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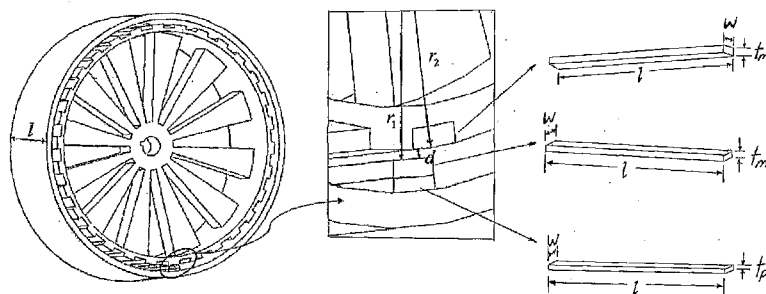
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(54) **Title:** A RING PIEZOELECTRIC ENERGY HARVESTER EXCITED BY MAGNETIC FORCES

Fig. 1. Schematic diagram and geometries of the piezoelectric energy harvester.



(57) **Abstract:** A ring piezoelectric harvester excited by magnetic forces with high excitation frequencies is developed. The harvester is made of a concentric outer ring stator and an inner ring rotator. The stator ring is made of a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. All the piezoelectric patches and the magnetic slabs are placed on an aluminum ring. The rotator ring is made of a series of magnetic rectangular slabs mounted on an aluminum ring with the exact size of the corresponding piezoelectric patches on the stator. Because of periodic magnetic forces between the stator ring and the rotator ring, a compression is induced to the piezoelectric patches leading to an electric charge for energy harvesting. To describe the energy harvesting process, a mathematical model is used to calculate the output charge and voltage from the piezoelectric patches. The influences of the size of the piezoelectric harvester and the rotating speed of the rotator ring on the root mean square of the generated electric power are discussed. Results show that a power up to 5274.81V can be realized for a practical design of the harvester with a radius around 0.5m.

A ring piezoelectric energy harvester excited by magnetic forces**FIELD OF THE INVENTION**

The present invention relates generally to piezoelectric energy harvesters, and more particularly to a piezoelectric energy harvester employing sets of magnets arranged on a spinning rotor and a surrounding ring-shaped stator with matching poles facing radially opposite one another in order to periodically compress piezoelectric patches sandwiched beneath one such set of magnets, and thereby generate electrical current.

BACKGROUND

Among the available vibration-to-electric energy conversion mechanisms such as electromagnetic, electrostatic and piezoelectric transductions, piezoelectric transduction is preferred because its energy density is three times higher than the other two transductions [1, 2]. Many prior research works on applications of piezoelectric materials to energy conversion from ambient environmental vibrations have been conducted [3-6]. Wang et al [7] proposed an optimal design of a collocated pair of piezoelectric patch actuators that are surface bonded onto beams. The design involves selecting the optimal locations and sizes (or lengths) of the piezoelectric actuators based on a controllability perspective. Rocha *et al.* [8] investigated an application of piezoelectric polymers in energy harvesting from people walking and designs of shoes capable of generating and accumulating the energy were discussed. Ajitsaria *et al.* [9] provided a modeling of a lead zirconium titanate (PZT) bender for voltage and power generation by transforming ambient vibrations into electric energy to supply powers in a microwatt range for operating sensors and data transmission. By both numerical simulations and experimental studies, Liao and Sodano [10] introduced a theoretical model of a simply piezoelectric energy harvesting system for an accurate prediction of generated powers. Waleed et al [11] proposed a design and testing of a vibration energy harvester with tunable resonance frequency, wherein the tuning is accomplished by changing the attraction force between two permanent magnets by adjusting the distance between the magnets. Wang and Wu [12] developed an optimal design of a piezoelectric patch mounted on a beam structure to

achieve a higher power-harvesting efficiency by both numerical simulations and experimental studies. Xie *et al* [13] introduced an optimal design of a piezoelectric coupled cantilever structure attached by a mass subjected to seismic motion to achieve a higher efficient energy harvesting.

5 There is a huge reservation of sustainable and clear wind and ocean energy on the earth. The flowing power of winds is usually from a typical intensity of $0.1\sim0.3\text{ kW/m}^2$ to 0.5 kW/m^2 on the earth surface along the wind direction, while the flowing power of ocean waves is round $2\sim3\text{ kW/m}^2$ under the ocean surface along the direction of the wave propagation [14]. In order to utilize these energies,
10 developments of new energy technologies using the piezoelectric transduction to absorb flowing water and/or wind energy on the earth owing to the existing achievements on piezoelectric harvesters were conducted. Priya [15] reported a theoretical model for determination of a generated electric power from piezoelectric bimorph transducers mounted on a windmill in a low frequency range far from the
15 piezoelectric resonance. An energy harvester using a piezoelectric polymer 'eel' to convert the mechanical flow energy, available in oceans and rivers, to electric power was presented by Taylor *et al* [16]. Using a similar principle, Li and Lipson [17] explored a "piezo-leaf" energy harvesting system where the PVDF strip of the "eel" system was replaced by a PVDF cantilever with a large triangular plastic "leaf"
20 attached to the free end of the cantilever to improve the power generation. Li *et al* [19] also proposed and tested a bioinspired piezo-leaf architecture converting wind energy into electric energy by wind-induced fluttering motion. Zurkinden *et al.* [21] designed a piezoelectric polymer wave energy harvester from wave motions at a characteristic wave frequency and investigated the influences of the free surface wave, the fluid-
25 structure-interaction, the mechanical energy input to the piezoelectric material, and the electric power output on the generated energy. Gao *et al.* [18] reported a flow energy harvester by a piezoelectric cantilever (PEC) with a cylindrical extension. This device utilized the flow-induced vibration of the cylindrical extension to directly drive a vibration of the PEC for energy harvesting from ambient flows such as wind or water
30 stream. Using the similar idea proposed by Gao *et al.*, Abdelkefi *et al.* [22] presented

a model for harvesting energy from galloping oscillations of a bar with an equilateral triangle cross-section attached to two cantilever beams. Murray and Rastegar [20] presented a novel class of two-stage electric energy generators on buoyant structure. These generators used the interaction between the buoy and sea wave as a low-speed input to a primary system to successively excite an array of vibratory elements (secondary system) into resonance. Electric energy may then be harvested from the vibrating elements of the secondary system with a high efficiency using piezoelectric elements. Wu and Wang [23] developed an energy harvester made of a cantilever attached by piezoelectric patches and a proof mass for wind energy harvesting from a cross wind-induced vibration of the cantilever by the electromechanical coupling effect of piezoelectric materials.

The existing piezoelectric harvesters can be classified into three main categories: (1) piezoelectric bimorph cantilevers mounted on a windmill to absorb wind energy or mounted on a buoyant structure to absorb the transverse ocean wave energy; (2) piezoelectric polymer 'eels' or cantilevers attached by a triangular plastic leaf on the free end to absorb the vortex shedding energy caused by bluff body fixed in the seabed, and (3) piezoelectric cantilever slabs fixed on the tall slender structure to absorb wind energy or fixed on seabed to absorb longitudinal sea wave energy. In the aforementioned energy harvesting structures, frictions exist between the piezoelectric cantilever structures and excitation objects and hence dissipations of the vibration energy and reductions of the energy harvesting efficiency are inevitable. Meanwhile, energy harvesting techniques with the above structures are mainly excited by external loadings, such as the water wave forces and wind loadings, with low frequencies (usually in a range of 0.1~0.5Hz for ocean waves [22] and 10~30Hz for wind loadings with the vortex shedding phenomenon [23]). The low frequency excitations may lead to a long charging period on the piezoelectric materials leading to a small output electric current and corresponding low energy harvesting effectiveness.

SUMMARY OF THE INVENTION

According to one aspect of the invention there is provided a

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piezoelectric energy harvester comprising:

a ring-shaped stator closing around a central axis;

a rotor rotatably supported at a position surrounded by the ring-shaped stator and rotatable about the central axis;

5 a first set of magnets carried on the ring shaped stator at respective positions around the central axis with inwardly facing poles of said first set of magnets facing inwardly toward the central axis;

a second set of magnets carried on the rotor at respective positions around the central axis with outwardly facing poles of said second set of magnets facing outwardly away from the central axis toward the surrounding ring-shaped stator; and

10 a set of piezoelectric patches cooperatively positioned with a respective one of either the first set of magnets or the second set of magnets so as to reside either between the first set of magnets and the ring-shaped stator, or between the second set of magnets and the rotor, in a radial direction relative to the central axis;

15 wherein the inwardly facing poles of said first set of magnets and the outwardly facing poles of said second set of magnets are the same, the respective set of magnets with which the piezoelectric patches are cooperatively positioned are supported in a radially displaceable manner enabling compression of said piezoelectric patches by radial displacement of said set of magnets, and the other set of magnets are spaced apart from one another around the central axis, whereby relative movement of one of said second set of magnets past one of said first set of magnets under rotation of the rotor acts to momentarily compress a respective one of said piezoelectric patches.

