Self Sustained Strain Monitor for Air Vehicle Structures

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ABSTRACT

Next generation air vehicles will need thousands of sensors to simplify diagnostics and to detect problems before they cause catastrophic failures. Self-sustained wireless sensors would allow attaching them to hard to reach places, eliminating wiring, and improving the reliability of the system. In this paper, the power generation capability of piezoelectric elements is evaluated to determine how effectively they can provide the necessary electricity for self-sustained sensors. A three-step process is proposed for the selection of location and hardware. The steps include the evaluation of strain variation using ANSYS, the attachment of proper number of piezoelectric elements, and the use of microprocessors with minimal power consumption.

Keywords

Piezoelectric, energy harvesting, vibration

1. INTRODUCTION

The cost of next generation air vehicles will be extremely high and their technology will be obsolete in very short time. To use them cost effectively, sophisticated health monitoring systems should be installed to identify the problems and their locations ahead of time. These health-monitoring systems will need thousands of sensors to monitor the condition of each critical component. Conventional electrical sensors require several wires to transfer power and signal. The weight and complexity of the wirings of these sensors are an important concern. Power harvesting would reduce the number of wires, allow attaching sensors to the hard to reach places and increase the reliability of the system. In this paper, vibration characteristics of a plate was studied using ANSYS Finite Element Analysis (FEM) program. The power generation capability of a piezoelectric element was experimentally evaluated and a basic design is proposed to monitor the strain without any external power source.

Recently, many researchers performed studies on energy harvesting. The inconvenience of carrying different types of batteries for each device, the need for removing the seals to change the batteries, and the costly and time consuming disassembly process requirements to replace batteries of sensors, which are installed at the hard to reach places, make the energy harvesting very desirable for many applications. To generate electricity alternators, solar cells or thermocouples have been used depending on the environment. It is difficult to find the necessary torque, light, or temperature difference at most of the locations of air and space vehicles to power sensors. However, almost all of the components are subjected to extreme vibrations during the critical stages of their operation. The use of piezoelectric elements is an excellent choice as long as their limited power is satisfactory for the operation of sensors. Commercially available FEM programs are excellent tools to determine the size and the location of the electricity generating and strain measuring piezoelectric elements. They help engineers to determine the size, the number and the location of necessary piezoelectric elements.

The structure of the piezoelectric elements is simple. To build piezoelectric generators, the two opposite sides of an aluminum plate is coated with a piezoelectric material .They are extremely compact and do not have a electromagnetic signature like the induction based alternators. On the other hand, alternators are capable of powering much bigger loads as long as enough torque is provided according to their size. It is possible to install piezoelectric elements inside the micro electromechanical systems (MEMS). Another advantage of the piezoelectric elements is their extremely long operation life, which depends on the applied force and external temperature, which needs to be within the specifications of the piezoelectric elements.

In the following sections of the paper, the theoretical background of the use of piezoelectric elements for electricity generation, and Finite Element Method (FEM) based analysis of strain of a plate will be discussed. The results of our experimental studies with piezoelectric elements will be presented. The selection of the number of elements and proper microprocessors will be discussed.

2. THEORETICAL BACKGROUND

Piezoelectric characteristics of materials have been known for a long time. Initially, they were used either as sensors since they gave very limited amount of energy or as an actuator to create very small and precise linear motions. Increasing demands for self sustained sensors and development of low power electronics attracted many researchers to investigate new designs to generate power using piezoelectric elements [1].

Dimitriadis et al. [2] studied the excitation of two-dimensional thin elastic structures using piezoelectric patch actuators. Thin piezoelectric patches were bonded symmetrically on both sides of the plate. Crawley and Luis [3] determined the 'strain nodes' which are the points along the beam where the strain changes from positive to negative. Piezoelectric elements should not be attached across these 'strain nodes' in order to maximize their effectiveness. Kulkarni and Hanagud [4] analyzed piezoelectric patches attached to a cantilever beam. A dynamic analysis is also performed with several different loading cases. Heyliger [5] obtained exact three-dimensional solutions for a laminated piezoelectric coating.

