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ENERGY HARVESTING POTENTIAL OF TERFENOL-D FOR ON-BOARD BEARING HEALTH MONITORING APPLICATIONS

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ABSTRACT

One of the limiting factors in on-board bearing health monitoring systems is the life of the batteries used to power the system. Thus, any device that can extend the life of the battery, or entirely replace it, is a notable improvement on any currently available systems. Existing on-board monitoring systems, not optimized for low power, are designed to run on approximately 300 mW of power. Current bearing health monitoring systems have proven effective with as few as one reading every four minutes. The environment under which railroad bearings operate is a harsh one, making most forms of energy harvesting very hard to implement. Terfenol-D is a novel and sustainable solution for this problem due to its durable characteristics and strong magnetostriction. A fixture is designed using multiple magnets of ranging magnetization to properly characterize energy harvesting using Terfenol-D. The maximum available power observed during these experiments is about 77 mW under ideal conditions. The generated power is sufficient to run low-power bearing health monitoring systems.

Key Words: Magnetostriction, Terfenol-D, Energy Harvesing, Sustainable On-Board Health Monitoring

INTRODUCTION

The conversion of mechanical stress to an electric potential was first discovered in 1881 when Gabriel Lippmann mathematically deduced the converse effect of pyroelectricity. Pyroelectricity is the generation of an electric potential from temperature changes. Piezoelectric materials are generally implemented in most energy harvesting situations using mechanical stress. They are chosen due to their ceramic nature and ease of use, simply creating a potential difference at opposing ends of their crystal structure. However, piezoelectric materials do not yield high power generation, generally producing high voltage and low current. Conversely, magnetostrictive materials generate more current with voltage that is at an easier level to use for most low power circuitry. Another limiting factor for piezoelectrics in applications with an environment as harsh as one present on railcar is their ceramic nature, making them fragile and unreliable. Magnetostrictive materials are much more durable in the direction of crystal alignment. With a properly designed fixture, they are capable of withstanding the environment in which they will be implemented. Out of the many magnetostrictive alloys, Terfenol-D is chosen for this application due to its significant magnetostriction. Terfenol-D is an alloy developed in the 1970s by the Naval

Ordnance Laboratory consisting of Terbium, Iron, and Dysprosium as a solution for sonar systems. The effect which will be utilized in this endeavor is inverse magnetostriction, commonly referred to as the Villari effect (the change in relative magnetic permeability of the material in response to a change in size). In order to exploit this effect, magnets are placed at either end of the Terfeno-D rod. This, in turn, generates a magnetic field through the core. When the fixture is either compressed or stretched, the relative permeability of the material will also change. This change in permeability will cause a fluctuation in the magnetic field emanating from the magnets, thereby generating a current in the coils of the wire.

FIXTURE DESIGN

To achieve maximum power generation and functional longevity of an energy harvesting system using Terfenol-D at its core, it is necessary to design a proper fixture. For this purpose, a cylindrical rod of Terfenol-D measuring 1.905 cm (0.75 in.) in length and 1.27 cm (0.5 in.) in diameter wide is used. A fixture for this application must not only confine the magnetic field, but also direct the majority of the force applied through the axis in which the crystals are aligned. By directing more magnetic field through the Terfenol-D core, energy generation is maximized and electromagnetic interference from the environment is minimized. Moreover, applying the majority of the force in the proper axis, the power generation is further increased, while protecting the Terfenol-D core from damage. To direct the magnetic field, it is necessary to surround the device with a material that has a high relative magnetic permeability. In order to focus the force applied along a single axis, the range of motion of the fixture must be restricted. Both of these requirements are achieved through the use of a piston-in-ring arrangement, shown in Figure 1.

The material chosen for the base, ring, and rod is 1018 steel as it has a high relative magnetic permeability, is very durable, and is easy to machine. The spool however, needs to be created out of a material with a low relative magnetic permeability, such that it does not direct the magnetic field away from the coils. Aluminum is chosen due to its relative permeability being close to one, allowing all the magnetic flux created in the Terfenol-D core to flow through the coil. That same spool is machined to be as long as the Terfenol-D core to ensure maximum flux is captured, then wound with 300 turns of size 28 AWG (American Wire Gauge) magnet wire. Smaller gauge would increase the energy generated, however a larger gauge was chosen to improve durability. A 1.905 cm (0.75 in.) notch is machined into the ring to allow the leads of the coil to be measured without greatly disrupting the flow of the magnetic field. The magnets will be placed on either end of the Terfenol-D rod. A magnetic model of this fixture was developed using Finite Element Method Magnetics (femm) and is shown in Figure 2.

