Parameter Study of the Variable Reluctance Energy Harvester for Smart Railway Axle Box Bearing

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*Abstract*—Self-powering capability for bearing health monitoring systems is an appealing ideal, which has attracted considerable attention but difficult to realize. This paper proposes a variable reluctance energy harvester (VREH) integrated within in smart railway axle box bearing. The effects of key parameters are numerically discussed to obtain the optimal geometrical parameters of the VREH under the limited inner space of the bearing. The experimental results verify that the optimization design of the VREH is practicable and effective. Under the rotational speed of 1200 r/min and impedance matching, the RMS voltage and power of the optimal load reaches 1.54 V and 39.53 mW, respectively.

Keywords—self-power, variable reluctance, health monitoring, theoretical modeling, finite element analysis, bearing

# Introduction

Sensors and sensor systems play an increasingly important role in the operation, management and maintenance of industrial machinery [1]. Conventional batteries provide power for such devices is inevitable to result in regular recharging and replacement, and the pollution of environment [2]. Electromagnetic [3,4], electrostatic [5,6] and piezoelectric [7,8] energy harvesters have been designed to convert the rotating motion into energy and power the wireless sensor and sensor system embedded on such rotating parts as bearings.

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In various energy harvesters, the electromagnetic energy harvester (EMEH) remains one of the leading topics because of the high energy density, easy fabrication and low cost [9]. Xu *et al.* [10,11] investigated a M-shaped VREH at low angular velocities. By optimizing the parameters affecting the performance of VREH through simulation and experimental analysis, the power density of VREH is demonstrated to be able to reach 157.29 mW/cm3. Kim *et al.* [12] combined a rotational module triggered by finger with an array of disc Halbach magnets to harvest electromagnetic energy. The proposed energy harvester could generate an open-circuit voltage of 1.39 V at an average power of 7.68 mW, with an optimal load of 36 Ω at an input frequency of 3 Hz. Kroener *et al.* [13] proposed a VREH for railroad monitoring applications. By conducting the finite element analysis (FEA) and experiments, a maximum energy output of 131 μJ per pulse was obtained under a train wheel passing speed of 81.5 km/h, corresponding to a mean output power of 5.9 mW. Zhang *et al.* [2,14] designed a EMEH with circular Halbach for bearing, and verified the effectiveness of proposed model numerically and experimentally. Under the rotational speed from 600-1000 r/min, the voltage of 2.79-4.59 V and the maximum average power of 50.8-131.1 mW can be obtained by the enhanced harvester.

This paper proposed a theoretical modal of VREH that extracted energy from the railway axle box bearing. Different from previous studies which put the energy harvester in the bearing end cover as an external accessory, we integrated the VREH with the bearing. According to the limited interior space of smart railway axle box bearing, to enhance the performance of VREH, the influences of various structure parameters on the output response are investigated through numerical simulation and experiments. The remainder of this paper is organized as follow: section 2 proposes the design and model of VREH; section 3 depicts the numerical analysis of VREH and analyzes the effects of system parameters on output response by comparing the simulation and theory; the effectiveness of VREH is verified by experiments in section 4; finally some conclusions are drawn in section 5.

# Modeling Of Vreh

* 1. *Structure of VREH*



Fig. 1. Schematic of the VREH in bearing.

Fig. 1 illustrates the proposed VREH in the smart railway axle box bearing. It comprises an E-shaped electrical steel, two permanent magnets, a coil, a toothed spacer, two inner rings, rollers and an outer ring of bearing. The E-shaped electrical steel, permanent magnets, coil and toothed spacer constitute a VREH. The E-shaped electrical steel is embedded in the outer ring of the bearing, and there is an air gap between the E-shaped electrical steel and the toothed spacer. The two permanent magnets with the same polarity are respectively located at the ends of two outer leg of the E-shaped electrical steel, and there is an air gap between the permanent magnets and teeth of the toothed spacer. The coil is wrapped around the middle leg of the E-shaped electrical steel.



Fig. 2. Structure of VREH and the magnetic flux density distribution at its two extreme position.

