Spectral Patterns for the Generation of Unidirectional Irregular Waves

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Abstract. The wave is a complex and important phenomenon for structures designs in the coastal zones and beaches. This paper presents a novel system for the generation of spectral patterns of unidirectional irregular waves in research laboratories. The system's control basic elements are a linear motor, a servo controller and a personal computer. The used main mathematical tools are a feed forward neural network, digital signal processing and statistical analysis. The research aim is to obtain a system of more accuracy and small response time. This behavior is interpreted, in marine hydraulics, as a fast calibration of experiments. The wave power spectrums are generated in a test channel of rectangular section with dimensions: length 12 m; depth 40 cm; width 30 cm.

1 Introduction

The design of coastal and maritime works is complex. The wave is a main element and its mathematical representation is difficult [1], [2]. The mathematical models make possible to represent the sea disturbance and to calculate its effects, although in many cases, they need a calibration by means of physical modeling on reduced scale [3], [4], [5], [6], [7]. In complex maritime work designs, the physical modeling on reduced scale is essential. This paper presents a system for the generation of spectral patterns of unidirectional irregular waves, in project and research laboratories. The system main elements are digital signal processing, neural network and linear motor.

The research aim is to obtain a system of easy operation and greater efficiency with respect to traditional methods. The traditional methods make a control of open loop and the operator has a fundamental function. In this work, we used a combined neural control [8], [9], [10] that makes shorter the transitory response. This behavior is interpreted, in marine hydraulics, as a fast calibration. In addition, the spectral patterns of the generated wave will have small errors with respect to the reference spectral patterns.

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2 Technical Support and Schemes of Operation

Fig.1 presents the combined neural control to generate spectral patterns of irregular unidirectional wave, where:

S_T : Target spectrum; S_G : Generated spectrum.

The controlled process is a wave channel and the control final element is a generator formed by a linear motor and a paddle device (see photo in fig 2).

A linear motor [11] is a type of electric motor, an induction motor in which the fixed stator and moving armature are straight and parallel to each other (rather than being circular and one inside the other as in an ordinary induction motor). Linear motors are used, for example, in power sliding doors. There is a magnetic force between the stator and armature; this force has been used to support a vehicle, as in the experimental maglev linear motor train [12].

A controller PI (proportional-integral) and an inverse neural network (INN) form the combined control.

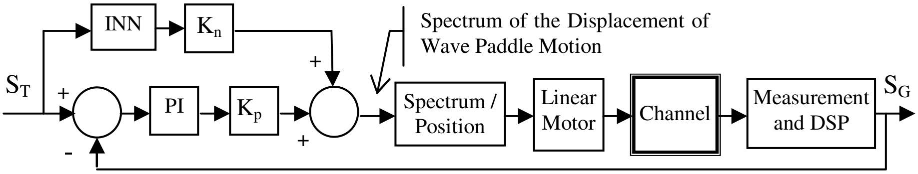

Fig. 1. Combined neural control to generate spectral patterns of irregular unidirectional wave

Fig. 2. Linear motor with paddle device and a channel of irregular and unidirectional wave

3 Wave Generation Theory

Eq. (1) is basic for the spectral analysis of a registry of irregular wave in a fixed station, and this defines the spectral density function *S(f)* [2].

$$\sum_{f}^{f+df} \frac{1}{2} a_n^2 = S(f)df \tag{1}$$

This equation, nevertheless, contains an infinite number of amplitudes a_n of components of the waves and, therefore, is not applicable to practical calculation. For the practical analysis, a wave registry of N points is acquired, with a constant sampling period: η(Δt), η(2Δt),…η(NΔt). Analyzing the harmonics of the wave profile η(t), the profile can be expressed as the well-known finite Fourier series [2], [13]:

$$\eta(t) = \frac{A_0}{2} + \sum_{k=1}^{N/2-1} (A_k \cos(\frac{2\pi k}{N} t_*) + B_k \sin(\frac{2\pi k}{N} t_*)) + \frac{A_{N/2}}{2} \cos(\pi t_*) \tag{2}$$

$$\mathrm{t}_* = t / \Delta t : t_* = 1, 2, 3, ...N$$

The wave power spectrum can be generated by two general methods: first, in discreet form, with a series of Fourier and the components of power of each harmonic. Second, in the continuous form, with the significant wave height and period and empirical equations of spectrum such as the Mitsuyasu [2], [8], Pierson and Moskowitz, JONSWAP [2], etc., for example, the spectra of wind waves fully- developed in the open sea, can be approximated by the following standard formulas:

$$S(f) = 0.257 H_{1/3}^2 T_{1/3}^{-4} f^{-5} \exp[-1.03(T_{1/3} f)^{-4}] \tag{3}$$

$$S(f) = 0.205 H_{1/3}^2 T_{1/3}^{-4} f^{-5} \exp[-0.75(T_{1/3} f)^{-4}] \tag{4}$$

where $H_{1/3}$: is the significant wave height; $T_{1/3}$: is the significant wave period; f : is the frequency.

