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Modular Wavemaker Design for Harbours and Ships Physical Model Testing

Professional paper

The paper presents design and implementation of a portable modular wavemaker system for producing regular and irregular waves in laboratory basins and flumes. The system was built for the purpose of testing the impact of the sea waves on ships and coastal facilities. It is suitable for generation of all tipes regular and irregular surface waves. Modular system structure maintains high degree of flexibility and reusability. Finally, the testing process on the physical model of Split harbour is described, and the currently obtained results are shown.

Keywords: *wave maker, harbor*

Modularni generator valova - konstrukcija i primjena u ispitivanju fizičkih modela brodova i luka

Stručni rad

U tekstu je opisana konstrukcija i primjena prijenosnog modularnog generatora pravilnih i nepravilnih valova u laboratorijskim uvjetima. Generator valova izrađen je za potrebe ispitivanja utjecaja morskih valova na brodove i priobalne građevine. Prikladan je za stvaranje svih vrsta pravilnih i nepravilnih površinskih valova. Modularna izvedba sustava osigurava visoku fleksibilnost i upotrebljivost. Funkcionalnost sustava dana je opisom ispitivanja na modelu luke Split.

Ključne riječi: *generator valova, luka*

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1 Introduction

Design of new ships and coastal sea facilities requires many tests to be done prior to actual construction. Validity of construction plans is often verified by simulations on numerical models and on scaled-size physical models.

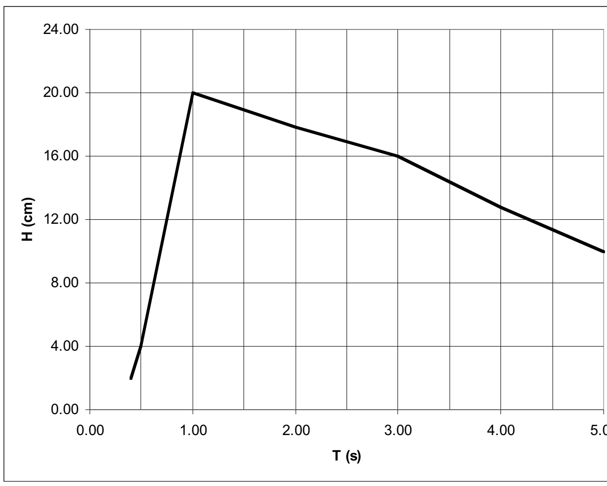
The article discusses design of portable modular wavemaker. The system was designed and built by *Brodarski Institute – Marine Research & Special Technologies, Zagreb Croatia,* in cooperation with *Faculty of Civil Engineering, Zagreb, Croatia*. It is installed in laboratory basin of *Civil Engineering Institute of Croatia*.

The goal of the project was to build a modular system which can be easily customised according to the end user requirements. Since the wavemaker is to be used mostly for shallow water wave generation, a piston-type paddle was chosen for water displacement. To achieve configurability, wavemaker paddle is broken to sections, each of which can be operated independently.

2 Wavemaker design

Wave producing system is designed as a two-dimensional piston-type wavemaker. Translational movement of the submerged paddles generates waves which propagate perpendicularly to the paddle surface. It is composed of 6 sections, each 3 m wide. Stroke of the piston equals 0.4 meters. Wave heights of up to 20 cm and wave periods of 0.4 - 5 s are supported. Performance graph of the system is shown in Figure 1.

Figure 1 **Wavemaker performance**
Slika 1 **Radna svojstva generatora valova**



a - Actuators and mechanical construction

Wavemaker section is composed of the frame, supporting the paddle submerged in the water. The frames are placed at the edge of the basin. Waves generated behind the frame are dampened using porous plates fixed to the frame. The frame and paddles are made of aluminium to minimize weight of the structure, while retaining construction strength and solidity.

Individual sections of the wavemaker can be grouped in various combinations. For example, all six paddles can be merged in a row to form one wide paddle, or they can be placed individually to generate waves from six different directions.

The paddle is actuated by electrical drive installed on the supporting frame, with a rigid link between the drive and the paddle, Figure 2. Optical encoder built in the drive is used to obtain paddle position. The wavemaker group, consisting of 3 sections, is shown in Figure 3.

