken to imply that a repeating wave train is generated which contains discrete, harmonically related components whose spectral densities are fixed in amplitude but randomized in phase. This is based on the fact that any repetitive time series may be expressed as a Fourier Series expansion with constant coefficients. Stocastic analysis (Averaging) is required, however, anytime the testing time is less than the repetition period of the wave generation record.* Since the repetition of the wave is the inverse of the spectral spacing of the discrete generating frequencies, the longer the repetition period, the closer a continuous spectrum is approximated. Time domain generation of this type of wave includes the mechanical gear systems of the type offered by Kempf and Remmers, and electronic sinusoidal summing devices, both of which have predetermined numbers of discrete components (some of which may have zero amplitude). The previously mentioned pseudo-random waveform generators pioneered by the Wallingford Research Station and available from EEL Laboratories of British Hovercraft Corporation, are generally hardwired to enable the user to choose the repetition period. They may contain manually adjusted or programmable shaping filters to compensate for the wavemaker transfer function in obtaining a desired spectrum in the tank (4, 5, 6).

Frequency domain generation techniques based on the inverse Fourier Transform are gaining increased popularity with those who have access to an on-line computer, since the desired spectrum can be achieved through iteration as demonstrated by Anderson and Johnson (9). Funke and Mansard (10) have added an additional dimension to this technique by combining amplitude and phase modulation to produce a desired grouping of the waves. This is discussed further under "extreme wave generation".

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*Footnote: Stocastic analysis can also be used to advantage in regular wave testing to compensate for the deficiencies of certain types of wavemakers which produce beat phenomena, etc. In this case, the waves are treated as a narrow band random process.

## III. DETERMINISTIC GENERATION AND ANALYSIS

The previously mentioned pseudo-random wave generation techniques can be deterministically analyzed provided that the analysis time is precisely equal to one or more repetition periods of the generation sequence. This "zero variance" technique (9) has the advantage of being "ergodic" in the sense that the accuracy of the analysis is independent of which portion of the wave record is analyzed, and it does not have to be averaged or windowed unless the model exhibits non-ergodic response. Since there is an integer number of cycles of each discrete frequency component in any analysis frame equal in length to the repetition period, decisions concerning averaging can be based on the desired number of wave encounters to insure the model response has stabilized. This is traded off against the possible influence of beach reflections on what was supposed to be a stationary, ergodic spectrum at the test location in the tank. If the testing time is not limited by a moving model or beach reflections, it would probably be better to double the number of spectral lines by doubling the repetition period rather than by averaging two "identical" records. There is still an unresolved issue concerning the *minimum number* of spectral lines, the maximum allowable spectral line spacing and maximum allowable wave height increments on histograms for various kinds of model tests which utilize discrete spectrum wave generation. In mooring studies, for example, misleading results can be obtained from both regular wave and irregular wave studies with widely spaced harmonic components (3). This is because non-linear and asymmetric elastic characteristics of mooring lines and fenders along with slowly varying wave drift forces can produce sub and super-harmonic components not identified by discretely spaced regular or irregular wave frequencies. However, the "zero variance" or periodic irregular wave tests can supply the same information as an equivalent number of regular wave tests for each of the discrete spectral components.

In order to make the analysis deterministic, it is important to match the clocks controlling the wave generation with clocks associated with the data acquisition. At the Naval Academy, for example, the data is digitized by an analogue to digital converter sampling at frequencies which are multiples of powers of two. This is to insure that the Fast Fourier Transform analysis (whose frame size normally must be a power of two unless a different radix is used in the algorithm) will yield "nice" frequency spacings like .1, .05, or .01 hertz. The clocking of the digitized wavemaker drive signal is at 25.6 samples per second (smoothed by an 8 pole analog filter) so that a repeating wave of 20 seconds duration (.05 Hz spacing) has a drive signal 512 words long.

