FLAP – A Removable elevated-hinge wave generator for testing marine energy devices

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Abstract— **A new removable elevated-hinge wave generator has been designed and commissioned to the O.H. Hinsdale Wave Research Laboratory (HWRL), at Oregon State University. The wave maker, built by Edinburgh Designs Ltd., is comprised by six electrically actuated dry-back paddles, self-contained in a single steel box and capable of generating mid-scale regular, irregular and user defined waves in a typical range of periods from 0.5 to 4 s at a maximum depth of 4 m. The system is intended to increase the available depth range in the Large Wave Flume (LWF) and satisfy the demand of intermediate to deep water waves at a relatively large scale by the marine energy industry. The uniqueness of the system relies on its flexibility. It was conceived to be, first, removable and can be relocated anywhere along the flume, at the full range of depths (from 1 m to 4 m) and it can be reversed facing both directions along the flume. This flexibility, required by the intention to keep the existing wave machine operational, increases its functionality by making it compatible to the generation of waves and co-linear currents, as well as expanding the available testing section along the flume, with generation on one side and absorption on the opposite.**

Keywords—**Wave generator, laboratory experiments, wave flume, Hinsdale Wave Research Laboratory.**

I. INTRODUCTION

The Large Wave Flume (LWF) at the O.H. Hinsdale Wave Research Laboratory (HWRL), Oregon State University, is currently equipped with a piston-type, dry-back wave generator with a 4.2 m maximum stroke, S_0, hydraulic actuator assembly. The flume is 104.24 m long, 3.66 m wide, and the sidewalls are 4.57 m high. The existing wavemaker can generate large regular, random and tsunami-like long waves for the purpose of scaled model tests. Currently, the maximum water depth, h, for generation of regular or random waves is 2.74 m, with a maximum wave height, H, of 1.7 m in a wave period, T, range from 4 to 8 s. The maximum depth for tsunami-like waves (solitary waves) in the flume is 2.0 m, with a maximum wave height of 1.4 m. The wave generator is equipped with position-control active wave absorption based on the measured free surface with two resistive wave gauges mounted at the face of the wave maker board. The board, covering the full cross section of the flume, is also fitted with 4 fins to reduce the generation of cross-waves. Fundamentally, the piston-type wave generator is able to work at any depth from "0 m" to the nominal maximum of 2.74 m. Fig. 1 shows a photograph of the piston-type wave generator.

The performance curves (derived with linear wave theory) of the existing piston-type wave generator at the Large Wave Flume are shown in Fig. 2.

Plots in Fig. 2 are defined by three fundamental limits:

Wave steepness [1]:

$$\left[\frac{H}{L}\right]_{max} = 0.142\tanh(kh) \quad (1)$$

Generation of evanescent modes (depth-limit):

$$\frac{H_{max}}{h} = 0.65 \quad (2)$$

Maximum stroke (first order) [2]:

$$\frac{H}{S_0} = \frac{4\sinh^2(kh)}{\sinh(2kh) + 2kh} \quad (3)$$

Where L is the wavelength and $k = 2\pi/L$ is the wave number (see e.g. [3]).

Note that the depth-limit as defined in (2) is a simplification based on practical observations, but it is

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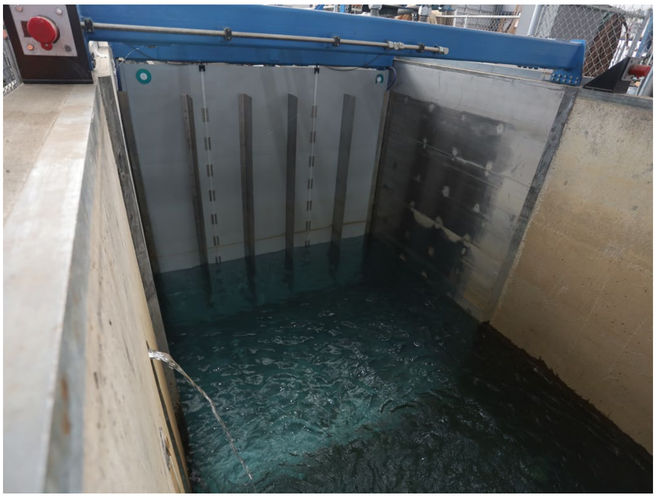

Fig. 1. Board paddle of the piston-type wave generator at the Large Wave Flume, HWRL, Oregon State University. Note the locations of the wave gauges as well as the fins at the board is not symmetrical to account for different frequencies across the flume.

