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Analysis of the mechanical system transforming convertible kinetic energy into electrical energy in the Inga 2 hydroelectric power plant

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Abstract

In this article, we present the study of a mechanical system that can transform the kinetic energy of the river at the surface of the dam into mechanical rotational energy, which can be transformed into electrical energy. The mathematical model is based on the principle of conservation of energy. The power taken from the waves must be at least equal to the power needed to operate the turbine. Interdependence laws between the characteristic quantities of the turbine are obtained, which allows to better exploit the results of this work.

Keywords: Mechanical system; Kinetic energy; Electrical energy; Hydroelectric plant; INGA2

1. Introduction

Energy is a vital need that is solicited in all aspects of our daily activities, particularly in industry, the domestic sector, commerce, transportation, etc. Access to energy in its various forms is a means to social, political and economic development. For most developing countries, gross national production is directly correlated with the amount of energy consumed [1-3]. Hydroelectric energy is generated by converting the potential, kinetic and pressure energy contained in the various water flows into electrical energy. Reservoirs offer a major advantage since they allow the storage of very large quantities of potential energy that will eventually be converted into electrical energy. The production of a hydroelectric power plant depends on two variables: the head and the turbined flow. The head is equal to the difference in altitude between the upstream and downstream levels of the plant. The turbined flow is the flow that will be distributed among the available turbines.

The hydroelectric power plant management problem is an optimization problem that consists in determining a management rule, ideally of the feedback type, to manage the water stored in the reservoirs that supply the power plants [4-5]. This problem is generally stochastic since the water inflow to the reservoirs is not known in advance. This problem is non-linear and non-separable since the electrical production generated by a power plant is the product of two functions whose variables are dependent on each other: the turbine flow and the head [5-11].

In the search for solutions to current energy problems, the contribution of our work is to propose a mechanism transforming the energy of waves that propagate periodically on the surface of the sea near the coast to transform it into mechanical energy and then into electrical energy through an alternator.

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The mechanical energy of the waves is captured by a flat rectangular plate. This plate plays the same role of engine as the piston for a crank-crank mechanism which transforms the oscillating rectilinear translation movement of the plate into a rotation movement of the crank. The angular velocity of this rotational movement is multiplied by a suitable system to reach the operating speed of the alternator.

2. Theoretical study

The construction of a series of large dams Colonel Vandeuren recommended at the same time the equipment of waterfalls. The dams of Inga I and Inga II were built.

Inga 2: 1424MW, commissioned in 1982

Figure 1 Inga 2 power plant

2.1. Installation description

A rectangular flat plate is fixed perpendicularly to the front of the assembly to be pushed by the wave (figure 2). The conduits of the pipes fixed on the protection wall are used to force the plate to be animated by the oscillating rectilinear translation movement.

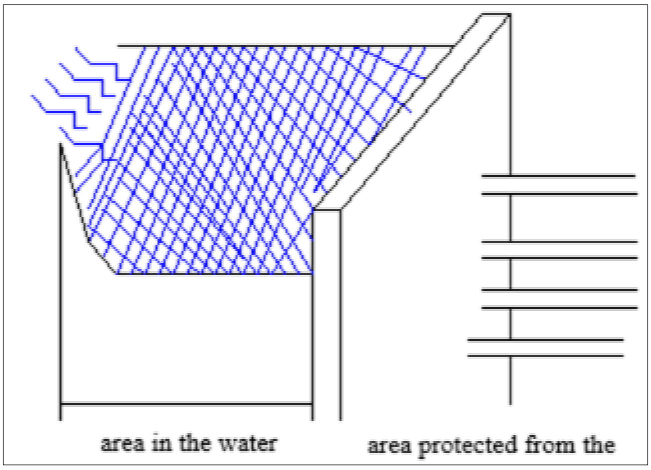


Figure 2 Schematic of the installation

Indeed, when the wave front hits the wall, the plate must be pushed back by the water discharging some of its energy to return to its initial position. The oscillating motion is transmitted to the turbine mechanism which in turn turns the alternator. The rotation axis of the alternator is connected to that of the turbine mechanism by a speed control system to reach the operating speed of the alternator.