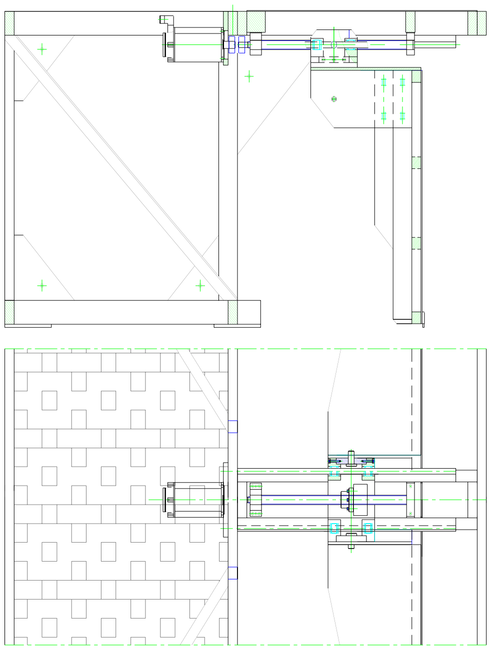


Figure 2 **Wavemaker section design**
Slika 2 **Nacrt sekcije generatora valova**

Figure 3 **Wavemaker - group of 3 sections**
Slika 3 **Generator valova - grupa od 3 sekcije**

Water surface elevation is measured by 20 electrical water level sensors, placed in front of the wavemaker and on the model. Sensors are used to verify the characteristics of the produced waves, and to analyze the behaviour of the water surface in the basin. Measurement is based on electrical resistance of the medium. Sensors used are BM500, manufactured by *Krohne*.

b - Control section

The wavemaker is controlled by personal computer (PC) via a programmable automation controller (PAC).

Paddle control, for all of the six paddles, and other real-time operations are performed by the programmable automation controller, NI CompactRIO 9012. The PC is used to set the experiment parameters, and to run and monitor the experiment.

Data transfer between the PC and the PAC is realized via LAN, over TCP-IP protocol. Interfaces to actuators and level gauges are achieved through a *floating point gate array* (FPGA) card within the PAC.

Block diagram of the wavemaker system is shown in Figure 4. η_a and X_a represent the surface elevation waveform and paddle movement control signals respectively, whereas η_i are the surface elevation signals measured on and in front of the wavemaker paddle. ω_{REF} is the velocity control signal for paddle motor axis, and ρ is the feedback signal of the motor axis angle.

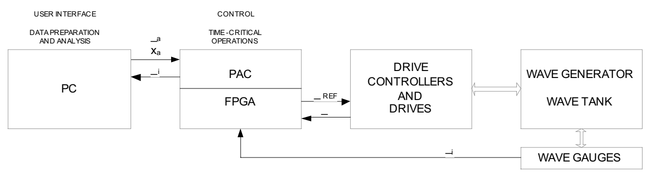


Figure 4 **Functional block diagram of the wavemaker system**
Slika 4 **Funkcionalni blok dijagram generatora valova**

Angle of the rotor is provided by incremental encoders embedded in the motors. Motor drives are equipped with an absolute encoder emulation module that outputs angle in the SSI (*Simple Sensor Interface*) communication protocol. The SSI signal is read in the PAC through a decoder implemented on the FPGA card. Motor control and wave gauges are read as analog voltage and current signals. *Indradrive* series by *Bosch-Rexroth* was used for motors and drives.

c - User interface

The wavemaker system is operated via user application installed on the PC. The following features are supported:
- simultaneous independent control of six paddles
- system configuration and setup of the experiment parameters
- starting/stopping the experiment
- online experiment monitoring
- data logging for offline analysis.

User application consists of two parts, experiment setup and online monitoring. In Figure 5, the user interface for experiment setup is shown. It is used to select paddle groups, set the experiment type and start the wavemaker. The graphs containing paddle movement and surface elevation signals and spectrum are interactively updated to represent the type of experiment set.