Fig 3 presents an example of sea spectrum. The dash-dot line is the result of fitting Eq. (4) with the values of the significant wave height and period of the record. Although some difference is observed between the actual and standard spectra, partly because of the shallow water effect in the wave record which was taken at the depth of 11 m, the standard spectrum describes the features of the actual spectrum quite well.

The wave generator of mechanical type is more useful and simple and it reproduces better the wave forms. The theory of displacement of the beater (paddle) and the characteristics of the generated waves are studied by several investigators [2], [3], [4], [8].

The desired wave power spectrum is multiplied by the transfer function of the wave generator, well-known as the equation of efficiency of the paddle. This transfer function is obtained solving the differential equation for the free boundary conditions (see Eq. 5 and 6)

Piston type:

$$F(f,h) = \frac{H}{2e} = \frac{4\sinh^2(2\pi h/L)}{4\pi h/L + \sinh(4\pi h/L)} \tag{5}$$

Flap type:

$$F(f,h) = \frac{H}{2e} = (\frac{4\sinh^2(2\pi h/L)}{4\pi h/L})(\frac{1-\cosh(2\pi h/L) + (2\pi h/L)\sinh(2\pi h/L)}{4\pi h/L + \sinh(4\pi h/L)}) \tag{6}$$

where H is the height of the produced wave in the channel; e is the amplitude of wave paddle at the mean water level; f denotes the wave frequency; L is the wavelength; h is the depth of the water at the front of the paddle in the channel.

The Inverse Fourier Transform is applied to product of Eq. (3) or Eq. (4) and Eq. (5) or Eq. (6) to obtain the wave signal in time domain. The Fig.4 presents the process of the preparation of input signal to an irregular wave generator. The control systems, in general of open loop, need a relatively great time for the calibration each experiment in order to generate a wave spectral pattern (target spectrum).

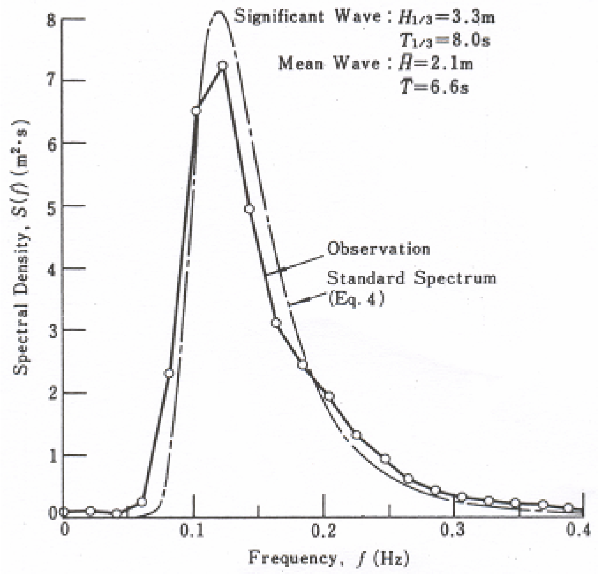

Fig. 3. Example of spectrum of sea waves

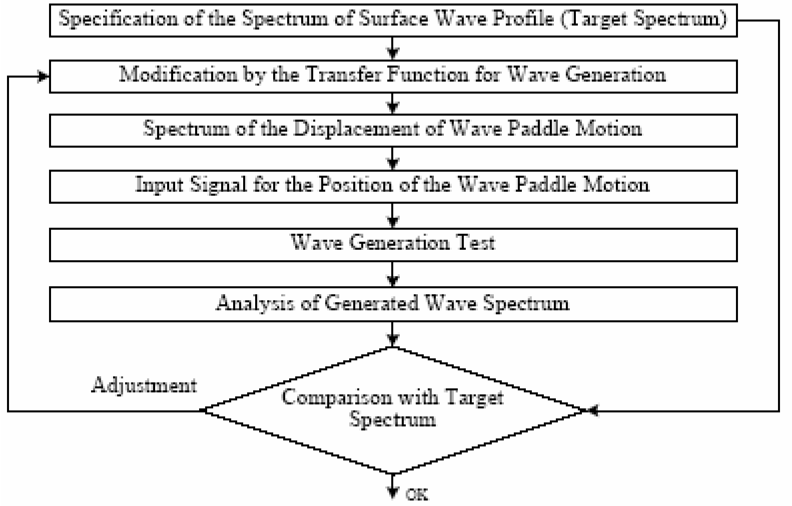

Fig. 4. Process of the preparation of input signal for an irregular wave generator

4 Feed Forward Neural Network

For identification and control systems, an artificial neural network (ANN) with three layers is adequate. A hidden layer is sufficient to identify any continuous function [10], [11], [14], [15]. The input neurons are determined by the number of frequency bands where the spectrum is divided. The tests were made with 128 and 64 inputs. The best results were obtained with 64 (training error and epochs). Another input neuron is added for the different water levels in the channel. The hidden layer uses a sigmoid function. The output layer uses a lineal function. The number of neurons of the output layer is determined by the number of frequency bands, where the generated wave spectrum will be divided (the number of output neurons were taken equal to the number of input neurons).