2.2. System modeling

The mathematical model that represents the open system formed by the wave and the mechanical system is obtained by equating the power that can be captured from the wave to the mechanical power needed to set the turbine in motion and turn the alternator. This mathematical model relates the characteristic magnitude of the load which is the alternator to the dimensions of the plate. The expression of the power recoverable from the wave pushing the plate is defined by :

$$p_1 = \frac{1}{2} C_P p_e S\, V_1^3 \dots\dots (1)$$

The area of the plate of width a and length b considered as explanatory variable is equal to :

$$S = \text{ab}\ (2)$$

The moment of inertia of the crank with respect to its axis of rotation is :

$$J_M = \frac{1}{3}\, P_M S_M l_1^3 \ \dots\dots\dots (3)$$

The mechanism is animated by both translation and rotation. Its kinetic energy is defined by :

$$E_{CB} = \frac{1}{2}(J_B + \text{M}_B l_2^2)\omega_2^2 \ \dots\dots (4)$$

The moment of inertia is both translation and rotation of the turbine is maximum when the two parts are perpendicular (Figure 2), is equal to :

$$J_B = p_M s_M l_2 \left(\frac{1}{3} l_2^2 + l_1^2\right) \dots\dots\dots\dots (5)$$

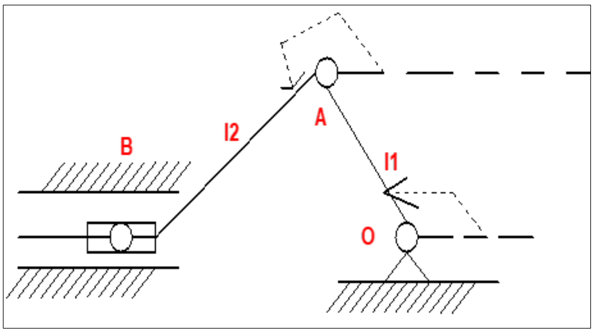


Figure 3 Diagram of the turbine mechanism

The mechanisms animated by translational movement are fork-shaped, of total length

$$L = (9l_1 + \tfrac{b}{2}).$$

Their total mass M is defined by:

$$\text{M} = p_p\,.\text{abe} + p_T s_T \left(9l_1 + \frac{b}{2}\right) (6)$$

The total kinetic energy of the moving part of the system is defined by:

$$E_C = \frac{1}{2}\left((\text{M} + \text{M}_B)l_1^2 + v_2^2 + J_M\omega_1^2 + J_B\omega_2^2 + J_{AL}\omega_{AL}^2\right) \dots\dots\dots (7)$$

The angular velocity ω_2 of the connecting rod is defined by:

$$\omega_2 = -\omega_1 \frac{I_1.\text{COS}\,\varphi_1}{I_{2.\cos\varphi_2}} \dots\dots (8)$$

The maximum speed of the assembly in translational motion is expressed by:

$$V_2 = \|\bar{\nabla}\,(B)\| = \left| -\omega_1 l_1 sin\varphi_1 (1 + \frac{l_1 \cos\varphi_1}{\sqrt{l_2^2 - l_2^2\, sin^2\varphi_1}}) \right| \ldots\ldots\ldots.(9)$$

The maximum value of ω_2 cannot exceed ω_1 but tends towards this value, that of V_2 and $\omega_1 I_1$1being given that $l_2 \gg l_1$.

Thus, during the driving phase of the system, which lasts half a period, the maximum power required to set in motion the entire moving part of the system is defined by:

$$E_C = \left((\mathrm{M} + M_B)l_1^2 + J_M + J_B + J_{AL}.K^2\right)\omega_1^2.\frac{1}{T_C}\ldots.(10)$$

When the wave front touches the plate, its speed decreases because of this obstacle. According to the theory of Betz, the velocity of the fluid at the plate, thus also the velocity of the plate, for which the power recoverable from the fluid is maximum is defined by :

$$V_2 = \frac{2}{3}V_1 \ldots\ldots\ldots..(11)$$

As a result of all these conditions, the theoretical angular velocity of the crank is :

$$\omega_{lh} = \frac{2}{3}\frac{V_1}{l_1}\ldots\ldots\ldots(12)$$

But in practice, taking into account various resistances and energy dissipation, this angular velocity is lower than this theoretical value is equal :

$$\omega_1 = \eta\frac{2}{3}\frac{V_1}{l_1}\ldots\ldots\ldots\ldots..(13)$$

The potential energy of gravity of the system varies on the side of the turbine mechanism; the axis of rotation of the crank being horizontal, this variation is :

$$\Delta E_P = P_M S_M(l_1 + l_2)g l_1 \ldots.(14)$$

The elastic potential energy of the two springs also varies each time they extend or compress; its maximum value is defined by :

$$\Delta E_{PE} = Cd^2 \ldots.(15)$$

Taking into account the energy dissipation in the different liaisons, the necessary condition that the system works is therefore expressed by the following relation:

$$\frac{1}{2}C_p p_e abV_1^3 - \mu\left(\left(p_e.abe + p_T s_T\left(9l_1 + \frac{b}{2}\right)\right)l_1^2 + J_M + J_B + J_{AL}.k^2\right).\left(\eta\frac{2V_1}{3l_1}\right)^3\frac{1}{2\pi} - \mu\left(p_M s_M(l_1 + l_2)g l_1 + Cd^2\right)\eta\frac{2V_1}{3\pi l_1} = 0 \ldots\ldots\ (16)$$