This type of testing is still more appropriate for stationary models, however, where testing time is not a function of the model speed and length of the tank. A more serious problem faced by moving models is that the encounter frequency shift causes a deterministically generated wave appear as a stocastic wave to the moving model. This is because the equally spaced generation frequencies are now unequally spaced in the encounter frequency domain; i.e.,

$$f_e = f + \frac{2\pi V f^2}{g} \qquad \text{and}$$

$$\Delta f_e = \left(1 + \frac{4\pi V f}{g}\right) \Delta f \qquad \text{where}$$

$f$ = wave frequency in fixed coordinates

$f_e$ = encounter frequency

$V$ = model velocity

$g$ = gravitational constant

This latter problem is currently being studied by the collaborators on this report, who are both working on "single pass" seakeeping tests for moving ship models in head or following seas. The goal of such studies is to reduce the testing time required for seakeeping tests which utilize regular waves. By replacing the tests in regular waves with tests in deterministic irregular or transient waves, the cost of such tests can be reduced, or the range of parameters investigated (such as non-linearity) can be increased for the same amount of tank time. Admittedly, such tests cannot handle deck wetness and slamming probabilities directly, but the resulting response amplitude operators can be used in such predictions just as well as those obtained from regular wave tests.

Professor Takezawa and his group at Yokohama National University (11, 12) are continuing to develop the "transient wave method" discussed in another presentation in this session (13). The transient wave method has the advantage of a continuous spectrum in both the stationary and encountered frequency domains. Professor Johnson and a group from both the Naval Academy and MTS Systems Corporations have developed the "Periodic Irregular Encountered Wave Technique" (14) which is deterministic (periodic) to the moving model, but is stocastic (never repeating) at the waveboard and in the tank. This is accomplished by equally spacing the harmonic components in the encounter frequency domain so that the irregular wave repeats exactly with a period equal to the inverse of the frequency spacing. The on-line computer which drives the waveboard calculates the non-equally spaced component frequencies which are then summed into a never-repeating drive signal for the wave generator. A different drive signal is required for each carriage speed since the frequency shift varies with the model velocity:

$$f = \frac{\sqrt{g^2 + 8\pi g V f_e} - g}{4\pi V}$$

and

$$\Delta f = [1 + \frac{8\pi V f_e}{g}]^{-1/2} \Delta f_e$$

## IV. EXTREME WAVE AND WAVEGROUP GENERATION AND ANALYSIS

Another area covered by this review is that of the generation and analysis of extreme waves and "wave groups". This type of wave action is of importance in severe wave load and capsize tests for ship models and for the testing of breakwaters and other coastal structures in hydraulic laboratories. An extensive project, "Ships in Rough Seas", has been underway at the Norwegian Hydrodynamic Laboratories since 1978 (15-22). The project includes detailed studies of breaking waves by Kjeldsen and Myrhaug which have produced new insights concerning extreme wave phenomenon.

For either stationary or moving models it is frequently desired to make a wave break precisely at the location of the structure or ship model. The methods utilizing sweep frequency modulation to generate transient waves may be used for this purpose (18, 21), including those for repeating transient waves (13). An equivalent method for hydraulics laboratories has been developed by Funke and Mansard of the NRC Hydraulics Laboratory in Canada (24). Their report contains a copy of the SPLISH software with sufficient remarks to reproduce it in other laboratories. Other useful wave generation programs are also available from NRC and are summarized in (25). A novel means of generating extreme waves by using a traveling flap fitted to a towing carriage was reported by Hogben (26).

Extreme waves may also be generated at a particular location through the use of inverse Fourier Transform techniques with predetermined phase control rather than randomizing the phases.* In the simplest form of inverse FFT generation, the spectral densities of each component are specified and the group velocity of each of the components is computed in order to predict the appropriate initial phase relationships to produce an additive super-position of all the frequency components at a particular location in the wave basin.

