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PERFORMANCE OF A THERMOELECTRIC-BASED ENERGY HARVESTING DEVICE ON A REALISTIC RAILROAD ROUTE

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ABSTRACT

Researchers at the University Transportation Center for Railway Safety (UTCRS) have developed an onboard wireless monitoring device to gauge the health of freight railcar rolling stock. A wireless system will allow for preemptive maintenance to occur, potentially saving millions of dollars in damages and ensuring the safety of passengers and cargo. A prototype energy harvester has been developed that can extend the battery life of the wireless monitoring device. It uses Thermoelectric Generators (TEGs) mounted on the bearing adapter to convert heat generated from the bearings to electricity. Previous results have shown that, under optimal conditions, TEGs have been able to produce enough energy to meet the power demands of low-power circuit boards. This paper summarizes the proof-of-concept validation of the complete energy harvesting device which includes the performance of the TEGs, heat sinks, boost converter, and the Battery Management Chip (BMC) working in tandem. The testing results were acquired by replicating field service conditions using a test plan that reproduces speeds encountered on a realistic railroad route and run on a laboratory dynamic bearing test rig. The test plan simulates a train completing a round trip between Billings, MT and Council Bluffs, IA. Preliminary testing results show that, over an average trip where train speeds vary, the energy harvesting system can significantly extend the battery life by producing enough energy to maintain or increase the charge of the battery while also powering the sensors and wireless transceiver for the duration of the trip.

Keywords: Energy harvesting, thermoelectric generators, health monitoring modules, rolling-stock condition monitoring.

1. INTRODUCTION

The wireless monitoring device is an onboard solution to continuously assess the health of axle wheels and bearings deployed in rail service. This device has been proven, both in a laboratory setting and in a pilot field test, to successfully flag defective bearings using an optimized algorithm that analyzes one-second of acceleration data [1]. The length of the time sample is significant for battery life, since it determines the amount of data that must be transferred. To allow fully wireless operation, an energy storing element is needed to provide a power source for continuous functionality. By implementing an energy harvesting system, the lifespan of the wireless monitoring device can be significantly increased minimizing, or perhaps eventually eliminating the maintenance required to replace the batteries. In addition to having a longer lifespan, the harvesting system is also able to increase the efficacy of the device. This is achieved by allowing the wireless monitoring device to use a more power demanding algorithm that will utilize four-seconds of data for a more accurate analysis.

Previously published work has shown the potential for thermoelectric generators (TEGs) on a bearing adapter to produce up to 60 mW under optimal conditions [2]. However, this previous work did not fully consider the efficiency of the boost conversion and battery management electronics under variations of speed and railcar load. The energy harvesting device is composed of two stages of electronic circuits: a boost converter, and a battery management chip (BMC). The boost converter is mostly composed of highly energy efficient elements that allow the booster to reach over 95% efficiency in its ideal range [3]. The battery management chip on the other hand can introduce losses due to the component not being optimized to track the maximum power point of the TEGs under various suboptimal railcar operating conditions.

The experiments in this study aim to validate the performance of the complete energy harvesting device. This will be achieved by mounting the prototype harvesting system to a UTCRS dynamic bearing test rig while using a test plan that simulates a common rail freight route. Three main experiments will be conducted to gauge the performance of the energy harvesting device. The first experiment will use the energy harvesting system connected to the batteries but not the onboard wireless condition monitoring device. This experiment will help quantify the losses that occur when the circuitry needed to recharge the batteries is added. The second experiment will only involve the wireless monitoring device connected to the battery. This experiment will be used to determine the power consumption of the wireless monitoring device. The third experiment will have the energy harvesting device connected to both the batteries and the wireless monitoring device. This test will help verify if the harvesting system can provide enough energy to keep the batteries charged as they simultaneously power the wireless monitoring device using a one-second algorithm.

2. MATERIALS AND METHODS

The UTCRS dynamic railroad bearing testers which replicate the operating conditions that railroad bearings experience in rail service were used to validate the performance of the energy harvesting device. The test rig used to perform the work for this study was the four-bearing tester housed in a temperature-controlled environmental chamber that allows for the ambient temperature to be maintained anywhere from -30°C to 60°C. Two energy harvesting devices will be tested simultaneously by placing one device on a defective bearing that contains a spall on the outer ring raceway (Bearing 2) and a second device placed on a healthy (control) bearing (Bearing 3) to compare how their operating temperatures will impact the performance of their corresponding harvesting devices.