20 At least one of the first and second sets of magnets may be axially constrained by a respective pair of opposing end walls on the stator or the rotor on which said set of magnets are carried.

25 At least one of the first and second sets of magnets may be constrained in a radially direction by axially in-turned flanges on the respective pair of opposing end walls on the stator or the rotor.

30

At least one of the first and second sets of magnets may be constrained in a rotational direction around the central axis by dividers extending axially from the respective pair of opposing end walls one both sides of each magnet of said set of magnets.

5 Alternatively, at least one of the first and second sets of magnets may be received in respective grooves of axial length and radial depth in the stator or the rotor, which thereby constrain the magnets in the rotational and radial directions.

In such instance, the magnets may be prevented from radial withdrawal from said grooves by cooperative shaping of said set of magnets and said respective
10 grooves.

Preferably the respective set of magnets with which the piezoelectric patches are cooperatively positioned are situated closer together around the central axis than the other set of magnets.

Preferably the respective set of magnets with which the piezoelectric
15 patches are cooperatively positioned are substantially placed immediately adjacent one another with minimal space therebetween.

Preferably the set of piezoelectric patches are mounted on the stator and cooperatively positioned with the first set of magnets carried thereon.

Preferably the second set of magnets carried on the rotor are provided
20 in a quantity that is half of a total number of magnets in the first set.

Preferably the facing-together poles of the first and second sets of magnets are equal in surface area.

Preferably a radially-facing surface area of each piezoelectric patch is fully covered by a respective individual magnet in the respective set of magnets.

25 Preferably the radially-facing surface area of each piezoelectric patch is equal to a radially facing area of a respective individual magnet that overlies said piezoelectric patch.

The rotor may be coupled to a shaft of a wind turbine for driven rotation of the rotor by wind power in order to generate electrical power from the piezoelectric
30 patches.

Alternatively, the rotor may be coupled to a shaft of a water turbine for driven rotation of the rotor by hydraulic power in order to generate electrical power from the piezoelectric patches.

BRIEF DESCRIPTION OF THE DRAWINGS

One embodiment of the invention will now be described in conjunction with the accompanying drawings in which:

Figure 1 is a schematic illustration demonstrating assembly of a piezoelectric harvester of the present invention that employs magnetic slabs mounted on an internal rotator ring to cooperate to repulse matching poles of magnetic slabs carried on an external stator ring in order to compress piezoelectric patches that are sandwiched between the stator ring and the magnetic slabs carried thereon.

Figure 2 is a plot of the RMS of the electric power (W) generated by the piezoelectric harvester of Figure 1 versus thicknesses of the magnetic slabs and piezoelectric patches, as determined from a numerical model of the first embodiment harvester.

Figure 3 is a plot of the RMS of the electric power (W) generated by the piezoelectric harvester of Figure 1 versus the rotational speed of the rotator ring and the space between the stator ring and the rotator ring.

Figure 4 is a plot of the RMS of the electric power (W) generated by the piezoelectric harvester of Figure 1 versus the residual flux density of the magnets.

Figure 5 is a plot of the RMS of the electric power (W) generated by the piezoelectric harvester of Figure 1 versus the length and width of the magnetic slabs.

Figure 6 is a perspective view of an assembled piezoelectric harvester of the present invention.

Figure 7A is a perspective view of a partially assembled stator of the piezoelectric harvester of Figure 6.

Figure 7B is a partial close-up perspective view of the partially assembled stator of Figure 7A.

Figure 8A is a perspective view of a partially assembled rotor of the piezoelectric harvester of Figure 6, prior to installation of magnetic slabs thereon.

Figure 8B is a perspective view of one of the magnetic slabs to be installed on the partially assembled rotor of Figure 8A.

In the drawings like characters of reference indicate corresponding parts in the different figures.

5 DETAILED DESCRIPTION

In order to solve the above two problems in the existing piezoelectric harvesters and improve the energy harvesting efficiency, a new ring piezoelectric harvester excited by magnetic forces has been developed. In one embodiment, the harvester is made of an outer ring stator and an inner ring rotator. The stator ring is made of a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. The rotator ring is made of a series of magnetic rectangular slabs mounted on an aluminum ring with the exact size of the corresponding piezoelectric patches on the stator. When the rotator ring is twirled, periodic magnetic forces between the stator ring and the rotator ring are induced to compress the piezoelectric patches leading to an electric charge for energy harvesting. In the new developed harvester, the frictions between the stator and rotator are made minimal since magnetic forces are used as excitations. In addition, the excitation frequency on piezoelectric patches can be increased by increasing the rotating speed of the rotator ring and the number of magnets embedded in the rotator ring. Thus, the two problems in the current piezoelectric harvesters can be solved in the new devices and hence generations of higher electric powers sufficiently for electric appliances of households become possible.

Further details of preferred embodiments are described as follows with additional reference to the drawings.

Figure 6 shows one embodiment of piezoelectric harvester 10 with a ring-shaped stator 12 that features a cylindrical peripheral wall 14 and a pair of matching annular end walls 16 that are fixed to the ends of the peripheral wall 14 in order to reach radially inward therefrom toward a central longitudinal axis A on which the peripheral wall and annular end walls are centered. A rotor 18 of the harvester 10 features a hollow cylindrical hub 20 that is centered on the longitudinal axis A, and

from which a plurality of radial spokes 22 emanate outward to an outer ring 24 of the rotor 18. Like the stator 12, the rotor 18 also features a pair of matching annular end walls 26 that are spaced apart along the central longitudinal axis A and lie in parallel planes perpendicular thereto. The rotor is rotatably supported inside the stator by a shaft (not shown) lying on the central axis A, to which the hub 20 is accordingly keyed. The shaft may be the shaft of a wind turbine or water turbine, for example the same shaft on which the turbine impeller is mounted, or an output shaft indirectly coupled to the turbine impeller for driven rotation thereby under the wind power or hydraulic power that operates the turbine.

Figures 7A and 7B illustrate the installation of internal components of the stator that are not visible in the fully assembled harvester of Figure 6. A piezoelectric patch 28 of elongated rectangular form is bonded to the internal surface 14a of the stator's peripheral wall 14 in an orientation placing the longitudinal of the patch's rectangular shape parallel to the central axis A of the peripheral wall's cylindrical shape. A generally rectangular slab magnet or bar magnet 30 is placed over the secured piezoelectric patch 28 in an aligned position placing a radially outward facing rectangular underside of the slab magnet 30 face-to-face against the radially inward side of the piezoelectric patch 28 that faces toward the central axis A. These facing-together rectangular faces of the piezoelectric patch 28 and the magnet 30 are of equal size, shape and surface area, whereby the magnet 30 fully covers the piezoelectric patch 28 in its properly aligned position over same. The matching longitudinal dimensions of the rectangular piezoelectric patch 28 and magnet are also equal the axial dimension of the peripheral wall 14, as measured along the central axis A.

Each end wall 16 of the stator reaches radially inward from the internal surface 14a of the peripheral wall 14 by a distance exceeding the combined thickness of the piezoelectric patch 28 and magnet 30. A distal edge of the end wall 16 located furthest from the peripheral wall features an in-turned flange 32 that juts axially from the end wall 16 around the full diameter thereof in order to reach a short distance inwardly over the peripheral wall 14 and thereby hook over a respective end of each

magnet 30. At the radially inward face of each magnet, the magnet's thickness (in the radial direction relative to central axis A) is stepped down to a reduced dimension relative to the uniform-thickness central span of the magnet 30 that remains between the two stepped-down ends 30a. The reduction in thickness at the stepped down edges 30a equals or exceeds the thickness of the in-turned flanges 32 of the end walls 16 of the stator so that the radially-inward facing surface of the magnet defines the radially innermost extent of the stator relative to the central axis A.

At regularly spaced intervals around the central axis A, thin gusset-like dividers or tabs 34 are fixed in place between the in-turned flange 32 of each end wall 16 and the inner face of the end wall that faces toward the opposing end wall. The spacing between any two adjacent dividers/tabs 34 is generally equal to the width of each magnet 30 so that, as shown in Figures 7B, the two dividers/tabs 34 lie adjacent two opposing sides of a respective magnet 30, and thereby prevent shifting or movement of the respective stepped-down end 30a of the magnet around the central axis A. Figure 7 shows an early stage in assembly of the rotor, in which one end wall 16 has been fastened to the cylindrical periphery wall 14, a first piezoelectric patch 28 has been mounted to the interior surface 14a of the periphery wall 14, and a respective magnet 30 has been placed over the patch 28 in alignment therewith between a respective pair of divider tabs 34. The end wall 16 may be fastened using threaded fasteners engaged in the axial direction through matching 36 in the annular end face of the peripheral wall 14, with match up with corresponding fastener holes in the annular end wall 16.

