Hydro-elastic interaction of polymer materials with regular waves

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Abstract— **Flexible materials could offer a step-change reduction in the cost of wave energy devices by enabling them to absorb more extreme wave loads through structural deformations. Flexible wave energy converters are usually manufactured from polymer, fabric, or reinforced polymer components. The elastic modulus, fatigue performance, seawater ageing, and manufacturing process determine the effectiveness of flexible components at replacing their rigid counterparts. During design, it is necessary to assess the hydrodynamic response of the WEC structure to different wave conditions. This work investigates the hydro-elastic response of a submerged polymer membrane, held in a horizontal frame, and exposed to regular wave loading. Fast-Fourier Transform analysis enabled assessment of the non-linear response of the membrane under different wave conditions. The harmonic to measured wave amplitude ratio gives insight into the excitation mode of the membrane as a function of frequency. It is found that the peak response of the membrane tends to coincide with the fundamental frequency of the regular waves. By varying the ratio of membrane length to wavelength an understanding is provided of the hydro-elastic response of the polymer membrane which should be useful in validating software used in the design of flexible WECs.**

Keywords— **Hydro-elasticity, Flexible membrane, Wave structure interaction.**

I. INTRODUCTION

Wave energy converters (WECs) are designed to harness energy from ocean waves and convert it to usable electricity. Flexible WECs utilize materials that bend and flex with the waves, reducing hydrodynamic loading and enabling energy capture over a broad range of wave conditions, thus maximising energy extraction. Ieuan et al. [1] and Renzi et al. [2] have presented reviews of flexible WECs and the challenges faced in developing the technologies. The flexible WEC design can withstand the harsh ocean environment, including strong waves, storms, and currents. Their flexibility also helps dissipate wave energy and reduces stress on the device, enhancing its durability. It may help pave the way to cost-efficient WEC designs. Selection of appropriate materials that can utilise their hydro-elastic response to withstand the harsh marine environment is crucial. Hydro-elastic interaction studies have previously been carried out for very large floating structures [3, 4, 5], ice sheet interactions [6, 7], and piezoelectric structures [8, 9]. Physical model studies have been performed to assess the interaction of waves with thin horizontal elastic plates. For example, Brown et al. [10] experimentally analysed the hydro-elastic behaviour of a floating flexible plate in a wave flume and compared their results with OpenFOAM model predictions. Brown et al.'s numerical model is reported to capture the wave induced deformation; however, there is future scope for developing the numerical model to solve 3-D problem applications. Sakai and Hanai [11] proposed an empirical equation for the dispersion relation based on experiments conducted on a model icesheet made of polyethylene and successfully estimated the wave celerity in the sea ice region. Kohout et al. [12] investigated wave propagation under many floating elastic plates of variable properties using a solution method matching eigenfunctions at the boundaries of the plates. Montiel et al. [13] conducted experiments to provide benchmark data for the validation of a linear time harmonic model capable of studying the flexural response of single and double discs. Montiel et al. [14] also reported the potential discrepancy between the theoretical predictions and experimental data for single and double discs. The numerical model is reported to agree well (5% to 20%) over the frequency range except for overestimating the response. Michele et al. [15] developed a matched eigenfunction expansion and dry-mode expansion-based theoretical model to evaluate the wave power extraction of a free-floating elastic plate attached with power take off (PTO) units. They reported a need to scale up experimental investigations on flexible WECs. Recently,

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Zheng et al. [16] investigated the hydro-elastic response of a floating elastic disk shaped WEC using a theoretical model based on the dispersion relation and Michele et al. [17] presented results from the physical model tests conducted on a floating flexible circular plate. Few physical model tests have been conducted to assess hydro-elastic interactions, and so it is necessary to develop and calibrate numerical modelling tools. This paper presents and analyses data from hydro-elastic physical model tests on the response of a flexible neoprene rubber material fixed at four edges exposed to different regular wave conditions.

