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DESIGN AND CONSTRUCTION OF A WAVE GENERATION SYSTEM TO MODEL OCEAN CONDITIONS IN THE GULF OF MEXICO

Yucheng Liu, Grant Cavalier, Jeremiah Pastor, Raul J. Viera, Clay Guillory, Kevin Judice, Kelly Guiberteau, Theodore A. Kozman

Email: yxl5763@louisiana.edu
Department of Mechanical Engineering
University of Louisiana at Lafayette
Lafayette, LA 70503, USA

ABSTRACT

A wave generation system was built and equipped in the wave energy and technology lab at the University of Louisiana at Lafayette (UL Lafayette). The system can generate dynamic waves to simulate the ocean conditions in the Gulf of Mexico. This paper explains the design, construction, and validation of such system. With the installation of the designed wave generation system, the ocean and wave model produced in the Gulf of Mexico can be reproduced and simulated in the lab, which allows us to explore the ocean and wave energy in that gulf through experimental and computational approaches. A workshop of wave energy technology was organized in the lab to reach a broad audience and look for potential partnerships with industry and research community.

Keywords: Wave generation system, wave and ocean energy, Gulf of Mexico, design and building of equipment, UL Lafayette

1. INTRODUCTION

As stated by previous investigators, Gulf of Mexico provides a vast source of wave energy resources [1, 2], and the wave energy has led to promising technologies and commercial deployment [3]. In order to better understand the wave motion in the Gulf of Mexico and further exploit the ocean and wave energy in that gulf, a wave energy and technology lab was established at the UL Lafayette. In that lab, technologies and prototypes will be developed and tested which can efficiently convert the wave energy to the electric energy, which is highly desired by local industry and residents. Therefore, it is critical that the lab must have some equipment that can generate different types of dynamic waves which are similar to those produced in the gulf. This paper demonstrates the design, construction, and validation of a wave generation system that can fulfill this task.

Before designing such system, a profound literature review was performed on the previously developed wave energy lab systems and technologies to form a substantial background for our work. Henderson [4] developed a hydraulic power take-off system for the Pelamis wave energy converter, which maximized power capture across a range of sea-states and also improved survivability. The system was tested through simulation and laboratory tests at 1/7th and full scale model. Denissenko et al. [5] presented an experimental study of the statistics of surface gravity wave turbulence in a flume of a horizontal size of 12 × 6 m. It was found from the study that at low wave amplitudes the wave statistics is affected by the flume finite size, and at high amplitudes the wave breaking effect dominates. Agamloh et al. [6] designed and tested a new rotary direct-drive ocean wave energy extraction system, which employed a contact-less force transmission system (CFTS) to couple a float to the power take-off mechanism. Simulation, design and testing of both the force transmission system and the ocean energy extraction system were presented along with preliminary wave flume test results of the buoy in irregular waves.

The present wave energy technologies and laboratory systems are very helpful for conducting experimental study on wave energy, however, there is no wave generation system presented and reported in previous literature.

2. PROBLEM STATEMENT AND OVERALL REQUIREMENTS

The goal of this project is to construct a wave generation system which will generate waves to simulate the wave motions and ocean conditions in the Gulf of Mexico. It is expected that such wave generation system can be used to test wave energy converter prototypes, as well as other scaled models of watercraft and floating structures.

The fundamental challenge of this project is that the waves generated in the laboratory system should achieve dynamic and geometric similarity to those in the gulf. The dynamic similitude can only be achieved after the geometric similarity is obtained. The geometric similitude means that all length parameters of the wave profile, including its height, wavelength, and depth, should be scaled down from the actual waves in the gulf at same ratio (scale factor). Important length parameters of the wave profile are defined in Fig. 1. Dynamic similitude, however, means that actual forces developed between the wave and other objects in the gulf should be related to the laboratory forces generated in the system through the same scale factor. In order to meet these requirements, following tasks had to be fulfilled in the design and construction of the wave generation system.

(1) Determination of parameters for the real wave conditions in the Gulf of Mexico.
(2) Determination of the scale factor to relate the actual waves to the waves generated in the lab.
(3) Design and construction of a water tank to simulate the marine environment of the gulf.
(4) Implementation of a wave generation mechanism to actuate the wave model.
(5) Installation of an absorption system to dissipate the waves.

Detailed design and manufacturing process are narrated in following sections.

