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ENERGY HARVESTING FROM SLOW ROTATIONAL MOTION

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Abstract. An electromechanical rotating energy harvester design is presented. The Energy Harvester is devoted to extract energy from a rotating flange in an agricultural machinery designed for ploughing and laying seeds. The harvested energy is used to supply a motion sensor that sends wireless signals to a console controlling the process. The device is structured as an axial electromechanical generator with excitation provided by permanent magnets. As no contact with stationary parts is allowed, an inertial reference is provided by a pendulum. Integrated design of electromechanical generator and pendulum is performed and results in terms of maximum harvested power are provided.

1 INTRODUCTION

Energy Harvesting (EH) is a technique to extract power dispersed in the environment providing power to detached and secluded apparels, like sensors, whose electrical supply would not be possible by regular wirings. This issue is becoming more and more important by the widespread use of sensors in the *Internet Of Things* where many devices are thought to dialogue with others to form a network both for sensing and for control purposes [1], [2]. An example of the application of this concept to the harvesting of energy from human motion is reported in [4]. The previous reference also gives a good overview of the reasons why the design of a EH has to be treated as a coupled phenomenon simulating the whole chain of power conversion from the primal one to the desired outcome, usually expressed in terms of electrical energy.

Several primal sources of energy can be found like light, electromagnetic radiation, temperature difference etc. In electromechanics harvesting the source of motion is a relative movement of some parts that can be unidirectional, as in the case of mechanical vibrations, or rotational. In the last case usually an electromagnetic structure shaped like an electrical machine can be used, as for instance in [3].

In the present work the design of a EH connected to the rotating parts of an agricultural machinery designed for ploughing and laying seeds is pursued. The application gets its rationale by the fact that ploughing disks get often stuck in obstacles and if they are blocked the whole process of ploughing and seeding can be disrupted. As a consequence there is a need to sense state of motion of these disks. As a modern machine can have tens of this disks, a central control of the process is sought by sending the state of motion of each disk to a central control unit. The EH is then devoted to the supply of a wireless transmitting device able to send a signal to the central unit.

The design of the EH has the requirement that no modifications should be made to the existing structure: the EH should be an add-on to the disk without requiring any change or machining to the existing disk. As a result the device will have to be attached on the external surface of the disk ball bearing. As the add-on must not have any other connections with the moving parts, a new standing reference has to be created in a limited space.

Another trouble in the conceptual design of this apparel is due to the relative slow motion of the ploughing disk. The electrical power requirements are set by the supply of wireless transmitter able to communicate the motion status of the wheel to a central unit located in the cockpit of the machine, this constraint will be the main target of the design.

The work performed is presented in the following structure: in first section the main geometrical and functional specifications will be presented, in second section the design of the electromechanical parts is outlined, in the third section the definition of the counterweight shape and mass is highlighted while in the last section the model of the whole structure is finally described. Eventually some conclusions on the design process are drawn.

2 TECHNICAL SPECIFICATION OF THE ENERGY HARVESTER

The EH to be designed has to be attached on the exterior part of the ball bearing of the ploughing disk, whose dimensions are reported in figure (1). The region where the EH can be located is highlighted in the same figure and regards the external part of the disk that is rotating. The radial encumbrance of the EH is limited between the internal radius $R_1 = 29.5$ mm and the external one $R_2 = 45.5$ mm, while the axial maximum dimension is of $h = 27$ mm. No connections to other parts of the structure are allowed so that the external part of the EH will be rotating solidly with the disk. The limits on the power generated by the EH are given by the designer of the `blue-tooth` transmitter that, due to the distance involved in the whole machine, is requiring an average value of 0.3 W to guarantee for the efficient communication with the central unit.

