Energy Scavenging From Ambient Vibrations Using MEMS Device

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Abstract - This paper presents design of MEMS based energy scavenger that detects ambient vibrations and also converts the vibration energy into electrical energy using piezoelectric material. The major load components of highway bridges are dead loads, live loads (static and dynamic), environmental loads (temperature, wind, earthquake) and other loads (collision, emergency braking). Avoiding resonance disasters is a major concern in every structure. It is intended to develop cantilever based energy scavenger by deposition of piezoelectric material to monitor the vibrations and convert the same into electrical energy. The cantilever of E shaped has been designed and simulated with dimensions of 3.332mm x1.180mm for loading on bridges. The materials play a vital role in sensitivity of the device and PZT 5H is selected on the basis of material analysis carried out. The voltage generation of about 3.12 mV and Z-displacement of 4.03µm has been recorded at 100 Hz of frequency.

Keywords: MEMS, Vibration Energy scavenger, PZT.

I. Introduction

In recent years, energy scavenging using piezoelectric materials has become a very popular research topic. Various device sizes and structures have been tested, but cannot be compared based on power measurements as device fabrication and experimental methods vary from paper to paper. Piezoelectric generators rely on resonance to generate useful quantities of power, and power output is highly sensitive to the frequency of the physical vibrations applied. While generators of this type could be useful if targeted to a specific application if the frequency of environmental vibrations is known, a more versatile approach would use a different design to reduce the frequency sensitivity. Broad-band designs, using either non-resonant or self-tuning structures, would be able to harvest energy much more efficiently in changing environments. Also, piezoelectric devices typically show better signal-to-noise ratio (SNR) over a large frequency range and are more suitable than piezoresistive devices for vibration signal detection.

In this paper, various piezoelectric materials have been explored which give maximum deflection as a result of vibrations caused by live load on bridges. This is important as the material which gives maximum Z- displacement would generate maximum energy. The cantilever geometrical structure also plays an important role in improving the efficiency. Rectangular-shaped cantilever structures are most commonly used in MEMS-based piezoelectric vibration energy scavengers. However, the study conducted by Mateu and Moll [2] showed that a triangular-shaped cantilever beam with a small free end can withstand higher strains and allows maximum deflections. Roundy et al. [3] discovered that the strain on a trapezoidal-shaped cantilever beam can be more distributed throughout its structure and delivers more than twice output than the rectangular-shaped beam can. Similarly, Baker et al. [4] experimentally tested a nearly triangular trapezoidal-shaped cantilever beam, along with a rectangular-shaped beam of the same volume. It is found that 30% more output could be achieved using the trapezoidal beam than that using the rectangular.

Shahruz [5,6] designed a piezoelectric MEMS device that can be resonated at various frequency ranges without the need for any adjustment. This device consisted of different cantilever beams with different lengths and different tip masses attached to its common base frame such that each cantilever has its own resonant frequency. The effect of the shared piezoelectric layer laid between the E-shaped cantilever branches connected to the different proof masses at their tips decreases the overall resonant frequency of the energy scavenger to meet the excited lower frequency of the ambient vibration. Hence, this type of cantilever beam would be considered for this study.

II. Design and Analysis of Cantilever with Different Materials

Material Analysis has been carried out in Comsol Multiphysics to understand which material provides maximum deflection at the frequency of interest. Here, the frequency range from 100Hz to 1000Hz has been taken into consideration [7]. The table showing the deflections obtained from different materials with respect to frequency is listed in Table1. It can be observed from the table that the material

PZT 5H gives maximum deflections than any other material for the required frequency range. Hence PZT 5H has been used for analysis. However, for simplicity it has been mentioned as PZT throughout the paper. PZT 5H has higher sensitivity and permittivity than other type of PZT which is good for a energy scavenger.

