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D. SAMPLE — **Proceeding Paper – shown only 1st and the Last pages for Full Papers**

Design of Mechanical Recti-converter for Wind Energy Harvesting

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ABSTRACT

Ocean wave energy harvesting is a rapidly evolving field of research, which has practical application prospects. Although ocean waves can generate enormous energy, it is difficult to harvest them for practical use because of the low frequency and irregular nature of wave motion. In this paper, a system that is simply named Recti-convertor is proposed for harvesting ocean wave energy. The Recti-converter consists of a mechanical rectifier and a converter. The converter is a combination of cam, follower, and springs to convert and gather the kinetic energy of the ocean wave to potential energy. The mechanical rectifier, which is made of gears and one-way clutches, converts the input oscillatory motion to one-way rotation. The one-way rotation, which becomes continuous by a flywheel, is used to rotate a generator. Finally, the electromechanical behavior of the ocean buoy equipped with the so-called Recti-converter energy harvester will be studied.

1. INTRODUCTION

In recent years, many researchers focused on generating electric power from ambient energy sources, like wind energy. To do so several kinds of transducers such as electromagnetic (X. Li et al., 2022; Zheng et al., 2021), and piezoelectric systems (Kim et al., 2022; Liu et al., 2022) are used. Among these systems, the electromagnetic devices are practical options for vibration-based energy harvesting. Flow-Induced Vibrations (FIV) are one of the accessible vibration sources, which can be considered for energy harvesting. Three main mechanisms of FIV include Vortex Induced Vibration

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(VIV) (Zhang et al., 2022), flutter (Z. Li et al., 2022) and galloping (Xu & Zhao, 2022). Among these sources of energy, the flutter and the galloping do not have resonant behavior and consequently the energy harvesting procedure is not restricted to a limited range of frequencies (Bibo & Daqaq, 2013). According to these studies, transverse galloping vibrations is an appropriate option for the present study.
The objective of present study is to propose a practical system, which can effectively harvest electrical energy from wind energy. In doing so, the oscillations of a bluff body a bluff body in fluid flow and its governing electromechanical equations are obtained and studied.

2. MATHEMATICAL MODELING

Consider the so-called Recti-convertor as shown in part (A) of Fig. 1. In this system the input reciprocal motions of the vibratory source of energy will be converted to continuous motion and gathered in the form of potential energy in the springs. In part (B) of Fig. 1, the force diagram of the follower which is pinned to the structural plates and supported by a spring is shown. This follower is excited by the cam and translates its motion to the pinion, which causes rotation in the flywheel. Regarding to the force diagram of the cam and if the mass of follower is negligible, following expression can be derived for the transmitted moment to the pinion

$$F_c L_3 \cos\theta = F_s L_2 \quad \text{; when cam moves upward} \tag{1}$$

$$F_s L_2 = F_G L_4 \quad \text{; when cam moves downward} \tag{2}$$

$$M = F_c (L_3 L_5 / L_4) \cos\theta \tag{3}$$

where F_G is the transmitted force between gears. Based on Work-energy principle, the transmitted energy to the flywheel can be calculated as follows:

$$\phi = L_4 \,(r_1 - r_2)/(L_3 L_5) \tag{4}$$

$$W_{out} = M\phi = F_c L_4 \cos\theta \,(r_1 - r_2)^2/(L_3 L_5) \tag{5}$$

in which ϕ is the rotation angle of the pinion, which is connected to the flywheel. The needed moment for rotating the cam can be calculated as follows:

$$M_{cam} = F_c L_1 \sin\theta \tag{6}$$

If the angle between the highest radius of cam (r_1) and its lowest radius (r_2) is considered to be β, the input energy can be calculated as follows:

$$W_{in} = M_{cam}(2\pi - \beta) = F_c L_1 (2\pi - \beta) \sin\theta \tag{7}$$

Obviously, the input energy should be bigger than the above obtained work. If the efficiency of the system is η the following relation can be obtained:

$$\eta = \{(r_1 - r_2)\tan\theta\}/\{(2\pi - \beta) L_1\} \tag{8}$$

Consider increasing the difference between maximum radius (r_1) and minimum radius and decreasing L_1 leads to improve the efficiency. Based on Fig. 2 the input moment can be obtained as follows:

$$M_{cam} = F l_1 \tag{8}$$

where l is the moment arm and F is the time variable aerodynamic transfer force that is obtained in the next section. Using this parameter, the contact force between cam and follower (F_c) can be obtained:

$$F_c = \eta F l_1 (r_1 - r_2)^{-1} \sec\theta \tag{9}$$

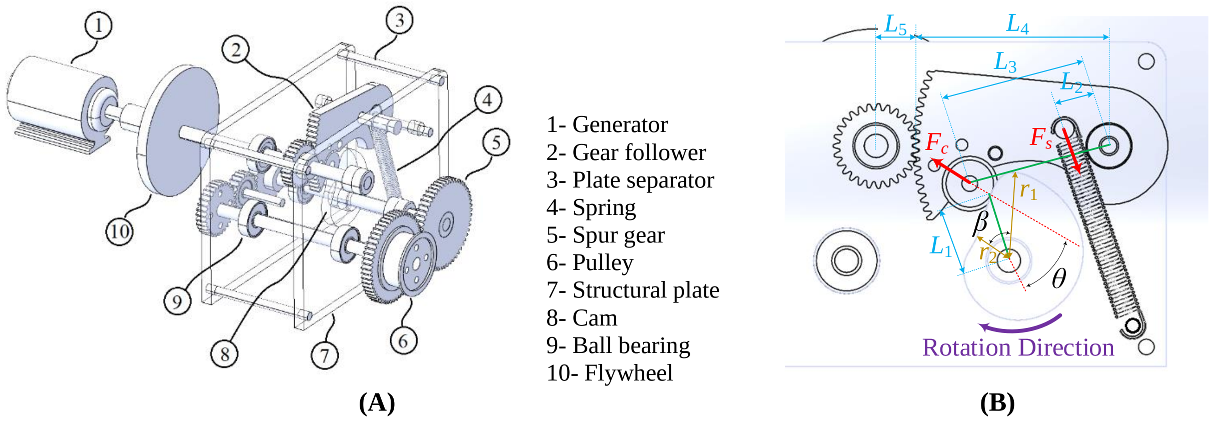

Fig. 1 Components of the recti-convertor (A); and force diagram of the follower (B)

In Fig. 2 the vibratory bluff body and its equivalent model are shown. Then using the total mass of the boat and exact dimensions of the floater, the parameters of the uncoupled pitch motion of the floater can be calculated. The calculated parameters are presented in Table (1).