Currently, many studies are available to estimate the strain variation of plates when they are subjected to forces, and to estimate the expected electricity from them if single or multiple layer materials are used. In this paper, we will use ANSYS to estimate strain distribution and work with experimental data of a piezoelectric actuator, which was attached to a vibrating plate.

3. EXPERIMENTAL STUDY

The experimental setup is presented in Figure 1. A piezoelectric actuator (APC International Ltd.'s piezoelectric ceramic stripe actuator (Lead-zirconate-titanate) *(Catalog Number: 600/200/60-SA)* was attached on a sheet metal plate and vibrated using an unbalanced weight with an electric motor. The leads of one piezoelectric layer were connected to Nicolet Integra 10 digital oscilloscope. The piezoelectric actuators are mainly designed to create displacement when a voltage is applied. However, we have successfully used them to obtain a continuous dim light from an LED in our previous studies. An accelerometer was also attached to the plate to observe the vibration characteristics of the plate during the test conditions.

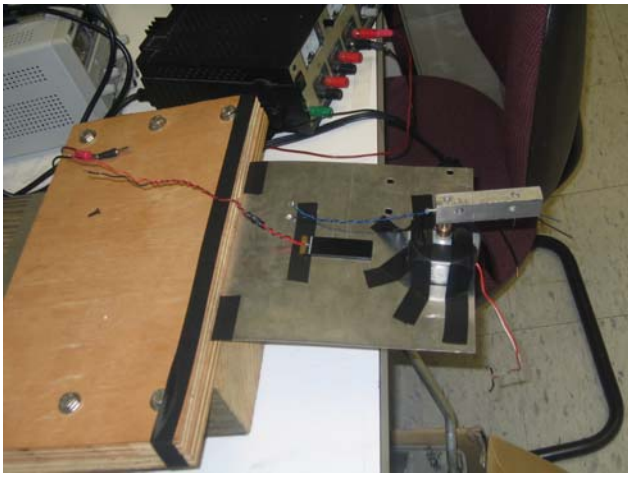

Figure 1. Experimental setup

A circuit is presented in Figure 2 to convert the generated AC of the piezoelectric elements into DC.

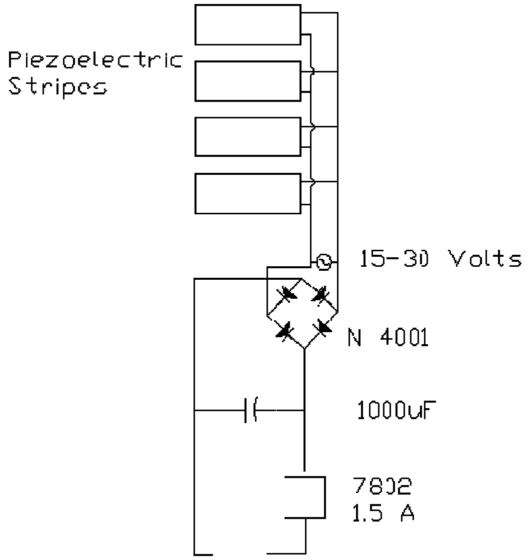

Figure 2. The circuit

4. RESULTS AND DISCUSSION

For the development of a self-sustained sensor, a three-step process is proposed. These steps are the following:

a. Selection of the proper location of the piezoelectric element on the plate for the piezoelectric element,

b. Determination of the power generation characteristics of the piezoelectric element experimentally,

c. Selection of the proper elements and low power microprocessor.

ANSYS was used to determine the suitability of the location of piezoelectric element on our plate. Initially, modal analysis was performed to determine five mode shapes. We selected the middle of the plate to attach the element since it would have satisfactory exposure to strain variations to create the power we desired. Secondly, the strains of the plate were calculated at the loading conditions.