In this equation (16), the long b of the moving water layer remains approximately constant.
The mathematical model of the installation is represented by the system of three equations (17):

$$\begin{cases} \frac{1}{2} C_P\, p_e abV_1^3 - \mu\left(\left(p_p.abe + p_T s_T\left(9l_1 + \frac{b}{2}\right)\right) l_1^2 + J_M + J_B + J_{AL}.k^2\right) \\ x(\eta\frac{2V_1}{3l_1})^3\, \frac{1}{2\pi} - \mu\left(p_M s_M(l_1 + l_2)gl_1 + Cd^2\right)\eta\frac{2V_1}{3\pi l_1} = 0\ (i) \\ \omega_{1=\frac{2\eta}{3l_1}V_1}\ (ii) \\ P_v = \frac{\mu}{2\pi}(\left(p_p.ade + p_T s_T\left(9l_1 + \frac{b}{2}\right)\right) l_1^2 + J_M + J_B)(\eta\frac{2V_1}{3l_1})^3 \\ +\mu\left(p_M s_M(p_1 + l_2)gl_1 + Cd^2\right)\eta\frac{2V_1}{3\pi l_1}\ (iii) \end{cases} \quad \ldots\ldots (17)$$

3. Results and discussion

3.1. Result of the angular velocity of the system

Solving the equations of system (17) allows us to obtain the results presented in the simulations. The root of equation (i) of (17) gives the linear dependence of the angular velocity of the crank rotation on the displacement velocity V_1 of the wave. Equation (iii) of (17) determines the power that the turbine can develop at no load, i.e., when the generator is disconnected from the turbine.

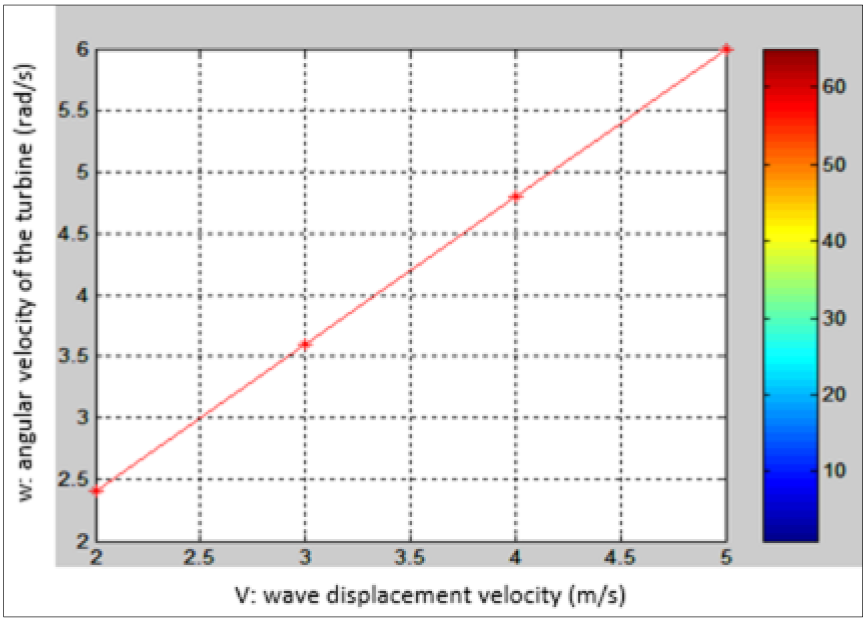


Figure 4 Angular speed of the turbine according to the speed of development of the wave

For a wave displacement speed of the order of 2m/s, the surface layer of moving water is of the order of 0.5m, a value we will maintain for all other wave speeds (Figure 4).

3.2. Result at the speed of movement

The power $\boldsymbol{P_V}$ developed by the turbine when it is running at no load (when the alternator is disconnected) according to the speed of the wave. The length b of the recuperator plate and the angular velocity ω_1 of the crank according to the speed V_1 of the wave and the moment of inertia J_{AL} of the alternator.

On figures (5) and (6), we have represented the length of the wave mechanism V_1 (figure 5) and the mechanical power provided by the system as a function of the moment of inertia. We found that the mechanical power increases when the moment of inertia increases and its maximum value is around 5500.

