Analysis of dynamic behaviour and power generation of a wind-tidal system for marine environment

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Abstract

This work presents the analysis of dynamic behaviour and power generation of a wind-tidal hybrid system. Mathematical models and system design approach were used to investigate the feasibility, reliability and economic impact of the system. From the system design analysis carried out, by harnessing the tidal energy with wind energy in marine environment, the total power generated (approximately 180KW) by the hybrid power system showed a significant improvement over a wind turbine system which only generates a maximum power of 25KW at the rotor diameter as reported in literature. The effects of aerodynamics and hydrodynamics forces on the structure were investigated through the analysis of dynamic behaviour of the system under different loads and at various sites in the marine environment. The stability and the optimum turbine design were found to depend on the wind and tidal speed distribution of the specific site in the environment. The long term benefit of this work is aimed at meeting the energy needs of coastal dwellers by implementing the hybrid power system. Also, the gridless system could be used to generate power for both large and small scale industries in the marine environment.

***Key words**: Wind Energy; Tidal Energy; Hybrid Power System; Dynamic behaviour; Power generation; Marine Environment*

1. Introduction

Growing concerns over the threat of global energy security and climate change have strengthened interest in harnessing renewable energy resources as a response to the global energy challenge. The inadequate supply or the epileptic nature of electricity generation in developing countries has also given rise to research into other source of energy generation like wind, tidal, solar etc. The rapid world population growth and the advancement in economy in no doubt resulted in rapid increase in energy demands. Moreover, the limited nature of fossil energy and its pollution on the enviroment has given rise to contradiction among energy providing, environment protection and economic development. The energy available from the renewable resources, with the availability of its renewability and non-pollution, will grow to be an effective and practical choice to guarantee the future developing countries of the world. On the other hand, the renewable energy sources like wind energy, solar energy, etc. is seasonal, periodic or unpredictable and most often such energy is affected by factors beyond human control. Also, in most cases such seasonal, intermittent and periodic renewable energy systems are backed up by conventional sources of energy or energy storage devices (which in consequent, gives rise to additional production, operation and maintenance costs) in order to ensure continuity of the energy supply. One of the solutions to combating the problem is to hybridize two or more energy sources for efficient and effective performance. Actually, the technique of hybrid power system is one of the currently most explored techniques for power generation which focuses on the generation of power from two different energy sources and it has proven to solve the power crisis in many countries around the world to a very large extent.

From the literatures for these two renewable energy sources, the power generation from wind turbines has already been studied extensively and very much literature on the topic exists. Wasynczuk et al (1981) investigated the dynamic behaviour of a class wind turbine generator during random wind fluctuations. Rajib and Ranganathan (2002) used a doubly fed wound rotor induction machine for a variable-speed wind power generation. Eduard and Butterfield (2001) presented pitch-controlled variable-speed wind turbine power generation. Antonios et al (2004) developed mathematical models for the dynamic performance and control for a grid-connected variable speed wind turbine. Erlich et al (2007) showed that with properly designed crowbar and DC-link chopper even zero voltage-through is possible using a Doubly-Fed Induction Generator, Fault-Ride through (DFIG) based wind turbines. Jonathan and Hiskens (2008) developed a model for estimating wind turbine parameters and quantifying their effects on dynamic behavior. Yuwei Li et al (2012) presented a simulation result of an overset computational fluid dynamics for wind turbine. Also, various work on the use of Tidal waves or currents for power generations have been presented in literatures [1, 3, 4, 8, 10, 13, and 16]. On the dynamic analysis of a Hybrid system, Gillie and Leithead (2003) developed dynamic models for the synchronous generator and induction generator of a hybrid generation system referred as a virtual power plant which consists of a wind farm and a gas turbine driven synchronous generator whose outputs are combined before connecting to the grid. With the various efforts towards energy generation through renewable energy sources, generating power with a hybridized power system operating on wind and tidal turbines to best of our knowledge has not been researched into. Consequently, in this work, we analyzed the dynamic behaviour and power generation of a hybrid system comprising wind and tidal sources that could operate in complementing or supplementing each other. Wind and Tidal energy are forms of renewable energy sources which contain clean and abundant source of energy. They provide a vast potential for renewable electric power generation and industrial energy supply. Since tides are generated by endless cycles of the rotation of the moon about the Earth, resulting in an almost limitless supply of energy, this gives the tidal power system a distinct advantage over other power systems. Moreover, the Wind power system produced by wind energy found at high altitudes where continuous wind speeds of over one hundred and sixty kilometer per hour occur is also very dependable. The hybridized system of these renewable energy sources posseses some advantages to its credit. It needs no fuel to maintain, and free of charge, totally no pollution, unlike fossil fuels, it produces no greenhouse gases or other waste. It is a predictable source of energy as compared with wind and solar hybridized system. It is independent of weather and climate change and follows the predictable relationship of the lunar orbit. It is more efficient and reliable than wind or tidal power generation system. It will protect a large stretch of coastline against damage from high storm tides. The disadvantages could be overcome and mitigated by proper design and practice. The development and utilization of such a hybrid system will enhance the reduction in major health risks through reduced air, land and water pollution. Adverse effects of global warming on weather and climate can be mitigated by reduced CO_2 emissions. As a result, there will be reduction in health care costs and the impact of likely stricter federal emission standards in the future. Such a healthy environment achieved by the proper utilization of wind-tidal turbines attracts and retain business and also encourages the tourist industry. Large and Small scale industries on the coast can benefit by using it. Thereby increasing their marginal profit and reducing their down time. Educational institutions can also benefit from the use of the plant since they can run their laboratory equipment on it. It will also give the institution an opportunity to explore, relocate and train its faculty and students in an emerging environmental technology. Consequently this will drastically reduce the over-dependent on petrol and the effects of petroleum scarcity in our nation if the work is properly supported and developed. Moreover, the fact that the proposed hybrid system has highly efficient process, flexibility in applications over a range of output ratings, comparable low initial investment, low cost of power production, better process control and convenience, and low maintenance cost gives the study undeniable advantages over the high-grade energy generated from fossil fuels.

As pointed out before, this effort seems to be the first attempt into such form of hybridized renewable energy system. Therefore, the possibilities and potentialities of the power generation by the system worth serious considerations. This will help to measure, mitigate and control negative consequences on the system. Since this work is basically designed to be an off-grid system, our main focus is to generate power for both large and small scale industries along the coast where the hybrid system is installed. Consequently, in remote and isolated areas far from the coast, it may not be an economically viable option to supply electric power from the coast. This is due to the high cost of transmission lines and higher transmission losses that accompany distribution of centrally generated power to remote areas.

2. The off-grid hybrid power system

Fig. 1 presents in block diagram, the hybrid power generating system. The components of the hybrid power system could however be classified into the wind power system components, the tidal power system components and an intelligent hybrid controller as shown in the block diagram.