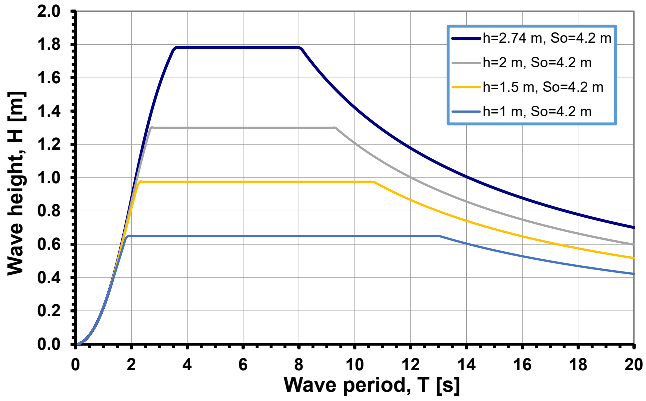

Fig. 2. Performance curves of the piston-type wave generator at the Large Wave Flume for different water depths. In theory, any wave condition (H, T) can be generated under the corresponding curve at a given water depth. Each plot is subdivided in three sections: a) the wave steepness limit as proposed by Miche [1], b) the depth-limited generation due to evanescent modes and, c) the wave board stroke limit.

largely a function of the imposed velocity field by the wave board (i.e. evanescent modes) and depends on the maximum velocity, acceleration, force or power limits of the wave machine, as well as the wave theory used (i.e. Airy, Stokes, Cnoidal, or Stream Function) and the implementation of second-order wave generation. For non-linear shallow water waves, the depth limit may range from ~0.45 for Airy waves to ~0.75 for Cnoidal waves.

The maximum depth at the flume for wave generation was limited by the structural design of the piston-type wave machine, where hydrodynamic and inertial forces are particularly high, associated to the dry-back condition, and reaching its maximum at an emergency stop. However, the flume wall height is capable of handling a maximum depth in excess of 4 m.

To augment the capabilities of the facility and responding to an increasing demand of deeper experimental conditions (particularly from the wave energy industry), the procurement of a new specialized wave machine able to generate high-quality waves in deeper waters was deemed necessary.

II. Elevated-hinge wave generator preliminary design

As indicated above, the new wave machine should be able to generate high-quality waves in deeper waters, while maintaining the operation of the existing piston-type wave machine at depths up to 2.74 m able to generate large shallow-water waves. The new proposed wave generator should be capable of simulating deep- and intermediate-water waves. Hence, the planned water depth during operation of the proposed wave generator is up to 4 meters. It should be stressed that the existing wave machine is able to withstand the hydrostatic and dynamic pressures for water depths from 2.74 m to 4 m, as long as is not operating.

Basic specifications for the new wavemaker include the generation of quality waves with heights up to 0.6 m and a wave period ranging from 0.5 s to 3.0+ s (depending on the wave height).

The basic solution found by HWRL is a removable, portable, elevated-hinge wave machine (see Fig. 3). Given the portability of the solution, the new wave machine can operate at various depths. The most stringent condition is found at the maximum target depth of 4 m, where the hinge elevation has been estimated at 3.05 m, the design wave height is 0.6 m with a period of 1.8 s. The corresponding stroke (S_0) would be 0.73 m (linear wave theory), equivalent to a flap angle of +/-21^0 requiring a minimum paddle height of 1.5 m.

The performance curves (derived with linear wave theory) of the proposed new elevated-hinge wave generator for the Large Wave Flume are shown in Fig. 4. Plots in Fig. 4 are now defined by two fundamental limits:

Wave steepness [1]:

$$\left[\frac{H}{L}\right]_{max} = 0.142\tanh(kh) \quad (4)$$

Maximum stroke (first order) [2]:

$$\frac{H}{S_0} = \frac{4\sinh(kh)}{\sinh(2kh)+2kh}\left[\sinh(kh) + \frac{\cosh(kl)-\cosh(kh)}{k(h-l)}\right] \quad (5)$$

Where l is the elevation of the hinge relative to the bottom of the flume.

The flume is fitted with a series of bolt-hole vertical patterns to assemble test specimens, fix instrumentation, as well as to support a movable/adjustable bathymetry made of 20 square concrete slabs. The new elevated-hinge wave machine would be installed and fixed with the existing bolt-hole pattern transferring the forces of the wave machine to the concrete side walls, and its design should be flexible enough to enable repositioning in the

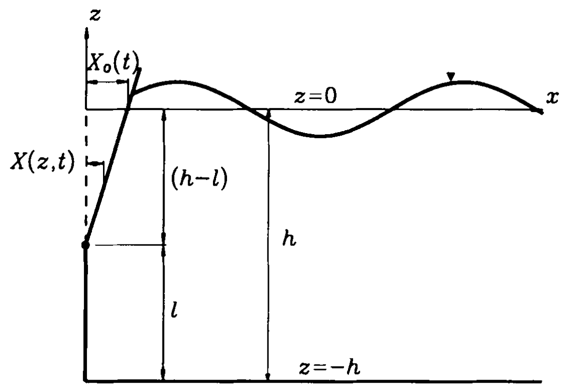

Fig. 3. General configuration of an elevated-hinge wave maker (from [2]).

