MATHEMATICAL MODELING AND DESIGN OF A BARREL CAM BASED TRANSMISSION MECHANISM FOR UNINTERRUPTED ENERGY HARNESSING FROM VORTICES

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Mathematical modeling and design of a unique transmission system for converting linear oscillatory motion of variable frequency and amplitude to uniform rotation is discussed in this paper. The transmission system discussed here derives its constructional and working principle from a candle holder which is further modified to suit a barrel cam mechanism. Any longitudinal motion with in the helical grooves produces rotation of the entire body about its vertical axis. This principle was adopted to convert the variable linear oscillations of the bluff body due to vortex shedding to bi-directional rotations of the barrel cam. A ratchet integrated gear mechanism is incorporated to convert the bi-directional rotations to uni-directional. The system forms an integral part of a renewable energy generator named Hydro Vortex Power Generator, which is capable of generating electricity from slow moving currents. The vertical oscillatory motion is transmitted to the slider and the same is transmitted to the barrel cam through the cam follower. A complete mathematical model of the transmission system is presented in this paper, through which the transmission efficiency is estimated to be 78.7 %. A computer aided design model with design specifications of each component of the transmission device is also presented. Based on the CAD model, transmission system is fabricated and is tested for its efficiency on a standalone HVPG module. The overall efficiency of the power generator with the novel transmission system was observed to be 60.2 % for an output power of 19. 8 W.

1. Introduction

The earth's water bodies constitute a huge portion of the planet and their slow and steady motion represents a vast, but yet untapped energy resource. Hydroelectric power generation is of course a clean source of energy but considering the capital investment and the effects of dams on natural ecosystem the need for a much cleaner and safer energy source becomes more important [1,2]. Vortex power and studies on its efficacy to produce electric power has always been a matter of research. Devices have been developed and deployed on ocean beds for harnessing the power of vortices shed in the wake of bluff bodies due to ocean currents [3]. The elastically mounted bluff body oscillates due to the induced lift force from the vortices. The oscillations are then tapped to useful electric power. This process entails the incorporation of an efficient power transmission system. There have been many mechanical power transmission systems reported in various literature that convert the hydro mechanical energy of the bluff body available as oscillations to useful electrical power output [4, 5, 6]. However, the transmission modes considered were conventional employing piezoelectric conversion or a simple mechanical conversion such as a slider-crank mechanism. The efficiency of transmission systems directly affects the power output. This paper presents a novel transmission system inspired from a spiral grooved candle holder developed into a barrel cam mechanism. The transmission efficiency is found to be satisfactory establishing the system's suitability in the design of power harnessing devices.

The Hydro Vortex Power Generator (HVPG) is a device used to tap the hydro mechanical power of vortices and then harness the same in the form of useful electrical output. When a cylindrical bluff body is placed with its longitudinal axis perpendicular to the direction of a flow, the body starts oscillating in mutually perpendicular directions. The oscillations in the direction of flow are called inflow (IF) oscillations and those in the direction perpendicular to the flow are known as cross-flow (CF) oscillations. The CF oscillations are more predominant and contribute to the power harnessing [7]. When the frequency of vortex shredding matches the natural frequency of that of the bluff body, the body undergoes harmonic oscillations of large amplitude. This phenomenon is known as 'lock-in' [8]. During lock-in, frequency of shed vortex shifts to natural frequency of the bluff body, leading to oscillations of greater amplitude. It may be noted here that though the phenomenon well underlies the principles of vortex induced vibrations (VIV), the rigid body response is referred to with the term oscillations.
Vortex shedding occurs at a discrete frequency and is a function of Reynolds number ($\boldsymbol{Re}$), given as in Equation (1) [9].

$$Re = \frac{\rho V D}{\mu} \tag{1}$$

When vortices are shed from the cylinder, uneven pressure distribution happens to develop around the upper and the lower part of the cylinder, giving rise to an oscillating hydrodynamic lift force on the cylinder. The lift force is given in Equation (2).

$$F_L = \frac{1}{2} C_L \rho A V^2 \tag{2}$$

where, F_L is the lift force, C_L is the coefficient of lift, ρ is the density of water, A the projected area in the direction of flow and V is the velocity of flowing water. The cylinder also experiences a net force along flow (IL) direction and is called the drag force. The drag force is given in Equation (3)

$$F_D = \frac{1}{2} C_D \rho A V^2 \tag{3}$$

where, F_D is the drag force and C_D is the drag coefficient.

