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Review Article
Modeling of MEMS Based Piezoelectric Cantilever Design Using Flow Induced Vibration for Low Power Micro Generator: A Review

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Abstract
Low power micro/nano devices are tremendously used in our daily life. Battery is a traditional energy source for portable or wearable devices and remote system application. But it has limited lifetime, bulky size and harmful during disposal to the environment. Ambient vibration energy can be considered for small-scale application and converted into electrical energy using three mechanisms: Piezoelectric, electrostatic and electromagnetic. In this study, piezoelectric mechanism will be used to develop a piezoelectric cantilever with a proof mass on its free-end to reduce resonant frequency. An ambient fluid flow energy will be applied to generate vibration of the cantilever. An analytical model will be developed to get an optimised geometrical dimensions of the cantilever which will be designed using SolidWorks. A bluff body will be placed in front of the piezoelectric cantilever with the integration of electronic circuits in a micro-channel where ambient fluid will get barrier due to the bluff body. As a result, turbulence will be created to displace the free-end and then generate vibration of the cantilever. The simulation of Finite Element Analysis (FEA) on the piezoelectric cantilever in CoventorWare will be carried out the modules of fluid dynamics, structural vibration and electrical response. The simulated results can be obtained such as stress, strain, resonant frequency, displacement, voltage and power output. A voltage output is expected from 2.9-4.5 mV at the wind speed of 2-5 m sec^{-1} from the developed piezoelectric energy harvester system. The achievement of the voltage can be used to drive an ultra-low power micro generator circuits.

Key words: Energy harvesting, flow induced vibration, MEMS, micro generator

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Energy harvesting is a process of recovering ambient energies from the environment and then converting it into electrical energy to supply (or store later usage) for low power devices[1,2]. Ambient energy harvesting has been in the focus of research efforts, aimed to provide an autonomous solution to power-up into small-scale for low-power electronic devices[3]. Traditional power sources same as electrochemical batteries have some drawbacks such as their environmental pollution, large maintenance requirements, limited storage capacity and limited lifetime. When it is used in the low-power-consuming wireless remote sensor systems. Currently it is employed for intelligent buildings and environmental monitoring[4]. The energy sources usable by energy harvesting devices mainly: Mechanical (i.e., deriving from vibrations, sounds, deformations and elastic stresses), thermal (i.e., waste heat from furnaces, heaters, motors and different kinds of attrition); light (i.e., sunlight and artificial light, with photodiodes or solar panels), electromagnetic (i.e., inductors, coils and transformers), natural (i.e., wind, tides, waves, ocean currents, solar energy), human body (i.e., thermal and walking) and chemical energy or biological sources[1] etc.

A vast study on ambient environmental energy including solar, wind, geothermal, etc., have already been used for large-scale application and the related technologies are very grown. In order to harvest and storage these natural energies for small-scale application, previous large-scale energy harvesting technologies are no more applicable. Photovoltaic cells are used to convert solar or light energy into electrical energy. However, certain flaws remain in case of solar energy. For example, light intensity can drop significantly during cloudy weather and relatively large surface areas may be required. Study on thermoelectric technology began in 1940's, reached its peak in 1960's and was used on the spacecraft successfully. Thermoelectric energy requires high temperature gradient to provide significant amounts of electrical energy[5,6]. For energy harvesting mechanical energy occurs almost in each engineering system, where harvesting generator can use energy of vibration, random moving, deformation and pressure fluctuation, medium flow (rivers, wind and ocean waves etc.) and energy of human body, which can be divided into active and passive sources of behaviour[7]. A general schematic diagram of the energy harvesting system is shown in Fig. 1. The energy harvesting system consists of an energy harvesting generator, power management, powered device and an energy storage element[7].

