SHORT-TERM AND LONG-TERM TESTING OF A VIBRATION HARVESTING SYSTEM FOR BRIDGE HEALTH MONITORING

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Abstract: Novel energy harvesting solutions are needed to power wireless sensor networks for structural health monitoring. We previously reported a harvester that scavenges the non-periodic, low acceleration vibrations found on bridges. Here, we significantly improve harvester robustness and performance, and add a circuit for conversion and storage of a DC voltage. The complete harvester system is installed on a California suspension bridge. In short-term testing, the average raw PFIG output power at several locations ranges from 1.6 to 5.0μW, a 10x improvement over our previous results. In long-term testing, the harvester improvements enable continuous operation on the bridge for more than 20 weeks (ongoing).

Keywords: Vibration Harvesting, Structural Health Monitoring, Wireless Sensors, Charge Pump

INTRODUCTION

The nation's bridges are deteriorating. Recently, the US Department of Transportation rated over 10% of the nation's bridges as structurally deficient [1]. Wireless sensors can monitor these bridges, however, these structural health monitoring (SHM) sensors may need to be placed in extremely hard to reach places where constantly replacing batteries can be expensive and dangerous. One example of this is under the middle of a large and heavily trafficked suspension bridge covering a significant body of water.

Novel energy harvesting solutions can be an effective way to power these wireless sensors. Previously, we introduced the Parametric Frequency Increased Generator (PFIG) in which a large inertial mass snaps back and forth between latching magnets on the springs of two electromagnetic transducers (FIGs) [2-4]. Thus the PFIG converts the low frequency, non-periodic, and low acceleration bridge vibrations into higher frequency mechanical oscillations to be electrically transduced and rectified.

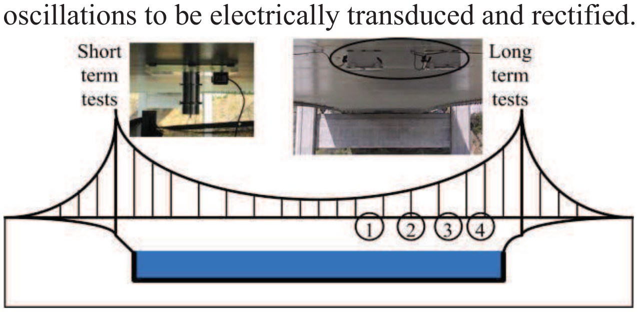

Figure 1. Approximate locations of short term (Locations 1-4) and long term (Location 1 only) installations are shown on a sketch of the new Carquinez bridge.

Previous generations of PFIG have been temporarily installed on the new Carquinez bridge near Vallejo, California (NCB, also known as the Alfred Zampa Memorial Bridge) for short periods to assess its technical viability for SHM (Fig. 1). The average measured output power is 0.5-0.75μW, based on bridge accelerations ranging from 0.1-0.5 m s^{-2} at frequencies between 2-30Hz [2]. Here, we improve the performance and robustness of PFIG and its interface electronics. In short-term tests the power harvested on the bridge is increased by 10x. We also install the PFIG system for a long-term test, and show continuous and ongoing harvesting on the bridge for more than 20 weeks since April 30, 2012.

IMPROVED SYSTEM PERFORMANCE

The PFIG architecture has been described previously in detail [2-3]. To improve harvester performance and long-term reliability, the inertial mass suspension springs were changed from copper to Stainless Steel 17-7. This increased their hardness by a factor of 11. The thickness of the inertial mass suspension spring was adjusted to obtain the desired spring constant of 544 N/m (of two springs combined). A double magnet structure with two opposing magnets was used to further increase the generated power. To maximize power transfer to the circuit, the number of coil turns was decreased to lower the PFIG output impedance to 300 Ω. With these improvements, in lab testing the PFIG produced 12.5 μW under an input acceleration of 0.34 m/s^2 and 2 Hz. This resulted in a 7.5x improvement in Volume Figure of Merit, FoMv, to 0.16% [2].

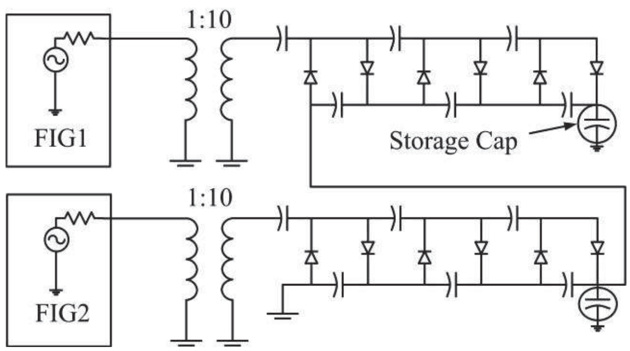

Figure 2. Circuit schematic. The two harvester outputs (FIGs) connect to transformers which are followed by cascaded 3-stage Cockcroft Multipliers.

