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Research Article

Design of Closed-Loop Control System for Flap-Type Wave Generator

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Abstract: Marine-origin loads encountered throughout the service life of ships and offshore structures play a critical role in their design. Prior to construction, it is essential to experimentally model these structures, subject them to representative wave conditions, and refine their designs accordingly. To support such experimental efforts, this study focuses on the design and mathematical modeling of a flap-type linear wave generator intended for operation in a wave basin. A mathematical model is developed based on the linear wave generator theory and simulated under varying parametric conditions to investigate its wave-making capabilities. The parametric analysis provides insights into feasible experimental conditions within physical constraints and establishes a methodological basis for the design of experimental setups and measurement strategies. The study aims to inform pre-experimental planning and contribute to theoretical foundation for future experimental investigations.

1. Introduction

The accurate modeling of wave-induced loads is essential in the design of marine and offshore structures, which are continuously exposed to complex and variable sea states throughout their operational life. Physical modeling in wave basins remains one of the most reliable methods to evaluate hydrodynamic performance and structural integrity under controlled but realistic marine conditions. Among the critical components of such experimental setups is the wave generator, which must be capable of producing predictable, controllable, and repeatable wave patterns. Flap-type wave generators, characterized by their hinged motion and ability to generate long-crested regular waves efficiently, are widely used in experimental hydrodynamics due to their mechanical simplicity and effectiveness. However, prior to physical implementation, it is necessary to develop accurate mathematical models of these systems to explore operational boundaries, optimize design parameters, and support the development of measurement and control strategies. Experimental studies play an important role in the design of ships and marine structures. The hydrodynamic forces acting on these structures, the motion analysis of floating structures, and wave geometries can be easily tested with the help of wave generators. Through his studies, William Froude conducted various resistance tests and examined the rolling motions of ships, contributing to the design of paddle-type wave generators [1-3]. Havelock's general wave generation theory, initially presented, forms a foundation for the design of wave generators [4]. Schäffer, through his work, presented the mathematical models to be used in the design of flap-type wave generators [5].

2. Materials and Methods

This study presents a theoretical investigation of a flap-type linear wave generator, aiming to establish a foundation for future experimental studies. By simulating the generator’s response under varying operational parameters, the work provides insights into feasible experimental conditions and offers a methodological reference for the design and planning of wave basin experiments.

2.1. Mathematical Model

The need for wave generators has been observed in theoretical studies conducted on wave energy systems, and mathematical models related to wave generators have been examined [6]. Additionally, other studies on wave generation frequently reference the wave maker theory [7]. In the development of mathematical models, examples created in previous studies have been used as a basis [8]. Wave Generator Theory is essentially a simplified approach to understanding how wave generators create waves in water. Therefore, the mathematical model as shown in Eq (1) used in the study is based on the general wave generator theory.

$$\frac{H}{S_0} = 4\left(\frac{\sinh k\square}{k\square}\right)\frac{k\square\sinh k\square - \cosh kh + 1}{\sinh 2kh + 2kh} \qquad (1)$$

2.2. Experimental Model

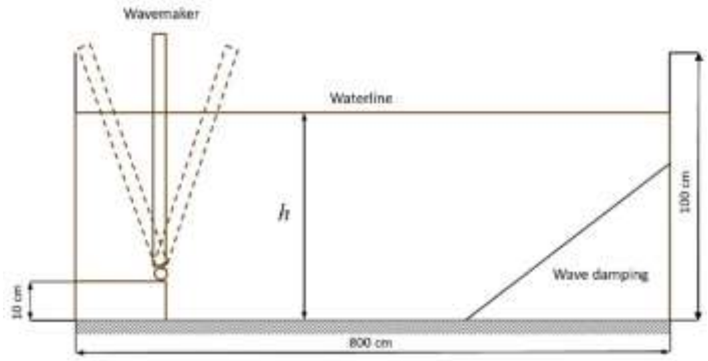

Figure 1. *Simple Sketch of Wavemaker.*

In Figure 1, a simple schematic of a flap-type wave generator is presented. Waves are produced through the oscillatory motion of vertical flaps, which are pivoted at a fixed hinge point slightly above the tank floor. This design intentionally positions the flaps 10 cm above the bottom to minimize hydrodynamic friction and boundary layer disturbances at deeper sections of the tank. The generator is configured to operate under variable water depths, denoted as in the figure, allowing for flexible testing conditions.
The schematic also includes a wave damping region on the right side of the tank, designed to absorb incident wave energy and reduce reflections. The total tank length is 800 cm with a vertical height of 100 cm, offering sufficient propagation distance for wave development and decay. The range of flap motion, shown with dashed outlines, illustrates the system's ability to generate waves of varying amplitudes depending on the angular displacement imposed by the actuator system.

3. Results and Discussions

The results show that for a fixed frequency, increasing the flap angle consistently leads to higher wave heights due to larger tip displacements and greater momentum transfer to the water. However, this increase is not linear at higher angles, particularly for longer flap lengths, where wave generation becomes less efficient due to increased hydrodynamic drag, flap inertia, and potential vortex shedding near the free surface.
Figure 2 illustrates the theoretical maximum wave heights (Hmax) calculated across a range of flap angles (5° to 25°) and excitation frequencies (0.5 Hz to 1.5 Hz), for different flap lengths L of 50 cm, 60 cm, 70 cm, and 80 cm. Each subplot presents a distinct flap length, enabling comparative analysis of geometric influence on wave generation dynamics. Given the total tank length of 8 meters, spatial constraints on wave development are significantly reduced compared to smaller laboratory setups. Still, when L= 80 cm, low-frequency waves (e.g., 0.5–0.7 Hz) can produce wavelengths that approach or exceed the tank's practical propagation distance before reflection occurs. This introduces potential interference effects or standing wave patterns, which are not captured in the linear theory used for these calculations. Moreover, the tank's height of 1 meter supports deep water behavior only partially. With a water depth of 60 cm, the system operates near the transitional regime between deep and intermediate-depth water waves. For frequencies below 0.8 Hz, the wavelength increases enough that shallow water effects—such as enhanced bottom friction, boundary layer shear,

and reduced wave celerity—start to influence wave behavior. These effects could result in discrepancies between theoretical and actual wave heights in practice.

