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Power Buoy represented by the kinematic chain of a robot

***Abstract**. The aim of this paper is to present possibility of description the Power Buoy movement as an kinematic chain of manipulator. To simulate movement of the buoy more accurately it is necessary to present kinematic chain of a manipulator with more degrees of freedom. All possible movements should be taken into account. The robotic approach to energy harvester simplify finding the solution of movement description. In the paper a few ways of the buoy movement will be considered.*

***Streszczenie.** Celem artykułu jest zaprezentowanie możliwości opisu ruchu boi odzyskującej energię jako łańcuch kinematyczny manipulatora. Zasymulowanie ruchu boi w dokładniejszy sposób wymaga przedstawienia boi jako łańcuch kinematyczny manipulatora o większej liczbie stopni swobody. Wszystkie możliwe ruchy boi na fali powinny zostać rozważone. Podejście ze strony robotyki do odzysku energii upraszcza znalezienie rozwiązania do opisu ruchu. W artykule zostanie rozważonych kilka sposobów ruchu boi. (**Boja odzyskująca energię reprezentowana przez łańcuch kinematyczny robota**)*

Keywords: energy harvesting, homogenous transformation, point absorber wave energy harvester, buoy movement
Słowa kluczowe: odzysk energii, transformacja jednorodna, punktowy odzysk energii z fal, ruch boi

Introduction

The wave energy is the most reliable renewable energy source, because of predictability of tidal waves [1,2]. It is also the most concentrated form of renewable energy [3,4]. The estimated tidal energy of all global resources is equal to over 300 TWh per year. The wave energy consists of kinetic and potential energy and depends on height and period of the wave [4]. There are a few types of energy harvesters that can harvest the wave energy. The most efficient wave energy harvester seems to be the Power Buoy because the Power Buoy plant can harvest more energy than other harvesters using the same area [5]. The Power Buoy is a point absorber energy harvester that means it can harvest energy from all direction at a single point [3,6]. That is why the buoy movement depends on waves movement which can move in different direction due to the wind and gravitational forces and reflection of waves [7].

The energy harvested from waves is kinetic energy [8]. To calculate the energy harvested from kinetic energy harvester it is necessary to know the movement of the energy carrier. It can be done by simulation of the movement. The kinematic chain of kinetic energy harvester can be compared to the kinematic chain of a robot and therefore the buoy can be considered as the end of the manipulator. To describe the movement of the end of the manipulator – the buoy, Euler-Lagrange's equations can be used [9]. In this paper Euler-Lagrange's equations are formulated for a few types of the buoy movement from the 1-DoF (degree of freedom) kinematic chain to the 5-DoF kinematic chain.

Euler-Lagrange's equations can be formulated also to describe the movement of other objects related to a robotic system, such as 3D printers, a hard disk drive head, a VCM motor. Then the equation can be used to simulate the movement by applying a computer software like Matlab [10-14]. Following this similarity we can assume that comparing the Power Buoy kinematic chain to the kinematic chain of a robot simplify finding the solution of the movement description.

The Power Buoy consists of an anchor attached to a seabed, a buoy, an energy accumulation spring, a linear to rotational movement translation system and a generator [8]. The idea of such Power Buoy model is shown in the figure 1. Translation system is unnecessary, when a generator is linear. The buoy is floating on the ocean and its movement is limited only by an anchor and a spring, it can be simplify in a kinematic chain to a spring and then to a spring elasticity. The buoy considered as the end of the manipulator is the only joint with the mass and all joints can be placed in the same point – the buoy mass center.