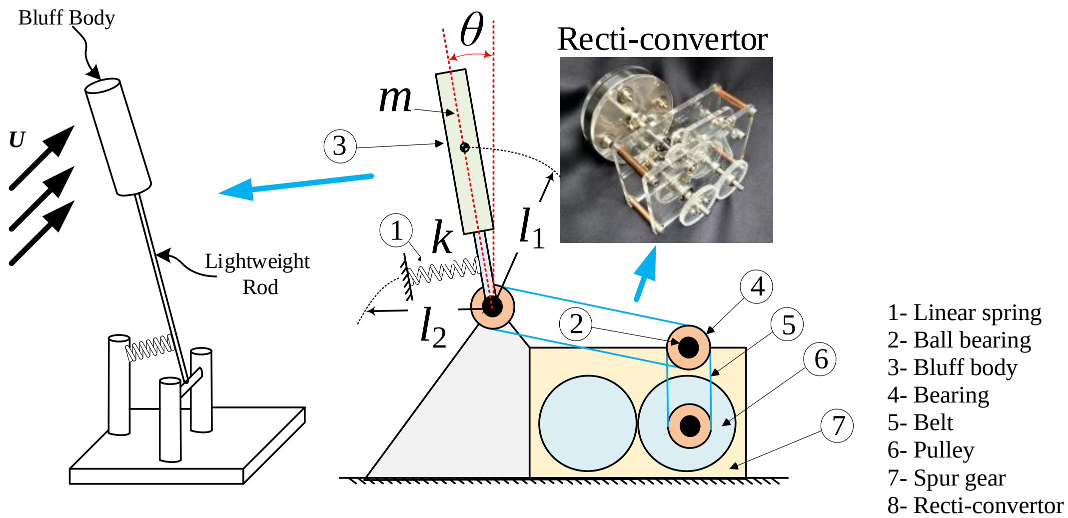

Fig. 2 Schematics of the floater and Recti-convertor

The fluid force on the structure can be obtained using quasi-static theory (Sobhanirad & Afsharfard, 2019). As shown in Fig. 3, a bluff body is considered to oscillate transversely in the fluid flow, where *α* is the angle of incidence. The bluff body is inserted in air flow of speed *U* and therefore the lift (F_L) and drag (F_D) forces are applied on it. The transverse fluid force for small values of incidence angle can be given by:

$$F = 0.5\rho U^2 DLC_z \quad (10)$$

where *L* is bluff body length, and C_z is the transverse force coefficient that is equal to:

$$C_z = (C_l + C_d \tan\alpha)/\cos\alpha \quad (11)$$

in which C_l and C_d are respectively the lift and drag coefficients. Expanding the transverse force coefficient in a Taylor series of the angle of attack, considering $\dot{w}_1/U=\tan\alpha\approx\alpha$, results in:

$$F = 0.5\rho U^2 DL\{\alpha_1(\dot{w}_1/U) + \alpha_3(\dot{w}_1/U)^3\} \quad (12)$$

Coefficients of a_1 and a_3 are the empirical coefficients and for several cross sections are presented in Table (1). In this study, the quasi-steady theory is used to simulate the fluid forces acting on the system in flow stream. Note that in the case of small displacement of the bluff body it can be considered that $w_1=l_1\theta$.

Table1. Properties of the galloping-based vibratory system

cross-section	a_1	a_3
Square	2.30	-18
D-section	0.79	-0.19
Isosceles Triangle	2.90	-6.20

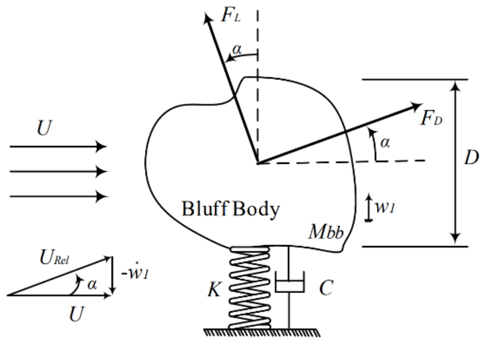

Fig 3. Schematic of the bluff body in fluid flow

Regarding to the system is shown in Fig. 2, and using the Lagrange equation, vibratory equation of motion for the system can be obtained as follows:

$$(0.5ml_1^2)\ddot{\theta} + (kl_2^2)\theta = Fl_1 \quad (13)$$

where m is mass of bluff body, l_1 is the distance of the bluff body centre of mass to the pivot, l_2 is the distance of the spring to the pivot and F is the aerodynamic force.

