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Editors

Soon Keat TAN
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PREFACE

The coastal zone has always been an important frontier – for trade, food and foundation for modern civilization. This same zone has also been exploited in one way or another and sometimes without regards to the nature's balance and scheme of things. It is only when somethings go terribly wrong that we begin to react and attempt to undo the mistakes of the past. At times we have succeeded, but at a high price. At times, we have to retreat and concede defeat as the technology of man is no match to the force of nature. Overtimes we learn to work with nature and leverage on science of nature to protect the coastal zone and hold our frontier between the sea and land.

We are now in the exciting and challenging era of climate change. The immediate future foretells higher seawater level, stronger winds, waves and currents. Globally we see increasing frequency of storm surges, increase intensity of rainfall and flood. We need to work together to advance the science and knowledge of the coastal zone. Scientists, engineers, and professionals need to work together to deal with coastal zone issues and challenges.

This set of four-volume proceedings collects all the papers presented at the 5th International Conference on Asian and Pacific Coasts and covers a wide range of topics, including coastal and harbor structures, sediment processes and shoreline changes, coastal environmental problems and marine ecology, coastal zone management and planning, tsunami, ocean energy, global environmental problems, laboratory and field measurement techniques, numerical simulations of coastal problems, and basic research in ocean waves, currents, and tides. The proceedings will be a valuable reference book for researchers, engineers, professionals, and postgraduate students working on the coastal engineering problems.

Tan Soon Keat
Zhenhua Huang
Nanyang Technological University, Singapore
October 2009

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HYDRODYNAMICS OF TWO DEVICES
FOR WAVE-POWER EXTRACTION

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We describe the theories for two types of wave-power absorbers that can have a wide bandwidth of high efficiency. One is a compact array of small buoys supported by a large platform. Because each buoy is much smaller than the wavelength, inertia is negligible hence the buoys are not resonated. However the efficiency of the array has a relatively broad frequency band. We shall show that such an array can be more advantageous than a single large buoy of the same total volume. The second devise is an oscillating water column attached either to a thin breakwater or to a cliff-like coast. We show that the system has an added inertia that varies with the wavenumber as a N-shaped curve. If the volume of chamber above the interior water surface is suitably chosen, the compressible air serves as a negative spring that broadens the efficiency bandwidth.

1. Introduction

For the economy of transmission and storage, wave-power absorbers are best installed not far from the coast. According to the physics of refraction, when ocean waves enter shallow waters, the crests tend to become parallel to the depth contours which are more or less parallel to the shore line. Therefore the wave power potential can be crudely estimated by the power influx per unit length of the coastline. Consider a train of simple monochromatic waves of frequency ω and amplitude A. It is known that the energy per unit length of the wave front is $E = \frac{1}{2}\rho g A^2$, and is transported by the group velocity C_g. The period-averaged rate of power influx per unit length is $\frac{1}{2}\rho g A^2 C_g$. If the annual average of the amplitude is $A = 1$ m then the averaged wave power influx is 40 kW per meter of the coast. Based on statistical data of wave climate, estimates of the wave power potential for many coastal sites in the world are now available.

There are now many designs of single unit absorbers for extracting wave energy. To achieve the capacity of a standard power plant, an array of many units will be needed. Therefore the design challenge is not only in maximizing the efficiency of single units for a broad range of frequencies, but also in optimizing the array configuration so as to make the interference not distructive. To date major efforts appear to have focussed on the development of single units. Each unit can involve

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floating bodies or a fixed structures. In the floating body category,there are (i) point aborbers such as a buoy which is insensitive to the direction of incoming waves, (ii) beam-sea devises which are parrallel to the front of incoming waves such as Salter's duck, and (iii) head-sea devises which is moored at the bow and can align itself with the direction of incoming waves. Cockerel's raft and its more advanced extension the Pelamis are representative. In the category of fixed structures the oscillating wave column has been much studied. Through a submerged opening the free surface inside the column can oscillate vertically and drive the dry air through a Wells turbine above.

Nearly all of the single-unit absorbers are designed on the basis of impedance matching. The typical mechanical principle is represented by a single buoy connected to a energy absorber which is modeled as a linear damper. In particular, the rate of energy removal is characterized by the product kL where L is the capture width and k the incident wavenumber. In normalized form the capture width L is

$$kL \equiv \frac{k}{C_g} \frac{\lambda_g \omega^2 |F_z^D|^2}{\omega^2 (\lambda_{zz} + \lambda_g)^2 + (\pi a^2 - \omega^2 (M + \mu_{zz}))^2} \tag{1}$$

where F_z^D is the heave exciting force on the buoy, a the buoy radius, M the buoy mass. μ_{zz} and λ_{zz} are respectively the hydrodynamic added mass and radiation damping, and λ_g the absorption coefficient of the power takeoff, all suitably normalized. It can be shown analytically and numerically that

- The maximum energy extraction is achieved at resonance

$$\pi a^2 - \omega^2 (M + \mu_{zz}) = 0 \tag{2}$$

  and the extraction rate equals the radiation damping rate

$$\lambda_g = \lambda_{zz}. \tag{3}$$

  At best the maximum capture width for a buoy with only one degree of freedom (heave) is such that $kL = 1$. To achieve this maximum it is necessary to choose the buoy size so that the resonance frequency coincides with the peak frequency of the incoming sea spectrum. For one system, this maximum is attained only for one frequency.
- The resonance frequency at which this maximum occurs satisfies the order equality $k_N a = O(1)$. Thus the buoys radius must be as large as large as $1/6$ of a wavelength for resonance to occur. A small buoy can only be resonated at a very high frequency.
- The bandwidth of the resonance peak increases as the size of the buoy decreases.

