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DATA PROCESSING METHODOLOGY FOR EXPERIMENTAL MODELING OF OCEAN WAVES

ABSTRACT

This paper presents the data processing methodology for the physical modeling of ocean waves in wave flumes which was developed for the purpose of conducting hydrodynamics research in laboratory conditions. It includes the description of the research cycle, applied wave theory and the measured data processing methods. A significant achievement presented in this paper is the originally developed data analysis algorithm for the practical improvement of the wave generation process.

Key words:
signal processing, data analysis, spectral analysis, stationary range, ocean waves, experimental methods.

INTRODUCTION

One of the main focus areas of hydrodynamics research facilities is the prediction of ships and offshore structures behavior in a real sea environment as described in [1], based on simulations and model testing. Such and environment has to be transferred onto the model scale so it can be tested in a laboratory environment. Great references to the significance and applications of hydrodynamic model research can be found in [3] and [8].

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The work presented in this paper was carried out in the Offshore Laboratory of the Ship Design and Research Center CTO S.A.

As part of the development work within the modernization strategy of the Offshore Laboratory a new research methodology had to be developed, which would adapt and update the wave generation process to be compatible with the new high-tech wave generator system. Figure 1 shows the Offshore Laboratory model basin and Wave Generator.

a)

b)

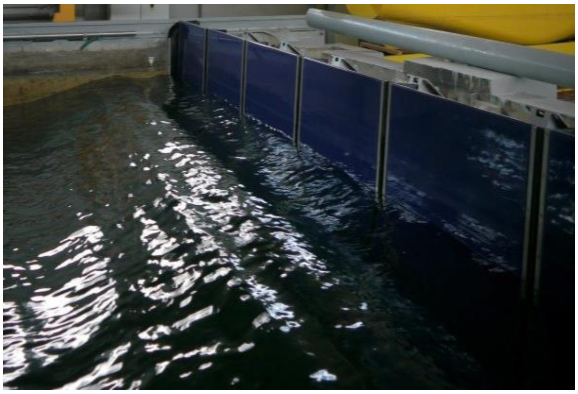

Fig. 1. CTO S.A. Offshore Laboratory(a) and Wave Generator (b) [authors' photos]

Generating model environmental conditions for hydromechanics model tests requires adequate methods and algorithms for control signal creation for the wave generator based on mathematical wave models as well as a specific measurement and data processing system that allows for verification of the generated wave against the assumed mathematical model.

A schematic of the simplified research logic for the physical modeling of ocean waves is presented in figure 2.

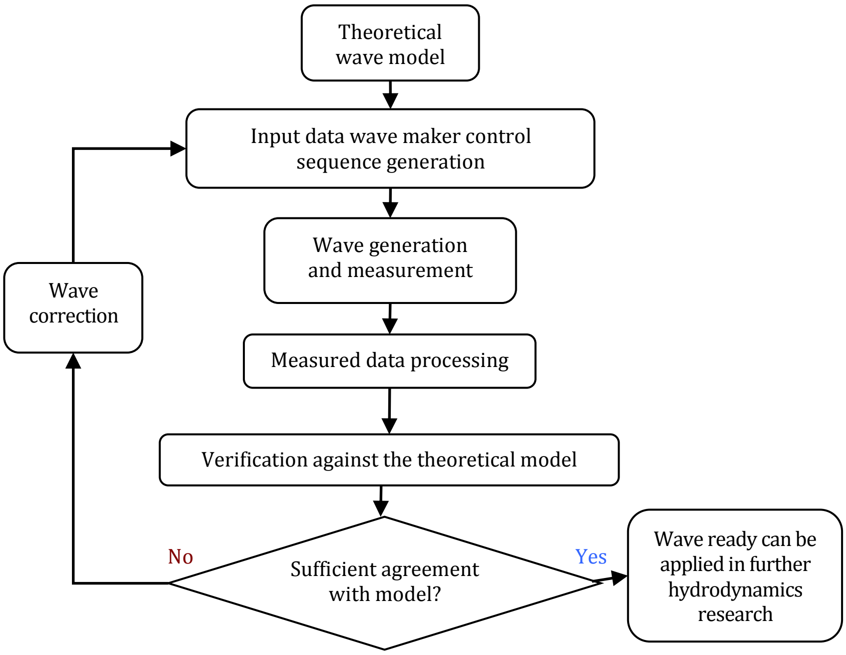

Fig. 2. Research logic for generating waves in a model basin [own work]

APPLIED WAVE THEORY

The overall theory and physics of wave mechanics and influence on the environment, wave generation and wave analysis is very well researched and described in extensively in specialized literature [10, 13] as well as generalized industrial and testing procedures [7, 12]. It includes, linear, gravity and air wave theory, Stoke's theory and takes into account typical properties of waves like kinematics, diffraction, refraction, interference, reflection, standing waves etc. In further description we will assume a linear wave theory described in [9] simplified to deep water waves, where the wave height is much smaller than the wave length and the water depth the wave propagates so we can adopt simplified and practical formulas according to [12].

