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This paper presents the design and fabrication of a rotary-impact magnetostrictive energy generator, used to harvest the rotation of human knee joint. The harvester consists of twelve movable Terfenol-D rods, surrounded by the picked up coils respectively, and alternate permanent magnet (PM) array sandwiched in each part of the shell. Rotational electromagnetic power generating effect and impacted magnetostrictive power generating effect are designed in the harvester. Modeling and simulation are used to validate the concept. Then, magnetic field and leakage of the harvester are analyzed, electromagnetic force in the harvester is simulated. A prototype of harvester is fabricated, and subjected to the experimental characterization. It can be concluded that huge induced voltage generated in the short-time impact situation and that induced voltage in the harvester can reach up to 60-80 volts at 0.91Hz low frequency rotation. Also, the presented harvester has good harvesting effects at low frequency human walking and periodic swing crus situation, which are suitable to be used for future researches of wearable knee joint applications.
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I. INTRODUCTION

Vibration energy harvester used to harvest the rotation of human knee joint has gotten more attention, which is widely employed in self-powered design of wearable electronic devices. Consider the characteristics of human knee joint rotation, its vibration always appears as low frequency (1-2Hz), small angle deflection (0-90°) and huge drive torque (>50Nm).[1–3] Traditional hybrid structures of electric machines and gearboxes were always accompanied by high power density, but the size and mass were larger for wearable applications.[4,5] Harvesters based on piezoelectric ceramics exist with smaller size and mass, but with lower output electricity.[6,7] Magnetostrictive materials, such as TbDyFe alloy, show relatively high power density and efficiency,[8,9] also can be used in the design of magnetostrictive/electromagnetic hybrid structure,[10,11] which is useful to improve the power density and output electricity.

This paper presents the design of a rotational magnetostrictive energy harvester. The proposed harvester converts vibration from the rotated human knee joint to electricity by using the magnetostrictive effect and electromagnetic effect. Modeling, simulation and testing are used to validate this concept. Prototype of harvester is fabricated, and its harvesting effect and induced voltage are discussed. In this paper, use of piezomagnetic effect to fabricated harvester is not new, but the use of movable magnetostrictive materials and alternate PM array is a new concept.

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II. CONCEPTUAL DESIGN

A. Concept and modeling

Villari effect, also called piezomagnetic effect, is a typical physical characteristic of magnetostrictive material. Terfenol-D is one of the typical products for magnetostrictive material, which exhibits larger piezomagnetic effect. The behavior of magnetostrictive material can be expressed by the linear constitutive equation

$$B = d_{33}^{*}\sigma + \mu^{\sigma} H \tag{1}$$

where B is magnetic flux density, σ is stress, H is magnetic field, $d^{*}{}_{33}$ is the change in B with stress at a constant H, and μ^{σ} is the relative magnetic permeability at a constant stress σ.

Magnetostrictive harvester converts magnetic flux changes in Terfenol-D rod to electricity using a wound coil. The induced voltage in the coil with N turns can be written as

$$V = -N\frac{d\Phi}{dt} = -NA\frac{dB}{dt} = -NA \cdot (d_{33}^{*} \cdot \frac{d\sigma}{dt} + \mu^{\sigma} \cdot \frac{dH}{dt}) \tag{2}$$

where A is a cross-sectional area of the Terfenol-D rod, dσ/dt and dH/dt are the change in stress and magnetic field with time, respectively.

In traditional magnetostrictive harvester,[8,9] magnetic field is considered as a constant parameter ($\triangle H$=0) in the action of stress. Its harvester effect can be expressed as $d_{33}^{*} \cdot d\sigma/dt$. But shown in equation (2), value of induced voltage in the wound coil including two parts: magnetostrictive effect ($d_{33}^{*} \cdot d\sigma/dt$) and electromagnetic effect ($\mu^{\sigma} \cdot dH/dt$). If both stress changes and magnetic field changes exist in a harvester, more electricity will be generated.

