PIEZOELECTRIC VIBRATION ENERGY HARVESTING USING CASING VIBRATION OF INDUSTRIAL ROTATING MACHINERY DUE TO ITS MASS IMBALANCE

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Abstract: The feasibility study of the piezoelectric vibration energy harvesting from the industrial rotating machinery with low-intensity of its casing vibration was experimentally performed by using a cantilever type of the vibration energy harvester. The allowable maximum casing vibration intensity of the newly commissioned class I rotating machinery (under 15 kW) at the rated speed under normal steady-state operating conditions is regulated at 0.71 mm/s rms by ISO 10186-1:1995. The maximum generated AC power was reached to 246.1 μW at the resonance of the cantilever type of the harvester about 29 Hz. However, DC output was 155.1 μW. Up to 90 μW (37.0%) power loss occurred by the AC-DC conversion at the rectifier in this experiment.

Keywords: vibration condition monitoring, piezocomposite, diode-bridge rectifier, power transfer efficiency, power loss

INTRODUCTION

In the normal operation of rotating machinery, due to the uneven axially mass distribution of the rotating part, "mass imbalance of the rotor," the whirl motion of the rotor is inherently occurred. That caused the vibration of the casing and/or bearing pedestal. The severe whirl motion of the rotor leads to the machine operating performance degradation or any kinds of the machine trouble. However, the complete mass imbalance correction is the time-consuming and sometimes difficult tasks.

The ISO categorizes the industrial rotating machinery into four classes by its rated output and then regulated the four vibration magnitude zones in each class; Zone A to D (Zone A is the lowest magnitude level) [1]. Each Zone is limited by the allowable maximum vibration magnitude (root mean square vibration amplitude) of the casing or bearing pedestal of the machinery, for example, the rotating machinery whose rated output is 15 kW or less is categorized the class I and its maximum casing vibration magnitude for the newly commissioned machinery at the rated speed under normal steady-state operating conditions is 0.71 mm/s rms (Zone A). Following ISO regulation 10816-1:1995 for the vibration magnitude of the casing or bearing pedestal of rotating machinery, the safety operation of the machinery could be maintained in the normal operation.

The vibration condition monitoring of rotating machinery is another solution to maintain the safety operation of rotating machinery, in which the severe whirl motion caused by the accidental mass imbalance of the rotor in the operation could be avoided. Recently, the self-powered remote wireless monitoring system is one of the key technologies for the rotor vibration condition monitoring. The upper limit of Zone A for class I rotating machinery is quite low. Following simple question is arising. "*Is the vibration energy harvesting applicable to the class I rotating machinery whose casing vibration magnitude is in Zone A*?" It means "*How much the generated electrical power could be obtained when the vibration energy harvester is installed on such low vibration intensity object.*"

In the past, various studies of cantilever types of piezoelectric vibration energy harvesters have been presented [2-8]. Figure 1 summarizes the characteristics of these vibration energy harvesters whose vibration sources were several common indoor vibration sources except the industrial rotating machinery [9]. The root mean square excitation vibration amplitude of these studies exceeds 2.25 (mm/s) which is the alarm level of the vibration level of the casing and/or pedestal of the rotating machinery. According to ISO regulation 10816-1:1995 [1], the vibration level of Zone B: 1.8 (mm/s rms) is normally considered acceptable for unrestricted long-term operation in classI rotating machinery. Furthermore, according to ISO 13373-1:2001 [10], the alarm level is normally set to 1.25 times the upper limit of Zone B. In order to develop the vibration energy harvester for vibration condition monitoring applications of rotating machinery, vibration sources should be considered from the practical vibration condition of the rotating

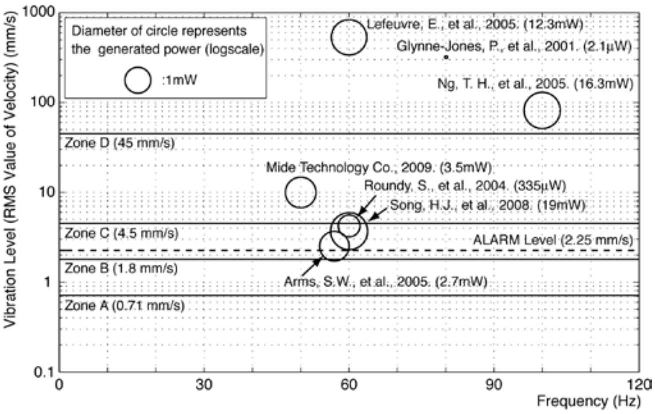

Fig. 1: Comparison of piezoelectric energy harvesters.