For the device HVPG to materialize for the intended purpose, a cylindrical bluff body has been mounted elastically, enabling the entire module to be considered as a spring-mass system undergoing harmonic oscillations. When the natural frequency of the spring-mass system matches the vortex shedding frequency, the system encounters resonance condition and the cylinder oscillate with large amplitudes [10]. The linear motion of the mass is then converted to rotary motions through an appropriate transmission mechanism. This paper discusses a novel transmission system for the device in detail.

2. Working Principle - Novel Transmission System

The transmission system discussed here derives its constructional and working principle from a candle holder show in Figure 1 (a) which could convert any linear motion with in the helical grooves to rotary. The system is further modified to suit a barrel cam mechanism. A ratchet integrated gear mechanism is incorporated to convert the bi-directional rotations to uni-directional.

The vertical oscillatory motion of the bluff body is transmitted to the slider and the same is transmitted to the barrel cam through the cam follower. The elements of transmission system are shown in Figure 1 (b). The follower reciprocates and the barrel cam rotates in clockwise direction during the upward motion and in the anticlockwise direction during the downward motion of the bluff body. The top end of the barrel cam is equipped with ratchet integrated differential gear system. One set consists of gears having ratchet drives attached to the axis coupled directly to the axis of barrel cam. As the cam rotates in clockwise direction the ratchet gear on one side attains the drive and the other undergoes free rotation.

In case of anti-clockwise rotation, the drive and free rotation are reversed. The other set of gears, known as output gears, facing each other are meshed at 90° to the ratchet gears. The output gears are placed face to face forming a differential gear arrangement. The bi-directional rotation of the barrel cam is converted to unidirectional rotation, and the rotation is obtained from the output gears. The output gears are coupled to the output shaft and further to a generator for extracting output DC power. The process of hydromechanical power transmission to generate useful electrical power output is demonstrated using a flow chart as in Figure 2.

