A PRACTICAL SELF-POWERED SENSOR SYSTEM WITH A TUNABLE VIBRATION ENERGY HARVESTER

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Abstract: Vibration energy harvesters are typically narrow-band devices that are designed to operate at line frequency (or a multiple thereof), hence are only suitable for deployment on electrical machinery powered from the grid. Tunable vibration energy harvesters offer the potential to harvest energy in a wider range of applications but have, to date, only been demonstrated in the lab and have not matched the vibration characteristics found on real machines. This paper reports on the considerations, design, and results from deployment of a tunable vibration energy harvesting system aimed at a real application – wireless monitoring of a vehicle ferry engine.

Keywords: vibration energy harvesting, tunable generator, wireless sensing system

INTRODUCTION

Vibration energy harvesting has recently become an established technology, with several devices available commercially [1]. However, these narrow-band harvesters have been developed to operate with line-powered machinery and hence are tuned to operate at 50 Hz or 60 Hz (line frequency), or a multiple thereof. This means that devices are suitable for deployment on equipment such as electric pumps and motors (which typically exhibit significant vibration in these bands), but not on variable-speed machinery such as internal combustion engines. To be able to generate energy effectively from variable vibration frequencies, harvesters should either be inherently broad-band, or should be able to 'tune' to the dominant vibration frequency. Tunable vibration harvesters have been reported in the literature [2], but have not been designed for (or deployed in) real applications [3]. This paper reports on the design of a tunable vibration energy harvesting sensor system, and its deployment in a real application (wireless condition monitoring of a ferry engine).

The roll-on, roll-off (ro-ro) vehicle ferries, Fig. 1, travel between Southampton and the Isle of Wight (on the south coast of England). They have a service speed of approx. 12 knots, and each crossing takes approx. one hour. These vessels each have two main engines and Voith-Schneider propulsion units. This propulsion allows the engines to operate at defined speeds, while the amount and direction of thrust is controlled by altering the angle of attack of the propeller blades. The engines operate at: 350 RPM (idle), 550 RPM (intermediate), 715 RPM (normal), and 750 RPM (fast). This application was selected as it features some unique challenges: variable vibration frequencies, rapidly-changing vibration amplitudes, and a real need for a wireless condition monitor to be powered by energy harvested from vibration.

Fig. 1: Application: ro-ro vehicle ferry

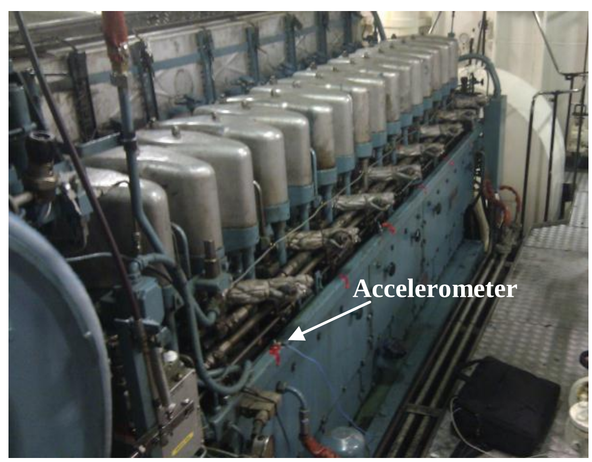

Fig. 2: Eight-cylinder diesel main engine on ferry

Condition monitoring equipment is often used in the management of industrial plant. Problems (e.g. bearing failure) can be detected before catastrophic failure, and preventative maintenance can be carried out [4]. Vibration characteristics of the ferry engines are not presently monitored in real-time, although engineers do have access to a portable unit that is used occasionally. By making a fixed system wireless and battery-free, it reduces the cost of installation and maintenance, and means that vibration characteristics can be monitored much more frequently. The new monitor is intended to measure the engine vibration characteristics, process them using an FFT, and transmit them to a monitor in the engine control room.

SYSTEM DESIGN

Vibration Energy Harvester

In order to define the specification for a tunable electromagnetic vibration energy harvester, real vibration data was collected from the engines of two ferries (Fig. 2, 3). In the test location, at the normal/fast speeds, dominant vibrations are at the firing frequency of the eight-cylinder four-stroke engines (4x revolution speed), i.e. ~47 or 50 Hz, respectively. The operating speed of the engine is set by a control card which is manually trimmed, which drifts over time (being corrected when maintenance is performed), and there are also variations between vessels and small perturbations in the operating frequency when the engine is under variable loading.