Previous versions of PFIG electronics have used a discrete charge pump with six stages to boost and rectify the PFIG output signal [2]. One challenge is that voltage drops across the Schottky diodes significantly reduce circuit efficiency. To improve efficiency, transformers were added after the PFIG outputs (Fig. 2). This was possible due to the decrease in the harvester output impedance. The addition of transformers reduces Schottky diode losses, reducing the number of required multiplier stages.

The maximum possible efficiency is 24.6%, measured under steady-state operation with 130-Hz sine wave input voltages delivered to the transformers through 300 Ω series resistances, and with a 1MΩ circuit load. To determine the expected efficiency during bridge tests, the two FIG output voltages are approximated with time-offset decaying sinusoids. An op-amp buffer with very low input current is used to monitor the voltage on the storage capacitor. During capacitor charging to 0.7 V, the measured efficiency is 5.5%. The reduced efficiency is due to circuit start-up and to the decaying sine wave input.

SHORT-TERM BRIDGE TESTS

The PFIG is installed temporarily on NCB for short-term tests, as shown in the left inset of Fig. 1. An accelerometer is attached to the same plate as the PFIG. In the first test, both FIGs have matched loads for maximum power transfer. The results, recorded by LabView, are shown in Fig. 3a. FIG2 actuates for instantaneous accelerations of 50-60 mg (1g=9.81 m/s^2), whereas FIG1 only begins to actuate around 100 mg. The average power produced in Fig. 3a is 3.24 µW. Table 1 shows the average power generated on the bridge at different locations. Two different designs were tested. A maximum of $P_{average}$=5.02 µW was generated over a time period of 125 seconds. This represents an 8-10x increase over our previously reported PFIG bridge testing results [2]. In a second test, the PFIG and circuit were combined, and the storage capacitor voltage was repeatedly allowed to rise and then manually discharged (Fig. 3b). The stored voltage reaches almost 2 V.

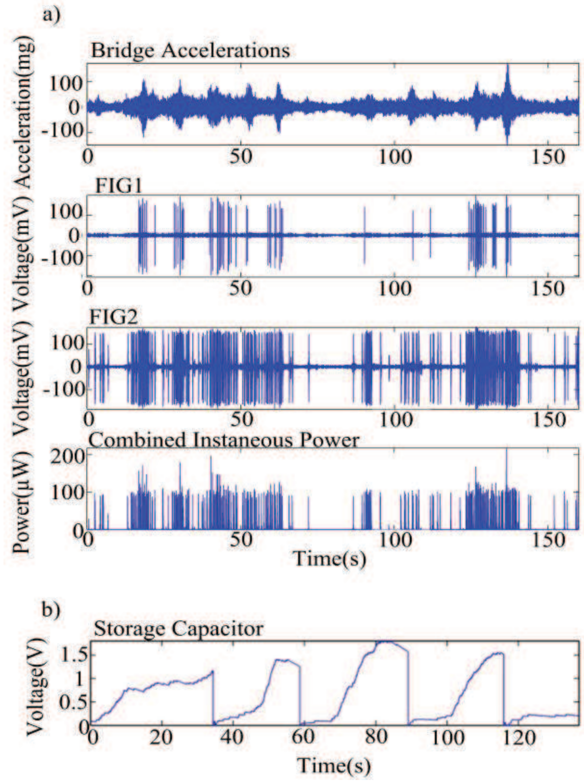

Figure 3. Short-term data taken on NCB shows: (a) simultaneously measured bridge acceleration, FIG1 and FIG2 outputs, and the calculated total instantaneous output power; and (b) storage capacitor voltage, measured separately.

Table 1. Short-term test results at different locations on the bridge using two different PFIG designs. Design A has a lower spring constant and uses a double magnet structure.

Location (ref. Fig. 1)	Average Power, Design A	Average Power, Design B
1	4.4 µW	3.24 µW
2	3.13 µW	5.02 µW
3	3.73 µW	--
4	1.6 µW	--

LONG-TERM BRIDGE TESTS

For the long-term test, we use a wireless sensor node, the *Narada [4]*, to monitor and record the FIG outputs and storage capacitor voltage, to quantitatively assess PFIG performance. These voltages are sampled every hour for 90 seconds at a sample rate of 100 Hz, and are wirelessly transmitted to a base station, while the PFIG operates continuously. Additionally, the *Narada* automatically discharges the storage capacitor when it reaches 0.7 V during recording, so that the average power harvested can be readily estimated by