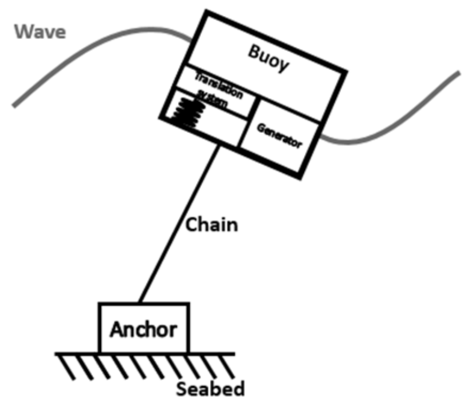


Fig.1. The Power Buoy model

Buoy movement variants

The buoy movement depends on the waves movement. The waves movement is caused by external forces such as a wind and gravitational forces. The waves movement direction changes also when the waves reflect from an obstacle for example a breakwater. That is why the buoy floating on the water heaves, pitches, rolls, yaws and drifts. These types of movement can be simulated by using prismatic and rotational joints in a kinematic chain, so incoming waves movement influences number of degrees of freedom. 1-DoF to 5-DoF kinematic chains of the buoy due to waves movement are shown in the figure 2.

A prismatic joint in the kinematic chain presents heaving movement, it means up and down movement. One rotational joint presents pitching movement and others present rolling and drifting movement.

kinematic chain of the buoy movement

For 1-DoF to 5-DoF kinematic chains that present buoy movements it is possible to make kinematic parameters tables and use Denavite-Hartenberg notation, then formulate homogenous transformation and force and torque equations. In the table of kinematic parameters: i is the ordinal number of link, ai is the distance between axis zi and zi-1, αi is the angle between axis zi and zi-1, di is the distance between axis xi and xi-1 and Θi is the angle between axis xi and xi-1. Kinematic chains with kinematic parameters tables are shown in the figure 3 with two different variants of 3-DoF kinematic chains. d1 is the distance between x0 and x1, d2 between x1 and x2, d3 between x2 and x3 and it presents changes of a buoy vertical position.

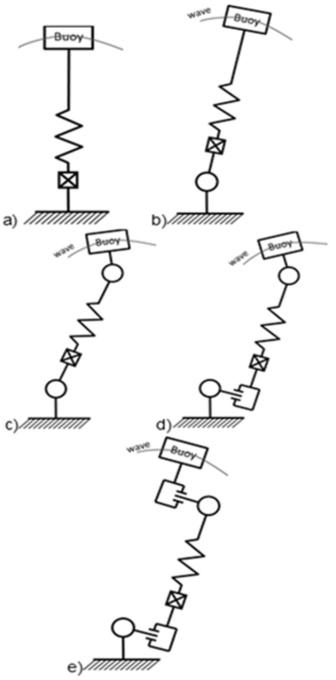
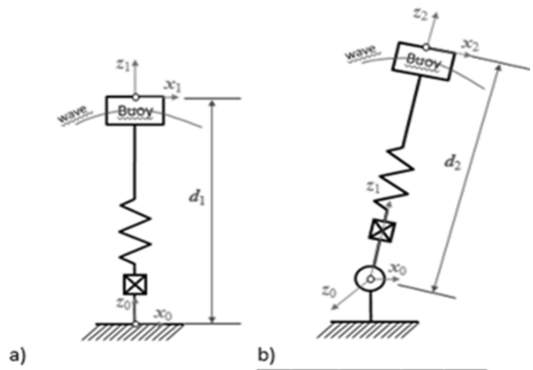


Fig.2. 1-DoF (a), 2-DoF (b), 3-DoF (c), 4-DoF (d), 5-DoF (e)

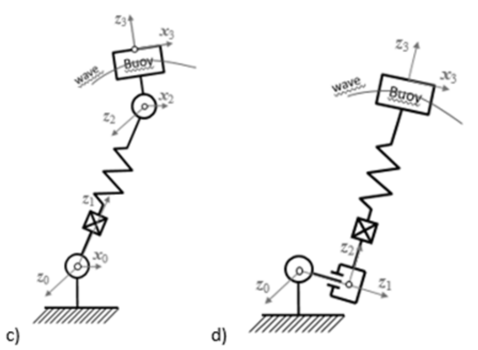


a)

i	a_i	α_i	d_i	θ_i
1	0	0	d_1	0

b)

i	a_i	α_i	d_i	θ_i
1	0	-90°	0	θ_1
2	0	0	d_2	0

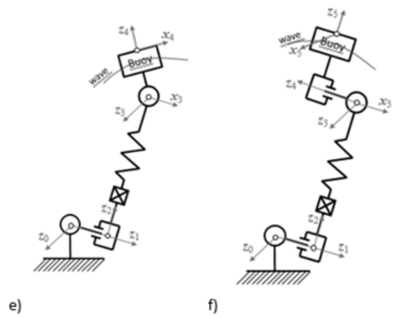


c)