Now-a-day low-power requirement scaling trend will enable micropower energy harvesting solutions in wireless applications such as medical monitoring, machining-condition monitoring and structural-health monitoring[8]. Low-power VLSI design have resulted in very low power requirements of 10-100 μW. Most of all, mechanical vibration is a potential power source which is easily accessible through Micro Electro Mechanical Systems (MEMS) technology for conversion to electrical energy[9]. When a part or device is under mechanical vibration, an inertial mass can be used to create movement. This movement displace the part or device from its original position and can be converted to electrical energy using three mechanisms: Piezoelectric, electrostatic and electromagnetic[5,10-13]. Among those conversion mechanisms, piezoelectric materials are most prominent. Mechanical vibration can be utilised to develop more stress and strain

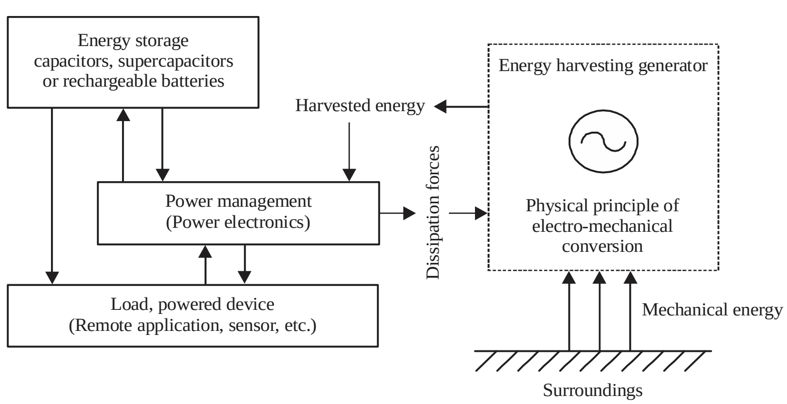

Fig. 1: Schematic diagram of energy harvesting system[7]

on a piezoelectric cantilever. By developing more stress in the cantilever, the more power will be generated and flow to the load through peripheral circuits. The next paragraphs are described on the mechanisms of piezoelectric, electrostatic and electromagnetic.

Electrostatic energy harvesting system generates voltage by changing the capacitance. It is needed to apply an initial voltage to the capacitance before the energy is supplied by the system[5,14,15]. When the quantity of charge stored in the capacitor was changed by the external vibrations, a charge flow is generated in the circuit and thus provides electrical power to the sensors[15]. Two operation modes are experienced for electrostatic energy harvester: Constant charge mode and constant voltage mode as shown in Fig. 2.

In case of constant charge mode, the capacitance is decreased with increases of the voltage. Similarly, as for constant voltage mode, with decreases of the charge the capacitance is decreased[14]. They do not need any smart material[5]. The electrostatic energy harvesting systems have their ability to integrate with microelectronics giving higher

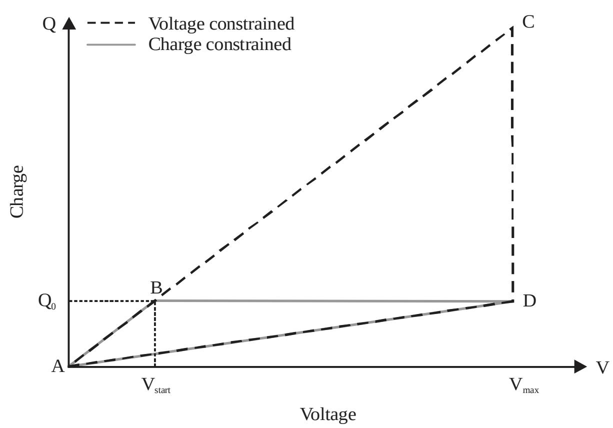

Fig. 2: Conversion cycles for micro-electrostatic energy harvester[14]

voltage and power density in the same size. But one of the key problems is that it needs an extra voltage source to initially charge the capacitor[5,15]. Electromagnetic energy harvesting is obtained by the principle of electromagnetic induction which is defined as a process of generating induced electromotive force in a conductor by changing the magnetic field around the conductor[5,14,15]. The electromagnetic generators provide some advantages like improved reliability, no separate voltage source and reduced mechanical damping as there would not be any mechanical contact among any parts. However, electromagnetic materials are not small in size and faces complexity to integrate with MEMS[5,15].