II. METHODOLOGY

A. Experimental set-up

Experiments were conducted in the sediment wave flume of length 35 m and width 0.6 m within the Coastal, Ocean and Sediment Transport (COAST) Laboratory, at the University of Plymouth. The wave flume was equipped with a piston type wave maker with active absorption capabilities and a foam beach. The neoprene rubber material flexible membrane was 998 mm long, 594 mm wide and 3 mm thick, supported by an aluminium sandwich frame on all four sides. This arrangement was supported using four flat bars at the four edges of the frame as shown in Fig. 1. Additional stiffeners were attached to the flat bars to support the aluminium frame and flexible membrane arrangement for additional rigidity. The same neoprene rubber material was used for making the hovercraft skirts and contained additives such as carbon black or micro-ceramics. The material properties, density 1500 kg/m^3, Young's modulus 5.9 MPa and Poisson's ratio 0.49 were determined from material lab testing. The flexible membrane and frame arrangement were immersed at a submersion depth of 108 mm from the free surface and tested in water of depth 700 mm. Wave gauges were arranged inside the wave flume set-up as illustrated in Fig. 2 to measure wave interaction with the flexible membrane arrangement. An empty tank test was initially conducted to measure free surface wave elevations inside the wave flume without the influence of any flexible membrane. Regular waves

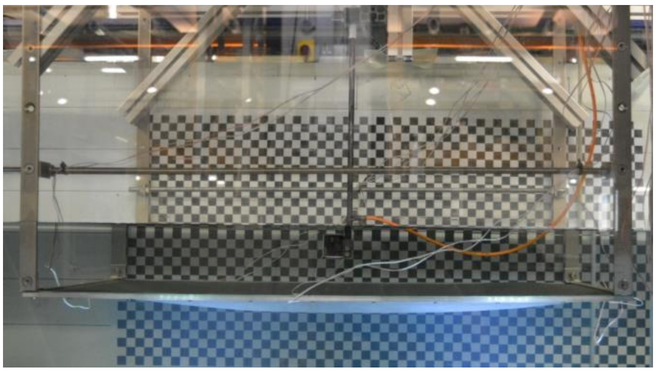

Fig. 1. Photograph of the flexible neoprene rubber material arranged inside the wave flume supported by four flat rods at the edges.

with three different wave frequencies of 1.75 Hz, 1.25 Hz and 1.02 Hz were tested for six different wave amplitudes. The ratio between the membrane length to wavelength was 0.5, 1.0 and 1.5, respectively. Table I shows the measured wave amplitudes for each wave

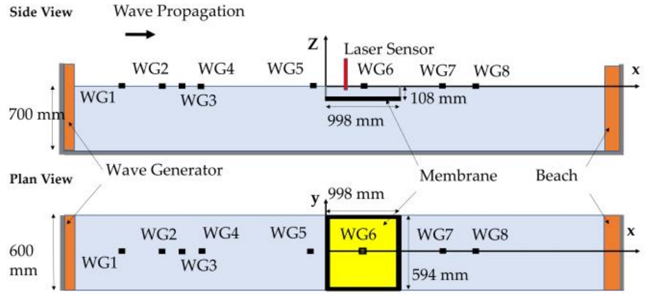

Fig. 2. Schematic of the wave flume facility with the membrane set-up and instrument position

frequency. An underwater laser distance sensor (BOD 21M-LA02-S92) with ± 1 mm accuracy measured the response of the membrane. The underwater laser distance sensor was calibrated with respect to known distance, and the percentage error in the measurement is determined to be 1%. This laser sensor was arranged at six different positions (L) along the membrane for the different wave conditions listed in Table II.