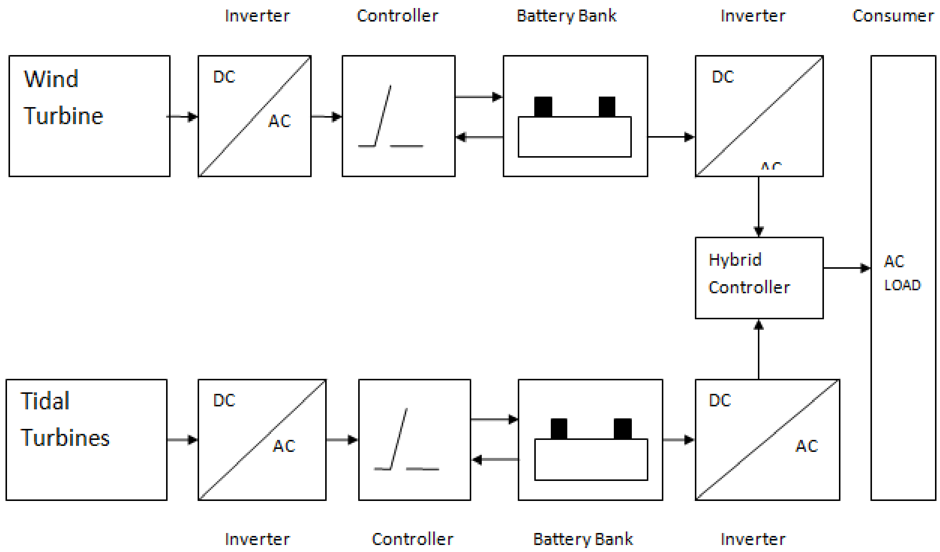

Fig. 1 Block diagram of the Wind-Tidal Power generating system

The off-grid hybrid energy system is battery based. It is limited in capacity by the size of the generating sources (wind turbine, tidal generator, etc.), the resources available, and the battery bank size. The users learn to live within the limitations of the system capacity.

3. Modeling the power generation by the system

Our first attempt in this work is to model the power generation by the system. This will be done by considering different power sections of the system.

3.1 Modeling the power generation by the wind turbine

Power Extraction from the air stream by the turbine is given as

$$P_{Wi} = \frac{1}{2}\rho . A V^{3} C_{P} \qquad 1$$

Where C_p is the fraction of the upstream wind power which is captured by the rotor blades and it has theoretical maximum value of 0.59. It is referred as the power coefficient of the rotor or the rotor efficiency in practical designs. The maximum achievable C_P is between 0.4 and 0.5 for high-speed, two – blade turbines and 0.2 and 0.4 for slow speed turbines with more blades.

An improved model for the rotor for the power coefficient varying with tip speed ratio, $\lambda = \frac{\omega R}{V}$ (the ratio between the blade tip speed V_t and product of the wind speed upstream of the rotor v) is given as

$$P_{Wi} = 0.22\left(\frac{125V}{\omega R} - 6.69\right) A\, V^{3} e^{\left(\frac{16.5V}{\omega R} + 0.33\right)}$$

2

R is the rotor blade radius in meter, ω is the rotor angular speed in $rad/\sec$.

.

The thrust from the air to the rotor is

$$T_{Wi} = 0.22AV^2\left(\frac{125V}{\omega R} - 6.69\right)e^{\left(\frac{16.5V}{\omega R}+0.33\right)} \qquad 3$$

For a wind turbine using a doubly fed induction generator, it shows that the performance coefficient C_p is not only dependent on the tip speed ratio λ, as before but also on the pitch angle $\theta[\deg]$. This is caused by the fact that variable speed wind turbines are assumed to be equipped with a pitch angle controller as in normally the case.

$$P_{Wi} = 0.365\rho A_r V^3\left[151\left(\frac{1}{\lambda - 0.02\theta} + \frac{0.003}{\theta^3+1}\right) - 0.58\theta - 0.002\theta^{2.14} - 13.2\right]\times e^{18.4\left(\frac{1}{\lambda-0.02\theta}+\frac{0.003}{\theta^3+1}\right)} \qquad 4$$

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In the previous section in this work, the power generated by waves and tidal has been referred to as the power generated by tidal. For the purpose of proper analysis and explanations in this section, a separation is made.

Energy Content of the Wind

$$EC = 0.00001073\rho A\sum_{i=1}^{N_m} V_i^3 \qquad 6$$

EC is the energy content of the wind in kWh, V_i is the hourly wind speed in km/h, for hour i, N_m is the total number of hours in the specified period

3.2 Modeling the Power generated by the Water Waves

The condition on the free surface for the water waves is given by:

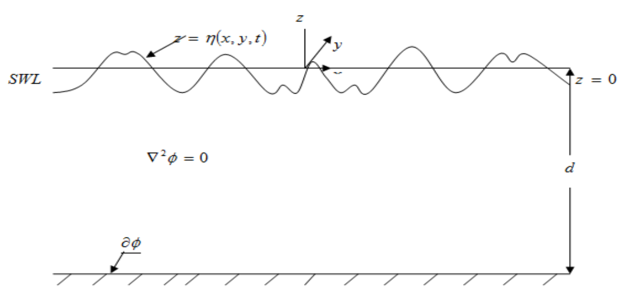

Fig. 2 condition on the free surface for the water waves

If we consider a fluid on which disturbances of height $\eta(x,y,t)$ above still water level are propagating. The vertical velocity at the free surface, taking into consideration at the surface moves with the fluid, is

The stream function,

$$\phi = \frac{ga_0}{\omega} f_0(z)\sin(\omega t - Kx) \qquad 7a$$

where $\omega^2 = gK\tanh Kd$, and we have written

$f_0(z)$ for the usual $\dfrac{\cosh[K(z+d)]}{\cosh Kd}$

a_0 is the airy wave amplitude

Hence

$$V_x = \frac{\partial\varphi}{\partial x} = \frac{g}{\omega}Ka_0\exp[-i(Kx-\omega t)]\frac{\cosh[K(z+d)]}{\cosh Kd}$$

$$V_z = \frac{\partial\varphi}{\partial z} = \frac{ig}{\omega}Ka_0\exp[-i(Kx-\omega t)]\frac{\sinh[K(z+d)]}{\cosh Kd}$$

7b

7c

Generally, we have;

$$\eta(x) = -i\,\frac{\omega\varphi(x)}{g} = a_0 \exp(-ikx)$$

$$\phi(x,z,t) = \frac{ig}{\omega}\eta(x)\frac{\cosh[K(z+d)]}{\cosh Kd}\exp(i\omega t)$$

$$V_x = \frac{\partial\phi}{\partial x} = \frac{g}{\omega}K\,\frac{\cosh[K(z+d)]}{\cosh Kd}\exp(i\omega t)\eta(x)$$

$$V_y = 0$$

$$V_z = \frac{\partial\phi}{\partial z} = \frac{ig}{\omega}K\,\frac{\sinh[K(z+d)]}{\cosh Kd}\exp(i\omega t)\eta(x)$$

$$V_t = \frac{\partial\varphi}{\partial t} = -\frac{g}{\omega}a_0 \exp[-i(Kx-\omega t)]\frac{\cosh[K(z+d)]}{\cosh Kd}$$

8a-f

The average rate at which work is done is P over wave period T, then P can be given as

$$P_{Wa} = \frac{1}{T}\int_0^T\int_{z=-d}^{z=0}\rho\left(-\frac{\partial\varphi}{\partial t}\right)\left(\frac{\partial\varphi}{\partial x}\right)dzdt \qquad 9$$

which gives

$$P_{Wa} = \frac{\rho a_o^2 g^2}{2\omega\cosh^2(Kd)}\left(\frac{\sinh(2Kd)}{4}+\frac{Kd}{2}\right) \qquad 10$$

Where $k = 2\pi/L$, a_o is the amplitude and $\boldsymbol{\omega}$ is the angular speed