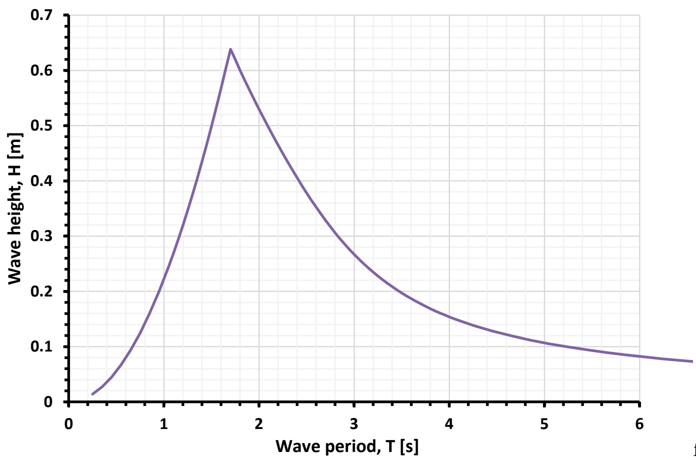

Fig. 4. Performance curve of the elevated-hinge flap-type wave generator at the Large Wave Flume for a hinge depth of 1.5 m. In theory, any wave condition (H, T) can be generated under the corresponding curve for unlimited water depths. Each plot is subdivided in two sections: a) the wave steepness limit as proposed by Miche [1] and, b) the wave board stroke limit.

flume at various locations along its length and at various heights (variable hinge height) using this bolt-hole pattern. This includes the possibility of installing the new wave machine in the opposite side of the flume and generate waves towards the existing wavemaker. Fig. 5 presents a cross-sectional detail of the Large Wave Flume, depicting the existing piston-type wavemaker, the bays along the flume where the bolt-hole pattern are located, and some sample locations and elevations of the new removable elevated-hinge wavemaker.

As an elevated-hinge system, the new wave machine will include a set of rigid panels to be installed underneath separating physically the zones forward and backwards. The set of panels will allow the placement of the new wave machine at different elevations in steps of max. 0.92 m (3 feet), i.e. the maximum panel height is 3 ft. Fig. 6 presents a cross-sectional view of the flume with the new wave generator installed to accommodate for the maximum water depth (4 m). The hinge elevation is at 3.05 m. The panels underneath have varying height (2 x 0.9144 m, 1 x 0.6096 m and 1 x 0.3048 m) so any elevation can be achieved in steps of 0.3048 m (1 ft).

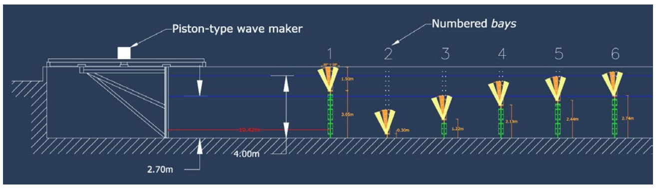

Fig. 5. Schematic configuration of the new elevated-hinge wave machine at various locations and elevations along the Large Wave Flume.

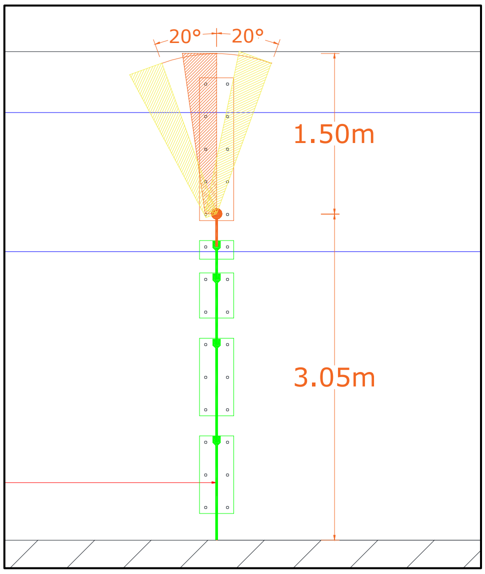

Fig. 6. Detail of the preliminary design of the new wave machine for the maximum depth of 4 m. Note the varying dimensions of the panels to accommodate for any elevation.

III. Elevated-Hinge Wave Generator Final Design

The final design, construction and delivery of the new elevated-hinge wave generator for the HWRL was commissioned to Edinburgh Designs Ltd. The proposed design considers a 6 x 1.5m depth hinged paddles built on a movable module that slides in rails mounted to the side of the flume. The rails are removable by design and are attached to the flume using the existing bolt-holes. This design enables repositioning in the flume at various locations along its length and at various heights (variable hinge height). The module is a watertight, self-contained system, with 6 segmented 60 cm wide dry-back paddles (see Fig. 7). The dry-back solution (no water on the leeside of the flap paddle) requires 50% of the electrical power of a wet-back system since does not generate waves in both directions. Moreover, the dry back design requires less space than a wet-back system given it does not require a leeside passive absorption system.

A. *Wave generator structure*

The wavemaker consists of a module box with paddles inside. The module box holds the paddles and all mechanical equipment. The fabricated module is made from galvanised mild steel. The module box is sealed and designed for the structural loads applied by the wavemaker and the water in the flume. An image of the module design is included in Fig. 8.