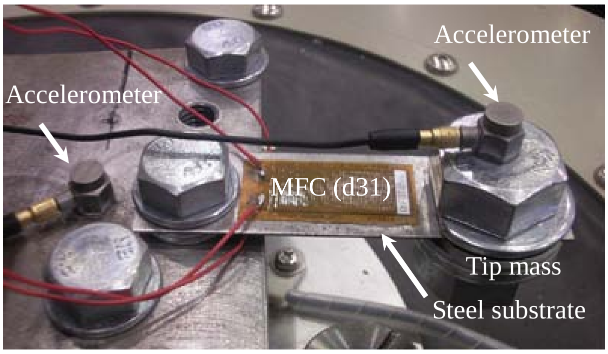

Fig. 2: Cantilever type of vibration energy harvester.

Table 1: Specification of vibration energy harvester.

Mechanical properties of cantilever	
Mass m	153.76 x 10^{-3} kg
Resonant Frequency f_d (1st bending, shunt-circuit condition)	29.31 Hz
Damping ratio ζ	6.81 x 10^{-3}
Length of cantilever l_s	49.25 x 10^{-3} m
Thickness of cantilever t_s	0.80 x 10^{-3} m
Piezocomposite	
Length l_p	28.00 x 10^{-3} m
Thickness t_p	0.30 x 10^{-3} m
Width w_p	14.00 x 10^{-3} m
Young's modules $1/s^E$	30.34 x 10^{9} Pa
Piezoelectric constant d_{31}	-3.70 x 10^{-10} C/N
Capacitance C_p *	50.30 x 10^{9} F
Resistance R_p *	6.40 x 10^{3} Ω

* measured in series configuration at the resonant frequency of 29.27 Hz (1st bending, open-circuit condition).

machinery.

In this study, under the sinusoidal base excitation condition which satisfied the upper level of the vibration magnitude of Zone A for class I rotating machinery, AC and DC power generation performance of the piezoelectric vibration energy harvester was experimentally evaluated. At the same time, the power loss of the AC-DC conversion using well-known diode-bridge rectifier was also experimentally evaluated.

EXPERIMENT

Experimental Setup

Figure 2 shows the vibration energy harvester [9]. The piezoelectric bimorph consisted of the two surface bonded piezocomposites (d31 type MFC actuator, Smart Materials) [11]. The properties of vibration energy harvester are shown in Table 1. The middle substrate was a steel plate of 0.8 mm thickness. The mechanical resonant frequency of the cantilever was tuned about 29 Hz by using tip mass shown in the figure. The resonant frequency was close to the normal operating speed of the 4-pole three-phase induction motor. In Table 1, the capacitance and the resistance of the piezocomposites were measured by impedance

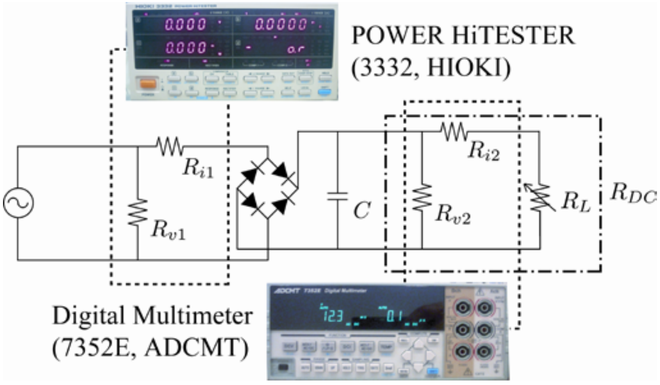

Fig. 3: Schematic diagram of generated AC/DC power measurement circuit with rectifier circuit.

analyzer in series and open-circuit configuration at the resonant frequency.

Measurement and Evaluation

In order to experimentally evaluate the AC/DC power generation performance and the power loss in the full-wave bridge rectifier when subjected to mechanical vibration, the vibration energy harvester was excited by using the electro-dynamic shaker. Both base and tip accelerations were measured by using the accelerometer (A353B15, PCB). The mechanical resonant frequency of the vibration energy harvester was measured by the signal analyzer for evaluating the frequency response function in the frequency range from 5 Hz to 50 Hz.

