

Thermal network modelling of hybrid piezo-pyro transducer for application in energy harvesting

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Abstract— In the current era, due to global climate change, a lot of emphasis has now shifted towards energy harvesting and making our devices more efficient. In automobile industry, a lot of research is going on in the field of electric vehicles, even the conventional vehicles efficiency has also been greatly increased in the past decade. Today, a lot of automation in the vehicle is incorporated in order to reduce human errors while driving. With increase in number of sensors in a vehicle its energy consumption has increased. In order to maintain a vehicle's energy efficiency, self-powered sensors are an interesting field to explore, which works on energy harvesting by various means. In this report, we present an optimized design of cantilevers fabricated over a block of thermally conductive pyroelectric block. Further, to do the modelling of the design we used thermal network modelling. It aims to validate a model of transducer for converting vibrational and thermal energy into electrical energy, for the application of energy harvesting in sensors for automobiles. This approach combines the pyroelectric, piezoelectric and thermal conductive properties of different material to enhance efficiency of the transducer hence, power output. In order to calculate theoretical efficiency more precisely, we propose the thermal network modelling.

Keywords—Energy harvesting, transducer, pyroelectricity, piezoelectricity, thermal conductivity, cantilevers, thermal network modelling.

I. INTRODUCTION

Pyroelectric materials have ability to transform temperature difference into electrical energy, which can be used for self-powered energy harvesters. The non-centrosymmetrical crystal lattice is the reason for energy generation from thermal fluctuations as-well as from vibrations which is called piezoelectricity. The piezoelectric and pyroelectric materials come from non-centrosymmetric crystal class and comes under the category of dielectrics. Conventionally, lead zirconate titanate (PZT) is the most commonly used piezoelectric material, as it has high piezoelectric coefficient. But the only disadvantage of using PZT is lead, which makes this material toxic. As a lot of emphasis is being given on eco-friendly material, materials

such as bismuth ferrite, potassium sodium niobate lithium niobate have now been considered to replace PZT.

At FEMTO-ST, AS2M department, in Modelling and Robust Control of Micromechatronic Systems (MACS) team; we are designing and fabricating piezo-pyro hybrid structure for application of energy harvesting in sensors, as a part of ENHANCE-EU Horizon 2020 project.

In the past decade, a lot of emphasis has been given for self-powered devices, using different principles, energy harvesting from photovoltaics, electromagnetic, triboelectric, piezoelectric principles, but these self-powered devices have some limitations and the most common in all of them is efficiency.

To maximize the power output, we are using hybrid approach, using cantilever fabricated using piezoelectric and pyroelectric materials. These materials are Lithium Niobate (LiNbO_3) and Polyvinylidene fluoride (PVDF) which are well known for their piezoelectric and pyroelectric properties respectively (LiNbO_3 : $d_{33}= 39.60 \text{ pC/N}$; $K_{33}= 0.60$ at 61.8° and 57.0° resp. ^[1] and PVDF: pyroelectric coefficient (P_v) of $28.3 \text{ nC/cm}^2 \text{ }^\circ\text{C}$ at $75 \text{ }^\circ\text{C}$ ^[2]. To further enhance the efficiency of our device, we are using a multi-cantilever approach, fabricated on a Metal+GaN composite block; as metals have high thermal and electrical conductivity, whereas, GaN is known for its pyroelectric properties. Although, a lot of research has been done in the field of hybrid thermoelectric transducers for instance, Gusarov and group ^[3], had combined pyroelectric material, piezoelectric material and shape memory alloy for thermal energy harvesting from narrow temperature range, Jie Hue ^[4] group did research on energy harvesting from PVDF hybrid piezo-pyro devices by coupling piezoelectric and pyroelectric energy generated within PVDF. Minoru Taya group ^[5] designed piezo-SMA composite, for thermal energy harvesting under fluctuating temperature, and presented simple laminated model and 3D model using Eshelby theory. However, from the best of our knowledge, no research group has worked on the multi-cantilever design, and inclusion of dynamic thermal modelling for making calculations and model more precise.

II. WORKING PRINCIPLE

A. Piezo-pyro hybrid

Our proposed design is based on the principle of thermal conductivity, piezoelectricity and pyroelectricity combined altogether, in a single transducer.

In this, when incorporated in an automobile, the input thermal energy from vehicle's thermal losses (such as in engine, brakes etc.) will transfer from thermally conductive pyroelectric block into the cantilevers, where the piezoelectric material is vibrating along with pyroelectric material. This input vibrational energy is produced from vibrational losses from the vehicle from its components; and has typical frequency range of 0-300 Hz.