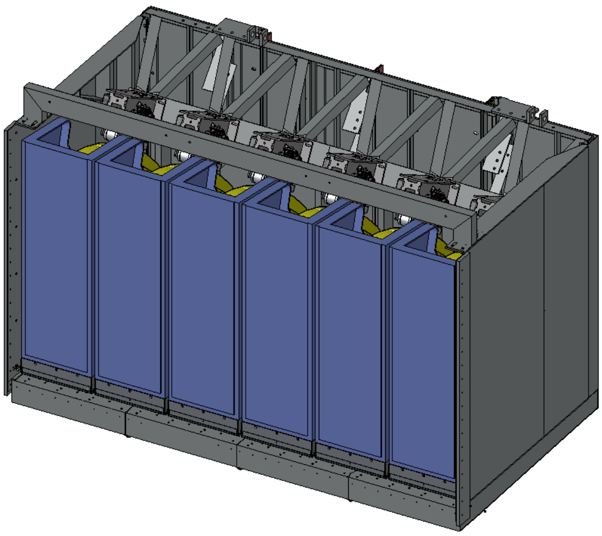

Fig. 7. Conceptual design of the removable elevated-hinge wave generator. Dark grey is the galvanized steel module and blue depicts the segmented hinged paddles.

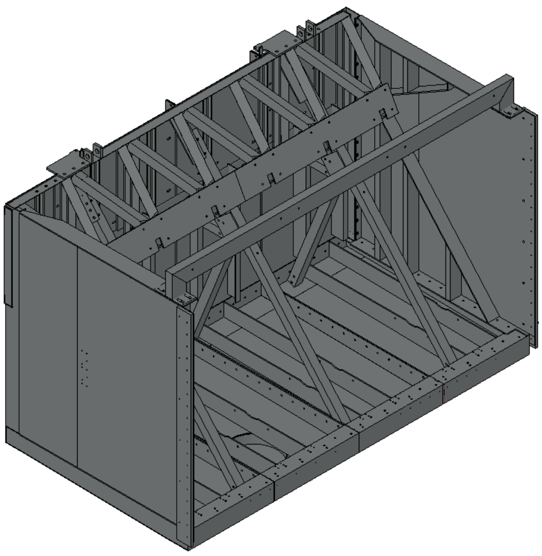

Fig. 8. Conceptual design of the removable elevated-hinge wave generator. Galvanized steel module.

B. *Wave generator*

All paddles have their own independent drive and control system. They are dry back and therefore have no water behind them. Each wavemaker consists of three major components; 1) the paddle assembly, 2) the air spring assembly, and 3) the motor drive assembly.

Each paddle has a brushless AC servomotor that drives a belt running over a curved guide on the top of the paddle (Fig. 9). The water height on the paddle is measured using a force transducer. Control electronics, power amplifier and power supply are contained in a self-contained steel cabinet.

C. *Paddle assembly*

The structure needs to be light and corrosion resistant. The paddle body is made from stainless steel. It is hinged at the lower edge using specially designed hinges manufactured by Edinburgh Designs from solid stainless

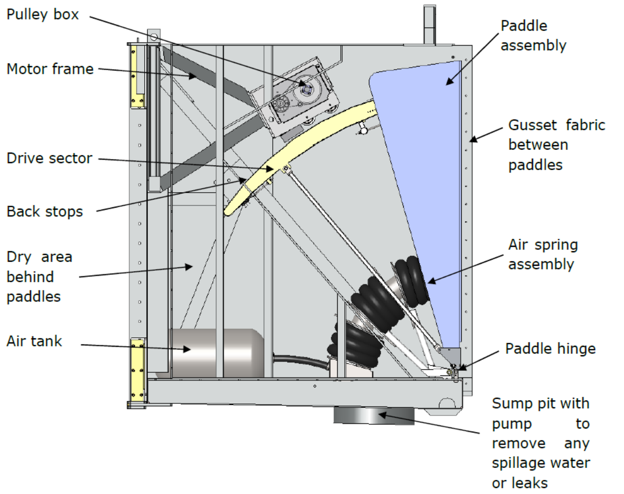

Fig. 9. Components of the hinged wave generator inside the watertight module.

steel. The drive sector is mounted to the paddle through flexible mountings so that the drive force can be measured with a force transducer. A frame fixes the bellow to the base of the paddle. A gusset is sealed to each paddle on three sides and held down with stainless steel strips screwed into the paddle.

D. *Air spring assembly*

Air springs are used to provide hydrostatic compensation. They are built onto a frame so that the force pushes one third of the way up to compensate for the hydrostatic load. Guide arms ensure the bellows move in a circular arc. A single airline connects to the tank to allow the pressure to be adjusted during the power up procedure. Once pressurised, the bellow springs do not require additional compressed air while making waves. The hydrostatic compensation force is measured and fed into the Wavemaker control algorithm.

E. *Wave quality and active reflection compensation*

The combination of force feedback absorption and iterative correction files produce very high-quality waves. Force based feedback is fundamentally different to wave gauge absorption in its implementation. It is normal practice in wave gauge absorption to compute an error signal using the wave gauge signal and expected wave free surface. This is then modified and fed back to quantify the position demand. In contrast, in a force-based absorption strategy, the paddle's force is regulated and the position filtered and added to provide a controlled impedance as seen by the water.