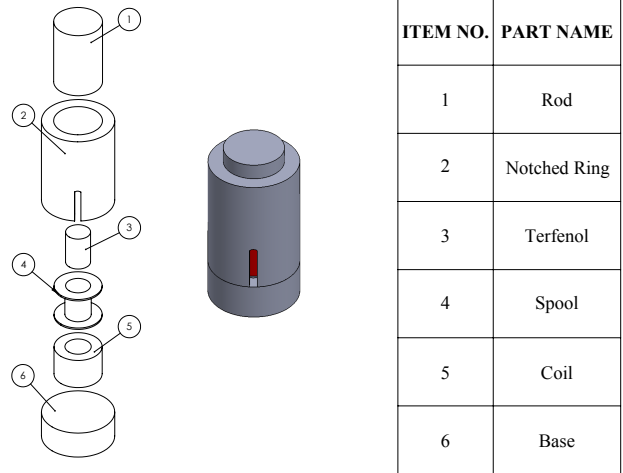The finite element modeling is important for two reasons.

ITEM NO.	PART NAME
1	Rod
2	Notched Ring
3	Terfenol
4	Spool
5	Coil
6	Base

FIGURE 1. MAGNETIC FIELD INSULATING FIXTURE

First, it is used to determine the precise effective permeability of the core material, which is dependent on operating conditions and is not tightly specified as manufactured. Inductance measurements are made with the sample in the fixture, and then the permeability in the FEM model is adjusted until a value matching measurements is found. Second, once the permeability has been found, the FEM simulation is used to ensure that the fixture adequately confines the magnetic field and provides a low reluctance magnetic circuit.

LOAD RANGE CALCULATION

Pressure film studies were carried out to show the distribution of load over the bearing adapter. The results of these studies at 50% and 100% load are shown in Figure 3. From the figure legend, the pressure exerted on the pad ranges from a minimum of 0 psi (no contact at all) to a maximum of about 1400 psi. The average pressure over the center of the pad is estimated to be approximately 600 psi. The average pressure can then be used to calculate the load range that needs to be withstood by the Terfenol-D based harvester. The relationship between pressure and force is: $p = F/A$, where p is the pressure, F is the force, and A is the surface area. Using the cross-sectional area of the widest point in the fixture, it is then possible to calculate the range of forces that will be used for testing:

$$F = pA \tag{1}$$
$$= (600psi)(\pi r^2) \tag{2}$$
$$= (600psi)(\pi(1in)^2) \tag{3}$$
$$\approx 1885lbf \tag{4}$$

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FIGURE 2. FEMM MODEL

FIGURE 3. PSEUDOCOLOR REPRESENTATION OF PRESSURE
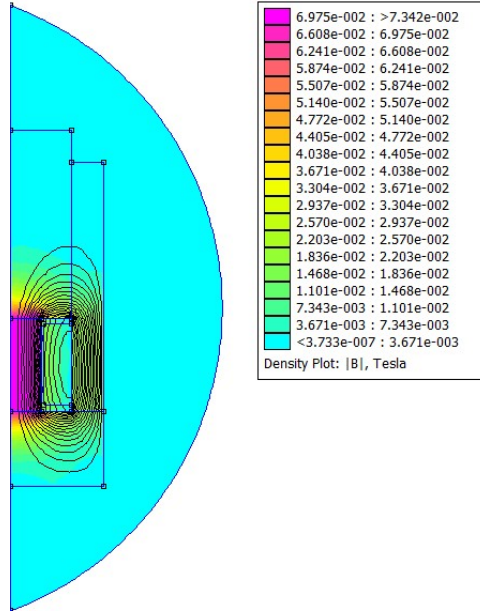
EXPERIMENTAL SETUP

All of the testing performed for characterization purposes was carried out using a Material Test System (MTS). A MTS is a system which can either compress or stretch a sample (depending on the setup) while simultaneously measuring the pressure, displacement, and force. By using a Flex Test 40 Controller in conjunction with Multipurpose Testware, it is possible to accurately control the MTS using force, displacement, and pressure. A load profile is created using the Multipurpose Testware software, oscillating load in a sinusoidal fashion from 50 to 2000 lbf (220 to 8900 N) at varying rates and idling long enough to record the voltage generated at each segment. A sample of the load profiles using a few different load rates is shown in Figure 4. The platens are aligned and an auto-level platen is installed to ensure the fixture remains centered. Once properly mounted, the ends of the coil are wired to an oscilloscope.