3.3 Modeling the Power generated by Tides is given as

Tidal Energy or tidal power is the power achieved by capturing the energy contained in moving water mass due to tides. Two types of tidal energy can be extracted: kinetic energy of currents between ebbing and surging tides and potential energy from the difference in height between high and low tides. Moving water has kinetic energy similar to wind. The energy per second intercepted by a device of frontal area A(m²) in water of density ρ, and current velocity V (m/s) is therefore given by:

$$P = \tfrac{1}{2}\rho.AV(t)^3 C_P \qquad 11$$

Assuming a gearbox transmission efficiency of η_T and generator efficiency of η_G then the electrical power output is given as:

$$P = 0.5\eta_T\eta_G\rho.AV(t)^3 C_P \qquad 12$$

Tidal currents are not constant. Generally they are a combination of quasi-steady marine currents and flows induced by the tides. Consequently, the estimation of energy capture therefore becomes a fairly complex procedure. However for most sites the flows are purely tidal, making it possible to parameterize the tidal currents as series of simple sinusoids. Assuming the current velocity *v(t)* follows a cyclic pattern then:

$$V(t) = V_{\max}\sin\omega t$$
$$where \quad \omega = \frac{2\pi}{T} \qquad 13$$

Vmax is the maximum current speed at the surface

ω is the angular velocity of the tide

T is the period of the cycle, typically 12h 25 min or 745 minutes.

$$P = \eta_T\eta_G C_P\rho AV_{\max}^3\sin^3\omega t \qquad 14$$

The energy captured during one half of each half tidal cycle is:

$$E_T = \int P(t)dt = \int_{T_1}^{T_2} (0.5\eta_T \eta_G C_P \rho A V_{\max}^3 \sin^3 \omega t)dt + P_{rated}(T_m - T_2) \qquad \text{15a}$$

which gives,

$$E_T = \eta_T \eta_G C_P \rho A V_{\max} \left[9\sin\left(\frac{\pi}{T}(T_1+T_2)\right)\sin\left(\frac{\pi}{T}(T_1-T_2)\right) + \sin\left(\frac{3\pi}{T}(T_1+T_2)\right)\sin\left(\frac{3\pi}{T}(T_1-T_2)\right)\right]$$
$$+ P_{rated}(T_m - T_1)$$

15b

where

T_1 and T_2 are the times at which cut-in and rated power occur (relative to the start of the cycle)

The design analysis of the power generated by the system is presented in the appendix

4. Models for the dynamic behaviour of the structure

When designing a wind or tidal turbine it is extremely important to calculate in advance how the different components will vibrate, both individually, and jointly. It is also important to calculate the forces involved in each bending or stretching of a component.

A 50 meter tall Hybrid wind-tidal turbine tower will have a tendency to swing back and forth, say, every three seconds. The frequency with which the tower oscillates back and forth is also known as the eigenfrequency of the tower. The eigenfrequency depends on both the height of the tower, the thickness of its walls, the type of steel, and the weight of the nacelle and rotor. Each time a rotor blade passes the wind/tidal shade of the tower, the rotor will push slightly less against the tower. If the rotor turns with a rotational speed such that a rotor blade passes the tower each time the tower is in one of its extreme positions, then the rotor blade may either dampen or amplify (reinforce) the oscillations of the tower.

The rotor blades themselves are also flexible, and may have a tendency to vibrate, say, once per second. So, it is very important analyse the dynamic behaviour of the in order to design a safe system that does not oscillate out of control

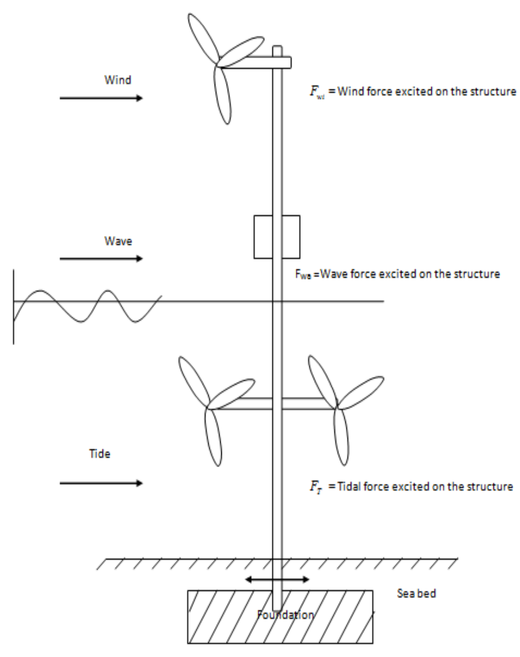

Fig.3 Environmental loads on the hybrid power-system structure.

In deriving the equation governing the vibration in the structure (modelled as flexure beam), the following assumptions were

i. Vibration occurs in one of the principal planes of the beam.
ii. The effects of rotatory inertia and transverse shear deformation are neglected.
iii. The gravity forces are neglected by measuring the displacement from the position of static equation of the beam.

After derivations, the governing differential equation becomes

$$EI\frac{\partial^4 u}{\partial z^4}+\rho A\frac{\partial^2 u}{\partial t^2}=F(z,t) \qquad 16$$

where

$$F(z,t)=F_{wind}(z,t)+F_{waves}(z,t)+F_{tides}(z,t)$$

Where

$F(z,t)$ are the applied forces along the beam

E is the modulus of electricity of the beam and I is the moment of inertia,

I is the moment of inertia;

u are the transverse displacement

A is the cross-sectional

One way of finding an approximate solution for these equations is by weighing equation and the boundary condition in the following way

$$\int_0^l -\left(EI\frac{\partial^4 u}{\partial z^4}+\rho A\frac{\partial^2 u}{\partial t^2}-P(z,t)W\ ddz\right)=\left[\left(\overline{M}-M\right)\frac{dW}{dz}\right]_{s_2}+\left[\left(\overline{Q}-Q\right)W\right]_{s_2} \qquad 17$$

Where W are weighting functions that are assumed to satisfy the essential boundary conditions, that is W and $\frac{dW}{dz}$ are identically zero on s_1.The essential or primary displacement condition on the s_1 part of the boundary is $u=0$ at $z=0$

The natural or force or secondary condition on the s_2 part of the boundary which are moment M and shear Q.

$$\overline{M}=EI\frac{d^2u}{dz^2}=0 \qquad \text{at } z=l$$

$$\overline{Q}=-EI\frac{d^3u}{dz^3}=0$$

$$\frac{du}{dz}=0 \text{ at } z=0$$

18a-c

Assuming that the shapes of the W functions are the same as the u functions, which was taken as approximate solutions, this leads to the following form of the principle of virtual displacement.

$$\int_0^l \left(EI\frac{\partial^4 u}{\partial z^4}+\rho A\frac{\partial^2 u}{\partial t^2}-P(z,t)\partial u\ dz\right)=\left[\left(\overline{M}-M\right)\frac{d\ \partial u}{dz}\right]_{s_2}+\left[\left(\overline{Q}-Q\right)\partial u\right]_{s_2} \qquad 19$$

Integrating equation (19) by parts twice, we obtain the best-known expression for virtual displacements, that is

$$\int_0^l \left(EI\left(\frac{d^2u}{dz^2}\right)\left(\frac{d\ \partial u}{dz^2}\right) + \rho A\ddot{u} \right) dz = \int P\ \partial u dz + \left[\overline{M}\ \frac{d\ \partial u}{dz} \right]_{s_2} + \left[\overline{Q}\ \partial u \right]_{s_2} \qquad 20$$

On putting the boundary condition we have the principle of virtual displacements for the equation (20) as

$$\int_0^l \left[EI\left(\frac{d^2u}{dz^2}\right)\left(\frac{d\ \partial u}{dz^2}\right) + \rho A\ddot{u} \right] dz = \int P\ \partial u dz \qquad 21$$

With the function u satisfying the essential boundary conditions at z=0, that is the part of the boundary s_2. Assuming an approximate function for u, such that

Where u represent the horizontal displacement at the top of the tower and $g(z)$ is a "shape" function that represents the shape of the tower substituting 14a and 14b into 5, we find

$$\partial u\left[\int_0^l EI\left(\frac{d^2g}{dz^2}\right)^2 dz\ u + \int_0^l \left(\rho A(g)^2 dz\ \ddot{u}\right) \right] = \partial u\left[\int_0^l \rho g\ dz \right] \qquad 22$$

As ∂u is arbitrary, we can simply write

$$Ku + M\ddot{u} = F \qquad 23$$

Where

$$\left. \begin{aligned} K &= \int_0^l EI\left(\frac{d^2g}{dz^2}\right) dz \\ M &= \int_0^l \rho A(g)^2 dz \\ F &= \int_0^l \rho g\ dz \end{aligned} \right\} \qquad 24$$

K, M, *and* F are the equivalent stiffness, mass and force coefficients for the one – degree of freedom system.