Additional pairs of magnets and piezoelectric patches are likewise installed around the full circumference of the peripheral wall until all available spaces between the pairs of divider tabs 34 are filled with a respective magnet and piezoelectric patch, thereby forming a substantially continuous span of discrete piezoelectric patches and corresponding slab magnets around the central axis A. At this point, the second end wall 16 is fastened to the other end of the peripheral wall's cylindrical shape with the divider tabs of this second end wall in alignment with those of the first end wall.

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With both end walls thus installed in order to complete the stator assembly, the two in-turned flanges 32 of the end walls 16 act to radially constrain the magnets 30 by blocking radially inward movement toward the central axis A, while the divider tabs 34 keep each magnet in proper circumferential alignment over the
5 respective piezoelectric patch 28 by blocking circumferential movement of the magnet about the central axis A. The inner faces of the two annular end walls 16 block sliding of the magnets in the axial direction parallel to the central axis A.

The radial span of the end walls 16 in the direction extending inwardly toward the central axis from the inside surface 14a of the stator's peripheral wall is at
10 least as great as the combined thickness of the magnet and piezoelectric patch 28 when the patch 28 is in an uncompressed state, whereby a radially outward force exerted on the magnet 30 can compress the piezoelectric patch 28 against the internal surface 14a of the peripheral wall 14, but such compression of the piezoelectric patch 28 can be subsequently relieved when the radially outward force
15 on the magnet 30 is removed. So while each magnet 30 is constrained in its allowable amount of radially inward movement toward the central axis A by the in-turned flanges 32 that hook over the stepped-down ends 30a of the magnet 30, the magnet is displaceable back and forth in the radial direction within its dedicated space confined between the respective divider tabs 34 that separate it from the adjacent
20 magnets around the axis A. The magnets 30 of the stator are all oriented in a same direction, so that the same north or south pole of each of these magnets faces inwardly toward the central axis A of the stator.

Turning now to the details of the rotor 18, Figure 8A shows the rotor 18 prior to installation of a second set of magnets 40 thereon that cooperate with the first
25 set of magnets 30 on the stator to momentarily compress each piezoelectric patch 28 on a periodic basis as the rotor spins on the central axis A inside the surrounding stator. To accommodate its respective set of magnets 40, the ring 24 of the rotor features a plurality of longitudinal grooves 42 evenly spaced around its circumference. Each groove 42 has a length that spans axially through the ring 24 in a direction
30 parallel to the central axis A, and a depth that is recessed radially into the ring 24 from

the exterior thereof toward the central axis A. The number of grooves in the illustrated embodiment is one-half of the number of stator magnets 30, whereby the rotor 18 is configured to carry half as many magnets 40 as the stator 12.

Each slab magnet 40 and respective groove 42 of the rotor 18 are cooperatively shaped in a manner that fixes the radial position of the magnet 40 relative to the central axis A once the magnet is slid axially into the groove 42. Particularly, each groove in the illustrated embodiment has a greater width at its bottom (i.e. at its radially innermost extent or depth) than at its top (i.e. at its radially outermost extent), and each slab magnet 40 likewise features a widened base 40a that creates a pair of flanges projecting from opposing sides of the rectangular remainder 40b of the magnet 40. When the magnet 40 is inserted into a respective groove 42, its base flanges prevent radial displacement of the magnet from this seated position on the rotor, at which point the two opposing end walls 26 of the rotor are fastened to the rotor ring 24. The installed end walls 26 block off the two ends of each groove 42 in order to axially retain the magnets 40 in place in fixed positions along the central axis A. Portions 44 of the rotor ring 24 that are left intact between the grooves 42 are of similar width to the narrower outer portions of the grooves and the radially outer faces of the magnets 40 received therein. The end walls 26 of the rotor may fasten to the rotor ring 24 via fastener holes 46 extending axially thereinto at these intact portions 44. The intact portions 44 of the rotor ring separate the rotor magnets 40 from one another and prevent them from moving circumferentially out of their respective positions around the central axis A.

As an alternative to seating, and radial and circumferential retention of the rotor magnets by the grooves 42, the rotor magnets may be held in place by other means, for example by adhesive bonding or by using in-turned flanges and separating dividers on the pair of opposing end walls, for example like those used for the stator but either with larger dividers 34 or by installation of magnets between only every second pair of thin tab-like dividers. Accordingly, the grooves and rotor magnets need not necessarily have cooperating magnet-retaining shapes, and so the rotor magnets, and optional grooves, may have a more simplistic geometry, for example employing a

basic purely-rectangular bar shape like that shown in Figure 1.

The rotor magnets are configured so that the same north or south pole of each magnet faces outwardly from the rotor in the radial direction, so as to face away from the central axis and toward the surrounding stator in the assembled harvester. These matching outwardly facing poles of the rotor magnets 40 are the same pole as the matching inwardly facing poles of the stator magnets 30. That is, if the north poles of the stator magnets 30 face inwardly, then the north poles of the rotor magnets 40 face outwardly. On the other hand, if the south poles of the stator magnets 30 face inwardly, then the south poles of the rotor magnets 40 face outwardly.

The peripheral and end walls of the stator and the ring and end walls of the rotor are made of a non-magnetic material, such as aluminum. In the assembled harvester, when the rotor is spinning, each pairing of a magnet 30 and piezoelectric patch 28 on the stator 12 is experiencing continual and alternating passage of rotor magnets 40 and non-magnetic rotor portions 44 thereby. As the rotor magnet 40 moves into alignment over the equally sized stator magnet 30, the facing-together like-poles of these two magnets repel one another, thus forcing the stator magnet 30 outwardly against the underlying piezoelectric patch 28, which is compressed by this action due its sandwiched position between the stator magnet 30 and the interior 14a of the peripheral wall 14 of the stator body. However, as the rotor magnet 40 continues onward past this particular stator magnet 30, a non-magnetic portion 44 of the rotor located between a given pair of the rotor magnets moves into place over this particular stator magnet 30, thus removing the magnetic repulsion force therefrom, and thereby releasing the compression force from the piezoelectric patch 28, which thus returns to its natural uncompressed state. This alternating compression and relaxation cycle is repeated on a continual basis for each and every piezoelectric patch 28 so long as the rotor continues to rotate, thus generating usable electric power from this vibration of the piezoelectric patches 28.

While having the piezoelectric patches 28 on the stator is preferred preferable, for example to simplify collection of electrical current from the patches due

to their stationary positions on the motionless stator body, it may be possible in other embodiments to instead mount piezoelectric patches 28 on the rotor. While it is preferable to keep the piezoelectric patches in close direct adjacency to one another around the central axis A in order to maximize the number of patches and optimize the power input, other embodiments may feature further spacing apart of the patches and overlying magnets.

Numerical Model

Fig. 1 illustrates schematically a similar piezoelectric energy harvester to those described above with reference to Figures 6 to 8. The harvester of Figure 1 features an outer ring stator and an inner ring rotator. The stator ring is made of a series of discrete piezoelectric patches with a rectangular shape surface mounted by magnetic ring slabs with the same size. All the piezoelectric patches and the magnetic slabs are placed on an aluminum ring. The rotator ring is made of a series of magnetic rectangular slabs mounted on an aluminum ring with the exact size of the piezoelectric patches. The rotator ring is supported by spokes, which are fixed on a centre shaft. From this configuration, it is seen clearly that a periodic magnetic force between the stator ring and the rotator ring can be generated, which is used to induce a compression on the piezoelectric patches leading to an electric charge for energy harvesting. In Fig. 1, r_1 is the inner radius of the stator ring; r_2 is the outer radius of the rotator ring; and hence the space between the stator ring and the rotator ring is $d=r_1-r_2$; l is the length of the ring harvester and the length of the piezoelectric patches and magnetic slabs along their axial direction; w is the width of the piezoelectric patches and magnetic slabs; t_m is the thickness of the magnetic slabs and t_p is the thickness of the piezoelectric patches. It is noted that the width of the teeth on the stator ring is the same with the widths of the piezoelectric patches and the magnetic slabs such that a continuous and periodic magnetic force is applied to the piezoelectric patches.

A mathematical model was developed to describe the principle of a ring piezoelectric energy harvester using magnetic excitation force for harvesting energy from harvesting from the water current in an ocean and/or winds. Some important

factors, such as the size of the piezoelectric harvester and the rotating speed of the rotator ring, that influence the root mean square (RMS) of the generated power are also investigated.