ANSYS 8.0 [6], which is a finite element program, is used to calculate the resonant frequency modes of the plate using an Intel Pentium 4 CPU 3.20 GHz computer. SOLID92, 3-D 10-node tetrahedral structural solid type element, which has a quadratic displacement behavior and is well suited to model irregular meshes, was used. After defining element types, meshing process was applied to the model. Simulation analysis was conducted with 30,922 nodes and 15,185 elements. One end of the plate was clamped and all degrees of freedom were constrained to zero. Then, modal analysis performed using the block lanczos numerical method (for large symmetric eigenvalue problems) as a mode-extraction method. The ANSYS simulation results for vibrating plate were achieved. Total displacements for each mode shape are shown in Figures 3-7.

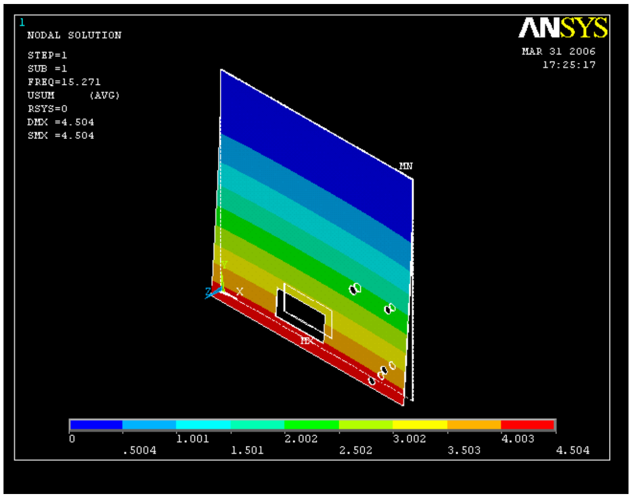

Figure 3. Total displacements for first mode shape

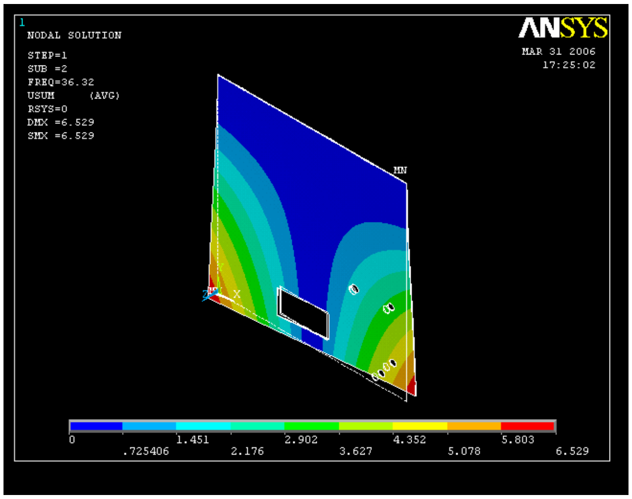

Figure 4. Total displacements for second mode shape

