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Effects of Wave Spreading on Performance of a Wave Energy Converter

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Highlights:

- Relative rotations (pitch and yaw motions) and shear forces (in vertical and horizontal directions) in an attenuator type wave energy converter have been investigated in uni-directional and multi-directional waves.
- Numerical results have shown that less energy may be harnessed in multi-directional seas.

1. Introduction

Ocean waves are irregular, nonlinear and directionally spread (short-crested). The irregularity of waves can be considered by superposing components at different frequencies. In many frequency-domain analyses, second-order contributions can be calculated to take account of the nonlinearity in wave-structure interactions. The directional spreading of the waves is usually described by introducing a directional spectrum. Several directional spectra have been suggested by researchers [1]. In short-crested waves, the wave energy propagates in different directions around principal wave directions, which will affect the performance of Wave Energy Converters (WEC). Especially, less energy may be harnessed for some directionally sensitive WEC.

In present paper, we have examined the performance of an attenuator type WEC by calculating the relative rotations (pitch and yaw motions) between floating modules in uni-directional and multi-directional waves. The emphases have been put on operational sea states and only linear incoming waves have been considered. In the next section, the description of multi-directional waves in a numerical model will be introduced briefly. Then the motions of an attenuator type WEC and shear forces (in vertical and horizontal directions) acting on power take-off system (PTO) will be investigated. Different wave spreadings have been considered.

2. Description of Multi-directional Waves

The basic idea in the present paper is to superpose all the wave components from different directions but with the same frequency as a single incoming wave [2, 3]. In the frequency domain, the linear incident wave velocity potential in directionally spread seas at a single frequency can be written as

$$\phi_i = \sum_{m=1}^{M} \phi_{im} e^{\mathrm{i}k(x\cos\theta_m + y\sin\theta_m)} \tag{1}$$

where k is wave number, θ_m is direction of wave component, and M is total number of directional components. For finite water depth, ϕ_{im} can be expressed as

$$\phi_{im} = \frac{-\mathrm{i}\omega A D(\theta_m - \beta)\Delta\theta}{k} \frac{\cosh k(z+d)}{\sinh kd} \tag{2}$$

where ω is angular frequency of the wave, A is the amplitude of the incident wave, d is water depth, β donates principal wave direction, $D(\theta_m - \beta)$ is directional spreading function which can have different expressions [1]. Similarly, ϕ_{im} in infinite water depth can also be derived easily.

3. Effects of Wave Spreading on Performance of a Wave Energy Converter

There are many concepts to harness the power of waves. Wave devices can be divided into different groups according to the method used to capture the wave power, i.e. attenuator, point absorber, oscillating wave surge converters, oscillating water column, overtopping/terminator device, submerged pressure differential, bulge wave, rotating mass, etc. An example of an attenuator WEC is the Pelamis, developed by Ocean Power Delivery Ltd (now known as Pelamis Wave Power). Pelamis is a floating device which operates parallel to the wave direction and captures energy from the relative pitch and yaw motions of the modules as the waves pass them. The machine is designed to operate in water depths greater than 50m and is typically installed 2-10km from the coast.

In the present paper, the wave energy converter has been simplified as 5 rigid rectangular boxes connected by 4 ideal hinge joints (without damping and friction) which only allow the relative rotations between boxes. The sizes of the simplified model are based on the latest Pelamis P2 machine. Each module has a length L=36 m, beam B=4 m, and the drafts of the boxes are 2 m. The Centres of Gravity are at mean water level (z=0) and water depth is assumed as infinite. More details of the simplified wave energy coveter and definition of coordinates can be found in Fig.1. For such interconnected multiple floating bodies, both hydrodynamic interactions and mechanical connections have to be considered in calculations. A two-stage approach [4, 5] has been adopted to calculate the hydrodynamic forces and solve the relative motions between floating modules in the WEC based on a boundary element analysis of the hydrodynamics using the program DIFFRACT.