Wave conditions applied in hydromechanics research can be described by deterministic or stochastic methods.

For sea states and structures that can be efficiently modeled with the linear wave theory the use of deterministic regular waves is often enough. The wave parameters can be then determined by statistical methods. The regular waves can be described by wave length and the corresponding wave period or frequency, surface elevation and wave height. The basic parameters are show on figure 3.

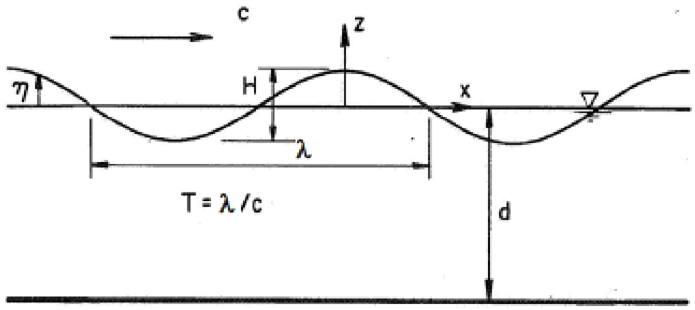

Fig. 3. Basic regular wave parameters: η — surface elevation, c — celerity, T — period, λ — wave length, d — water depth, x and z — spatial axes [own work]

Structures that cannot be sufficiently and accurately modeled with a linear response require stochastic modeling of sea surface elevation and it's kinematics by irregular time sequences where the surface elevation is a random process.

This stochastic wave model is a sum of smaller wave components with different amplitude, frequency and direction and the phases are random in respect to each other. In practical applications it is assumed that a sea state is a stationary random process over a time of 20 min to 6 h in real conditions and it can be described by awave spectra, which are power density spectra or the sea surface elevation, examples of which are shown on figure 3. From these spectra a set of environmental parameters can be derived like the significant wave height H_s, the peak period T_s or zero-crossing period T_z. These parameters are calculated from spectral moments described in (3)–(9).

The specific wave spectrum for a tested structure is matched based on the destined geographical area with a specific sea state.

One of the most reliable and popular mathematical wave models for irregular waves describing developed sea states is the JONSWAP model [12]:

$$S_J(\omega) = A_\gamma S_{PM}(\omega)\gamma^{\exp\left(-0.5\left(\frac{\omega-\omega_p}{\sigma\omega_p}\right)^2\right)}, \tag{1}$$

where:

$$S_{PM}(\omega) = \frac{5}{16} H_s^{\,2} \omega_p^{\,4} \omega^{-5} \exp\left(-\frac{5}{4}\left(\frac{\omega}{\omega_p}\right)^{-4} \right); \tag{2}$$

ωp — angular spectral peak frequency;

$A\gamma$ — 1–0.287 *ln*(γ) is a normalizing factor;

Γ — non-dimensional peak shape parameter;

σ — spectral width parameter.

Figure 4 shows plots of example wave spectra created with the JONSWAP model and for different values of the peak shape parameter *γ.*

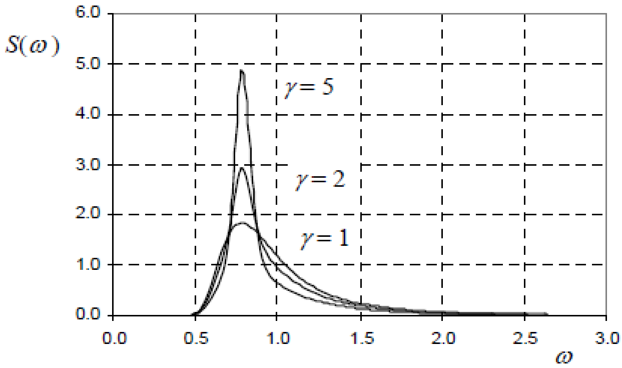

Fig. 4. JONSWAP wave spectra for different γ values [12]

Based on such a specific wave spectrum an algorithm was implemented for generating wave time sequences according to the random phase method described in [14]. These time series can then be implemented in the laboratory wave generator and consequently the actual wave can be generated and measured. The next step in the wave design methodology is then to develop an appropriate algorithm for data analysis of the generated and measured wave and verification of wave parameters against the assumed wave model.