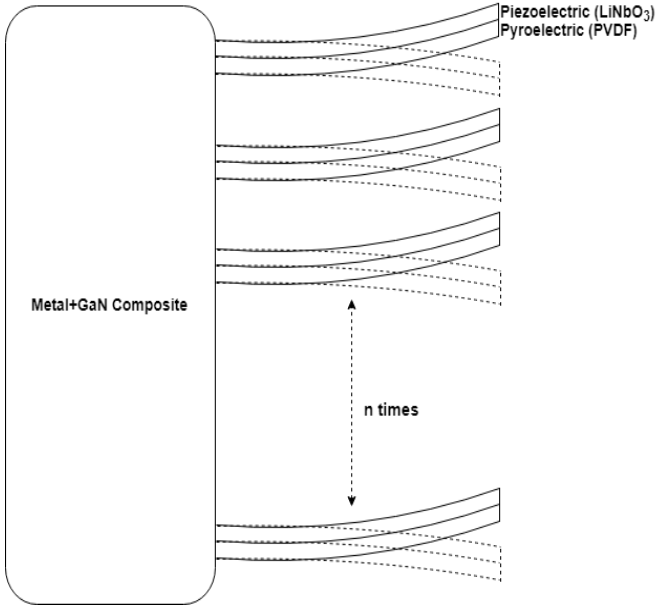


Fig. 1: Diagram showing piezo-pyro cantilevers design on thermally conductive-pyroelectric block.

The energy generated by piezoelectric part will reach its maximum when external vibrations are at resonance with the cantilevers. Also, the pyroelectric part's efficiency is a function of rate of change of temperature difference (dT/dt). In order to increase the efficiency of the device, metal-GaN composite has been selected, as GaN is well known for its pyroelectric properties ($P_V = 7 \times 10^5 \text{ V/m-K}$)^[6].

In figure 1, we are showing basic design of our transducer along with the materials involved. The malleability, and elastic properties of metal will help minimize the input frequency loss, as well as possessing thermal conductivity. In counterpart, the incorporation of GaN, will give this composite a pyroelectric energy harvesting property. This composite material will aid to adhere the cantilever design and provide relatively high electronic conductivity for harvesting electric charge transport.

In the cantilever, the PVDF will act as a pyroelectric material, its flexible polymeric nature further aids to increase elasticity of the cantilever and reduce damping under resonance frequency. LiNbO_3 is well known piezoelectric material for its high electromechanical coupling factor^{[7], [8]}.

B. Specifications

The Objective of thermal network modelling is to have an idea about the working of our designed transducer (fig. 1), predict its working conditions, theoretical behavior by the means of simulation.

III. THERMAL NETWORK MODELLING

The design of hybrid piezo-pyro device includes the optimization of its structure for better performance and controlled synthesis.

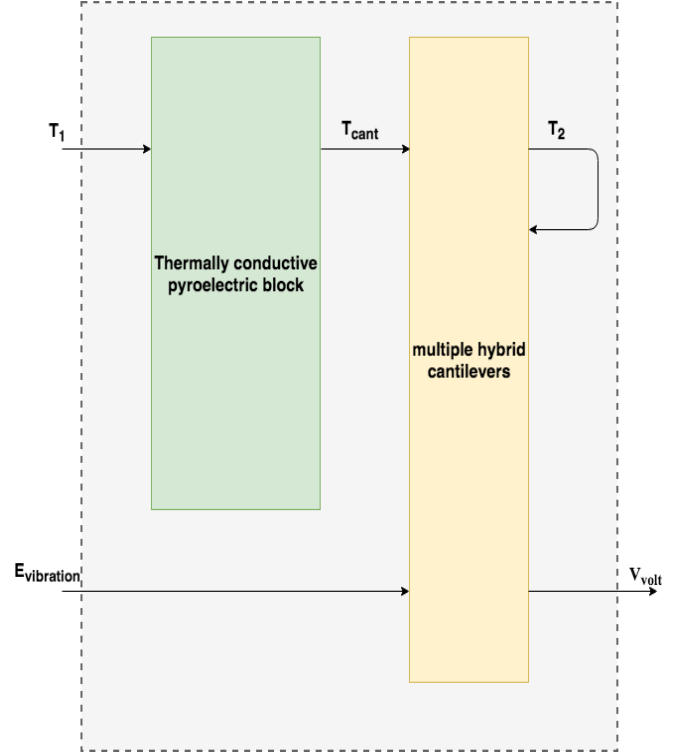


Fig. 2: Schematic of thermal network modelling

In the schematic (fig. 2), T_{cant} is the temperature at the interface between the pyroelectric block and cantilevers. This corresponds to the temperature applied by the device to the cantilever. The thermal gradient within the actuator is weak as we are dealing in μm range with high thermal and electrical conductivity of the materials.