Typically, the vibration amplitude when operational at normal or fast speeds is between 300-1000 m$\boldsymbol{g}_{\mathrm{pk}}$ (1$\boldsymbol{g}$ = 9.81m·s^{-2}). The results are summarized in Table 1. The generator was specified (Table 2) to accommodate this range of frequencies, plus a ±10% margin allowing for engine speed drift and any nonlinear effects of the generator/power conditioning circuit combination.

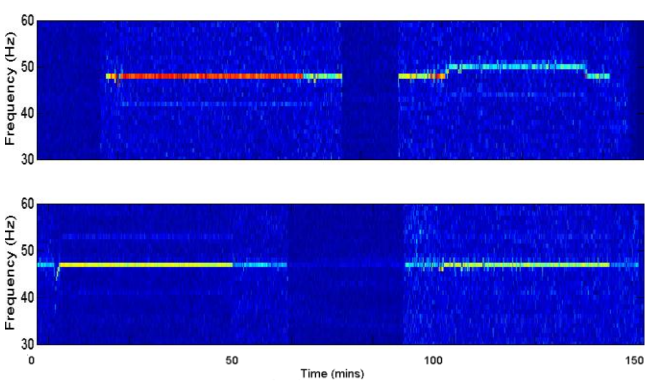

Fig 3: Processed vibration data from two ferries (one return crossing per ferry). Red = 1000m$\boldsymbol{g}_{pk}$

Table 1: Typical vibration levels on two engines.

Ferry	Normal Speed (~715 RPM)		Fast Speed (~750 RPM)	
	Freq. (Hz)	Ampl. (m$\boldsymbol{g}_{\mathrm{pk}}$)	Freq. (Hz)	Ampl. (m$\boldsymbol{g}_{\mathrm{pk}}$)
1	47	700	Not tested	
2	48	950	50	450

Table 2: Specification for tunable harvester.

Min. frequency	42 Hz
Max. frequency	55 Hz
Max. amplitude	1000 m$\boldsymbol{g}_{\mathrm{pk}}$
Max. power output (loaded)	10 mW

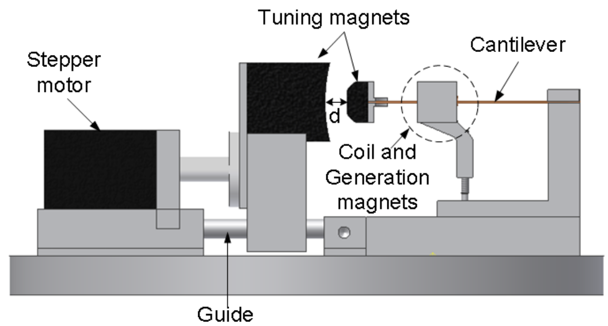

Fig. 4: Elevation view of tunable harvester

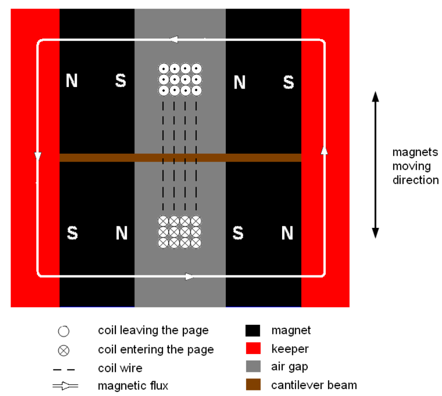

Fig. 5: Cross-section of magnets around coil

The vibration energy harvester (Fig. 4) was designed in line with these specifications, and to be robust enough to function in this high-$\boldsymbol{g}$ application (it has been designed to withstand up to 1.5$\boldsymbol{g}_{\mathrm{pk}}$ at resonance). The device is based on an electromagnetic transduction mechanism, where the energy generation magnets are suspended on a cantilever and resonate past a fixed coil. Tuning is performed by a stepper motor, which adjusts the distance, *d*, between the tuning magnets and thus the axial force on the cantilever (thus modifying its resonant frequency).

The cantilever is 0.3 mm thick and made of Beryllium Copper (BeCu), a material possessing good mechanical properties and excellent fatigue characteristics. The magnetic circuit of this generator is shown in Fig. 5. Two mild steel keepers were used to couple the magnetic flux between top and bottom magnets, which ensures a uniform magnetic field within the air gap. The coil is attached to the base of the generator, and the four-magnet structure is fixed to the cantilever beam which vibrates with the ambient vibration. The magnets move with respect to the static coil so that the induced current is generated within the coil according to Faraday's law. The tuning magnets and the magnets used for generating power are all made of Neodymium Iron Boron (NdFeB), a high energy density rare earth magnet. The resonant frequency can be tuned between 42 and 55 Hz by varying the distance *d* from 19 mm to 13 mm.

