Wavemaker Control System for Irregular Developed Sea Waves Generation

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Abstract – The paper presents implementation and performance of an irregular sea wavemaker system. The system is designed for the purpose of testing sea waves impact on coastal facilities. It is suitable for long-crested two-dimensional irregular sea waves generation. The control algorithm is comprised of the offline calculation of the control waveform and the real-time governing of the wave paddle. Offline algorithm is implemented on a personal computer, whereas paddle control is realized on a programmable automation controller. The paper describes the generation procedure of a stochastic waveform according to criteria set in advance, as well as the control algorithm for producing the desired waveform. Functionality of the system is validated by experiments.

I. INTRODUCTION

Prior to major construction operations at large coastal sea facilities (ports, marinas), it is necessary to examine the impact of sea waves on the planned structure. Testing is done both by simulations using numerical models and on scaled-size physical models.

In nature, there are many causes for the forming of sea waves: wind, earthquakes, gravity influences of the Sun and the Moon. The article discusses only wind generated waves.

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 on the ocean surface. Waves have many different lengths and are moving randomly in the direction of the wind. How large the waves get depends on three factors:

- wind speed,
- length of the sea spanned by the wind (fetch), and
- the duration of time the wind blows.

The process of wave generation eventually achieves the balance between the wave energy accumulation and dissipation. Such state is called a developed sea.

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 usually performed by motion of a vertical paddle submerged in the basin. The paddle motion can be translational or rotational, the choice depending mostly on the basin water depth. The piston-based wavemaker, used for rather shallow waters, is described in this paper.

A wavemaker of irregular sea waves is designed and implemented for testing of sea waves impact on coastal structures (ports, piers, etc.). It is installed on the edge of a laboratory basin, in order to simulate waves coming from the open sea. It consists of six paddles (pistons) [4] placed side by side, with a total length of 18 meters. Wave heights of up to 20cm and wave periods of 0.4-5s are supported. The system is based on the linear wavemaker theory for two-dimensional waves [1].

II. SYSTEM DESCRIPTION

The main components of the wavemaker system are personal computer (PC), programmable automation controller (PAC), electrical motors and power system, resistance-based wave level gauges and wave paddles.

Desired surface elevation and paddle position time series are generated on a personal computer. PC is also used for acquisition and logging of the measured data. The application is implemented using the LabVIEW development environment, National Instruments (NI).

Paddle control and other real-time operations are performed by the programmable automation controller, NI CompactRIO 9012.

Data transfer between PC and PAC is realized via LAN,

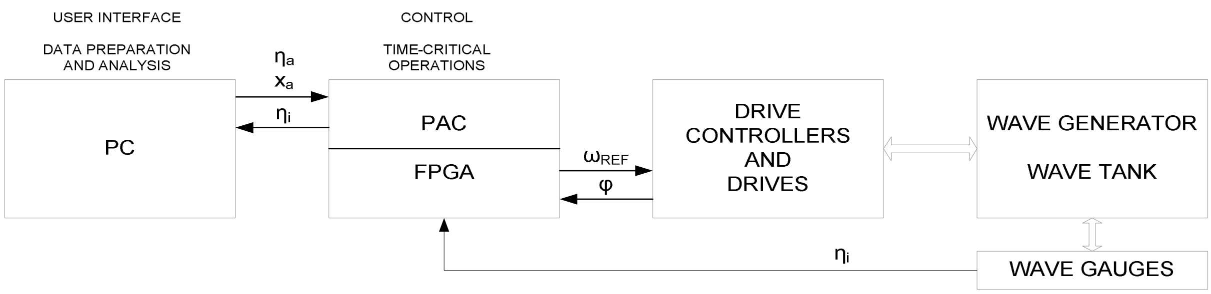

Fig. 1. Functional block diagram of the wavemaker system

using TCP-IP protocol. Interfaces to actuators and level gauges are achieved through a Field Programmable Gate Array card (FPGA) within PAC.

Block diagram of the wavemaker system is shown in Fig. 1. In the figure, η_a and x_a represent 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 φ is the feedback signal of motor axis angle.