TABLE 1 FREQUENCY VS Z-DISPLACEMENT FOR DIFFERENT PIEZOELECTRIC MATERIALS

Frequency	PZT2	PZT5A	PZT5H	PZT8	ZnO
100	0.058	0.0713	0.0758	0.055	0.0296
200	0.0584	0.0721	0.0767	0.0555	0.0297
300	0.059	0.0736	0.0783	0.0563	0.03
400	0.0599	0.0757	0.0807	0.0575	0.0304
500	0.0611	0.0785	0.0839	0.0592	0.031
600	0.0627	0.0824	0.0882	0.0613	0.0316
700	0.0647	0.0874	0.0939	0.064	0.0325
800	0.0671	0.0941	0.1015	0.0675	0.0335
900	0.07	0.1029	0.1117	0.0719	0.0347
1000	0.0736	0.115	0.1258	0.0776	0.0362

The material properties of Silicon and PZT5H are listed in table 2.

TABLE 2 MATERIAL PROPERTIES

Material	Density	Young's Modulus	Poisson's Ratio
Silicon	2.329g/cm3	130-188 GPa	0.064- 0.28
PZT	7.6 g/cm^3	63 GPa	0.31

III. DESIGN OF CANTILEVER BASED ENERGY SCAVENGER

At first a square shaped cantilever beam vibration energy scavenger [8] has been designed to obtain the resonant frequency near to nth multiple of the natural frequency of the bridge. However, the dimensions which worked for that frequency are quite high i.e. 50mm x 50mm cantilever with the deposition of PZT layer of about 50 μm. The simulated cantilever of above dimensions is shown in fig 3.

The above cantilever however is too large and hence E shaped cantilever beam has been designed to obtain the desired frequency at feasible dimensions. Typically the vibration frequency obtained in bridges is of the range of 10-70 Hz [9].

A key aspect of structural dynamic analysis concerns the behavior of a structure at "resonance." The natural frequency of vibration of a structure whether a wood-frame house or a radio tower corresponds to that structure's resonant frequency. If a structure is subjected to vibration at its natural frequency, the displacements of that structure will reach a maximum ("resonance"). The greater the displacements, the greater the stresses that are developed in the framing members and connections of the structure.

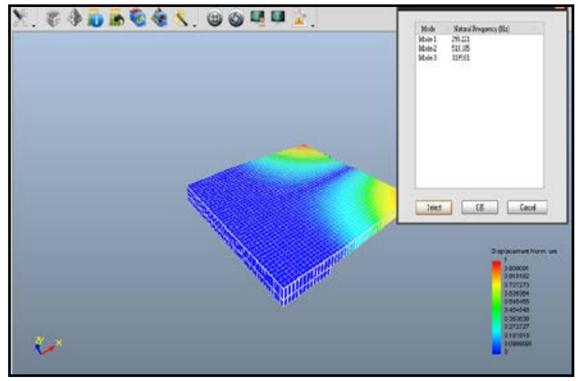


Fig.1. Cantilever with 50mm x 50mm Dimension

Hence, the E beam is designed approximately 2.5 times of the maximum vibrations obtained in the bridges.

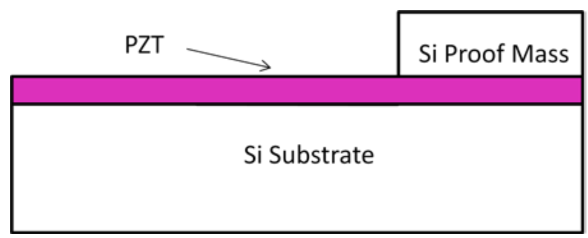


Fig.2 Side View of E beam Cantilever Beam

TABLE 3 E-BEAM CANTILEVER DESIGN PARAMETERS

Material	Length	Width	Thickness
Silicon Substrate	3.332mm	1.180mm	5μm
PZT Layer	3.332mm	1.180mm	5μm
Silicon Proof Mass Branch1	1.217mm	250μm	50μm
Silicon Proof Mass Branch2	1.160mm	217μm	50μm
Silicon Proof Mass Branch3	1.727mm	250μm	50μm

IV. COMSOL MULTIPHYSICS ANALYSIS

The analysis is carried out in Coventorware tool. The material damping has been set to 0.01 for the analysis. The pressure applied on the cantilever beam has been calculated as per the loading standard of AASHTO for the bridges. As the cantilever designed is subjected to real time vibrations which is subjected to earth's gravitation of 9.81m/s² is always acting on the cantilever.