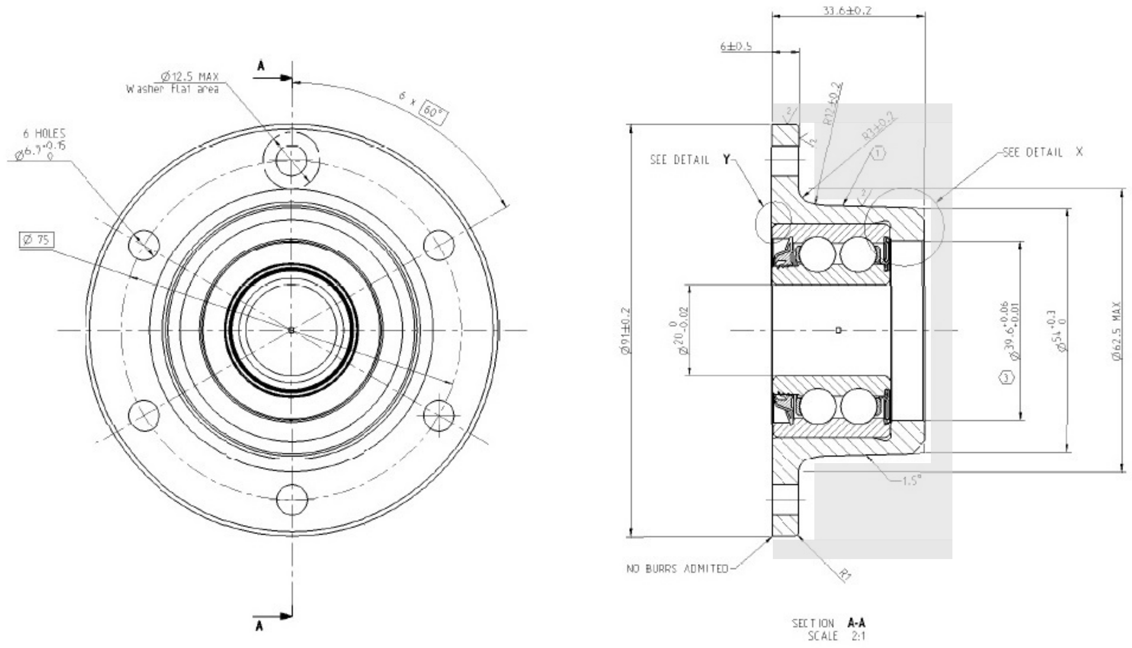

Figure 1: Dimensions of the disk ball bearing with highlighted in grey the region that can be used by the harvester.

3 DESIGN OF THE MAGNETIC STRUCTURE

Due to the limits on the geometric dimensions of the device, it is not possible to resort to a classical radial flux machine, due to the hindrance of the coil ends. The choice is then that of an axial flux machine where an array of permanent magnets faces a set of coils where electromagnetic flux is linked. The relative slow rotational speed of the ploughing disk is another challenge to the design. In fact the disk is rotating at approximately 140 rpm leading to a value of angular velocity of $\omega = 14,62$ rad/s. In order to increase the rate of change of linked flux to raise a decent value of voltage, a quite large number of magnetic pole-pairs has to the used. After a study involving permanent magnet dimensions and number of turns on the coil, the number of pole-pairs was set to $N_p = 7$ using a number of $N_{mag} = 14$ magnets with reversing polarity, as sketched in figure (2). By neglecting the presence of ferromagnetic parts in the surrounding, the value of magnetic linked flux with the coils can be performed by means of analytical formulas of permanent magnets. Magnetic vector potential is calculated and thus its circulation gives the value of the linked flux. The linked flux as calculated for the whole set of coils is reported in figure (3). The electric speed of the flux variation is obtained by:

$$\omega_{el} = \frac{N_{mag}}{2}\omega \tag{1}$$

By considering the first harmonic of the linked flux and λ_{max} its maximum value, the estimation of the value of the maximum electro-motive force obtained is obtained as:

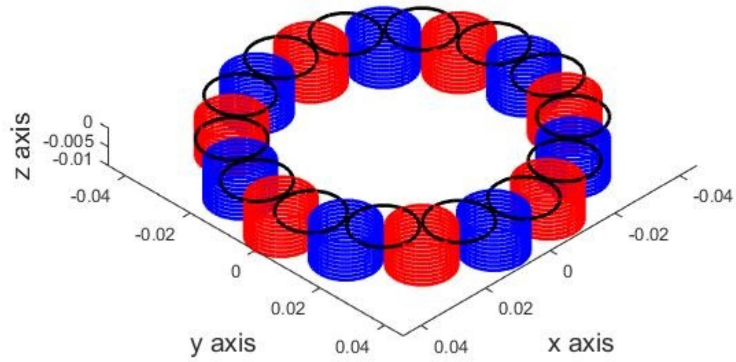

Figure 2: Schematic structure of the magnetic part of the EH: red and blue cylinders are permanent magnets with opposite polarity while circular turns are placed facing them, dimensions in m.