We can similarly include the damping term into the equation. Therefore more general equilibrium equation will then be

$$Ku + C\dot{u} + M\ddot{u} = F \qquad 25$$

Where

$$C = \int_0^l c(g)^2 dz \qquad 26$$

$$M\ddot{u} + C\dot{u} + Ku = F \qquad 27$$

where M is the mass of the tower, the mass of the platform and the hydrodynamic mass. The term C includes the structural and hydrodynamic damping. K include the structural and hydrodynamic stiffness. u is the displacement at the top of the column $x = L$.

The Force F in equation has three components, that is $F = F_{Wi} + F_{Wa} + F_T$

$$F = \left[\left(C_I v_x + C_D \sqrt{\frac{8}{\pi}} \sigma_{vx} v_x \right)^2 + \frac{1}{4} \rho^2 D^2 v_m^4 \left(\sum_{n=1}^{N} C_1^n \cos(m\omega_0 + \varphi_n) \right)^2 \right]^{\frac{1}{2}}$$
$$+ 4\rho_{air} v^2 D \left(\sqrt{C_D^2 C_L^2} \right) (z)^{2\alpha_s} \left(\frac{H_0}{D_0} \right) f(t) + F_{ZNB} \delta(z-1) + M_{YNB} \eta(z-1) - m_T \frac{\partial^2 \omega}{\partial t^2} - g_2 \frac{\partial \omega}{\partial t}$$
$$+ 4\rho_{water} v_x^2 D \sqrt{C_D + C_L^2} x^{2\alpha_s} + 2F_{TNB} \delta(z-1) + 2M_T \eta(z-1) \quad 28$$

Thus, we have

$$M\ddot{u}_t + C\dot{u} + Ku = \left[\left(C_I v_x + C_D \sqrt{\frac{8}{\pi}} \sigma_{vx} v_x \right)^2 + \frac{1}{4} \rho^2 D^2 v_m^4 \left(\sum_{n=1}^{N} C_1^n \cos(m\omega_0 + \varphi_n) \right)^2 \right]^{\frac{1}{2}}$$
$$+ 4\rho_{air} v^2 D \left(\sqrt{C_D^2 C_L^2} \right) (z)^{2\alpha_s} \left(\frac{H_0}{D_0} \right) f(t) + F_{ZNB} \delta(z-1) + M_{YNB} \eta(z-1) - m_T \frac{\partial^2 \omega}{\partial t^2} - g_2 \frac{\partial \omega}{\partial t} \quad 29$$
$$+ 4\rho_{water} v_x^2 D \sqrt{C_D + C_L^2} x^{2\alpha_s} + 2F_{TNB} \delta(z-1) + 2M_T \eta(z-1)$$

This model seems complex in obtaining the closed form solution due to the non-linear nature of the force function. One of the ways of approximating the force function is neglect the effect of wind load on the structure. This approximation is justified if we compare the effect wind load to that of wave and tidal loads on the structure.

Morison et al [1950] postulated an empirical formula for the forces on vertical cylinders in the presence of surface waves. They postulated that the force had two components;

- the drag force, proportional to the square of the water-particle velocity, the constant of proportionality being a drag co-efficient having substantially the same value as for steady state
- An inverted or virtual – mass force, proportional to the horizontal component of acceleration of the water particles.

So, the force per unit length in the x direction (horizontal direction) at depth z is

$$F(z,t) = C_m(\dot{v}_x - \ddot{u}) + C_A \dot{v}_x + C_D(v_x - \dot{u})|v_x - \dot{u}| \quad 30$$

This force is in the direction of the wave advance and the water – particle velocities and acceleration v and $\dot{v}_x$ are evaluated at the cylinder axis. C_I is a constant due to inertia constituting of two terms; one due to the "hydrodynamic" mass contribution and the other to the variation of the pressure gradient within the accelerating fluid.

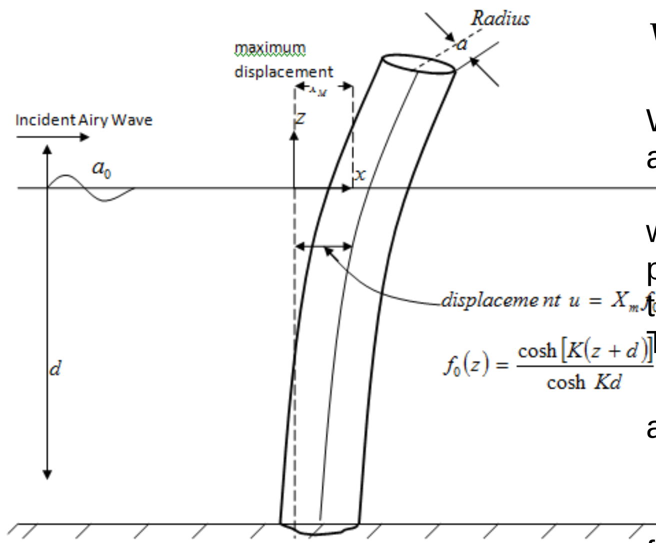

Fig. 4 Physical model for the bending and vibration of the structure

Recall from equation (7b);

$$V_x = \frac{\partial\varphi}{\partial x} = -\frac{Kga_0}{\omega} f_0(z)\cos(\omega t - Kx)$$

$$V_x = Kga_0 f_0(z)\sin(\omega t - Kx)$$

We have for displacement of the column axis:

where α is the angle representing the phase difference between the motion of the column and the wave.

The velocity of the column axis is:

$$\dot{u} = \omega X_m f_0(z)\cos(\omega t + \alpha)$$

and the acceleration is given by

$$\ddot{u} = -\omega^2 X_m f_0(z)\sin(\omega t + \alpha)$$

for a circular cylinder radius a, taking

$$C_m = C_A = C_d = 1,\ C_m = \pi a^2\rho, \qquad C_A = \pi a^2\rho, \qquad C_m = a\rho \qquad 31$$

Hence, the Morison's equation,

$$F(z,t) = \pi a^2\rho f_0(z)\left[2gKa\sin(\omega t) + \omega^2 X_m\sin(\omega t+\alpha)\right]\times\rho a\left[f_0(z)\right]^2\left[\frac{gKa_0}{\omega}\cos(\omega t) + \omega X_m\cos(\omega t+\alpha)\right]$$
$$\times\left|\left[\frac{gKa_0}{\omega}\cos(\omega t) + \omega X_m\cos(\omega t+\alpha)\right]\right|$$

32

For deep water, $f_0(z) \approx \exp(Kz)$ and $\omega^2 = gK$, then we have

$$F(z,t) = \exp(Kz)\pi a^2\rho\omega\left[2a_0\sin(\omega t) + X_m\sin(\omega t+\alpha)\right]\times -\exp(2Kz)\rho a\omega^2\left[a_0\cos(\omega t) + X_m\cos(\omega t+\alpha)\right]$$
$$\times\left|a_0\cos(\omega t) + X_m\cos(\omega t+\alpha)\right|$$