DATA PROCESSING METHOD

Taking into account the basic wave design assumptions as shown in figure 2 and the mathematical model (1), the new data processing algorithms were developed that are based on this following logic:

Input data (measurement) > statistical (time series) analysis > determination of the stationary range > spectral analysis > verification against the model > determination of required corrections > modification of input data (if necessary).

For a signal to be properly analyzed it has to be stationary within an acceptable tolerance. To realize such an analysis statistical and spectral moments [6] were used. Moments are very practical mathematical tools for describing a wide set of signal characteristics and they can be used for calculating the specific parameters of analyzed phenomena. On top of that for a stationary signal its statistical and spectral moments should stay constant over time. This property can then be used to determine the stationary range of signals.

To prepare the signal it is divided into overlapping time windows — segments. For each of those windows the Fourier Transform is calculated by means of the FFT algorithm and consequently the power density spectra are determined.

For each segment and its spectrum statistical and spectra moments up to the 4-th level are calculated according to [6], where:

- Moment of order *r* of a discrete random variable ξ is a number:

$$\overline{\xi^{r}} = \sum_{k=0}^{N-1} x_k^r P_{\xi}(x_k). \tag{3}$$

- Central moment of order *r* of a discrete random variable ξ is a number:

$$\overline{(\xi - \overline{\xi})^{r}} = \sum_{k=0}^{N-1} (x_k - \overline{\xi})^r P_{\xi}(x_k), \tag{4}$$

where:
$\{P_{\xi}(x_k);\ k = 0, 1, \ldots, N-1\}$ — a set of probabilities assigned to these realizations.

- Spectral moment of order *r:*

$$M(r) = \sum_{k=0}^{N-1} P_k f_k^r . \tag{5}$$

- Normalized spectra moment of order *r:*

$$M_u(r) = \frac{M(r)}{M(0)}, \tag{6}$$

where:
f_k — the frequency;
P_k — an estimate of the power spectra density;

$$M(0) = \sum_{k=0}^{N-1} P_k \tag{7}$$

is the spectra moment of order zero, which has a normalizing function and the meaning of the signals power.

- Normalized central spectral moment of order *r:*

$$M_{uc}(r) = \sum_{k=0}^{N-1} \frac{P_k[f_k - M_u(1)]^r}{M(0)}, \tag{8}$$

where:

$$M_u(1) = \sum_{k=0}^{N-1} \frac{P_k f_k}{M(0)} \tag{9}$$

is the normalized spectral moment of order one, which is used to calculate the central moments of higher order and has the interpretation of the center of gravity of a spectrum.

The more practical moments for signal analysis are the normalized central spectra moment of order two is interpreter as the square of the frequency bandwidth of the spectrum, of order three which is the asymmetry of the spectrum or *skewness* and of order four which is the measure of the spectrum flatness or *kurtosis*.

With the use of moments and according to [12] environmental wave parameters can be calculated for each segment and verified against the model:

- Significant wave height:

$$H_S = 4\sqrt{M(0)}. \tag{10}$$

- Zero up-crossing period:

$$T_z = \sqrt{\frac{M(0)}{M(2)}}. \tag{11}$$

- Mean wave period:

$$T_m = \sqrt{\frac{M(0)}{M(1)}}. \tag{12}$$

- Mean crest period:

$$T_c = \sqrt{\frac{M(2)}{M(4)}}. \tag{13}$$

- Significant wave steepness:

$$S_s = \frac{2\pi}{g}\frac{H_S}{T_Z^2} = \frac{2}{\pi g}\frac{M(2)}{\sqrt{M(0)}}, \tag{14}$$

where:
g — acceleration due to gravity.

The next step in the algorithm is to determine the moment that will serve as the reference parameter.

A very sensitive parameter is the *kurtosis* but a good and sufficient parameter for this type of analysis and big scale phenomena is the 2nd order statistical moment which is the signal variance. For this moment calculated for each segment and evolving over time a stable reference level and acceptable tolerance has to be assumed, here the median and a multiple of the standard deviation were found to be very good and stable parameters.