The piezoelectric material (e.g., PZT, PVDF) is widely used for mechanical to electrical energy conversion. The piezoelectric material is physically deformed by pressure, vibration or force to get induced electrical field as shown in Fig. 3a[5,14] and a typical piezoelectric cantilever as shown in Fig. 3b[16]. In contrast, if electrical energy is applied then mechanical deformation will be induced. This effect is showed due to the spontaneous separation of electric charge in certain crystal structure required to produce electric dipoles[14,17]. Piezoelectric materials are perfect choice for harvesting power from ambient vibration sources[9]. Because piezoelectric vibration-to-electricity converters can efficiently convert mechanical strain to an electrical charge without any external power[10]. Piezoelectric effect is highly used in piezoelectric cantilever to generate electric power. Generally, a proof mass is added on tip of cantilever to lower resonance frequency and maximise the output voltages. At present, a wide variety of piezoelectric materials i.e., piezoelectric monocrystal, piezoelectric ceramics, piezoelectric polymers and piezoelectric composites[15] are available. The appropriate choice for harvesting energy, sensing or actuating depends on that materials characteristics. Lead Zirconate Titanate (PZT) is the most commonly used piezoelectric materials having the

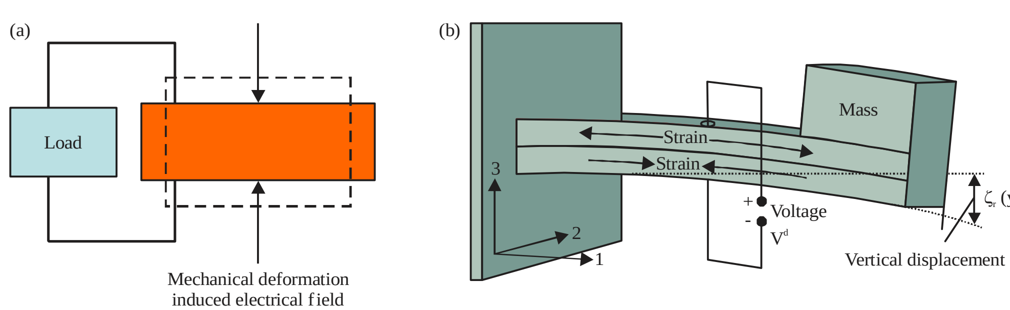

Fig. 3(a-b): (a) Piezoelectric effect[14] and (b) Piezoelectric cantilever[16]

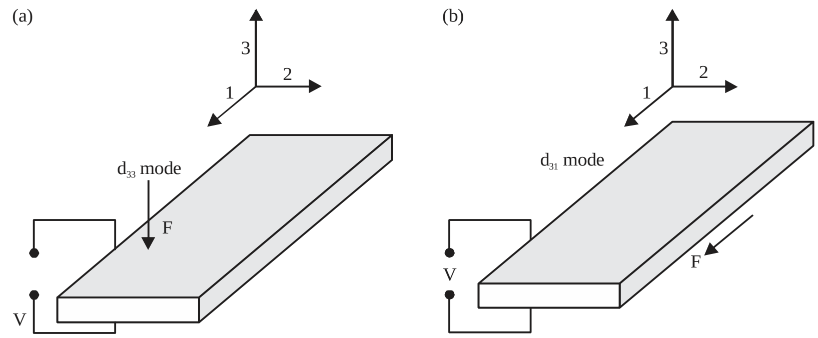

Fig. 4(a-b): Illustration of (a) d_{33} mode and (b) d_{31} mode[15]

advantages of mature manufacturing process, low cost, large electromechanical coupling constants and high energy conversion rate[5]. But PZT is fragile and unable to bear large strain and it is easy to produce fatigue crack and brittle fracture by the impact of high-frequency cyclic load. Another commonly used piezoelectric material is polyvinylidene fluoride (PVDF). Compared to piezoelectric ceramic PZT, PVDF has smaller electromechanical coupling constants[18] but it has advantages of good flexibility, high mechanical strength, good fatigue resistance and chemical stability[19]. It is suitable for the application with under the high-frequency periodic load[15].

Two piezoelectric coupling modes are practically found for operation as shown in Fig. 4. In the d_{33} mode, the vibration force is applied in the same direction as the poling direction, while in the d_{31} mode the force is applied perpendicular to the poling direction[15,20]. The d_{33} mode has a higher coupling coefficient than d_{31} mode. But d_{31} mode is able to produce a larger strain in a small external force at very low voltage source and small-sized devices compared to d_{33} mode[15,20].