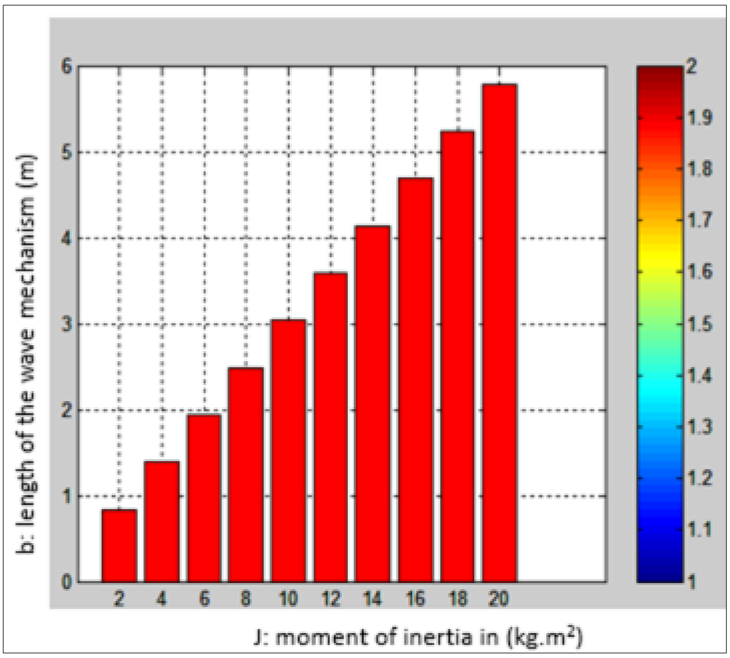


Figure 5 Resulting moment of inertia as a function of the length of the wave mechanism V1

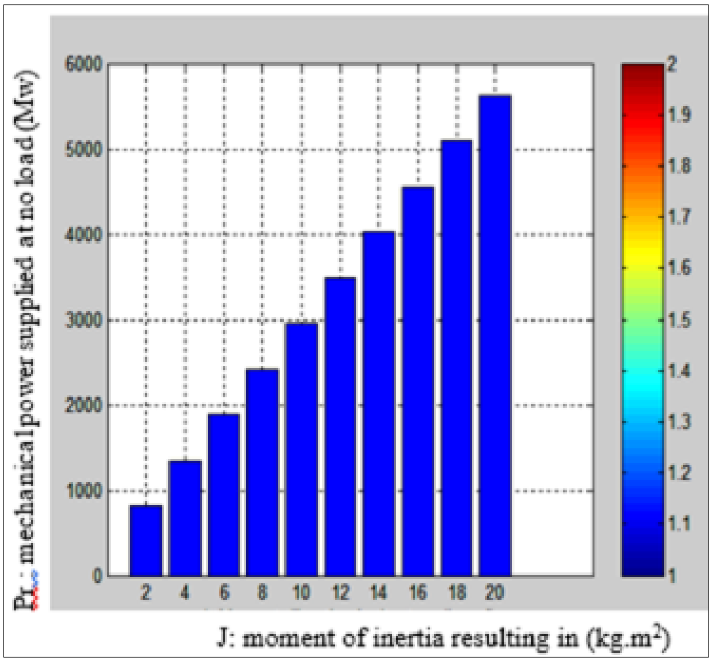


Figure 6 Resulting moment of inertia as a function of the mechanical power supplied by the wave system V_1. (2 m/s)

We have represented on figures (7) and (8) the length of the wave mechanism and the mechanical power supplied at no load by the system as a function of the resultant moment of inertia of the alternator. We note that the length of the wave mechanism is almost found.

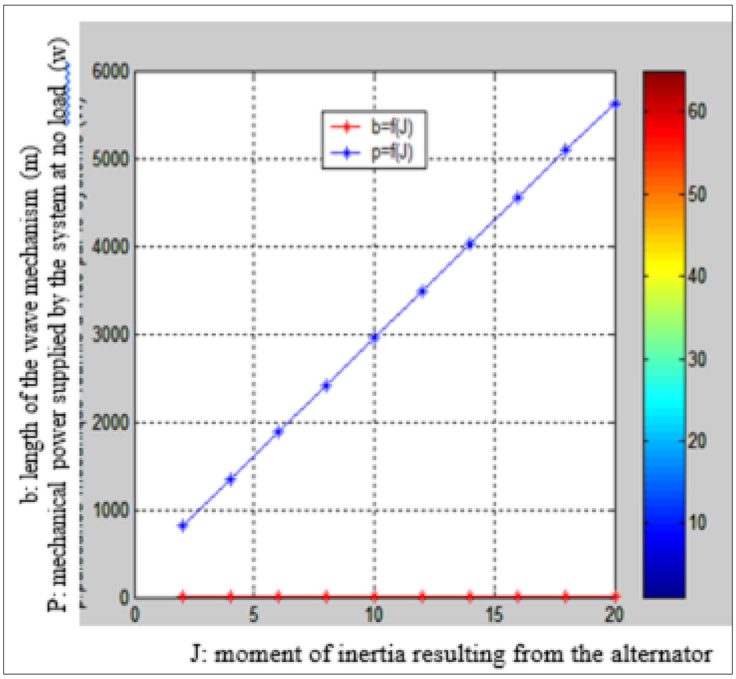


Figure 7 Angular speed of the turbine according to the speed of development of the wave V1. (2 m/s)