$$e_{max} = \frac{N_{mag}}{2}\omega_{el}N_{turn}\lambda_{max} = \frac{N_{mag}^2}{2}\omega N_{turn}\lambda_{max} \quad (2)$$

By taking into account the maximum geometric dimensions and considering a winding made of a copper wire with diameter $D_{wire} = 0.108$ mm, the number of turns is $N_{turn} = 1232$ which leads to a value of maximum voltage $e_{max} = 35.6$ V. The dimensions of the coils and the number of turns allow to compute the value of electrical resistance of the whole set of coils of $R = 535\ \Omega$ and a self inductance of $L = 0.22$ H.

The induced voltage value is then applied as an independent source to a load circuit whose resistance is equal, due to the maximum power transfer theorem in linear circuits to the one of the coil. By the analysis of the circuit so defined the average value of power transferred to the load resistance is equal to $P = 0.56$ W. This value is considered sufficiently higher than the requested one (0.3 W) so that it could accommodate also the needed power electronics for the voltage conditioning and supply of the transmitter.

4 DESIGN OF THE MECHANICAL STRUCTURE

The previously described magnetic structure can generate the desired power only in presence of a relative velocity between the magnets, fixed to the rotating disk, and the coils. As the coils cannot be linked to a static structure, a out of axis mass acting as a pendulum is connected to the coils. The effect of this mass is to contrast the torque that is created between magnets and coils and that is responsible for the electrical power generation. A sketch of the system is presented in figure (4). The dynamics of the system should ensure that the pendulum is able to counteract the electromagnetic torque exerted by the coils.

In order to optimize the encumbrance and the effect of the mass of the pendulum, it is realised by a ABS structure enclosing three masses made of lead. The geometric structure

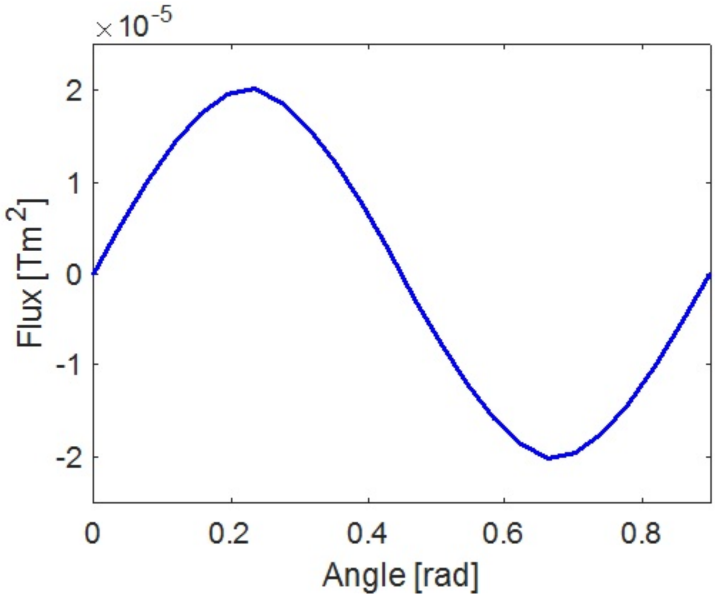

Figure 3: Linked magnetic flux with the whole set of coils.

of the system is shown in figure (5). The overall constructive vision is reported in figures (6) and (7). The geometric parameters of the three masses structures are carefully chosen in order to maximise the effect of the eccentricity, that is of the moment of inertia. Once this process is completed, a dynamic model of the system is defined by:

$$I_0\ddot{\theta} + c_m\left(\dot{\theta} - \dot{\theta}_{inp}\right) + mgl\sin(\theta) = T_{em}\left(\theta\right) \tag{3}$$

where:

- θ and $\dot{\theta}$ are respectively the angular position and the angular speed of the pendulum;
- $\dot{\theta}_{inp}$ is the rotational speed of the disk and of the magnets;
- I_0 is the momentum of inertia of the all rotating parts (coils+pendulum);
- c_m is a coefficient that takes into account mechanical friction between the parts;
- m is the pendulum mass, g the acceleration of gravity and l the distance between the mass center of gravity and the rotation axis of the system;
- T_{em} is the electromagnetic force that is dependent on the relative position and velocity between coils and magnets and on the circuit response.

$$T_{em} = \frac{P_{el}}{\omega} = \frac{e \cdot i}{\dot{\theta}} = -\frac{\frac{d\lambda(\theta(t))}{dt} \cdot i}{\frac{d\theta}{dt}} = -\frac{\frac{d\lambda}{d\theta}\frac{d\theta}{dt} \cdot i}{\frac{d\theta}{dt}} = -\frac{d\lambda}{d\theta}i \tag{4}$$

In turn the current i is obtained by the solution of the ohmic-inductive circuit.

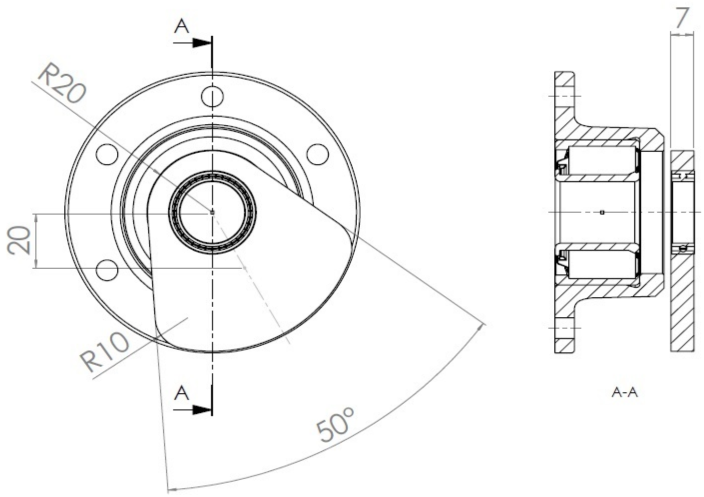

Figure 4: Out of axis mass joined with coils.

The dynamic model is implemented in a Simulink model and its output is obtained for an input velocity that starts from zero and reaches the steady state speed of 140 rpm in an interval of 5 s.

The analysis showed that the pendulum is able to keep a position that in average is different from zero, so that there is relative motion between the magnets and the coils. Nevertheless, the position of the pendulum it is not fixed but it is subject to a ripple as this is the result of the electro-motive force that is dependent on the angular position θ and on the partially reactive circuit, as it is shown in figure (8). The model gives also the results for the electric variables current voltage and instantaneous power. The values are shown in figure (9). Both voltage values due to the electromagnetic induction ($V_0 = -d\lambda/dt$) and at the load terminals (V_{in}) are shown.

5 CONCLUSIONS

The work presented regards the design of an energy harvester taking energy from the motion of a rotating disk. Both geometrical and electrical constraints make the design challenging and requires the definition of an integrated electro-mechanical model to assess the device performances.

Even if the design of the system is quite classical, the magnetic structure and the corresponding mechanical shape of the pendulum required ad-hoc procedures that has shown the feasibility of the harvester.

Prototyping would be anyhow necessary to validate the quality of the design choices made.

