# A VIBRATION HARVESTING SYSTEM FOR BRIDGE HEALTH MONITORING APPLICATIONS

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**Abstract:** This paper presents the design, fabrication, and testing of an electromagnetic inertial micro power generation system for scavenging the very low-amplitude, low-frequency, and non-periodic vibrations present on bridges. The fabricated device can generate a peak power of 57μW and an average power of 2.3μW from an input acceleration of $0.54m/s^2$ at only 2Hz. The generator is capable of operating over an unprecedentedly large acceleration ($0.54$-$9.8m/s^2$) and frequency range (up to 30Hz) without any modifications or tuning. Scavenging energy from arbitrary vibrations is demonstrated using an acceleration recording from a highway overpass bridge.

**Keywords:** Vibration Harvesting, Vibration Scavenging, Frequency Up-Conversion, Parametric Generator

## INTRODUCTION

Our societies function with the aid of vast networks of infrastructure such as buildings, highways, bridges, dams, and railways. However the health and performance of civil infrastructure is severely undermanaged. As of December 2009 the US Department of Transportation rates 71,179 bridges as structurally deficient and 78,468 as functionally obsolete [1], which constitutes 25% of the 603,254 bridges in total. Efforts to develop cyber-based systems to monitor critical infrastructure have been ongoing for quite sometime [2]. These systems would allow more thorough and rigorous tracking of bridge performance while reducing the costs associated with manual inspection. One of the main challenges with this approach rests in the wires used to route power and data from the sensors to the processing point because wires are physically vulnerable and expensive to install and to maintain [3]. This cost can be mitigated with the use of wireless technology. Powering a distributed network of wireless sensors across a bridge remains an issue. Traditional wired power is not feasible and battery replacement is expensive and places limits on sensor locations. This makes energy harvesting technology very important in these systems.

This paper presents the design, fabrication, and testing of an inertial micro power generation system for scavenging traffic-induced bridge vibrations. An electromagnetic Parametric Frequency Increased Generator (PFIG) [4] coupled with a hybrid power management system is used to harvest the very low-amplitude, low-frequency, and non-periodic bridge vibrations.

## CHARACTERISTICS OF BRIDGE VIBRATIONS

The design of the mechanical harvester is guided by acceleration data (Figure 1) collected from a typical highway flyover steel girder-concrete deck composite structure located in Ypsilanti, Michigan. A tri-axial accelerometer (Crossbow CXL02TG3) was sampled at 100Hz. There were 20 measurement points on the bridge. Acceleration recordings were made under routine traffic loads. The waveform in Figure 1 is very typical of the remaining 19 sensor locations where peak acceleration was also in the 10-35mg (1mg = 9.8 x $10^{-3}m/s^2$) range. In addition, the figure shows the frequency response of the vibrations. The spectral content is mostly contained within the very low end of the frequency spectrum (2-30Hz) with no identifiable peak. This data shows that a resonant harvester approach will not be effective in this application.

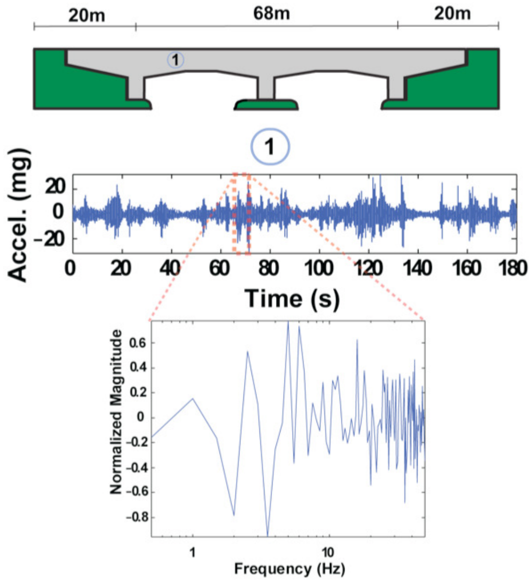


*Figure 1. Vibration data from a typical bridge showing the amplitude of the acceleration as well as the frequency response of the waveform. The traffic-induced vibrations are very small in amplitude and low in frequency.*