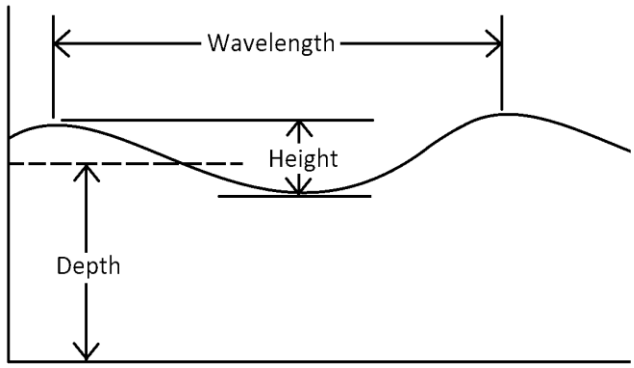

Figure 1. Height, wavelength, and depth of the wave profile

3. DESIGN OF MODEL WAVE AND REQUIREMENTS FOR GENERATION

3.1 Dynamic Similarity and Scaling

Wave design refers to the selection of the real wave conditions to be modeled and the determination of the wave parameters to be used for the wave generation system. It is known that average waves in the Gulf of Mexico are short waves [7], whose period is on the order of seconds. The interactions between the waves and the seabed are neglected because for a short wave, the depth of the gulf is much greater than half of its wavelength.

As recommended by Hughes [8], the maximum recommended scale factor for short wave models is 1:50, but considering the actual size of water tank, a factor of 1:8 was chosen for our wave generation system, which fell well within the acceptable range according to Hughes. Thus, the geometrical similarity is described as: $\lambda = L_F/L_M$, where λ [-] is the scale factor, L means length, subscripts "F" and "M" denote full scale dimension and model dimension, respectively.

Froude scaling was used to achieve the dynamic similarity in the system based on the obtained geometric similarities. The Froude scaling requires that time parameters, such as the wave period, be scaled by the square root of the scale factor: $\sqrt{\lambda} = U_F/U_M$, where U is the time parameter, and the square root of the scale factor λ is referred to as the Froude time scale. Important dimensionless numbers including Froude, Strouhal, and Euler numbers therefore had to equal to one for the wave models generated in the lab to achieve an optimal dynamic similarity to the Gulf of Mexico.

The Froude number is defined as the ratio of a characteristic velocity to a gravitational wave velocity, which is the most important criterion for dynamic similarity. Besides the Froude number, the Strouhal number, which scales convective acceleration terms, and the Euler number, which relates to pressure terms, of the laboratory wave model must also equal to 1, as shown in Eqns. (1-3) [8].

Froude Number:

$$\frac{N_V}{\sqrt{N_g N_L}} = 1 \tag{1}$$

Strouhal Number:

$$\frac{N_L}{N_V N_T} = 1 \tag{2}$$

Euler Number:

$$\frac{N_P}{N_\rho N_V^2} = 1 \tag{3}$$

In above equations, N represents the ratio of quantity in the full scale model (the gulf) to the quantity in the laboratory model (water tank). Subscripts "V", "L", "P", and "ρ" denote velocity [m s^{-1}], period [s^{-1}], length [m], pressure [N m^{-2}], and density [kg m^{-3}], respectively.

Examination of above equations reveals that the wave velocity and wave period must be scaled by the Froude time scale. The Euler number (Eqn. (3)) is automatically satisfied if Eqns. (1) and (2) are satisfied.

3.2 Actual Wave Data from the Gulf of Mexico

The benchmark wave data that will be modeled in our wave generation system were the average wave data recorded by Wavcis data collection Buoy #9, which is located about 5 miles south of the Grand Isle (Fig. 2). This is because that the wave conditions in the areas around the Buoy #9 typically reflect the wave conditions along the shelf region of the Gulf of Mexico, where the wave energy conversion project will be implemented.