Thus, the whole cantilever denoted with T can be considered uniform. except nearby the interface with pyro block. T_1 and $E_{\text{vibration}}$ are the temperature and vibration inputs respectively, which are always present when the automobile is in working ('ON' state). The thermal model can be rapidly a tedious task if the mechanical shapes and structures and connection between them are not standard. The modelling complexity increased if the interconnected system is non-homogeneous^[9].

The thermal network modelling is based on the similarities between electrical and thermal models. It is a lucid way to compare heat flow Q to an electrical current, temperature difference to a voltage, and thermal resistance to an electrical resistance.

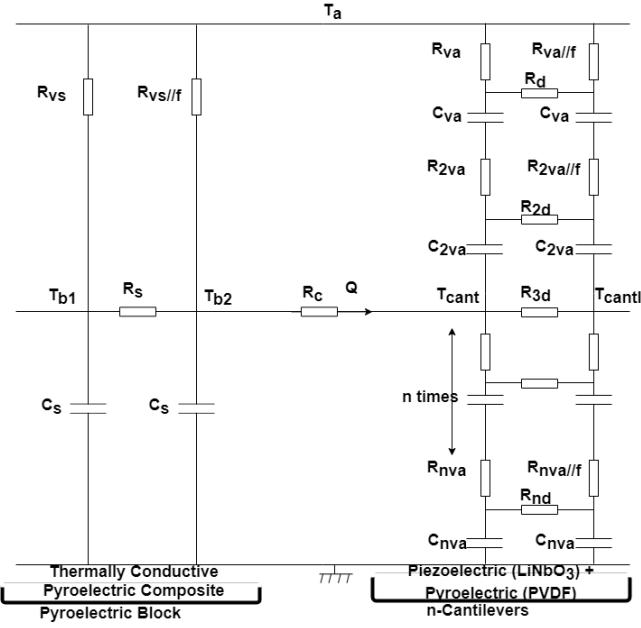


Fig. 3: Thermal network modelling representing hybrid cantilever design on a thermally conductive pyroelectric block.

In figure 3, we introduce the thermal network modelling based on the schematic shown in figure 1 and 2. The thermal energy (T_{b1}) is a function of vehicles energy loses, and is transferred into the pyroelectric block, which is in direct contact with vehicles components. This thermal energy is then transferred to the cantilevers by means of thermal conductivity. These cantilevers are parallel to each other (see fig 1). During each interface, of transducer and along the distance from energy source to cantilevers, there will be a thermal gradient ($T_{b1} > T_{b2} > T_{cant} > T_{cantl}$). The reason of this thermal gradient is the internal passive components will show their internal resistance and capacitance against the flow of thermal energy.

Modelling for thermally conductive pyroelectric block:

The thermally conductive pyroelectric block is in contact with the vehicle's components, T_{b1} is the thermal energy point of contact of the vehicle and block to the cantilever. T_{b2} is the thermal energy at the interface of block and cantilevers. These materials are not perfectly thermally conductive, hence shows internal resistance.

$$R_{vs} = \frac{2}{h_{air} P_S L_S} \quad (1.1)$$

$$R_{vsf} = \frac{2}{h_{air} (b_s a_s - S_p)} \quad (1.2)$$

$$R_{vs//f} = \frac{R_{vs} R_{vf}}{(R_{vs} + R_{vf})} \quad (1.3)$$

$$R_s = \frac{L_s}{K_S S_S} \quad (1.4)$$

$$R_c = \frac{L_c}{K_S S_P} \quad (1.5)$$

$$C_S = \frac{\rho_S C_{PS} S_S L_S}{2} \quad (1.6)$$

Where, K_S is the thermal conductivity, C_S is the heat capacity, ρ_S is the density of thermally conductive material. S_S is the section= $b_s a_s$, $P_S = 4(a_s + 2b_s + h_s)$ perimeter of the thermally conductive material. h_{air} is the heat transfer coefficient. Q_f is the heat flow from the pyroelectric block to the cantilevers. L_s is the length of the block.