Figure 3 shows a schematic diagram of the generated AC/DC power measurement circuit [12]. A full-wave bridge rectifier was used to convert the sinusoidal waveform of the AC signal from the vibration energy harvester to the DC signal. The dotted boxes shown in Fig. 3 indicate the equivalent circuit of the AC and DC power meters, respectively. The generated AC power was measured by using the AC power meter, where the input impedance of its voltmeter was R_{v1} = 2 MΩ and the input impedance of the ammeter was R_{i1} = 2 mΩ. The generated DC power was measured by using the DC power meter, in which the input impedance of its voltmeter was R_{v2} = 10 MΩ and the input impedance of the ammeter was R_{i2} = 102 Ω. The dashed box shown in Fig. 3 indicates the electrical resistive load R_{DC} whose electrical impedance was adjusted by changing the variable resistance R_L. The generated AC power $\overline{P}_{AC}$ was evaluated by the total power loss at the AC power meter (R_{v1} and R_{i1}), full-wave bridge rectifier and electrical resistive load R_{DC}. The generated DC power $\overline{P}_{DC}$ was evaluated by the power at the electrical resistive load R_{DC}.

POWER TRANSFER EFFICIENCY

Governing Equations

The governing equations of the piezoelectric vibration energy harvester shown in Fig. 2 were given by following form based on Lagrangian equations of motion and the constitutive equations of the piezoelectric material [13].

$$m\ddot{x}+c(\dot{x}-\dot{y})+k(x-y)=\frac{\theta}{2}q \quad (1)$$

$$(R_p+R_I)\dot{q}+\frac{1}{C_p}q=\frac{\theta}{2}(x-y) \quad (2)$$

where x and y are the base and tip displacements of the harvester. m, c and k are the equivalent mass, damping and stiffness of the host structure considering the surface bonded piezocomposites. θ is the electro-mechanical coupling due to the piezocomposites. q and C_p are the electric charge and capacitance of the piezocomposites. R_p is the internal electrical resistance of the piezocomposites and R_I is the electrical resistive load which includes the internal impedances of AC power meter and full-wave bridge rectifier, the electrical resistive load R_{DC} shown in Fig. 3.

In the case of the open-circuit condition of the piezocomposites, Eq. 1 was rearranged to Eq. 3 and Eq. 2 was eliminated.

$$m\ddot{x}_o+c\dot{x}_o+kx_o=c\dot{y}+ky \quad (3)$$

Energy Balance of Vibration Energy Harvester

Under the sinusoidal base excitation which was the model of the casing vibration of the rotating machinery caused by the whirl motion of the rotor due to its mass imbalance, the base and tip displacement for the open-circuit condition of the piezocomposites were given by follows.

$$y=Y\cos\omega t \quad (4)$$

$$x_o=X_o\cos\left(\omega_n t-\frac{\pi}{2}\right)=X_o\sin\omega_n t \quad (5)$$

where ω_n is the natural circular frequency of the harvester. Multiplying the both sides of Eq. 3 by $\dot{x}_o-\dot{y}$ and then integrating the equation over T_n which is the natural period of the harvester, the following energy balance equation for the open-circuit condition of the piezocomposites was derived.

$$c\omega_n X_o^2\pi=\{-c\omega_n Y^2\pi+kX_oY\pi\} \quad (6)$$

In the case of the short-circuit condition of the piezocomposites, the following energy balance equation could be obtained by the same manner.

$$c\omega_n X^2\pi=\frac{\theta}{2}\int_0^{\frac{2\pi}{\omega_n}}\{(\dot{x}-\dot{y})q\}dt+\{-c\omega_n Y^2\pi+kXY\pi\} \quad (7)$$

Power Transfer Efficiency and Power Loss

The mechanical vibration energy of the harvester which induced by the unbalance response of the rotating machinery was assumed as the input vibration power. And then, the generated AC power by the harvester was the output power. The theoretical energy transfer efficiency η of the harvester was given by the

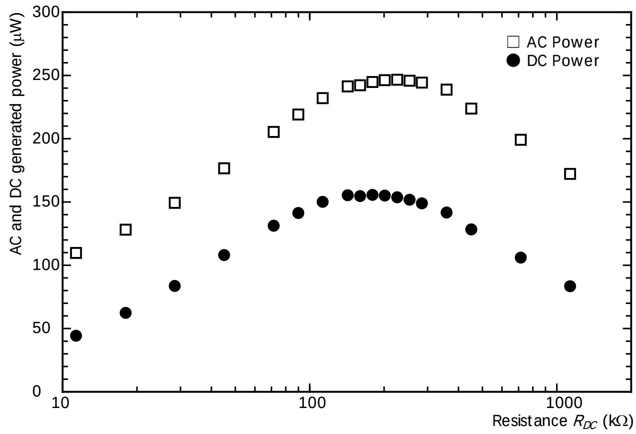

Fig. 4: Power generation performance of the vibration energy harvester with respect to electrical resistance; experimentally measured AC and DC power.