The absorption system is embedded into the controllers and relies on precision filters to provide the necessary paddle impedance. This is optimised through an automated algorithm developed in partnership with Imperial College London. This technique provides theoretical absorption capabilities that are utilised by the absorption system. The model has recently been extended to include the effect of the feedback loop on the actual impedance seen by the waves.

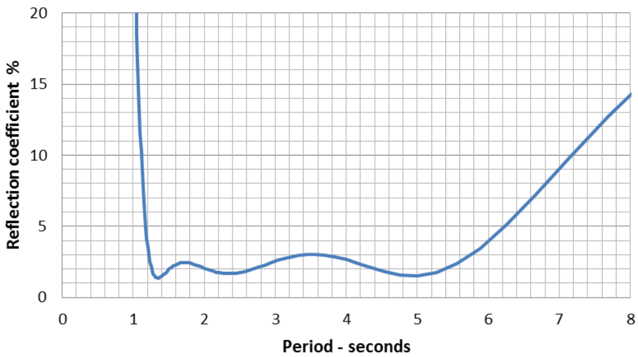

Fig. 10. Theoretical wave energy reflection for an elevated-hinge wave generation system.

Fig. 11. Arrival of the elevated-hinge wave generator to the HWRL.

In this way, less than 3% energy reflection can be achieved for a machine of this design down to about a 1 s wave period. A 3% energy reflection equates to a 17% wave amplitude reflection when acting as an absorber.

From theory, the impedance of the paddle has been determined, and the controller optimised giving the absorption curve shown in Fig. 10. This shows that the reflected energy is 3% or less between 1.2 seconds and 5.5 seconds. The impedance of the water and paddle was measured during commissioning and any correction was incorporated into the optimiser.

The absorption limit below about 1.2 seconds is due to the added mass of the evanescent wave; while the reduced absorption for waves with period greater than 6 seconds is necessary to prevent the paddle exceeding its stroke while absorbing very long waves. The lowest standing wave frequency in the Large Wave Flume when operating at full depth will have a 14 second period, and the Wavemaker will still absorb 75% of this energy, preventing a build-up of energy at this frequency.

F. *Wave generation software*

The new elevated-hinge wave generator is equipped with Edinburgh Designs Njord software suite, consisting of tools for designing and analysing waves and running them in the flume, along with software to provide diagnostic and troubleshooting for the Wavemaker hardware. Additionally, the wave generation software allows the upload of user-defined time series derived from the implementation of advanced generation of highly non-linear waves derived and implemented by the HWRL [4].

IV. Delivery and Commissioning

On October 11, 2022, the new removable elevated-hinge wave generator arrived finally to the HWRL, after COVID and supply chain delays, as well as sailing twice the Atlantic Ocean due to importing complications. Fig. 11 depicts the new wavemaker once it was fully unloaded.

Edinburgh Designs team arrived in November 2023 for the final assembly, System ID, commissioning and user training. Installation of the rails and panels, as well as wave generator assembly are shown in Fig. 12 and 13.

Fig. 12. Installation of the rails and panels in the Large Wave Flume.

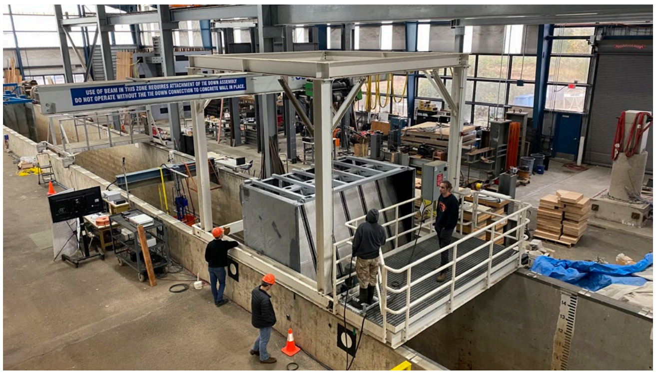

Fig. 13. Setting up and commissioning of the wave generator in the Large Wave Flume. Deployment at Bay 8 with the flume gantry crane.

Once installed, a series of performance tests were conducted by the HWRL staff, as part of the acceptance tests of the new wave generator. Commissioning was performed at a water depth of 1.675 m, hence no panels were installed underneath, while acceptance tests were executed at a water depth of 2.8 m. In Fig. 14, the wave generator is shown during one of the acceptance tests.

During the acceptance tests, the wave generator was installed at Bay 8, approximately 40 m from the existing piston-type wavemaker, and waves were generated in the opposite direction, towards the spending beach at the end of the flume. The selected location for the new wavemaker and the water depth were determined by a concurrent

Fig. 14. The elevated-hinge wave generator during the acceptance tests. Water depth is 2.8 m and hinge elevation at 1.3 m. In the background, a point absorber Wave Energy Converter and the piston-type wave generator in the Large Wave Flume.

series of experiments of a point absorber developed by Oregon State University under the same U.S. Department of Energy award.