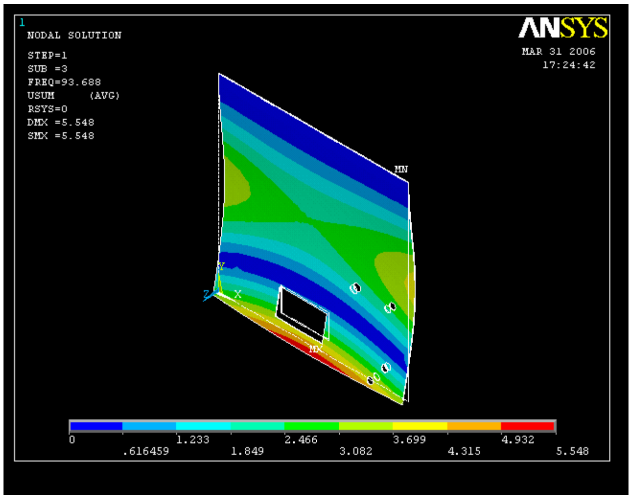

Figure 5. Total displacements for third mode shape

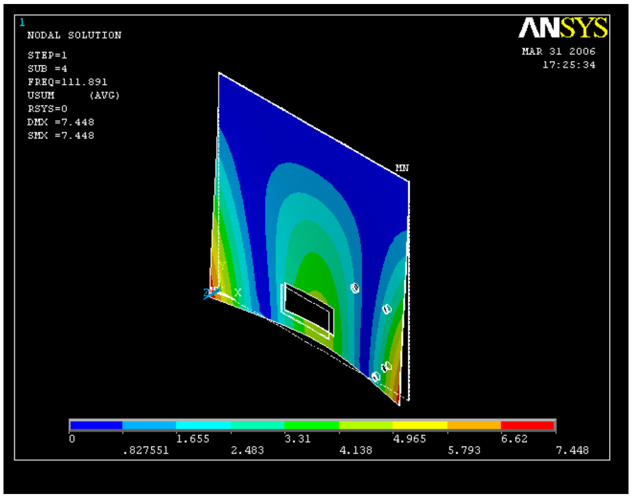

Figure 6. Total displacements for fourth mode shape

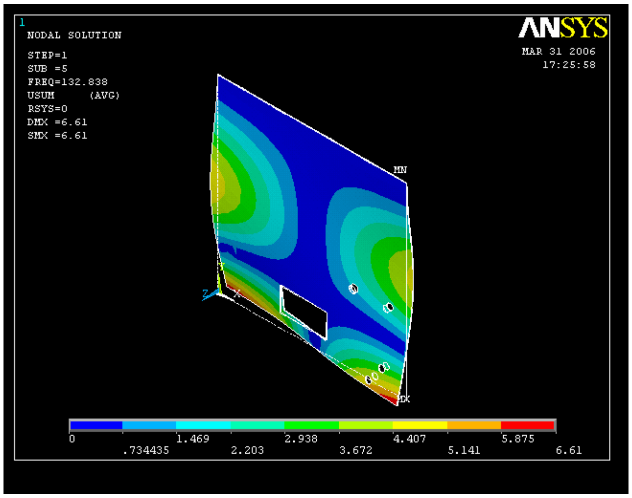

Figure 7. Total displacements for fifth mode shape

The mechanical response of the plate is modeled using static analysis under a uniformly applied load. In these simulations, SOLID92 elements, which are available in ANSYS, were used to model the plate for calculation of the stress/strain distribution. After creating the model, it was meshed using free meshing options with finer meshes around the holes. 30,922 nodes and 15,185 elements were created and the model is shown in Figure 8 below. When the displacements were applied in Z direction of the vibrating end of the plate, static analysis was performed to determine the response of the plate. Strain variations in X and Y directions are presented in Figures 9-10, when one side of the plate is subjected to the displacements.

