Connected Floating Balls Dynamics for Harvesting Energy of Sinusoidal Water Wave

Sparisoma Viridi¹,²,*, Dwi Irwanto³, Nanang Hariyanto³, Sudarmono Sasmono⁴

¹Research Center for Nanosciences and Nanotechnology, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
²Departement of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Jalan Ganesha 10, Bandung 40132, Indonesia
³Department of Electrical Power Engineering, School of Electrical Engineering and Informatics, Jalan Ganesha 10, Bandung 40132, Indonesia
⁴Quadran Energi Rekayasa, AP Research Group, Gedung Salman Business Center 3rd floor, Jalan Gelap Nyawang No. 4, Bandung 40132, Indonesia

*du dung@gmail.com

Abstract. Dynamics of connected balls floating on surface of fluid oscillating sinusoidally has reported. In this work a simple electrical generator is simply modeled based on the change of distance between connected balls from its initial value or \( \Delta l \). By considering only one-dimensional motion of each ball, all the changes \( \Delta l \) are positive, that makes the system easier to be predicted. Sum of all \( \Delta l \) as function of initial initial distance between balls or \( l \) is discussed. Water wave wavelength \( \lambda \) is also varied to see how it influences the sum of all \( \Delta l \).

1. Introduction
There are various mechanisms in harvesting mechanical energy, especially in the form of vibration, from inertial-based generator with spring to cantilever-based system [1], where the mechanism similar to the last system has been further transformed into flexible films based on nanowires [2]. Multiple coils and freestanding magnet-based system has also been developed to accomodate all-direction in-plane vibration for more efficient energy harvesting [3]. For low-frequency vibration, e.g. impact of human steps while walking, piezoelectric-based energy harvester system is more practical in the implementation [4]. Accompanying electromagnetic and piezoelectric, electrostatic method play also important role in miniaturizing the energy harvesting system [5]. Triboelectric nanogenerator is promising approach since it can harvest vibration energy from a system that produces vibration while operating or has vibration due to environment change, a self-powered system [6], that has been implemented into the buoy ball for harvesting wave energy [7]. Interaction between a buoy ball and sinusoidal surface wave shows interesting motion modes [8], which is neglected in this work for simplicity. Interaction between two buoy balls is only the given connector acting like spring, while the natural attractive force due to inbalance surface tension [9] is not considered.

2. Model
A ball \( i \) with density \( \rho_i \) and diameter \( D_i \) will have mass of
\[ m_i = \frac{1}{6} \pi D_i^3 \rho_i , \]  

which relates to gravitational force

\[ \ddot{G}_i = -m_i g \hat{y}, \]  

where vertical direction is \( \hat{y} \). If position of fluid surface is \( y_f \) and vertical position of ball \( i \) is \( y_i \) then immersed volume of ball \( i \) is given by [8]

\[
V_i = \begin{cases} 
\frac{1}{2} \pi D_i^3, & y \leq y_f - \frac{1}{2} D_i, \\
\frac{1}{3} \left[ (y_f - y_i)^3 + \frac{1}{2} D_i \right], & y_f - \frac{1}{2} D_i \leq y \leq y_f + \frac{1}{2} D_i, \\
0, & y_f + \frac{1}{2} D_i \leq y.
\end{cases}
\]  

Using equation (3) the buoyant force on the ball \( i \) is simply

\[ \ddot{B}_i = \rho_f g V_i \hat{y}, \]  

with \( \rho_f \) is fluid density. Spring force between ball \( i \) and \( j \) with normal length \( l_{ij} \) and spring constant \( k_{ij} \) is given by

\[ \ddot{S}_{ij} = -k_{ij}(r_{ij} - l_{ij})\ddot{r}_{ij}, \]  

with

\[
\ddot{r}_{ij} = \ddot{r}_i - \ddot{r}_j, \\
r_{ij} = |\ddot{r}_{ij}| = |\ddot{r}_i - \ddot{r}_j|, \\
\ddot{\hat{r}}_{ij} = \ddot{r}_{ij}/r_{ij}.
\]  

Total force works on ball \( i \) is

\[ \ddot{F}_i = \ddot{G}_i + \ddot{B}_i + \sum_{j \neq i} \ddot{S}_{ij}, \]  

and its acceleration at this time \( t \)

\[ \ddot{a}_i(t) = \frac{1}{m_i} \ddot{F}_i, \]  

using Newton’s second law of motion. At time \( t + \Delta t \) velocity and position can be calculated with Euler algorithm

\[
\ddot{v}_i(t + \Delta t) = \ddot{v}_i(t) + \ddot{a}_i(t) \Delta t, \\
\ddot{r}_i(t + \Delta t) = \ddot{r}_i(t) + \ddot{v}_i(t) \Delta t.
\]  

Position of fluid surface is obtained from a sinusoidal function

\[ y_f(x, t) = A_f \sin(\omega t + \varphi_0). \]
where $A_f$ and $\omega_f$ are oscillation amplitude and angular frequency, respectively. The time $t$ in equation (13) will be advanced from $t_{\text{beg}}$ to $t_{\text{end}}$ in the simulation according to

$$t(t + \Delta t) = t(t) + \Delta t.$$  

(14)

Notice that $y_f$ in equation (3) is different for every ball $i$, where from equation (13), it is clearer to state that $y_{fi}(t) = y(x, t)$ instead of only $y_f$. Figure 1(a) shows the simulation flow chart in using equations (1) – (14), where vectors are written in bold but without arrow. Output is time, position and velocity of all buoy balls in the system, which later can be used to calculate converted electric power from the vibration as shown in figure 1(b).