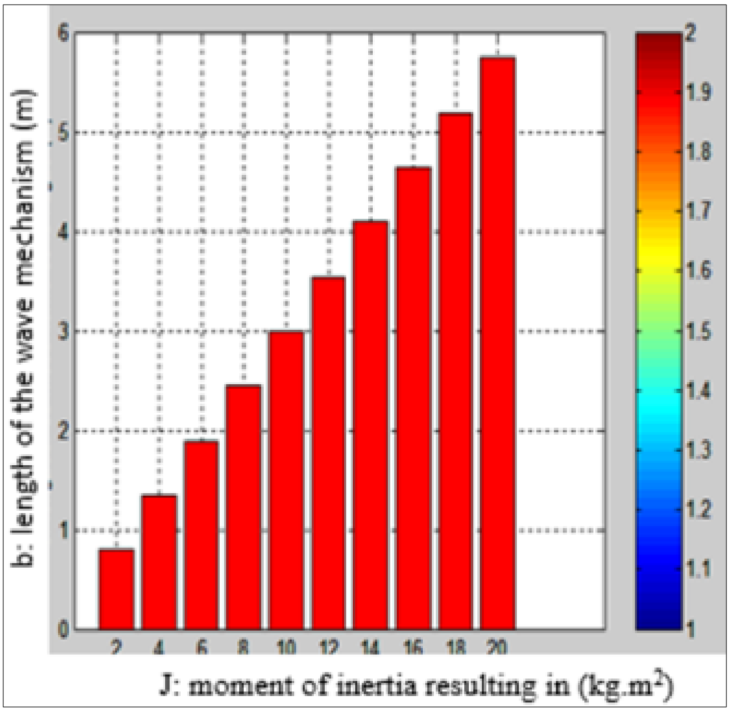


Figure 8 Resulting moment of inertia as a function of the length of the wave mechanism V2. (3 m/s)

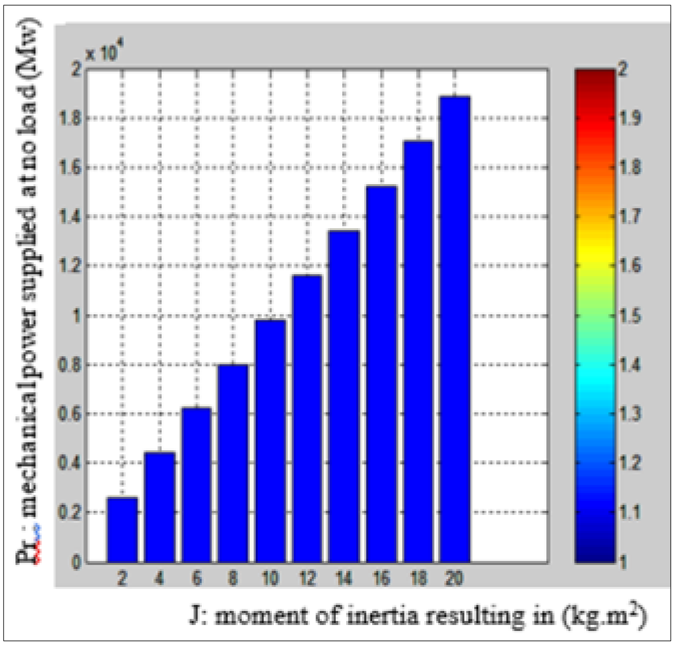
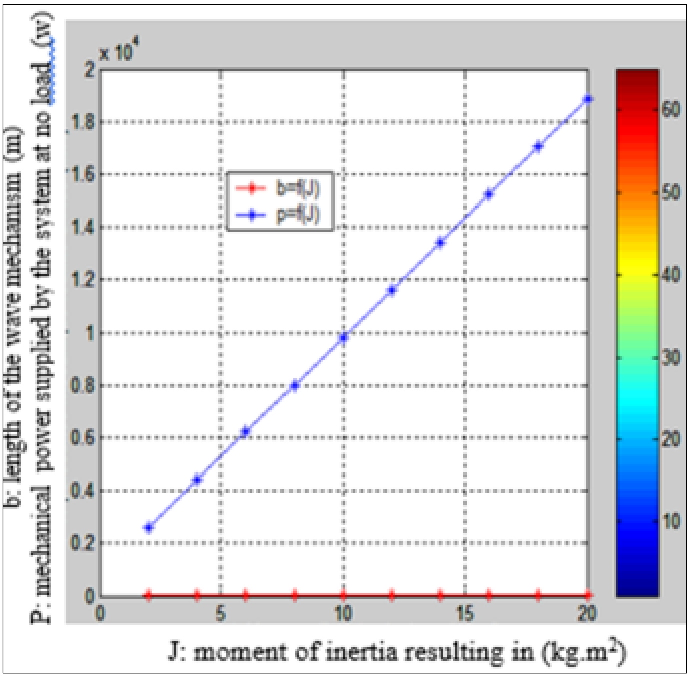


