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Designing, Programming and Feasibility study of a Paddle Wavemaker to increase quality and decrease production costs

Karim Kenarkoohi [1], Ruhollah Jafari [2*], Mostafa Tamtaji [3]

1. Department of Physics, Malek Ashtar University of Technology, Tehran, Iran.
2. Department of English Language, Humanities Faculty, Shahid Rajaee Teacher Training University.
3. Department of Service Management and Technology Development, Allameh Tabataba'i University, Tehran, Iran.

Abstract

Quality needs to be included in the core of the manufactured products; it should not be left to the after-production inspection. Hence this paper aims at changing the structure of the wavemakers which are mainly mechanical to electronically controlled devices from the beginning of the design process in order to lead to increased quality. Besides, to increase the accuracy of the produced waves, servomotor which is better controlled is used instead of stepper motors. Designing a marine structure requires marine laboratories and model testing. In such laboratories, a device called wavemaker is needed to create and model sea waves. In this project, first samples of existing water flume and wavemaker are analyzed. Then basic information about design and construction is extracted. Afterward, the initial outline for the wavemaker is proposed and detailed design is done. The initial goal is to build a scale-appropriate model for use in the laboratory that could generate regular waves with maximum amplitude. This requires a servomotor and ball screw system. Albeit such a scheme was considered so that it would be similar to the original system, which could later, produce irregular waves with the desired spectrum; otherwise, in the case of using other systems, which are much simpler and cheaper than the servo system, we would be able to produce regular waves. Some programs are written to create a regular wave and an appropriate set of controls for generating a regular and irregular wave are created to prepare the system for producing irregular waves, if necessary. Although due to the limitation of the dimensions we might not be able to generate such waves in the laboratory, it can be used in the integrated water flume to generate irregular waves. Given the range of the desired waves, the best system for producing irregular and regular a wave in flume is the paddle wavemaker for which the designs are provided.

Keywords Sea wave modeling, Paddle wavemaker, Servomotor

Introduction

It is known that "the only criterion for measuring performance is the cost of quality" [1]. The only acceptable standard is zero defect work. In fact, zero defect production means to do the job right from the start. Therefore, this paper is aimed at designing correctly and using electrical commands instead of the mechanical ones to reduce production costs from the start of the designing, in other words to increase the quality. To do so, servomotors are chosen because they enjoy the capability of electrical sig-

* Correspondence:
Ruhollahj@sru.ac.ir

nals reception. The servomotor is designed so as to have built-in microcontrollers that can do a great deal of tasks using very simple commands. In addition, using servomotors can lead to reduction of size, noise and contamination which are dire burdens of mechanical systems.

Commonly manufactured wave generators are paddle wavemakers and Piston wavemakers [2] either of which can generate regular and irregular waves. They selection is proportionate with water depth. Since it is easier to analyze and theoretically explain the relations of regular waves compared to irregular waves, the waves are usually considered regular which later combine to yield irregular waves [3]. The piston wavemaker generates concurrent and roughly similar waves in the water flume [4], [5]. In practice, this kind of wavemaker is used in flumes where shallow water tests are implemented because there is a rather weak flow of water resulted from the generated waves. However, the rotation center in the paddle or hinged wavemaker is fixed such that it is mainly used in deep water tests because it generates no flow at the bottom of the flume [6]. Therefore, as the waves generated by the paddle/hinged wavemaker are very similar to the deep-water waves and deep water is much more similar to the real situations, this kind of wavemaker will produce better results (see figure 1).

2. Background Research

The development of an effective mathematical model of a control system used in an irregular wave maker-hinged flap type, featuring active wave reflection compensation is discussed in the paper titled “a wave maker with active reflected wave compensation system” by Fábio Nascimento et al. (2002) [7]. The writers conclude that ‘a very efficient absorbing scheme can be developed for a wide range of reflected wave frequencies. Also, absorbing features can be easily implemented with relatively low hardware cost, on a wave-maker with a computer based closed loop controller’.