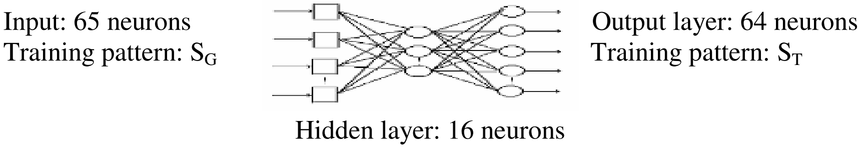

Fig. 5. Neural network topology

4.1 Training Patterns

P^{μ} : Input patterns [$f(1)$, $f(2)$,........$f(nf)$, h]

T_0^{μ} : Output patterns [$f_o(1)$, $f_o(2)$,........$f_o(nf)$]

where f: power spectrum harmonics; h: channel level

Quality factor in spectrum estimation:
Generally, the sea disturbance is simulated by a random (pseudorandom) process. The variability of the sea disturbance spectrum is given by:

$$\hat{S}(f) = S(f)\chi_2^2 \tag{7}$$

The variability of the spectrum is determined by the chi-square distribution with two degrees of freedom, that is the estimation by the periodogram method [2]. In order to reduce the variation, the temporary registry of the wave measurement is divided in a set of M windows. The training patterns for neural network are obtained according to the scheme in Fig. 6.

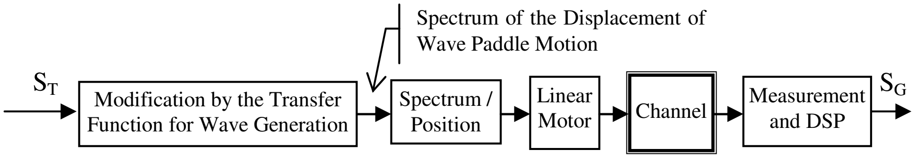

Fig. 6. Acquisition scheme for the neural network training patterns

4.1.1 Patterns and Neural Control Versus Open Loop Control

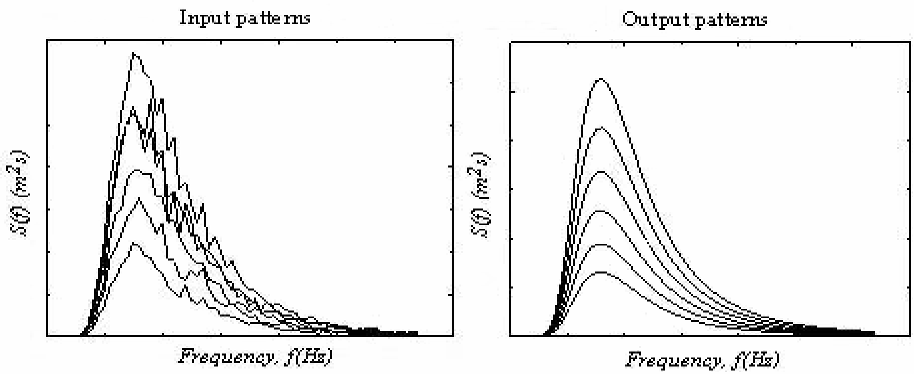

Fig. 7. Example of Patterns .Training performance is 6.97697e^{-10}, Goal is 1e^{-10}. Epochs: 25.