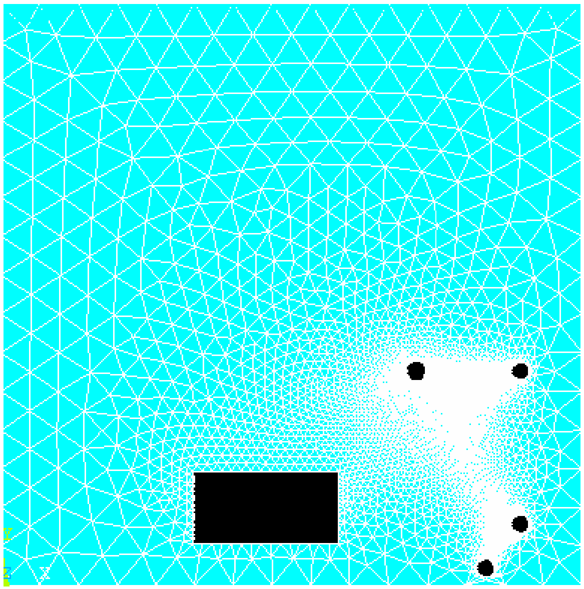

Figure 8. Meshed plate

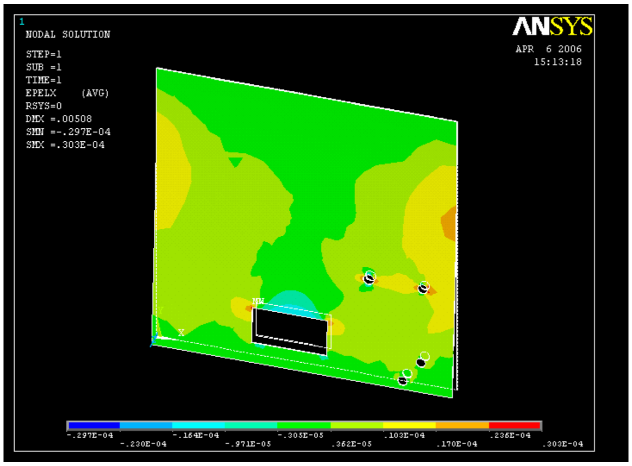

Figure 9. Strain variation in X direction when one side of the plate is subjected to displacement

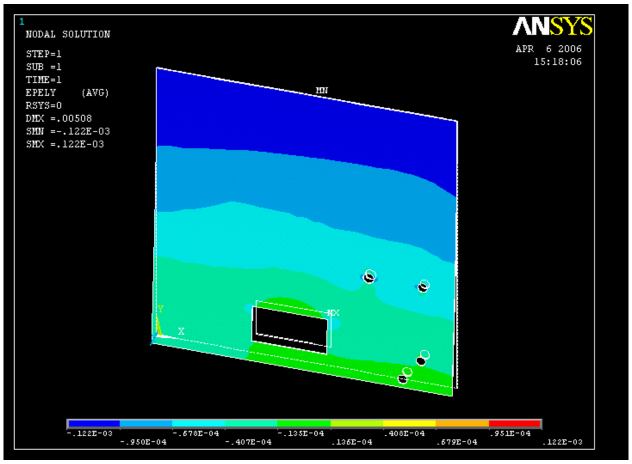

Figure 10. Strain variation in Y direction when one side of the plate is subjected to displacement

In the experiments, a piezoelectric actuator was used to obtain its characteristics experimentally. The actuator has an aluminum plate. Two sides of the plate were coated with piezoelectric material. It was connected to a digital oscilloscope by following the recommendation of the manufacturer. In addition, the acceleration at the perpendicular direction of the plate was measured with an accelerometer. Both signals were plotted together in the Figures 11-14 at four different loading frequencies.

Voltage variation of the piezoelectric actuator was around 30 Volts peak to peak. The input impedance of the digital oscilloscope was 1MΩ. The current was extremely small.