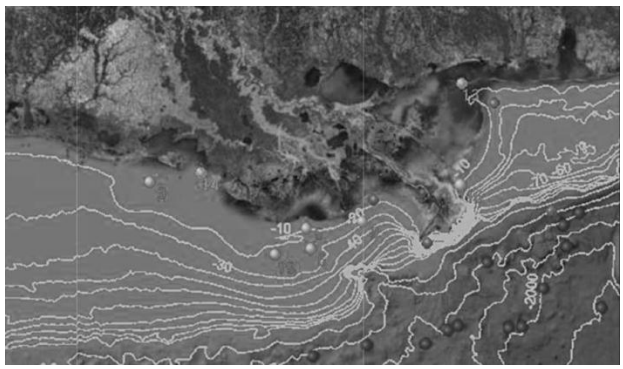

Figure 2. Wavcis data collection buoys

Important properties recorded by the buoys include the water depth, wave height, and period of incident waves. Table 1 lists the wave data recorded by the Buoy #9, based on which the properties of the wave model generated in the water tank of the wave generation system can be calculated through the scale factor, which are also displayed in that table. It should also be noted that the wave properties listed in Table 1 represent mean values of the design range. Bigger and smaller

waves which represent different ocean conditions can also be simulated in the laboratory system.

Table 1. Data of the waves produced in the gulf and those generated in the water tank

Properties	Buoy #9 Data	Laboratory Wave Design	Scale Factor
Wave Height	53,1 cm	6,63 cm	8:1
Period	3,68 sec	1,30 s	$\sqrt{8}$:1
Wavelength	21,1 m	2,64 m	8:1
Water Depth	17,3 m	0,86 m (minimum)	

3.3 Requirements for Generating the Desired Wave Model in the lab

The stroke length of the generator needed to create the desired wave was calculated based on the wave properties listed in Table 1. The ratio of wave height to the stroke length is calculated with Eqn. (4) [9]:

$$\frac{H}{S_0} = \frac{4\sinh(kh)}{2\sinh(2kh) + 2kh}\left[\sinh(kh) + \frac{1+\cosh(kh)}{kh}\right] \quad (4)$$

In that equation, H [m] is the wave height, S_0 [m] the stroke length measured at the water surface, k = 2π/wavelength [m^{-1}], and h [m] the water depth. After inserting the values from Table 1 into that equation (H = 0,0663 m, k = 2,38 m^{-1}, and h = 0,86 m, the stroke length S_0 [m] was determined to be 0,0612 m at the minimum water depth (0,86 m). However, because this value can be adjusted with the changing water depth, for design convenience, the stroke length of 6,12 cm was round to 6,35 cm.

3.4 Dynamic Design

The maximum power required for generating the wave model specified in the previous section, as well as the maximum total force on the flap were calculated following the approaches presented in Reference [8] as: maximum power required = 31,5 W; maximum force on flap = 193 N. Here the maximum total force on the flap refers to the maximum net force applied normal to the flap and opposed to its motion, which could be expected at any point on the flap during the flap's motion cycle, as discussed in [8]. The equations of calculating the maximum power P_{max} [W] and maximum force F_{max} [N] are listed in the Appendix.

As suggested by Budynas and Nisbett [10], the maximum design load was increased to 445 N for safety and to account for force losses due to friction. If such load acts at the water with maximum level of 0,91 m (from Table 1, maximum water level = water depth + wave height = 0,86 m + 0,05 m), the resulting maximum design moment is 407 N m. Thus, the laboratory wave generation system would include a motor, a speed reducer (belt-and-pulley systems), and a flap, with the output of the motor attached to the speed reducer and the output of the speed reducer linked to the flap. More mechanical design details are illustrated in later sections.

The power of 31,5 W in [8] represents the required power that has to be transmitted to the water under ideal conditions to generate the wave. Other required system power includes the power to overcome losses in the gear reduction in the belt-and-pulley systems, to overcome the effects of sloshing water behind the flap without significant deviations in rotational speed, and to drive the flap. Therefore, it was estimated that the power requirements to the wave generation system should be 373 W.

Based on above estimation and considering the safety and variability of the design, a Dayton 0,75 hp (560 W), 2500 rpm DC motor with a variable-speed controller and a constant torque output of 2,14 N m over the entire speed range was chosen for our wave generation system. This motor will output 373 W to 560 W in the range of operating speeds used for the wave generation, which fully satisfies the design requirement.

A gear reduction of 42:1 was chosen to reduce the delivered speed and increase the transmitted torque to the flap. At this ratio, the design period of 1,3 seconds (Table 1) is achieved at 77,5% of maximum motor speed, which corresponds to an output power of about 447 W. This gear reduction was attained through V-belt pulleys, which can steadily provide sufficient power to drive the wave generation system when the wave period increases or decreases.