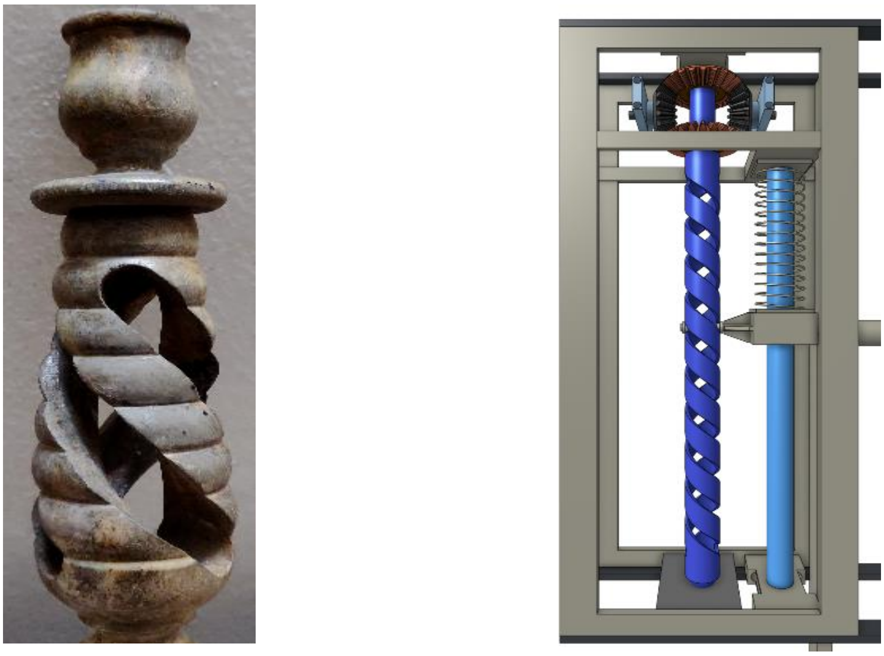


Fig. 1. Transmission mechanicsm (a) inspirational candle stand (b) CAD model

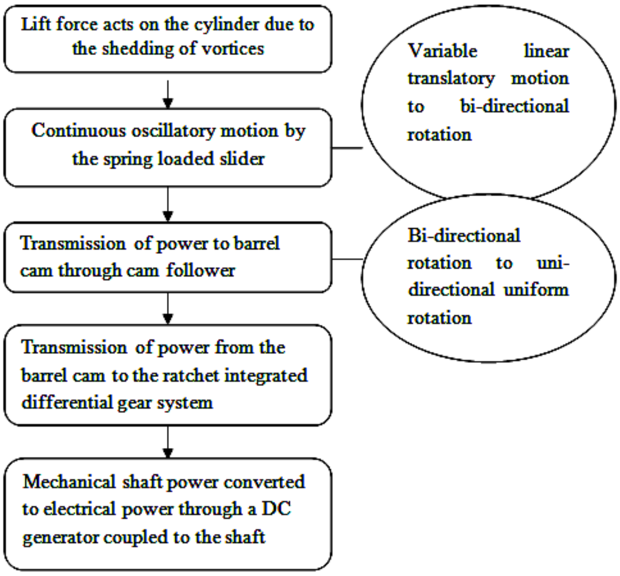


Fig. 2. Flow diagram of power transmission system

3. Transmission Mechanism

The load acting on the slider in the direction of its motion is F_L. A slider bearing of 25 mm inner diameter for load carrying capacity of 980N is selected [11]. Details of the bluff body and the slider, spring specifications, details of barrel cam and the ratchet arrangement are listed in Table 1[12, 13]. The barrel cam in the present design is used to convert linear motion into rotary motion, i.e. back driving. The main factor responsible for providing the back drive is the lead or helix angle [13, 14]. The barrel cam is provided with screw thread with double start thread groove. It has already been proved that thread angle greater than 20° shows the tendency to back drive [15]. On further increasing the thread or the lead angle, the back-drive efficiency increases.

In the ratchet gear arrangement, the larger gears rotate clockwise and anti-clockwise giving unidirectional rotation as output. Here maximum angular speed is obtained when the number of teeth on the planetary gear is reduced to that of the sun gears. On further reduction, the module of the gears changes resulting in backlash [16]. The net output is unidirectional rotary motion at the output shaft which in turn is coupled to a DC generator to produce power.

4. Theoretical Power Calculations

According to previously published work from the authors [14] reduced velocity, $U_r = 5$ for frequency ratio, $\eta = 1$. Therefore, the natural frequency is given by Equation (4).

Table 1 Specifications of the transmission system

Bluff body and slider		**Spring**		**Barrel cam**		**Ratchet gear arrangement**	
Paramet ers	**Specific ation**	**Paramet ers**	**Specific ation**	**Paramet ers**	**Specific ation**	**Paramet ers**	**Specifict io n**
Cylinder Diameter	76.2 mm	Material	SS 134a	Material	SS	Materia l	PLA
Cylinder Length	800 mm	Type	Square	Thread	Doubl e start	Sun gear: No.of teeth (t1)	24
Oscillati ng Mass	**6.2 kg**	Free length	300mm	OD	40mm	Planetary gear: No. of teeth (t_2)	18
C_A	0.7	OD	34 mm	ID	32mm	Module (m)	1mm
Slider rod OD	25m m	ID	30 mm		50mm	Shaft angle	90°
Slider bearing ID	25m m	Wire thickness	2 mm	Helix angle	50.19°	Teeth width	5.08mm
Slider Capacity	980 N	Coils (Active)	8	Length of cam	680 mm		
		Coils (Total)	10				

$$f_n = f_s = \frac{V}{DU^*} \tag{4}$$

4.1. Mass Ratio

Mass ratio (m^*) of the oscillating system is an important parameter that influences the amplitude of response and is given by Equation (5), where m, virtual mass of the system is taken as $m_a + m_b$, m_a is the added mass and m_b is the mass of the bluff body. m_{dis} is the mass of fluid displaced by the body.