Wave grouping is also possible using the frequency domain developed for the Periodic Irregular Encountered Wave Technique (9). In this technique, one has the option of: a) equally spaced harmonic frequencies can be used to produce a breaking wave at a particular location every repeat period, or b) unequally spaced component frequencies can be used to produce a never repeating wave which breaks just once at the desired location. If the equal frequency spacings are chosen in the encountered frequency domain, the program can produce a breaking wave on the moving model once each repeat period. In the latter case, the extreme wave location moves toward the wavemaker at the speed of the carriage and does not occur anywhere else in the basin. The program can start the high frequencies first and systematically add in the lower frequencies to avoid beach reflections as long as possible.

At this point, a distinction should be made between the types of breaking waves. The largest wave forces and the greatest capsize dangers for smaller vessels are associated with plunging breakers which are readily produced by shoaling the wave into shallow water (28) or by narrowing the vertical sides of a wave flume (29). Wave-wave interactions involving very steep Stokes waves can also produce plunging breakers in deep water as reported by Kjeldsen, et.al. (18-22). Spilling breakers and deep water bores (defined in reference 18) are more commonly found for

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*Footnote: Interestingly, the proper choice of random phases to insure that breaking waves would not occur for standard ship motion tests was discussed by Anderson and Johnson (27). To determine a response amplitude operator, the spectrum should be essentially constant throughout the tank. Breaking waves distort the achieved spectrum downstream of the break point.

deterministically generated irregular waves in most deep water basins. However, a current created in the opposite direction to the wave direction will steepen the wave sufficiently to cause it to "plunge" (18,21).

Although wave spectra, significant wave heights and model periods are generally reported for both ocean data and for model testing in waves, these parameters are not adequate to properly describe tests involving extreme waves or "wave groups". The averaging process tends to mask unusual "events" and several radically different time series can all be represented by the same spectrum (30). Spectral shape parameters are also inadequate for describing events which are related to the effects of phase on the superposition of wave harmonics. An adequate characterization of "episodic" waves and/or "groupiness" appears to require a time domain analysis of the events. Three approaches to such an analysis have recently been put forward. The first method was proposed by Kjeldsen and Myrhaug in 1978 (15,17,21). It involves the use of the "zero down-cross" method of waveheight analysis and the probability distributions of four wave shape parameters. They are the crest front steepness parameter, $\varepsilon$, the crest rear steepness parameters, $\delta$, the vertical asymmetry factor, $\lambda$, and the horizontal asymmetry factor, $\mu$. They analyzed 25,000 waves and report the results of their statistical analysis. It is not yet apparent how to reduce these characterizations to simple numbers for the purpose of specifying a desired irregular wave record.

The second method is the "Smoothed Instantaneous Wave Energy History" or SIWEH as proposed by Funke and Mansard (10) in 1979. From the SIWEH, which has a time axis the same length as the wave record, Funke and Mansard have proposed a Groupiness Factor which equals the standard deviation of the SIWEH about its mean, normalized by the area under the wave spectrum. They also propose that three other parameters related to wave grouping be specified: the average group length, average group repetition period, and some measure of the group repetition period. This is a developmental proposal, and operational definitions of all the parameters have not yet been worked out.

The third approach to a time domain analysis of the extreme wave phenomena is the "Half-Cycle Counting Technique" proposed by Buckley at the 19th American Towing Tank Conference (31). This technique was adapted from a computerized procedure to accumulate fatigue load data in structural tests. The wave record is banded into uniform amplitude intervals on either side of the mean value or still water level. The peaks (both maxima and minima, thus the term half cycle) are then detected within each elevation interval and summed into the appropriate bin depending on whether the data peak is a "first" peak or a "second" peak. The counts stored in the bins form a "data matrix" which is presented in a visually satisfying format that simultaneously logs the "half cycle counts", the amplitude histograms of the occurrences, the peak count occurrences, and any "episodic" events which lie outside the expected range of wave elevations for a particular sea state. This procedure is also developmental at the present time and has the choice of the proper dead zone band (threshold) as an unresolved problem. Neverless, it has generated quite a bit of interest from those exposed to its interesting presentation of irregular wave data.