As the smart railway axle box bearing rotates, there is relative motion between the toothed spacer and E-shaped electrical steel, which makes the magnetic flux through the coil change with time. Therefore, according to Faraday's law of electromagnetic induction, the induction electromotive force will be generated by the coil. Since E-shaped electrical steel and toothed spacer are made of materials with high permeability, there are two extreme cases of magnetic flux within the coil, as shown in the Fig. 2. At the aligned position, the teeth of the toothed spacer are aligned with the legs of E-shaped electrical steel. The magnetic field induced by the two permanent magnets passes through the coil along the E-shaped silicon steel, and then passes through the air gap with the teeth of the toothed spacer to form the minimum magnetic path resistance, as shown in Fig. 2a. At the unaligned position, the teeth of the toothed spacer are not aligned with the legs of E-shaped silicon steel, and the magnetic field induced by the two permanent magnets passes through the coil along the E-shaped silicon steel, and then passes through the air gap and the slot instead of the teeth of the toothed spacer, forming the maximum magnetic path resistance, as shown in Fig.2b.

## Modeling of VREH

 Fig. 3. Definitions of geometric parameters in VREH.

With the rotation of the smart railway axle box bearing, the internal VREH converts the kinetic energy into the electric energy. The cross-section of smart railway axle box bearing without showing the inner ring and the roller is plotted in Fig. 3a. According to Faraday's law of electromagnetic induction, the induced electromotive force of the coil can be expressed as

 (1)

where *Nc* is the turns of coil, *Ф* is the magnetic flux through the coil, *dФ/dt* is the gradient of magnetic flux.

As shown in Fig. 3b, according to the geometry of the coil, the number of turns of the coil can be expressed as

 (2)

where *χ*, *δc*, *hc* and *dc* are the filling rate, width, height and the wire diameter of the coil, respectively.

The frequency of the output voltage of the coil is linear with the speed of the bearing and the number of teeth of the toothed spacer, which can be expressed as

 (3)

where *n* (unit: r/min) is the speed of the bearing, *Nt* is the number of teeth, *DI*\_2 is the outer diameter of the bearing inner ring, *ht* and *bt* are the height and width of the tooth of the toothed spacer, respectively.

As the time-varying flux in (1) is a uniform sinusoidal voltage, the peak-peak value of the output voltage *Vpp* generated by the coil can be expressed as

 (4)

where *ΔФ* is the difference between the maximum flux *Фmax* and minimum flux *Фmin* of the coil, *Tc* is the period of the induced electromotive force of the coil, *ζm=H•hm* is the magnetomotive force generated by the permanent magnet, *H* is the magnetic field strength of the magnet, *hm* is the height of the magnet, and *τmin* and *τmax* are the minimum and maximum reluctance, respectively.

In the magnetic path of the proposed VREH, the permeability of the material used in the E-shaped electrical steel and the toothed spacer are relatively larger. When calculating the reluctance, only the magnets and air gap between the permanent magnet and the toothed spacer is considered, which can be expressed as

 (5)

where *g=gmin* is the air gap at the maximum flux of the coil, the air gap is *g=gmin+ht* at the minimum flux, and *μg* is the relative permeability of the air, *at* and *bt* are the thickness and width of any tooth of the toothed spacer, *μm* is the relative permeability of the permanent magnet, and *am* and *bm* are the thickness and width of the permanent magnet, respectively.

Since the magnetization direction of the permanent magnet is along the radial direction of the bearing, a coordinate system is established with the original point located at the center of the permanent magnet, as shown in Fig. 3c, according to the magnetic load theory [15] and the magnetic node theory [16], the magnetic field strength of given point *P(x,y,z)* along the magnetization direction, which produced by this magnet can be expressed as

 (6)

where, *J* is the uniform magnetization along the magnetization direction, *μ0* is the vacuum permeability, and *Uq=x-*(-1)*q •am, Vm=y-*(-1)*m•bm, Wk=z-*(-1)*k•hm, r=√Uq*2*+ Vm*2*+ Wk*2.

Substituting (3), (5), and (6) into (4), the expression of the peak-peak voltage *Vpp* generated by the coil is easily obtained as

 (7)

where *b=bt=bm*.



Fig. 4. External circuit with impedance matching.

Due to the high speed of railway bearing, the inductance of the coil cannot be neglected. In order to obtain the optimal output power from the VREH, the coil is equivalent to a series of inductance and resistance, after impedance matching, as shown in Fig. 4, the RMS voltage of the load resistance *UL,rms* can be expressed as

 (8)

where, *Ztotal=RL-j/*2*π•fc•CL+Rc+j•*2*π•fc•Lc*is the total impedance, *CL=1/(2π•fc)2•Lc* is the matched capacitance, and *RL=Rc* is the matched resistance.