In this study, a modeling of a MEMS based piezoelectric cantilever was proposed design using flow induced vibration. The cantilever will be designed such a way which can be operated at low wind speed, having small volume and providing optimised electrical power. It will be comprised of a piezoelectric cantilever with a bluff body. The bluff body placed in front of the cantilever. The ambient fluid flow will experience barrier due to bluff body. Flow separation of the ambient flow will be happened to make the flow turbulent. The consequences of turbulent flow lead to create vortex around the cantilever to develop flow induced vibration of the cantilever. The generated vibration is required for piezoelectric materials to obtain the required electrical energy using fluid flow for low power micro generator.

PROBLEM STATEMENT

Energy harvesting is a great concern for powering up the low power electronics devices. Most of the research work on energy harvesting have been done on direct ambient vibration[9,10,21,22]. Wind driven energy harvester is significant because it does not require an external vibration sources and also take a consideration of aerodynamics with vibrations to supply necessary power[23]. Flow induced vibration have a great potential to investigate for generating energy from ambient flow[24,25]. Energy can be harvested from pipe flows, blood flow in arteries, or air flow in tire cavities. To generate flow induced vibration bluff body was used. Previously rectangular[25], cylindrical[26] and half cylindrical[27] bluff body was used. An output voltage of 2.9 mV was found at air speed 5 m sec^{-1} having PZT-5A. The PZT-5A was 58 μm long, 50 μm wide and 3 μm thick with volume of $8.7e^{-9}$ cm^3 [28]. A more output voltage of 18.1 mV was obtained from 3000 μm long and 300 μm wide piezoelectric cantilever at wind speed of 15.6 m sec^{-1} [23]. It was found that with the increased of fluid speed, output voltage also increased. The main challenges is to generate more output voltage by using low speed in between 1.5-5 m sec^{-1} of wind speed and optimum dimensions with low volume of the piezoelectric cantilever. The target is to change the shape of bluff body so that it generate effective fluid vortex to vibrate the cantilever more effectively.

LITERATURE REVIEW

Researchers are working on energy harvesting to make it more useable for low power application devices around the globe. Mechanical vibration is one of the prominent source of ambient energy. Ambient flow energy is a challenging sources for researchers to harness energy from it. Using piezoelectric materials mechanical vibration can be converted into electrical energy. A Piezoelectric Micro Power Generator (PMPG) has been modeled and simulated using four different approaches, (1) COMSOL Multiphysics 3.5a, (2) Coventor, (3) ANSYS and (4) Lumped element analysis. It was found that four approaches closely agree with each other. The scope of this study is to investigate a nominal design of the PMPG and analyse its response with a view to arrive at an optimal design[17]. Transient analysis had been carried out by using different methods such as ANSYS, CoventoreWare and Lumped Mass model. Three of them are approximately matched in the transient response and the oscillating voltage amplitude was around ± 2 µV[16]. An investigation have carried out of an acoustic energy harvester which consists of a quarter-wavelength straight tube resonator and piezoelectric cantilever plates placed inside the tube using COMSOL Multiphysics 4.3. The tube length is designed to get a low operating frequency of ~200 Hz. In simulation, the maximum total output voltage and power generated by multiple piezoelectric plates are 4.06 V at 189 Hz using 5 PZT plates and 0.37 mW at 190 Hz using 4 plates with the incident SPL of 100 dB. The experimental data are 7 and 19% lower than the simulated results (3.79 V at 193 Hz and 0.31 mW at 194 Hz)[29].

An analytical model was developed for a unimorph piezoelectric cantilever. This cantilever was designed for frequencies 60-200 Hz and modeled using COMSOL Multiphysics[30]. Using moving mesh Arbitrary Lagrangian Eulerian (ALE) model available in COMSOL Multiphysics an energy harvester based on piezoelectric micro generator has been optimized. The length, width and thickness of cantilever are obtained as 2000 µm$\times$120 µm$\times$5.4 µm. The dimensions of proof mass are 237 µm$\times$120 µm$\times$237 µm and mass is 0.145 mg. The output voltages was found 1.06 V for d_{31} and 3.85 V for d_{33} and a resonant frequency of 630 Hz with acceleration of 1 g for the cantilever beam[11].