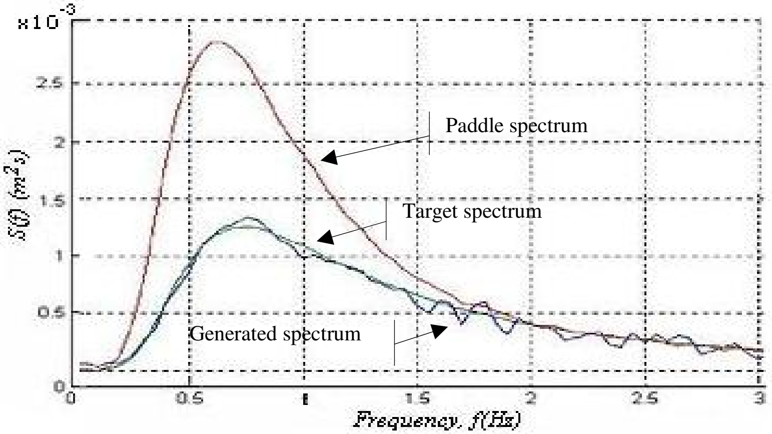

Fig. 8. Example of neural control performance

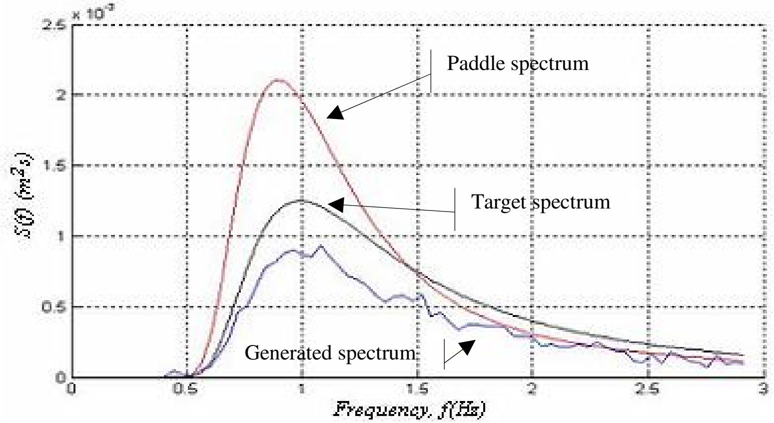

Fig. 9. Example of open loop control performance

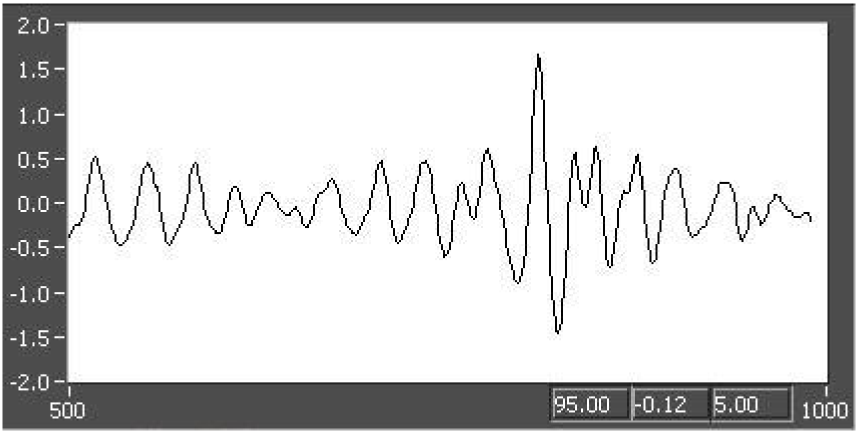

Fig. 10. Example of irregular wave profile. Axis X: samples; Axis Y: water level in cm.

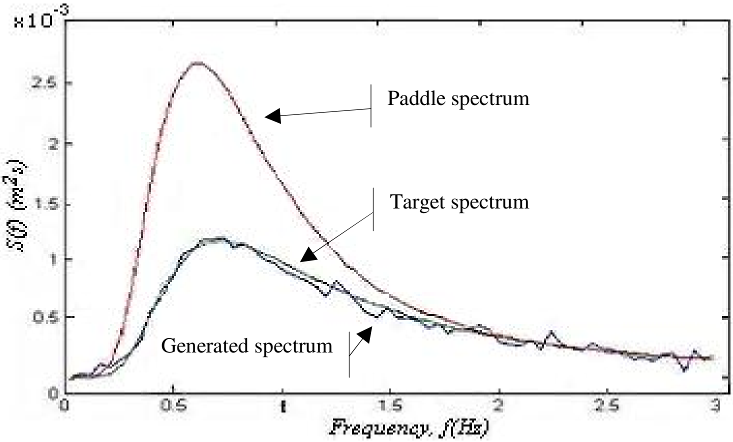

Fig. 11. Neural control performance for the irregular wave profile in Fig. 10

5 Conclusions and Future Work

The coastal and maritime work are complex and highly expensive. The optimal design requires the physical modeling. The sea phenomena are reproduced in the hydraulic research laboratories, this way, the designs can be tested. This works include “pedraplenes”, oil platforms, artificial beaches, protective installations of the coasts, conservation of the ecosystem, etc.

The presented work on the spectral patterns for the generation of unidirectional irregular waves creates a novel method that uses linear motors and neural networks to generate irregular wave with high accuracy and fast calibration, obtaining satisfactory results. The combined neural control allows to generate spectrums more exact than the spectrums generated with conventional systems (open-loop control). The system does not require an expert operator in "experiments calibration". The linear motors reduce the mechanical facilities. The hydraulic pistons and complex electro-mechanic devices are unnecessary.

The control is made with a distributed architecture, because the linear motor has a system of independent control.

For the future work, self-learning elements will be introduced. These elements will make possible to create spectral patterns during the operation of the system and to suggest a new training of the neural network, when the conditions of channel operation have large changes.

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