4. MECHANICAL DESIGN OF WAVE GENERATOR

In order to create wave profiles that satisfy the specified geometric and dynamic similarities and meet all the dynamic requirements, a mechanism was designed which could provide a smooth harmonic input motion to the wave flap. Two drive pegs, which trace circular paths, transit motion to the flap through two linkage arms. Major components of the designed wave generation system include power transmission system, wave generation mechanism, and absorption structure. A schematic of the wave generation system is shown in Fig. 3. Detailed description of the components is presented as follows.

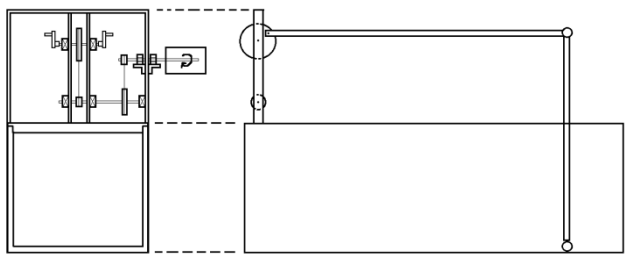

Figure 3. Drawing of the wave generation system

4.1 Power Transmission System

The power transmission system is composed of a motor, a drive shaft, and a belt-and-pulley system for gear reduction. The motor provides all power for the system and is located above and away from the water level so as to avoid splashes of water. The drive shaft transmits the output power of the motor to the pulley system. It is supported and located by a pair of pillow-block journal bearings, where oil lubrication is required due to the high operating speeds of the shaft and the corresponding high temperature in the bearings.

The motion is then transmitted from the drive shaft to the pulley system to attain the gear reduction of 42:1, which requires the use of a gear train. As shown in Fig. 4, such gear train includes four pulleys, whose diameters were chosen so as to minimize the overall size of the gear train while

guaranteeing the specified reduction ratio. For convenience, pulleys with nominal diameters were chose for our design, which are: P1 = 2” (5,1 cm), P2 = 12” (30,5 cm), P3 = 2” (5,1 cm), P4 = 14” (35,6). As depicted in Fig. 4, Pulley 2 and 3 are mounted on the same shaft so that the overall gear reduction ratio is calculated as (2/12) × (2/14) = 1/42. In another words, with such pulley system, the output speed will be 1/42 of the input speed.

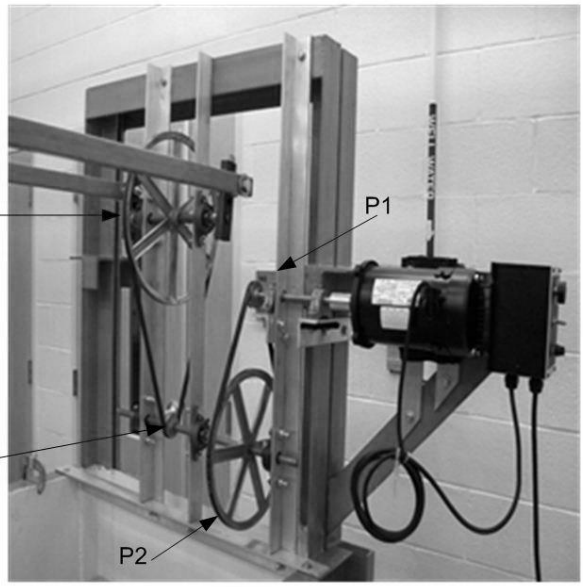

Figure 4. Power transmission system

Standard belts were selected for the pulley system based on the recommended values published in [10], specifically, the nominal V-belt A45 and A59 were selected for the P1P2 and P3P4 pairs, respectively. After deciding the pulleys and belts, the shaft center distances could be easily determined as 27,9 cm and 41,9 cm. However, the actually distances were increased by 1,27 cm to account for an undesirable amount of slack in the belts. The shafts are located with flange-type ball bearings, which are bolted to an aluminum frame (Fig. 4). Grease-lubricated bearings were chosen for use with the shafts because such bearings can operate at relatively low speeds and temperatures.