Substituting (7) into (8), the expression of the effective value of voltage of the load resistance *UL,rms* can be easily obtained as

 (9)

where the internal resistance of the coil can be expressed as

 (10)

Under impedance matching, the RMS power *PL,rms* of the load can be expressed as

 (11)

According to (9) and (11), the RMS voltage of the load is linear with the speed of the bearing n, the width *δc* and height *hc* of the coil, while RMS power is quadratic with those parameters. Moreover, the value of RMS voltage and power of the load are related with the minimum air gap *gmin*, the height of the permanent magnet *hm*, the height of the toothed spacer *ht* and the tooth width of the permanent magnet and the toothed spacer *b*. Due to the limited inner space of the bearing, the summation of coil height *hc* and the tooth height *ht* of the toothed spacer are set as a fixed value, namely *hc+ht=C*, and the thicknesses of E-shaped electrical steel, magnets, toothed spacer are the same, 3mm, and other parameters are listed in the Table Ⅰ according to the actual working condition of the VREH. Then the RMS voltage and power of the load as functions of the coil height *hc* and the tooth height *ht* of the toothed spacer are shown in the Fig. 5a and Fig. 5b, respectively.



Fig. 5. Theoretical calculation of the response of load with *hc+ht*=27mm.

Fig. 5 shows that the optimal value of RMS power of the load can be obtained with *hc*=17 mm and *ht*=10 mm.

1. Geometrical Parameters And Material Specification

|  |  |  |
| --- | --- | --- |
| **Domain** | **Parameters** | **Value** |
| Magnet | hm | 2-10 mm |
| bm | 5-15 mm |
| Material | N33AH |
| Coil | hc | 1-27 mm |
| dc | 0.15 mm |
| δc | 1.5 mm |
| χ | 0.45 |
| E-shaped electric steel | bE | 5-15 mm |
| Material | B35A230 |
| Toothed spacer | ht | 1-27 mm |
| bt | 5-15 mm |
| Material | Steel 45 |
| Air | gmin | 1-4 mm |
| μg | 1 |
| Inner ring and outer ring of bearing | DI\_2 | 150 mm |
| DO\_1 | 193 mm |
| DO\_2 | 230 mm |
| Material | GCr15 |

# Numerical Analysis Of Vreh

## Numerical Analysis Setup

To verify the validity and accuracy of the theoretical model, the finite element method is used to compare the simulation results with the theoretical calculation. Therefore, considering the influence of bearing outer ring and the symmetry of smart railway axle box bearing, the VREH structure is numerically analyzed based on 2D electromagnetic model. All the simulations are implemented in the Maxwell Ansoft. The parameters used in the simulation are consistent with those used in the previous theoretical calculation.

Due to the high speed of the bearing, the inductance of the coil cannot be neglected. In the simulation process, the external circuit of the coil is shown in Fig. 4. Where, *Rc* and *Lc* are the internal resistance and inductance of the coil and *RL* and *CL* are the matched resistance and inductance of the load, respectively.

## Effect of Key Parameters

According to the numerical results and the inner space limitation of the bearing, the influence of the air gap gmin, permanent magnet height hm, and tooth width of the permanent magnet and toothed spacer b are investigated under the rotating speed of 600r/min.



Fig. 6. The RMS response of the load under different minimum air gap.

The relationship between the RMS voltage and power of the load with the minimum air gap are shown in Fig. 6a and Fig. 6b, respectively. The trend of simulation results is consistent with that of theoretical calculation, which both decrease rapidly with the increase of the air gap.



Fig. 7. The RMS response of the load under different permanent magnet height.

Fig. 7a describes the RMS value of voltage and power of the load varying with the height of permanent magnet. The trend of simulation results is consistent with that of theoretical calculation, which increases first and then decreases with the increase of permanent magnet height. The optimal value occurs at *hm*=3 mm is with a low rate of change.



Fig. 8. The RMS response of the load under different the width of the permanent magnet and the teeth of toothed spacer.

Fig. 8 represents the RMS voltage and power of the load with different width of the permanent magnet and the teeth of toothed spacer. The theoretical results increase with the increase of the width of permanent magnet and teeth of the toothed spacer, while the simulation results decrease first and then increase. This difference can be caused by errors in the magnetic field distribution under the two-dimensional simulation model.