i	a_i	α_i	d_i	θ_i
1	0	-90°	0	θ_1
2	0	90°	d_2	0
3	0	-90°	0	θ_3

d)

i	a_i	α_i	d_i	θ_i
1	0	90°	0	θ_1
2	0	90°	0	θ_2
3	0	0	d_3	90°



e)

i	a_i	α_i	d_i	θ_i
1	0	90°	0	θ_1
2	0	90°	0	θ_2
3	0	90°	d_3	90°
4	0	-90°	0	θ_4

f)

i	a_i	α_i	d_i	θ_i
1	0	90°	0	θ_1
2	0	90°	0	θ_2
3	0	90°	d_3	90°
4	0	-90°	0	θ_4
5	0	-90°	0	θ_5

Fig.3. 1-DoF (a), 2-DoF (b), 3-DoF (c,d), 4-DoF (e), 5-DoF (f) kinematic chain of the buoy movement with kinematic parameters tables

Robotic approach to the Power Buoy

From kinematic parameters for each kinematic chain, homogenous transformation and then force and torque can be formulated. Homogenous transformation *T* (Eqn.1) for whole kinematic chain is a product of homogenous transformations *A* (Eqn 2) for each transformation from frame *i* to frame *i*-1, where R_i^n is the rotation and d_i^n is the transformation.

$$\text{(1)} \qquad T_i^n = A_{i+1}A_{i+2}\dots A_n = \begin{bmatrix} R_i^n & d_i^n \\ 0 & 1 \end{bmatrix}$$

$$\text{(2)} \qquad A_i = Rot_{z_i\theta_i} Trans_{z_i d_i} Trans_{x_i a_i} Rot_{x_i\alpha_i} =$$

$$= \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

To find the movement description it is necessary to formulate a centre of mass kinematic. In each kinematic parameters table only the distance between axis z_i and z_{i-1}, the distance between axis x_i and x_{i-1} and the angle between axis x_i and x_{i-1} should be considered. The distance between axis z_i and z_{i-1} is always equal to zero in this problem, because the only mass here is the mass of the buoy.

Calculation of linear and rotational velocity is possible by applying calculation of Jacobian matrix that contains Jacobians of linear and rotational speed. Jacobian matrix for prismatic joint is shown in (Eqn.3) and for rotational joint in (Eqn.4).

$$\text{(3)} \qquad J_i = \begin{bmatrix} J_{vi} \\ J_{\omega i} \end{bmatrix} = \begin{bmatrix} z_{i-1} \\ 0 \end{bmatrix}$$

$$\text{(4)} \qquad J_i = \begin{bmatrix} J_{vi} \\ J_{\omega i} \end{bmatrix} = \begin{bmatrix} z_{i-1} \times (o_n - o_{i-1}) \\ z_{i-1} \end{bmatrix}$$

The *z* axis of i-1 joint and coordinates of the centre of the i-1 joint o_{i-1} can be formulated from the homogenous transformation Ti. The *z* axis is the third column of T and coordinates of the centre joint is the fourth column of T. Coordinates of the centre of the last joint o_n can be formulated from the homogenous transformation Ti calculated from kinematic parameters of the mass centre. Coordinates for the base are [0;0;1] for the z_0 axis and [0;0;0] for the centre of the base o_0.