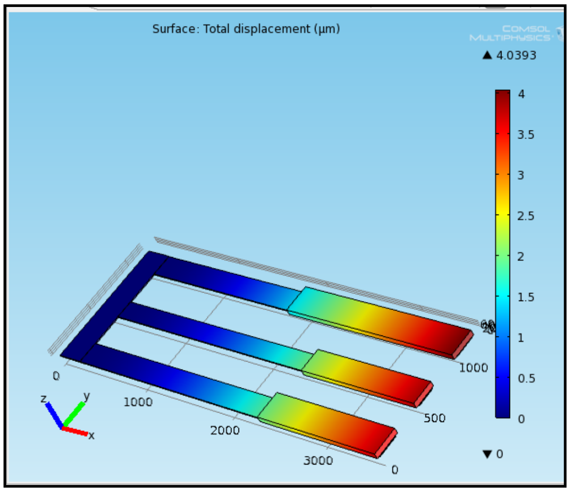


Fig.3 E-Beam Cantilever Design

It is observed that each branch shows different resonant frequency. The displacement vs frequency for each mode is depicted in fig 4. The frequencies observed are 300 Hz, 305Hz , 310 Hz for each branch at Mode1, Mode2 and Mode3 of the cantilever beam.

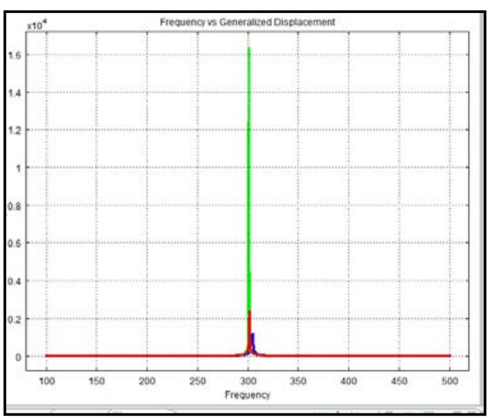


Fig.4 Proof Mass displacement vs Frequency

The maximum deflections obtained at nf i.e nth multiple of the natural frequency of the bridge has been obtained. The branches of the cantilever can be increased to improve sensitivity upto certain number.

The energy generated by this energy scavenger is quite high as compared to other researchers work in MEMS shown in Table 4. Here, 3.1277 mV has been generated by 3 branches of single cantilever beam.

TABLE 4 ELECTROMAGNETIC ENERGY HARVESTER BY OTHER RESEARCHERS

Authors	Paper Title	Power Generated
Huicong Liua, You Qianb, Chengkuo Leeb	A multi-frequency vibration-based MEMS electromagnetic energy harvesting device	0.157 µW at 840 Hz
Adnan Harb	Energy Harvesting: State of the art	290 µW at 102 Hz
Huicong Liu, Bo Woon Soon, Nan Wang, C J Tay, Chenggen Quan and Chengkuo Lee	Feasibility study of a 3D vibration-driven electromagnetic MEMS energy harvester with multiple vibration modes	0.125 µW at 1550 Hz

Also, Ideal energy scavengers are designed to be linear to some simple mathematical function of the measurement, typically logarithmic. Energy scavenger linearity plays a very important part in designing and determining the energy scavenger sensitivity. Fig.6 shows device linearity for first three modes.