33

The total force on the cylinder (tower) $F_t(t)$ is obtained from F by integrating $F(z,t)$ from $z = -d \quad to\ z = 0$ in equ. 33

$$F_t(t) = \int_{-d}^{0} F(z,t)dz$$

$$F_t(t) = \int_{-d}^{0} \Big[\exp(Kz)\pi a^2 \rho\omega[2a_0 \sin(\omega t) + X_m \sin(\omega t + \alpha)] - \exp(2Kz)\rho a\omega^2 [\cos(\omega t) + X_m \cos(\omega t + \alpha)] \times \left|a_0 \cos(\omega t) + X_m \cos(\omega t + \alpha)\right|\Big]dz$$

$$F_t(t) = \Big[K\pi a^2 [2a_0 \sin(\omega t) + X_m \sin(\omega t + \alpha)] - 2K\rho a\omega^2 [a_0 \cos(\omega t) + X_m \cos(\omega t + \alpha)]\Big](1 - \exp(-Kd)) \times \left|a_0 \cos(\omega t) + X_m \cos(\omega t + \alpha)\right|\Big] \quad 34$$

For a stationary tower (cylinder), $X_m = 0$

So,

$$F_t(t) = 2\pi a^2 \rho g K a_0 f_0(z) \sin \omega t + \rho a[f_0(z)]^2 \frac{g^2 K^2 a_0^2}{\omega^2} \cos \omega t |\cos \omega t| \quad 35$$

For deep water, $f_0(z) \approx \exp(Kz)$

$$F_t(t) = \left[2\pi a^2 \rho g K^2 a_0 \sin \omega t + \frac{2\rho a g^2 K^2 a_0^2}{\omega^2} \cos \omega t |\cos \omega t|\right](1 - \exp(-Kd)) \quad 36$$

On substituting this into equation (27) and solve analytically,

The closed form solution for the vibration of the tower is given by

$$u(t) = e^{-\gamma\omega_n t}\left[\frac{u(0) + \gamma\omega_n u(0)}{\omega_n\sqrt{1-\gamma^2}}\sin\left(\sqrt{1-\gamma^2}\right)\omega_n t + u(0)\cos\left(\sqrt{1-\gamma^2}\right)\omega_n t\right] +$$

$$\frac{2\pi a^2\rho g K^2 a_0\left(M\omega^2 - K\right)\sin\omega t}{K\left(M\omega^2 - K\right) - M\omega^2\left(M\omega^2 - K\right) - (C\omega)^2} +$$

$$+ \frac{2\pi a^2\rho g K^2 a_0\left(M\omega^2 - K\right)CM\omega^2\cos\omega t}{M\omega\left(M\omega^2 - K\right)\left[K\left(M\omega^2 - K\right) - M\omega^2\left(M\omega^2 - K\right) - (C\omega)^2\right]} +$$

$$+ \frac{\rho a K^3 g^2 a_0\left(\exp(Kd) - 1\right)\left(M\omega^2 - K\right)}{K\left(M\omega^2 - K\right) - M\omega^2\left(M\omega^2 - K\right) - (C\omega)^2}\sin 2\omega t +$$

$$\frac{\rho a K^3 g^2 a_0\exp\left[(Kd) - 1\right]\left(M\omega^2 - K\right)CM\omega^2\cos 2\omega t}{M\omega\left(M\omega^2 - K\right)\left[K\left(M\omega^2 - K\right) - M\omega^2\left(M\omega^2 - K\right) - (C\omega)^2\right]}\cos 2\omega t +$$

$$+ \frac{\rho a K^3 g^2 a_0}{\omega^2}\exp\left[(Kd) - 1\right] \qquad 38$$

5. Dynamic analysis of the foundation

The vertical oscillation of the foundation of the hybrid power system can be modeled using Dashpot-spring-mass system.

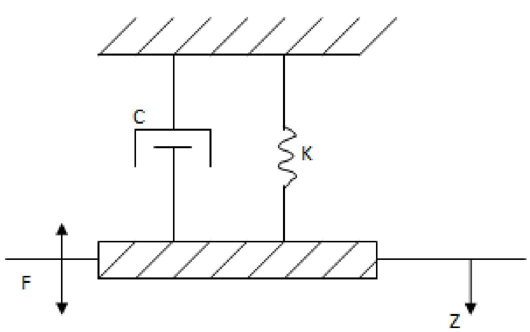

Fig.5 Physical model for foundation vibration.

$$M_{eff}\ddot{z} + C\dot{z} + Kz = F$$
40

For the Harmonically exciting force, we can write

$$F = P\sin\omega t$$
41

Hence:

$$M_{eff}\ddot{z} + C\dot{z} + Kz = P\sin\omega t$$
42

Where P the amplitude of the exciting force and ω is the forced frequency. M. Hanler etal gave the following relationship

$$C = \frac{3.4r^2\sqrt{G\rho}}{1-v} \text{ and } K = \frac{4Gr}{1-v}$$

G is the shear modulus of the foundation, *v* is the poisson ratio

On putting this into equation 43, we have

$$M_{eff}\ddot{z} + \frac{3.4r^2\sqrt{G\rho}}{1-\nu}\dot{z} + \frac{4Gr}{1-\nu}z = P\sin\omega t \qquad 44$$

Thus the complete solution is

$$z(t) = \frac{P}{\sqrt{M_{eff}\left\{\left[4\left(\frac{Gr}{1-\nu}\right) - M_{eff}\omega^2\right]^2 + \left[11.56\left(\frac{r^2\omega\sqrt{G\rho}}{1-\nu}\right)\right]^2\right\}}}\sin\left\{\omega t - \tan^{-1}\left[\frac{3.4r^2\sqrt{G\rho}}{4Gr - M_{eff}\omega^2(1-\nu)}\right]\right\} \qquad 45$$

The amplitude of the vibration is given as

$$Z = \frac{P}{\sqrt{M_{eff}\left\{\left[4\left(\frac{Gr}{1-\nu}\right) - M_{eff}\omega^2\right]^2 + \left[11.56\left(\frac{r^2\omega\sqrt{G\rho}}{1-\nu}\right)\right]^2\right\}}} \qquad 46$$

The phase angle is given by

$$\phi = \tan^{-1}\left[\frac{3.4r^2\sqrt{G\rho}}{4Gr - M_{eff}\omega^2(1-\nu)}\right] \qquad 47$$

The power generated by the turbines, the dynamic response of the structure to the wind, wind and tidal loads and the vibration of the foundation were investigated were simulated and the results were presented as follows.

6.0 economic models of the hybrid power gerating system

For the success and commercialization of any new technology, it is essential to know whether the technology is economically viable or not. Therefore, an attempt was made to evaluate economics of the Hybrid system. The merits and the economic potential and analysis of the technology can be evaluated in terms of the following indices:

i. Net Present Value (NPV): The present worth of the project
ii. Benefit Cost Ratio (BCR): The benefits from the project which are in proportion with the costs involved
iii. Pay Back Period (PBP): The years it will take to get the investment back from the project i.e is the year in which the net present value of all costs equals with the net present value of all benefits. It could also be defined as the minimum period over which the investment for the project is recovered

iv. Internal Rate of Return (IRR): The real return of the project or the maximum rate of interest at which capital can be arranged for the project

The Net Present Value (NPV) is given by the following:

$$NPV = B_A\left[\frac{(1+I)^n-1}{I(1+I)^n}\right]-\left[C_I\left\{1+m\left(\frac{(1+I)^n-1}{I(1+I)^n}\right)\right\}\right] \quad 48$$

The economic viability is established when the NPV is greater than 0

The Benefit Cost Ratio (BCR) is given by the following:

$$BCR = \frac{B_A}{C_l}\left[\frac{\dfrac{(1+I)^n-1}{I(1+I)^n}}{1+m\left(\dfrac{(1+I)^n-1}{I(1+I)^n}\right)}\right] \quad 49$$

The project is acceptable if BCR is greater than 1.