Simulation and theoretical results shows that the trends with the key parameters are the same, but the simulation results are smaller than the theoretical calculation, the difference is close to 20%. This is because we assume that the magnetic path of the VREH passes through the bottom of the slot of the toothed spacer at unaligned position. In fact, much of the magnetic flux leaks to the edges of the teeth, thus most of the magnetic flux cannot passes the slot as assumed, which can be verified in Fig 2b. Therefore, the modeled magnetic resistance difference between the aligned and unaligned positions is higher than the real case, resulting into a higher output compared with the simulation.

# Experiment Verifivications

## Experimental Setup

The VREH prototype is shown in Fig. 9, which consists of a toothed rotor, an E-shaped electrical steel, two permanent magnets, a coil and a 3D printed bracket. The permanent magnets and coil are bonded to the legs of E-shaped electrical steel, and the E-shaped electrical steel is supported by the PLA printed bracket.



Fig. 9. The prototype and installation of VREH.



Fig. 10. Experimental platform of VREH.

1. Optimal Geometrical Parameters

|  |  |  |
| --- | --- | --- |
| **Domain** | **Parameters** | **Value** |
| Magnet | hm | 3 mm |
| bm | 14.6 mm |
| Coil | hc | 17 mm |
| Toothed spacer | ht | 10 mm |
| bt | 14.6 mm |
| Air | gmin | 1 mm |

To verify the practicability and effectiveness of the proposed VREH and simulate the motion of VREH in the bearing, the VREH prototype is installed on a rotating platform, as shown in Fig. 10. The bracket is screw-mounted on the three-dimensional mobile platform, so the position of E-shaped electrical steel can be adjusted, to align its legs with the toothed spacer with a desired air gap. In order to avoid the eddy current effect, E-shaped electrical steel is processed by wire cutting, then stacked and welded by 6-layers of electrical steel laminations, with an overall thickness of 3.15mm. The toothed rotor is also screw-mounted on the balance disc of the platform. The toothed rotor is actuated by the rotating platform with shaft and the rotating speed can be adjusted. According to the previous parameter optimization study, structural parameters listed in Table Ⅱ are used for the prototype.

To obtain the optimal output power of the load, the output end of the coil is connected in series with a matching capacitor and resistor box, and the internal resistance and inductance of the coil was measured by a LCR-meter. All the experimental data are collected by the oscilloscope.

## Voltage Response



Fig. 11. Voltage response of the load under 600 r/min.

The minimum air gap is selected to 1 mm, and a 50 Ω load is connected at the output end of the coil in series. At the speed of 600 r/min, the voltage response of the load is shown in Fig. 11. As shown in the figure, the maximum value of the voltage response fluctuates periodically, and it is due to the construction of the experimental platform. There exist an eccentric errors between the toothed rotor and the shaft, causing a gap difference of 0.44mm between the maximum and minimum air gaps.



Fig. 12. The RMS response of the load under different rotational speed.

Figure 12 illustrates a linear relationship between the RMS voltage and rotation speed, which is consistent with the simulation results. Due to the existence of the air gap difference, the experimental results are slightly smaller than the simulation at higher speed.

## Response Range

In order to obtain response range of the load, the values of RMS voltage and power of the load are obtained under the speed of 1200 r/min. Fig. 13 compares the RMS voltage and power of the load with and without matched capacitance. Without the matching capacitor, the RMS voltage of 1.42 V and the RMS power of 22.4 mW are obtained, with an optimal load of 90 Ω. With the matching capacitor, the RMS voltage of 1.54 V and the RMS power of 39.53 mW can be achieved, with an optimal load of 60 Ω.



Fig. 13. The RMS response of the load with and without matched capacitor.

# Conclusion

### A VREH with enhanced configuration is proposed to support the wireless sensor in smart railway axle box bearing, which converts rotational motion into electric energy. The design device consists of an E-shaped electrical steel, two permanent magnets, a coil, a toothed spacer, two inner rings, rollers and an outer ring of bearing. Under the limitation of inner space of the bearing, the effect of several key parameters were investigated through theoretical modeling and finite element simulation, and optimal parameters of VREH were obtained. The experimental prototype was fabricated based on the optimal geometrical parameters, and rotating experimental platform is constructed to verify the accuracy of output prediction. In addition, the effect of the key system parameters and external excitation on output response characteristics are investigated. Experimental results indicate that the optimized VREH can generate a voltage of 1.54 V and a power response of 39.53 mW under the rotation speed of 1200 r/min.

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