Interface Circuitry

Ultimately, power from the generator must be used both to provide power to the sensor node to carry out its condition monitoring functions, and to the system controller to allow the generator to be tuned to adapt to changes in the source vibration. This is a complex system, which is summarized by the topology in Fig. 6. To reduce power loss due to leakage, the decision was made to reduce the operating voltage of the system modules to the lowest possible: for this reason, the stepper motor is a Haydon-Kerk E21H4U-2.5-900, which operates at 2.5 V (rather than the 5 V device used in the earlier reported works [3]); other modules operate at 2 V. Other power conditioning modules have been selected for their overall efficiency and have been described in an earlier publication [5].

To facilitate control of the generator and monitoring of the beam deflection, a polyvinylidene fluoride (PVDF) membrane was adhered to the cantilever. An analog accelerometer is also mounted on the base of the generator. The outputs from both transducers go through identical band-pass filters which are sensitive only to the operating range of the generator (this is essential to avoid vibrations at other frequencies disrupting the control of the generator).

The assembled prototype generator is shown in Fig. 7. It may be observed that a linear position sensor has also been installed on the base. This allows the position of the tuning actuator to be measured when the system first starts up, thus avoiding the costly step of retracting to the minimum position to determine that the system is at its zero-point.

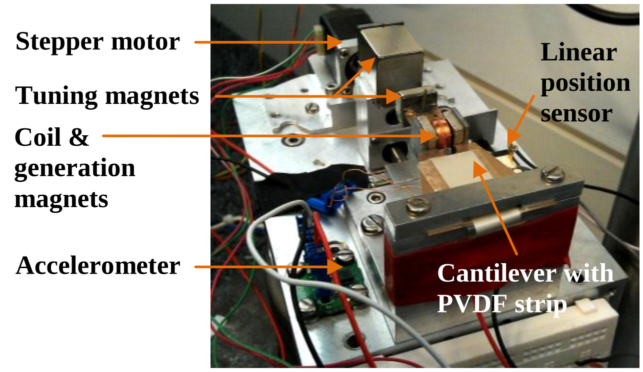

Fig. 7: Assembled generator

TESTING & RESULTS

The system has been tested in the lab and on the ferry. The performance of the generator under a sinusoidal excitation of 750m$\boldsymbol{g}_{\text{pk}}$ through a resistive load is shown in Fig. 8. It may be observed that there is a non-linear response, which leads to two 'cliff edges' on up-sweep and down-sweep. This means that the generator output suddenly picks up when the excitation frequency crosses into the sensitive region, and drops off rapidly (but at a different point) when the excitation frequency decreases.

Fig. 9 shows the performance of the generator at its maximum operational amplitude at a range of actuator positions. The phase relationship between the PVDF output and the accelerometer output is shown, along with the tip displacement, when subjected to an up-sweeping excitation frequency from 40 to 60 Hz. Here, it may be observed that the phase difference between the outputs from the accelerometer and the PVDF strip crosses zero close to the up-sweeping cliff edge. However, the phase relationship in this system is dependent on both the supercapacitor voltage and the excitation amplitude, meaning that tuning control