Figure 9 Resulting moment of inertia as a function of the mechanical power supplied by the wave system V2



. Figure 10 Angular velocity of the turbine according to the wave development velocity V2 (3 m/s)

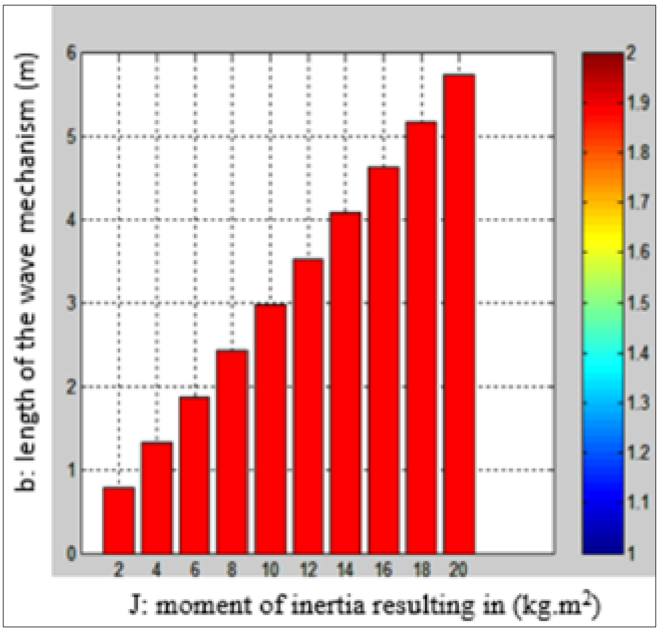


Figure 11 Resulting moment of inertia as a function of the length of the wave mechanism V3

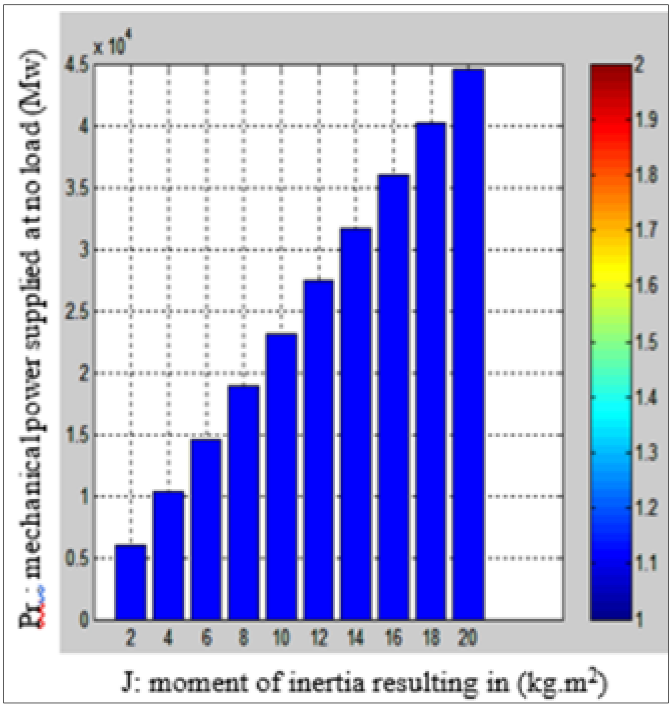


Figure 12 Resulting moment of inertia as a function of the mechanical power supplied at no load by the wave system V3. (4m/s)

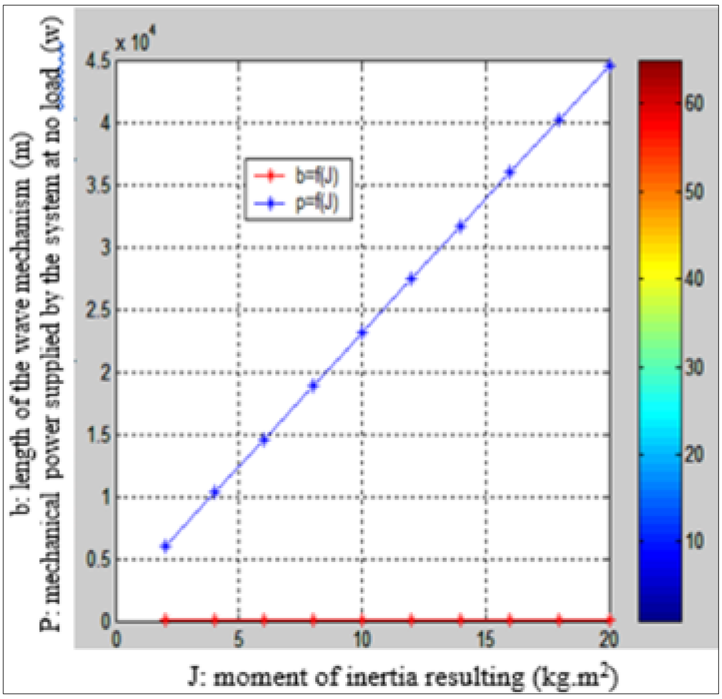


Figure 13 Angular velocity of the turbine according to the wave development speed V3 (4m/s)