Another MEMS piezoelectric energy harvesting cantilever consists of a silicon beam integrated with piezoelectric thin film (PZT) elements was designed, microfabricated and characterized. The cantilever has thin film (PZT) elements parallel-arranged on top and a silicon proof mass resulting in a low resonant frequency of 36 Hz. The energy harvesting device has a wideband and steadily increased power generation from 19.4-51.3 µW within the operation frequency bandwidth ranging from 30-47 Hz for input acceleration of 1.0 g[31]. To investigate design parameter such as thickness of piezoelectric material, displacement of vibration and maximum pressure of a raindrop energy harvester using PVDF as a piezoelectric material have been simulated by CoventorWare. Aluminium was used as an electrode. Among the design parameters, thickness of these materials played a significant role in displacement and output power[32]. In order to study the effect on resonance frequency and power enhancement techniques of piezoelectric MEMS, a piezoelectric generator based on a two-layer bending element was modeled, designed and optimized by using COMSOL Multiphysics. An analytical relation was developed and analysed by MATLAB/Simulink interface for easy understanding of design dimensions, material parameter values and force signal stimuli[33]. A MEMS based cantilever devices with thin film lead zirconate titanate, Pb (Zr, Ti) O_3 (PZT) is developed and fabricated that uses the d_{33} piezoelectric mode. From the PZT cantilever, a continuous electrical power of 1 µW can be delivered to a resistive load at 2.3 V DC and resonance frequency of 13.7 kHz[34].

A governing equation of a PVDF bimorph with a corrugation shape was derived from the transfer matrix technique. The PVDF bimorph power harvester structure was fixed at the two edges in the corrugation direction and free at the other edges. The harvester provided a closer match to the ambient vibration frequencies by changing the resonant frequency[35]. Researchers developed an analytical model of piezoelectric bimorph transducer to optimise the dimensions of the bimorph and predict its performance. The piezoelectric bimorphs was fabricated that showed resonance in the loaded condition in the range of ~200 Hz with a high power density of 0.49 µW mm^{-3}. A correlation between the output power and material properties was found and power density can be improved by enhancing the magnitude of product (d and g), where d is the piezoelectric strain constant and g is the piezoelectric voltage constant[36]. Researchers designed, fabricated and characterized a piezoelectric laminated cantilever with proof mass. The micro power generator generate a voltage of 1.6 V and an output power of 1.4 µW at 870 Hz[37].

Fluid flow is used to generate vibration of piezoelectric materials. Taking airflow as input energy, simulations and experiments have been carried out to develop energy harvester from piezoelectric materials. A piezoelectric cantilever beam was developed with an aerofoil that attached to the free end of the cantilever spring while the other end was clamped. A rectangular shaped bluff body was placed in front of the cantilever to generate induced vibration. The position of the bluff body, both its distance to the cantilever and height affect the oscillations of the cantilever[25]. Researchers developed a wind-driven piezoelectric microcantilever energy harvester. It completely eliminates the operating bandwidth issue that a traditional vibration driven

Table 1: Comparison table on fluid flow energy harvesting for generating power to load

References	Input	Volume	Output voltage	Output power	Power density	Load
Sun *et al.*[25]	Wind speed 1.5-8 m sec^{-1}	37.5 cm^3	0.5-1.32 V (open circuit)	0.1-0.8 μW	-	800 kΩ
Bhuyan *et al.*[28]	Air speed 5 m sec^{-1}	8.7e^{-9} cm^3	2.9 mV	-	-	-
Zhao *et al.*[48]	Wind speed 14 m sec^{-1}	-	-	-	12.96 mW cm^{-3}	-
Liu *et al.*[23]	Wind speed 15.6 m sec^{-1}	-	18.1 mV	3.3 nW	0.36 mW cm^{-3}	100 kΩ
Weinstein *et al.*[40]	Wind speed 2.5 m sec^{-1}	-	-	200 μW	-	-
	5 m sec^{-1}			3 mW		
Sirohi and Mahadik[39]	Wind speed 11.6 mph (≡ 5.19 m sec^{-1})	-	-	53 mW	-	36.9 kΩ
Kim *et al.*[46]	Air speed 6.1 m sec^{-1}	-	0.44 V	-	Max 6.7 μW cm^{-2}	22 MΩ
	12.4 m sec^{-1}		0.62 V			
	21.6 m sec^{-1}		0.82 V			