According to the online interpolator based on a large datasets of experimental measurements, an empirical equation for the repelling force F_M between two identical rectangular permanent magnets can be expressed as [11, 24]:

$$F_m = l w t_m^{1/3} B_r |B(d)| f(d), \quad (1)$$

where B_r is the residual flux density of the magnet, $|B(d)|$ is the magnitude of the magnetic flux density field, and $f(d)$ is an empirical function describing the decay of the repelling force between two magnets. For a rectangular magnet, $|B(d)|$ and $f(d)$ can be calculated by the following formulas [25]:

$$B(d) = \frac{B_r}{\pi} \left[\tan^{-1} \left(\frac{l w}{2d \sqrt{4d^2 + l^2 + w^2}} \right) - \tan^{-1} \left(\frac{l w}{2(t_m + d) \sqrt{4(t_m + d)^2 + l^2 + w^2}} \right) \right], \quad (2)$$

$$f(d) = \left(1.749 + 1.145 e^{\left(-\frac{d}{d_0} \right)} \right) \times 10^6 NT^{-2} m^{-7/3}, \quad (3)$$

where $d_0 = 1mm$.

The compression induced on piezoelectric patches can be obtained through the constitutive relationship of the piezoelectric material in its poling direction:

$$D_3 = d_{33} T_3, \quad (4)$$

where D_3 is the surface charge-density displacement; d_{33} is the piezoelectric coefficient in the poling direction of the piezoelectric material; T_3 is the stress applied in the poling direction.

The generated charge Q_g^i and voltage V_g on the surface of the i th piezoelectric patch due to the application of the periodic magnetic force applied to the piezoelectric patch are provided as:

$$\begin{cases} Q_g^i(t) = D_{3i} l w = d_{33} F_{mi} \sin(n_1 n_2 \pi t) & \text{if } \sin(n_1 n_2 \pi t) \geq 0 \\ Q_g^i(t) = -d_{33} F_{mi} \sin(n_1 n_2 \pi t) & \text{if } \sin(n_1 n_2 \pi t) < 0 \end{cases} \quad (5)$$

15

$$\begin{cases} V_g^i(t) = Q_g^i(t)/C_v = d_{33}F_{mi}\sin(n_1n_2\pi t)/C_v & \text{if } \sin(n_1n_2\pi t) \geq 0 \\ V_g^i(t) = -d_{33}F_{mi}\sin(n_1n_2\pi t)/C_v & \text{if } \sin(n_1n_2\pi t) < 0 \end{cases} \quad (6)$$

$$C_v = 0.75 \times 10^{-9} \times l \times w \times 0.0003 / (0.01 \times 0.06 \times t_p), \quad (7)$$

where n_1 is the excitation frequency in cycles per second; $n_2 = [\pi r_2 / w_m]$ is the number of magnetic slabs embedded in the outer face of the rotator ring. C_v is the electric capacity of the piezoelectric patch in nF ; $1 \leq i \leq 2n_2$, and $2n_2$ is the number of the piezoelectric patches bonded on the inner surface of the stator ring. From Eq. (5), it is seen that a decrease in the width of the magnetic slabs would lead to an increase in the value of the n_2 and hence an increase in the excitation frequency on the piezoelectric patches.

10 The RMS of the generated power from time 0 to T can be given as:

$$p_e^{rms} = \sqrt{\frac{1}{T} \int_0^T [p_e(t)]^2 dt}, \quad (8)$$

where $p_e(t)$ is the total generated power of all the piezoelectric patches on the stator ring at time t ($0 < t < T$) which is given by :

$$p_e(t) = \sum_{i=1}^{2n_2} \frac{dQ_g^i(t)}{dt} V_g^i(t) = \sum_{i=1}^{2n_2} d_{33}^2 n_1 n_2 \pi F_{mi}^2 \sin(n_1 n_2 \pi t) \cos(n_1 n_2 \pi t) / C_v. \quad (9)$$

15 To estimate the RMS of the generated power, the period, T , can be separated into j time steps with a sufficiently short time interval Δt . As a result, the expression in Eq. (8) can be rewritten in a discrete form below:

$$p_e^{rms} = \sqrt{\frac{\Delta t}{2(T - \Delta t)} \sum_{i=2}^j ([P_e(t_i)]^2 + [P_e(t_{i-1})]^2)} \quad (10)$$

20 Simulations and Discussions

In this section, the effectiveness of the newly developed piezoelectric harvester is investigated. Particularly, the effects of the length, width and thicknesses of the piezoelectric patch and magnetic slab, the rotating speed of the rotator ring, the

space between the stator ring and the rotator ring, and the residual flux density of the magnet on the generated power are studied. The dimensions and material properties of the energy harvester in the simulations are provided in Table 1 and 2.

5

Table 1

Material properties and dimensions of piezoelectric patches (PZT4)

$e_{21}(C/m^2)$	$e_{22}(C/m^2)$	$c_{11}^E(N/m^2)$	$c_{22}^E(N/m^2)$	$c_{12}^E(N/m^2)$	$d_{33}(C/N)$	$l(m)$	$w(mm)$	$t_p(mm)$
-2.92	23.4	1.14e11	1.11e11	7.24e10	6.40e-10	0.2~0.4	5~20	2~10
$C_v(nF)$	0.75 for the piezoelectric patch with the geometry of 0.01, 0.06, 0.0003m							

10 **Table 2**

Material properties and dimensions of rings (Al) and magnets(Neodymium Iron Boron, N5311)

$r_1(m)$	$r_2(m)$	$d(mm)$	$B_r(T)$	n	$l(m)$	$w(mm)$	$t_m(mm)$
0.5	0.497~0.4995	0.5~3	1.42~1.48	1/3	0.2~0.4	5~20	2~10

For energy harvesting from water currents and winds, the rotating speed of the rotator ring is set in a range of common speeds excited by general water and wind turbines. For example, the rotation speeds of the hydro turbine of a generator produced by TD Power Systems Limited are in a range of 6.25~30 cycles/s [26]. The piezoelectric patches, magnets, and main structures of the ring and rotator ring are made of PZT4 (lead zirconate titanate), N5311 (Neodymium Iron Boron) and aluminum, respectively.

20

Fig. 2 depicts the contours of the RMS of the electric power with respect to the thicknesses of the piezoelectric patch t_p and the magnetic slab t_m . The dimensions of the energy harvester in these simulations are set to be: $l=0.2m$, $w=0.02m$, $d=0.001m$, $n_1=30c/s$, $r_1=0.5m$, $r_2=0.499m$ and $B_r=1.48T$ with the rotating speed of the rotator ring of $n_1=30c/s$. This figure shows a linear increase of the RMS with an increase in the thickness of the piezoelectric patch and a nonlinear increase of the RMS with an increase in the thickness of the magnetic slab. The findings can be interpreted by the fact that the RMS is proportional to the thickness of the piezoelectric patch (see Eqs.(7), (9)) and an exponential power of 2/3 of the thickness of the magnetic slab (see Eqs.(1), (9)). It can be seen from Fig. 2 that the highest RMS of generated power can reach $381.7W$ with the thicknesses being $t_p=t_m=0.01m$. Thus it can be concluded that the increase of the thicknesses of the piezoelectric patch and/or magnetic slab will lead to a notable growth of the RMS leading to high efficiency of harvesters.

Fig. 3 displays the variations of the RMS versus the rotating speed of the rotator ring and the space between the stator ring and the rotator ring, d . The dimensions of the energy harvester in this simulation are set to be: $l=0.2m$, $w=0.02m$, $t_m=t_p=0.01m$, $r_1=0.5m$, $r_2=0.497\sim0.4995m$ and $B_r=1.48T$. It can be found that the RMS increases linearly with an increase in the rotating speed of the rotator ring and increases nonlinearly with a decrease in the space between the stator ring and the rotator ring. It is obvious that a larger rotating speed of the rotator ring leads to a larger excitation frequency of the magnetic force applied to the piezoelectric patch leading to a corresponding increase in the generated electric current. On the other hand, a narrower space between the stator ring and the rotator ring leads to a larger magnetic force and hence the generated power can be increased. It can be seen from Fig. 3 that the RMS increases from 12.7 to $381.7W$ when the rotating speed changes from 1 to $30c/s$ at a space between the stator ring and the rotator ring of $0.001m$; while the RMS increases from 122.8 to $519.3W$ when the space between the stator ring and the rotator ring changes from 0.005 to $0.0005m$ at a rotating speed of the rotator ring of $30c/s$. Hence, an increase in the rotating speeds of the rotator ring and

a decrease in the spaces between the stator ring and the rotator ring will lead to a significantly increase of the generated power up to a value of 519.3W with a radius of the rotator ring of 0.4995m.

Fig. 4 demonstrates the relationship between the RMS and the residual flux density of the magnet changing from 0.5 to 1.5T for a given structure with the following geometric parameters: $l=0.2m$, $w=0.02m$, $t_m=t_p=0.01m$, $n_1=30c/s$, $r_1=0.5m$, $r_2=0.499m$ and $d=0.001m$. The figure shows that the RMS nonlinearly increases with an increase in the residual flux density of the magnet. It is seen that that the RMS is exponentially proportional to the residual flux density of the magnet with an power of 4 as shown in Eqs.(1), (2) and (9). The RMS increases dramatically from 5.0 to 402.8W when the residual flux density changes from 0.5 to 1.5T. Thus it is obvious that a slight increase in the residual flux density of magnets will lead to a remarkable augment of the RMS.