We have represented on figures (14) and (15) the length of the wave mechanism and the mechanical power supplied at no load by the system as a function of the moment of inertia resulting from the alternator. We note that the mechanical power supplied at no load increases when the moment of inertia increases (figure 16).

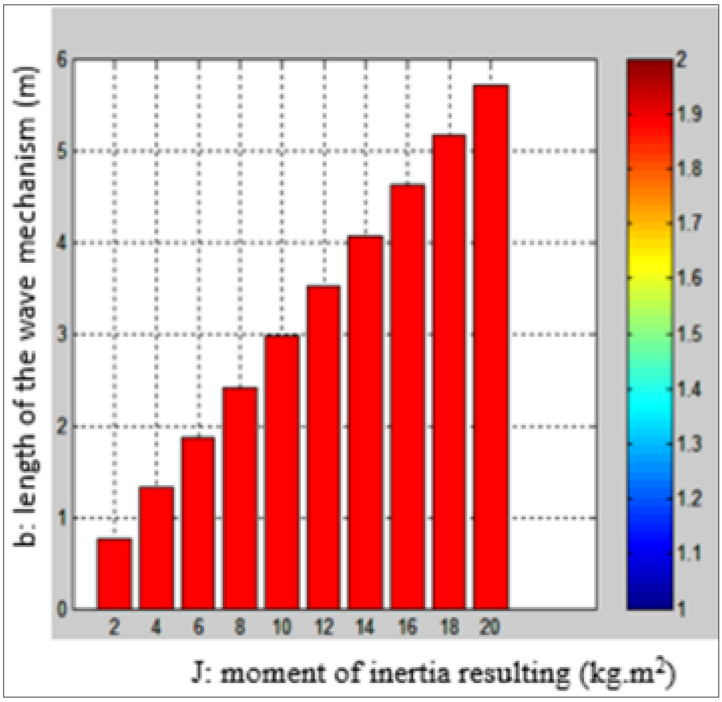


Figure 14 Resulting moment of inertia as a function of the length of the wave mechanism V4 (V=5 m/s)

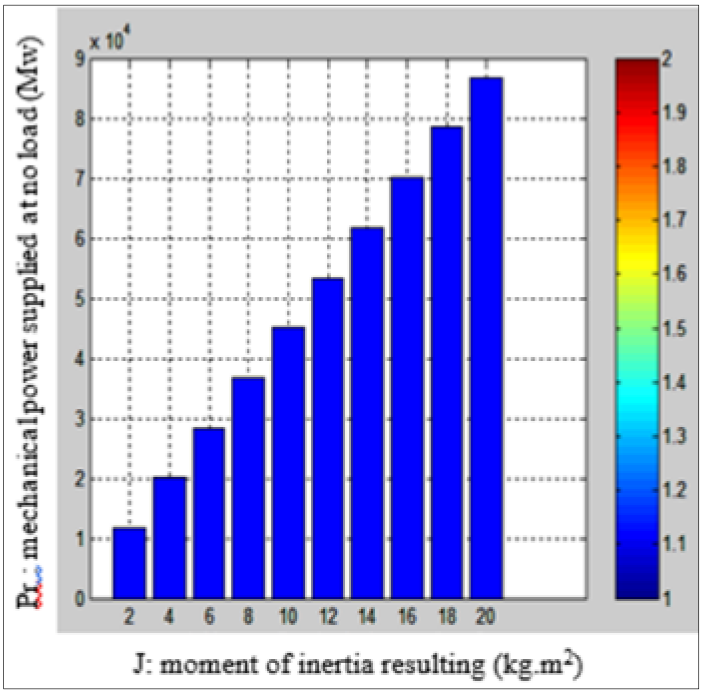


Figure 15 Resulting moment of inertia as a function of the mechanical power supplied at no load by the wave system V4