The rotor angle is provided by incremental encoders embedded in the motors. Motor drives are equipped with absolute encoder emulation module that outputs angle in SSI (*Synchronous Serial Interface*) communication protocol. 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.

III. CONTROL ALGORITHM

The wave generation procedure consists of two steps:

- calculation of the desired surface elevation and paddle position data, and
- governing of the paddles according to the calculated control signals.

Surface elevation control signal is calculated in advance. Upon the start of the experiment, it is forwarded to the wavemaker control loop.

A. Calculation of the Control Signal

Wind-generated waves are by nature stochastic and consist of individual waves with different heights and lengths. Since most sea wave analysis deals primarily with the wave energy, wave characteristics are interpreted in frequency domain as a spectral density function.

Spectral density functions that are used for testing are empirical functions obtained by measurements in the world oceans. Most commonly used are the Pierson-Moskowitz and Jonswap spectra.

The Pierson-Moskowitz spectrum is based on measurements taken in the North Atlantic Ocean:

$$S_\eta^{PM}(f) = \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right), \quad (1)$$

where f is the frequency, f_p is the peak frequency, g is the gravitational acceleration, and α is the scaling parameter, $\alpha = 8.1 \cdot 10^{-3}$. The spectrum is suitable for fully developed wind sea analysis.

More accurate is the Jonswap spectrum, a generalized form of the Pierson-Moskowitz spectrum, found from field studies of wave-wave interactions in a finite bottom depth area [13].

$$\begin{aligned} S_\eta^{JONSWAP}(f) &= \frac{\alpha g^2}{(2\pi)^4 f^5} \exp\left(-\frac{5}{4}\left(\frac{f_p}{f}\right)^4\right) \cdot \\ &\exp\left(\ln(\gamma)\exp\left(\frac{-(f-f_p)^2}{2\sigma^2 f_p^2}\right)\right) \\ \gamma &= 3.3 \\ \sigma &= 0.07 \quad \text{for} \quad f \le f_p \\ \sigma &= 0.09 \quad \text{for} \quad f > f_p \end{aligned} , \quad (2)$$

where α is the scaling parameter, γ is the peak enhancement factor, and σ is the spectral shape parameter. Usually, the wave spectrum is defined by two parameters: the peak frequency f_p and the significant wave height H_S.

Jonswap spectrum defined by H_S and f_p can be calculated by using (2) with $\alpha = 1$ first. Significant wave height of the generated spectrum can be estimated with:

$$H_S \approx 4\sqrt{\int_0^\infty S_\eta(f)df} \ . \quad (3)$$

The scaling parameter α can then be readjusted according to (3), in order to obtain the spectrum function with correct H_S.

Once the desired wave spectrum is chosen, the surface elevation signal having such spectrum needs to be generated. To achieve this, the spectrum is discretized to M equidistant samples. M has to be large enough to enable fine reproduction of the spectrum.

Each sample represents amplitude of one harmonic in the resulting signal. Phase is chosen randomly for each harmonic. The resulting elevation signal is calculated as a sum of individual harmonics[2]:

$$\eta(k) = \sum_{f=f_1}^{f_M} \sqrt{2S_\eta(f)\Delta f} \cos(2\pi f \Delta t k + \varphi(f)), \quad (4)$$

where k is the time index, Δt is the time step of the control signal, Δf is the frequency interval, $\varphi(f)$ is the signal phase offset.

Surface elevation of the wave caused by paddle motion is described by the Biesel equation:

$$\eta(f) = 0 + ie_0 x(f), \quad (5)$$

where $\eta(f)$ and $x(f)$ are surface elevation and paddle motion in frequency-domain, respectively, and e_0 is the wave transfer function, dependent on the type of the paddle. Surface elevation and paddle movement signals are shifted by 90 degrees.

For piston-based paddles transfer function e_0 is

$$e_0 = \frac{4\sinh^2(k_0 h)}{2k_0 h + \sinh(2k_0 h)}, \quad (6)$$

where k_0 is the wave number, and h is the water depth [2].