Fig. 5 shows the contours of the RMS versus the length l and width w of the piezoelectric patch and magnetic slab with the parameters of $l=0.2\sim0.4m$, $w=0.005\sim0.02m$, $t_m=t_p=0.01m$, $n_1=30c/s$, $r_1=0.5m$, $r_2=0.499m$, $d=0.001m$ and $B_r=1.48T$. From the simulations, the following observations can be made. Firstly, the RMS of the generated power increases linearly with an increase in the length of the magnetic slab l from 0.2 to 0.4m. It is seen that a maximum RMS is 2642.4W at the length of the magnetic slab of 0.2 m, and the RMS shows a maximum value of 5274.8W at the length of the magnetic slab of 0.4 m. Second, the RMS increases nonlinearly with a decrease in the width of the magnetic slab w . It is clearly seen from Eq. (5) that a decrease of w will cause a nonlinear increase of the number of magnetic slabs embedded on the rotator ring of $n_2=[\pi r_2/w]$ and the excitation frequency of the magnetic force of $\omega=n_1 n_2 \pi$, which cause the rapid growth of the RMS. It is noted that the excitation frequency of the magnetic force can reach 9000Hz with the parameters of $w=0.005m$ and $n_1=30$ cycles/s, which is much larger than that of the previous developed harvesters in the references that is no more than 30Hz. These findings provide a guideline on choosing width of the piezoelectric patch and magnetic slab for higher generated power of an energy harvester with a certain size. From the Fig. 5, it

is seen that the RMS has a significant increase when the width of the magnetic slab changes in the range of 0.01 to 0.005m. In summary, an increase in the length and a decrease in the width of the piezoelectric patch and magnetic will cause an efficient increase of the RMS.

5 It should be noted that all the RMS of the generated power above are calculated with the outer radius of the rotator ring being only 0.5m. From the performed simulations, it is found that the proposed ring piezoelectric device can still generates hundreds to thousands of watts (W) of electric power to supply most household electric equipment, such as lamps, TVs, computers, washing machines,
10 air-conditionings, fridges, and microwave ovens, etc. It is expected that the newly designed piezoelectric energy harvesters from the water current in an ocean and/or winds can generate electric power in an order of dozens kilowatts to satisfy the daily life electricity consumptions of households.

In summary, a ring piezoelectric harvester with high excitation
15 frequencies up to 9000Hz has been developed and a corresponding mathematical model has been employed to calculate the output charge and voltage from the piezoelectric patches excited by the magnetic force. Owing to the high frequencies of the magnetic excitation forces applied to the piezoelectric patches and the low friction between the stator and rotator, the new ring piezoelectric harvester disclosed herein
20 has a high efficiency for energy harvesting. The RMS of the electric power generated from piezoelectric energy harvester is also solved and the results show that the RMS increases with an increase in the length and thicknesses of the piezoelectric patch and magnetic slab, the rotating speed of the rotator ring and the residual flux density of the magnet and a decrease in the space between the stator ring and the rotator
25 ring and the width of the piezoelectric patch and magnetic slab. For an energy harvester structure with geometric parameters of $l=0.4m$, $w=0.005m$, $t_m=t_p=0.01m$, $n_1=30c/s$, $d=0.001m$, $r_1=0.5m$, $r_2=0.499m$ and $B_r=1.48T$, the RMS can reach 5274.8W. It is expected that in practice the newly designed piezoelectric energy harvester can provide more efficient energy harvesting under a higher dimension of

the ring harvester and/or a higher rotating speed of the rotator ring to satisfy the demand of normal operations of household appliances.

It will be appreciated that the particular numerical values expressed herein above in terms of the simulations performed using the described numerical model are presented as examples only, and are not intended to limit the scope of the present invention.

Since various modifications can be made in my invention as herein above described, and many apparently widely different embodiments of same made within the scope of the claims without departure from such scope, it is intended that all matter contained in the accompanying specification shall be interpreted as illustrative only and not in a limiting sense.

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CLAIMS:

1. A piezoelectric energy harvester comprising:
a ring-shaped stator closing around a central axis;
a rotor rotatably supported at a position surrounded by the ring-shaped
5 stator and rotatable about the central axis;
a first set of magnets carried on the ring shaped stator at respective
positions around the central axis with inwardly facing poles of said first set of magnets
facing inwardly toward the central axis;
a second set of magnets carried on the rotor at respective positions
10 around the central axis with outwardly facing poles of said second set of magnets
facing outwardly away from the central axis toward the surrounding ring-shaped rotor;
and
a set of piezoelectric patches cooperatively positioned with a respective
one of either the first set of magnets or the second set of magnets so as to reside
15 either between the first set of magnets and the ring-shaped stator, or between the
second set of magnets and the rotor, in a radial direction relative to the central axis;
wherein the inwardly facing poles of said first set of magnets and the
outwardly facing poles of said second set of magnets are the same, the respective set
of magnets with which the piezoelectric patches are cooperatively positioned are
20 supported in a radially displaceable manner enabling compression of said
piezoelectric patches by radial displacement of said set of magnets, and the other set
of magnets are spaced apart from one another around the central axis, whereby
relative movement of one of said second set of magnets past one of said first set of
magnets under rotation of the rotor acts to momentarily compress a respective one of
25 said piezoelectric patches.
2. The piezoelectric energy harvester of claim 1 wherein at least
one of the first and second sets of magnets are axially constrained by a respective
pair of opposing end walls on the stator or the rotor on which said set of magnets are
carried.
3. The piezoelectric energy harvester of claim 2 wherein said at
30

least one of the first and second sets of magnets are constrained in a radially direction by axially in-turned flanges on the respective pair of opposing end walls on the stator or the rotor.

4. The piezoelectric energy harvester of claim 2 or 3 wherein said
5 each of the first set of magnets is constrained in a rotational direction around the central axis by dividers extending axially from the respective pair of opposing end walls one both sides of each magnet of said first set of magnets.

5. The piezoelectric energy harvester of claim 1 wherein at least
10 one of the first and second sets of magnets are received in respective grooves of axial length and radial depth in the stator or the rotor.

6. The piezoelectric energy harvester of claim 5 wherein said at
least one of the first and second sets of magnets are prevented from radial withdrawal from said grooves by cooperative shaping of said set of magnets and said respective grooves.

15 7. The piezoelectric energy harvester of any one of claims 1 to 6 wherein the respective set of magnets with which the piezoelectric patches are cooperatively positioned are situated closer together around the central axis than the other set of magnets.

8. The piezoelectric energy harvester of any one of claims 1 to 7
20 wherein the respective set of magnets with which the piezoelectric patches are cooperatively positioned are substantially placed immediately adjacent one another with minimal space therebetween.

9. The piezoelectric energy harvester of any one of claims 1 to 8
25 wherein the set of piezoelectric patches are mounted on the stator and cooperatively positioned with the first set of magnets carried thereon.

10. The piezoelectric energy harvester of claim 9 wherein the second
set of magnets carried on the rotor are provided in a quantity that is half of a total number of magnets in the first set.

11. The piezoelectric energy harvester of any one of claims 1 to 10
30 wherein the facing-together poles of the first and second sets of magnets are equal in

surface area.