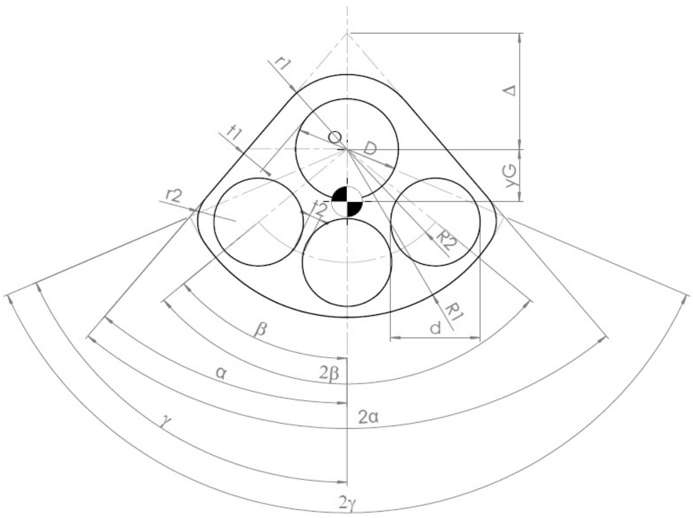

Figure 5: Realisation of the pendulum by three lead masses joined within a plastic structure.

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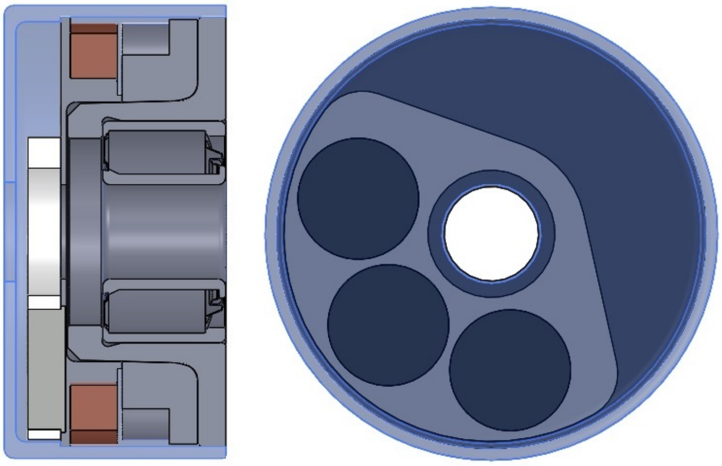

Figure 6: Rendering of the whole structure in a plain view.

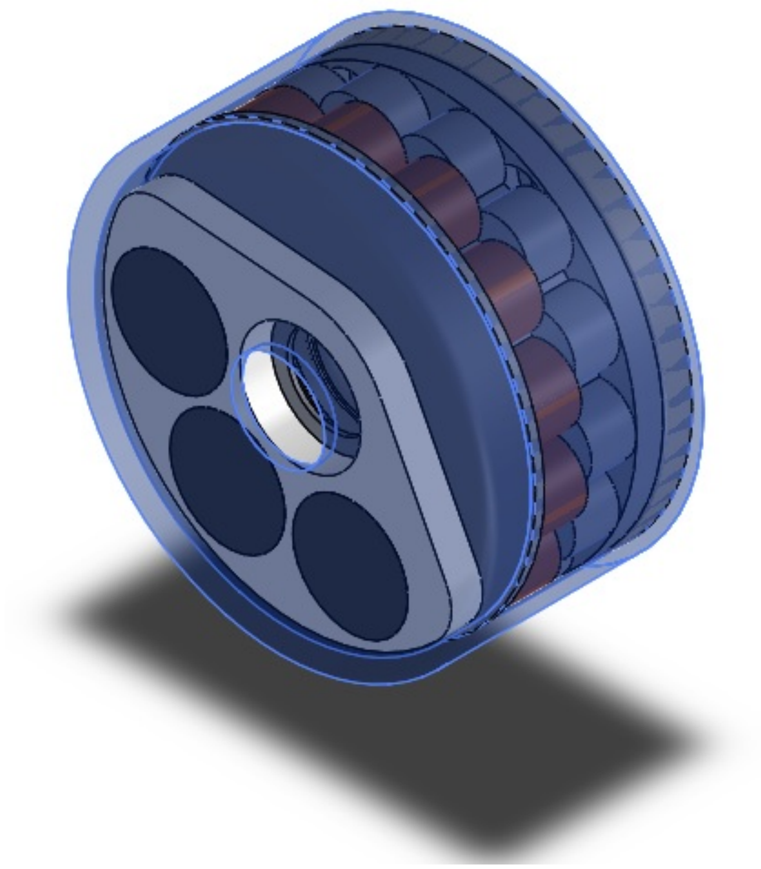

Figure 7: Rendering of the whole structure in a three-dimensional view.