A new active absorption system based on wave gauges mounted on the moving paddle was presented by T.Lykke Anderson et al. (2016) [8] in the paper titled “A new active absorption system and its performance to linear and non-linear waves” .The active absorption system was extended to cases where the wave gauge had a gap to the paddle face. Such gap could be used to compensate wavemaker systems with large control delay. The active absorption transfer function was approximated by a FIR filter which led to similar or slightly better performance than IIR filters applied in earlier studies.

S.H. Salter (1981) in the paper “Absorbing Wave-Makers and Wide Tanks” [9] which was presented in *The Conference on Directional Wave Spectra Application* stated that’ displacement of a wave-maker is a bad signal to use for control. The size of wave created is affected by reflections and waves from adjacent units. Several techniques can be used to absorb unwanted waves, but force measurement is attractive on practical grounds. Absorption makes for good stability. Asymmetric wave-makers save power and the cost of power control elements. Asymmetry can be achieved for piston displacers for shallow water, but flaps are good for deep water. Directional spectra can be generated by the superposition of discrete monochromatic wave fronts. Provided that sufficient fronts are used it is difficult to distinguish the sea state from that of a continuous spectrum. The discrete method enables the controlled composition of abnormal seas.

The paper “Closed-loop Discrete-time Control of a Hinged Wavemaker” by S.E. Hodge and D.B. Chechas (1988) developed a control strategy for the discrete-time control of a particular wave generation system using conventional discrete-time control theory [4]. The main difference from conventional discrete-time control theory in their work was the use of a long duration discrete timestep between successive controller actions. They showed that an effective stability analysis is possible and useful for determining control parameters assuming that for each frequency in the desired wave spectrum, there is a unique controller gain combination as opposed to using one gain combination for all frequencies.

M.H. Patel and P.A. Ionnaou (1980) in the paper “Comparative Performance Study of Paddle and Wedge-Type Wave Generators” carefully measured the wave generating performance of a paddle- and wedge-type wave generator and compared with predictions from linear theory [6]. They concluded, despite the fact that a good agreement between theory and experiment is obtained, the tests highlight the importance of avoiding both wave generator edge leakage and wave reflection effects if optimum performance is required of the generators when installed in a wave testing tank. Finally, they suggested alternative methods of overcoming both of these difficulties.

The paper “Dynamic covariance Equations for hinged wavemakers” by Robert T. Hudspeth and John W. Leonard (1980) verified experimentally the squared modulus of the theoretical dimensionless frequency response functions for the wavemaker stroke spectrum and for the wavemaker hydrodynamic pressure moment spectrum of the hinged wavemakers [5],[10]. The writers showed that ‘the use of the theoretical dimensionless frequency response functions for the stochastic design of hinged wavemakers of variable-draft now appears to be experimentally justified by these unique measurements of hydrodynamic pressure moment spectra on hinged wavemakers.

W.M. Kusumawinahyu, et al., in the paper titled “linear theory for single and double flap wavemakers" concerned themselves with deterministic wave generation in a hydrodynamic laboratory [11]. They developed a linear wavemaker theory based on the fully dispersive water wave equations and considered both single-flap and double-flap wavemakers. The velocity potential and surface wave elevation were derived and the relation between the propagating wave height and wavemaker stroke was formulated. This formulation was then used to find how to operate the wavemaker in an efficient way to generate the desired propagating waves with minimal disturbances near the wavemaker.

3. Paddle/hinged wavemaker equations

Paddle wavemaker performs very well in deeper tanks. In this type of wavemaker the wave plate is hinged from one side to the bottom of the tank and the other side is moved which eventually results in the wave generation. Like the piston wavemaker, in order to achieve a better performance, the sealing between the wave plate and the walls has to be observed. Displacement velocity of the wave plate at different distances from the water line is very close to the velocity of the water particles beneath the wave crest and the wave trough from the water line to water depth, which is why this type of wavemaker performs well in deeper tanks. Figure 2 shows an overview of the paddle wavemaker and how a wave is created in the paddle/hinged wavemaker.