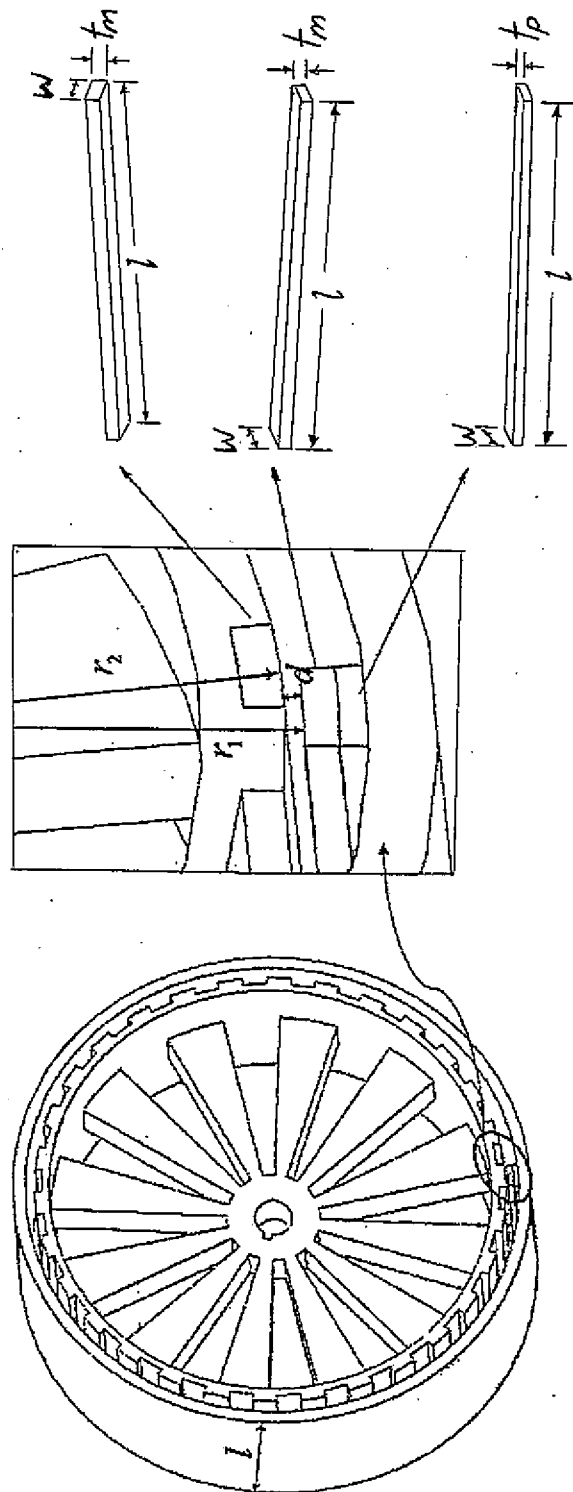
12. The piezoelectric energy harvester of any one of claims 1 to 11 wherein a radially-facing surface area of each piezoelectric patch is fully covered by a respective individual magnet in the respective set of magnets.

5 13. The piezoelectric energy harvester of any one of claims 1 to 11 wherein a radially-facing surface area of each piezoelectric patch is equal to a radially facing area of a respective individual magnet that overlies said piezoelectric patch.

14. The piezoelectric energy harvester of any one of claims 1 to 13 wherein the rotor is coupled to a shaft of a wind turbine for driven rotation of the rotor
10 by wind power in order to generate electrical power from the piezoelectric patches.

15. The piezoelectric energy harvester of any one of claims 1 to 13 wherein the rotor is coupled to a shaft of a water turbine for driven rotation of the rotor by hydraulic power in order to generate electrical power from the piezoelectric patches.

Fig. 1. Schematic diagram and geometries of the piezoelectric energy harvester.



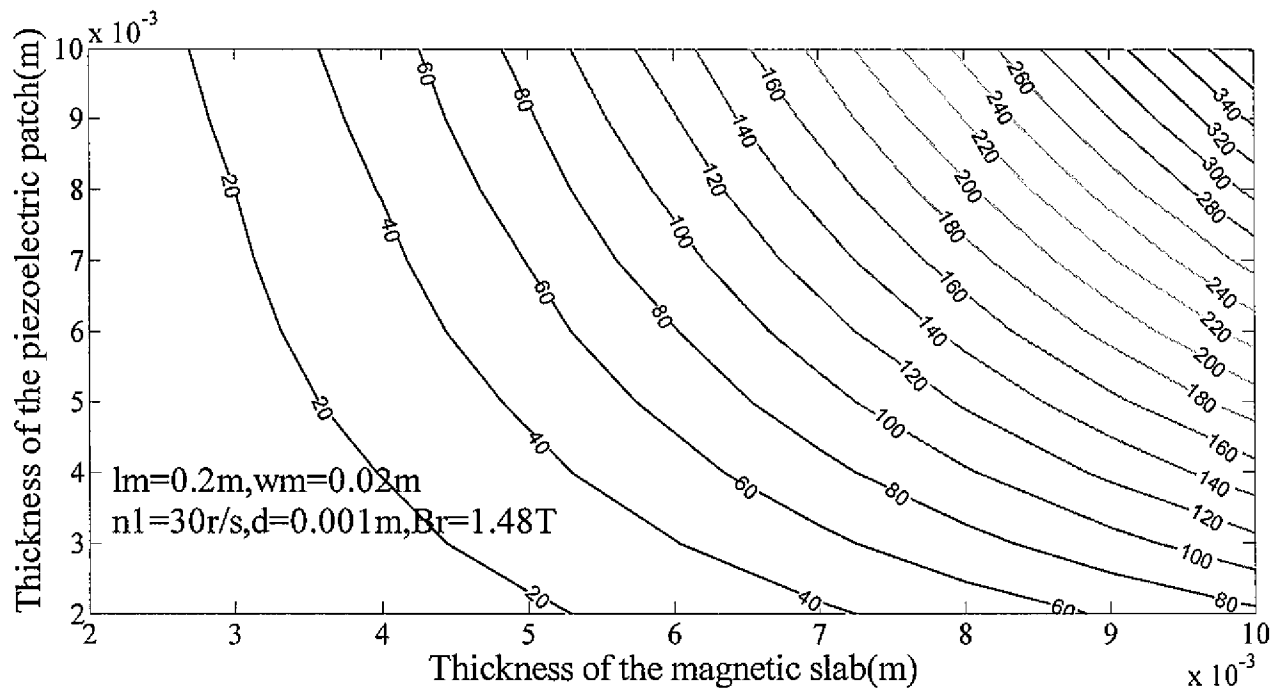


Fig. 2. RMS of the electric power (W) versus thicknesses of the magnetic slab and piezoelectric patch.

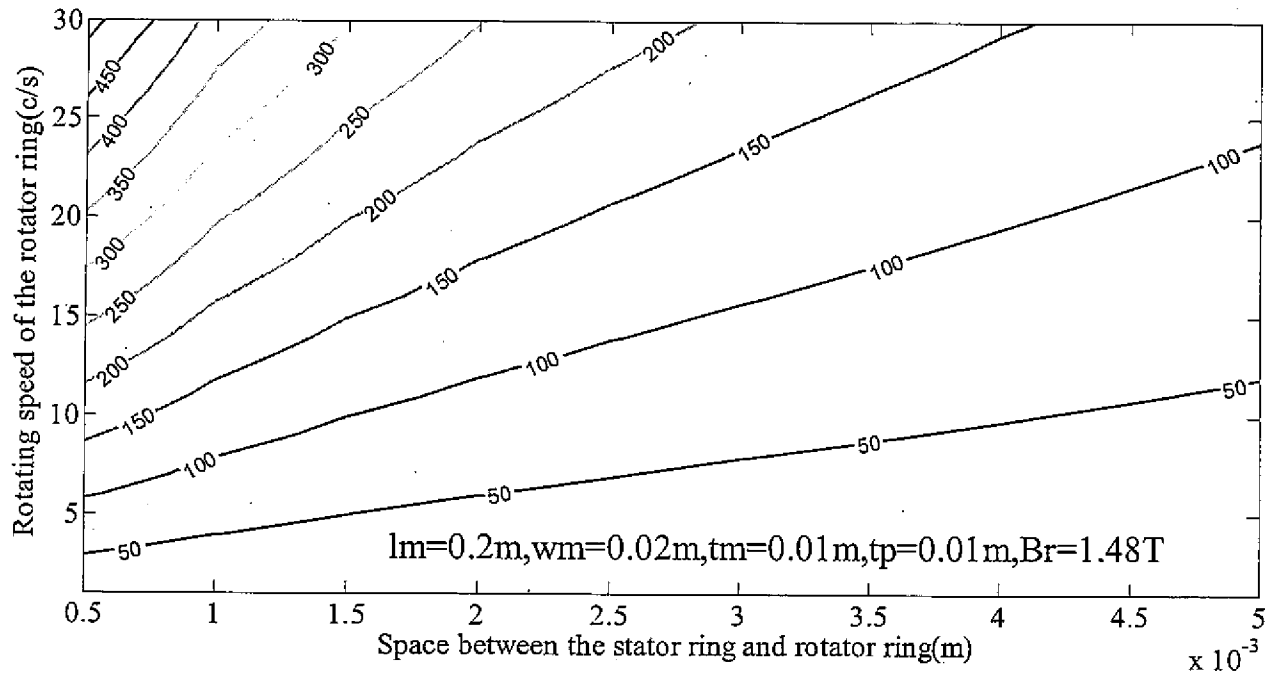


Fig. 3. RMS of the electric power ($\mathcal{W}$) versus the rotating speed of the rotator ring and the space between the stator ring and the rotator ring.