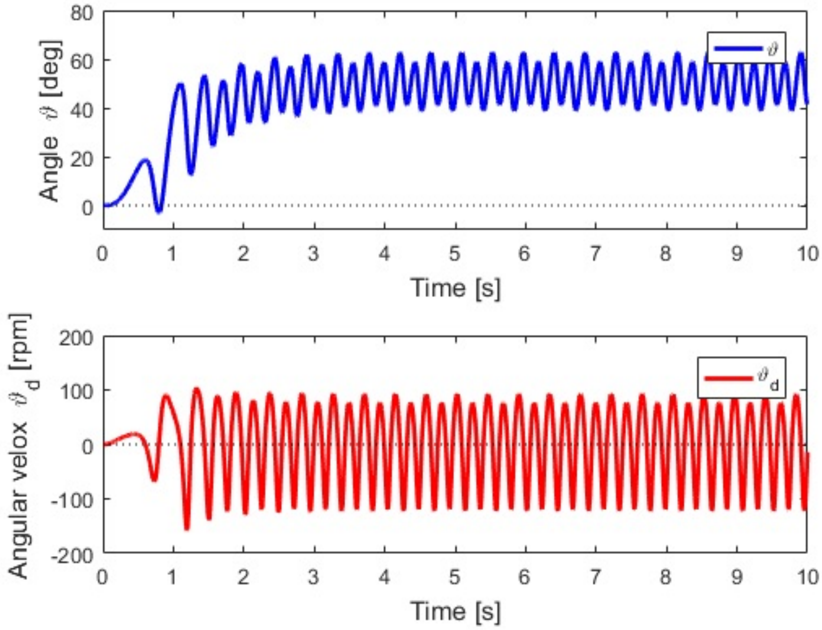

Figure 8: Time behaviour of the angular position and velocity as a response to a ramp disk velocity saturated at 140 rpm.

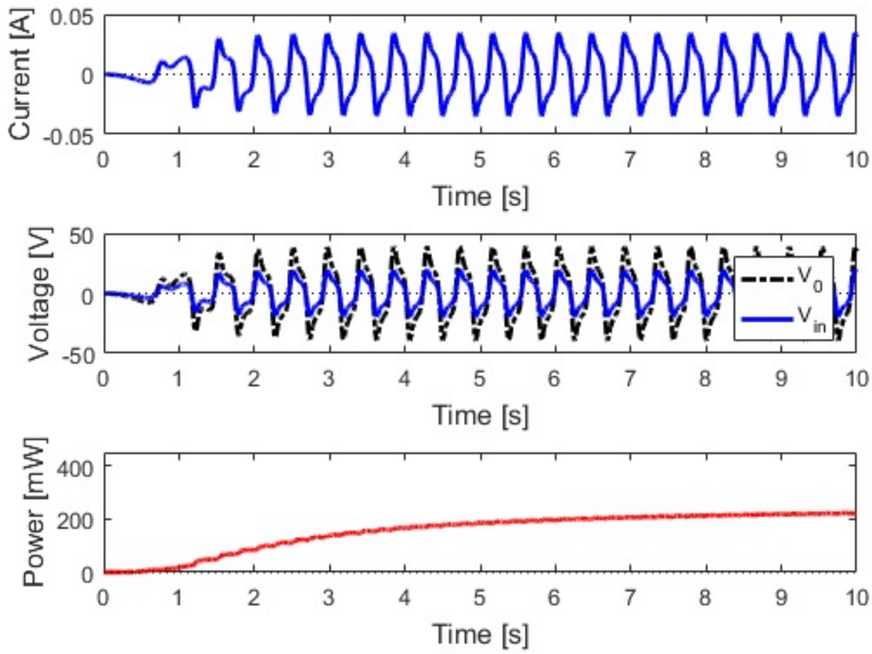

Figure 9: Time behaviour of the electric variables as a response to a ramp disk velocity saturated at 140 rpm.