## HARVESTER DESIGN AND FABRICATION

The mechanical harvester is designed as a Parametric Frequency Increased Generator (PFIG). The PFIG is a non-resonant architecture (Figure 2a) where a bi-stable low-frequency mechanical structure

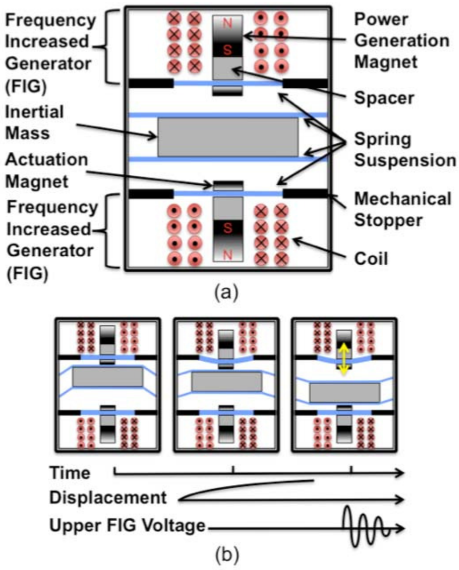


*Figure 2. a) Parametric Frequency Increased Generator (PFIG) architecture b) Illustration of the method of operation.*

is used to induce high-frequency mechanical oscillations in an electromechanical scavenger. By up-converting the ambient vibration frequency, the PFIG achieves better electromechanical coupling and efficiency. The PFIG is able to operate over a wide band of frequencies because it does not rely on resonant amplification. A large inertial mass is used to couple kinetic energy from the ambient inside the generator structure, and pass a portion of it to one of two Frequency Increased Generators (FIGs), which then convert this mechanical energy to electrical via electromagnetic induction. Two FIGs are placed on either side of the inertial mass, oriented to face each other. Attached to the bottom of the FIG spring is an NdFeB magnet for power generation, while on top, a smaller magnet is used to generate a magnetic force in order to latch the FIG and the inertial mass together. The operation of the PFIG is outlined in Figure 2b. The generator operates such that the inertial mass moves back and forth between the two FIG generators, attaching magnetically. As the inertial mass moves, it pulls the FIG spring along. As the forces on the FIG/inertial mass system overwhelm the holding magnetic force, the inertial mass detaches and is pulled to the opposing FIG. The freed device now resonates at its high natural frequency converting the stored mechanical energy in its spring, to electrical. This process is subsequently repeated in the opposite direction.

An illustration of the physical implementation of the PFIG is shown in Figure 3. The generator is housed within an aluminum enclosure. A large tungsten carbide (WC) inertial mass can be seen in the middle suspended on either side using copper springs. The two FIGs (top and bottom) surround the inertial mass. Each FIG consists of an aluminum outer case with a hole bored through the middle, where a secondary enclosure containing the transduction components is able to move. This internal transducer compartment is held in place by setscrews from all four sides. The movable

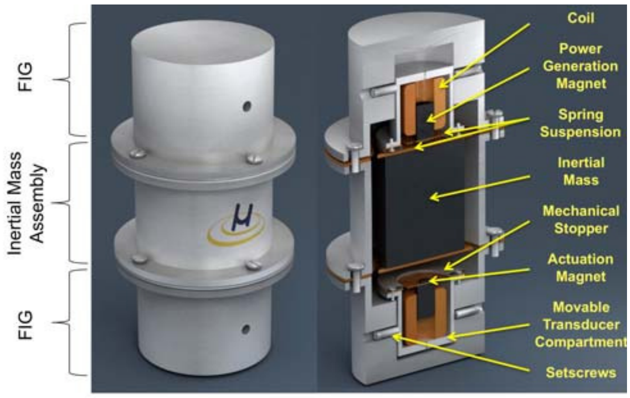


*Figure 3. Conceptual diagram of the bridge harvester implementation. The WC inertial mass is suspended on two copper springs in the middle. The FIGs are shown on top and bottom, clamped using setscrews inside a holding fixture.*

transducer is necessary in order to adjust the equilibrium position of the PFIG and remove the bias due to gravity.