Kinetic energy depends on Jacobians of linear and rotational speed for all joints, mass and inertia of these joints and on differential of vector of generalized displacement (Eqn.5). Matrix R_i is rotation matrix that enforces formulation of rotational speed coordinates depending on link i coordinates. I_i is an inertia matrix of link i, evaluated around a coordinate parallel to frame i. The product of mass of the i joint and square of Jacobian of linear speed for the i joint is a component of linear kinetic energy (Eqn.6). The product of inertia of the i joint and square of Jacobian of rotational speed for first joint is component of rotational kinetic energy (Eqn.7). [9]

(5) $$\boldsymbol{E_k}=\frac{1}{2}\dot{\boldsymbol{q}}^T\sum_{i=1}^{n}[m_i\boldsymbol{J}_{\boldsymbol{v_{ci}}}(q)^T\boldsymbol{J}_{\boldsymbol{v_{ci}}}(q)+$$
$$+\boldsymbol{J}_{\boldsymbol{\omega_{ci}}}(q)^T\boldsymbol{R_i}(q)I_i\boldsymbol{R_i}(q)^T\boldsymbol{J}_{\boldsymbol{\omega_{ci}}}(q)]\dot{\boldsymbol{q}}=\frac{1}{2}\dot{\boldsymbol{q}}^T\boldsymbol{D}(q)\dot{\boldsymbol{q}}$$

(6) $$\boldsymbol{K_{vi}}=m_i*\boldsymbol{J}'_{\boldsymbol{vi}}*\boldsymbol{J_{vi}}$$

(7) $$\boldsymbol{K_{\omega i}}=I_i*\boldsymbol{J}'_{\boldsymbol{\omega i}}*\boldsymbol{J_{\omega i}}$$

From components of kinetic energy inertia matrix ***D*** (Eqn.8) and then components c_{kj} of Christoffel's matrix ***C*** (Eqn.9) can be calculated. k and j is the row and column of matrix.

(8) $$\boldsymbol{D}=\sum_{i=1}^{n}(\boldsymbol{K_{vi}}+\boldsymbol{K_{\omega i}})$$

(9) $$c_{kj}=\sum_{i=1}^{n}c_{ijk}(q)\dot{q}_i=\sum_{i=1}^{n}\frac{1}{2}\left(\frac{\partial d_{kj}}{\partial q_i}+\frac{\partial d_{ki}}{\partial q_j}-\frac{\partial d_{ij}}{\partial q_k}\right)(q)\dot{q}_i$$

The equation 10 is a dynamic equation, where τ is external force or torque. Force F_v is potential force, which is differential of potential energy V_e (11).

(10) $$[\boldsymbol{\tau}]=[\boldsymbol{D}][\ddot{\boldsymbol{q}}]+[\boldsymbol{C}][\dot{\boldsymbol{q}}]+F_v$$

Components of potential energy is buoyancy of the water, gravity of the earth and energy of the spring (Eqn.11).

(11) $$V_e=mgd_i-\rho gVd_i+\frac{1}{2}kd_i^2$$

Generalized variable d_i is a prismatic joint position and the movement of the buoy in z-axis direction. Mass m is the only mass and it is the mass of the buoy.

1-DoF kinematic chain of the buoy

1-DoF kinematic chain has the prismatic joint only, that means only up and down movement of the buoy is considered. That kinematic joint with the kinematic parameters table is shown in the figure 3 a).

Using the proper transformations force equation can be formulated. Variable d_1 is a generalized variable. Firstly Jacobians of linear and rotational speed can be obtained from coordinates of the z_0 axis and the centre of the base. For the prismatic joint Jacobian of linear speed is equal to coordinates of the z axis and Jacobian of rotational speed is equal to 0 (Eqn.12).

(12) $$\boldsymbol{J_{c1}}=\begin{bmatrix}\boldsymbol{J_{v1}}\\ \boldsymbol{J_{\omega 1}}\end{bmatrix}=\begin{bmatrix}0\\0\\1\\0\\0\\0\end{bmatrix}$$

Matrix ***D*** is equal to mass of the buoy m. Matrix ***C*** is equal to zero, because elements of matrix ***D*** are independent of generalized variable. Canonical form of the force equation describes the movement of the buoy (Eqn.13).

(13) $$\frac{\partial^2 d_1}{\partial t^2}=\frac{F-mg+\rho gV-kd_1}{m}$$

2-DoF kinematic chain of the buoy

2-DoF kinematic chain has prismatic joint and rotational joint, that means heaving and pitching movement of the buoy is considered. That kinematic joint with the kinematic parameters table is shown in the figure 3 b).

