Design of a New Piezoelectric Force Sensor

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Abstract

In this paper (Part 1), new utilization of piezoelectric materials for development of a force sensor is presented. Measurement of force in certain point is done by transferring it through incompressible fluid to the piezoelectric layer assembled in a designed structure. The new structure used changes the locally imposed force to equally distributed hydrostatic pressure on the piezoelectric layer. This produces unique stress in the layer and the result is a measurable proportional voltage to generated strain. The sensitivity, durability and measurement range of the new sensor has been investigated by numerical simulations, which shows promising space for industrial progress.

Keywords: Piezoelectric, Force sensor, Numerical analysis.

1. Introduction

Piezo comes from a Greek word that means “to squeeze or press” and electric refers to a Greek word “amber”, a mineral that can accumulate a charge of static electricity when rubbed. Crystals, such as quartz and also some ceramic and plastic materials, generate electricity when they are flexed back and forth. This is the piezoelectric effect.

Due to their special physical and material properties, dynamic force measurements are usually carried out by using piezoelectric devices (Kumme et al. (2002); Mack (2007)). They are used in production control, test rigs or in biomechanics to analyze the forces exerted in walking, running or jumping (Mack (2002); Gautschi (202)).

The finite element method applied to piezoelectric transducers provides highly adequate dynamic models (Allik et al. (1974); Bathe and Wilson (1976)).

In this paper a novel structure for making force sensors using piezoelectric material is introduced. The proposed new structure transfers the force property to a unique hydrostatic pressure which applies stress on piezoelectric layer. Finite element analysis (ANSYS software) is used to simulate piezoelectric transducers behavior this approach compensates the lack of empirical results (Saulius and Rimantas (2006)).

The proposed system is registered by Iranian patent organization under 48305/IRI.

2. Governing Principles Description

Generally piezoelectric properties are simply described with the following two equations (Kumme et al. (2002); Mack (2007)). In Eq. (1), T is stress vector and in Eq. (2), D is electrical flow vector.

$$T = c^e S - e^t E \tag{1}$$

$$D = eS + \varepsilon^s E \tag{2}$$

Stiffness matrix

$$c^E = \begin{bmatrix} c^{E_{11}} & c^{E_{12}} & c^{E_{13}} & 0 & 0 & 0 \\ c^{E_{12}} & c^{E_{11}} & c^{E_{13}} & 0 & 0 & 0 \\ c^{E_{13}} & c^{E_{13}} & c^{E_{33}} & 0 & 0 & 0 \\ 0 & 0 & 0 & c^{E_{44}} & 0 & 0 \\ 0 & 0 & 0 & 0 & c^{E_{44}} & 0 \\ 0 & 0 & 0 & 0 & 0 & (c^{E_{11}} - c^{E_{12}})/2 \end{bmatrix} \tag{3}$$

Piezoelectric coupling matrix

$$e = \begin{bmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{bmatrix} \tag{4}$$

Dielectric matrix

$$\varepsilon^S = \begin{bmatrix} \varepsilon^{S_{11}} & 0 & 0 \\ 0 & \varepsilon^{S_{11}} & 0 \\ 0 & 0 & \varepsilon^{S_{33}} \end{bmatrix} \tag{5}$$

3. Conventional piezoelectric sensors

Conventionally force is loaded directly on the electrode as is shown in Fig1.

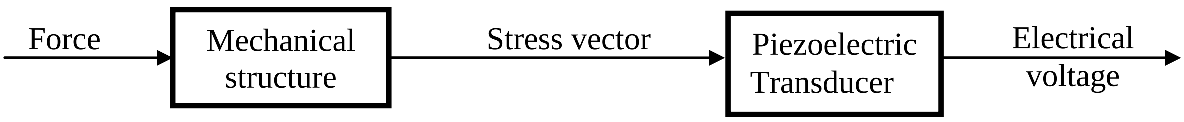

Fig 1: Conventional sensor force and signal flow structure

4. Proposed new piezoelectric sensor structure

In the new proposed structure, the force is applied on the plastic diaphragm of a rigid container which is filled up with a dielectric and incompressible liquid, where the piezoelectric transducer is immersed into it (Fig. 2).