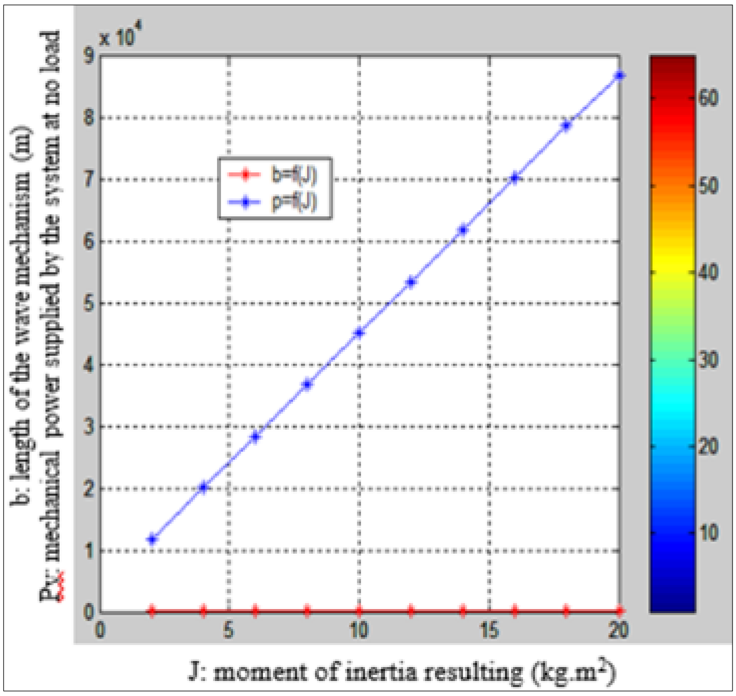


Figure 16 Angular speed of the turbine according to the speed of development of the wave V3

3.3. Linear model of the mechanical system

3.3.1. Velocity model

The dependencies obtained are linear which are very close to each other.

$$\begin{cases} V_1 = 2m.s^{-2}: b = 0{,}2748.J_{AL} + 0{,}2883; \\ V_1 = 3m.s^{-1}: b = 0{,}2748.J_{AL} + 0{,}2415; \\ V_1 = 4m.s^{-1}: b = 0{,}2748.J_{AL} + 0{,}2251; \\ V_1 = 5m.s^{-1}: b = 0{,}2748.J_{AL} + 0{,}2175. \end{cases} \quad \dots\dots\dots\dots\dots..(18)$$

For $2m.s^{-1} \leq V_1 \leq 5m.s^{-1}$ and $2kg.m^2 \leq J_{AL} \leq 20kg.m^2$, a mathematical adjustment gives us the following global variable expression J_{AL} et V_1:

$$b = 0{,}2748.J_{AL} + (-0{,}0036.V_1^3 + 0{,}0476.V_1^2 - 0{,}2164.V_1 + 0{,}5595) \dots\dots \ (19)$$

The variation of the length b of the receiving plate as a function of the moment of inertia of the alternator.

3.3.2. Power model

Variation of the power developed by the turbine in no-load as a function of the length of the plate. For each speed V_1 the following laws are obtained:

$$\begin{cases} V_{11} = 2m.s^{-1}: P_V = 972{,}32.b + 0{,}01; \\ V_{12} = 3ms^{-1}: P_V = 3281{,}6.b - 0{,}0; \\ V_{13} = 4ms^{-1}: P_V = 7778{,}7.b - 0{,}6; \\ V_{14} = 5m.s^{-1} P_V = 15193.b - 1{,}0. \end{cases} \quad \dots\dots\dots (20)$$

For $2m.s^{-1} \leq V_1 \leq 5m.s^{-1}$, a more global adjustment gives us the following expression:

$$P_V = (1276{,}3.V_1^2 - 4217{,}9.V_1 + 4339{,}5).b + (0{,}1.V_1^2 - 1{,}3.V_1 + 3{,}0) \ (21)$$

The dependences of the power developed P_V by the turbine, when it is not connected to the alternator, with the length b of the receiving plate whose value varied from **0.8m to 5.8m,** are also linear relations. However, the global law of this dependence expresses that the linearity parameters of this dependence are polynomials of the 2nd degree of the speed V_1 of displacement of the wave.

4. Conclusion

The numerical results obtained, allow us to assert the alternator J_{AL}, whose value varies around 2 kg.m2, are linear relations. However, the general law of this dependence contains a term of the third degree of the speed V1 of displacement of the wave. The dependence of the no-load power developed by the turbine on the length of the receiver plate is linear; the greater the speed of displacement of the wave, the greater the slope of the line. The graphs show that the dependencies obtained are linear; the curves representing the numerical values and the fitting laws are superimposed. The angular velocity of the crank rotation is proportional to the wave displacement speed: $\omega_1 = 1{,}2.V_1$ The length of the plate grows linearly with increasing moment of inertia of the alternator; but it decreases with increasing wave displacement speed. The simple laws obtained in this work are convenient for practical purposes for the applications of this work. The turbine designer who wants to exploit the kinetic energy of the waves can use the proposed model to obtain is necessary to better exploit the renewable energy sources existing in the seaside and reduce the use of fossil fuels.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest.

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