energy harvester achieves the maximum power at only a particular resonant frequency[23]. Researchers used cross fluid flow to fluctuate a piezoelectric cantilever. A half cylindrical bluff body was placed in front of the cantilever to induced pressure by the kármán vortex street. The COMSOL finite element analysis was used to find out mechanical analysis, eigen frequency analysis and transient analysis[27]. The same researchers used laminar fluid flow to investigate cantilever tip displacement, maximum stress, temperature analysis and electric potential of the cantilever. Researchers developed an energy harvester where a piezoelectric film is placed on top of a flexible diaphragm, which is located in the wake of a bluff body. The piezoelectric film oscillates due to the vortices shed from the bluff body in a water flow. Experimental results show that an open circuit output voltage of 0.12 Vpp and an instantaneous output power of 0.7 nW are generated when the pressure oscillates with an amplitude of ~0.3 kPa and a frequency of ~52 Hz[38]. A wind energy-harvesting device based on a galloping beam with piezoelectric sheets has been fabricated, tested and analysed. The prototype device of size approximately 160×250 mm generated a maximum output power of 53 mW was measured at a wind velocity of 11.6 m h^{-1} [39]. A piezoelectric cantilever beam with an aerodynamic fin attached at the end of the beam is placed and vibrated in a Heating, Ventilation and Air Conditioning (HVAC) flow. The vibration was generated by the vortex shedding downstream from a bluff body placed in the air flow ahead of the cantilever. From a 15 cm diameter air duct, power generation of 200 μW and 3 mW achieved at a wind speed of 2.5 and 5 m sec^{-1}, respectively[40].

Researchers have designed, tested and characterized two prototype of energy harvester from pressure ripple in hydraulic systems through piezoelectric stack configurations. The harvester provided a maximum power output of 1.2 mW from a dynamic pressure ripple of 400 kPa. An improvement of power output capability have found from the second version of the prototype having an effective area ratio greater than unity[41]. Researchers presented pressure distribution and deflection of a piezoelectric cantilever beam immersed in fluid flows and subjected to controlled vortices[42]. A comparison on fluid flow energy harvesting is shown in Table 1.

DESCRIPTION OF PIEZOELECTRIC BASED ENERGY HARVESTER SYSTEM USING FIV FOR MICRO-GENERATOR

Energy harvesting from ambient sources (vibrations, heat and light etc.) are a vital issue. A conventional block diagram of the energy harvesting system is shown[43] in Fig. 5. In a conventional energy harvester, environmental vibration is taken as input energy to obtain electrical power as output energy.

Generally mechanical vibration convert into electrical energy by using piezoelectric material characteristics[21]. Single piezoelectric cantilever can be considered as a most movable element. Its maximum electrical power is only found at a particular resonant frequency but not enough to power-up the low power electronic devices for a long period. Instead of single piezoelectric cantilever, an array of piezoelectric cantilever was used to obtain maximum power[23]. The harvested energy is stored through efficient interface electronic circuits for ultra-low power energy harvesting[44].

The propose diagram for energy harvesting system using flow induced vibration is shown in Fig. 6. The piezoelectric harvester system use the input sources of wind and water to provide power source for small electronics[45]. It also can be used blood flow as a potential fluid. High windy environment is found on the top of infrastructure of bridges and buildings. The induced wind energy can be used by piezoelectric energy harvester as a power source of the infrastructure monitoring sensor. With the increase of air flow, generated voltage[23,46] and RMS power output[25] was increased. It is noted that the second block (i.e., moveable element) in Fig. 5, can be extended on the following sub-blocks (Blocks 1-5) which is