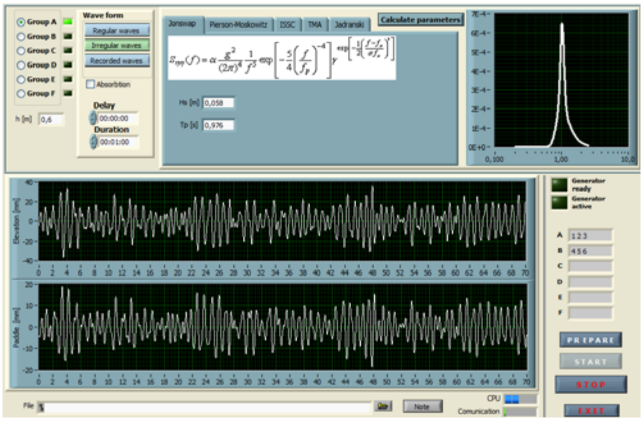


Figure 5 **User interface – experiment setup**
Slika 5 **Korisničko sučelje – postavke eksperimenta**

The user interface for online monitoring is displayed upon the start of the experiment (Figure 6). Signals from all level sensors can be displayed, with corresponding energy spectra of the signal.

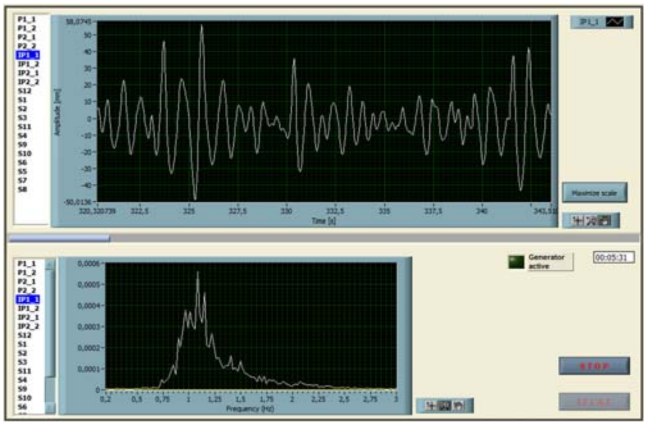


Figure 6 **User interface – online monitoring**
Slika 6 **Korisničko sučelje – nadzor eksperimenta**

3 Waveform calculation

Wind blowing across the sea surface transfers energy into the water. Initially, light winds generate small ripples on the water surface. The added roughness causes an increase in energy transfer and waves begin to form. By observing the energy spectra of sea surface elevations, waves with identical characteristics can be reproduced in wave flume or basin. Generation of such waves is performed here by translational motion of a vertical paddle submerged in the basin.

Different waveform calculation algorithm is used for each of the three kinds of wave forms: regular waves, irregular waves, and prerecorded waves.

Generation of all waveforms relies on Biesel equations to transform surface elevation data to paddle movement:

$$S_\eta\left(f\right) = 0 + ie_0 S_x\left(f\right), \tag{1}$$

where S_x represents paddle movement and S_η surface elevation data.

For piston-type paddles transfer function e_o is

$$e_0 = \frac{4\sinh^2\left(k_0 h\right)}{2k_0 h + \sinh\left(2k_0 h\right)}, \tag{2}$$

where k_0 is the wave number, and h is the water depth.

a - Regular waves

System design allows for all kinds of regular waves to be generated. The following wave types are presently supported:

- Stokes first-order,
- cnoidal, and
- solitary waves.

Waveform generation for Stokes first-order (sinusoidal) waves is based on the Biesel equations for piston-type wavemaker, (1) and (2).

b - Irregular waves

Irregular waves are used to simulate sea water behaviour in nature more accurately. The waveform is calculated from energy density spectra functions, specifically:

- Jonswap
- Pierson - Moskowitz
- ISSC
- TMA
- Adriatic Sea waves spectrum

Waveform is calculated from the discrete spectrum using the random phase method. Random phase is assigned to each component in the frequency domain [2]. Subsequent use of the Inverse Fast Fourier Transform (IFFT) algorithm provides the time domain representation of the wave train.

Energy density spectrum with added phase data is also used to calculate paddle movement. Prior to IFFT, the Biesel equation is used for each component in the frequency domain (1).

$$x\left(k\right) = \sum_{f=f_1}^{f_M} \sqrt{2S_x\left(f\right)\Delta f}\,\sin\left(2\pi f \Delta t k\right), \tag{3}$$

where S_x is the wave spectrum, f is the frequency, Δf is the frequency interval, Δt is the time period, f_1 is the starting frequency, and f_M is the maximum frequency.

c - Prerecorded waves

The wavemaker system is able to reproduce waveform made in software or acquired from measurement of natural waves. Paddle position data are computed in the following steps:

1 - calculation of wave spectral density,
2 - calculating paddle position data – inverse Biesel function in the spectral domain,
3 - frequency to time domain transformation.