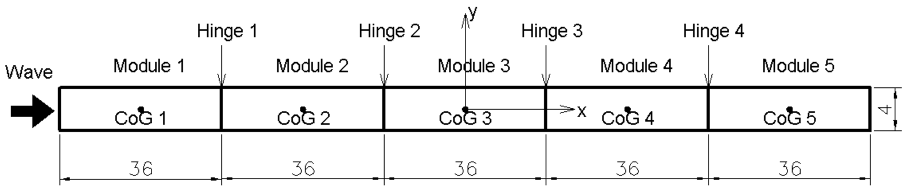

Fig.1 Plan view of simplified wave energy converter (β=0)

Both uni-directional waves and multi-directional waves with different directional spreadings have been considered in numerical analyses. For multi-directional sea states, the wave spreading has been modelled using the following directional spreading function,

$$D(\theta_m - \beta) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\Gamma(s+\frac{1}{2})}\cos^{2s}(\frac{\theta_m - \beta}{2}) \tag{3}$$

where Γ is the gamma function and s is the wave spreading parameter. Three directional spreadings have been considered in the analyses (s=5, 15 and 25). Corresponding directional distributions $D(\theta_m - \beta)$ can be found in Fig. 2. It can be seen that more energy propagates in the principal wave direction β when a larger spreading parameter s is used.

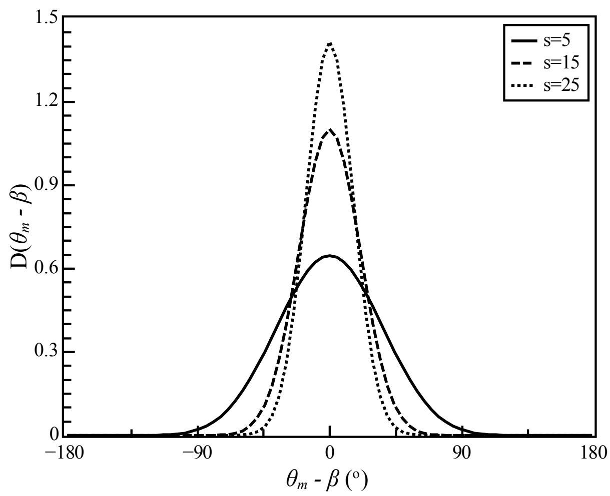

Fig.2 Directional energy distribution under idealized conditions

Relative pitch motions at 4 hinges have been plotted in Fig.3 separately when principal wave direction β=0, which have been non-dimensionalised by $2kA$. Peak values of relative pitch motions can be found at wave period of 7~8s. Larger relative pitch motions are obtained at all wave periods in uni-directional waves, which imply that more energy is expected to be extracted under such assumption. In multi-directional seas, smaller relative pitch motions are obtained. Especially for s=5, the reductions of relative pitch motions at peak values are up to 27%. With the increase of spreading factor s, the relative pitch motions approach those in uni-directional waves. In both uni- and multi-directional waves, smallest relative pitch motions are always found at hinge 4.

Another concern in the design of WECs is the forces acting on the power take-off systems which are usually assumed as the most complicated and weakest parts of WECs. To address this issue, Fig.4 shows the vertical shear forces acting on hinges in the present simplified WEC when principal wave direction β=0. The vertical shear forces are normalized by $\rho g A l^2$, where ρ is the fluid density, g is the acceleration due to gravity, and l^2 is a reference area equal to 1 m^2. It seems that there are no significant differences in vertical shear forces for uni-directional waves and multi-directional waves when s=15 and 25. However for multi-directional waves when s=5, peak shear forces have been reduced by up to 26%. Similar to the results of relative pitch motions in Fig.3, smallest vertical shear forces are always achieved at hinge 4. However, largest vertical shear forces are found at hinge 2.

4. Concluding Remarks

The results of relative pitch motions (when WECs are parallel to principal wave direction β, β=0) have shown the significance of wave directional spreading on performance of attenuator type WECs, in particular when wave spreading factor *s* is small. Larger relative pitch motions are obtained in uni-directional waves. Similar to the relative pitch motions, vertical shear forces acting on hinges for small wave spreading factor (s=5) have been reduced by up to 26% of the shear forces in uni-directional waves. However with the increase of spreading factor *s*, wave directional spreading has less effect on vertical shear forces acting on ideal hinges. Further results for relative pitch and yaw motions, horizontal and vertical shear forces when principal wave direction β=15^o and 30^o will be discussed in the workshop.