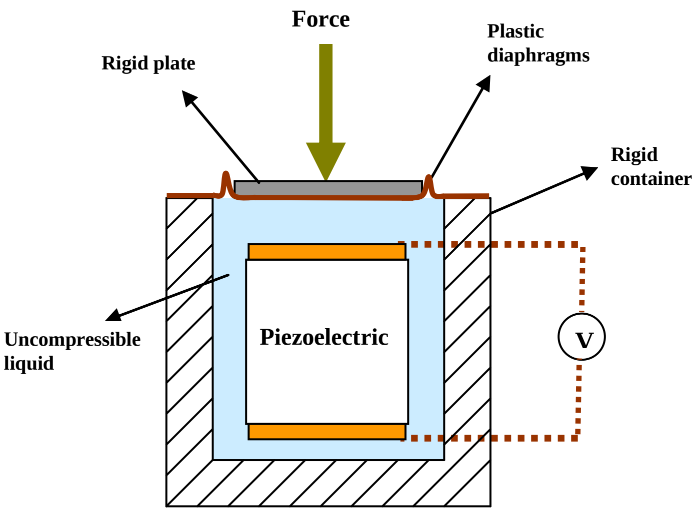

Fig 2: New proposed sensor structure

So the pressure applied to the plastic diaphragm is transferred hydrostatically to the piezoelectric transducer (Fig. 3).

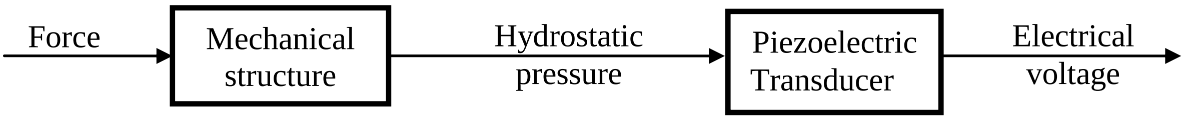

Fig 3: New sensor force and signal flow structure

The importance of keeping highly near linear relation between the applied force and the produced hydrostatic pressure is not hidden from the author's point of view. Fig. (4) shows that the applied force (F) produces hydrostatic pressure (P), plus resisted moment (M) and longitudinal tension force (f) produced in diaphragm boundary.

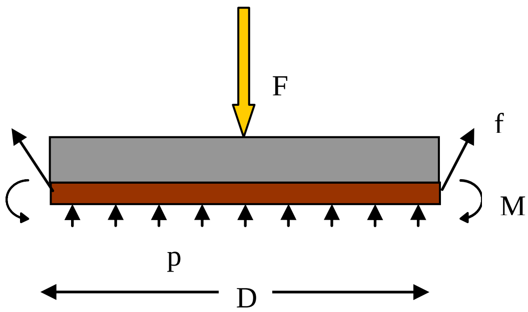

Fig 4: Free body diagram of plastic diaphragm

Eq. (6) and Eq. (7) show the relations**:**

$$F = (p \times A) + f + (M \times D) \tag{6}$$

$$\begin{Bmatrix} f \ll (p \times A) \\ (M \times D) \ll (p \times A) \end{Bmatrix} \Rightarrow F \approx (p \times A) \tag{7}$$

5. Method of Analyses

5.1 Numerical Analysis

Finite Element analysis is used to calculate output voltage and natural frequencies, the results for calculated voltage by ANSYS is then verified by analytical approach.

5.1.1 Modeling Piezoelectric Material Behavior

For modeling piezoelectric material properties with ANSYS, use of mechanical and electrical coupled field elements are necessary. Therefore SOLID 226 element is employed for simulation. In order to carry out simulation it is necessary, first to know the structure of the sensor and then know how it is formed.

We knew that piezoelectric sensors are formed using materials in a paste state drying it with heat processing in a furnace at certain temperature, then adding a thin conductive metal layer (like cooper) in both sides. So they join together and form a unit particle. Therefore to obtain a model in ANSYS, we need to select electrode and piezoelectric material, and then connect them together. Figure5 shows piezoelectric model built in ANSYS.