It is also possible to rescale and resample loaded waveform to match the scaled model values.

4 Testing on the physical model

a - Model description

The model of the Split harbour was built in the *Water Engineering Department* laboratory of the *Civil Engineering Institute of Croatia* (*IGH*).

The city harbour of Split is scheduled for large reconstruction in a few years. Different variants of piers and docks are tested with an objective to get the best solution in wind wave suppression in the harbour. Testing is done with both regular and irregular waves. Wind waveforms are simulated using theories for developed sea waves.

Model scale is 1:50, with dimensions of 30 m x 25.0 m. The layout of the model is shown in Figure 7.

The current setup includes two wavemakers placed on the southwest and southeast of the harbour entrance. Each wavemaker is 9 meters wide. Routers are placed at the sides of the wavemakers to minimize wave dissipation between the paddles and the harbour entrance. The model is shown in Figures 8 and 9.

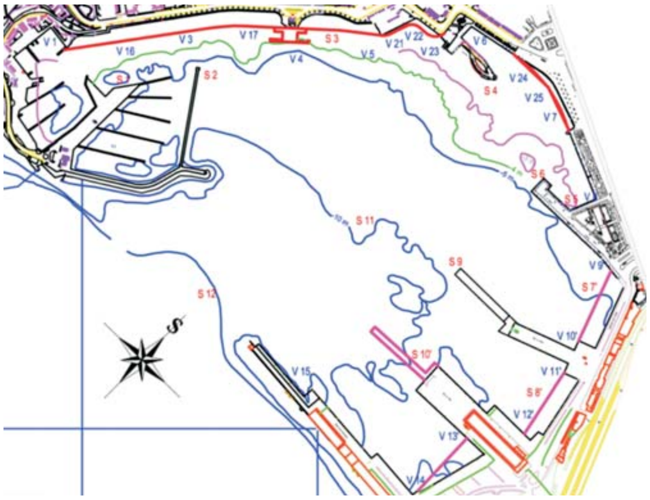
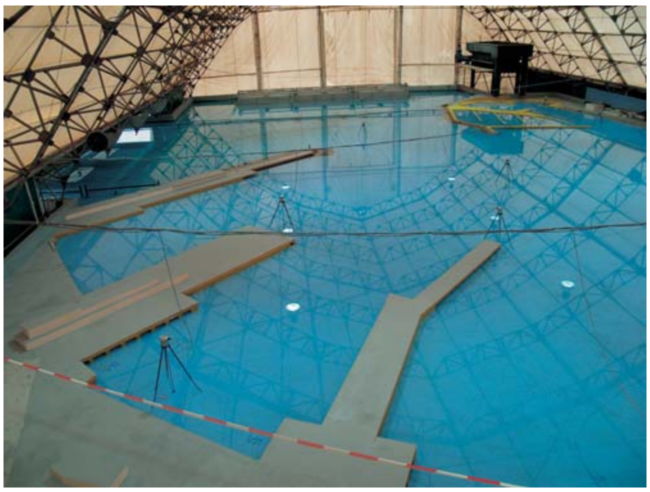


Figure 7 **Model of Split city harbour - layout**
Slika 7 **Model splitske luke – tlocrt**

Figure 8 **Split harbour model - south**
Slika 8 **Model splitske luke - jug**



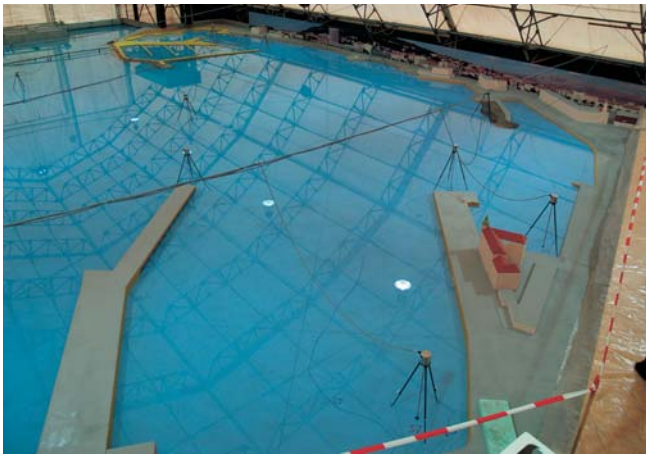


Figure 9 **Split harbour model - north**
Slika 9 **Model splitske luke - sjever**

b - Results

The main goal of model testing of the Split harbour is to analyze the impact of the reconstruction of harbour facilities on the propagation and reflection of sea waves. Yearly measurements of the wind speeds around the Split harbour have provided statistical data regarding the occurrences and directions of sea waves in front of the harbour. Based on the data provided, a set of experiments was prepared (Table 1). The experiment set was conducted on the harbour model, with and without planned harbour modifications. Reconstruction of the harbour is organized in phases. Thus, the impact of each modification can be inspected individually.