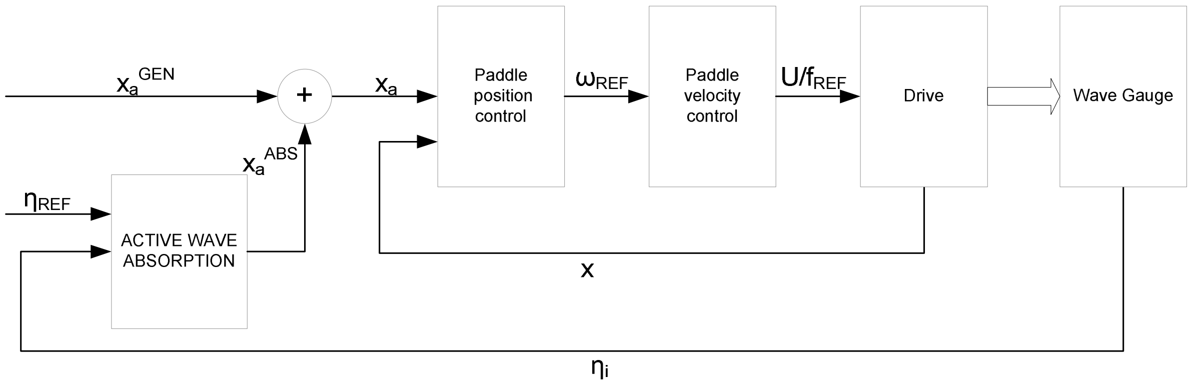

Fig. 2. Setup of the Real-time control loop

Equation (5) describes surface elevation in front of the paddle. Evanescent modes, which appear only at the paddle surface and disappear as the wave progresses, are not accounted.

Using Biesel functions, paddle control signal can be calculated from the wave spectrum [1]:

$$S_\eta(f) = ie_0 S_x(f) \qquad (7)$$

and, same as with equation (4):

$$x(k) = \sum_{f=f_1}^{f_M} \sqrt{2S_x(f)\Delta f}\,\sin\left(2\pi f \Delta tk + \varphi(f)\right) \qquad (8)$$

B. Wave and Paddle Control System

The algorithm for paddle control is organized in three layers. The top layer functions as a state machine; it is used for starting, stopping and supervision of the control system, and as an interface to the PC. In the middle layer the control loop is implemented. The bottom layer is used to interface the actuators and wave gauges; it is implemented at the FPGA platform of the PAC.

A cascade of PID controllers is used to govern the paddle. Paddle position feedback is deduced from the angle of the motor axis, which is possible due to the rigid link between the motor shaft and the paddle. Motor power transducers are equipped with rotational speed controllers, also based on cascade control, the inner loop being used as motor current governor.

With regard to the wave generation, the described control scheme belongs to the direct control paradigm, not having the feedback, making it sensitive to disturbances, especially wave re-reflection. The re-reflection occurs when the generated wave bounces off from the end of the wave flume and returns to the wavemaker paddle.

The re-reflection problem is addressed by introduction of additional feedback obtained by water level measurement at the paddle. The feedback signal is subtracted from the control signal to obtain the control deviation. Corrective movement of the paddle is derived using (5). The output signal of the reflection absorption algorithm is added to the direct paddle control signal [1], [12].

$$X_a = X_a^{gen} + X_a^{abs}, \qquad (9)$$

$$X_a^{abs} = (A_I - A_0)\frac{1}{ie_0} \qquad (10)$$

where X_a^{gen} is the direct paddle control signal computed offline and X_a^{abs} is the corrective paddle movement. A_I and A_0 are the Fourier transforms of the wave elevation control signal and measured elevation at the paddle front, respectively.

The algorithm described uses Biesel equations to transform waveform deviation to the paddle movement, thus it is necessary to transform all the signals to Fourier-domain in real-time. Inverse Fourier transform is used to obtain control signal in time-domain [1], [5].

In Fig 2, block diagram of the control loop is shown.

The absorption algorithm could be further improved by taking evanescent modes into account. Some additional deviations might also occur from the nonlinearities in the system, as the algorithm relies on the linear wavemaker theory.