The Pay Back Period of the project is given by

$$n = -\frac{In\left(1-\dfrac{IC_l}{B_A-mC_l}\right)}{In(1+I)} \quad 50$$

The Internal Rate of Return (IRR) is determined from the following model using Numerical methods such as Newton-Raphson:

$$B_A\left[\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right]=\left[C_I\left\{1+m\left(\frac{(1+IRR)^n-1}{IRR(1+IRR)^n}\right)\right\}\right] \quad 51$$

The cost of kWh of biomass gasification electricity generated is given by

$$C = \frac{C_l}{Nn}\left[\left(\frac{1}{P_RC_F}\right)\left\{1+m\left(\frac{(1+I)^n-1}{I(1+I)^n}\right)\right\}\right] \quad 52$$

Annual energy production (E) is given by

$$E = NP_R C_F \tag{53}$$

Annual revenue (AR) from the sale of electricity is given by

$$AR = \frac{C_I}{n}\left[\left\{1 + m\left(\frac{(1+I)^n - 1}{I(1+I)^n}\right)\right\}\right] \tag{54}$$

Where

AR is the Annual revenue, B_A Benefit delivered annually, BCR Benefit Cost Ratio, C Cost of kWh of biomass gasification electricity generated, C_F Site capacity factor, C_I Capital Investment of the Project, E Annual Electricity Production from the plant, I Real rate of return, IRR Internal Rate of Return, N Annual hour of the plant, n Life in Years of Plant NPV Net Present Value, PBP Pay Back Period of Investment, P_R Plant installed capacity

7.0 Result and Discussion

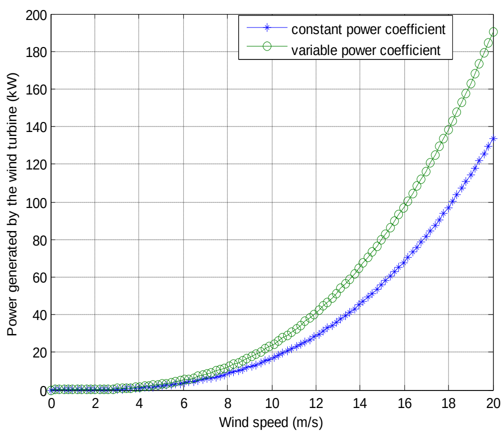

Fig.5 Effects of wind speed on power the generation by the wind turbine.

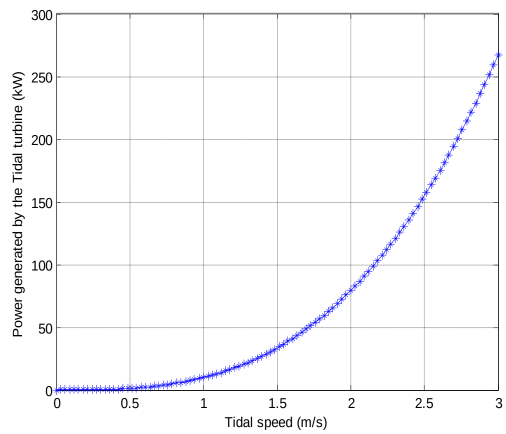

Fig.6 Effects of tidal speed on power the generation by the tidal turbine

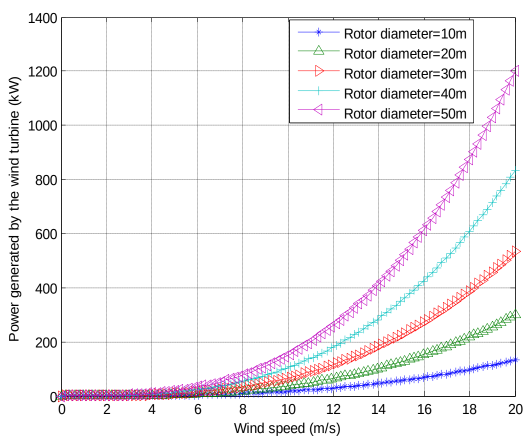

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Fig.7 Effects of rotor diameter on power the generation by the wind turbine of constant C_p

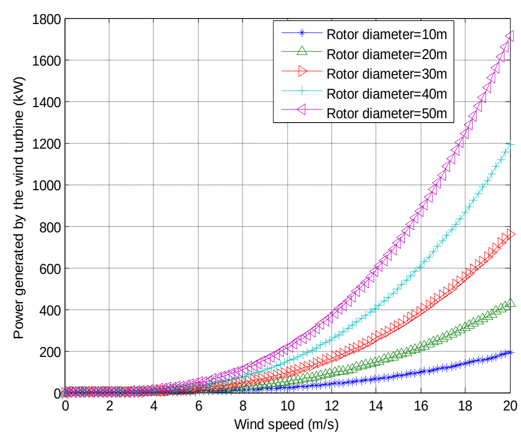

Fig.8 Effects of rotor diameter on power the generation by the wind turbine of variable C_p.

Fig. 5 and 6 depict that the power generated by the wind turbine and the tidal turbine increases with wind and tidal speed respectively. Fig. 7 and 8 show the effects of rotor diameter on the power generated by the wind turbine. From the figures, the power generated by the wind turbine increases with increase in rotor diameter. This is because, as the rotor diameter increases, the swept area of the turbine increases and more power are extracted by the rotor from the wind. Also from the model, it is shown that the power absorption and operating condition of a turbine are determined by the effective area of the rotor blades, wind speed and wind flow condition at the rotor. The output power of the turbine can be varied by the effective area and by changing the flow condition of the rotor system, which forms the basis of control of wind energy conversion system. Tip speed Ratio (TSR) is related to the wind turbine operating point for extracting power. The maximum rotor efficiency C_P is achieved at a particular TSR, which is speed to the aerodynamics design of a given turbine. The rotor must turn at high – speed at high – wind and at low – speed at low – wind, to keep TSR constant at the optimum level at all times. The larger the TSR, the faster is the rotation of the wind turbine rotor at a given wind speed. High (rotational) speed turbines are preferred for efficient electricity generation. From the tip speed ratio equation, for a particular value of speed v, turbine with large blade radius R results in low rotational speed, and vice versa. For operation over wide range of wind speeds, wind turbines with high tip speed ratios are preferred.