The spending beach has a uniform slope of 1:12 and starts approximately 5.3 m from the new wave generator hinge. Three resistive wave gauges (WG1, WG2 and WG3) were also installed along the flume to assess the performance of the wave generator. The gauges were located 5.315 m, 12.629 m and 19.946 m from the wave generator hinge and had a local water depth of 2.643 m, 1.957 m and 1.347 m, respectively.

A broad series of different experiments were carried out, exploring the performance of the wave generator under a range of wave heights and wave periods. A set of regular and irregular wave experiments at a very specific wave period are presented herein for conciseness and clarity reasons.

The selected set of wave conditions include nine regular wave and two irregular wave tests, all of them with a wave period, T, of 2 seconds.

G. *Regular wave tests, T=2 s*

Regular wave tests were conducted with varying wave height and constant wave period (T=2 s), water depth (h=2.8 m) and hinge elevation (l=1.3 m). Firstly, a series of bursts of regular waves with defined wave heights were executed. The purpose of these tests is to observe the quality of waves with different steepness as well as the calm-down time in the flume while the active wave absorption system is operational. Wave heights ranged from 10 cm to 70 cm, and different trials were executed at 10 cm increments. Note that the nominal design wave height of the wave generator is 60 cm, but an additional extreme condition was tested to verify the limits in generation. The duration of each trial included 15 to 80 waves while the DAQ continued recording for another 120 s.

The tested wave conditions are presented in dimensionless form in Fig. 15, where the validity range of different wave theories have been included for comparison purposes. Moreover, the theoretical wave generation limit for an elevated-hinge paddle (5) is also plotted.

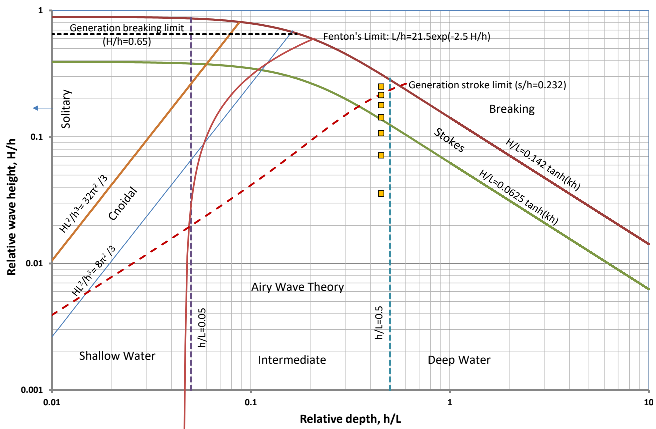

Fig. 15. Selected regular wave conditions tested as part of the performance and acceptance tests, plotted in dimensionless form. Different lines depict the validity of the different wave theories (Airy, Stokes, Cnoidal) as well as the breaking limit as suggested by Miche (1). Dashed red curve represents the wave generation limit of an elevated-hinge generator (5) at the tested conditions (h=2.8 m, l=1.3 m). The different trials considered constant wave period (T=2 s) and a range of wave heights from 10 cm to 70 cm with 10 cm increments. Note that the tested conditions are almost at the deep-water limit, most of them in the validity range of the Airy Wave Theory (i.e. Linear Wave Theory), where three conditions tested are within the steepness of a Stokes higher-order wave.

A sample time series of the measured free surface at the second wave gauge (WG2) for a wave height of 20 and 70 cm are shown in Fig. 16. The time series show the effect of the steepness on the asymmetry of the wave. Fig. 17 presents the results of the time-domain analysis for the regular wave trials with a wave period of 2 s in all wave gauges. Note that, in the first iteration, the measured height matches the target up to a wave height of 40 cm, which corresponds sensibly to the Airy wave theory limit. Bigger waves deviate progressively from the target since linear wave theory generation (5) have been used instead of a more appropriate non-linear wave generation method,

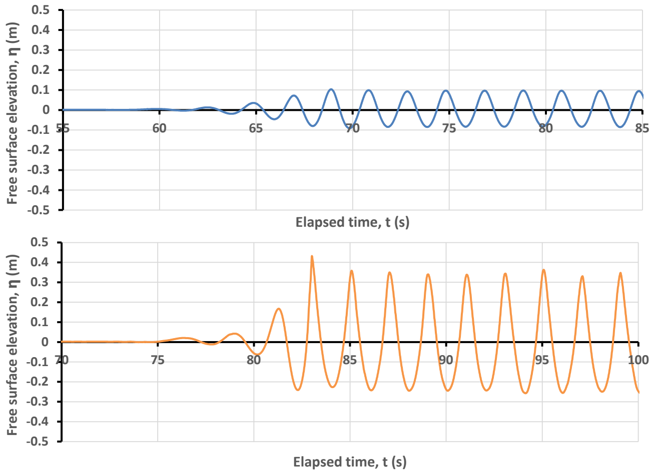

Fig. 16. Sample cases of the performance tests. Free surface elevation measured 12.629 m from the elevated-hinge wave generator (WG2). Water depth is 2.8 m and the elevation of the hinge is 1.3 m. Top: Target wave height of 20 cm, Bottom: Target wave height of 70 cm.