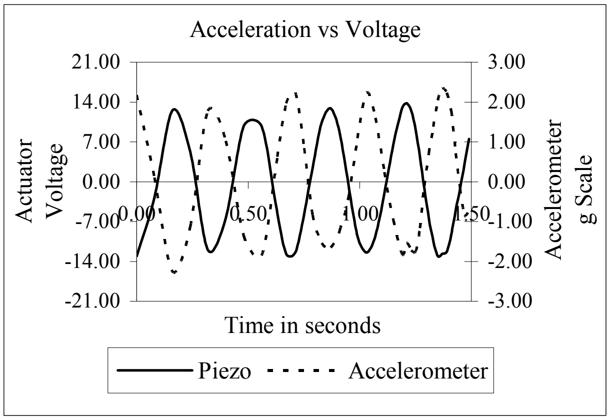

Figure 11. The variation of acceleration versus the generated voltage at 187 rpm

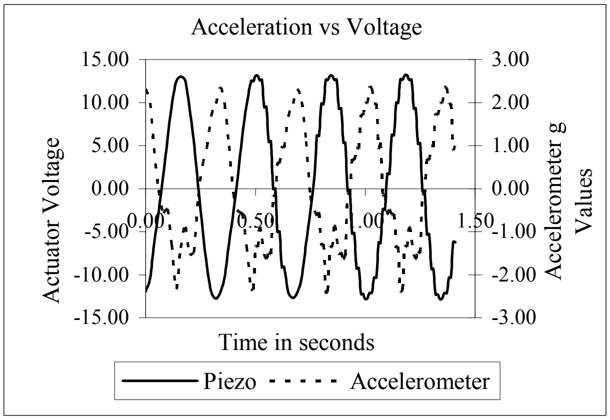

Figure 12. The variation of acceleration versus the generated voltage at 188 rpm

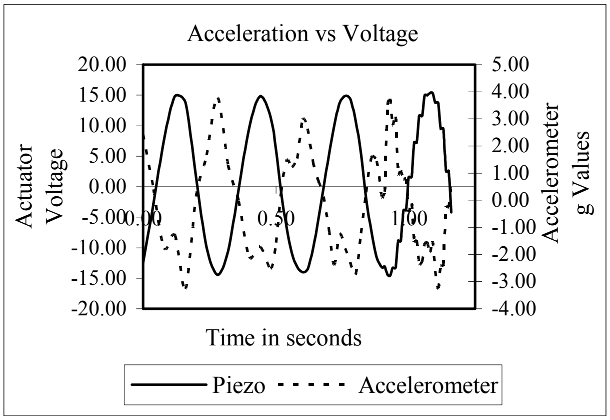

Figure 13. The variation of acceleration versus the generated voltage at 214 rpm

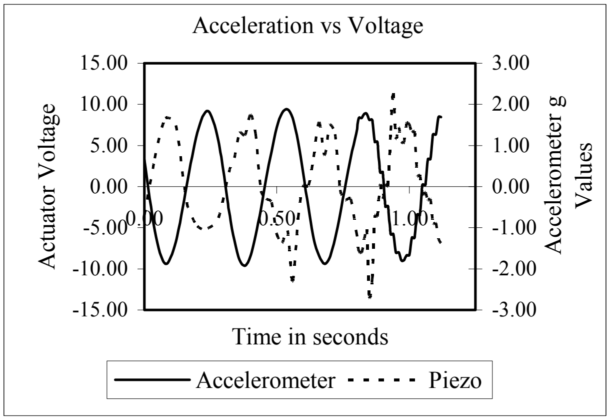

Figure 14. Variation of acceleration versus the generated voltage at 200 rpm

The generated power by the piezoelectric actuator was calculated using the following equation:

$$p = V_{RMS}^{2} / R$$

Where, p represents the energy. V_{RMS} and R are the RMS voltages and the resistance of the oscilloscope respectively. The peak to peak voltage is represented by V.

$$V_{RMS} = V / \sqrt{2}$$

V= 30 Volts

Each strip generated about 0.45 mW power. Unfortunately, DC-DC voltage conversion is very inefficient particularly, when a regulator is used. We expect to use 2-5V for the microprocessor. We expect to get about 0.005 mA with a regulator and 50% efficiency.

Microchip's PIC12F683 is a very low power consuming microprocessor and introduced as nanoWatt Technology. It operates at 0.0085 mA at 2V, when the clock speed is selected 32kHz. Current need increases to 0.1mA if the clock speed is selected 1MHz. Two actuators would provide the necessary current to the PIC12F683, if the internal oscillator of the chip is set to the minimum 31 KHz operating speed with software and 2V voltage supply is used. Power consumption of Microchip's PIC12F683 microprocessor at different operating voltages and clock speeds is presented in the Table 1.