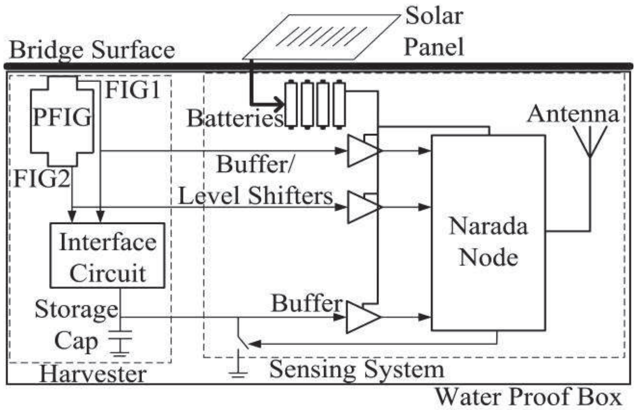

Figure 4. Schematic of the system used for long-term bridge tests. The outputs of the PFIG and its circuit are monitored by the Narada wireless sensor node, which wirelessly transmits the recorded data.

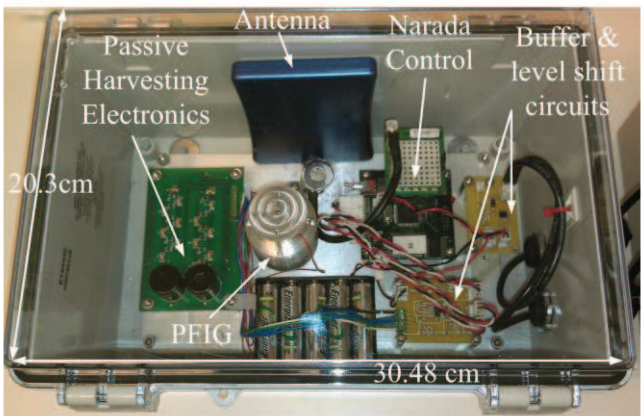

Figure 5. Interior of the water tight box used for long-term installation on the New Carquinez bridge. The PFIG, passive harvesting circuit, Narada control, Narada antenna, buffer and level shift circuits are visible.

the number of discharge cycles in a 90-second sample period. In order to perform these functions, the *Narada* is powered by external solar cells. That is to say, in this implementation, the PFIG is not being used to power the wireless sensor node. Rather, PFIG is being monitored by the sensor node to assess its long-term performance in a real bridge environment.

A diagram of the long-term test system is shown in Fig. 4. Inside a water-tight box are the PFIG, harvesting circuit, buffer and level shift circuits, transmission antenna, *Narada* node, and rechargeable batteries which are powered by solar panels on top of the bridge. The batteries are used to power the *Narada* system and the buffers and level-shift circuits, which are needed to increase the input current into *Narada*. The batteries are not connected to PFIG and its electronics.

Figure 5 shows a photograph of the harvester system box. The box dimensions are 30.48cm x 20.3cm x 13.2cm. The relatively large size is needed to fit all components in the bottom of the box, to leave room for the transmission antenna. For this long-term monitoring test, no attempt was made to miniaturize the box size; a real energy harvesting system could be made significantly smaller. Two boxes were installed on the bottom of the bridge deck at location 1 (Fig. 1) on April 30, 2012.

Figure 6 shows a sample of recorded data: the output capacitor is charged and discharged as the two FIGs provide voltage output. When the FIGs actuate more frequently and at higher amplitudes, the stored voltage rises more quickly and is more frequently discharged. Note that the FIG outputs are severely under-sampled at the chosen sample rate of 100 Hz. (This rate is chosen to minimize *Narada* power consumption.) Nonetheless, the FIG output traces usefully indicate the basic functionality of the system.

One week of data is summarized in Fig. 7. The harvested power is greater during the day compared to at night, and on weekdays compared to on weekends (Saturday and Sundays). Each discharge of 0.7 V stored on a 10 μF capacitor during a 90-second period corresponds to circuit power output of 27 nW. Assuming 5.5% circuit efficiency, as measured, each capacitor discharge corresponds to raw PFIG output power of ~0.5 μW. The long term test results of Fig. 7

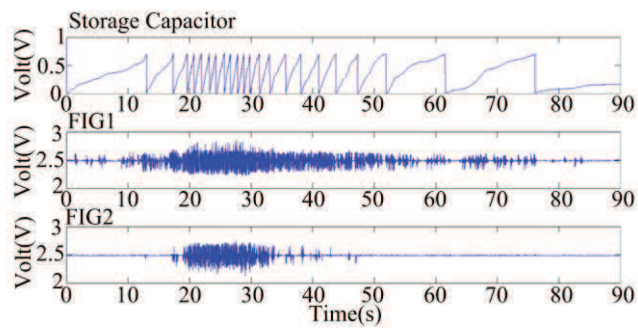

Figure 6. The two FIG outputs and the storage capacitor output voltage, as sampled by the wireless monitoring node on May 29, 2012, during the long term test.