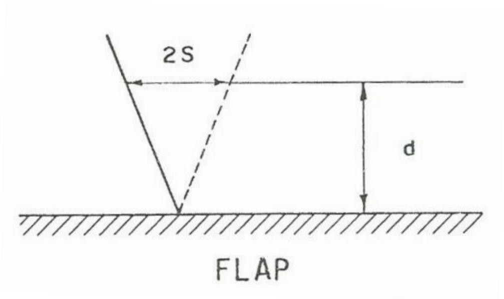

Fig 1. The paddle/hinged wavemaker [11]

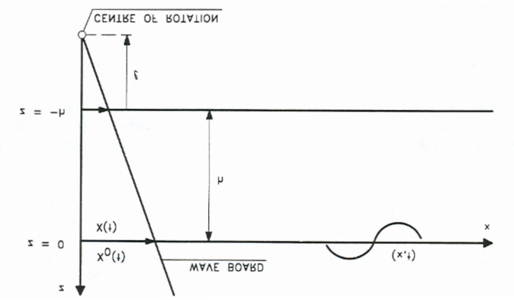

Fig 2. How to create a wave in a paddle wavemaker [6]

The following relationship expresses the wave height-to-stroke ratio of a paddle wavemaker system resulting from the Laplace's equation.

$$\frac{H}{S}=\frac{4\sinh kh}{\sinh 2kh+2kh}\left[\sinh kh+\frac{(1-\cosh kh)}{kh}\right]$$

In this relationship, it is assumed that the wave plate has been hinged at the bottom of the flume and ***h*** is the depth of the flume.

The following relationship describes the wave plate motion equation in the paddle wavemaker [12].

$$X(t)=\frac{H}{2m_1}\sin\sigma t+\frac{H^2}{16h}\left(\frac{3\cosh kh}{\sinh^3 kh}-\frac{2}{m_1}\right)\sin 2\sigma t$$

$$m_1=\frac{4\sinh kh}{\sinh 2kh+2kh}\left[\sinh kh+\frac{(1-\cosh kh)}{kh}\right]$$

Where:

X: hinge location, **H**: wave height, σ: Frequency, **t**: time, ***h***: flume depth, **k**: wave number and equal to $\frac{2\pi}{L}$ where L is wave number

Having the wave plane displacement equation in the paddle wavemaker clarified, the speed and spatial position of the wave plate can be controlled with good accuracy.

4. Design details

Since the paddle wavemaker is used in deep water, **d/λ** must first be calculated, which should be greater than 0.5 for deep water to meet the deep-water condition. Given that the depth of the flume is known, **λ** can be calculated [12], [3].

Now the ratio for each force could be calculated. Since **λ** and **H** are known in each force, by obtaining the **λ** and $\frac{H_1}{H_2}=\lambda_1/\lambda_2$, the ratio $\frac{H_1}{H_2}$ and as a result, the model ratio is obtained. H_2 is also obtained.

For example, for a model with force 4 and depth 0.7 m, the following equation exists:

$$H_1=0.77\text{m}\ ,\ \lambda_1=25\text{m}$$

And from the deep-water relationship we have:

$$\frac{d}{\lambda}>0.5\Rightarrow\lambda<\frac{\mathrm{d}}{0.5}=\frac{0.7}{0.5}=1.4\Rightarrow\lambda_{\max}=1.4\mathrm{m}$$

$$\frac{0.77}{H_2}=\frac{25}{1.4}=17.86\Rightarrow H_2=0.043m=4.3cm$$

$$T=\sqrt{\frac{\lambda}{1.56}}=0.95\mathrm{s}\Rightarrow\mathrm{f}=1.06\mathrm{Hz}$$

$$\frac{\mathrm{H}}{\mathrm{S}} = \frac{\pi}{\lambda} d = \frac{\pi}{1.4} * 0.7 = 1.57 \Rightarrow \mathrm{S} = \frac{\mathrm{H}}{1.57} = .027\mathrm{m} = 2.7\mathrm{cm}$$