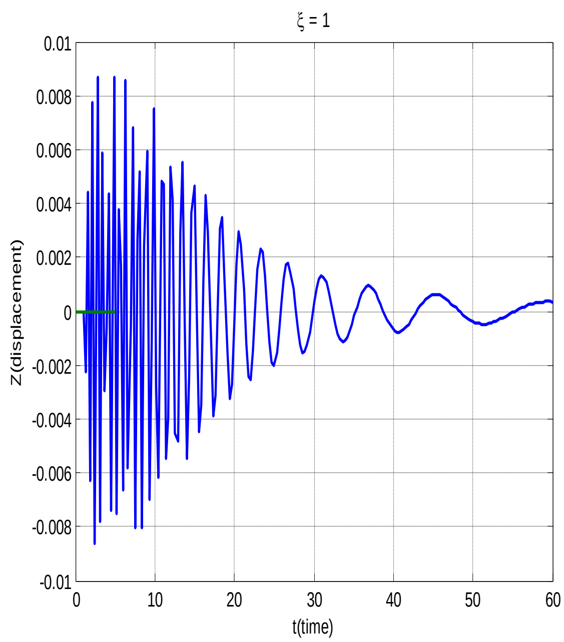

Fig.9a

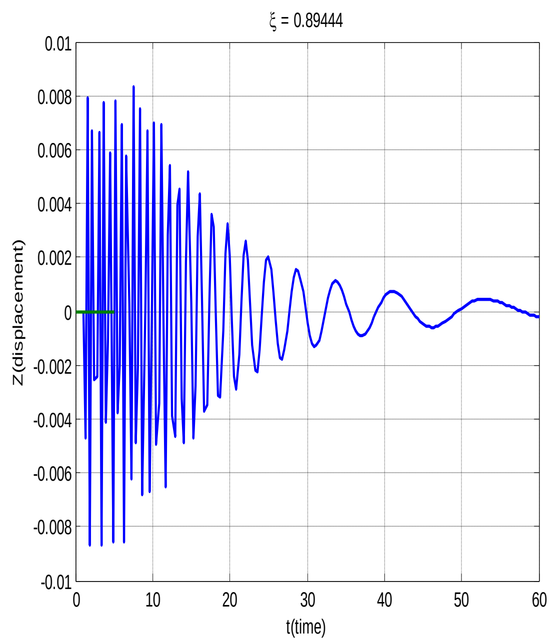

Fig.9b

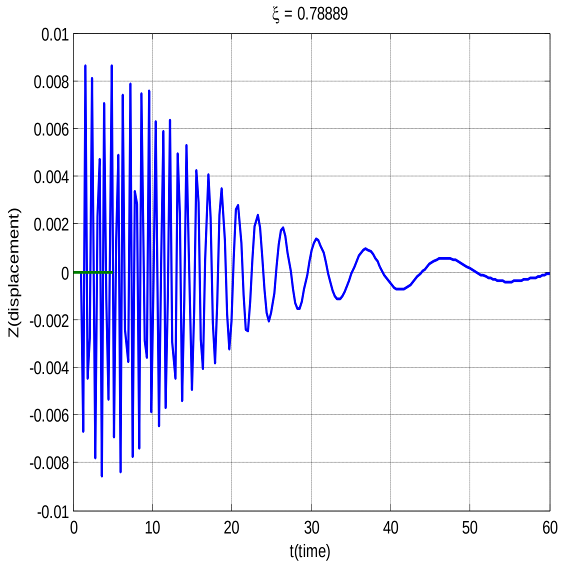

Fig.9c

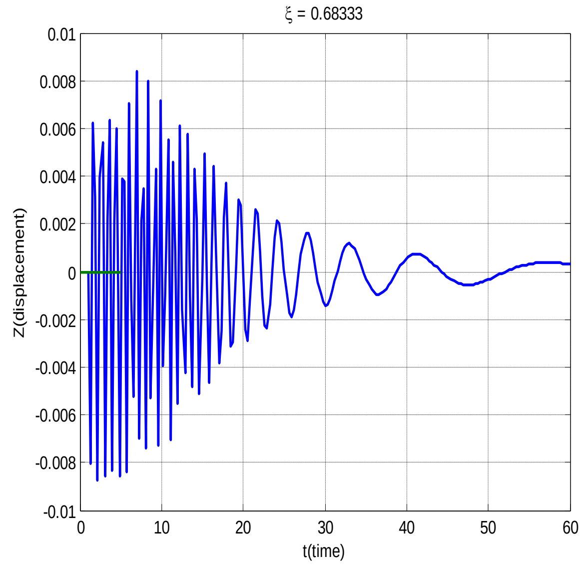

Fig.9d

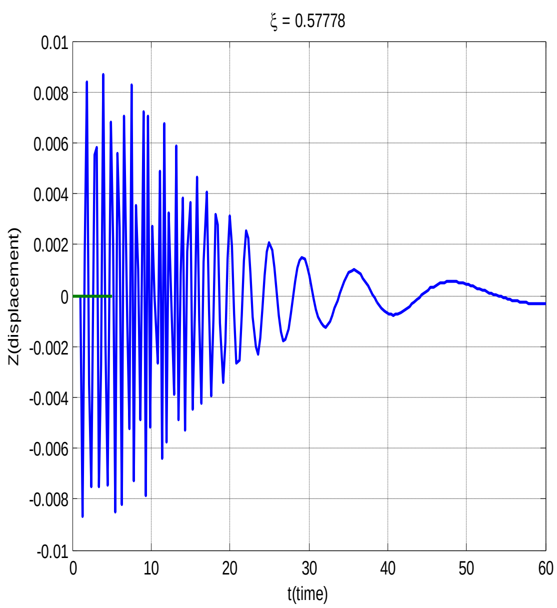

Fig.9e

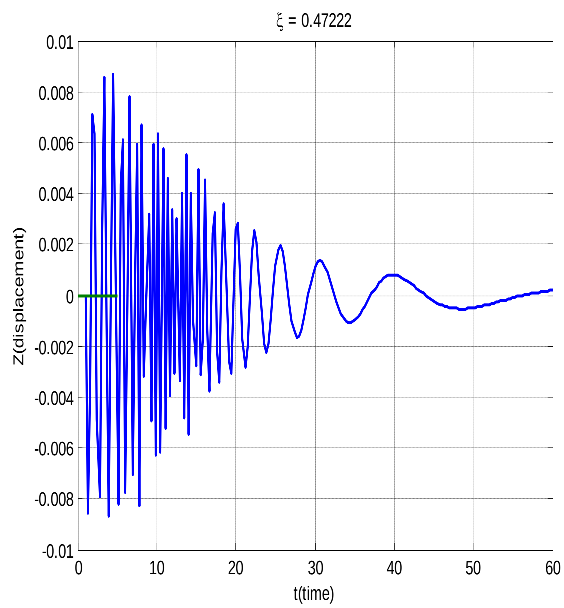

Fig.9f

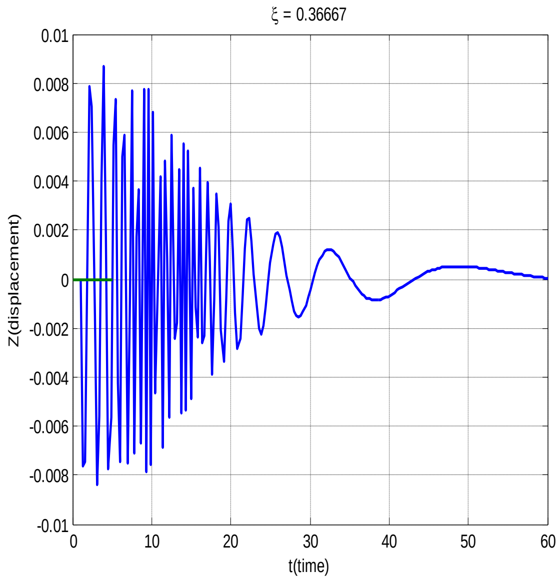

Fig.9g

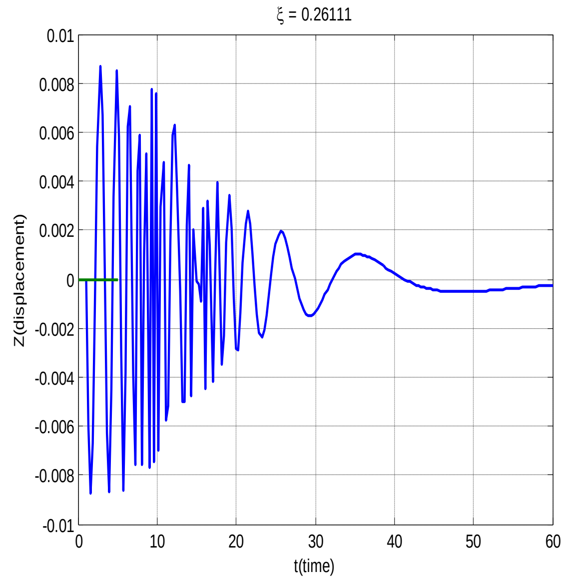

Fig.9h

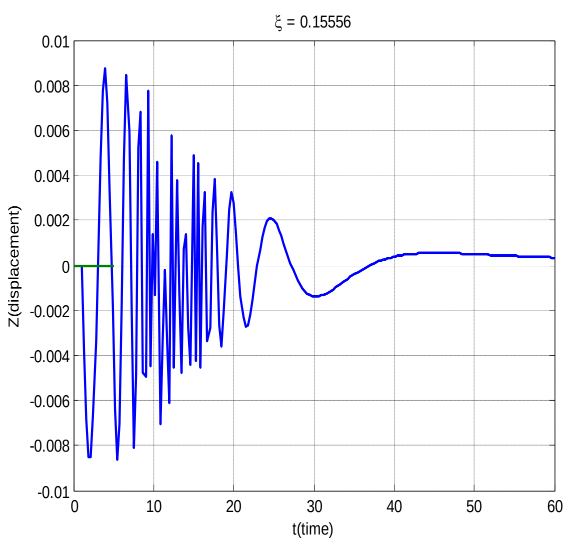

Fig.9i

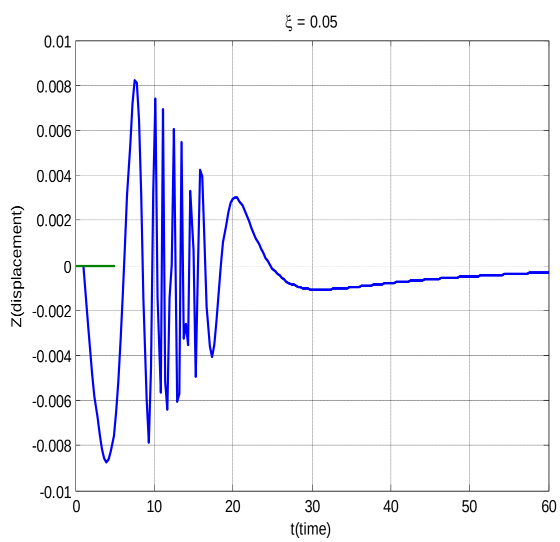

Fig.9j

Fig.9a-9j Effects of damping ratio on the vibration of structure for different damping ratio.

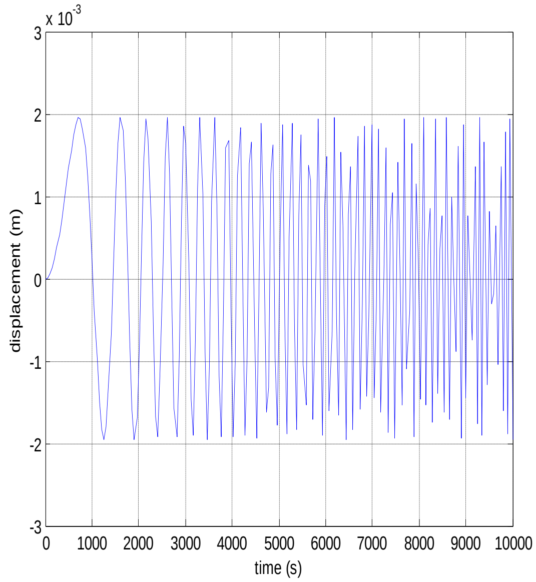

Fig.10a

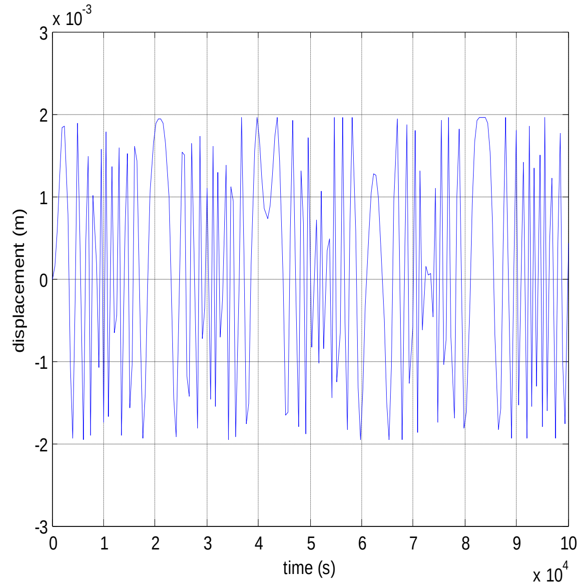

Fig.10b

Fig.10a-10b Effects of damping ratio on the vibration of structure.

Fig.9a-9j show the effects of damping ratio on the vibration of structure while Fig.10a-10b depict the effects of damping ratio on the vibration of structure.

8.0 Conclusion

In this work, the analysis of dynamic behaviour and power generation of a wind - tidal hybrid system were investigated. The power generated by 10m diameter rotor was used to investigate the potential power generated wind and tidal turbines. The effects of aerodynamics and hydrodynamics forces on the structure were investigated through the analysis of dynamic behaviour of the system under different loads and at various sites in the marine environment. The stability and the optimum turbine design were found to depend on the wind and tidal speed distribution of the specific site in the environment. It could be established from the work that the wind and tides provide vast sources of potential energy resources, and as renewable energy technologies develop, investment in wind and tidal energy is likely to grow. These sources have the potential to help alleviate the global climate change threat, but the ocean environment should be protected while these technologies are developed. Renewable energy sources