Although the power take-off systems (PTO) have been simplified as ideal hinges (nonlinearity and damping in PTO have not been considered), it can be concluded that available wave energy will be over predicted under a uni-directional wave assumption. Damping in the PTO can be considered by introducing damping coefficients in the motion equations. To take account of the nonlinearities of the PTO, the motion equations have to be solved in time domain. Another possible improvement to the present analysis is to calculate the higher-order contributions in strongly nonlinear waves.

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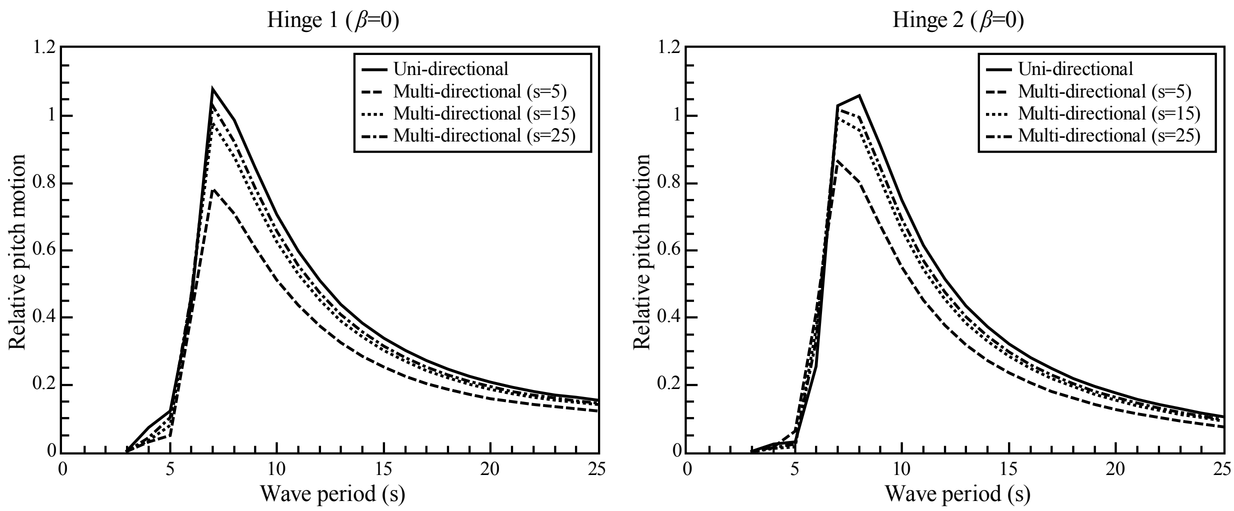

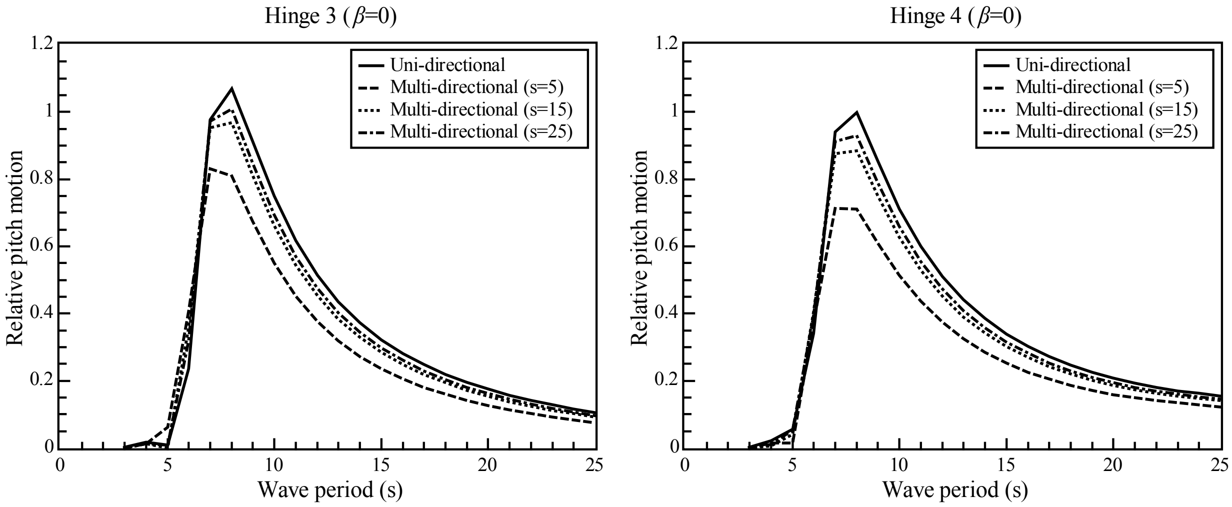

Fig.3 Relative pitch motions at hinges in uni- and multi-directional waves (β=0)