A close-up of one of the fabricated FIGs can be seen in Figure 4. The springs for both the FIG and the inertial mass are fabricated out of 250µm thick copper alloy. The copper is patterned using a double-sided spray etching process. NdFeB magnets are adhered to the FIG springs using cyanoacrylate. The spring is clamped in place using a screwed in aluminum ring. Coils are wound from 50µm diameter enameled copper wire around specially machined aluminum bobbins and screwed in place within the transducer compartment.

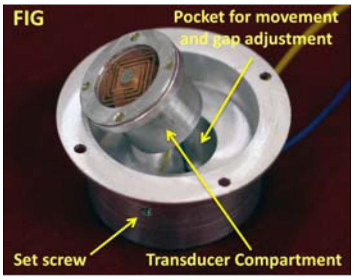


*Figure 4. Photograph showing a close-up of the fabricated FIG and movable transducer.*

The finished PFIG measures 3.3cm in diameter and is 7.3cm tall. The internal volume of the device, featuring all of the transduction mechanisms, the inertial mass, and all of the space needed for the components to move is 43cm$^3$ (68 including the casing). The finished device is shown in Figure 5. The left side of the figure shows the PFIG partially opened exposing the internal components. The top right side of the figure shows details of the electromagnetic transducer components including the spring assembly and the wound coil. The complete PFIG is shown on the bottom right and compared to the size of a standard "D" size battery.

## HARVESTER TESTING AND RESULTS

The harvester was tested on an APS Dynamics APS113 long stroke linear shaker. An Agilent 33250A

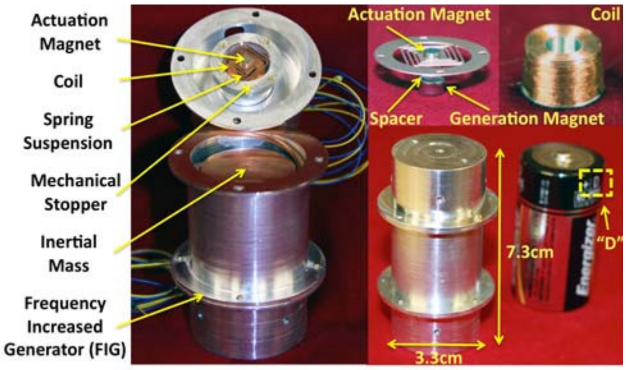


*Figure 5. Photographs showing the completed PFIG. On the left, the device is opened exposing the internal components. The electromagnetic transducer components are shown on the top right. The completed PFIG is shown alongside a standard "D" size battery on the bottom right.*

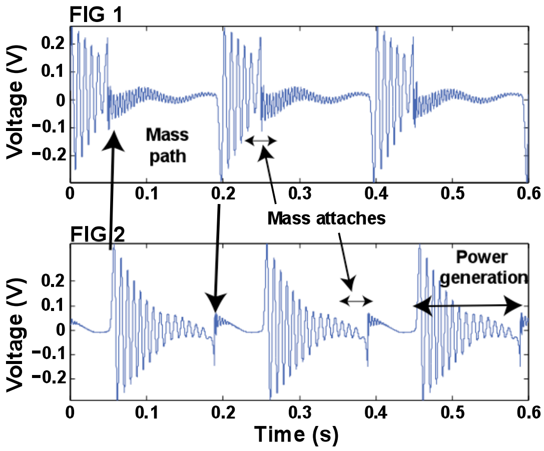


*Figure 6. Oscilloscope recording showing the parametric generator operation from 55mg at 5 Hz. The top and bottom voltage waveforms correspond to the top and bottom FIG devices as the inertial mass snaps back and forth between them.*