What is currently needed is a data analysis package which included both the Groupiness Factor and Half-Cycle counting technique for analyzing wave groups and extreme waves. More analysis of actual wave records is required in order to define appropriate wave groupiness parameters. Representative wave data which is known to contain extreme waves and wave groups should be analyzed by various tanks to get a consensus on the usefulness and adequacy of these approaches before any standards are recommended.

## V. SHORT CRESTED IRREGULAR WAVE GENERATION AND ANALYSIS

A state-of-the-art summary of multi-directional wave generation and analysis was presented at the 15th ITTC by Hogben (32). Recent progress in methods for the generation of short crested seas in a wave basin through the use of multiple wave generators is summarized in a contribution to the 16th ITTC Seakeeping Committee by Naeser (33). Three methods are discussed for producing directional spectra. The "snake principle", pioneered by NSMB, has been expanded to multi-frequency inputs at the University of Edinburgh. Their wave tank is equipped with 89 wavemakers which may be independently driven through the use of a minicomputer (34). The "Wallingford principle" which utilized ten independently controlled wavemakers arranged in a crescent to produce a desired directional wave spectrum at the center of the basin is described by Huntington and Thompson (35). The "diffraction principle" also uses independently driven, snake type wavemakers, arranged along one wall in combination with reflecting side walls rather than beaches (36). Naeser reports that this principle will be tested using the 144 wavemakers arranged along the 63 m wall of the Ocean Laboratory in Trondheim in 1981 (33).

Naeser also points out that none of the techniques is able to produce a multi-directional spectrum which is continuous in both frequency and direction. The snake method produces a discontinuous spectrum containing discrete frequencies and discrete directions.

The Wallingford method produces a nearly continuous frequency spectrum containing discrete directions, while the diffraction method produces discrete frequencies from "quasi continuous" directions.

The analysis of multi-directional spectra is not a simple task. The most recent discussion of this problem is that of Matheisen (37) which presents the theory and a computer program for the calculation of directional wave spectra from measurements of wave heights at the corners of a square. The well known review of techniques for directional wave spectra by Panicker (38) is recommended reading for those involved in such studies.

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38. PANICKER, N. N., "Review of Techniques for Directional Wave Spectra", Proc. of the WAVES '74 Conf., New Orleans, 1974.

## DISCUSSION TO INVITED PAPER BY BRUCE JOHNSON

- By Stephen J. Rowe
National Maritime Institute, England

Mr. Chairman I have two points.

Firstly, I am concerned about the concept of the generation of waves using the amplitude modulation of the component sine waves, and the confusion this introduces. It seems to me that all this achieves is the extension of the time series before repetition, (the length of the wave sequence becomes a complex function of the modulation frequencies). If one were to record such a time series and perform a Fourier transformation and obtain the coefficients, one could in principle set up a multi-component sine wave synthesizer or a shift register synthesizer in amplitude and phase to produce exactly the same time series. The amplitude modulation therefore is effectively simply inserting additional lines into the spectrum, and one will of course have to analyse long runs in the tank to make use of the finer spectral resolution that has been thus obtained.

If one looks at the time history of such a long time series (however produced) it will 'appear non-stationary'. Physically, this is because adjacent lines, or groups of lines in the spectrum are coming to anti-phase, and thus cancelling out the energy for this frequency band for a period of time.

Finally, I would like to emphasize that in my view there is absolutely no point in averaging the analysis results from two or more repeating sequences of waves. All this will tell you is the repeatability of your wavemaker and instrumentation. (You may prefer not to know this!). Worse still, if you transform as one block two or more sequences, your analysis resolution will be closer than the 'wet lines' in the tank and you will over-resolve the spectrum. It is essential therefore that one should generate long sequences of waves that are as long as, or longer than, the total length of run record that you wish to analyse.