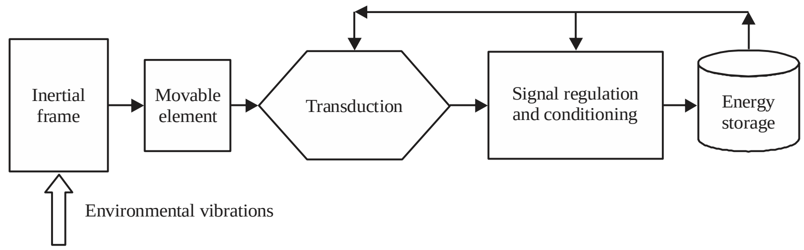

Fig. 5: Conventional energy harvesting system[43]

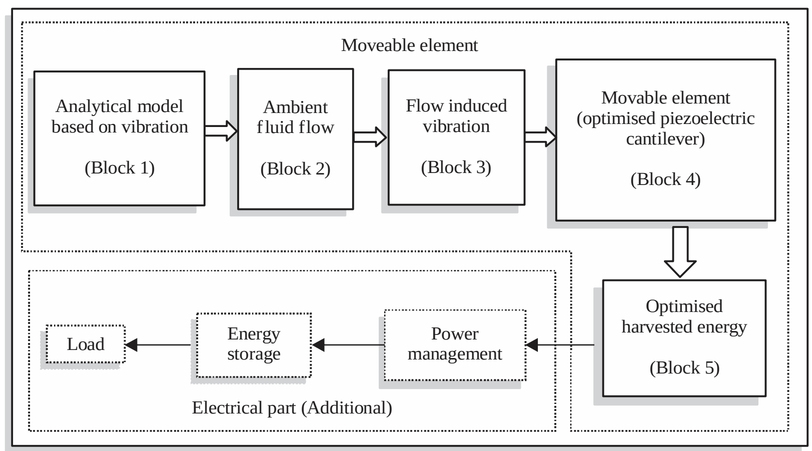

Fig. 6: Proposed block diagram of the piezoelectric energy harvester system using FIV, FIV: Flow induced vibration

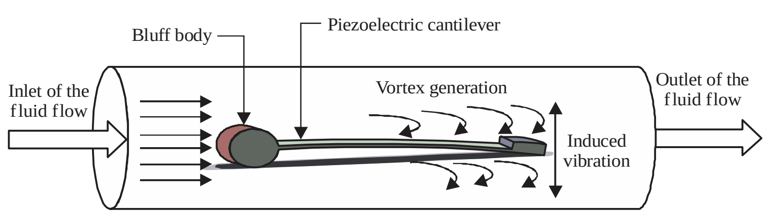

Fig. 7: An expected schematic of a piezoelectric energy harvesting system using FIV, FIV: Flow induced vibration

shown in Fig. 6. In Block-1 the piezoelectric cantilever can be considered as a spring mass system. An analytical model for the piezoelectric cantilever beam with an end mass of its free end will be developed based on vibration. From the analytical model the length, width and height of the cantilever with end mass can be found. The weight of the end mass play a vital issue in the determination of the beam's resonant frequency. To lower the resonant frequency an end mass will be added according to the analytical model. In this system the vibration will be generated by induced flow of ambient fluid.

In Block-2 the Navier-Stokes equation and kármán vortex street will be considered. Navier-Stokes equation provides a mathematical model of the motion of viscous fluid. Kármán Vortex Street is generated due to unsteady separation of flow of a fluid around a bluff body. In Block-3, kármán vortex street[47] is responsible for generating pressure fluctuation along the piezoelectric cantilever beam. Because fluid flow was induced by putting a bluff body in front of the beam[27]. In Block-4 horizontal cantilever beam is deformed from its original position because of pressure fluctuation along the beam. In Block-5 maximum electrical energy will be obtained from the energy harvester due to piezoelectric effect. An expected schematic of the piezoelectric energy harvesting system using FIV in this study is shown in Fig. 7. The beam try to get back to its original position due to pressure fluctuation since it is considered as spring mass system. However, inertia force keep the beam in vertical deflection with respect to the beam length (i.e., vibrating). The free end of the beam will reach its peak vertical displacement at resonant frequency.