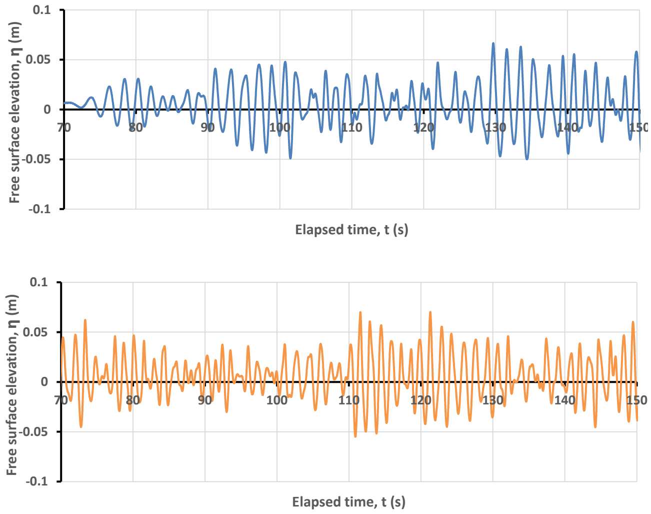

Fig. 18. Sample irregular wave cases of the performance tests. Free surface elevation measured 12.629 m from the elevated-hinge wave generator. Water depth is 2.8 m and the elevation of the hinge is 1.3 m. Top: H_{m0}=0.1 m, T_p=1.99 s, Bottom: H_{m0}=0.09 m, T_p=1.5 s.

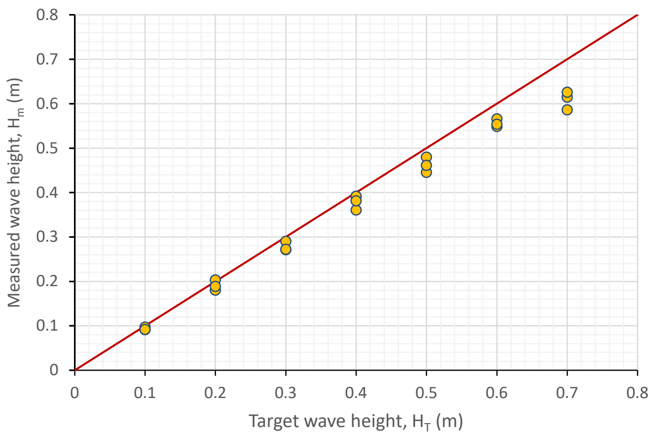

Fig. 17. Regular wave tests for T=2 s. Target and measured wave height comparison for all regular wave cases and at all wave gauges.

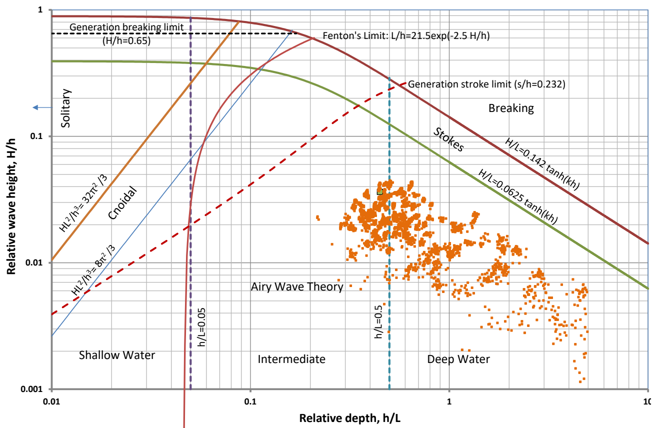

Fig. 19. Selected irregular wave conditions part of the performance and acceptance tests, plotted in dimensionless form. Different lines depict the validity of the different wave theories (Airy, Stokes, Cnoidal) as well as the breaking limit as suggested by Miche (1). Dashed red curve represents the wave generation limit of an elevated-hinge generator (5) at the tested conditions (h=2.8 m, l=1.3 m). The trial shown has a significant wave height of 0.1 m and a peak wave period of 1.99 s.

reinforcing the conclusions found in [4]. Nevertheless, it was verified that the new elevated-hinge wave generator is able to achieve the nominal design wave height.

H. *Irregular wave tests*

Irregular waves have also been tested with different heights and periods. For simplicity, two conditions are presented herein, one with a significant wave height, H_{m0}, of 0.1 m and peak period, T_p, of 1.99 s, and another with a significant wave height, H_{m0}, of 0.09 m and peak period, T_p, of 1.5 s. Both cases followed a JONSWAP spectrum with peak enhancement factor, γ, of 3.3. Water depth and hinge elevation are the same as during the regular wave tests.