following expression.

$$\eta=\frac{\{-c\omega_n Y^2\pi+kXY\pi\}-\{c\omega_n X^2\pi\}}{\{-c\omega_n Y^2\pi+kXY\pi\}}\times 100\ (\%) \quad (8)$$

The power loss P_{Loss} in the full-wave bridge rectifier was estimated by

$$P_{Loss}=P_{AC}-\overline{P}_{DC}, \quad (9)$$

using the measured values [12]. In Eq. 9, P_{AC} was the power loss at the full-wave bridge rectifier and electrical resistive load R_{DC}, not including the power loss at the AC power meter.

RESULTS AND DISCUSSIONS

Figures 4 shows experimentally measured AC/DC power with respect to the electrical resistive load R_{DC}. From Fig. 4, the generated maximum AC power was 246.1 µW which obtained with the electrical resistive load R_{DC} = 227.3 kΩ at the excitation frequency 29.31 Hz. On the other hand, the generated maximum DC power was 155.1 µW which obtained with the electrical resistive load R_{DC} = 180.5 kΩ at the same excitation frequency. It indicates that the impedance matching between the piezocomposites and electrical resistive load was effective for maximizing the power transfer of the vibration energy harvester. Fortunately, the impedance matching conditions for each maximum power transfer did not sensitive to the electrical resistive load R_{DC}. According to the Fig. 4, the value of R_{DC} is in between about 100 kΩ and 300 kΩ, both generated AC and DC power could be maximized.

Substituting the measured base and tip displacements of the harvester into Eq. 7, the input vibration energy was evaluated by the second term of the right hand side of Eq. 7.

$$-c\omega_n Y^2\pi+kXY\pi$$
$$=-k\left(\frac{c\omega_n}{k}\right)Y^2\pi+kXY\pi=kY\pi(X-2\zeta Y)$$

$$= 25.128 \times 10^{-6} \text{ J} \quad (10)$$

Similarly, the dissipation energy was evaluated by the left hand side of Eq. 7.

$$c\omega_n X^2 \pi = k\left(\frac{c\omega_n}{k}\right) X^2 \pi = 2\zeta k X^2 \pi = 20.118 \times 10^{-6} \text{ J} \quad (11)$$

As a result, the transfer energy from the mechanical system to the electrical system was

$$-\left\{\frac{\theta}{2}\int_0^{\frac{2\pi}{\omega_n}} \{(\dot{x}-\dot{y})q\} dt\right\} = \{-c\omega_n Y^2 \pi + kXY\pi\} - \{c\omega_n X^2 \pi\} = 5.010 \times 10^{-6} \text{ J} . \quad (12)$$

The energy transfer efficiency of the vibration energy harvester was estimated as 19.94% using Eq. 8.

$$\eta = \frac{\{-c\omega_n Y^2 \pi + kXY\pi\} - \{c\omega_n X^2 \pi\}}{\{-c\omega_n Y^2 \pi + kXY\pi\}} \times 100 \ (\%) = 19.94 \ (\%) \quad (13)$$

At the same time, Fig. 4 also shows the experimentally evaluated power loss of the AC-DC conversion using well-known diode-bridge rectifier. The power loss in the bridge rectifier depends on the electrical resistive load R_{DC}. The maximum power loss in the bridge rectifier reached up to about 90 μW. In this study, the power loss in the bridge rectifier could not neglect in the vibration energy harvester.

CONCLUSION

In this study, under the sinusoidal base excitation condition which satisfied the upper level of the vibration magnitude of Zone A for class I rotating machinery, AC and DC power generation performance of the piezoelectric vibration energy harvester was experimentally evaluated. The maximum generated AC power was reached to 246.1 μW at the resonance of the cantilever type of the harvester about 29 Hz. However, DC output was 155.1 μW. Up to 90 μW (about 37.0%) power loss occurred by the AC-DC conversion at the rectifier in this experiment.

Over 100 μW DC output was available under the vibration magnitude of Zone A for class I rotating machinery at the impedance matching condition. Small power battery could be charged by the obtained DC power, and then the vibration data acquisition and data processing could be performed for the vibration condition monitoring of rotating machinery.

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