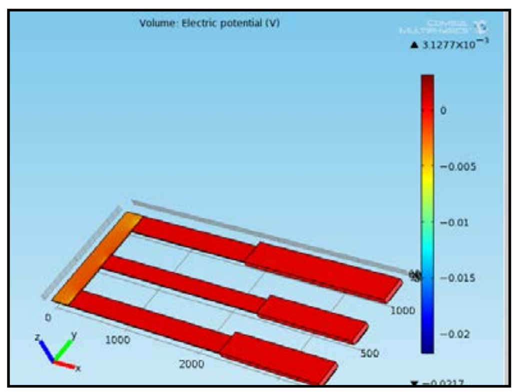


Fig.5 E-Beam Cantilever subjected to Load generated 3.1277 mV

V. RESULTS AND DISCUSSIONS

In comparison with available studies on MEMS-based Structural monitoring systems, the design proposed and discussed here is a framework to obtain a simple device to detect frequency changes and generate energy from the same. Such investigation was indeed possible thanks to the geometry of the considered test, for which the above mentioned energy scavenger monitoring protocol proved sufficient.

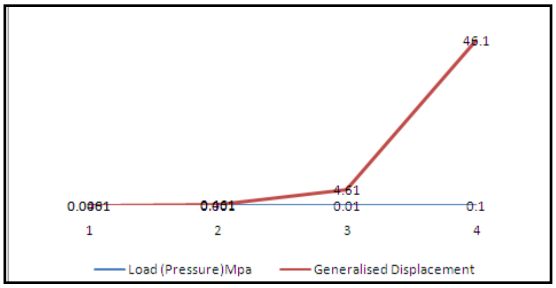
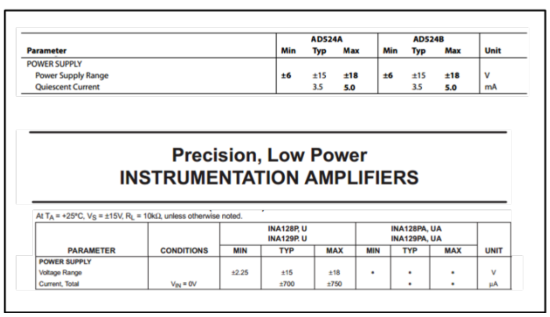


Fig.6 Load vs Z-Displacement (Linearity)

Accounting for the very low cost of commercial MEMS energy scavengers developed for the consumer market, an effective methodology, exploiting redundancies in the energy scavenger network, could help to reduce much the cost of the monitoring systems for bridge health, if compared with current standards. It has been observed that vibrational frequency nf (in this case approx 2.5 times max range of vibrations) can be recorded and processed in order to generate alert. For bridge health monitoring system to process the signals a processing unit including instrumentation amplifier, controller and trans-receiver unit etc. is needed. This instrumentation amplifier and associated unit need to be driven by external batteries. Fig 7 shows that the Precision Low Power Instrumentation Amplifiers which run at ±2.25 V.



Parameter	AD524A Min	Typ	Max	AD524B Min	Typ	Max	Unit
POWER SUPPLY							
Power Supply Range	±6	±15	±18	±6	±15	±18	V
Quiescent Current		3.5	5.0		3.5	5.0	mA

Precision, Low Power
INSTRUMENTATION AMPLIFIERS

At T_A = +25°C, V_S = ±15V, R_L = 10kΩ, unless otherwise noted.

PARAMETER	CONDITIONS	INA128P, U INA129P, U MIN	TYP	MAX	INA128PA, UA INA129PA, UA MIN	TYP	MAX	UNIT
POWER SUPPLY								
Voltage Range		±2.25	±15	±18	•	•	•	V
Current, Total	V_{IN} = 0V		±700	±750		•	•	μA

Fig 7. Instrumentation Amplifiers for Bridge Health

Hence, if we can harvest the energy from the vibrations (generated on the bridges due to loaded vehicles) this same energy can be used to power the subsystem. Here, about 1000 such cantilevers need to be fabricated on a single die to obtain a voltage of 2.25 V. Hence, it can be proven that our design is suitable for bridge health.

VI. CONCLUSION

MEMS based Vibrational Energy scavenger offer a promising technology for future Structural Health Monitoring Systems. The results obtained prove that the vibration energy scavenger is effective at miniscule frequency of vibration of bridges. Also, the excess wirings in current available systems would be reduced to none if such dynamically operated MEMS energy scavengers are used. The above vibration energy scavenger can be modified further for higher accuracy and self powered mechanism.

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