Next the selected spectral or statistical moment is charted against the segments and the assumed tolerance is applied. Every segment that doesn't comply with the tolerance is then rejected and the corresponding time range of the signal, where the stationary condition is fulfilled is thus determined. This part of the algorithm has been represented on an example time signal figures 5 and 6 for two assumed tolerance levels of 0.5σ and 0.15σ from the median.

Figure 5 shows a noticeable jump in the moments distribution, which can be a result of some wave amplification instabilities of the generator in the early stages of the generation sequence. The impact of this effect is not very significant and the assumed tolerance is too big to eliminate this effect. The tolerance condition can then be adjusted to be more restrictive and even this small deviation from stationarity can be then eliminated.

Using the more restrictive tolerance a very stable stationary range of the time signal can be then determined for further analysis. The signal limited to its determined stationary range can now be taken for the next processing step which is the spectral analysis.

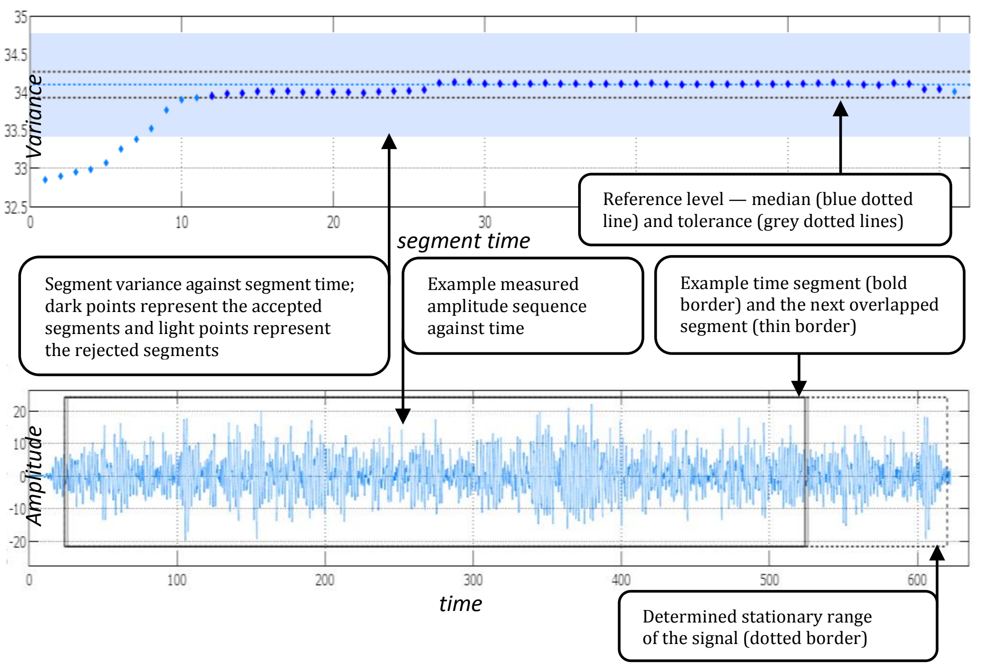

Fig. 5. Example statistical analysis and stationary range determination with a tolerance of 0.5 σ [own work]

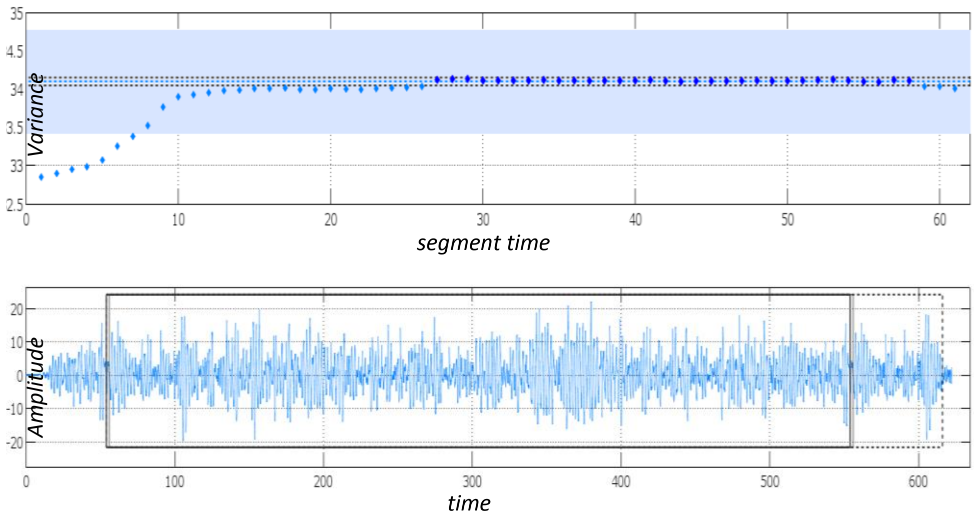

Fig. 6. Example statistical analysis and stationary range determination with a tolerance of 0.15 σ [own work]