$$m^* = \frac{m}{m_{dis}} \tag{5}$$

4.2. Stiffness of the spring (*k*)

Spring stiffness is a very important parameter in the design [19]. The body oscillations depend on the restoring forces and the spring should have enough stiffness to sustain the oscillations. The spring stiffness is calculated from the circular natural frequency value, ω_n corresponding to $U_r = 5$ using Equation (6).

$$\omega_n = \sqrt{\frac{k}{m}} \tag{6}$$

The device uses a pair of springs connected in parallel and stiffness of each spring (*k/2)*

4.3. Amplitude of Oscillation (y)

The amplitude of oscillation y_{max} during resonance is given as in Equation (7),

$$y_{max} = \frac{F_L}{2k\xi} \tag{7}$$

where ξ is the damping ratio. Various parameters and the calculated values using Equations (5) through (14) used in the design of HVPG is shown in Table 2. C_L value is taken from the previously published work of the authors for the same *Re* and m^*[11].

Table 5 Design parameters

Parameters	**Specifications**	**Parameters**	**Specifications**
Design velocity (V)	1.2 m/s	Output speed (N_{gen})	120 rpm
Density of water (ρ)	998.3 kg/m^3	Supply Voltage	4.5 – 15 V DC
Reynold's number (Re)	1.02 x 10^5	DC motor type	Brushed
Coefficient of lift (C_L)	0.75	Shaft diameter ($d_{genshaft}$)	6 mm
Lift force (F_L)	32.86 N	Gearhead type	Spur
Strouhal number (*St*)	0.2	Length (L_{gen})	78 mm
Mass ratio (m*)	2.89	Width (B_{gen})	37 mm
Natural frequency (f_n)	3.15 Hz	Current Rating (I)	2.81 A
Stiffness (k)	4124 N/m	Core	Iron
Maximum amplitude – theoretical (Y_{max})	0.1327 m		
Damping ratio (ξ)	0.03		

4.4. Mechanical Efficiency

The hydro-mechanical efficiency, η_{hymech} of the system is given as the ratio of power available at the bluff body to the power available at the slider, and is shown in Equation (8).

$$\eta_{hymech} = \frac{P_{slider}}{P_{bluff}} \tag{8}$$

where P_{slider} is estimated considering the actual amplitude of oscillation obtained from field test conducted at Palissery irrigation canal which is presented in Table 3. P_{bluff} is estimated considering the maximum velocity and the corresponding amplitude Y_{max}., estimated theoretically from the value of lift force calculated from Equation (2). C_L has been assumed based on the numerical simulation carried out in the previously published work by the authors. Lift and drag coefficients of a horizontal cylinder were also estimated from a wind tunnel experiment conducted at the same *Re* in the published work [11].

4.5. Transmission Efficiency

The transmission efficiency, $\eta_{trans}$of the system is given as in Equation (9)

$$\eta_{trans} = \left(\frac{P_{shaft}}{P_{slider}}\right) \tag{9}$$

The output power of the transmission system is given as in Equation (10)

$$P_{shaft} = \frac{2\pi N_{shaft} T_{shaft}}{60} \tag{10}$$

$$T_{planetary} = T_b \left(\frac{t_2}{t_1}\right) \eta_{gear} \tag{11}$$

Torque on the barrel cam Tb presented in Equation (11) can be estimated from the force acting on the barrel cam. Estimated values of the output parameters are presented in Table 4.

5. Electric Power Generation

Two direct current (DC) generators with specifications as given in Table 6 are connected to the shaft of the linear transmission system to covert the mechanical power into electricity. The efficiency of the generator, η_{gen} can be obtained from Equation (12) [18, 229].

$$\eta_{gen} = \frac{P_{gen}}{P_{shaft}} \tag{12}$$

Using a suitable compound gear the speed is reduced from 550 rpm at the shaft to 120 rpm at the generator shaft. Corresponding torque at the generator shaft will be 0.59 N m. Torque at the generator shaft, T_{gen} and the efficiency of the generator, η_{elec}in Table 4.