TABLE I
MEASURED WAVE AMPLITUDE

Wave amplitude, a_w (mm)	Wave frequency, f_0 (Hz)		
	1.75	1.25	1.02
Amplitude 1	0.9	0.9	1.4
Amplitude 2	2.0	3.0	2.4
Amplitude 3	4.8	7.3	6.2
Amplitude 4	10.2	13.9	13.5
Amplitude 5	-	26.8	26.9
Amplitude 6	-	33.3	33.2

TABLE II
POSITIONS OF LASER DISTANCE SENSOR MEASUREMENTS ALONG THE MEMBRANE WITH RESPECT TO THE X AND Y COORDINATE

Coordinate (mm)	L1	L2	L3	L4	L5	L6
x	245	498	748	498	748	748
y	172	172	172	322	322	461

III. RESULTS AND DISCUSSIONS

The hydro-elastic response of the membrane at different measurement positions (L) along the membrane is examined in the present work. Fig. 3 illustrates the measured elevation of the neoprene rubber membrane at six positions in air and water. It is evident that near the centre of the membrane, L4, the membrane displacement has a minimum (-47.2 mm in air and -41.3 mm in water) that is partly due to material deformation during the manufacturing process. The deflection of the membrane in water is reduced by approximately 7% with respect to that in air owing to buoyancy of the membrane. Fig. 4 illustrates typical free surface elevation and membrane displacements plotted against time at different locations for a wave frequency of 1.25 Hz and wave amplitude of 33.3 mm.

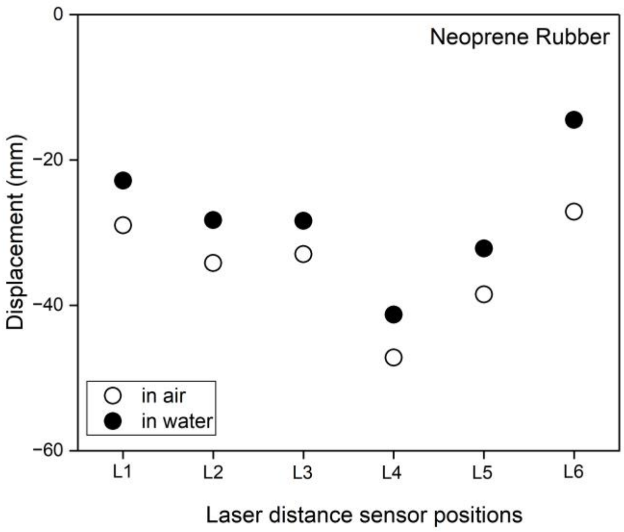

Fig. 3. Elevation of the neoprene rubber membrane at 6 positions in air and water, relative to that of a rigid plate

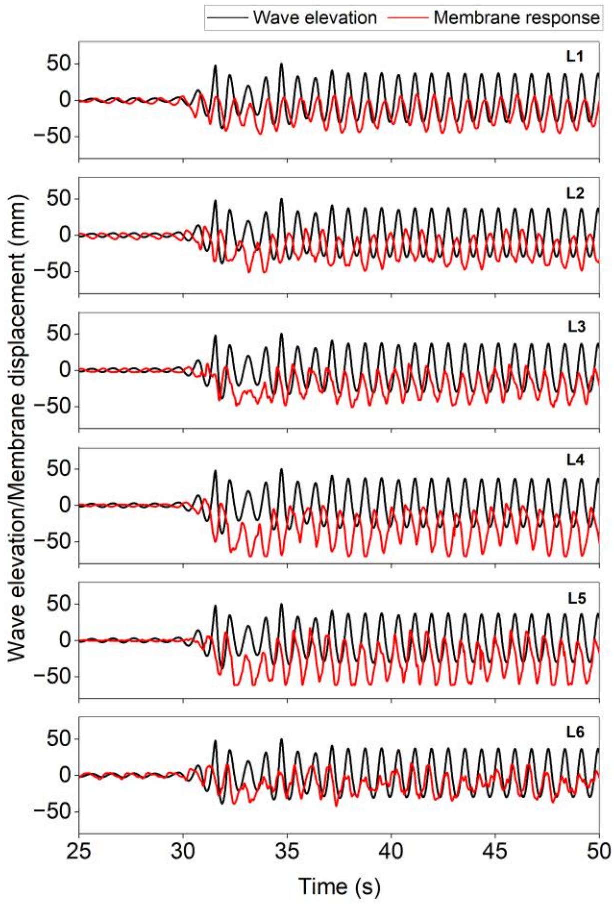

Fig. 4. Free surface elevation and membrane response for a wave of frequency 1.25 Hz and amplitude 33.3 mm