THEORETICAL DEVELOPMENT

The power can be calculated from the voltage measured with a known impedance for the coil. The impedance over a range of frequencies can be obtained for a coil by using the formula for the impedance of a coil at a given frequency and deriving the real resistance of the wire. The meter used for the duration of these experiments can measure the inductance at several testing frequencies: 100 Hz, 120 Hz, 1 kHz, and 10kHz . Those values, in conjunction with the series resistance present in the wire, can then be used to determine the exact impedance of the coil necessary for determining the generated power:
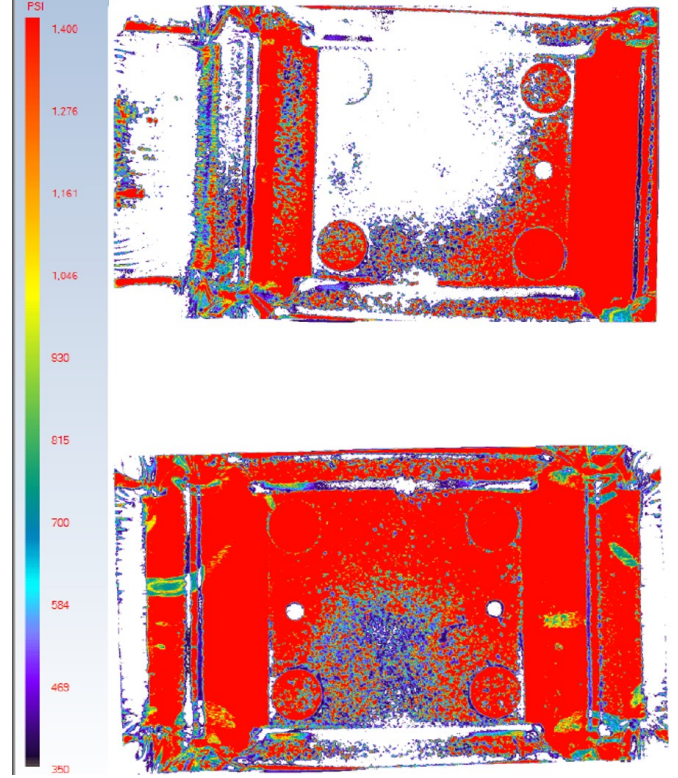
where Z is the total impedance of the coil, R_1 is the real part of the impedance, R_2 is the imaginary impedance, l is the length of the wire, A is the cross-sectional area, ρ is the resistivity of the copper, j is the square root of -1, L is the inductance of the coil, and f is the frequency of the system. It is difficult to measure the exact length of wire used to hand wind an inductor, however, the real impedance can be approximated by using the LCR meter and subtracting the imaginary impedance of the inductor. The inductance and impedance are measured at 100 Hz because it is the closest to the frequency range that will be used.

$$Z = R_1 + R_2 \tag{5}$$
$$R_1 = \rho l/A \tag{6}$$
$$R_2 = j\omega L \tag{7}$$
$$\omega = 2\pi f \tag{8}$$