For each segment in the determined range amplitude spectra are calculated by means of parametric time windows and the FFT algorithm. Each spectrum can then be plotted against both the time and frequency as another verification method of the accuracy of the algorithm for determining the stationary range. If the algorithm is correct we should see the entire spectrum being constant in the determined time period. An example of this can be seen in figure 7.

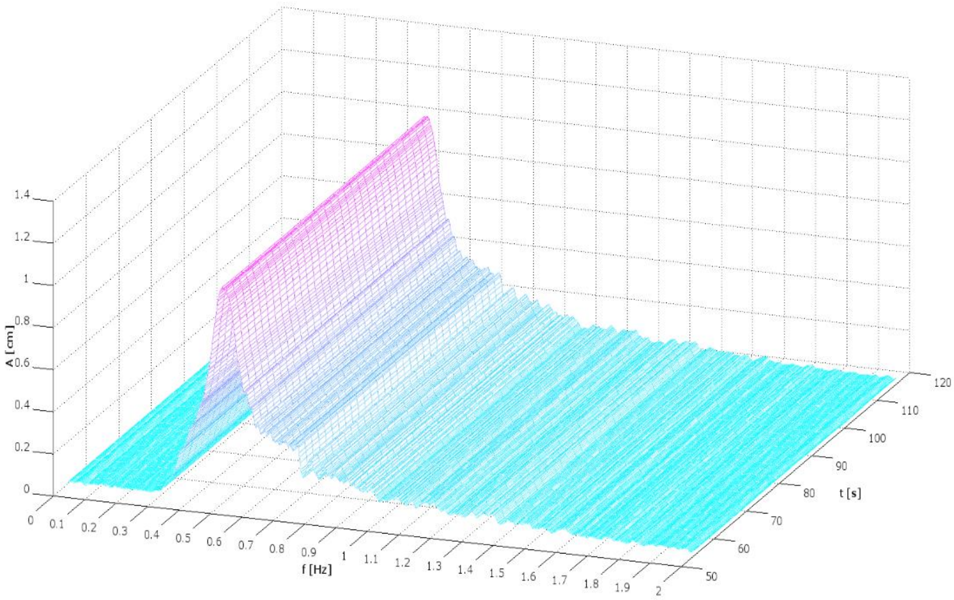

Fig. 7. Example 3D amplitude Spectrum *A(f, t)* [own work]

Moving forward the effective spectrum estimate is then the average of all segment spectra and the uncertainty of individual bins can be derived. This method is an extrapolation of the Welch Method for spectrum estimation. The effective amplitude spectrum leads then to the power spectral density from which the characteristic spectral moments and wave parameters H_s and T_z can be calculated.

In designing specific environmental conditions for model tests it will be fundamental to verify the agreement of the generated spectral density and wave parameters against the assumed model and apply corrections if necessary. These parameters are calculated and compared on every step of the data processing algorithm according to (3)–(14). Moreover to visualize the accuracy of the designed wave the theoretical model spectrum against the spectrum calculated from the generated and measured signal should be plotted.

This step also includes application of a newly developed, specifically for this research methodology, smoothing algorithm for the measured data which preserves the characteristics of the original signal very well including the specific spectral moments and parameters and should be very stable for a wide range of signals. This will give the observer the needed information of the designed conditions and a very good idea of the achieved accuracy. It is also a needed step for even further signal analysis.

The general idea of the signal filtering is based on a few known mathematical concepts but the specific smoothing algorithm has been originally designed and perfected iteratively over a long period of time and a wide range of test signals.

Eventually a very good result and a very stable and versatile algorithm was acquired using a combination of the Savitzky-Golay filter, the moving average filter, signal down sampling and piecewise cubic hermite polynomial interpolation. This algorithm preserves all the appropriate information and the parameter estimation error resulting from a filtered and unfiltered decomposition is negligible. An example of the spectral analysis, including these elements of the smoothing algorithm as well as the model spectrum and uncertainty of frequency bins can be seen in figure 8.