Table 1 **Experiment set**
Tablica 1 **Lista valova za eksperimente**

Wave type	Source direction	Wave height *Hn*[m]	Wave period *Tn*[s]	Model wave height *Hm*[m]	Model Wave period *Tm*[s]
Stoke's 1'	SE	2.0	4.38	0.04	0.62
Stoke's 1'	SE	2.9	5.28	0.058	0.75
Stoke's 1'	SE	4	6.2	0.08	0.88
Stoke's 1'	SW	2.1	4.49	0.042	0.635
Jonswap	SE	2.9	6.9	0.058	0.976
Jonswap	SE	3.6	7.7	0.072	1.089
Jonswap	SW	1.2	4.5	0.024	0.636
Jonswap	SW	2.0	5.6	0.04	0.806

Irregular waves were tested using Jonswap spectrum:

$$S_\eta^{JONSWAP}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right) \cdot \exp\left(\ln(\gamma)\exp\left(\frac{-\left(f-f_p\right)^2}{2\sigma^2 f_p^2}\right)\right) \tag{4}$$

$$\gamma = 3.3$$

$$\sigma = 0.07 \quad \text{for} \quad f \le f_p$$

$$\sigma = 0.09 \quad \text{for} \quad f > f_p$$

where α is the scaling parameter, γ is the peak enhancement factor, f_p is the peak frequency and σ is the spectral shape parameter.

An example of generated wave spectrum is shown in Figure 10. Jonswap spectrum is used with significant wave height of H_S = 2.9 *m* and a peak period of T_S = 6.9 *s*. Density spectrum shown in the figure is measured at the wavemaker, 2 meters in front of the paddles.

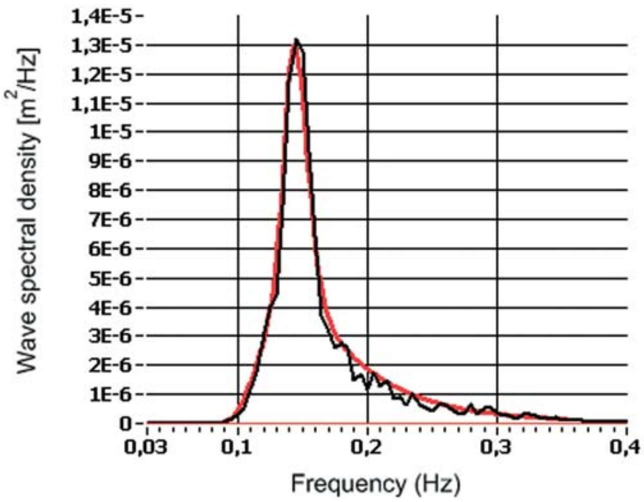


Figure 10 **Spectral density of control signal (red) and measured wave elevation (black)**
Slika 10 **Energetski spektar zadanog (crveno) i izmjerenog valnog oblika (crno)**

Once the necessary data are collected, they are sorted by measurement site and reconstruction phase for comparison and analysis. Figure 11 shows an example diagram of the data collected in one point, for four phases.

Figure 11 **Sample of measurement result**
Slika 11 **Primjer usporednih rezultata**

Irregular waves from the experiment set are also tested on the numerical model, for additional validation of the obtained results.

5 Conclusion

Modular wavemaker was built for the purpose of testing sea wave's interactions with ships and coastal facilities. The system was designed and constructed by *Brodarski Institute* in cooperation with *Faculty of Civil Engineering, Zagreb*. Modular implementation allows the system to be used in various combinations of paddle widths and wave propagation directions. It can also be reinstalled without difficulties in another basin or flume.

Measured spectral density deviation of obtained waveform to the control signal is within 5%, which proves the system suitable for intended purposes. Further work will focus on expansion of waveform calculation algorithms and improvements of wave making accuracy.

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