The electrical energy from Block-5 in Fig. 6, will be fed to the additional electrical circuit components, namely power management, energy storage and finally to the load. Here the power management block converts the achieved energy which needed to the system and store it into storage device. The storage device can be capacitor, super-capacitor which are the primary types of storage component for energy harvesting system. Later on, the storage energy will be applied to the specific load.

METHODOLOGY

The design flow chart for the proposed piezoelectric cantilever energy harvester is shown in the following Fig. 8. The flow chart started with a comprehensive literature review based on piezoelectric cantilever for energy harvesting. In order to harvest energy, a geometrical specification of the piezoelectric cantilever is required. An optimised three dimensional geometry of a piezoelectric cantilever will be calculated through a development of an analytical model. The three dimensional geometry of the piezoelectric cantilever will be designed by using SolidWorks. After modeling of the cantilever, it will be imported into CoventorWare software to perform simulation on the designed model. Then the boundary conditions and other parameters will be set up. The process can be divided into three sections:

- Pre-processing (geometry, mesh, materials properties, boundary conditions)
- Solver (governing equations solve on a mesh)
- Post processing (graphs, contour, velocity vectors, others)

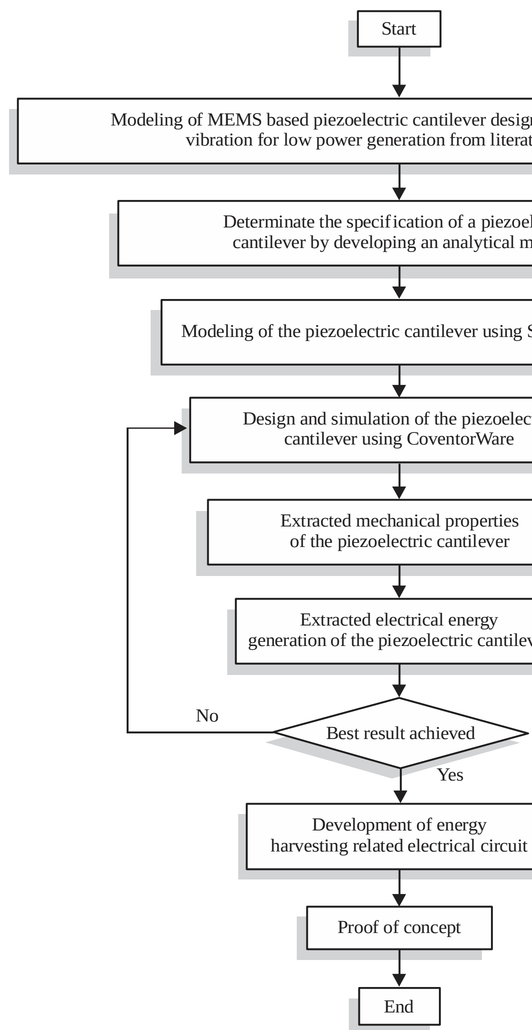

Fig. 8: Design flow chart for implementing the piezoelectric energy harvester, MEMS: Micro electro mechanical system

After the simulation the mechanical properties such as stress, strain, displacement, lift and drag will be obtained. Electrical properties such as voltage and power output also can be obtained. Here if any undesirable or erroneous results occur then it will be required to feed back for checking boundary conditions or pre-processing to the solver. After getting the desired results a system (with electrical circuits) will be integrated to demonstrate the Proof of Concept (PoC) for verifying the expected simulated results which can be used for low power micro-generator.

CONCLUSION

In this study, the modeling of MEMS based piezoelectric cantilever design using FIV for low power micro generator has been presented. A process of piezoelectric cantilever design is also suggested. Firstly the geometry of piezoelectric cantilever has been described based on vibrational analytical model. From the vibrational analytical model an optimised dimension of the cantilever will be obtained. The fluid flow energy will be used to generate induced vibration. The flow will be induced by placing a barrier in front of the piezoelectric cantilever. Then the optimised cantilever will be simulated in the CoventorWare. In post processing of the simulation; mechanical properties such as stress, strain, displacement, resonance frequency (with their expected results) and also related electrical parameters of power density, voltage (2.9-4.5 mV) and power output will be obtained.

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