Thus it is difficult for one buoy to be resonated at a low frequency typical of the peak of usual sea spectrum, and to have a wide bandwidth of high efficiency.

To improve the frequency bandwidth of absorption efficiency, phase control of the power-takeoff system has been the most prominent candidate.[1,2] As an alternative,

three groups have recently proposed similar designs that are not based on impedance matching. Each of them involves a compact array of small buoys gathered on a large platform. One is the FO3 system initiated by Fred Olsen in Norway and being developed by ABB & Associates[a]. The second is the Manchester Bobber system initiated by Peter Stansby in UK[b]. In both systems the platform is a square in plan form. The Wave Star[c], the third system under development in Denmark, has only two rows of small buoys lined along two sides of a long beam. In §2 we shall sketch a recent work by[3] on small buoys in a compact array, relevant to both the FO3 and the Manchester Bobber.

To limit the cost of construction, maintenance, energy storage and transmission, etc., some wave power devices will likely be installed on the coast. In 1985 a test model of OWC was installed on a cliff at Toftestallen, near Bergen, Norway. Since 1990 an OWC pilot plant has been in operation on the coast of Pico, Island of Azores, Portugal.[4] New plans have been under consideration for another full-size OWC station at the head of a breakwater at the mouth of Foz do Douro River, Portugal.[5] The proximity of coastline affects the wave climate near the absorber, hence its performance. In §3 we shall discuss an OWC at the the tip of a breakwater,[7] and in §4 an OWC along a cliff coast.[6]

In thei presentation most ot the ideas and results are reviewed. Numerical results and graphs hacan be found in the cited references and will not be repeated here.

2. Compact array of small buoys

We consider an array of small buoys supported by a common platform whose horizontal dimension L is comparable to the incident wavelength $2\pi/k$ and the sea depth h. The radius a of and spacing d between the buoys are comparable but are much smaller than the sea depth. Owing to the presence of two vastly different length scales (the macroscale ($L \sim 2\pi/k \sim h$) and the micro-scale $a \sim d$ with $a/h = \mu \ll 1$), a formal theory based on homogenization can be developed.[3] Here we shall give a more physical derivation.

2.1. Averaged governing equations

Let us first give a heuristic derivation of the governing equations for the macro-scale motion averaged over the micro-scale. In the fluid, we have

$$\nabla^2 \phi = 0, \quad -h < z < 0, \tag{4}$$

Assume the seabed to be horizontal. then

$$\frac{\partial \phi}{\partial z} = 0, \quad z = -1. \tag{5}$$

On the mean free surface away from the buoys, the kinematic and dynamic conditions combine to give

$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\phi = 0, \quad z = 0 \tag{6}$$

On the free surface covered by buoys, let us consider one small buoy first. Assuming that the buoy radius and draft to be small compared to the wavelength, continuity of vertical velocity requires

$$\frac{\partial \phi}{\partial z} = \frac{\partial \zeta}{\partial t}, \quad z = 0 \tag{7}$$

where ζ denotes the heave displacement. Modeling the effect of power-takeoff by a linear damping force $-\lambda_g \frac{\partial \zeta}{\partial t}$ on the buoy where λ_g is he damping coefficient, Newton's law for the buoy requires,

$$M \frac{\partial^2 \zeta}{\partial t^2} = -\pi a^2 \rho \left(g\zeta + \frac{\partial \langle \phi \rangle}{\partial t} \right) - \lambda_g \frac{\partial \zeta}{\partial t}, \quad z = 0 \tag{8}$$

where $\langle \cdot \rangle$ denotes the spatial average over the bottom of the buoy. For small buoys both conditions can be approximately applied on the mean sea level $z = 0$. Since the typical length scale of ϕ is much larger than the size of the buoy, $\langle \phi \rangle$ can be approximated by ϕ in (8). Eliminating ζ we get a condition for ϕ only,

$$\left(M \frac{\partial^2}{\partial t^2} + \rho g \pi a^2 + \lambda_g \frac{\partial}{\partial t} \right) \frac{\partial \phi}{\partial z} + \pi a^2 \frac{\partial^2 \phi}{\partial t^2} = 0. \quad z = 0. \tag{9}$$

For simple harmonic motion (9) becomes

$$\left(1 - \frac{M\omega^2 + \mathrm{i}\lambda_g \omega}{\rho g \pi a^2} \right) \frac{\partial \phi}{\partial z} - \frac{\omega^2}{g}\phi = 0. \tag{10}$$

The above condition is applied at $z = 0$. By Archimedis principle $M = \rho \pi a^2 H$ where H is the small draft. The ratio $M\omega^2/(\rho g \pi a^2) = \omega^2 H/g = O(\mu)$ is small, hence buoy inertia is negligible to the first order of approximation.

From here on we turn to dimensionless quantities defined by

$$x \to hx, \quad t \to t\sqrt{hg}, \quad p \to \rho g A p \quad \phi \to \phi A \sqrt{gh}, \quad k \to \frac{k}{h},$$

$$a \to ha, \quad \omega \to \omega \sqrt{gh}, \quad \lambda_g \to \lambda_g \rho g \pi a^2 \sqrt{\frac{h}{g}}. \tag{11}$$

Eq. (10) reads, in dimensionless form,

$$\frac{\partial \phi}{\partial z} - \frac{\omega^2}{1 - \mathrm{i}\lambda_g \omega}\phi = 0, \quad z = 0, \tag{12}$$

under each buoy. Let f be the area fraction of the free surface covered by buoys, then the averaged free surface condition is

$$(1 - f)\left(\frac{\partial \phi}{\partial z} - \omega^2 \phi \right) + f \left(\frac{\partial \phi}{\partial z} - \frac{\omega^2}{1 - \mathrm{i}\lambda_g \omega}\phi \right) = 0, \tag{13}$$