## DISCUSSIONS TO PAPERS BY PROFS. JOHNSON AND TAKEZAWA

- By Hun Chol Kim
Ship Research Station, KIMM, Korea

Irregular wave generation assumes an applicability of linear superposition. There would be non-linearity arising from wave decay along the length of a towing tank, decay being dependent not only on each wave component but on the whole system of waves.

Particularly once the wave or the wave system breaks there would occur, it would seem, almost certain reduction in amplitude(s) as well as phase shifts in certain components.

I wonder if such has been noted, and if so, how serious it is and how one should go about in compensating.

## RESPONSE TO THE DISCUSSIONS CONCERNING THE STATE OF THE ART REVIEW OF IRREGULAR WAVE GENERATION AND ANALYSIS

- Bruce Johnson

Mr. Chairman, Mr. Rowe has raised two very interesting points which I have had to research after returning home from the ITTC. With regard to the first point, it is not my understanding that any time series can be reproduced by use of a Fourier transform and a multi-component sine wave synthesizer or shift register synthesizer. Linear wave phenomena represented by a periodic time series (however long the repetition period so long as it is finite) can be reproduced by the sum of sinusoids technique. Transient phenomena which begin and end with zero amplitude will have a valid Fourier transform, but the frequency resolution will be infinitesimal and these time series require an infinite number of component waves to be reproduced exactly. All other time series cannot be reproduced exactly - only an approximation to the original series can be produced. If the wave generation system is a linear system (true for small amplitudes) this approximation will be quite good. Since the discussion concerned large amplitude waves which may be quite non-linear, the reproduction of the original time series will not be possible using Fourier transform techniques.

Amplitude modulation of the individual components does more than "effectively inserting additional lines into the spectrum". In recent attempts to generate extreme waves, I have been unable to prevent premature breaking when using the sum of *sinusoids technique* with constant component amplitudes to try to obtain phase convergence at a particular location in the tank. Using the sweep frequency method (transient wave method) in which the component amplitudes vary from zero to whatever amplitude is generated at a particular frequency during the sweep, very large plunging breakers can be produced in deep water. Neither of these generation techniques approximate a real storm sea, which must contain time varying component amplitudes to realize observed extreme waves. I also question whether the extreme values predicted for a stationary Gausian random process are adequate for predicting the occurance of extreme waves in non-stationary storm seas. Incidently, I am not aware of how one tells whether or not a time series "appears non-stationary" just by looking at the time history.

With regard to the second point, I agree that averaging the analysis results from two or more repeating sequences of waves has no point if the system is linear. If, however, the system has a non-linear response which may involve transient decay or amplification, the analysis of more than one repeating sequence will establish whether or not a steady state response has been established.

I also discovered another reference (1) to random testing techniques which should have been included in the original paper. Although the reference addresses the testing of automotive structures, its conclusions are also applicable to the testing of marine structures. The authors of this paper state that pseudo random techniques involving sufficiently long repetition periods to insure adequate spectral resolution of the phenomena being observed are the most efficient for linear systems. However, pure random testing is considered to be better for non-linear systems since "it gives the best linear approximation of a non-linear system." Impact testing (transient method) gave good results for linear systems, but is less effective for non-linear systems, unless only a "quick look" estimate is desired.

Dr. Schmiechen has raised a valid point about the use of mathematically defined time series analysis terms. Since there are semantic difficulties arising from the use of these terms to describe and categorize wave time histories, the Information Committee should consider the inclusion of operational definitions of time series analysis terms in the updated Dictionary of Ship Hydrodynamics.

Dr. Kim discussed the influence of wave breaking on the wave system at various locations in the tank. This problem was mentioned in the footnote on the fourth page of the paper, but the author is not aware of any means of compensating for the wave breaking once it has occured.

Reference (1)

BROWN, D., CARBON, G., AND RAMSEY, K., "Survey of Excitation Techniques Applicable to the Testing of Automotive Structures", Paper No. 770029, Proceedings of the International Automotive Engineering Congress and Exposition, Detroit, Michigan, Society of Automotive Engineers, March, 1977.

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