As seen in figure amplitude bins in some frequency bands have a much bigger uncertainty than others and further work in already underway on the algorithm to develop a smart filter to achieve higher smoothing in bands with higher uncertainty of bins.

The final step in the design methodology is be then to account for possible deviations from the model in the generated wave which is very likely, given that the wave generator and the water in the laboratory basin don't transfer all frequencies and spectral densities with the same efficiency.

In order for the generated wave to be as close to the assumed mathematical model as possible it is prudent to assume and prepare for the need to iteratively attune the wave decomposition and parameters to a high accuracy and this is how we finally arrive at the actual experimental wave design concept.

After the experimental wave signal is acquired and the spectral analysis and smoothing is performed it is then numerically compared against the theoretical spectrum and a frequency gain correction function for the generated signal can be calculated. The signal is then again filtered as seen in figure 9 to account for the wave generators specific capabilities and requirements assuring the equipment will transfer the gain correction as effectively as possible.

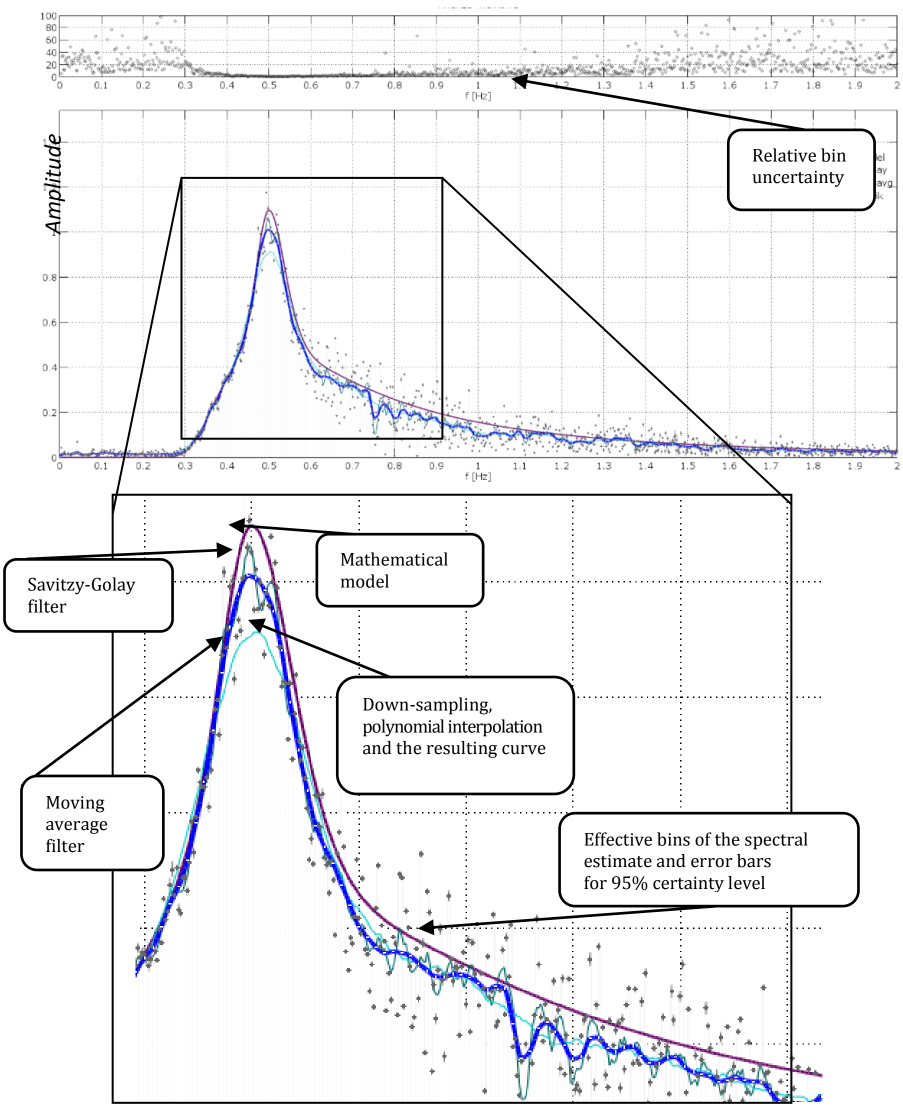

Fig. 8. Example visualization of spectral analysis and results of the smoothing algorithm [own work]

The type of correction function presented on figure 9 can then be implemented and the wave generator will apply it to the originally generated wave sequence. The wave generation and measurement process has to be then repeated as many times as needed for the effective wave spectrum and parameters to comply with assumed tolerance limits.