IV. TESTING RESULTS

As an example, the wavemaker system is tested in laboratory basin built for the purpose of testing sea waves

Fig. 3. Model of Split harbor – basin layout

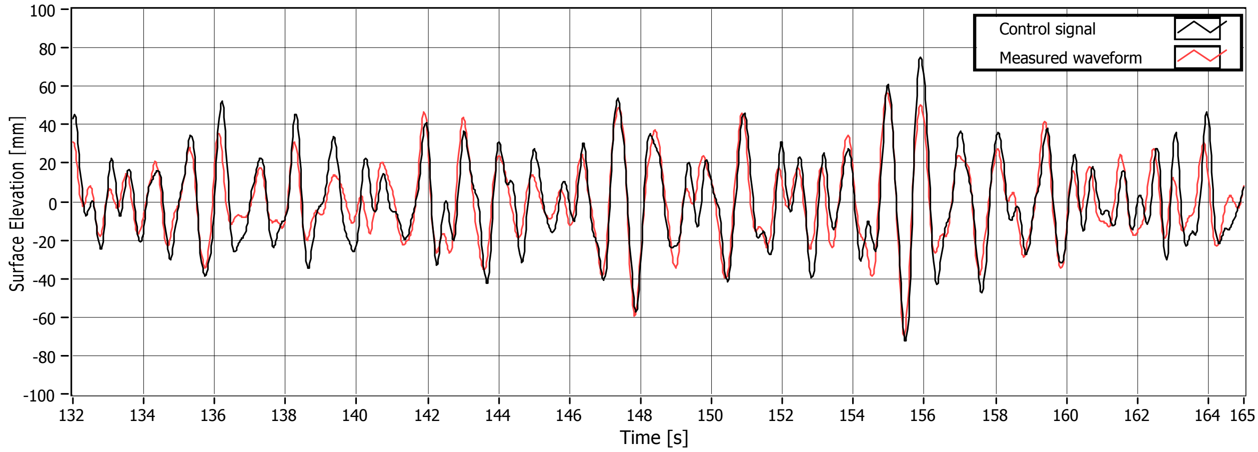

Fig. 4. Control signal and measured wave elevation in front of the paddle

impact on Split harbor, Croatia. Basin layout with wavemaker (red line) is shown in Fig 3.

The waves to be generated are described by the Jonswap spectrum having significant wave height $H_s = 0.083m$, and peak period $T_p = 1.089s$. Water depth at the paddles of the wavemaker is 0.6m. The spectrum is discretized to M=230 samples. Duration of the experiment is set to 20 minutes.

Fig. 4. shows control signal and surface elevation measured in front of the wavemaker paddle. Spectral density of the measured wave compared to the reference spectrum is shown in Fig. 5. Both figures show a good match between the control signal and the measured data.

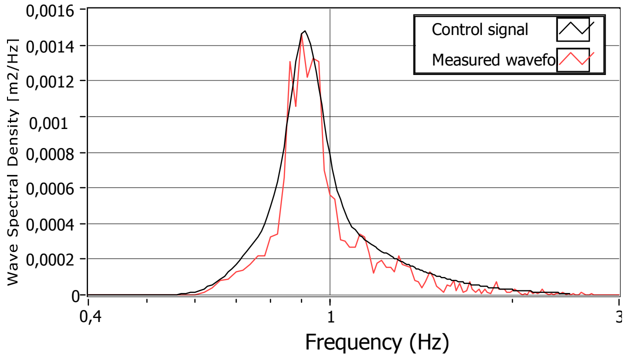

Fig. 5. Spectral density of control signal and measured wave elevation

V. CONCLUSION

A wavemaker producing irregular sea waves has been built for the purpose of testing sea waves impact on coastal facilities. The Control section of the wavemaker was implemented on a personal computer and programmable automation controller. Thus, benefits of both platforms were combined. PC provided computational power and memory necessary for fast calculation of long time series, whereas time-critical operation of PAC was used for real-time control and acquisition. The system implemented is also suitable for remote operation via TCP-IP protocol.

Tests conducted in laboratory basin confirm system functionality and usability for analysis of the sea waves interactions with coastal facilities.

Future work will focus on the improvement of wave absorption algorithm. Evanescent modes are to be included into equation. Including additional sensors in the equation should also improve the quality of the control algorithm.

VI. REFERENCES

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