Fig. 5. presents the hydro-elastic response amplitudes at position L4 for three wave frequencies and six wave amplitudes analysed using Fast Fourier transforms (FFT) method, in which the response of the membrane amplitude (a_m) to the wave amplitude (a_w) is plotted with respect to the normalised frequency (f/f_0), where f is the measured membrane frequency and f_0 is the fundamental frequency of the regular waves. It is observed that the response of the flexible neoprene rubber membrane is highest at $f = f_0$ for all the tested wave conditions. The variation in harmonic amplitudes of membrane response at the second harmonic ($2f_0$) and third harmonic ($3f_0$) at different wave amplitudes is found to be low at higher wave frequencies. However, at a lower wave frequency of 1.02 Hz the membrane is observed to be excited at subharmonic wave frequencies. The magnitude of a_m/ a_w ratio at these frequencies is much lower than the first harmonic ($1f$). Excitation of the flexible membrane at subharmonic wave frequencies is also observed at higher wave amplitude cases. For wave frequency of 1.25 Hz and amplitudes (a_w) of 26.8 mm and 33.3 mm, it is observed that the membrane is excited at a frequency of approximately 0.20 Hz. At the wave frequency (i.e., f/f_0=1.0), a higher peak a_m/ a_w ratio is observed at a lower wave amplitude for wave frequency of 1.75 Hz, however, the measured membrane amplitude for this case is lower than other tested wave amplitude cases. The a_m/ a_w ratio is between 0.09 to 0.61 at a wave frequency of 1.75 Hz, and increases up to 0.855 at a wave frequency of 1.02 Hz. A peak value of the a_m/ a_w ratio observed at the sub-harmonic frequency for wave frequency 1.02 Hz is 0.577. This may be because the 1.02 Hz wave frequency case corresponds to the lowest frequency in the test cases and is closest to the natural frequency of the membrane.

Fig. 6 illustrates the harmonic response amplitudes of the membrane at different wave frequencies. As tabulated in Table II, wave amplitudes are grouped under amplitudes 1-6, respectively for this discussion. For the amplitude 4 group, the membrane is found to be excited at a frequency of 0.25 Hz (f_0=1.75 Hz and 1.25 Hz) and 0.20 Hz (f_0=1.02 Hz). For the higher amplitude group 5, the membrane response is excited at a frequency 0.17 Hz (f_0=1.25 Hz) and 0.20 Hz (f_0=1.02 Hz). The same range is observed for the highest amplitude group 6. This observed frequency could be the natural frequency of the membrane. However, more tests are required to confirm the finding. It is evident from the results that the membrane response is highest at the wave frequency and that there is an influence of the natural frequency of the membrane. The results could help to develop and calibrate a numerical model to assess complex non- linear hydro-elastic behaviour of flexible structures.