Based on this idea, a rotational magnetostrictive/electromagnetic hybrid harvester is presented, as shown in Fig. 1. Twelve flat Terfenol-D rods set in a rotator uniformly, surrounded by the corresponding picked up coils, can slide in the middle of each coil freely. The rotor is fixed on the shaft, driven by the rotation of human knee joint. Six permanent magnets with the same magnetizing direction assemble at each inside part of the stator, which is surrounded by the soft magnetic materials. A certain air gap exists between the stator and the rotor. Fig. 1c introduces the magnetostrictive materials and alternate PM array in the harvester. When the rotor rotates, Terfenol-D rod named b moving smoothly from right to left, magnetic field in Terfenol-D changes, expressed as $\triangle H \neq 0$. In this process of rotation, the electromagnetic force in the axial of Terfenol-D rod also changes, which leads to Terfenol-D rod named b jumping from bottom to top with huge impact stress appearing in this moment. Movable magnetostrictive materials are designed and alternate PM array is selected and used to fabricate the hybrid harvesting effect. Rotational electromagnetic power generating effect and

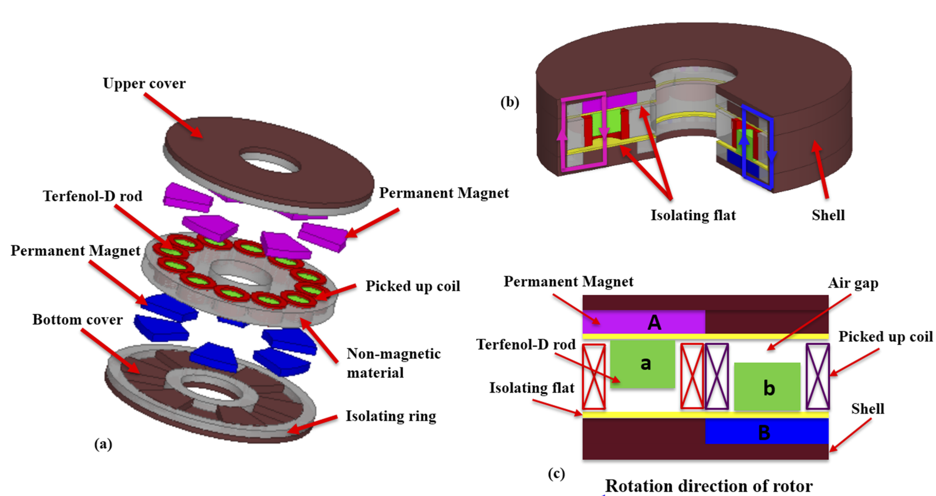

FIG. 1. Concept of magnetostrictive harvester. (a) exploded diagram, (b) closed magnetic circuit in the harvester, (c) magnetostrictive materials and PM array.

impacted magnetostrictive power generating effect are designed in the harvester, which shows more power density and efficiency.

B. Simulation

Simulation using Ansys software is conducted to design a proper air gap configuration in the harvester. In the simulation, the shell is made by 10 gage steel, and non-magnetic material is made by aluminum alloy. Permanent magnetic is selected as NdFe35. Also, relative permeability of Terfenol-D rod used in this paper is 12. The turns of the solenoid coil are 530.

The dimension of Terfenol-D rod is φ10×5mm, surrounded by a φ11-φ18mm (internal diameter-external diameter) solenoid coil, set at the position of circle r=45mm uniformly. The internal diameter and external diameter of the permanent magnetic (PM) is φ30mm and φ60mm respectively, and the angle of each PM is 30°. In the simulation, Terfenol-D rod is modeled as a fixed rod, set in the middle of the coil with a same value length l_g in each part. Simulation results of harvester are introduced in Fig. 2.