To calculate Jacobians it is necessary to use Denavite-Hartenberg notation for the mass centre, mass of the buoy only. Kinematic parameters for mass centre is shown in the table 1.

Table 1. Kinematic parameters for the mass centre for 2-DoF kinematic chain of the buoy.

i	a_i	α_i	d_i	Θ_i
1	0	0	0	Θ_1
2	0	0	d_2	0

Variables d_2 and Θ_1 are generalized variables. Jacobians of linear and rotational speed for the first joint are similar to Jacobians 1-DoF kinematic chain (Eqn.12) but in the third row of the first column is 0 and in the last row is 1 and Jacobian have the second column with zero vector and for the whole kinematic chain are shown in (Eqn.14). To calculate components of kinetic energy Jacobians for each joint have to be considered.

(14) $$\boldsymbol{J_{c2}}=\begin{bmatrix}d_2{}^*c\theta_1 & s\theta_1\\ d_2{}^*s\theta_1 & -c\theta_1\\ 0 & 0\\ 0 & 0\\ 0 & 0\\ 1 & 0\end{bmatrix}$$

Inertia matrix ***D*** and Christoffel's matrix ***C*** are shown in (Eqn.15) and (Eqn.16).

(15) $$\boldsymbol{D}=\begin{bmatrix}md_2+I_1 & 0\\ 0 & m\end{bmatrix}$$

(16) $$\boldsymbol{C}=\begin{bmatrix}md_2\dot{z}_2 & md_2\dot{\theta}_1\\ -md_2\dot{\theta}_1 & 0\end{bmatrix}$$

Canonical forms of force and torque equations describe the movement of the buoy (Eqn.17) and (Eqn.18).

(17) $$\frac{\partial^2 d_2}{\partial t^2}=\frac{F+m\dot{\theta}_1^2d_2-mg+\rho gV-kd_2}{m}$$

(18) $$\frac{\partial^2 \theta_1}{\partial t^2}=\frac{\tau-2md_2\dot{\theta}_1\dot{d}_2}{md_2^2+I_1}$$

5-DoF kinematic chain of the buoy

5-DoF kinematic chain has the prismatic joint and rotational joints, that means heaving, pitching, rolling and drifting movement of the buoy is considered. That kinematic joint with the kinematic parameters table is shown in the figure 3 f).

Kinematic parameters for mass centre is shown in table 2.

Table 2. Kinematic parameters for the mass centre for 5-DoF kinematic chain of the buoy.

i	a_i	α_i	d_i	Θ_i
1	0	0	0	Θ_1
2	0	0	0	Θ_2
3	0	0	d_3	0
4	0	0	0	Θ_4
5	0	0	0	Θ_5

Variables d_3 and Θ_1, Θ_2, Θ_4, Θ_5 are generalized variables. Jacobians of linear and rotational speed for each joint are shown in (Eqn.19). Jacobians of linear and rotational speed for the first joint are similar to Jacobians for the first joint of 2-DoF kinematic chain (Eqn.12) but have 3 additional columns with zero vectors.

$$J_{c2}=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & s_1 & 0 & 0 & 0 \\ 0 & -c_1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{19}$$

$$J_{c3}=\begin{bmatrix} -d_3s_1s_2 & 0 & c_1s_2 & 0 & 0 \\ d_3c_1s_2 & 0 & s_1s_2 & 0 & 0 \\ 0 & 0 & -c_2 & 0 & 0 \\ 0 & s_1 & 0 & 0 & 0 \\ 0 & -c_1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$J_{c4}=\begin{bmatrix} -d_3s_1s_2 & d_3c_1c_2 & c_1s_2 & -d_3c_2^2s_1 -d_3s_1s_2^2 & 0 \\ d_3c_1s_2 & d_3c_2s_1 & s_1s_2 & d_3c_1c_2^2+d_3c_1s_2^2 & 0 \\ 0 & d_3c_1^2c_2+d_3s_1^2s_2 & -c_2 & 0 & 0 \\ 0 & s_1 & 0 & c_1c_2 & 0 \\ 0 & -c_1 & 0 & c_2s_1 & 0 \\ 1 & 0 & 0 & s_2 & 0 \end{bmatrix}$$

Jacobians for the last joint is similar to Jacobian for the fourth joint and the only difference is in the last column. That column is represented by the vector below.