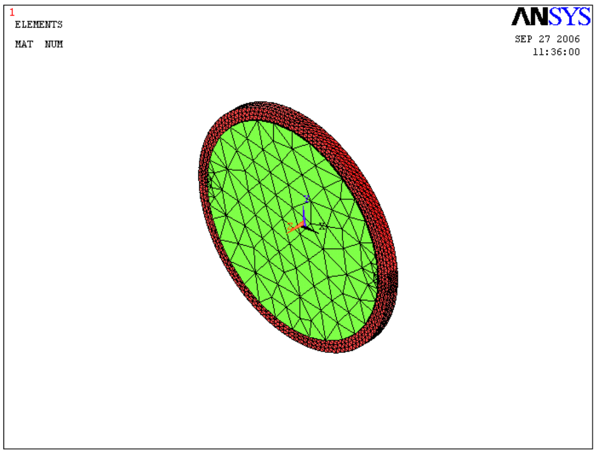

Fig 5: ANSYS model of piezoelectric

5.1.2 Modeling Piezoelectric behavior under hydrostatic pressure

Investigation of material behavior under hydrostatic pressure needs to define the boundary conditions as follows:

1. Gravity effect is neglected.
2. Displacement constraint is not considered.
3. Unique Pressure is applied to all surfaces.

So by applying pressure and calculating voltage through ANSYS the results are illustrated in Fig. 6.

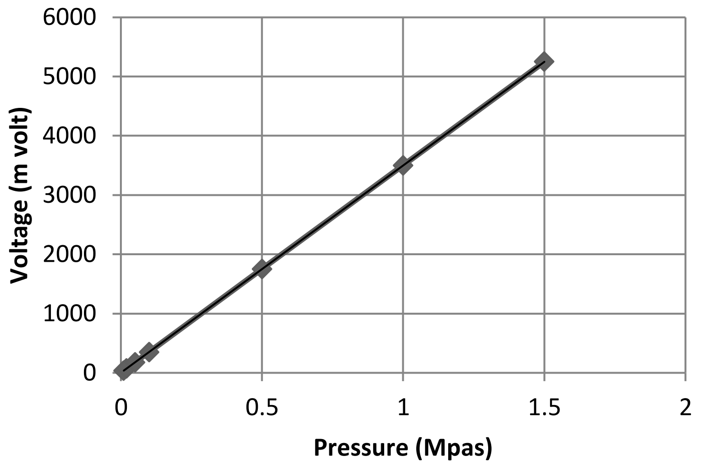

Fig 6: Voltage-pressure diagram

It is found that when constant pressure is applied, the produced electrical polarization remains constant. Also it is observed that induced voltage is proportional to layer thickness which means that if thickness is doubled, the electrical polarization is doubled too. In Fig. 7, electrical polarization vector is depicted for all points of surface.

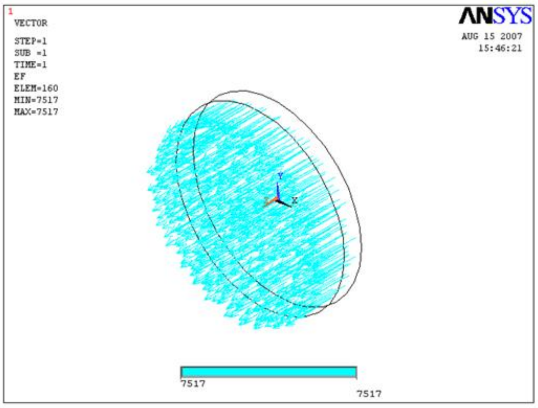

Fig 7: Electrical polarization

5.2 Analytical Approach

The derivation of theoretical relations for piezoelectric under hydrostatic pressure (p) is discussed by Hana et al. (2004). The polarization (P) on the sample induced by hydrostatic pressure (p) is given by:

$$\mathrm{Pol} = (\mathrm{d}_{31} + \mathrm{d}_{32} + \mathrm{d}_{33})(-\mathrm{p}) \tag{8}$$

$$\mathrm{d}_{3n} = (\mathrm{d}_{31} + \mathrm{d}_{32} + \mathrm{d}_{33}) \tag{9}$$

