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A Tri-Axial Accelerometer with Structure-Based Voltage Operation by Using Series-Connected Piezoelectric Elements

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Abstract

Output-voltage operation on a sensor structure is proposed and a tri-axial accelerometer with low cross-axis sensitivities is designed. The output voltage between the electrodes sandwiching piezoelectric thin-films on a deforming structure is proportional to the in-plane stress of the piezoelectric thin-film. If the piezoelectric thin-film is processed to separated elements and the electrodes of the elements are connected in series, the output voltages from the series-connected piezoelectric elements are multiplied or canceled depending on the situations of the internal-stresses (i.e. compressive or tensile) of the elements. Proper design of the electrode connections by taking the deformation shape of structures into consideration can realize expected output-voltage operations on the device structure. The principle of structure-based output-voltage operation is applied to the design of a tri-axial accelerometer with low cross-axes sensitivities. Finite-element-method (FEM) simulations of the tri-axial accelerometer revealed the cross-axis sensitivity of less than 1.5 %.

Keywords: Piezoelectric materials, structure design, accelerometer, series conection, voltage operation

1. Introduction

Sensor network system for monitoring human activities have been attracted attention recent years. Aging of population has driven the progress of miniaturization, reduction in energy consumption, and wireless communication for human monitoring systems for the last decade. Monitoring human activity for elderly people having chronic illness and accidents becomes more and more important. Conventional healthcare, e.g. periodically scheduled evaluations in clinic, takes vast cost for both of governments and patients. An unconscious, low-cost, and long-term monitoring of human activity would be required for the routine daily healthcare because the systems should not prevent usual human activities in natural environment, such as home or in the workplace. In addition,

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accidents usually take place at such the natural places. Human-activity monitoring is valuable to detect physical and mental stress and to avoid overwork, depression and insomnia not only for elderly people but also for the all people. The use of healthcare monitoring system would become frequent in the near future.

Sensors, peripheral circuitries, and software should be totally designed for the realization of well integrated, miniaturized, and unconscious monitoring devices. Competitive demands such as reductions of sensor and circuit size, enhancement of sensitivity of sensors, and control of energy consumptions are expected to be satisfied. Piezoelectric materials that produce electric charges proportional to the stress undergoing are suitable for the devices. A sensing manner employed the deformation of piezoelectric structure can reduce circuit size and energy consumption of the system. Electrostatic-type sensors are easy to be affected by parasitic capacitances and need capacitance-voltage transformation circuits. Piezo-resistive-type sensors and electromagnetic-type sensors require electrical current, resulting in large energy consumption. The authors have reported an output-voltage multiplication technique using piezoelectric elements series-connected [1,2]. Pb[Zr, Ti]O_3 (PZT) thin-films were deposited on a Si wafer, processed to separated elements, and electrically connected in series. Passive voltage operations such as multiplications or cancellations on the structures can reduce the circuit size and energy consumption moreover.

The output voltage operation on the sensor structure and its application to tri-axes accelerometer with low cross-sectional sensitivity are proposed in this study.

2. Output voltage operation on the structure

The design of electrodes connection of piezoelectric elements realizes the output voltage operation. Figure 1 shows the schematic diagram of the output-voltage multiplication using series-connected piezoelectric elements (SCPs). In the literature [2], the output-voltage multiplication was verified experimentally and numerically. The output voltage multiplication was performed on a cantilever. While the deformation shape of cantilever has no inflection points, for beams with both sides fixed (we refer to the beams as spokes), the deformation shape has an inflection point. The inflection point produces convex and concave bending on a spoke. The electric voltage produced from the piezoelectric elements on a deforming structure is proportional to the stress undergoing. Therefore, the signs of voltages obtained from each element are different dependent on the deformation shape, i.e. convex or concave. The series connection of the elements on the different deformation shapes results in the cancellation of the output voltage.

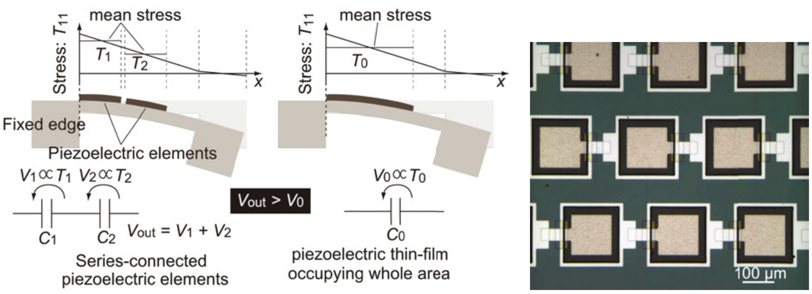

Fig. 1. (a) output-voltage multiplication using SCPs; (b) fabricated SCPs. each elements have Pt/Ti electrodes sandwiching PZT [1].

3. Design of tri-axial accelerometer with low cross-axis sensitivity

Conventional tri-axial accelerometers often comprise of a proof-mass and four spokes [3]. When the structure is accelerated, each spoke deforms approximately point-symmetrical to the spoke center, i.e. there is an inflection point (Fig. 2). The in-plane stresses of adjacent piezoelectric elements on the spoke have opposite situations (compressive or tensile) at the both ends. To quantify the accelerations of three axes, output-voltages are usually operated by an external circuitry. The SCPs performs the operations on the sensor structure. Each piezoelectric element is located to undergo compressive or tensile stress, and the adjacent elements are series-connected "symmetrically" or "asymmetrically" dependent on the situations of the stresses as shown in Fig. 3. For the output-voltage multiplication, the elements in same situations of the stresses are series-connected "symmetrically", while "asymmetrically" for different situations in the stresses. The contrary order of connections results in an output-voltage cancellation. The output voltages from SCPs can be operated (multiplied or cancelled) arbitrarily according to our design.