Modelling for piezoelectric part:

The piezoelectric part is multiple cantilevers of equal dimension as its attached pyroelectric part. The thermal energy T_{cant} is at the initial point of cantilever, T_{cantl} is the energy at the end point of cantilevers. As the piezoelectric part is a metal oxide, it is a poor thermal conductor, hence offers resistance.

$$R_{va} = \frac{2}{h_{2air} P_{2S} L_{2S}}; R_{nva} = \frac{2}{h_{nair} P_{nS} L_{nS}} \quad (2.1)$$

$$R_{vaf} = \frac{2}{h_{2air} (b_{2s} a_{2s} - S_{2P})}; R_{nvaf} = \frac{2}{h_{air} (b_{ns} a_{ns} - S_{2nP})} \quad (2.2)$$

$$R_{va//f} = \frac{R_{va} R_{vaf}}{(R_{va} + R_{vaf})}; R_{nva//f} = \frac{R_{nva} R_{nvaf}}{(R_{nva} + R_{nvaf})} \quad (2.3)$$

$$R_d = \frac{L_{2s}}{K_{2S} S_{2S}}; R_{nd} = \frac{L_{2ns}}{K_{2S} S_{2S}} \quad (2.4)$$

$$C_{va} = \frac{\rho_{2s} C_{2PS} S_{2S} L_{2S}}{2}; C_{nva} = \frac{\rho_{n2s} C_{n2PS} S_{n2S} L_{n2S}}{2} \quad (2.5)$$

Where, K_{2S} is the thermal conductivity, C_{2S} is the heat capacity, ρ_{2S} is the density of piezoelectric material. S_{2S} is the section= $b_{2s} a_{2s}$, $P_S = 4(a_{2s} + 2b_{2s} + h_{2s})$ perimeter of the piezoelectric material. h_{2air} is the heat transfer coefficient. Q_f is the heat flow. That is between thermally conductive block towards hybrid cantilever. L_{2s} is the length of piezoelectric cantilever.

Similarly, S_{2nS} is the n^{th} section= $b_{2nS} a_{2nS}$, $P_{nS} = 4(a_{2nS} + 2b_{2nS} + h_{2nS})$ perimeter of the n^{th} piezoelectric material. h_{2air} is the heat transfer coefficient. L_{2nS} is the length of n^{th} piezoelectric cantilever.

Modelling for pyroelectric part:

The pyroelectric electric part is multiple cantilevers of equal dimension as its attached beneath the piezoelectric part. The thermal energy T_{cant} is at the initial point of cantilever, T_{cantl} is the energy at the end point of cantilevers. As the pyroelectric part is a polymer, it is a poor thermal conductor, hence offers resistance.

$$R_{2va} = \frac{2}{h_{3air}P_{3S}L_{3S}}; R_{n2va} = \frac{2}{h_{n3air}P_{n3S}L_{n3S}} \quad (3.1)$$

$$R_{2vaf} = \frac{2}{h_{3air}(b_{3S}a_{3S} - S_{3P})}; R_{n2vaf} = \frac{2}{h_{n3air}(b_{n3S}a_{n3S} - S_{n3P})} \quad (3.2)$$

$$R_{2va//f} = \frac{R_{2va}R_{2vaf}}{(R_{2va}+R_{2vaf})}; R_{n2va//f} = \frac{R_{n2va}R_{n2vaf}}{(R_{n2va}+R_{n2vaf})} \quad (3.3)$$

$$R_{2d} = \frac{L_{3S}}{K_{3S}S_{3S}}; R_{n2d} = \frac{L_{n3S}}{K_{n3S}S_{n3S}} \quad (3.4)$$

$$C_{2vS} = \frac{\rho_{3S}C_{3PS}S_{3S}L_{3S}}{2}; C_{n2vS} = \frac{\rho_{n3S}C_{n3PS}S_{n3S}L_{n3S}}{2} \quad (3.5)$$

Where, h_{3air} is heat transfer coefficient of pyroelectric material. K_{3S} is the thermal conductivity, C_{3S} is the heat capacity, ρ_{3S} is the density of pyroelectric material. S_{3S} is the section= $b_{3S}a_{3S}$, $P_{3S} = 4(a_{3S}+2b_{3S}+h_{3S})$ perimeter of the pyroelectric material. h_{3air} is the heat transfer coefficient. Similarly, S_{n3S} is the n^{th} section= $b_{2S}a_{2S}$, $P_{n3S} = 4(a_{2S}+2b_{2S}+h_{2S})$ perimeter of the n^{th} pyroelectric material. h_{3air} is the heat transfer coefficient. L_{3ns} is the length of n^{th} pyroelectric cantilever.

IV. CONCLUSIONS

In the report, we presented the concept, design and principle of energy harvesting using a hybrid piezoelectric-pyroelectric transducer design using thermal network modelling, by combining piezoelectric material (LiNbO₃) and pyroelectric materials (PVDF and GaN). Using this, we develop a model of hybrid energy harvester for application

in self-powered sensors in automobiles. However, challenges such as frequency range and high temperature limitation of PVDF might occur which can affect electrical efficiency of the transducer. Further investigations are going for its validation.

ACKNOWLEDGMENT

The author(s) would like to acknowledge ITN ENHANCE and Marie Curie for their financial support. Members of MACS group at FEMTO-ST are also acknowledge for their kind support.

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