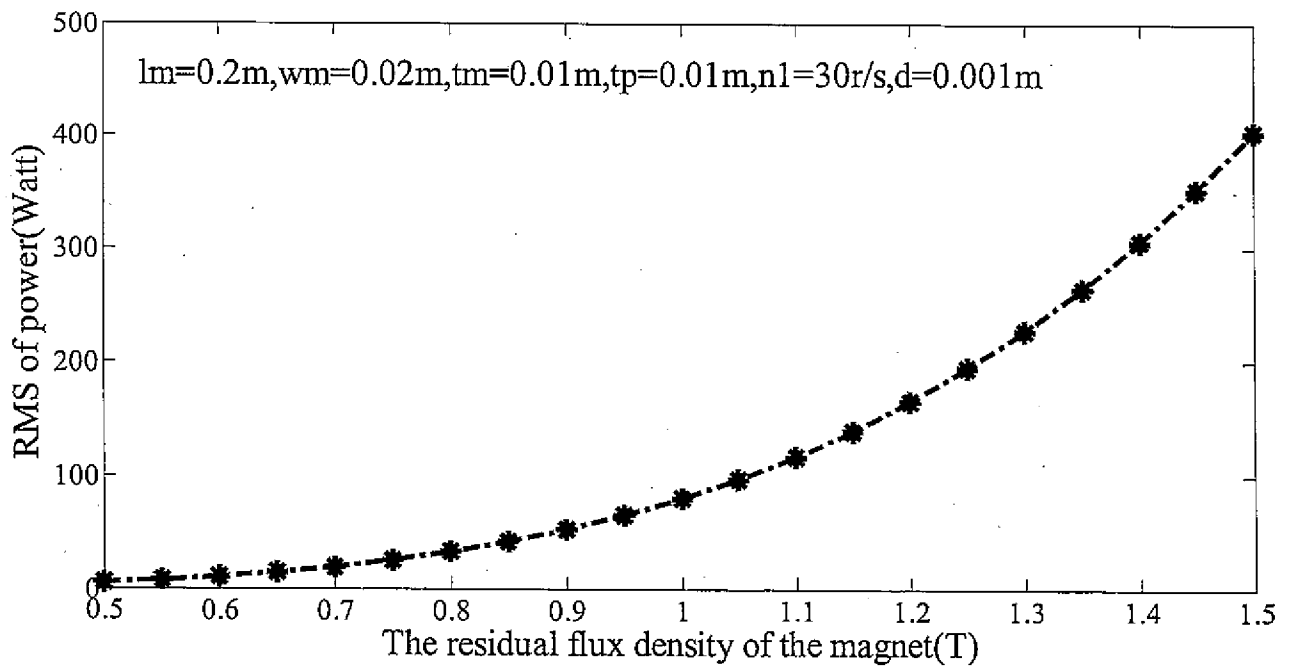


Fig. 4. RMS of the electric power ($\mathcal{W}$) versus the residual flux density of the magnet.

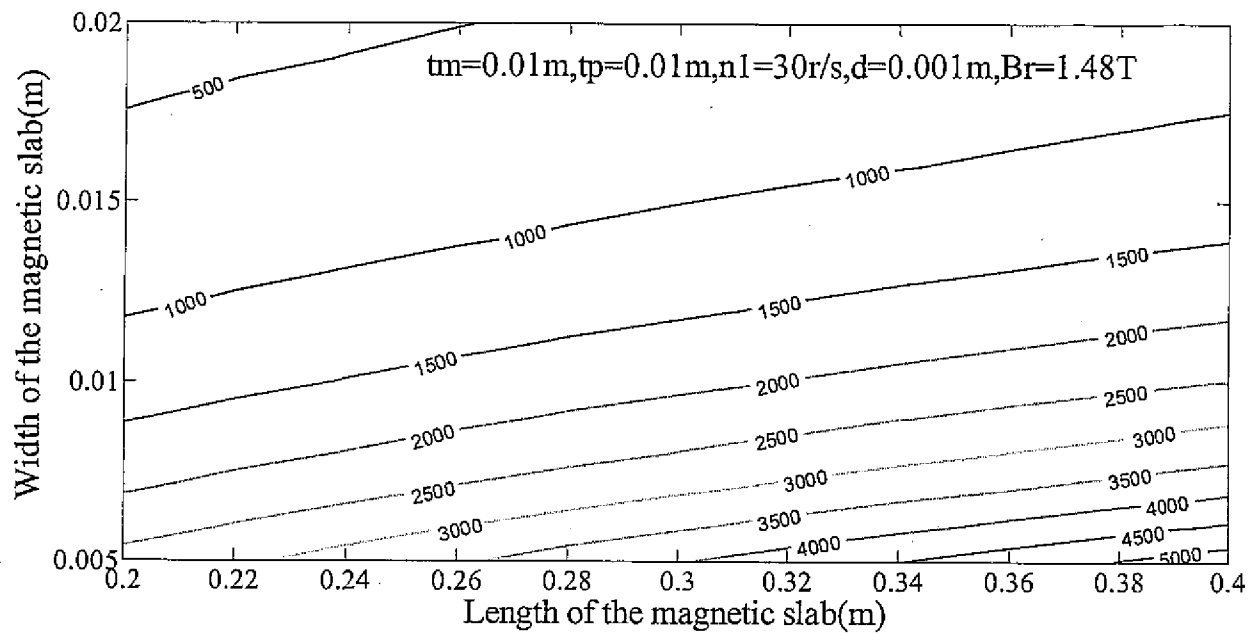


Fig. 5. RMS of the electric power (W) versus the length and width of the magnetic slab.

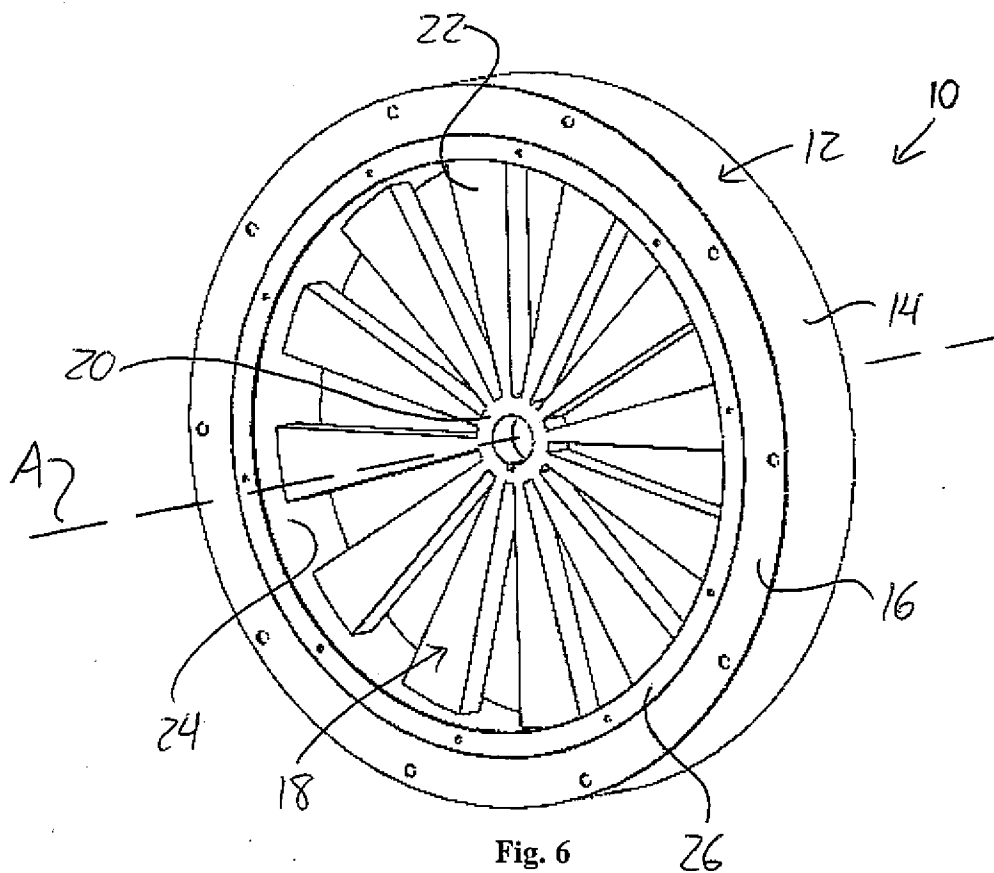
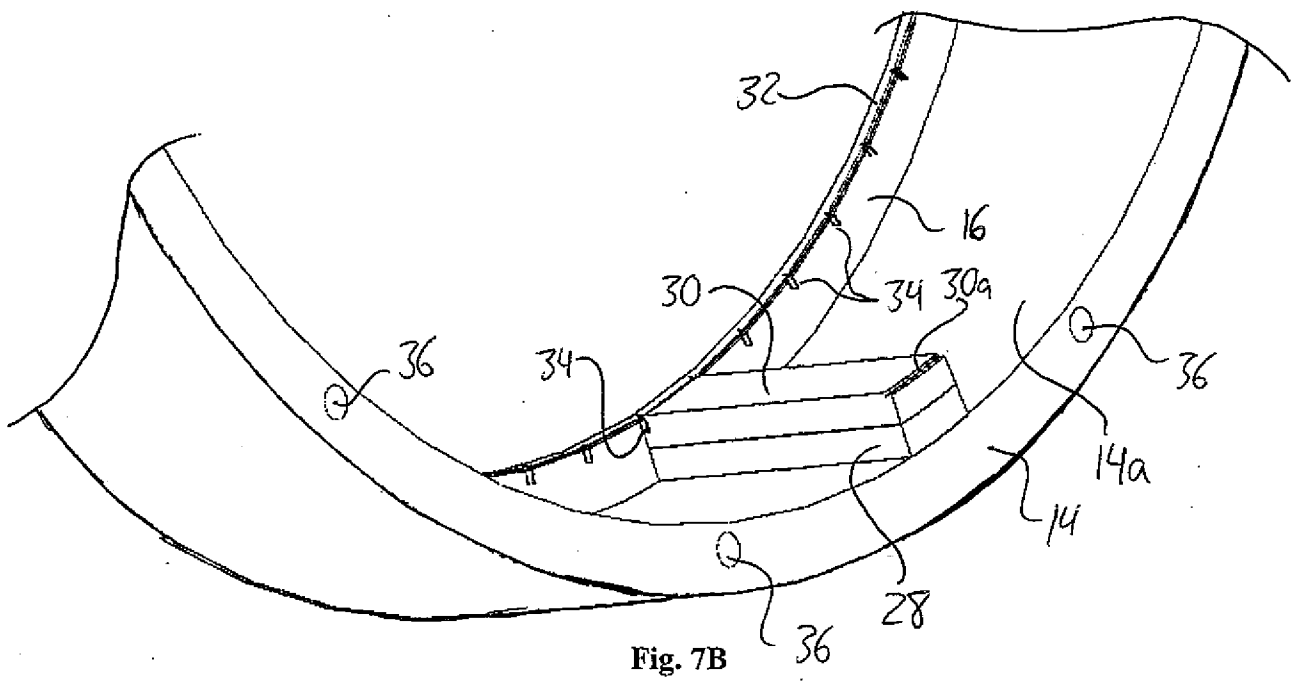
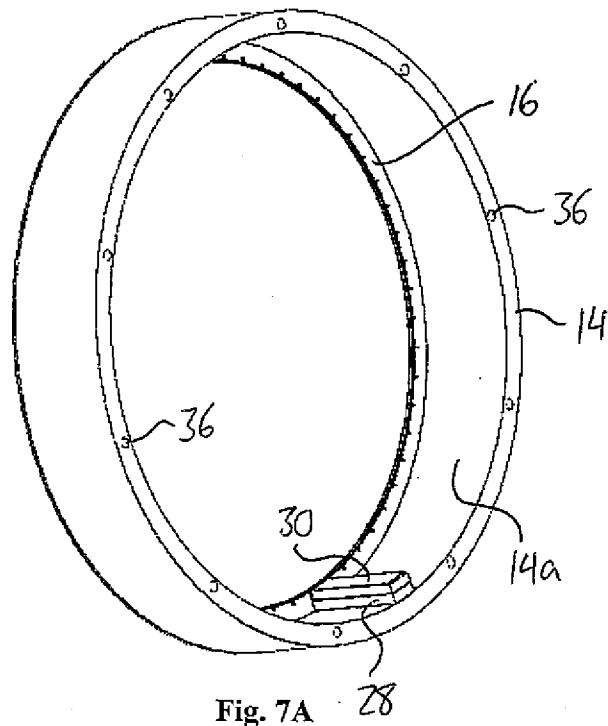