Fig. 2a–2c introduces the FEM model and distribution results of magnetic density. As shown in Fig. 2b and 2c, magnetic leakage in the radial direction of each Terfenol-D rod induced larger value. The average value of magnetic field in rod can be calculated as

$$B_{avg} = \frac{\int_0^{r_0} B(r) \cdot 2rdr}{r_0^2} \tag{3}$$

where r_0 is the radius of the rod. Results of magnetic density B_{avg} with differ length of lg can be concluded, introduced in Fig. 2d. Magnetic density declines rapidly with the increasing of the length lg. In order to obtain larger rotational electromagnetic power generating effect in the harvester, the value of length lg should be selected smaller. lg<2mm (peak value of magnetic density B>0.53) is a good optimized choice.

Impact stress σ as shown in equation (2) is also another important factor in fabrication of the harvester, which can be calculated as

$$\sigma = \frac{F_{impact}}{A} = \frac{\sum_{i=1}^{n} (f_i \cdot \Delta t)/\Delta T_{impact}}{A} \approx \frac{\frac{1}{n}\sum_{i=1}^{n} f_i \cdot t}{A \cdot \Delta T_{impact}} = \frac{\frac{1}{n}\sum_{i=1}^{n} f_i \cdot \sqrt{4l_g/(\frac{1}{n}\sum_{i=1}^{n} f_i/m)}}{A \cdot \Delta T_{impact}} = \frac{\sqrt{4l_g \cdot m \cdot \frac{1}{n}\sum_{i=1}^{n} f_i}}{A \cdot \Delta T_{impact}} \tag{4}$$

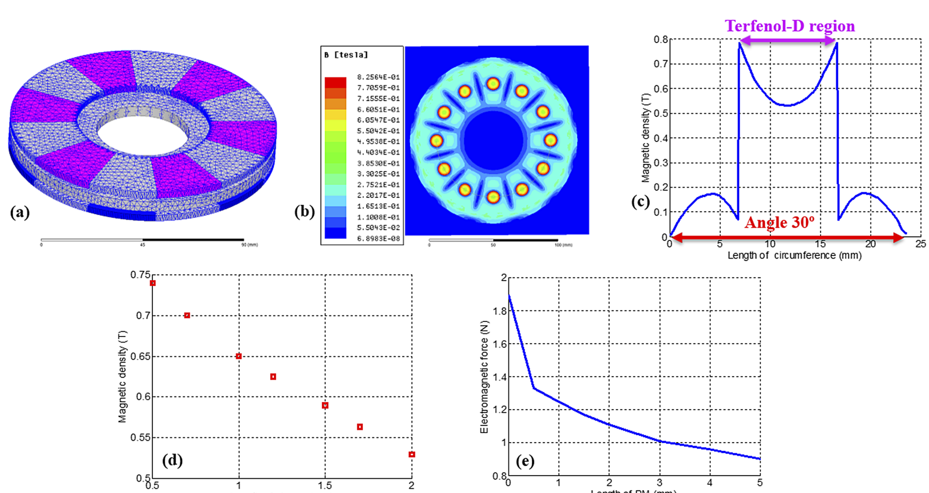

FIG. 2. Simulation results of the harvester. (a) mesh generation, (b) nephogram of magnetic density, (c) value of magnetic density in the radial of Terfenol-D rod (lg=1mm), (d) value of magnetic density with differ length of lg, (e) value of electromagnetic force with differ length of lg.

Here, F_{impact} is the impact force, $\triangle T_{\text{impact}}$ is the impact time, f_i is the electromagnetic force in Terfenol-D rod, and t is the slide time of the rod in the axial direction, m is the mass of the rod. As introduced in Fig. 1c, Terfenol-D rod named b jumps from bottom to top can be separated as: slide time t and impact time $\triangle T_{\text{impact}}$. $\triangle T_{\text{impact}} << t$, and slide process in the time of t can be consider as a constant acceleration motion for the small value of t. Fig. 2e is the simulation results of electromagnetic force in the rod, which can be briefly expressed as

$$f = k_1 \frac{B^2 A}{(1 + k_2 \cdot 2l_g)} \tag{5}$$

With the equations (3)–(5), it can be obtained that larger value of both magnetic density B and length lg are useful to enlarge the impact stress in the rod. So, l_g = 2mm is selected in the fabrication of harvester.