To find the maximum power required, a condition needs to be considered where a wave with the maximum amplitude is generated. In this case, an additional condition must also be considered which is the wave steepness condition or $\frac{\mathrm{H}}{\lambda} < \frac{1}{7} = 0.14$ [5]. Hence, to calculate the maximum height and velocity, one must calculate **λ** from the above relation with respect to the depth and calculate the time **T** using the equation and then obtain the frequency. In this case, the value of **H** should be calculated using the wave steepness condition or $\frac{\mathrm{H}}{\lambda} < \frac{1}{7} = 0.14$ which is the maximum wave height and can be used to calculate the stroke. Using the existing equations, one can calculate the wave plane velocity and its acceleration, as well as the applied forces and the desired power.

For example, for the desired flume in the laboratory with a water depth of 0.7 we have:

$$\frac{d}{\lambda} > 0.5 \Rightarrow \lambda < \frac{\mathrm{d}}{0.5} = \frac{0.7}{0.5} = 1.4 \Rightarrow \lambda_{\max} = 1.4\mathrm{m}$$

$$T = \sqrt{\frac{\lambda}{1.56}} = 0.95\mathrm{s} \Rightarrow \mathrm{f} = 1.06\mathrm{Hz}$$

$$\frac{\mathrm{H}}{\lambda} < \frac{1}{7} = 0.14 \Rightarrow \mathrm{H} < \frac{1}{7} * \lambda = \frac{1.4}{7} = 0.2m$$

Considering the deep-water assumptions, the plate motion relations can be simplified as follows:

$$\frac{H}{\mathrm{S}} = \frac{\pi\mathrm{d}}{\lambda} \Rightarrow \mathrm{S} = \frac{\mathrm{H}\lambda}{\pi\mathrm{d}} = \frac{0.2 * 1.4}{\pi * 0.7} = 0.13\mathrm{m} \Rightarrow \mathrm{v}_{\max} = 2\pi\mathrm{fS} = 2 * \pi * 1.06 * 0.13 \Rightarrow$$

$$\mathrm{v}_{\max} = 0.86m/s$$

$$\mathrm{a}_{\max} = 4\mathrm{S}\pi^2\mathrm{f}^2 = 4 * 0.13 * 9.87 * 1.12 = 5.77$$

The mass of water displaced, and the metal used is equal to:

$$m_w = \rho(S * \mathrm{d} * 0.5) = 1000 * 0.13 * 0.7 * 0.5 = 45.5\mathrm{kg}$$

Assuming that the density of metal used is 10 times the water and has a thickness of 3 mm, and also the width of the flume is 1.2m, the metal mass is obtained as follows:

$$m_m = \rho(w * \mathrm{d} * 0.003) = 10000 * 1.2 * 0.7 * 0.003 = 25.2\mathrm{kg}$$

Therefore, the total force is calculated as follows whereby the power can also be calculated:

$$F_{\max} = \mathrm{m} * \mathrm{a}_{\max} = 70.7 * 5.77 = 408$$

$$P_{\max} = \mathrm{v}_{\max} * \mathrm{F}_{\max} = 0.86 * 408 = 350\mathrm{watt}$$

The MRJ3A 400watt servomotor system was selected given the calculated power [13], [14], [15], [16], however, in practice, the required power may be less than this amount. The overall shape of the wavemaker using the servomotor should be designed as follows, where its different parts will be described (figure 3.).

