A wave energy system based on converting wave-induced motions into peristaltic flow in a rectangular channel

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A wave energy system based on converting wave-induced motions into peristaltic flow in a rectangular channel

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Abstract. Energy from the waves at sea is one of the areas that has been an area of interest of the engineering communities worldwide. Recent decades have witnessed the development of various wave energy systems, using various schemes and principles. The main challenge for most systems in efficient energy converting is posed by converting energy into a usable form from the reciprocating wave induced motions due to the harmonic motion of water particles. The authors have conceived a scheme to convert the harmonic motions of water particles which manifest themselves as the near-sinusoidal motion of the free water surface into a unidirectional water flow that can be exploited for harvesting energy: An array of buoys that are arranged in a line perpendicular to the wave direction, that are allowed to oscillate in heaving motion. The heaving motion enforces a series of actuators to induce a sinusoidal motion to a diaphragm sheet placed inside a rectangular channel, which is placed beneath the free surface at a sufficient depth. The motion of the diaphragm sheet shall result in the peristaltic motion of the otherwise stagnant water. The mass of flowing water peristaltic-pumped then can be channelled to a turbine from which energy can be obtained.

1. Introduction

The waves at sea, especially in heavy weather, transmits an enormous amount of energy as witnessed by their devastating effects on the coasts and coastal structures, on floating platforms and ships. Harnessing this energy for the benefit of mankind is one of the challenges that has intrigued engineering communities worldwide, especially in the past few decades, as can be observed from the various schemes depending on various physical phenomena. Each of the proposed/designed systems have their merits and inherent problems. Due to the harshness of the marine environment, such a system should be robust, cost effective and not be far away from the electrical grid. Summary of the existing wave energy systems and their classification can be found in [1] and [2].

A floating object on the surface of sea experiences a six degree of freedom motion under the effect of external disturbances, mainly that of sea waves. For a moored floating body, one of the most obvious is the heaving motion. If the natural frequency of the floating body is significantly higher than that of the sea wave in a monochromatic sea state, the body shall follow the wave contour. In a mixed sea state, the physical dimensions of the body shall act as a filter to eliminate the higher frequency components of the waveform.

The authors have conceived a system to convert the near-sinusoidal heaving motion of an array of buoys arranged in a direction perpendicular to the wavefront into peristaltic pumping of the seawater at
a depth where the environment is otherwise stagnant. The buoys have a hydraulic linkage to the wave conversion device, with a reciprocating pump and a reciprocating hydraulic ram using seawater as the hydraulic fluid. The peristaltic pump element is a flexible diaphragm sheet, which is actuated by the hydraulic ram and is housed in a rectangular channel sufficiently below the free surface (figure 1). As the buoys oscillate, they shall induce the diaphragm inside the rectangular channel below to a sinusoidal motion that mimics the waveform on the free surface, which in turn shall result in peristaltic pumping action of seawater. The energy from the pumped seawater can be converted into electrical energy via a turbine (figure 2).

Figure 1. Buoy and peristaltic pump element

Figure 2. The proposed system- array of buoys and peristaltic pump in the rectangular channel
2. Peristaltic Pumps

The words “Peristaltic motion” or “peristaltic pump” are derived from the word “peristaltis” as defined by the Webster dictionary as “successive waves of involuntary contraction passing along the walls of a hollow muscular structure (such as the esophagus or intestine) and forcing the contents onward”. Peristaltic pumps are bio-mimetic devices that are a class of positive displacement pumps by which the fluid is induced to move by the sinusoidal motion of the walls of the pump channel. Rotary peristaltic pumps are used in a variety of applications, especially in cases where the fluid that is handled should be isolated from the environment. A linear peristaltic pump is a device where the fluid is pumped by the sinusoidal motion of either of the surrounding walls. The geometry of a two-dimensional ideal peristaltic pump is shown below in figure 3. An analysis of linear peristaltic pumps has been given in [3]. The ideal flow rate, \( Q_{ideal} \) through the pump is given by:

\[
Q_{ideal} = f \cdot w_p \int_{-\frac{\lambda}{2}}^{\frac{\lambda}{2}} y \cdot dx = f \alpha w_p \int_{-\frac{\lambda}{2}}^{\frac{\lambda}{2}} \left(1 + \cos\frac{2\pi x}{\lambda}\right) \cdot dx = f \alpha w_p \lambda
\]

where \( \alpha \) is the “design amplitude of peristaltis” determined by the “design wave amplitude” and \( \lambda \) is the wavelength and \( f \) is the frequency of the peristaltic motion of the upper wall, \( w_p \) being the width of the rectangular pump channel.

![Figure 3. Waveform in peristaltic flow](image)

For a sea wave which excites the system described, wavelength and wave period are related, thus, using linear, deep water approximations [4],

\[
\lambda = \frac{gT^2}{2\pi}
\]

the ideal flow rate shall be:

\[
Q_{ideal} = \frac{g}{2\pi} aw_p T = 1.56 aw_p T
\]

\( \alpha \) is the amplitude of the waveform, \( w_p \) is the breadth of the peristaltic diaphragm and \( T \) is the period of wave. The pressure expected to be obtained from the peristaltic pumping configuration above is limited due to leakages in the diaphragm and shall be pulsed. Therefore, it is conceived that more than one sets of units with different phases, feeding an axial flow turbine shall be appropriate.

In waves with wave heights greater than designed height of the peristaltic pump’s stroke amplitude, together with wavelengths greater than the length of the pump channel, i.e., in heavy seas, the pump shall function as a “travelling wave pump” (figure 4), rather than an ideal sinusoidal peristaltic pump.
In this case, the flow rate shall be:

\[ Q_{\text{long wave}} = 2\alpha w_p \cdot c = \frac{g}{\pi} \alpha w_p T = 3.12 \alpha w_p T \] (4)

3. Buoy system

The buoy shall be able to oscillate with an almost fixed amplitude of oscillation. In order to limit the amplitude of oscillations to the height of the peristaltic pump amplitude, a buoy with geometry indicated in figure 4 is adopted. The buoy shall have a waterline area defined by:

\[ A_{wp} = w \left( b_0 + b(z) \right) \] (5)

where \( w \) is the length of the buoy, \( b_0 \) is the minimum breadth, and the breadth \( b(x) \) expands away from the waterline as can be seen in Figure 5. By opting for such a buoy, a “hardening spring” type oscillation mechanism for heaving is aimed, which shall oscillate with a near-constant amplitude in the low excitation frequency regime [5].

The governing differential equation of heave shall be [6]:

\[ \ddot{z} + \frac{c}{m + m_a} \dot{z} + \left( \omega_{n0}^2 + K \right) z = F \cos(\Omega t + \sigma) \] (6)

where:

- \( z \) Amplitude of heave
- \( c \) Damping constant (including both equivalent viscous damping and damping due to power extraction)
- \( m \) Mass of the buoy system
\( m_a \)  Added mass of the buoy system

\( \omega_n \)  Natural angular frequency in small heave, \( \omega_n = \sqrt{\frac{\rho_{gw} w}{m + m_a}} \)

\( K \)  Coefficient of buoy’s flare, \( K = \frac{\rho_{gw} w}{m + m_a} \)

\( b_0 \)  Minimum breadth of buoy (figure 5 and equation (5))

\( b_1 \)  Described by equation (5)

\( w \)  Width of buoy (in the direction of wave propagation)

\( n \)  Exponent of buoy flare, \( n >1 \) (equation 5)

\( F \)  Wave excitation force, normalized by total mass, \((m + m_a)\)

\( \Omega \)  Wave angular frequency

\( \sigma \)  Phase angle

As a special value of flare exponent, \( n = 2 \) yields the well-known damped-forced form of Duffing’s equation, used to model vibrations of “hardening springs”:

\[
\ddot{z} + c \dot{z} + \omega_n^2 z + \mu z^3 = f(t)
\]

(7)

Although various methods of solving Duffing’s equation exist in literature, as summarised by [7], the authors have opted for a numerical solution to equation (6) above to analyse the behaviour of the system. The pumping action of the buoy, and hence power extraction, is modelled as the equivalent linear damping.