Equivalent as in Fig. 16, Fig. 18 shows a sample time series of the measured free surface at the second wave gauge (WG2) for both irregular wave tests. Moreover, applying a standard time-domain analysis, measured individual waves at WG2 during the trial with H_{m0}= 0.1 m and T_p= 1.99 s are presented in dimensionless form in Fig. 19.

Some characteristic descriptive parameters of the measured time series for both wave conditions are presented in Table 1 and 2, respectively. The descriptive parameters include results from a standard frequency-domain and time-domain analysis. The results provide relevant information on the wave generator performance, but mainly serve to assess the impact of repeating a short irregular wave time series to conduct a long duration experiment, a methodology applied on a regular basis in deep water testing. The major impact of this procedure is that the wave distribution is not representative (primarily of a Rayleigh distribution), where the general characteristics parameters ($H_{1/3}$, H_{m0}, H_{max}, T_p, T_z,…) may not be achieved.

This is shown in Fig. 20, where the computed energy density spectrum is plotted with the corresponding target JONSWAP spectrum at the second gauge for the case of H_{m0}= 0.1 m and T_p= 1.99 s. Note the shape of the spectrum is correct, but the energy density has not achieved the correct magnitude. Note that the upper bound of the wave height

TABLE I
CHARACTERISTIC PARAMETERS OF THE MEASURED TIME SERIES.
H_{M0}=0.1 M AND T_P=1.99 S

Parameter	WG1	WG2	WG3
H_{m0} (m)	0.094	0.090	0.088
T_p (s)	1.998	1.950	1.998
# of waves	3019	3068	3050
Mean H (m)	0.061	0.058	0.056
$H_{1/3}$ (m)	0.092	0.086	0.084
T_z (s)	1.729	1.702	1.712
H_{max} (m)	0.126	0.112	0.138
$T_{(Hmax)}$ (s)	1.893	1.905	2.142

TABLE 2
CHARACTERISTIC PARAMETERS OF THE MEASURED TIME SERIES.
H_{M0}=0.09 M AND T_P=1.5 S

Parameter	WG1	WG2	WG3
H_{m0} (m)	0.080	0.078	0.075
T_p (s)	1.463	1.463	1.463
# of waves	1615	1622	1605
Mean H (m)	0.050	0.049	0.047
$H_{1/3}$ (m)	0.078	0.078	0.074
T_z (s)	1.298	1.292	1.307
H_{max} (m)	0.117	0.125	0.131
$T_{(Hmax)}$ (s)	1.427	1.327	1.314

distribution cannot be seen in this plot, hence the proper representation of largest waves in the distribution will not be depicted here. However, it is worth saying that the trial executed did not undergo a wave calibration procedure, hence it is not necessarily expected that the significant wave height, expressed via the zeroth-moment, is accurately reproduced.

Summarizing, the new elevated-hinge wave generator was able to simulate the target wave conditions for an extended amount of time, and care should be taken in the composition of the steering signal to avoid improper representation of the target spectrum and wave height probability distribution.

V. CONCLUSIONS AND FUTURE WORK

A new, removable elevated-hinge wave generator, conceived to complement the existing piston-type wave generator in the Large Wave Flume at Oregon State University, was commissioned to Edinburgh Designs Ltd. Initial testing of the new wave generator proved the quality and efficiency of the system, able to generate intermediate to deep water waves at a depth up to 4 m, a depth range not available in the LWF until now. The solution adopted for the system includes 6 stainless steel segmented paddles, electrically actuated. Each paddle is fitted with force-controlled active wave absorption that allows absorption of spurious cross-waves typically

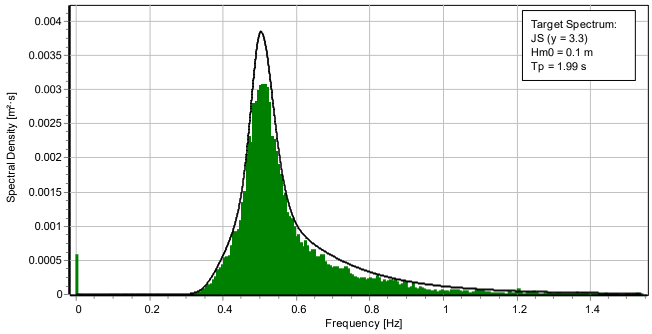

Fig. 20. Estimated energy spectrum at WG2 compared with the target spectrum for the trial with H_{m0}=0.1 m and T_p=1.99 s.

observed during the testing of marine energy devices, particularly floating wave energy converters. Preliminary experiments included regular waves up to 70 cm high, and long duration irregular waves, where the system was able to maintain the energy content preventing build-up due to reflected waves. The system is compatible with the possibility of having both wave generators at opposite sides of the flume, one used for generation and the other for absorption, increasing the testing section in the flume to ~80 m. Moreover, the elevated-hinge wave generator system is compatible with the generation of following or opposing currents in the flume, opening a full new research capability at the HWRL.

Future work already includes the use of FLAP, i.e. the new elevated-hinge wave generator in two upcoming projects at the LWF. Additional performance tests are planned mainly to assess the wave generation and absorption capabilities.

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