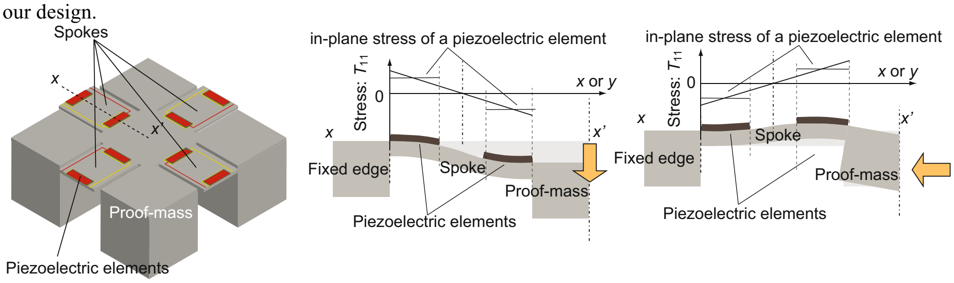

Fig. 2. Schematic diagram of a conventional tri-axial accelerometer and the in-plane stresses of the piezoelectric elements on the spokes when accelerations are applied.

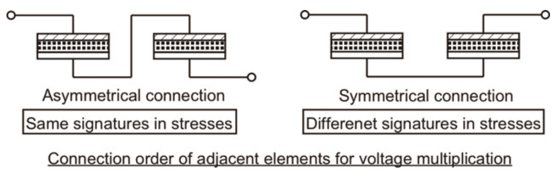

Fig. 3. Electrodes of adjacent piezoelectric elements with the different signatures in the stress should be connected "asymmetrically" for voltage multiplication, while that with the same signatures should be connected "symmetrically".

A tri-axial accelerometer with low cross-axis sensitivities is designed as an application of the structure-based output-voltage operation. By combining the multiplication and cancellation of the output voltages from individual piezoelectric elements, the tri-axial accelerometer performs low cross-axis sensitivity. The dimensions of the designed sensor are described in Fig. 4(a). Four spokes are jointed to a proof-mass in a device sizing 1 x 1 mm^2. Six piezoelectric elements are located on a spoke and three pairs of elements are utilized to measure three axial accelerations. All elements for sensing z-axis acceleration are series-connected to multiply the output voltage. For x- and y- directional acceleration, the low cross-axis sensitivities can be achieved by cancelling the output voltages on the twisting beam caused by the accelerations parallel to the surface. The connections of piezoelectric elements for each direction are shown in Fig. 4(b)(c).

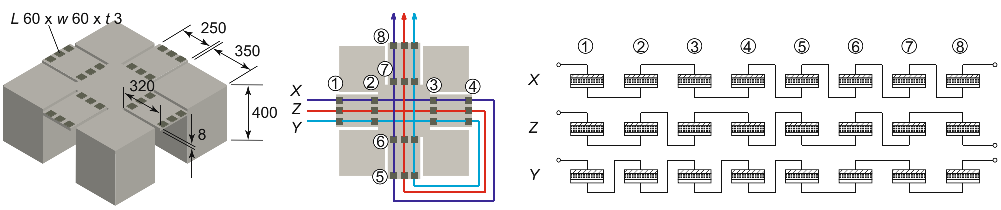

Fig. 4. (a)Dimensions of designed tri-axis accelerometer; (b),(c) the connection sequence for low cross-axis sensitivity.

The sensitivities and cross-axes sensitivities are estimated by using piezoelectric FEM. PZT is assumed to the piezoelectric material used. The produced potentials on individual piezoelectric elements and displacements when accelerations are applied to the structures are calculated. The typical results are shown in Fig. 5. The sensitivities are summarized in Table 1. Operating output voltages on the sensor structure can reduce the cross-axes sensitivities.

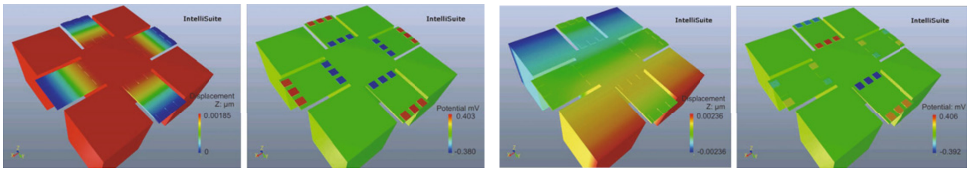

Fig. 5. *z*-directional displacement (a) and the output potential (b) on the electrodes of piezoelectric elements accelerated in direction of z-axis. For y-axis acceleration, displacement and potential, (c) and (d).

Table 1. Calculated sensitivity and cross-axial selectivity of tri-axial accelerometer designed.

Direction in acceleration	Sensitivity [mV/G] or Cross-axis sensitivity [%]		
	Output for x-axis	Output for y-axis	Output for z-axis
X-axis	1.37 mV/G	<0.1 %	<0.1 %
Y-axis	<0.1 %	1.37 mV/G	<0.1 %
Z-axis	1.34 %	1.34 %	3.19 mV/G

4. Conclusion

We proposed output-voltage operation on the sensor structure using series connection of piezoelectric elements. Determination of the sequence of the connection with taking deformation shape into account performs ambient operation of the voltages obtained from piezoelectric elements. The voltage-operation technique is applied to a tri-axial accelerometer with low cross-axes sensitivities. FEM calculations revealed cross-axes sensitivities less than 1.5 %.

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