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ c_1c_4s_2-s_1s_4 \\ c_1s_4-c_4s_1s_2 \\ -c_2c_4 \end{bmatrix}$$

Where c_i means $\cos\Theta_i$ and s_i means $\sin\Theta_i$.

Inertia matrix ***D*** and Christoffel's matrix ***C*** are shown in (Eqn.20) and (Eqn.21).

$$\boldsymbol{D}=\begin{bmatrix} d_{11} & d_{12} & 0 & d_{14} & d_{15} \\ d_{21} & d_{22} & 0 & 0 & d_{25} \\ 0 & 0 & d_{33} & 0 & 0 \\ d_{41} & 0 & 0 & d_{44} & 0 \\ d_{51} & d_{52} & 0 & 0 & 0 \end{bmatrix} \tag{20}$$

Where all components are:

$$d_{11}=I_5\cos^2\theta_2\cos^2\theta_4+m_5d_3^2\sin^2\theta_2$$
$$d_{12}=d_{21}=I_5\cos\theta_2\cos\theta_4\sin\theta_4$$
$$d_{14}=d_{41}=d_3^2m_5\sin\theta_2$$
$$d_{15}=d_{51}=-I_5\cos\theta_2\cos\theta_4$$
$$d_{22}=d_3^2m_5+I_5\sin^2\theta_4$$
$$d_{25}=d_{52}=-I_5\sin\theta_4$$
$$d_{33}=m_3+m_4+m_5$$
$$d_{44}=I_4+d_3^2(m_4+m_5)$$

$$\boldsymbol{C}=\begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} \\ c_{21} & c_{22} & c_{23} & c_{24} & c_{25} \\ c_{31} & c_{32} & 0 & c_{34} & 0 \\ c_{41} & c_{42} & c_{43} & c_{44} & c_{45} \\ c_{51} & c_{52} & 0 & c_{54} & 0 \end{bmatrix} \tag{21}$$

Where all components are:

$$c_{11}=\dot\theta_2\cos\theta_2\sin\theta_2(-I_5\cos^2\theta_4+d_3^2m_5+$$
$$+d_3\dot d_3m_5\sin^2\theta_4+$$
$$-I_5\dot\theta_2\cos^2\theta_2\cos\theta_4\sin\theta_4$$

$$c_{12}=\frac{1}{2}\dot\theta_4\cos\theta_2\left(I_5\left(2\cos^2\theta_4-1\right)+d_3^2m_5\right)+$$
$$+\dot\theta_1\cos\theta_2\sin\theta_2\left(-I_5\cos^2\theta_4+d_3^2m_5\right)+$$
$$+I_5\cos\theta_4\sin\theta_2\left(\tfrac{1}{2}\dot\theta_5-\dot\theta_2\sin\theta_4\right)$$

$$c_{13}=-c_{31}=m_5d_3\left(\dot\theta_4\sin\theta_2+\dot\theta_1\sin^2\theta_3\right)$$

$$c_{14}=\frac{1}{2}\cos\theta_2\left(I_5\dot\theta_2(2\cos^2\theta_4-1)+m_5\dot\theta_2d_3^2+\right.$$
$$\left.-2I_5\dot\theta_1\cos\theta_2\cos\theta_4\sin\theta_2\right)+$$
$$+m_5d_3\dot d_3\sin\theta_2+\tfrac{1}{2}I_5\dot\theta_5\cos\theta_2\sin\theta_4$$

$$c_{15}=c_{51}=\frac{1}{2}I_5\left(\dot\theta_2\cos\theta_4\sin\theta_2+\dot\theta_4\cos\theta_2\sin\theta_4\right)$$