4.2 Wave Generation Mechanism

The wave generation mechanism includes two drive arms, two linkage arms, and one flap (Fig. 5). The drive arms transmit motion from the pulley system to the linkage arms, which are located outside of flange bearings on the common shaft associated with the pulley 4. Both drive arms are made of rectangular steel tubes and welded to a collar for placement on the shaft. Three holes were drilled in each drive arm, the position of the center hole reflects the designed stroke length (6,35 cm) and the other two holes reflect the upper and lower limits of the stroke length. Several removable drive pegs were used to select appropriate stroke length and to transmit motion to the linkage arms.

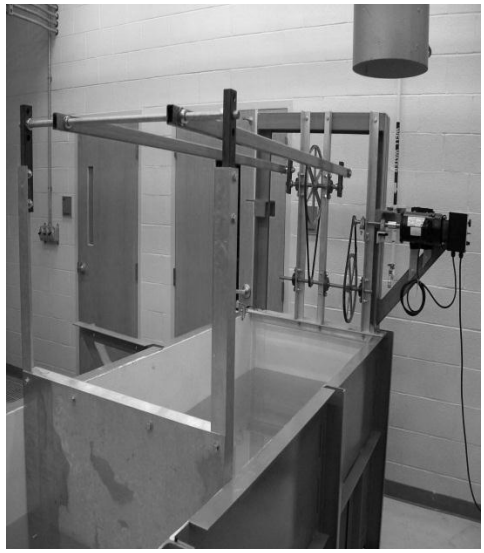

Figure 5. Wave Generation Mechanism

The linkage arms transmit motion from the drive pegs to the flap through a connecting rod. The linkage arms are also made of rectangular steel tubes, which are 2,03 m long and have pressed-in bushings at 3,8 cm from each end. Similar to the power transmission system, grease was used as lubricant because the arms would operate at very low speeds and temperatures.

The flap transmits motion from the linkage arms to the water in tank trough a rigidly attached connecting rod. Aluminum sheet was used to manufacture the surface of the flap and the flap extends 5,1 cm above the top edge of the water tank. Three 7,6 cm steel hinges were bolted to the bottom edge of the flap and welded to the floor of the tank so that the flap is free to pivot.

4.3 Absorption Structure

The absorption structure (absorber) is basically a gentle slope located on the terminal end of the tank (Fig. 6), which is used to dissipate the energy of incoming waves at far end of the tank. Through the dissipation process, the effects of reflection and interference on the generated waves are minimized. As shown in Fig. 6, the absorption structure consists of two long edge members and four cross supports and its frame is covered with an aluminum sheet to create the gentle slope. As suggested in reference [8], the slope ratio should not exceed 1:4; in our design, we chose a ratio of 1:4,5 for safety.

4.4 Final Design

After finishing the design, the desired parameter values and the actual values provided by the final design were compared and listed in Table 2. The actual parameter values were calculated based on the Dayton 0,75 hp (560 W), 2500 rpm DC motor.

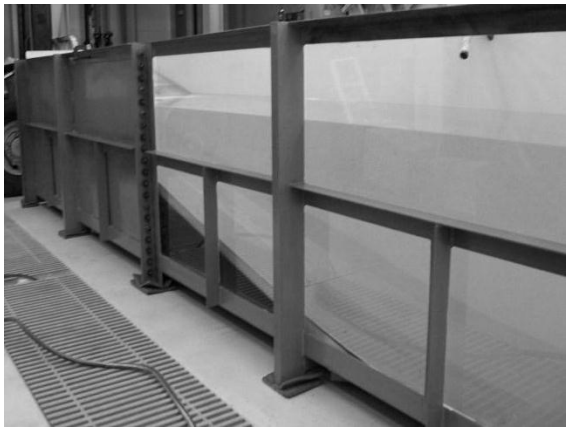

Figure 6. Absorption Structure

Table 2. Preliminary design requirements and actual design parameter values

Parameter	Required	Actual	Pass/Fail
Max force on linkage arms	890 N	1410 N	Pass
Speed	46,2 rpm	29,8 rpm to 59,5 rpm	Pass
Stroke Length	6,35 cm	3,81 cm, 6,35 cm, 8,89 cm	Pass

All shafts and arms will no doubt pass the failure analysis because they were designed based on recommendations presented in [8]. Failure analyses were also performed on all connections to make sure that those connections would not fail by fatigue during the operation.