The simulated route selected is commonly used by freight trains to transport coal between Billings, MT and Council Bluffs, IA. It is approximately 896 miles long and takes about 16 testing hours to complete this route on our test rig. Figure 1 shows this simulated route on the map.

FIGURE 1: MAP OF SIMULATED ROUTE [4]

TABLE 1: TEST PLAN FOR SIMULATED ROUTE

City/Area	Distance [mi]	Speed [mph]	Time [h]
Council Bluffs	0	25	0.97
Gretna	24.25	35	0.30
Ashland	34.75	60	9.83
Moorcroft	624.55	53	0.25
Rozet	637.80	45	0.40
Sheridan	655.80	60	4.01
Billings	896.40	60	0

Table 1 summarizes the cities the route intersects, the distances along the route, the train speeds simulated by the tester, and the time of operation at the set speed. The experiments are divided into two sections replicating the train traveling to its destination fully loaded (100% railcar load), and the train returning empty (17% railcar load) to its point of origin.

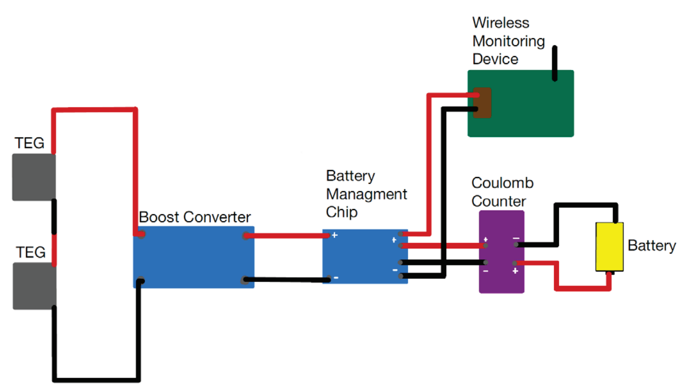

FIGURE 2: ENERGY HARVESTING DEVICE SCHEMATIC DIAGRAM

The schematic diagram of Figure 2 displays the wiring of the TEG devices, boost converter, battery charging module, Lithium-Ion battery, and the coulomb counter. A LTC 4150 Coulomb counter was installed between the battery and the battery management chip to keep track of the charge going in and out of the battery. The State of Charge (SoC) is measured in milliamp hours (mAh) and will be used to determine the average current and power going in the battery during the specified interval. The coulomb counter is paired with an Arduino-Uno circuit that is used to keep track of the charge. The coulomb counter setup is used solely for monitoring of the experiment and will not be implemented in the field. Since the coulomb counter and Arduino-Uno need energy to operate, they are powered using a separate power source to avoid affecting the results.

3. RESULTS AND DISCUSSION

3.1 Energy Harvesting Device Charging

The experiments for this study were performed on the chamber four-bearing test rig at an ambient temperature of 22°C (72°F). For this portion of the study, the energy harvesting system was connected to the battery only and not the wireless monitoring device. This setup allowed the amount of charge that could be generated in a single trip to be quantified. The batteries used for these experiments were 14500 Lithium-Ion cells with a capacity of 1100 mAh (4070 mWh). They were initially discharged to 0 mAh to determine if the harvesting device can produce enough current to start the charging process. This is an important criterion since the boost converters require a higher input voltage to self-start than to continue harvesting once started. This test determines if a completely discharged wireless onboard condition monitoring module could recover operation solely from power generated from the energy harvesting device. Table 2 through Table 5 give the duration, simulated train speed, average ambient temperature (T_{amb}), average bearing adapter temperature (T_{adp}), temperature difference (ΔT), the charge generated for the interval, and the average power.

TABLE 2: ENERGY HARVESTING DEVICE RECHARGING BATTERY AT 100% RAILCAR LOAD (BEARING 2) – DEFECTIVE BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
0.97	234 / 25	20.9	31.3	10.4	0.0	0.0
0.30	327 / 35	20.9	32.0	11.1	0.0	0.0
9.83	560 / 60	22.2	53.3	31.1	97.5	33.8
0.25	498 / 53	22.4	56.7	34.3	2.9	39.0
0.40	420 / 45	22.2	53.7	31.5	4.1	35.0
4.01	560 / 60	22.6	57.0	34.4	47.1	40.4
				Total:	**151.6**	