$$c_{21}=\frac{1}{2}\dot\theta_4\cos\theta_2\left(I_5\left(2\cos^2\theta_4-1\right)+d_3^2m_5\right)+$$
$$+\dot\theta_1\cos\theta_2\sin\theta_2\left(I_5\cos^2\theta_4-d_3^2m_5\right)+$$
$$-\tfrac{1}{2}I_5\dot\theta_5\cos\theta_4\sin\theta_2$$

$$c_{22}=\frac{1}{2}I_5\dot\theta_4\sin(2\theta_4)+m_5d_3\dot d_3$$

$$c_{23}=-c_{32}=m_5d_3\dot\theta_2$$

$$c_{24}=-c_{42}=I_5\dot\theta_2\cos\theta_4\sin\theta_4-\frac{1}{2}I_5\dot\theta_5\cos\theta_4+$$
$$-\tfrac{1}{2}\dot\theta_1\cos\theta_2\left(m_5d_3^2-I_5\left(2\cos^2\theta_4-1\right)\right)$$

$$c_{25}=-\frac{1}{2}I_5\cos\theta_4\left(\dot\theta_4+\dot\theta_1\sin\theta_2\right)$$

$$c_{33}=c_{35}=c_{53}=c_{55}=0$$

$$c_{34}=-c_{43}=-m_5d_3\left(\dot\theta_4+\dot\theta_1\sin\theta_2\right)$$

$$c_{41}=-\frac{1}{2}\cos\theta_2\left(I_5\dot\theta_2(2\cos^2\theta_4-1)-m_5\dot\theta_2d_3^2+\right.$$
$$\left.-2I_5\dot\theta_1\cos\theta_2\cos\theta_4\sin\theta_2\right)+$$
$$+m_5d_3\dot d_3\sin\theta_2-\tfrac{1}{2}I_5\dot\theta_5\cos\theta_2\sin\theta_4$$

$$c_{44}=m_5d_3\dot d_3$$

$$c_{45}=-c_{54}=\frac{1}{2}I_5\left(\dot\theta_2\cos\theta_4-\dot\theta_1\cos\theta_2\sin\theta_4\right)$$

$$c_{52}=-\frac{1}{2}I_5\cos\theta_4\left(\dot\theta_4-\dot\theta_1\sin\theta_2\right)$$

By substituting matrix (Eqn.20) and (Eqn.21) to equation 10 it is possible to obtain equations of the buoy movement (Eqn.22).

$$\begin{bmatrix} \tau_1 \\ \tau_2 \\ F_3 \\ \tau_4 \\ \tau_5 \end{bmatrix}=\boldsymbol{D}\begin{bmatrix} \ddot\theta_1 \\ \ddot\theta_2 \\ \ddot d_3 \\ \ddot\theta_4 \\ \ddot\theta_5 \end{bmatrix}+\boldsymbol{C}\begin{bmatrix} \dot\theta_1 \\ \dot\theta_2 \\ \dot d_3 \\ \dot\theta_4 \\ \dot\theta_5 \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ F_v \\ 0 \\ 0 \end{bmatrix} \tag{22}$$

Where τ_1, τ_2, τ_4, τ_5 are external torques and F_3 is external force acting on the buoy as a result of the wave movement. After bringing equation 22 to canonical form like equations 13,17 and 18 it is possible to simulate the movement of the buoy.

Conclusions

It is possible to present the Power Buoy movement using the theory of formulation of robot movement equations. The more degree of freedom the Power Buoy has the more accurate the movement simulation is. To simulate the Power Buoy movement considering the waves movement that influence the energy harvester, it is necessary to use at least 2-DoF kinematic chain to present heaving and pitching movement of the buoy. The exact specification of the Power Buoy movement is possible by observing influence of the wave movement on the buoy acting. 5-DoF kinematic chain considers heaving, pitching, rolling, yawing and drifting of the buoy, so it is very precise. It allows to simulate the Power Buoy movement and as a result to simulate energy harvested by such buoy. This method can be used also to describe the movement of other kinetic energy harvesters but it is necessary to determine what influence of the environment on the energy harvester is. For less complicated kinematic chains of energy harvester this method can be more complicated than other methods like force balance equation but more complicated systems can be simulated by using the kinematic chain of manipulator to improve and ease simulation of energy harvester movement.

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