5. CONSTRUCTION OF WAVE GENERATION SYSTEM

The wave generation system was built in the wave energy and technology lab, and the lab space was donated by the National Oceanic and Atmospheric Administration (NOAA), which is located at the University Research Park. A large wave tank was first constructed, whose dimension is large enough to accommodate the wave models (Fig. 7). The water tank is 9,75 m long and 0,9 m wide, which can hold approximately 8330 L of water. Steel plates and beams were bolted and welded together to build up frame of the tank. The outer and inner surfaces of the tank were sanded and painted with marine grade enamel coating for protection. Seals and gaskets were employed to prevent water leak, which were donated by Acadiana Rubber and Gasket Co. Glass sheets were adhered to the inside of the tank and sealed with caulk.

Figure 7. Water Tank

As described in section 3, wave generation is accomplished by the wave flap, which enforces a wave potential profile in the tank, which will propagate through the channel. At the terminal end of the channel, a gentle slope is used as the absorption structure to dissipate the wave energy and minimize the reflection and interference of the waves. The wave flap was then manufactured and fit into the tank, where precise machining was applied. In generating waves, the wave flap is calibrated to create the profile of the wave model by selecting its stroke length and adjusting the period of motion..

6. TEST OF EQUIPMENT

In running the wave generation system, it was found that the system performed very well: a smooth and steady wave profile was created by the flap and the shape of waves showed almost no degradation as they traveled along the tank. The absorption structure also worked well, few interference patterns were observed even after the generator had run for several minutes. Besides qualitative observation, a quantitative test was also carried out to determine if the wave generation system meet all the design requirements. Important parameters were measured according to following procedure: (1) Water depth was measured prior to the test; (2) the generator was turned on and when the waves reached a steady state, the wave height was recorded; (3) the period corresponding to each wave height was inferred from the indicated speed read from the motor speed controller. This procedure was repeated at maximum and minimum of the motor speed (59,5 rpm and 29,8 rpm) for each of the three available stroke lengths (3,81 cm, 6,35 cm, 8,89 cm). In Table 3, the high and low bounds of the wave generation spectrum are compared with the target design values for an ideal wave model which is scaled down from the real wave in the Gulf of Mexico by the factor of 8 (see Table 1).

Table 3. Actual values measured from the generated waves and the design target values

Wave Parameter	Target Design Value	Wave Generated in Tank
Height	6,63 cm	6,60 cm
Period	1,30 sec	1,26 sec

From Table 3, it is clear that the wave height and period measured from the test agreed with the target design values very well. Thus, it can be concluded that the generated waves are both geometrically and dynamically similar to those produced in the Gulf of Mexico. It should also be noticed that the height of 6,60 cm and period of 1,26 seconds were read when the motor was running at 80% of its full speed, the closest one to the desired speed of 46,2 rpm which could be attained during the test.

7. WORKSHOP

After installing the wave generation system in the wave energy technology lab, an ocean wave energy workshop was organized at the Estuarine Habitats and Coastal Fisheries Center to demonstrate the lab facilities and highlight the wave energy potential and prospect in the Gulf of Mexico. More than 20 attendants from United States and Mexico attended this workshop. The attendants came from universities, federal

agency, and industrial company. Six presentations and a lab demonstration were given in the workshop and the attendants were impressed by the wave generation system as well as other facilities in the wave energy technology lab, and highly complimented the effort and achievements the UL Ocean Energy & Technology Team. Potential partnerships between the university and the NOAA, as well as the local industry were also established through this workshop.

8. DISCUSSION AND CONCLUSIONS

A wave generation system was designed and constructed and tested in the wave energy and technology laboratory at UL Lafayette. The system can produce wave models which are geometrically and dynamically similar to the average wave conditions generated in the shelf region of the Gulf of Mexico. In the designed system, the wave flap is driven by a 560 W variable-speed electric motor; a compound 42:1 belt-and-pulley reduction is employed to decrease the motor output speed and increase the available torque so as to drive the flap to generate the wave models. Three stroke lengths (3,81 cm, 6,35 cm, 8,89 cm) are available for creating different wave profiles. The wave profiles generated by the flap will propagate all the way through the tank to the absorber, which is applied to minimize the reflected waves so that the wave profiles in the water tank are repeatable at a steady state. The slop ratio (length:height) of the absorber was set as 4,5:1 so that the height of all the reflected waves would be reduced to less than 5% of the incoming wave height. A sketch of such wave generation system is illustrated in Fig. 8.