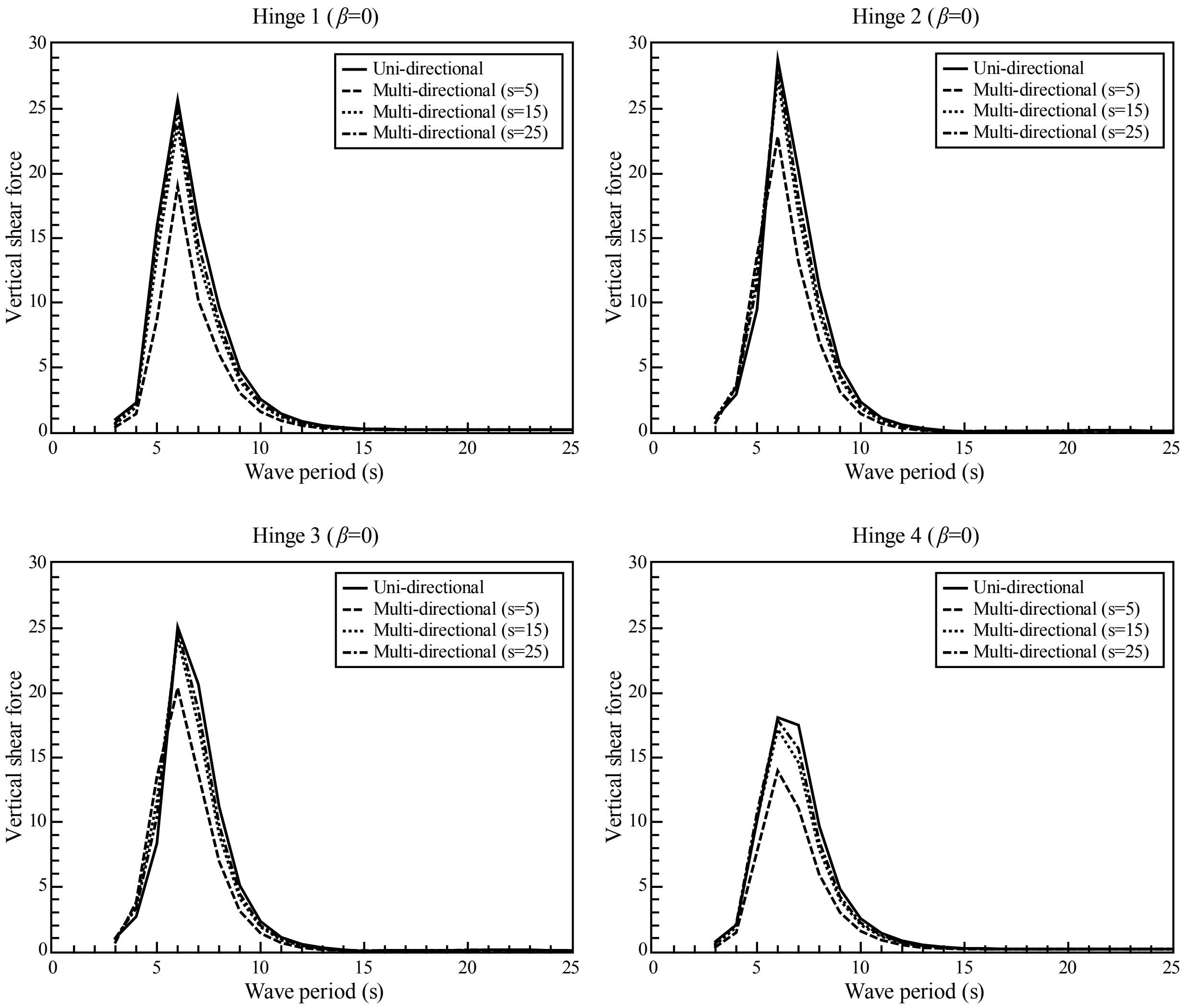

Fig.4 Vertical shear force acting on hinges in uni- and multi-directional waves (β=0)