6. Overall Efficiency of Hydro Vortex Power Generator (HVPG)

Overall efficiency of the HVPG module developed is obtained from Equation (13).

$$\eta_{overall} = \eta_{hymec\,h} \times \eta_{trans} \times \eta_{gen} \tag{13}$$

7. Experimental Validation

The design calculations presented in this paper are based on the amplitude of the slider measured from a field test carried out in Palissery[1] irrigation canal. The measurements were carried out using a pantograph with a pencil attached to the mechanism. The pencil was attached to the slider of the barrel cam mechanism and the paper was fixed to the frame of the device. The board holding the paper was replaced for each value of k during every loop. The pencil was permitted to move against a paper and the readings were recorded on a linear scale. Observation corresponding to maximum oscillation value was noted for calculating the design parameters. Three observation were made for each value of k, repeating the experiment in loops. During the first loop spring stiffness was varied in the ascending order and during the second loop in the descending order. Further the first loop was repeated.

[1]Palissery is a country side place in the Ernakulam District, the state of Kerala, India.

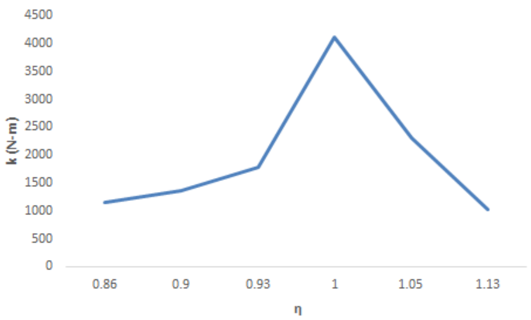
Deviation of oscillation magnitude obtained during each observation was found to be negligible. The calculated value of N_{barrel} is verified using a digital tachometer and is obtained as 400 rpm instead of 500 rpm. This change when reflected in the rest of the calculation indicate an over prediction of 3% in the overall efficiency, $\boldsymbol{\eta_{overall}}$.

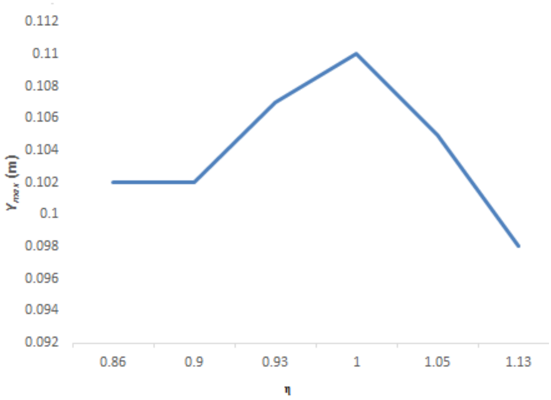
The HVPG module with specifications as in Table 2 has been tested for response and output power at the Palissery irrigation canal. The module was tested for a range of natural frequencies to validate the argument that lock –in vibration with highest amplitude occurs not only at the discrete frequency when η =1, but over a range of frequency ratios, thus widening the efficient regime of operation. Actual value of Y_{max} observed during the field test is used for calculating mechanical efficiency of the module. The observations are presented in Table 3. A photograph during the test is presented in Figure 3. Relationship of spring stiffness and oscillation amplitude with frequency ratio is presented in Fig. 4.

Table 3 Output parameters from the field test of HVPG Phase III

Frequency Ratio (η)	**Spring Stiffness (k) (N-m)**	**Maximum Amplitude (Y_{max}) (m)**
1.13	1020	0.098
1.05	2314	0.105
1.0	4124	0.11
0.93	1784	0.107
0.9	1363	0.102
0.86	1156	0.102

Fig. 3. Field test of HVPG Module Phase III at Palissery irrigation canal





(a) (b)

Fig.4 Variation of spring stiffness and motion amplitude with frequency ratio

8. Results and Discussions

From the calculations carried out the design parameters of the device in discussion are arrived at and are shown in Table 4. The measurable output of the device is terms of various efficiencies are presented in Table.