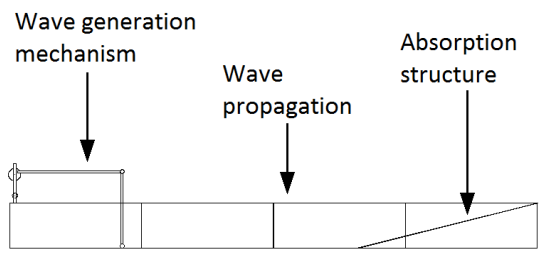

Figure 8. Structure of the generation system

Test results showed that the designed system is capable of creating desired waves similar to the real waves produced in the Gulf of Mexico. In the future, the wave generation system will be equipped with measuring instruments such as precise wave gauges and data acquisition system and will be extensively used to test scale models of wave energy converter prototypes for the purpose of exploiting the wave energy in the Gulf of Mexico.

Besides its impact on research, the wave energy and technology lab will also substantially enhance the mechanical engineering curriculum at UL Lafayette. With this lab, a hands-on demonstration can be included in the discussion of hydrodynamic modeling, which is an important topic of fluid mechanics courses. Also, the water tank can be used by the students to design and test oceanic mechanisms or vehicles in the Engineering Design course. Moreover, the equipment in this lab will also be shared by other academic departments, students, and faculty members for curricular improvements and research projects.

9. ACKNOWLEDGEMENTS

This project was sponsored by U.S. Department of Energy through the Louisiana Department of Natural Resources. The wave technology lab was housed at the Estuarine Habitats and Coastal Fisheries Center, National Oceanic and Atmospheric Administration (NOAA), which is located in the University Research Park. The authors are grateful to Dr. John Foret in NOAA for his substantial support in this work. The authors also want to acknowledge generous donations from following industrial donors: Aggreko, Comm Engineering, Grainger Industrial Supply, Bearing Service and Supply, Acadiana Rubber and Gasket, and Southern Steel; and services provided by WaterJet and Lowry's Printing.

10. APPENDIX

$$F_{max} = 2\sqrt{F_R^2 + F_I^2} \tag{5}$$

$$F_R = 2\left(\frac{\rho\sigma A \sinh(kh)}{k}\right) \tag{6}$$

$$F_I = 2\left(\rho\sigma \sum_{n=1}^{\infty} \frac{C_n}{k_n} \sin(k_n h)\right) \tag{7}$$

$$P_{max} = 2\sqrt{P_R^2 + P_I^2} \tag{8}$$

$$P_R = \left(\frac{\rho\sigma^2 S_0 A}{2k}\right)\left[\sinh(kh) + \frac{1-\cosh(kh)}{kh}\right] \tag{9}$$

$$P_I = \left(\frac{\rho\sigma^2 S_0}{2}\right)\sum_{n=1}^{\infty} \frac{C_n}{k_n}\left[\sin\left(k_n h + \frac{\cos(k_n h)}{k_n h}\right)\right] \tag{10}$$

$$\sigma^2 = -g * k_n \tan(k_n h) \tag{11}$$

$$C_n = -\frac{2\sigma S_0}{k_n(\sin(2k_n h) + 2k_n h)}\left[\sin(k_n h) + \frac{\cos(k_n h - 1)}{k_n h}\right] \tag{12}$$

$$A_0 = -\frac{2\sigma S_0}{k(\sinh(2kh) + 2kh)}\left[\sinh(kh) + \frac{1-\cosh(kh)}{kh}\right] \tag{13}$$

11. NOMENCLATURE

h:	water depth [m]
H:	wave height [m]
k:	wavenumber [m^{-1}]
λ:	scale factor [-]
ρ:	fluid density [kg m^{-3}]
σ:	circular frequency [s^{-1}]
A_0:	analysis term [m^2 s]
C_n:	analysis series [m^2 s]
F_{max}:	maximum force on wave board [N]
F_I:	inertial force component [N]
F_R:	resistive force component [N]
g:	acceleration due to gravity [m s^{-2}]
L_F:	full scale length [m]
L_M:	model length [m]
N_X:	ratio of property X in full scale to property X in model [-]
P_{max}:	maximum power required to wave board [W]

P_I: inertial power component [W]
P_R: resistive power component [W]
U_F: full scale time [s]
U_M: model time [s].

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