III. FABRICATION AND TESTING

Fig. 3 shows a prototype of the fabricated harvester. Alternate PM array sandwiched inside each part of the stator, as shown in Fig. 3a and 3c. Materials and its properties in the harvester are introduced in the first paragraph of Sec. II B. The diameter of proposed structure is 13cm, its size is control as 265cm^3, and its mass is 0.87kg.

In order to study the hybrid effect of the harvester, experiment includes four parts: 1) magnetic density test to validate the simulation, 2) impact test to predict the impact time and stress, 3) induced voltage test to calculate output power, 4) harvester test to simulate human walking (walking and swing crus). In the experimental setup, magnetic density is tested by use a tesla meter, and induced voltage is displayed on a digital oscilloscope.

IV. RESULTS AND DISCUSSION

Table I shows experimental and calculation results of magnetic density in the air gap. When the centerlines between the PM and the rod coincides (moment as shown in Fig. 1c), the angle mark as θ=0°. Distance a is the length between the centerlines of rod and test point in radial direction. As introduced in the testing results, max value of magnetic density appear at a=4mm, and min value of magnetic field exit at a=12mm. Experimental results are in good agreement with the calculation results (Fig. 2c), which verifies the accuracy of the theoretical analysis.

Fig. 4a introduces the testing results of induced voltage in the slide and impact situation. In this process, the rotor is fixed, and the centerlines of PM and rod are coincided (θ=0°). We test

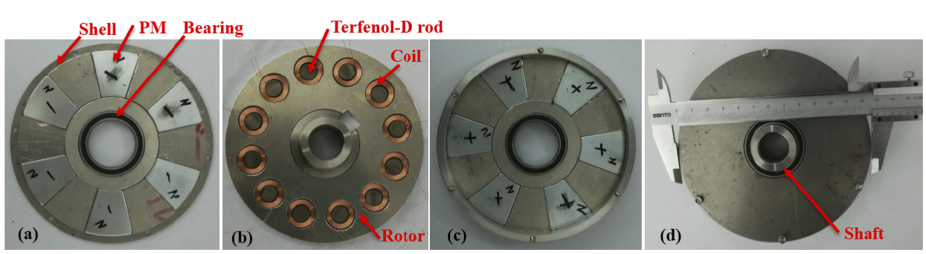

FIG. 3. Prototype of the harvester. (a) one part of stator, (b) rotor including Terfenol-D rods and pick up coils, (c) the other part of stator, (d) assembled harvester.

TABLE I. Values of magnetic density in the air gap.

Distance a (mm)	0	4	8	12	16	20	24
Exp. results	0.406	0.622	0.108	0.012	−0.11	−0.63	−0.412
Cal. results	0.42	0.64	0.12	0.02	−0.12	−0.64	−0.42