Table 1. Power consumption of Microchip's PIC12F683 microprocessor at different operating voltage and clock speeds (Table is taken from the Microchip catalog)

DC CHARACTERISTICS			Standard Operating Conditions (unless otherwise stated) Operating temperature -40°C ≤ TA ≤ +85°C for industrial					
Param No.	Sym	Device Characteristics	Min	Typ†	Max	Units	Conditions	
							VDD	Note
D010	IDD	**Supply Current**[1,2]	—	9	TBD	µA	2.0	Fosc = 32 kHz LP Oscillator mode
			—	18	TBD	µA	3.0	
			—	35	TBD	µA	5.0	
D011			—	110	TBD	µA	2.0	Fosc = 1 MHz XT Oscillator mode
			—	190	TBD	µA	3.0	
			—	330	TBD	µA	5.0	
D012			—	220	TBD	µA	2.0	Fosc = 4 MHz XT Oscillator mode
			—	370	TBD	µA	3.0	
			—	0.6	TBD	µA	5.0	
D013			—	70	TBD	µA	2.0	Fosc = 1 MHz EC Oscillator mode
			—	140	TBD	µA	3.0	
			—	260	TBD	µA	5.0	
D014			—	180	TBD	µA	2.0	Fosc = 4 MHz EC Oscillator mode
			—	320	TBD	µA	3.0	
			—	580	TBD	µA	5.0	
D015			—	10	TBD	µA	2.0	Fosc = 31 kHz INTRC mode
			—	25	TBD	µA	3.0	
			—	40	TBD	µA	5.0	
D016			—	340	TBD	µA	2.0	Fosc = 4 MHz INTOSC mode
			—	500	TBD	µA	3.0	
			—	0.8	TBD	mA	5.0	
D017			—	250	TBD	µA	2.0	Fosc = 4 MHz EXTRC mode
			—	375	TBD	µA	3.0	
			—	750	TBD	µA	5.0	
D018			—	3.0	TBD	mA	4.5	Fosc = 20 MHz HS Oscillator mode
			—	3.7	TBD	mA	5.0	

The proposed Self Sustained Dynamic Strain Monitor (SSDM) is presented in Figure 15. SSDM uses two or more piezoelectric actuators to generate the AC from the plate vibrations. The AC-DC converter and regulator provide 2V electricity to the microprocessor. A third small piezoelectric element is attached to the plate to monitor the dynamic strain. The size of this element is selected to generate maximum 2V at the extreme conditions. The small element would be connected directly to A/D converting pins of the microprocessor without any additional component.

5. CONCLUSIONS

A three-step procedure was proposed to design a Self Sustained Dynamic Strain Monitor (SSDM). The procedure involved the evaluation of the vibration characteristics of the considered location using ANSYS, experimental evaluation of the output of piezoelectric elements, and the selection of a microprocessor with low power consumption.

FEM was found an extremely effective tool for the estimation of strain distribution and for the calculation of mode shapes. ANSYS estimated the theoretical natural frequencies of plates accurately. Piezoelectric elements created impressive peak-to-peak voltage variation. Unfortunately, current was low and DC/DC voltage conversion is extremely inefficient using the regulators.

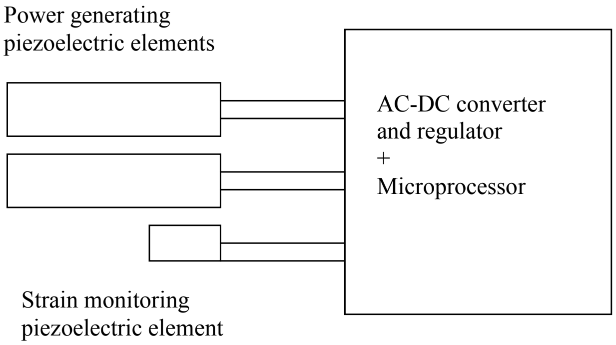

Figure 15. The proposed Self Sustained Dynamic Strain Monitor (SSDM)

The selection of proper microprocessor, the operating voltage, and the clock speed was found essential for the development of successful smart sensors.

The proposed conceptual Self Sustained Dynamic Strain Monitor (SSDM) had three piezoelectric elements. Two of them generated the power for the system. The output of the smaller piezoelectric element was measured to estimate the dynamic strain.

6. ACKNOWLEDGEMENT

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