signal generator was used to generate the driving waveform. This waveform was then amplified using an APS Model 124 amplifier and fed into the shaker table. The resultant acceleration was monitored using an ADXL203 accelerometer. The performance of the PFIG was analyzed under sinusoidal excitation. Each FIG was loaded with a 1.5kΩ resistor in order to match its output impedance. The designed harvester is able to operate down to 55mg. This is close to the range of acceleration found on typical bridges. Figure 6 shows the operation of the PFIG at its minimum acceleration level from a 5Hz sinusoidal signal. The two plots show the voltage generated by each FIG across the load resistor. By looking at the voltage waveform it becomes evident where the inertial mass attaches to each FIG, and where the mass detaches and travels to the opposing device.

The frequency response to an acceleration range of 0.054-1g was measured and the results are presented in Figure 7. This is a span of almost two full orders of magnitude, which constitutes an unprecedented operation range. These measurements were performed without any modifications or tuning to the PFIG. At 55mg the shaker table can be accurately controlled down to 2Hz. At this frequency the PFIG generates and average power of 2.3µW (57µW peak power).

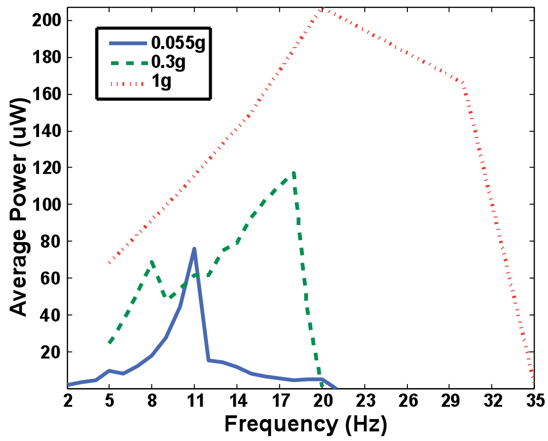


*Figure 7. Frequency response of the PFIG generator at different vibration amplitudes. The PFIG generator is able to operate over an unprecedented acceleration range of nearly 2 orders of magnitude.*

## HARVESTER SYSTEM DESIGN

The electrical energy produced by the PFIG is not in a form usable by most electronic devices. The alternating (AC) voltage has to, at a minimum, be converted to a constant (DC) voltage. Additionally, the voltage levels produced by the PFIG are relatively low. Therefore, a circuit that boosts the voltage to an appropriate value should follow the rectification stage. The necessary output voltage for the power management system is application dependant. In order to directly power some of the more advanced integrated circuits ~1V is needed, whereas if the voltage is used for charging a super capacitor or rechargeable battery then it needs to be in the ~3-4V range. In order to avoid the complex switching associated with typical DC-DC converters, a charge pump is favored in this implementation. The switching is less complex and could be done with as little as one timing signal. It makes sense when pursuing a charge pump approach to incorporate the rectification in a single unit. This type of circuit is typically referred to as a voltage multiplier and at its core is simply a cascade of single wave rectifiers.

The design of the full energy harvesting system is shown in Figure 8. A 6 stage Cockcroft-Walton (CW) multiplier is attached to each of the two FIGs. Schottky diodes (BAT54WS) and 10µF capacitors are used to construct the multiplier stages. The output of the two multipliers is cascaded to further increase the voltage and to combine the two outputs into one. The resulting charge is stored on a 47µF electrolytic capacitor. The feasibility of attaching a load and powering it using scavenged energy is demonstrated using a ring oscillator. The oscillator is made out of 3 NC7SP04 inverters.