$$R_1 = Z - R_2 \tag{9}$$
$$R_1 = (2.62 + j0.8466) - (j(2\pi(100Hz))(1.3483mH) \tag{10}$$
$$R_1 = 2.62 + j0.85 - j0.85 \tag{11}$$
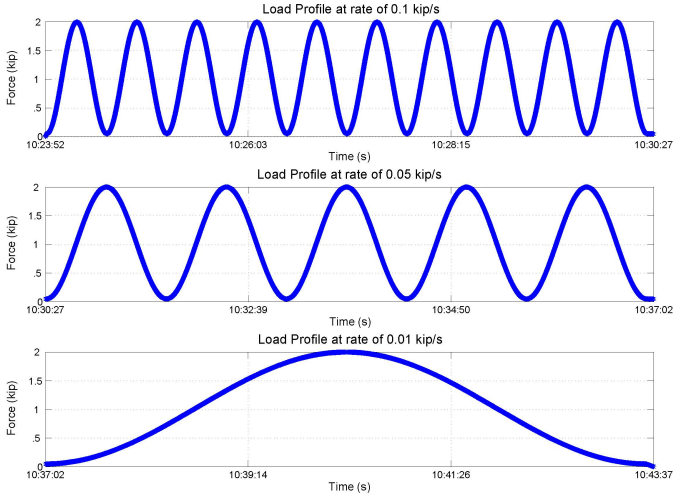$$R_1 = 2.62\Omega \tag{12}$$

FIGURE 4. LOAD PROFILE

Ideally, the voltage induced in a coil can be mathematically approximated using the formula:

$$V_{induced} = (d\phi)/(dt) \tag{13}$$
$$= NA(dB/dt) \tag{14}$$

where ϕ is the flux present inside the coil, t is time, N is the number of turns in the coil, A is the cross-sectional area, and B is the magnetic flux density vector. The magnetic flux between two dipoles can most closely be approximated by:

$$B = \mu_0 M_0/2 \tag{15}$$

where M_0 is the magnetization in the axis along which the magnets are aligned. The available power generated can then be calculated by manipulating the electric power equation:

$$P = V_{load}I_{load} \tag{16}$$
$$= (V_{oc}/2) * (V_{oc}/(2Re(Z))) \tag{17}$$
$$= V_{oc}^2/(4Re(Z)) \tag{18}$$

where V_{oc} is the RMS open-circuit voltage and a matched load is assumed. Using these formulas, the estimated values for the variables, and a conservative estimate of the magnetostrictive properties of Terfenol-D, power generation in the range of $(0.03 - 0.06$ *Watts*) can be expected.

INITIAL EXPERIMENT

Initial energy harvesting experiments were conducted using relatively strong magnets (~ 4500 *Gauss*) with the assumption

that the stronger the magnetic field, the greater the flux will be for a set change in permeability. This experiment is carried out using a 300 turn coil with a base inductance of $350\mu H(microHenry)$ inside of the "Magnetic Field Insulating Fixture" increasing the rate of load from $16\ kip/s$ to $120\ kip/s$ in increments of $4\ kip/s$. The load profile is similar to the one shown in Figure 4. The results for the initial energy harvesting experiments are presented in Figure 5.
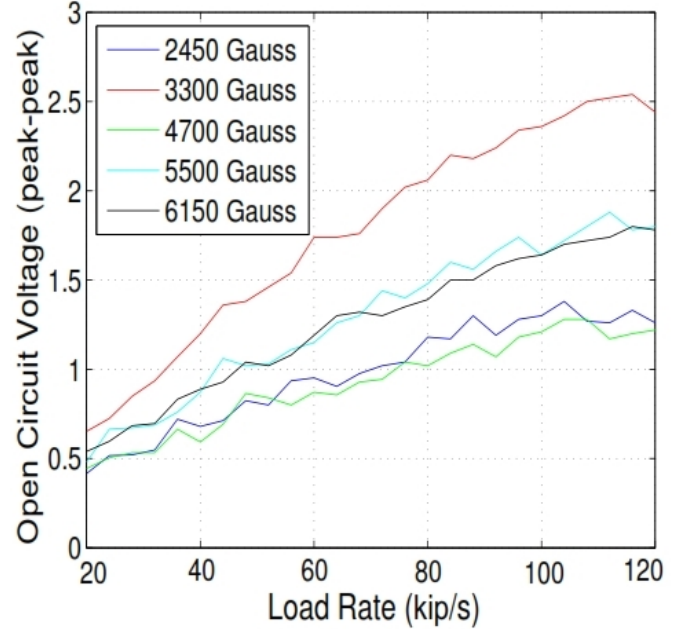

FIGURE 5. INITIAL ENERGY HARVESTING EXPERIMENT

The relationship between the load rate and the voltage generated appears to have an almost linear relationship until $88\ kip/s$, indicating that either the limitations of the MTS were reached, or $1.7\ V_{pk-pk}$ (peak-peak) is the maximum voltage these conditions can produce. Nevertheless, the power generated between $80\ kip/s$ and $120\ kip/s$ is more than sufficient to power a wireless bearing health monitoring system. With a general trend in mind, the experiment is repeated three more times to validate accuracy and repeatability. The recorded measurements are listed in Table 1 for simpler comparison across the three trials.