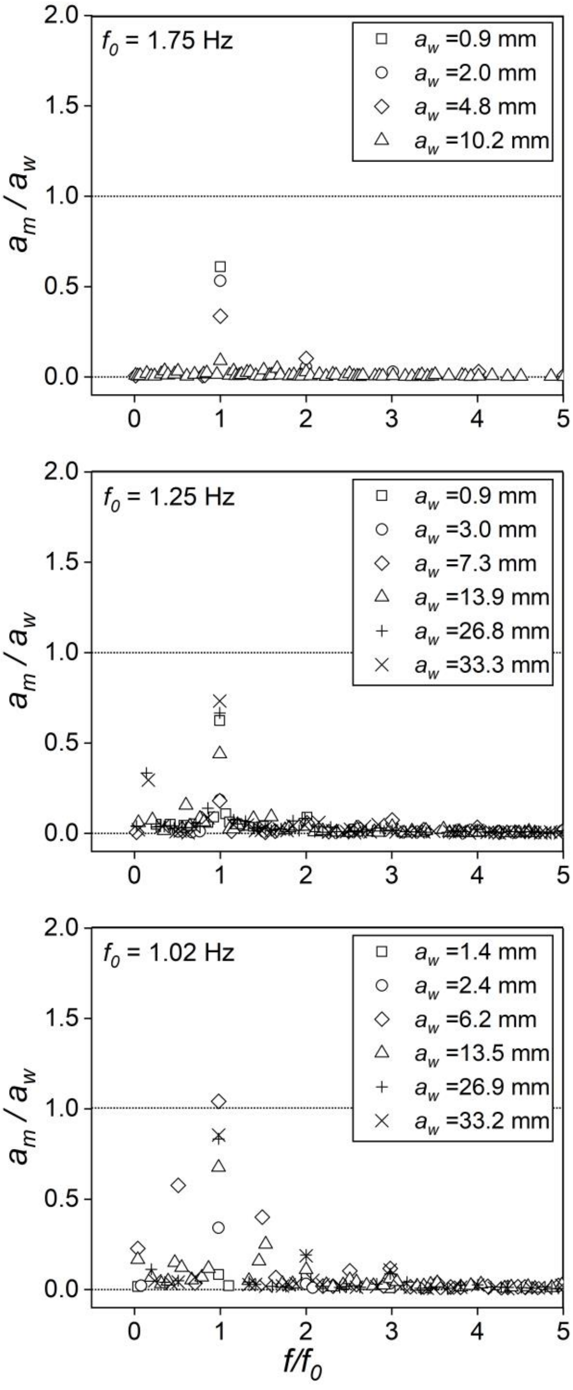

Fig. 5. Hydro-elastic response amplitude at position L4 at each wave frequency

IV. Conclusion

This paper discusses the observed hydro-elastic response of a flexible membrane made of neoprene rubber material exposed to different regular wave cases. The flexible membrane is found to be excited more at the wave frequency than at other frequencies for all the tested wave

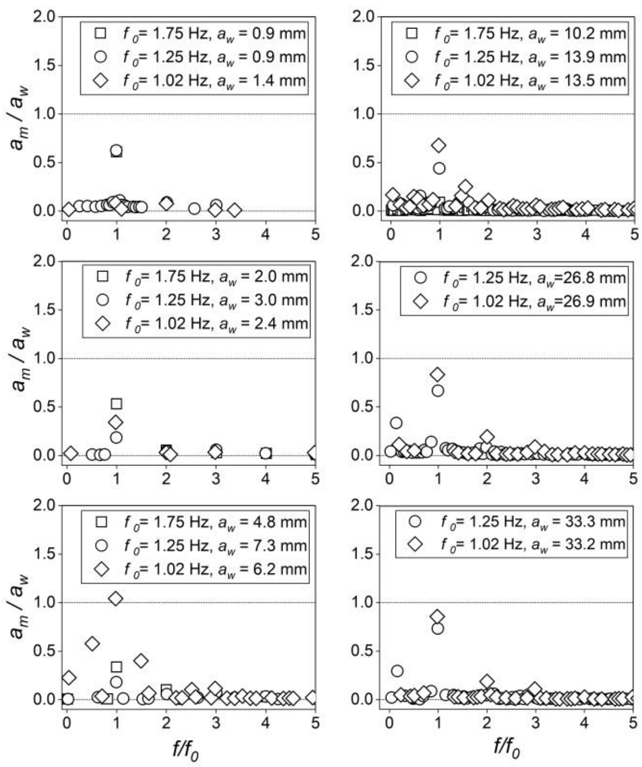

Fig. 6. Hydro-elastic response of Neoprene rubber material at position L4 with respect to amplitude of waves at different wave frequencies

conditions. It is also evident from the results that the flexible membranes are excited at a very low frequency, apparently away from submultiple components of the wave frequency, and which could be the natural frequency of the membrane. Further experiments are required to determine exactly the natural frequency of the flexible membrane and confirm whether this observation is correct.

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