![Simulation flow chart](image)

**Figure 1.** Simulation flow chart of the connected floating balls system for harvesting vibration energy from sinusoidal water wave: (a) scope of this work, (b) obtained power calculation, which depends on chosen technology type $n$.

Illustration of the system is given in figure 2 for two different time, e.g. $t$ and $t + \Delta t$, where each buoy ball will have different vertical position due to wave of water surface given in equation (13).
Figure 2. Vibration energy harvesting system of connected buoy balls without wave (top), with wave at time $t$ (middle) and $t + \Delta t$ (bottom).

It can be seen from figure 2 that due to local oscillation of water surface, vertical position of each buoy ball will be altered periodically, which stretches the spring-like connectors (red line) or at least let the connector at its normal length (green line). Length variation $l$ of the connectors will be used to calculate harvestable vibration energy to be converted to electrical one. The conversion function is given in figure 2 as

$$U = f(t, \{v_i\}, \{v_i\}, n).$$

where $n$ is the type of implemented technology.

3. Results and discussion

For the water wave following values are used: $A = 0.1$ m, $T = 5$ s, $\lambda = 1$ m, $\varphi_0 = 0$ rad. Illustration for the buoy balls are given in figure 3 at time $t = 0$ s. Number of balls $N = 11$.

Figure 3. System of buoy balls with different separation distance $l$: (a) 0.05 m, (b) 0.1 m, (c) 0.15 m, and (d) 0.2 m.
As the time $t$ is advanced all buoy balls will also be altered in vertical direction, while their horizontal position are assumed to be constant. An illustration for $l = 0.15$ m is given in figure 4.

![Figure 4. Snapshots of buoy balls position with $l = 0.15$ m for different time $t$: (a) 0 s, (b) 1 s, (c) 2 s, (d) 3 s, (e) 4 s.](image)

It can be seen from figure 4 that the water wave propagates to the right. Distance between two succesive buoy balls will be substrated with the initial distance, that will produce $\Delta l$ between two connected balls. There are $N$ different values of $\Delta l$ that the sum as function of $l$ is given in figure 5.

![Figure 5. Sum of $\Delta l$ as function of $l$ with different $\lambda$: 0.9 m, 1 m, 1.2 m, 1.7 m, and 1.95 m.](image)
As function of \( l \) the sum of \( \Delta l \) is no simply linear but can be said that it increases as \( l \) increases as shown in figure 5. There is also influence of \( \lambda \), where larger value will reduce the gradient of sum of \( \Delta l \) as function of \( l \). By assuming that equation (15) holds for linear relation between \( U \) and \( \Delta l \), then figure 5 can already tell how the obtained energy as function of \( l \) and \( \lambda \). The first is system parameter, while the second is environment parameter.

Further investigation of the relation between \( \Sigma \Delta l \) and \( l \) in figure 5 in the form of linear fit

\[
\sum \Delta l = ml + c
\]

for each water wavelength \( \lambda \), gives the relation as shown in figure 6, that the gradient \( m \) decreases as \( \lambda \) increases. Coefficient of determination for each \( \lambda \) in figure 6 are 0.9702, 0.95759, 0.9674, 0.9494, and 0.9523, which show that the linear fit can still be accepted.

4. Summary
Model of vibration energy system based on connecting floating balls or buoy balls has been discussed. By assuming that each ball only move in vertical direction under influence of sinusoidal water wave, it has been observed that energy increases as distance between two buoy balls increases, while energy decreases as water wavelength increases.

Acknowledgments
Authors wishing to acknowledge the support from KK FNB ITB.

References
[1] Wei C, Jing X 2017 Renew. Sust. Energ. Rev. 74 1.
[2] Jin CC, Liu XC, Liu CH, Wang Y, Hwang HI, Wang Q 2018 Mater. Design 144 55.
[3] Chen X, Guo H, Wu H, Chen H, Song Y, Su Z, Zhang H 2018 Nano Energy 49 51.
[4] Untoro T, Viridi S, Suprijanto, Ekawati E 2017 J. Phys. Conf. Series 877 012042.
[5] Zhang Y, Wang T, Luo A, Hu Y, Li X, Wang F 2018 Appl. Energy 212 362.
[6] Wu H, Shi Q, Wang F, Thean AV-Y, Lee C 2018 Small Methods 2 1800078.
[7] Shi Q, Wang H, Wu H, Lee C 2017 Nano Energy 40 203.
[8] Viridi S, Nurhayati, Sabaryati J, Muliyati D 2018 Spektra J. Fis. Aplikasi. 3 133.
[9] Viridi S, Suendo V 2019 the 5th International Symposium on Current Progress in Mathematics and Sciences (ISCPMS 2019), 9-10 July, Depok, Indonesia.