4. Damping and power extraction

Total power (sum of power dissipated by natural damping and extracted hydraulic pump power from the system) from the system with \( N \) buoys can be evaluated from the linear damping term, assuming no interaction related to damping between individual buoys:

\[
P = N \cdot \frac{1}{T} \int_0^T F_D \dot{z} \cdot dt = \frac{N}{T} \int_0^T (m + m_a) \cdot (c \dot{z}^2) \cdot dt
\]

(8)

where \( F_D \) is the damping force and \( T \) is the period of motion of heave being equal to the period of main component of the waveform. Assuming the heave motion is periodic with the wave period, \( T \),

\[
z = Z_0 \cos \Omega t
\]

(9)

the total power of the system shall be:

\[
P = (m + m_a) N \xi Z_0^2 \Omega^2 \omega_n
\]

(10)

where the classical assumption \( c = 2\omega_n \xi (m + m_a) \) was made, \( \xi \) being the nondimensional damping coefficient.

5. Heaving motions of the buoy - a numerical example

As an illustrative example, a system with six buoys, each 1 m apart, and connected to the peristaltic pumping system described above at 5 m depth is conceived. The characteristics of an individual buoy is below:

| Characteristic          | Value   |
|-------------------------|---------|
| Draught, T              | 1.0 m   |
| Breadth                 | \( b(z) = 0.50 + 0.25z^2 \) |
| Width, w                | 2.0 m   |
| Space between two buoys | 1.0 m   |
| Mass                    | 1367 kg |

Nondimensional damping coefficient (\( \xi \)) was arbitrarily taken to be 0.40. Added mass (\( m_a \)) was taken to be 0.20\( m \), also arbitrarily. Natural frequency of heave for limitingly small amplitudes (\( \omega_n \))
of an individual buoy is \( \omega_{n0} = \sqrt{\frac{\rho g b w}{m + m_a}} = 2.476 \text{ rad/s} \). The resonant frequency \( \omega_r = \omega_{n0} \sqrt{1 - \xi^2} = 2.269 \text{ rad/s} \). (Thomson and Dahleh, 2005). From linear wave approximation, Equation (5), this amounts to a wavelength of 12 m. With the well-accepted deep water approximation of wave steepness \( a/\lambda = 0.025 \), \( a = 0.30 \text{ m} \), the differential equation, Equation (8) was solved numerically. Plot of wave motion is in Figure (5) and the initial transient behaviour in terms of phase plane is in Figure (6).

![Figure 6. Heaving behaviour of an individual buoy, with resonant wave period \( T_r = 2.77 \text{ s} \) and corresponding waves with \( \lambda = 12 \text{ m} \), \( a = 0.30 \text{ m} \), initially at rest](image)

![Figure 7. Heaving velocity \( \dot{z} \) versus heaving ordinate, \( z \), resonant wave period case of the case in Figure 6](image)

As can be seen, the amplification factor, \( \frac{z_{max}}{a} = 1.19 \) for this resonant state. However, for a more efficient operation, heavier sea states should be assumed.