3. Result and Discussion

Therefore, regarding to equations 5, 9 and 12 and considering $w_1=l_1\theta$, the following expression can be obtained for the output work of system:

$$W_{out} = \left(0.5\eta\rho U^2 DLlL_4(r_1 - r_2)\right)\left(\alpha_1\left(l_1\dot{\theta}_1/U\right) + \alpha_3\left(l_1\dot{\theta}_1/U\right)^3\right)/(L_3L_5) \quad (14)$$

The above obtained work is used to rotate the flywheel that smooth the rotation of the output shaft. Therefore, the output electrical voltage of generator can be calculated as follows:

$$V = K_{\mathrm{emf}}\sqrt{\left(\eta\rho U^2 DLl_1L_4(r_1 - r_2)\right)\left(\alpha_1\left(l_1\dot{\theta}_1/U\right) + \alpha_3\left(l_1\dot{\theta}_1/U\right)^3\right)/(I_{\mathrm{fw}}L_3L_5)} \quad (15)$$

where K_{emf} is the electromechanical coupling coefficient of motor and I_{fw} is the flywheel mass moment of inertia. Finally, the output electrical power can be calculated as follows:

$$P_{\mathrm{rms}} = V_{\mathrm{rms}}^2/R \quad (16)$$

in which R is the electrical load resistance. Considering the values presented in Table 2, variation of the output electrical power of the system is shown in Fig. 4. As shown in this figure, maximum power output of this small energy harvester reaches to 14.19 W, which is an acceptable value.

Table2. parameters of the recti-convertor

Parameter	Value	Parameter	Value	Parameter	Value
L_2 (cm)	2	l_2 (cm)	5	K_{emf} (V.s/rad)	0.55
L_3 (cm)	4	k (N/m)	100	R (Ω)	0.5
L_4 (cm)	6	m (gr)	100	I_{fw} (gr.m^2)	10
L_5 (cm)	2	D (cm)	5	η	0.8
l_1 (cm)	50	L (cm)	50		

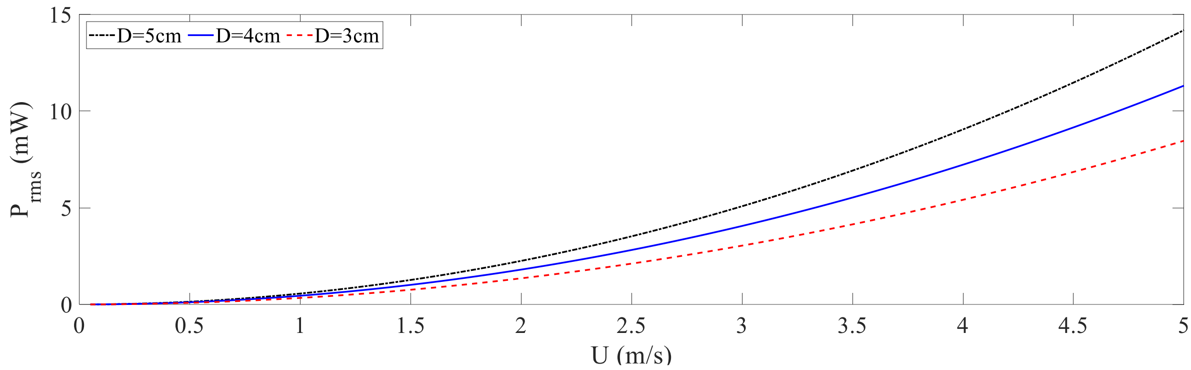

Fig 4. Schematic of the bluff body in fluid flow

4. CONCLUSIONS

In this study, the so-called fully mechanical Recti-converter is introduced and theoretically investigated. This system, which consists of a cam, follower, springs, gears, bearing, and clutches is a novel energy harvester, which not only converts the reciprocal motion of the bluff body to smooth continuous one-direction rotation but also saves the energy in form of potential energy. The accumulated potential energy can be released at special times or levels. This Idea can improve the efficiency of energy harvesting systems and increase their reliability. It is shown the output electrical voltage of the Recti-convertor system can be derived based on its electromechanical parameters. Consequently, the presented system can easily be designed, studied, and optimized for special applications like wind energy harvesting and ocean wave energy harvesting. Finally, it is shown the output power of this system with the bluff body with a diameter of 5 cm and wind speed of 5 m/s can be more than 14 W.

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