With the overall efficiency of 60%, and output power approximately 21 kW, the module is a promising source of renewable and clean hydrokinetic energy.

Hydro Vortex Power Generator with the efficient transmission system developed through this research possess high scalability and is capable of harnessing energy from vortices shed by ocean currents. Research can be taken ahead with a vision of tapping green energy of vortices from the vast costal line of India. HVPG modules can be design improvised and installed in array, of which further numerical analysis is required, to produce green and sustainable energy.

Table 4 Performance parameters for the HVPG module

Design Parameter	Value	Design Parameter	Value
Power of bluff body (P_{bluff})	86W	Speed of planetary gear in rpm ($N_{planetary.}$)	550.4 rpm
Maximum amplitude – actual (Y_{act})	0.11m	Gear efficiency (η_{gear})	95%
Power at slider (P_{slider})	71.5W	Torque transmitted to shaft (T_{shaft})	0.364 Nm
Hydro-Mechanical efficiency (η_{hymech})	83.14%	Power available at the shaft (P_{shaft})	20.98 W
Velocity ratio (V_r)	1.13	Transmission efficiency (η_{trans})	78.7%
Coefficient of friction (f)	0.3	Torque transmitted to the generator (T_{gen})	0.59 Nm
Efficiency of barrel cam (η_{bcam})	71.2 %	Motor Power	19.8 W
Force on barrel cam (F_b)	28.401 N	Generator efficiency (η_{gen})	94.4 %

Torque on barrel cam (T_{barrel})	0.5112 N/m	Number of individual threads (n)	2
Slider displacement during field tests (y_{act})	110 mm	Hydromechanical efficiency (η_{hymech})	83.14%
Actual velocity ($V_{barrel.act}$)	0.688 m/s	Transmission efficiency (η_{trans})	78.7 %
Speed of barrel cam in rpm (N_{barrel})	412.8 rpm	Electrical efficiency (η_{elec})	94.4 %
Power at barrel cam (P_{barrel})	22.098 W	Overall efficiency ($\eta_{overall}$)	60.2%

9. Conclusions

The standalone module of HVPG developed in this work has considerable efficiency and output power, which can be used to light up tribal areas of the nation in an absolutely green way. During the course of the project three models I, II and III have been built and tested in the Palissery irrigation canal which is a low-turbulence free surface water channel. HVPG allows efficient extraction of energy with minor and slow adjustment of basic design parameters such as the spring stiffness and induced damping. It is capable of generating energy with high power conversion ratio at speeds as slow as 0.5m/s, and as high as 5 m/s. The proposed design of the transmission mechanism can be used as a universal transmission device where it can convert non-uniform oscillations into rotation. The ratchet integrated differential gear mechanism alone can be used in high speed switching in the direction of rotation. Hydro Vortex Power Generator with the efficient transmission system developed through this research possess high scalability and is capable of harnessing energy from vortices shed by ocean currents. Research can be taken ahead with a vision of tapping green energy of vortices from the vast costal line of India. HVPG modules can be design improvised and installed in array, of which further numerical analysis is required, to produce green and sustainable energy.

10. Scope for Future Work

The standalone module of HVPG developed in this work has considerable efficiency and output power, which can be used to light up tribal areas of the nation in an absolutely green way. Hydro Vortex Power Generator with the efficient transmission system developed through this research possess high scalability and is capable of harnessing energy from vortices shed by ocean currents. Research can be taken ahead with a vision of tapping green energy of vortices from the vast costal line of India. HVPG modules can be design improvised and installed in array, of which further numerical analysis is required, to produce green and sustainable energy.

11. Author Contributions

Conceptualization, S.J.; Data curation, V.C.; Ideation, G.G.N. Formal analysis, G.G.N., GGN, VC Investigation, G.G.N, Methodology, D.V and S.J.; Project administration, D.V.; Resources, G.G.N, Fabrication, G.G.N., Supervision, S.J and VC.; Validation, V.C.; Visualization, G.G.N.; Writing—original draft, V.C and G.G.N, Writing—review and editing, D.V and S. J

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