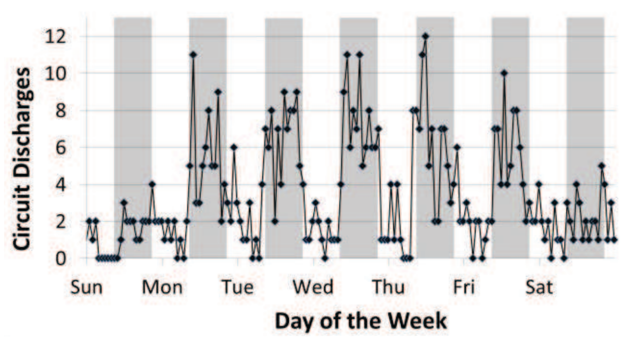

Figure 7. Circuit discharges per 90-second cycle over one week starting May 13, 2012. The shaded areas represent 8am to 8pm. The greatest available power is during the day on weekdays. Note: each discharge corresponds to approx. 0.5μW in raw PFIG output power.

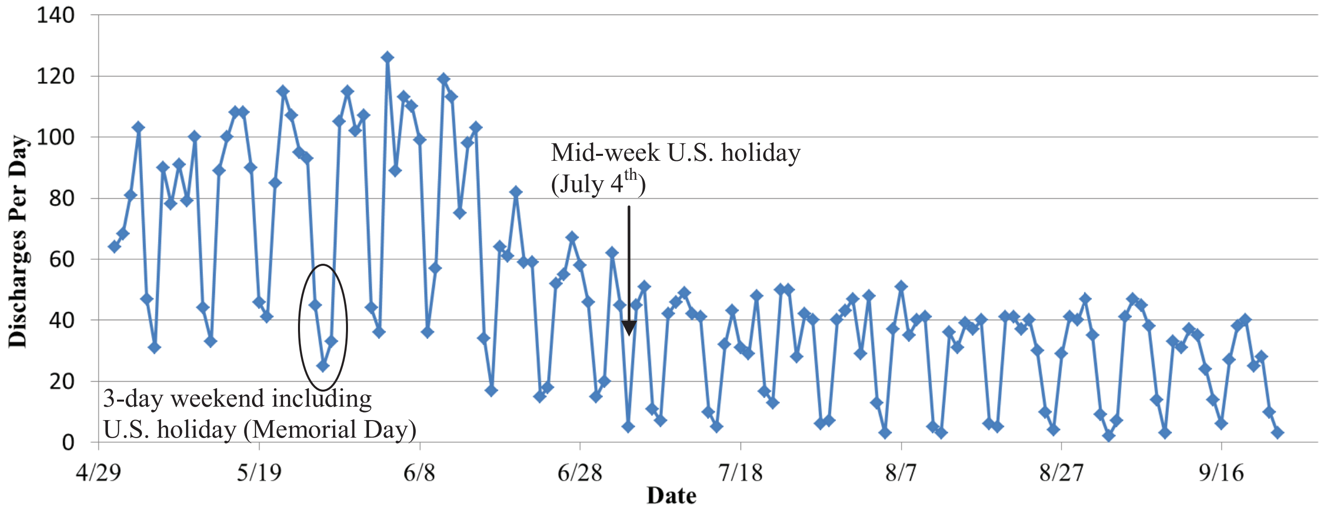

Figure 8. The number of discharges per day since PFIG installation on April 30, 2012. One can clearly observe weekly work-related traffic patterns, as well as traffic reductions on two national holidays.

thus indicate a nearly identical amount of power harvested during daytime (2-12 discharges or 1.0-6.0 µW) as that measured during short-term tests, shown in Table 1.

The PFIG has operated continuously on NCB for almost five months (Fig. 8.) Weekly variations as well as different traffic patterns on two national holidays are observed. The harvested power remains relatively constant over the first six weeks. The highest power recorded was on the morning of May 29th and is estimated to be 10.9µW (22 discharges over 90-sec, Fig. 6). As time progresses, the PFIG generates less power. It may be that an individual FIG, held in place by set screws, has slipped from its original position. A PFIG autopsy will be performed to determine the cause after the long-term test has concluded.

CONCLUSION

Short-term and long-term testing of the PFIG on the New Carquinez suspension bridge has been completed. An 8-10x improvement is seen in harvested power on the bridge. A new interface circuit is used with PFIG to charge a 10 µF capacitor up to 2 V based on the vibrations from cars passing overhead. Finally, the harvester was installed for long term testing on the bridge. It has worked continuously, producing stored power, for almost 5 months starting April 30th 2012. The maximum harvested power over a 90-second period is estimated to be 10.9µW. This study is unique compared other harvester systems which have been tested only in well-controlled, short term, high-acceleration environments [5, 6].

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