from the wind and ocean may be exploited without harming the marine environment if projects are sited and scaled appropriately and environmental guidelines are followed. The utilization of these energy sources will abate over-dependent on fossil fuel as sources of power generation in Nigeria as it will meet the energy needs of coastal dwellers especially of those in remote areas.

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APPENDIX

1. Design for a 10m Diameter Wind Turbine

Power in the area swept by the wind turbine rotor:

$P = 0.5 \times \rho \times A \times V^3$

where:

P = power in watts (746 watts = 1 hp) (1,000 watts = 1 kilowatt)

ρ = air density (about 1.225 kg/m^3 at sea level, less higher up)

A = rotor swept area, exposed to the wind (m^2)

V = wind speed in meters/sec (20 mph = 9 m/s) (mph/2.24 = m/s)

This yields the power in a free flowing stream of wind. Of course, it is impossible to extract all the power from the wind because some flow must be maintained through the rotor (otherwise a brick wall would be a 100% efficient wind power extractor). On including some additional terms to get a practical equation for a wind turbine.

Wind Turbine Power:

$P = 0.5 \times \rho \times A \times Cp \times V^3 \times Ng \times Nb$

where:

Ng = generator efficiency (50% for car alternator, 80% or possibly more for a permanent magnet generator or grid-connected induction generator)

Nb = gearbox/bearings efficiency (depends, could be as high as 95% if good)

$P = 0.5 \times 1 \times 78.55 \times 0.35 \times 14^3 \times 0.8\times 0.90 = 21.7444KW$

2. Design for two 10m Diameter Tidal Turbines

Tidal Turbine Power:

$P = 0.5 \times 1000 \times 78.55 \times 0.35 \times 2^3 \times 0.8 \times 0.90 = 79.178KW$

From the Fig. 2, two tidal turbines are to be used in the system. The total power to be generated by the two turbines is 2×79.178 = 158.356KW

Total power generated by the system = 158.356 + 21.744 = 180.1kW