RANGING MAGNETIZATION

While the power generated from the initial energy harvesting experiments is sufficient to power a low-power on-board monitoring system during ideal conditions, it is still necessary to determine how the power generated is related to the level of magnetization and if anything else can be done to maximize power

TABLE 1. VOLTAGE GENERATION VS LOAD RATE CHANGE

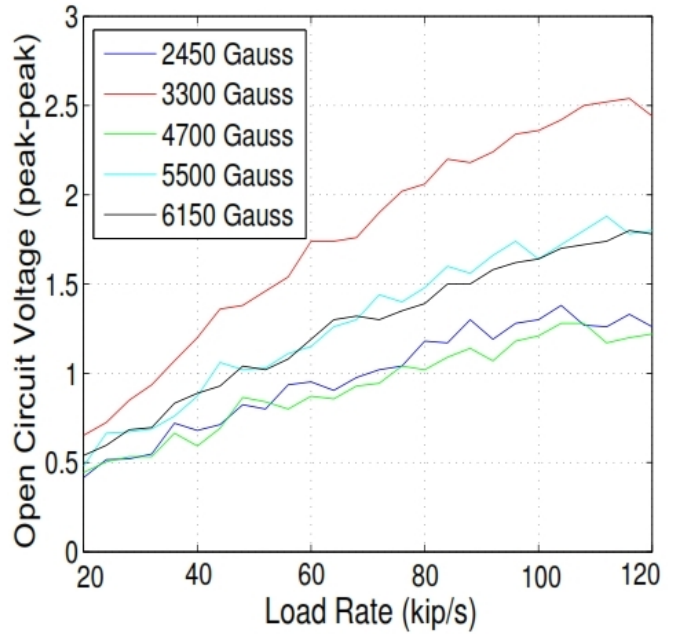| Rate	$Test 1$	$Test 2$	$Test 3$
(kip/s)	V_{pk-pk}	V_{pk-pk}	V_{pk-pk}
20	0.35	0.35	0.35
24	0.44	0.43	0.43
28	0.51	0.5	0.5
32	0.59	0.58	0.59
36	0.67	0.66	0.67
40	0.75	0.75	0.75
44	0.82	0.82	0.82
48	0.9	0.89	0.89
52	0.96	0.96	0.96
56	1.04	1.04	1.04
60	1.12	1.12	1.12
64	1.18	1.19	1.18
68	1.25	1.24	1.24
72	1.32	1.32	1.32
76	1.4	1.38	1.38
80	1.44	1.43	1.43
84	1.52	1.52	1.5
88	1.54	1.54	1.56
92	1.6	1.62	1.6
96	1.54	1.52	1.5
100	1.6	1.58	1.58
104	1.66	1.64	1.66
108	1.7	1.7	1.68
112	1.7	1.7	1.68
116	1.7	1.7	1.7
120	1.7	1.7	1.68

FIGURE 6. VARYING MAGNETIZATION ENERGY HARVESTING

MAXIMUM AVAILABLE POWER

From the plot shown in Figure 6, it can be noted that more energy was generated in a particular range of magnetization. This can be attributed to the magnetostrictive properties of Terfenol-D saturating below and above certain levels of magnetization. The relationship between the magnetosrictive strain and the applied field under different loads is shown in Figure 7.
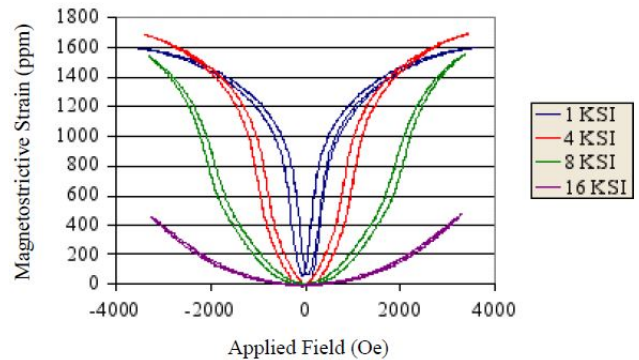