Fig. 6



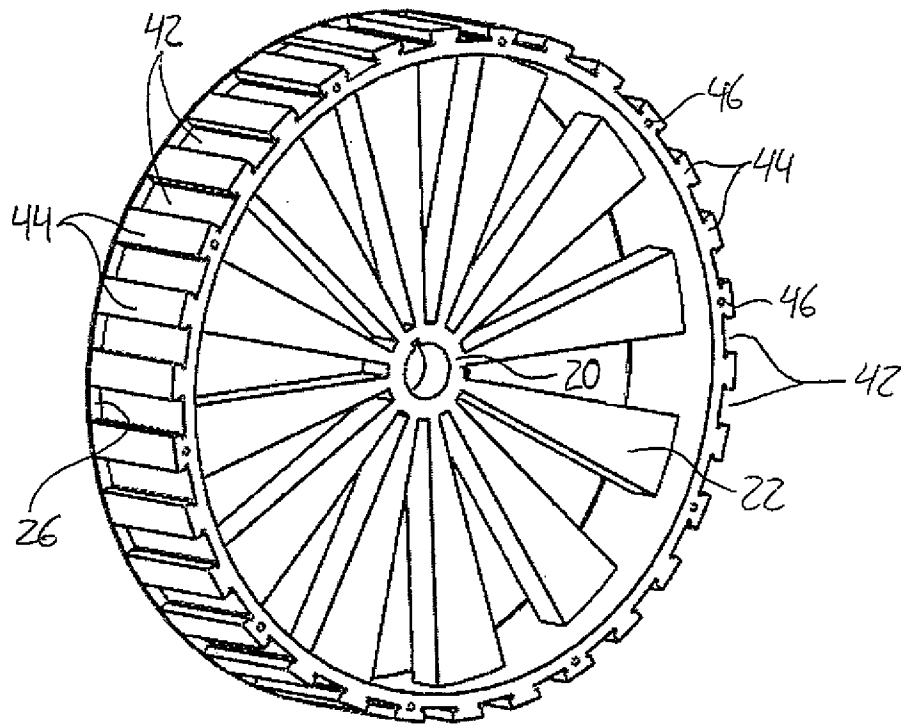


Fig. 8A

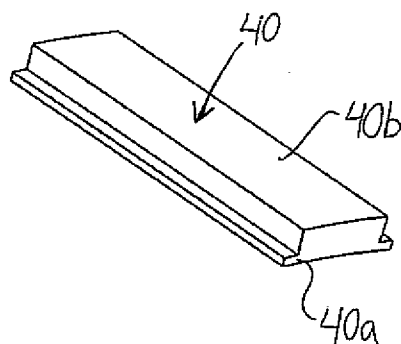


Fig. 8B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/CA2015/050270

A. CLASSIFICATION OF SUBJECT MATTER
IPC: **H02N 2/18** (2006.01), **H02K 1/27** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: **H02N 2/18** (2006.01), **H02K 1/27** (2006.01)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)

Canadian Patents database, Google Patents, Questel-Orbit Keywords: piezoelectric, stator, rotor, magnet

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US3539841, 10 November 1970 (10-11-1970), Riff Figure 1 Column 2, lines 4-20, 40-53	1, 14-15
X	WO2014012845A1, 23 January 2014 (23-01-2014), Kleipa Figure 1	1, 14-15
X	CN102223106, 19 October 2011 (19-10-2011), Yaoyu Figure 1	1, 14-15
P, X	CN103973161, 06 August 2014 (06-08-2014), Wang et al. Figures 1, 3	

 Further documents are listed in the continuation of Box C.

 See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
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"E" earlier application or patent but published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search
04 May 2015 (04-05-2015)

Date of mailing of the international search report
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INTERNATIONAL SEARCH REPORT

International application No.

PCT/CA2015/050270

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US7696673, 13 April 2010 (13-04-2010), Yavid - Whole document	
A	US5512795, 30 April 1996 (30-04-1996), Epstein et al. - Whole document	
A	US5637937, 10 June 1997 (10-06-1997), Nakajima - Whole document	

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/CA2015/050270

Patent Document Cited in Search Report	Publication Date	Patent Family Member(s)	Publication Date
US3539841A	10 November 1970 (10-11-1970)	None	
WO2014012845A1	23 January 2014 (23-01-2014)	WO2014012845A1 DE102012106376A1	23 January 2014 (23-01-2014) 30 January 2014 (30-01-2014)
CN102223106A	19 October 2011 (19-10-2011)	None	
CN103973161A	06 August 2014 (06-08-2014)	None	
US7696673B1	13 April 2010 (13-04-2010)	None	
US5512795A	30 April 1996 (30-04-1996)	US5512795A AU5117796A WO9628854A1	30 April 1996 (30-04-1996) 02 October 1996 (02-10-1996) 19 September 1996 (19-09-1996)
US5637937A	10 June 1997 (10-06-1997)	US5637937A DE69324603D1 DE69324603T2 EP0682403A1 EP0682403A4 EP0682403B1 WO9515610A1	10 June 1997 (10-06-1997) 27 May 1999 (27-05-1999) 16 September 1999 (16-09-1999) 15 November 1995 (15-11-1995) 17 September 1997 (17-09-1997) 21 April 1999 (21-04-1999) 08 June 1995 (08-06-1995)