In Eq. (8) and Eq. (9), **“**Pol**”** is polarization, **“**P**”** is pressure applied to the piezoelectric sensor and **“**d_{3n}**”** is piezoelectric coefficient. The induced charge Q on the sample is:

$$Q = Pol \times A \tag{10}$$

Where, A is the area of the electrode surface. We can calculate generated voltage in a capacitor using Eq. (10) where (C) is defined by Eq. (12) having surface electrode area (A), electrode gap (h), and relative Permittivity (ε_r).

$$V = \frac{Q}{C} \tag{11}$$

$$C = \frac{\varepsilon_r.A}{h} \tag{12}$$

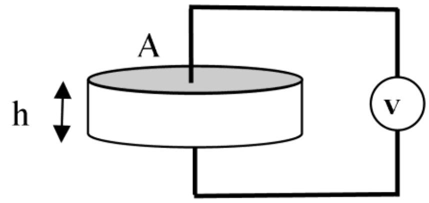

Fig 8: Schematic of electrical activity

Calculated (ε_r) has dielectric coefficient (K) which is the relation between dielectric permittivity of free space (ε_0) and (ε_r).

$$\varepsilon_r = K.\varepsilon_0 \tag{13}$$

By putting Eq. (8,9) in Eq. (10,11), V is obtained:

$$V = \frac{Pol.A.h}{\varepsilon_r.A} = \frac{-p.d_{3n}.h}{\varepsilon_r} = -\frac{d_{3n}}{\varepsilon_r}.h.p \tag{14}$$

Taking α as:

$$\alpha = \frac{d_{3n}}{\varepsilon_r} \tag{15}$$

$$V = -\alpha.h.p \tag{16}$$

6. Sensitivity

The sensor sensitivity is defined as ratio of output to unit input (Bentley (2005)). Piezoelectric sensor is a transducer which changes mechanical stress to electrical voltage (Regtien et al. (2000)).

$$S = \frac{V}{F} = S_1 \times S_1 \tag{17}$$

$$S_1 = \frac{p}{F} \tag{18}$$

$$S_2 = \frac{V}{p} \tag{19}$$

Using new proposed structure sensitivity will increase by additional container structural thickness, costs will decrease and also, it reduces the piezoelectric diameter with no threat of buckling, while these are big problem**s** in conventional piezoelectric sensors (Abdullah et al. (1994))**.**

7. Measurement Domains

7.1 Amplitude Measurement

Since the applied pressure on piezoelectric transformer is in hydrostatic state form therefore:

$$\sigma_1 = \sigma_2 = \sigma_3 = -p \tag{20}$$

Substituting $-p$ into Von Mises criterion Eq. given by:

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 < 2.Y^2 \tag{21}$$

The result is:

$$0 \leq 2.Y^2 \tag{22}$$

This implies that the yield condition based on Von Mises does not occur.
Therefore from pressure amplitude measurement, ability point of view the range of measurement is only limited by the strength of the container because Von Mises permits unlimited pressure on the piezoelectric transformer.

7.2 Frequency Measurement
Frequency domain consideration of the proposed piezoelectric force sensor shows that it is mainly restricted by the natural frequency of the container mechanical structure f_{nm} so that we should have:

$$0 \leq f < f_{nm} \tag{23}$$

The piezoelectric transformer natural frequency f_{ne} is governed by the hydrostatic state conditions, which has a very high frequency.

$$f_{nm} \ll f_{ne} \tag{24}$$

This has been under consideration using Finite Element Method (FEM).

8. Numerical Simulation
Vibration simulation analysis of a piezoelectric disk (Hana et al. (2004)) which is having a diameter of 20mm and thickness of 2mm shows that as was expected, no mode shape appears in low frequencies region (see Fig.9). This concludes that only high frequency mode shapes are distinguished for the piezoelectric disk. It can be concluded that, new sensor has the advantage in dealing with measurement of dynamic forces.