FIGURE 7. TERFENOL-D VS FIELD AT VARIOUS PRELOADS [1]

generation. Doing so would ensure that enough power is harvested even under unfavorable conditions. For this reason, five magnets of varying strengths from 2450 to 6150 *Gauss* are selected for testing. The same experiment is repeated several times for each magnet and then the average is taken across the trials. The acquired results are shown in Figure 6.

From the trends observed in Figure 7, a relationship for the applicable load range can be interpolated. The power gener-

ated by the fixture is dependent on the amount of flux created in the magnetic field. The flux in turn is directly related to the magnetostrictive strain of the Terfenol-D. Therefore, maximum power generation can be achieved during the linear segment of the curve. The only magnets available that are within this region are those with 3300 *Gauss* of magnetic flux density. Further experiments are conducted using those magnets to characterize the power generation and verify repeatability and reliability. The results of these tests along with an appropriate correlation are provided in Figure 8.
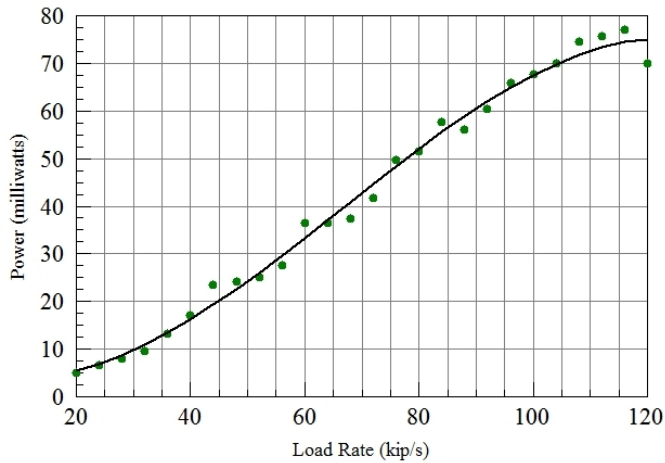

FIGURE 8. OPTIMAL ENERGY HARVESTING CHARACTERIZATION

The tests performed at nominal magnetization, indicate that a maximum power of 77 *mW* is feasible, with the sustainable power dependent on the actual operating conditions. If the aforementioned conditions are available for at least ten seconds, enough energy will have been generated to power a 40 *mW* onboard monitoring system for at least eighteen seconds. That amount of time is sufficient for relevant data to be recorded and transmitted. Therefore, an average of ten seconds of optimal excitation conditions (i.e. 120 *kip/s* of compression) available every four minutes would be sufficient to power such systems.

CONCLUSION

The main objective of the study presented here is to investigate the applicability of Terfenol-D as a potential energy harvester for low-power bearing health monitoring systems. A fixture was designed to enhance the power generating aspects while protecting the Terfenol-D core from damage. Calculations were performed to determine a possible load range for the dimensions of the fixture. Once the parameters were determined, a Material Test System program simulated the conditions of railcar going over an uneven track. Preliminary calculations estimated that the designed energy harvester is capable of providing a sustainable power generation in the range of $30 - 60$ *mW* during periods of high vibration. The actual power generated was 77 *mW*, which is significantly greater than the preliminary estimations. Moreover, this power range is relatively higher than preexisting power generation techniques that utilize Terfenol-D ($1 - 2$ *mW*). With the advancements made in low power electrical component design, the power generation levels produced by the developed Terfenol-D energy harvester are sufficient to run low-power bearing health monitoring systems. An example of the power consumption of the main components required for a bearing health monitoring system is presented in Table 2. Future research will include measurement of average power generation using an actual bearing adapter mounted in a vehicle operating on its regular route.

TABLE 2. POWER CONSUMPTION OF MAIN COMPONENTS

Component	Power Consumption (*mW*)
Microcontroller	5
Accelerometer	1
Strain gauge	1
Thermocouple	1
Transmitter	20
Assorted Supporting Circuitry	5
Total	**33**

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