Next, a heavier sea state with wave period \( (T_w) = 5.06 \text{ s} \) corresponding to wavelength \( (\lambda) = 40 \text{ m} \) and wave amplitude \( a = 1.00 \text{ m} \) was studied. The results for heaving versus time and heave velocity versus heave ordinate are exhibited in Figures 8 and 9 respectively below. It is noteworthy to observe that \( \frac{z_{max}}{a} = 0.865 \) for this case. The heaving behaviour of the buoy is shown in figure 9.
waves with $\lambda = 40$ m, $a = 1.0$ m, initially at rest

Figure 8. Heaving behaviour of an individual buoy, with wave period $T_r = 5.06$ s and corresponding waves with $\lambda = 40$ m, $a = 1.0$ m, initially at rest

Figure 9. Heaving velocity $\dot{z}$ versus heaving ordinate, $z$, with wave period $T_r = 5.06$ s and corresponding waves with $\lambda = 40$ m, $a = 1.0$ m of the case in Figure 7
Therefore, for this particular buoy configuration, based on 40 m design wavelength, a design with rectangular channel height = 2α = 1.5 m shall be selected. Ideal pump capacity for this design case shall be, from Equation (3), 7.11 m³/s. The power obtained, from Equation (10) was deducted to be approximately 7.5 kW, assuming power extraction was responsible for half of the dissipated energy. The pumping rate was found to be 23.68 m³/s from Equation (4), for α = 0.75 m and \( w_p = 2 \text{ m} \).

6. Some design considerations and conclusions

The proposed wave energy system has to be robust enough to endure heavy sea states and harsh marine environment, like all other wave energy systems. There should be another part above the water surface in addition to the buoys, where the electrical generation outfitting shall be located at. The peristaltic pump should be placed at a depth where the water is relatively stagnant, approximately at half the wavelength of the heavy seas expected.

The height of the peristaltic channel, 2α, is at the same order but also can be different from the waveheight, thanks to the hydraulic systems ratio of the pump piston area to ram piston area. In heavy seas, where both the hydraulic pump’s and the hydraulic ram’s amplitudes are restricted by maximum stroke lengths, the shape of the diaphragm’s deflection shall approach to that of a square wave, rather than a sinusoidal one.

This study takes only the heaving motion of the buoys into account. However, the buoys also experience yaw and sway motions, as well as roll, pitch and yaw motions. Sway and surge motions shall also have an effect on the peristaltic pumping action. To ensure proper operation, the rod connecting the buoy to the hydraulic pump should be equipped with universal joints. Also, the buoys should be connected by a loose tether.

The proposed system with pump can either be bottom mounted or can be installed on a floating platform incorporating the peristaltic pump channel and apparatus, turbine and electrical generator and the buoys.

Like all other wave energy systems, it is proposed to manufacture a prototype system and test it at a location in sea where the waves are predictable and energetic enough for an efficient operation. If further studies and model tests shall be made, a more complex non-linear and short-term motions analysis might be considered. The damping coefficient \( \xi \) and the added mass \( m_a \) were taken arbitrarily in this study, although more refined values, supported by tank tests can be taken. As a final word, other means of converting the surface wave shapes into peristaltic motion can be developed, although it is deemed that this is the mechanically simplest way.
References

[1] Falcao A 2010 *Wave energy utilization: A review of the technologies*, Renewable and Sustainable Energy Reviews 14 899–918

[2] Ganiev R T Ganiev S R Kasilov V P Pustovgar AP 2015 *Wave Technology in Mechanical Engineering*, Scrivener Publishing, 2015

[3] Latham T W 1966 *Fluid Motions in a Peristaltic Pump* M.S. Thesis, Massachusetts Institute of Technology, Boston, U.S.A.

[4] Le Mehaute B 1976 *An Introduction to Hydrodynamics and Water Waves*, Springer-Verlag, New York, U.S.A.

[5] Thomson, W T, Dahleh M D 2005 *Theory of Vibration with Applications*, Pearson Education Asia, Tsinghua, China

[6] Sabuncu T *Gemi Hareketleri, (2nd ed)*, 1993 İstanbul Technical University Press, İstanbul, Turkey

[7] Marinca, V, Herisanu N 2011 *Nonlinear Dynamical Systems in Engineering*, Springer Verlag, Berlin-Heidelberg