TABLE 3: ENERGY HARVESTING DEVICE RECHARGING BATTERY AT 100% RAILCAR LOAD (BEARING 3) – HEALTHY BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
0.97	234 / 25	20.9	41	20.1	4.3	14.3
0.30	327 / 35	20.9	42.6	21.6	1.7	18.6
9.83	560 / 60	22.2	58.8	36.6	128.7	45.3
0.25	498 / 53	22.4	56.4	34.0	3.1	42.6
0.40	420 / 45	22.2	54.1	31.9	4.3	37.0
4.01	560 / 60	22.6	57.3	34.7	48.1	42.0
				Total:	**190.2**	

Table 2 and Table 3 show the data collected for Bearing 2 and Bearing 3 at a full railcar load. At the initial 25 mph and 35 mph part of the experiment, the temperature difference between the ambient and the bearing adapter was about 10°C higher for Bearing 3 compared to Bearing 2. This resulted in the harvesting device attached to Bearing 3 producing 14.3 mW and 18.6 mW of power when the tester was set to 25 and 35 mph, respectively. In contrast, Bearing 2 produced 0 mW of power for both speeds. The zero-power production is believed to be the result of the temperature difference (ΔT) being too low for the TEGs to produce a voltage sufficient to start the boost converter. Once the tester speed was set to 60 mph, the temperature difference between the ambient and the bearing adapter increased significantly resulting in the highest amount of energy produced by both energy harvesting devices. This is due to the bearings generating more frictional heating at the higher operating speeds under full load conditions. For the first half of this experiment, the harvesting device on Bearing 2 produced a total charge of 151.6 mAh (13.8% of battery charge) while the device on Bearing 3 produced 190.2 mAh (17.3% of battery charge).

Table 4 and Table 5 show the data for Bearing 2 and Bearing 3 at an empty railcar load (17% load). The results presented in these tables show the temperature difference (ΔT) for both bearings being significantly smaller than that at the full railcar load (100% load). This is due to the lower weight of the railcar when it is unloaded reducing the frictional heating generated by the bearings and thus their operating temperature. This has a direct impact on the performance of the energy harvesting devices, reducing the amount of power that they can generate. For the empty railcar trip, which constitutes the second half of this experiment, Bearing 2 produced a total charge of 17.6 mAh (1.6% of battery charge) while Bearing 3 produced 23.3 mAh (2.1% of battery charge). Thus, for the round trip (loaded on the outbound and unloaded on the inbound), the energy harvesting devices on Bearing 2 and Bearing 3 produced a total charge of 169.2 mAh (15.4% of battery charge) and 213.5 mAh (19.4% of battery charge), respectively.

TABLE 4: ENERGY HARVESTING DEVICE RECHARGING BATTERY AT 17% RAILCAR LOAD (BEARING 2) – DEFECTIVE BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
4.01	560 / 60	21.0	37.1	16.1	7.5	6.5
0.40	420 / 45	21.3	37.8	16.6	0.9	7.3
0.25	498 / 53	21.3	36.9	15.6	0.4	4.8
9.83	560 / 60	21.5	34.7	13.2	8.7	3.1
0.30	327 / 35	21.3	32.3	10.9	0.1	2.0
0.97	234 / 25	21.0	28.9	7.8	0.0	0.0
				Total:	**17.6**	

TABLE 5: ENERGY HARVESTING DEVICE RECHARGING BATTERY AT 17% RAILCAR LOAD (BEARING 3) – HEALTHY BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
4.01	560 / 60	21.0	35.5	14.5	4.8	4.2
0.40	420 / 45	21.3	36.0	15.2	0.7	6.0
0.25	498 / 53	21.3	36.0	14.7	0.3	4.8
9.83	560 / 60	21.5	37.3	15.8	16.7	6.0
0.30	327 / 35	21.3	36.3	14.9	0.5	6.0
0.97	234 / 25	21.0	32.4	11.4	0.3	1.2
				Total:	**23.3**	

3.2 Wireless Onboard Condition Monitoring Device Power Consumption

For the next stage of testing, the wireless onboard bearing health monitoring device was connected to the battery without the energy harvesting device. This was done to provide a reference on how much power is being consumed during testing. Like what is proposed for field implementation, a one-second algorithm was executed on the wireless onboard modules to simulate the power draw in field service. The wireless monitoring device was powered using the same fully charged 14500 batteries previously used. The coulomb counter was placed between the battery and the wireless monitoring device to measure the amount of charge being consumed. The tester was operated for the same duration as in the previous experiment. However, since the wireless monitoring device power draw is not dependent on the speed or operating temperatures of the bearings, the power consumption should be consistent throughout the experiment, thus, no changes in the operating speed or load were needed.