Using such a methodology focused on using high accuracy data processing methods a desired wave can be acquired very quickly without the need for numerous iterations. The aim is for one or two iterations to give the assumed spectrum and parameters.

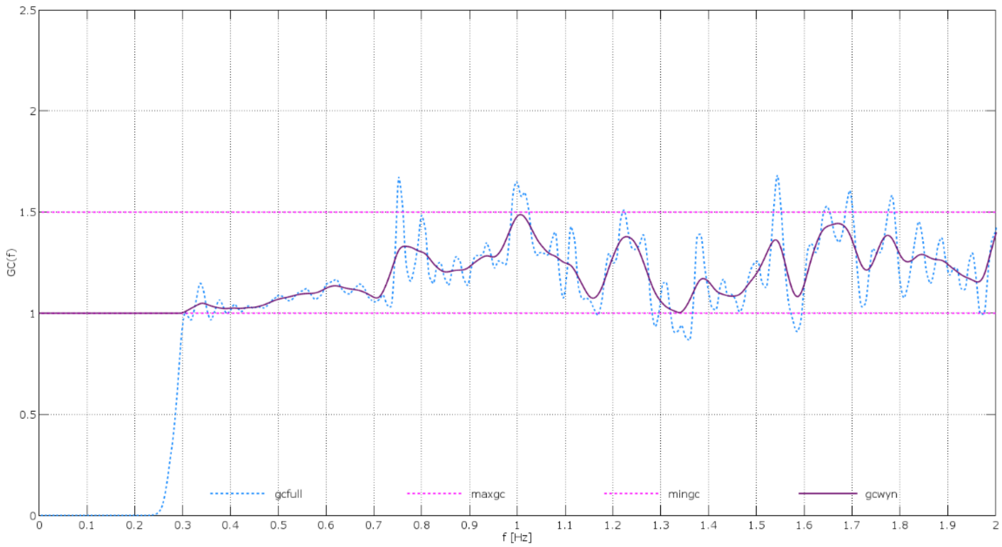

Fig. 9. Example gain correction frequency signal [own work]

CONCLUSIONS

The paper shows the research methodology needed for designing model ocean waves in laboratory conditions. Based on mathematical wave theory a wave model is assumed and control time sequence is numerically generated. After that the sequence is implemented in the wave generator system which can realize the designed wave. The methodology then requires for the generated wave to be measured.

The primary achievement of the work presented in this paper is the development of an original data processing method of measured wave data, that allows for very accurate information determination and verification against the assumed mathematical model. The inclusion of very accurate stationary range analysis by means of spectral and statistical moments ensures a very stable input signal for further analysis. On every further step as well the aim was to achieve a very accurate algorithm, including spectral estimation, data smoothing and wave parameter estimation as well as the correction function estimation.

Thanks to the developed method some of the complexity of the wave generation can be moved to the data processing side of the research, which with current standard computing power can be easily implemented and achieved without special equipment, and away from the bigger time and resource commitment at the experimental side of the process.

Further research should now be conducted by following the design methodology for different wave distributions and applying the data processing algorithms to verify the effectiveness and accuracy of the developed tools.

Additionally the measurement system and data acquisition process is an very significant element of the entire research methodology and should be appropriately examined separately.

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METODY PRZETWARZANIA DANYCH NA POTRZEBY EKSPERYMENTALNEGO MODELOWANIA FAL OCEANICZNYCH

STRESZCZENIE

W artykule przedstawiono analizę danych przeprowadzoną na potrzeby procesu fizycznego modelowania fal oceanicznych w basenach falowych. Metodologia opracowana została w celu realizacji badań hydrodynamicznych. Uwzględnia ona opis cyklu badawczego, teorię falową oraz metody przetwarzania danych pomiarowych. Istotnym osiągnięciem jest autorski algorytm przetwarzania danych służący praktycznej poprawie procesu generowania fal.

Słowa kluczowe:

przetwarzanie sygnałów, analiza danych, analiza widmowa, zakres stacjonarności, fale oceaniczne, metody badawcze.