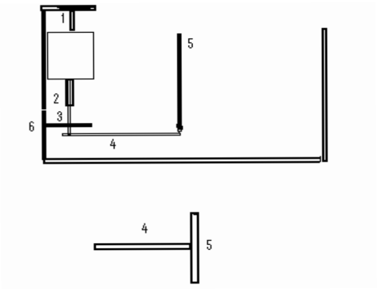

Fig 3. The overal shape of wavemaker using servomotor

Part 1 in the figure shows the servomotor and the relevant connections to fix it at the desired location. Part 2 shows the coupling required to attach the servomotor to the ball screw. Part 3 is the required ball screw with an appropriate step to move the wave plane up or down. This part converts the rotational motions of the motor into reciprocating linear motions through the systems in part 6 which is fixed-connected. The number of desired rotations in this section is limited by the ball screw step. Part 4 is a rod that connects the wavemaker plate to the ball screw system. Finally, part 5 is the wavemaker plate.

The most important point that must be considered with regards to servomotor specifications is that every 2000-pulse is considered one cycle for the servomotor. This is essential when programming to control the servomotor [13], [14], [15], [16].

Requirements for connecting the servomotor to the computer, as well as the specifications of the computer required, and how to connect it to the computer, and how to install the software, are given in appendix.

To program the servomotor internal microcontroller, the following commands are needed that will be explained, albeit care needs to be exercised that the program can be up to 300 lines:

SPN: Indicates the servomotor speed per minute, which is 6000 rpm for the servomotor in question. This value is displayed by the software as error if it is exceeded.

STC: is used to adjust the servomotor acceleration. Since the wave plane should not be displaced by impact, this option is used to move the wave plane in sinusoidal form. In fact, this option determines the time required to reach the selected speed. The value of this option is between 0 and 50,000 milliseconds. The larger the selected number, the lesser the acceleration to reach the selected value.

MOV: This command actually indicates the amount of servomotor displacement that can range between -9999999 to 9999999 pulses. If a counterclockwise rotation is desired, no sign is needed and if the clockwise rotation is needed, a negative sign is required. Since the wave plane needs to have a reciprocal motion against the middle point, positive and negative motions should be used in the program. Also notice should be given that by setting the required parameters in this case, every 2000 pulse is considered as one cycle.

SYNC: Using this command, the servomotor will wait for an external signal to start operating. The signals that can be used for MRJ3A servomotors are as follows: SON, LSP, LSN, TL, PC, RES, CR, and given that these signals were manually grounded, they were not used in the program.

TIM: This command specifies the time between two consecutive commands, and its value is between 0 and 50 seconds. If irregular waves are to be generated, this command is used for creating a gap between the regular output waves that cause the final irregular wave.

TIMES: This command displays the number of times a program has been executed. In the software booklet, the number of times a program can run is from 1 to 99, but with practical tests specified, there is no limit to that, and the program can be repeated to any desired number.

STOP: It is used to stop the program and does not need to be used in cases where the reiteration of the program is desired.

Various programs have been written that can be used to generate regular waves. The following program is written to produce a wave with a certain specification (amplitude$\leq$ than 50 Cm) :

```
TIMES(10), SPN(6000), STC(1000), MOV(55), SPN(6000),
STC(2000), MOV(55), SPN(6000), STC(3000), MOV(55)
,SPN(6000), STC(4000), MOV(55), SPN(6000), STC(5000),
MOV(55),  SPN(6000),STC(1000),MOV(-55),SPN(6000),S
TC(2000), MOV(-55), SPN(6000), STC(3000), MOV(-55),
SPN(6000), STC(4000), MOV(-55), SPN(6000), STC(5000),
MOV(-55), STOP,
```

5. Conclusions

In this work, first a brief review of the piston and paddle/hinged wavemakers is presented. Then the design and feasibility study of the hinged wavemaker is addressed; to make a hinged wavemaker, a 400watt servomotor is utilized in or to generate waves with desired amplitudes. The servomotor is preferred over stepper motor in that it creates better results. The required programs are written with an appropriate microcontroller in such a way that a regular set of waves can be generated. The findings of this work could be utilized for making paddle wavemaker used in water channels.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

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