Table 6 gives the charge and voltage of the battery along with the average current and power consumed by the wireless monitoring device. Negative values indicate power consumed rather than produced. During the first 15.76 hours of the trip, the wireless monitoring device consumed 7.7 mAh, while in the second half of the trip, the device consumed 7.5 mAh. The average power consumption of the wireless monitoring device was 1.9 mW while the average current was roughly 0.5 mA. At this rate, the 1100 mAh battery should last 2142 hours of operation or around three months of continuous operation in the absence of any energy harvesting.

TABLE 6: WIRELESS ONBOARD CONDITION MONITORING DEVICE POWER CONSUMPTION

Time [h]	Battery Capacity [mAh]	Battery Voltage [V]	Average Current [mA]	Average Power [mW]
1.00	1099.7	4.10	-0.3	-1.2
2.00	1099.2	4.10	-0.5	-2.1
4.00	1098.1	4.10	-0.6	-2.3
6.00	1097.3	4.09	-0.3	-1.2
11.50	1094.4	4.09	-0.5	-2.2
15.76	1092.3	4.09	-0.5	-2.0
24.00	1088.4	4.08	-0.5	-2.0
26.00	1087.5	4.08	-0.6	-2.4
28.00	1086.5	4.08	-0.5	-2.0
31.52	1084.8	4.08	-0.6	-2.4
Total Drained:	**-15.2**	**Average:**	**-0.5**	**-1.9**

3.3 Energy Harvesting Device Performance

For the final part of this study, the energy harvesting device was connected to both the wireless health monitoring device and the battery to determine if the energy harvested was enough to keep the wireless monitoring device functional while also increasing the charge of the battery. The same dynamic bearing test rig operating at the same ambient temperature as in previous experiments carried out for this study was used for consistency and for direct comparison with previous results. The wireless monitoring devices ran the same one-second algorithm to replicate the power draw needed to properly function throughout the round trip. The 14500 batteries used were slightly discharged to around 3.8 volts to observe if the energy harvested would increase the charge of the batteries.

TABLE 7: ENERGY HARVESTING DEVICE PERFORMANCE AT 100% RAILCAR LOAD (BEARING 2) – DEFECTIVE BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
0.97	234 / 25	21.9	35.1	13.2	0.0	0.0
0.30	327 / 35	21.6	32.8	11.1	0.0	0.0
9.83	560 / 60	22.6	38.7	16.1	6.0	2.3
0.25	498 / 53	22.9	39.6	16.7	0.2	2.6
0.40	420 / 45	22.8	39.9	17.1	0.4	3.4
4.01	560 / 60	22.8	39.2	16.4	2.9	2.8
				Total:	**9.4**	

TABLE 8: ENERGY HARVESTING DEVICE PERFORMANCE AT 100% RAILCAR LOAD (BEARING 3) – HEALTHY BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
0.97	234 / 25	21.9	41.7	19.8	2.4	9.4
0.30	327 / 35	21.6	39.8	18.1	0.5	6.5
9.83	560 / 60	22.6	50.1	27.5	65.7	26.0
0.25	498 / 53	22.9	51.6	28.7	2.1	32.0
0.40	420 / 45	22.8	50.2	27.3	2.6	25.0
4.01	560 / 60	22.8	52.6	29.8	36.5	35.7
				Total:	**109.8**	

Table 7 and Table 8 provide the data for Bearing 2 (defective) and Bearing 3 (healthy), respectively, at full railcar load (100% load). The energy harvesting device on Bearing 2 was not able to produce excess power for the first 1.27 hours of the experiment because the small amount of power produced was barely enough to keep the wireless device functioning. Hence, the battery was not being charged as exhibited by the 0-mW average power. Meanwhile, the temperature difference (ΔT) for Bearing 3 was significantly higher than that for Bearing 2, which resulted in an average power production of 9.4 and 6.5 mW at 25 and 35 mph, respectively. For the first half of the experiment, the battery connected to Bearing 2 gained a total of 9.4 mAh (~1% of battery charge), whereas the battery connected to Bearing 3 gained a total of 109.8 mAh (~10% of battery charge).

Table 9 and Table 10 present the data for Bearing 2 and Bearing 3, respectively, at an empty railcar load. In these data sets, the average temperature difference is not high enough to produce the voltage needed for the boost converter to start. During the second half of the experiment, the battery in Bearing 2 lost 4.3 mAh (0.4% of battery charge) while the battery in Bearing 3 lost 6.8 mAh (0.6% of battery charge). Examining the data presented in this study, a minimum temperature difference of about 15°C must be present between the bearing adapter and the ambient for the energy harvesting device to generate enough power for the boost converter to start.