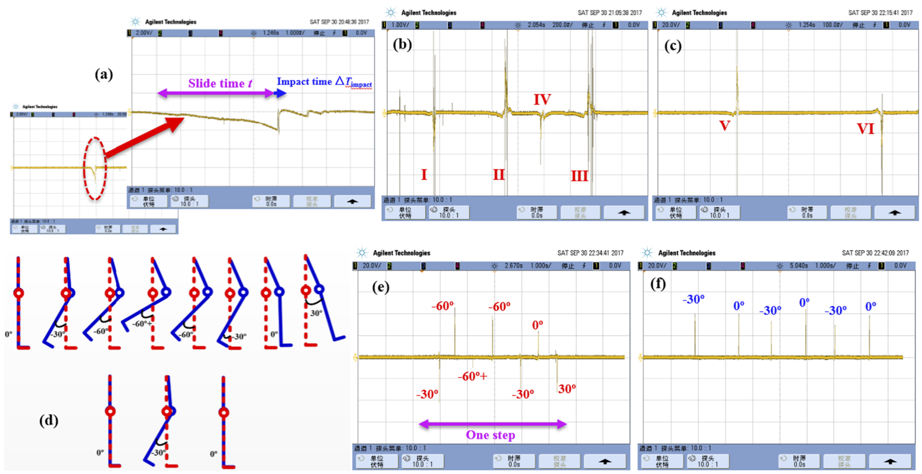

FIG. 4. Testing results of the harvester. (a) induced voltage in the impact situation (singal of one coil), (b) induced voltage in the harvester rotation (singal in one coil), (c) induced voltage (singal in the twelve series coils), (d) similate of human motion, (e) induced voltage in human walking situation, (f) induced voltage in periodic swing crus situation.

the induced voltage when the rod slides from the non-PM stator part to the PM part. As shown in Fig. 4a, the motion of the Terfenol-D rod includes two part: slide about t=5ms in the axial direction (pink line) and impact in a short-time about $\triangle T_{\text{impact}}$ = 0.2ms (blue line). So the impact force is easy to get up to 25 times the electromagnetic force as shown in equation (4), which leads to larger induced voltage in the coil. Peak value of the induced voltage in one coil is about 2V shown in Fig. 4a.

Fig. 4b–4c shows the testing results of induced voltage in the harvester (series connection of twelve coils). The harvester rotates smoothly and slowly, its speed of revolution is about 30°/0.55s (about 9.1 rpm). In the harvester, we can calculate angle 60°(two PMs) as one cycle, the frequency of the harvester is about 0.91Hz. Huge induced voltage exists in impact situation, such as I, II, III in Fig. 4b and V, VI in Fig. 4c. IV is a stochastic disturbance signal in the harvester rotation. Also, the value of voltage induced by the electromagnetic effect is smaller than impact situation, and its peak of voltage is only about 0.2-0.5V at 0.91Hz frequency in one coil. The summed peak value of induced voltage is about 3-5V in one coil, and about 60-80V in the twelve series coils.

Two types of rotation in the human knee joint are considered in our testing: one is a step of normal human walking with the angle changes about 0°→-30°→-60°→-60°+→-60°→-30°→0°→30°(top in Fig. 4d), the other is the periodic swing crus with the angle changes 0°→-30°→0°(bottom in Fig. 4d). The testing results are introduced in Fig. 4e–4f. Huge induced voltage exists in impact situation, like the angle position of 0°, -30°, -60°, 30°. The peak value of induced voltage in the human walking is about 20-40V. In the normal human walking situation, the induced voltage alters with periodic positive and negative effect, induced by the periodic variation of magnetic density and impact stress. In the periodic swing crus situation, all the values of induced voltage are positive, which can be calculated as changes between two same state parameter as (H_0, σ_0)→. . .→(H_0, σ_0).

As introduced in testing results, the induced voltage of the proposed harvester can be described as

$$V = K_1 \cdot \frac{\Delta\sigma}{\Delta T_{impact}} + K_2 \cdot \frac{\Delta H}{\Delta t} \tag{6}$$

Due to $\triangle T_{\text{impact}} << \triangle t$ and impact stress is larger, electricity is mainly induced by magnetostrictive effect, particularly in the low frequency situation (1-2Hz). Also, the harvester can generate more electricity in the higher frequency situation, which can be easily designed by shorten the time of ∆t, such as double the number of the PMs on each PM array.

V. CONCLUSION

In this paper, a new structure of magnetostrictive generator for harvesting the rotation of human knee joint was presented. In the harvester, rotational electromagnetic power generating effect and impacted magnetostrictive power generating effect were designed, movable magnetostrictive materials and alternate PM array were fabricated. The harvester can generate up to 60-80V induced voltage under 0.91Hz low frequency rotation, larger than traditional coil-type electromagnetic harvesters. The harvester also can be safely and efficiently used in low frequency human walking and periodic swing crus situation and has 20-40V induced voltage with V/W magnitude output electricity.

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