## HARVESTER SYSTEM RESULTS

In order to show the viability of scavenging and using the vibration energy found on bridges, the

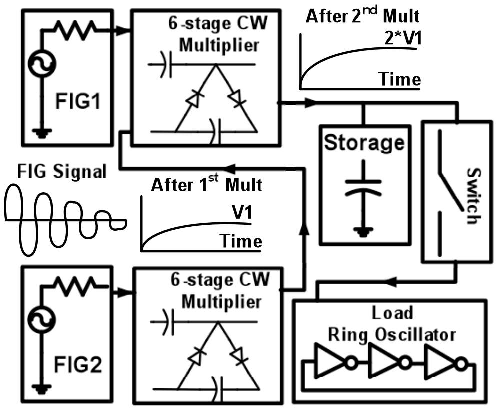


*Figure 8. A preliminary power management system is assembled on a breadboard. Each FIG is connected to a 6-stage Cockroft-Walton multiplier. The output of these multipliers is cascaded and stored on a capacitor. The charged capacitor can be used to power a ring oscillator.*

harvester system was attached to the shaker table and subjected to bridge-like vibrations. The result of this test is shown in Figure 9. A 20 second sample from the bridge acceleration data was stored in a function generator and used to drive the shaker table. The acceleration produced by the shaker table can be seen in Figure 9a (original bridge data shown in figure insert). The minimum acceleration at which the PFIG is able to operate is still higher than the bridge vibrations and the efficiency of the initial power management circuit is low. In order to accommodate this, testing was performed at amplified acceleration levels compared with the original bridge data. The voltage on the storage capacitor at the end of the multiplier is shown in Figure 9b. Some ripples can be seen on the rising voltage. The ripples were caused by the parasitics associated with the circuit discharging the capacitor in the portions of time where there was a gap between acceleration spikes. Figure 9c shows the output of the ring oscillator, which was connected to the multiplier via a push-button switch. The oscillation of the load device decays since the voltage output from the storage capacitor was not regulated. This test demonstrates the operation of a vibration harvester from random (non-periodic) traffic-induced bridge vibrations. Additionally, the power conversion system shows for the first time that the decaying voltage produced by PFIG operation could be rectified, boosted, and stored.

## CONCLUSION

This paper presents the design, fabrication, and testing of an electromagnetic inertial micro power generation system for scavenging low frequency non-periodic bridge vibrations. The design of the system was based on analysis of the ambient environment found on a popular type of bridge. The fabricated device can generate a peak power of 57μW and an average power of 2.3μW from an input acceleration of 0.54m/s$^2$ at only 2Hz. The device bandwidth at 55mg is 18Hz. The total volume of the generator is 68cm$^3$.

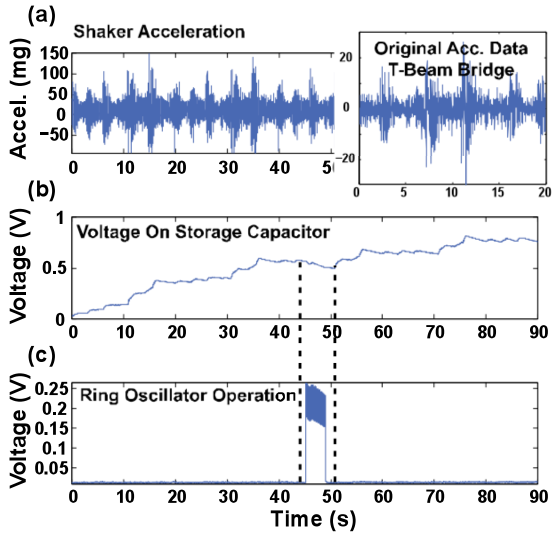


*Figure 9. The PFIG can scavenge non-periodic wide-band vibrations. a) A recording of the acceleration used to drive the PFIG (this is an amplified signal measured on a highway flyover bridge). b) Voltage of the storage capacitor rising over time. c) Unregulated power is used to drive the ring oscillator.*

The generator is capable of operating over an unprecedentedly large acceleration range (0.54-9.8m/s$^2$) and frequency range (up to 30Hz) without any modifications or tuning. Scavenging energy from arbitrary vibrations was demonstrated by using an acceleration recording from a real bridge, and by reproducing the same environment on a shaker table.

## ACKNOWLEDGEMENTS

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