TABLE 9: ENERGY HARVESTING DEVICE PERFORMANCE AT 17% RAILCAR LOAD (BEARING 2) – DEFECTIVE BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
4.01	560 / 60	21.5	31.1	9.6	-0.9	-0.8
0.40	420 / 45	21.6	31.0	9.3	-0.2	-1.6
0.25	498 / 53	21.6	30.4	8.8	-0.2	-2.6
9.83	560 / 60	21.8	31.3	9.5	-2.4	-0.9
0.30	327 / 35	21.9	31.1	9.2	-0.2	-2.2
0.97	234 / 25	21.4	29.1	7.7	-0.5	-2.0
				Total:	**-4.3**	

Table 10: ENERGY HARVESTING DEVICE PERFORMANCE AT 17% RAILCAR LOAD (BEARING 3) – HEALTHY BEARING

Time [h]	Speed [rpm]/[mph]	Average T_{amb} [°C]	Average T_{adp} [°C]	ΔT [°C]	Charge [mAh]	Average Power [mW]
4.01	560 / 60	21.5	35.6	14.1	-1.7	-1.7
0.40	420 / 45	21.6	35.1	13.5	-0.2	-1.7
0.25	498 / 53	21.6	34.5	12.9	-0.2	-2.7
9.83	560 / 60	21.8	36	14.2	-4.1	-1.6
0.30	327 / 35	21.9	35.5	13.6	-0.2	-2.3
0.97	234 / 25	21.41	31.7	10.3	-0.5	-2.0
				Total:	**-6.8**	

4. CONCLUSIONS

The purpose of this study was to assess the performance of a prototype thermoelectric based energy harvesting device. A test plan was derived from a common freight route to simulate the operating conditions the harvesting device will experience in field service. Multiple experiments were conducted using the UTCRS dynamic four-bearing test rig housed within an environmental chamber to quantify the performance of the prototype energy harvesting system. The data was analyzed to determine the conditions at which the energy harvesting device would be most effective.

The first experiment found that the harvesting device on Bearing 2 (defective bearing) was able to generate 169.2 mAh of charge while the harvesting device on Bearing 3 (healthy bearing) generated 213.5 mAh of charge. This translates into an increase in the battery's SoC of 15.4% for Bearing 2 and 19.4% for Bearing 3. The second experiment concluded that the wireless onboard bearing condition monitoring device consumed an average of 1.9 mW of power to run the one-second algorithm. The wireless device consumed only about 15 mAh or 1.4% of the battery's SoC for the round trip of 31.52 h. The third experiment verified the performance of the energy harvesting system while it powered a functioning wireless monitoring device. Although the energy harvesting system was not able to generate the energy needed to recharge the battery for the empty railcar (17% load) portion of the trip, enough charge was generated during the full railcar load portion of the trip to maintain the batteries at a higher SoC than that at the start of the trip. The experiment concluded with the energy harvesting device on Bearing 2 increasing the charge of the battery by 5.1 mAh (0.5%) while the harvesting device on Bearing 3 increased the battery charge by 103 mAh (9.4%). The data also shows that a minimal temperature difference of about 15°C is needed to generate enough voltage for the boost converter to start, thus, initializing the battery management chip.

The data acquired in this study presents a conservative estimate of the performance of the TEG-based energy harvesting device. Although the harvesting device can produce enough charge to maintain the wireless onboard device functioning, there are steps that can be taken to improve its performance. The implementation of a pressure mounted solution will eliminate the need for a thermal adhesive to affix the energy harvesting device to the bearing adapter. Although the adhesive used in this study is designed to have good thermal conductivity, the TEGs have a thin graphite layer that, under pressure, should help increase the surface contact area. Moreover, smoothing the adapter surface at the location where the thermal adhesive is applied will also result in improving the surface contact area, thus, enhancing performance. Lastly, boost convertors with a lower self-start voltage, which corresponds to energy harvesting at lower temperature differentials, are available. Future prototype designs will consider implementing boost convertors with low self-start voltage to maximize energy harvesting at various bearing operating conditions.

The information presented in this study demonstrates that the developed energy harvesting device is effective and can increase the lifespan of the Lithium-Ion batteries powering the wireless onboard condition monitoring device.

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