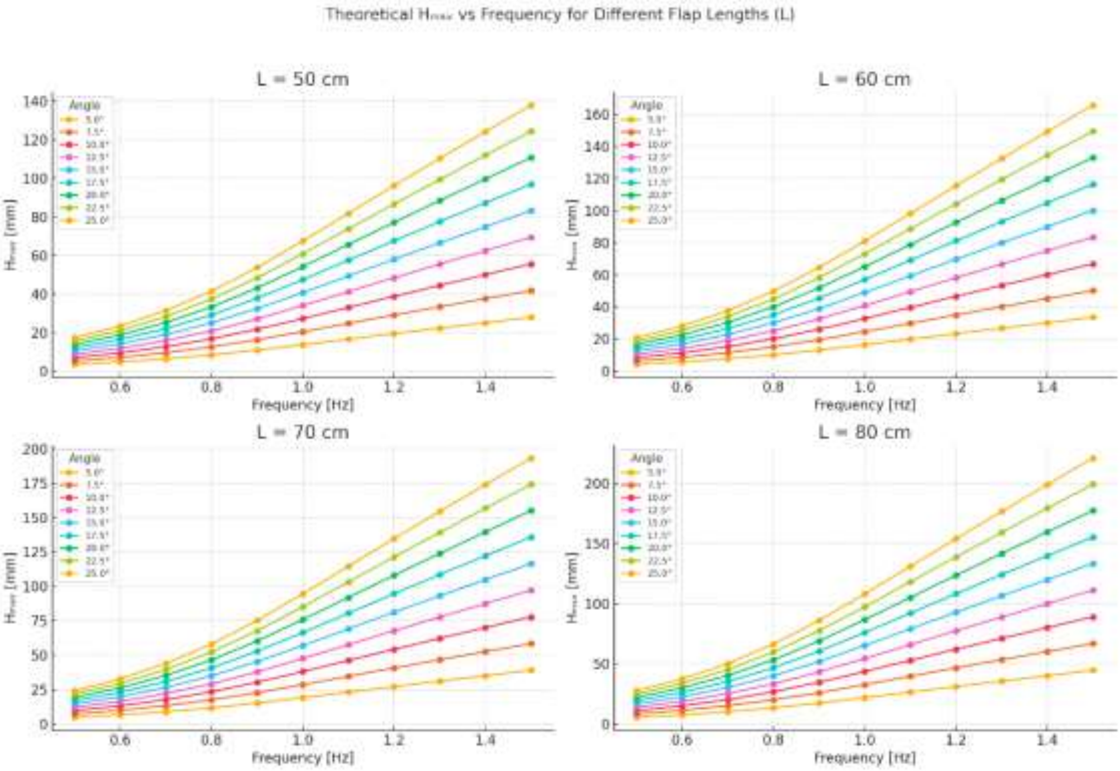

Figure 1. *Theoretical maximum wave heights (Hmax) calculated for varying flap angles (5°–25°) and excitation frequencies (0.5–1.5 Hz) under different flap lengths: (a) L = 50 cm, (b) L = 60 cm, (c) L = 70 cm, (d) L = 80 cm. The analysis highlights the influence of geometric and kinematic parameters on wave generation efficiency*.

Notably, flap lengths of 50 cm and 60 cm appear to produce the most stable and predictable *H*max profiles, especially in the central frequency range (0.8–1.2 Hz). These configurations balance geometric actuation and spatial wave development, minimizing nonlinear distortions while remaining within the tank's physical and hydrodynamic limits. As such, they offer practical advantages for experimental replication and model validation. In terms of angular displacement, the simulations suggest that flap angles between 10° and 15° offer a favorable balance between wave height amplification and theoretical consistency. Angles below 10° lead to inadequate energy transfer for generating measurable waves, while angles above 15° tend to induce nonlinear effects and increased deviation from the linear model—especially when combined with longer flap lengths. These findings emphasize the importance of optimizing flap motion parameters alongside frequency and geometry to achieve stable wave generation.

4. Conclusions

In this study, the performance of flap-type wave makers was theoretically evaluated by varying flap length, angular displacement, and excitation frequency. The analysis indicated that wave generation is most efficient and consistent within the mid-frequency range (0.8–1.2 Hz) and for flap lengths between 50 and 60 cm. Under these conditions, the calculated maximum wave heights remain well within the expected limits of linear wave theory.

At the boundaries of the investigated parameter space, particularly at low frequencies combined with long flaps, noticeable amplification of wave heights was observed in the model due to unaccounted factors such as energy losses, reflections, and shallow water effects. These results highlight the limitations of the linear theory in such regimes and suggest the presence of nonlinear hydrodynamic phenomena. Although no experimental validation was conducted within the scope of this study, the findings contribute to defining the theoretical performance boundaries of flap-type wave makers. The insights gained here can inform future experimental designs and serve as a foundation for developing more comprehensive wave generation models and control strategies. In addition, angular displacements in the range of 10° to 15° appear to be optimal for ensuring effective and consistent wave generation within the tested theoretical framework.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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- **Data availability statement:** The data that supports the findings of this study are available on request from the corresponding author. The data is not publicly available due to privacy or ethical restrictions.

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