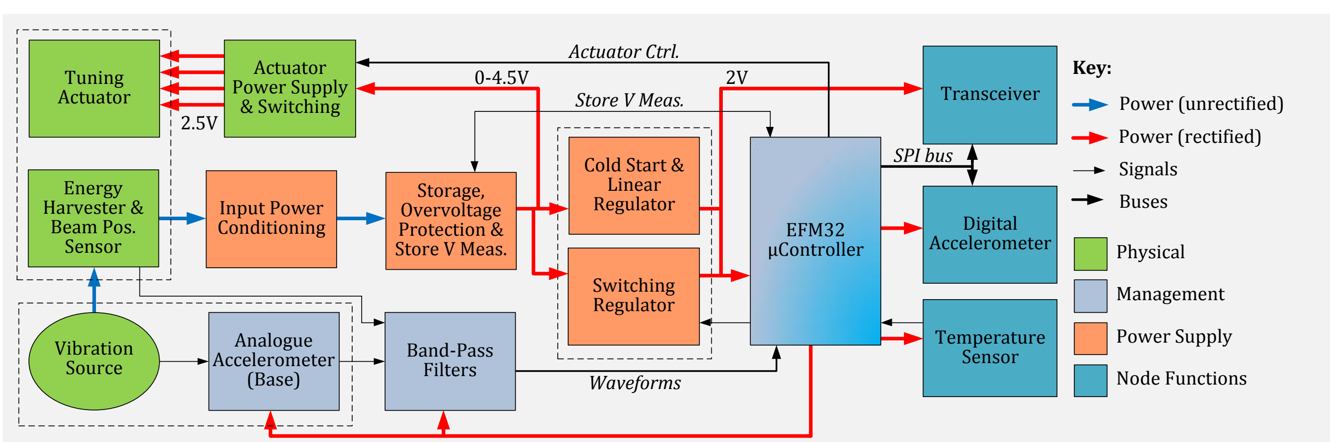

Fig. 6: Topology of the system, including harvester, tuning control, and sensor node functions (adapted from [5])

of the generator is not straightforward.

Results from a test on the ferry during a crossing are shown on Fig. 10. Here, the generator was manually tuned to give maximum output amplitude at the start of the crossing. It may be observed that there are rapid changes in the power output from the generator: this is partially due to amplitude variation, but mainly due to the nonlinear performance of the generator meaning that perturbations in the excitation frequency and amplitude caused the generator to fall off the 'cliff edge' on several occasions. A mean power output of 7.8 mW was measured from the generator during this crossing.

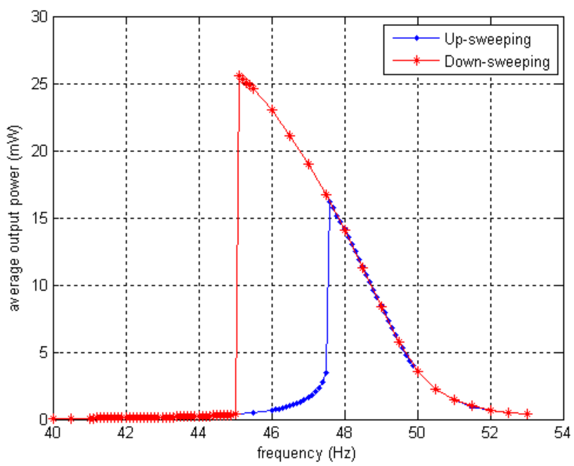

Fig. 8: Average output power when the generator was excited at 950mg$_{pk}$ at 48Hz

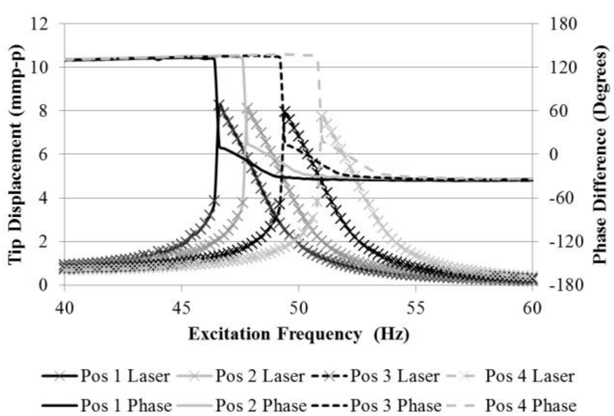

*Figure 9: Generator performance with excitation frequency up-sweeping, amplitude 1000m**g**$_{pk}$*

CONCLUSIONS AND FUTURE WORK

This paper has described the first deployment of a tunable vibration energy harvester in a real application. It forms part of a complete system that is self-powered and able both to control the tuning of the energy harvester and the sensing operations. This work is particularly relevant as it allows energy to be

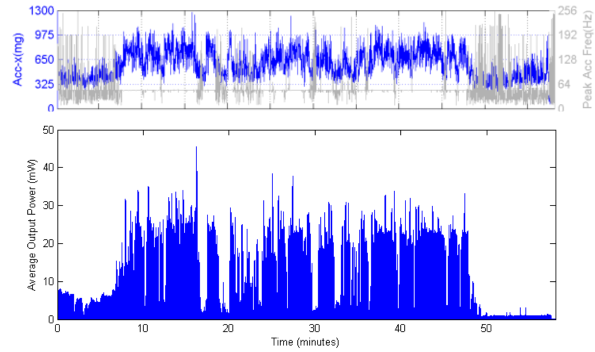

Fig. 10: Results from real test on ferry: power delivered to optimal load, and vibration levels

harvested from the vibration of variable-speed machinery, representing a substantial improvement over the state-of-the-art. Results have been presented from testing in the lab and on the ferry engine. Work is ongoing to refine the tuning algorithm to be robust to frequency and amplitude perturbations and be less sensitive to the nonlinear response of the generator.

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