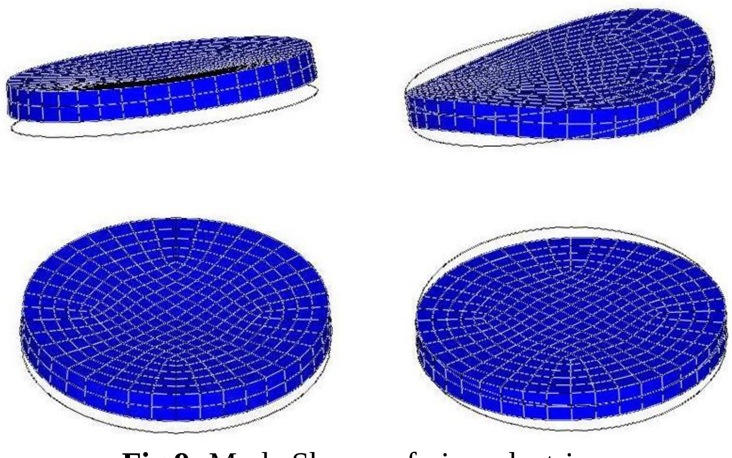

Fig 9: Mode Shapes of piezoelectric

9. Comparison between New Proposed Sensor and Conventional Sensor

Simulation of conventional piezoelectric sensors will show that induced electrical voltage by the new one, when measuring force is considerably higher than conventional sensors. The reason is that, new sensor abilities are only limited by dimensional manufacturing capabilities in terms of container design including flexible surface under pressure.

The new proposed sensor will remain in elastic region since the effective force on the sensor is hydrostatic permanently. So there is no fracture in this kind of sensor and it can be used while induced electrical voltage exceeds the permitted electrical voltage range.

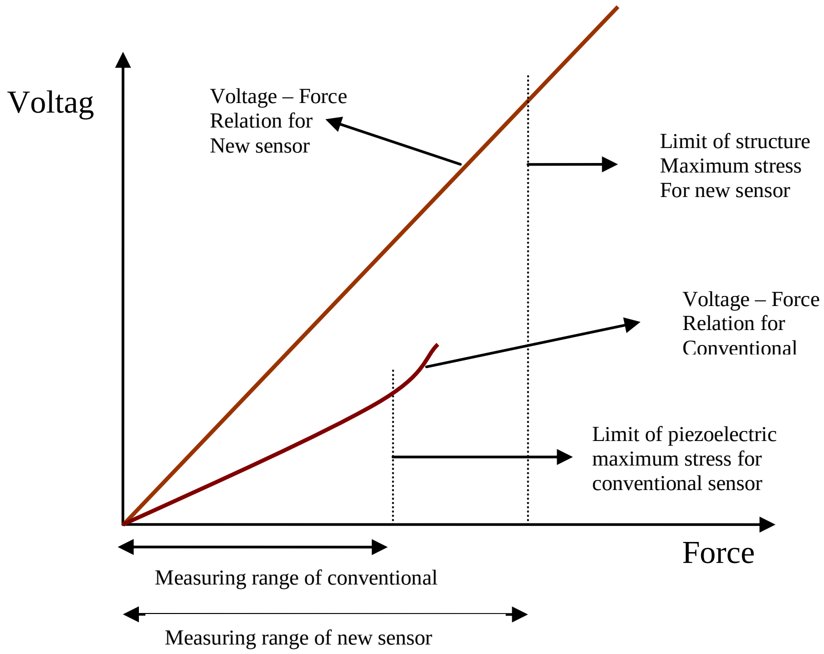

Fig 10: Voltage-Force diagram

10. Conclusions

This paper described the practical and theoretical (numerical simulation and analytical solution) capabilities of the new proposed piezoelectric sensor. The comparison made between this and the conventional sensors shows that considerable improvement has been achieved with respect to sensitivity, amplitude and frequency measurement ranges plus ability to withstand and measure high and dynamic forces.

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