The Effect Of Substrate To Piezoelectric Thickness Ratio On Performance Of Unimorph Sensor

*[1]Action Nechibvute, [2]Courage Mudzingwa
[1,2]*Physics Department, Midlands State University, P/Bag 9055, Gweru, Zimbabwe*

Abstract

This paper reports on our investigation of the influence of the piezoelectric to substrate thickness ratio on the output voltage and resonance frequency of a rectangular unimorph sensor. The results show that the sensitivity of the sensor is degraded for high values of thickness ratio beyond 1.0. Too small values of thickness ratio below 0.2 will result in low sensitivity due to high capacitance of the unimorph bender. In addition a comparison of aluminium and structural steel as substrates to PZT-5H piezoelectric material was also investigated. The findings are a useful guide to design engineers enabling the selection of appropriate material and geometry for a rectangular sensor depending on whether the primary design goal is large deflection, voltage or resonance frequency.

Keywords - *sensor, piezoelectric, unimorph, thickness ratio, sensitivity*

1. Introduction

Piezoelectric materials have found use in a wide range of electromechanical systems as either actuators or sensors. A piezoelectric material produces a voltage when a mechanical force or pressure is applied on the material. This is called the direct piezoelectric effect and it is the one employed in sensors [1-3]. On the other hand, if a voltage is applied to the piezoelectric material, the material is mechanically deformed. This is called the indirect piezoelectric effect and is employed in actuation systems [1,4-7]. A typical piezoelectric device is a unimorph cantilever structure where a piezoelectric ceramic is bonded to a metal substrate [1-7]. Numerical modelling and computer simulations are becoming indispensable tools in design and optimization of sensor and actuator systems [8,9]. Central to these tasks is the understanding and estimation of the influence of different geometrical parameters in the performance of a device. In this work, the effect of the piezoelectric to substrate thickness ratio on the performance of a unimorph sensor is studied using the FEM software, COMSOL Multiphysics® (version 4.3) [10]. COMSOL is very effective FEM software and simulation results in the software have excellent agreement with experimental observations [10-12]. PZT-5H was chosen as the active piezoelectric material since it is one of the most commonly used material for sensors because of its high sensitivity [1-6]. Aluminium and structural metals were chosen as the substrates in this study since they are the materials often used by designers [1,3,5].

2. Simulation Experiments and Methods

The FEM study employed the piezoelectric material interface (*pzd*) which combines the piezoelectricity and mechanics modules. The material properties used in the study are shown in Table 1. The properties were obtained from the COMSOL material library.

Table 1. Material properties used in the study

	PZT-5H	Aluminium	Structural Steel
Young Modulus (GPa)	62	70	200
Poisson ratio	-	0.33	0.33
Density (kg/m^3)	7500	7850	2700
Elastic constants (GPa)	$c_{11} = c_{22}$ =126, c_{12} = 80.5, $c_{13} = c_{23}$ = 126, c_{33} = 117, c_{44} = 23.3, $c_{55} = c_{66}$ = 23,	-	-
piezoelectric stress constants (C/m^2)	$e_{51} = e_{42}$ = 17, $e_{13} = e_{23}$ = 17, e_{33} = 23.3,	-	-
Dielectric constants	$\varepsilon_{11} = \varepsilon_{22}$ =1704 ε_{33} = 1433	-	-

The geometry of the unimorph device was drawn using the in-built CAD tools in COMSOL. Both 2D and 3D analysis were performed. One end of the unimorph device was clamped along its width and the other end was left free. In order to pole the piezoelectric layer along thickness direction, two electrodes were defined at the top and bottom of the PZT-5H layer using the electrostatic boundary conditions. The upper and lower face of PZT layer were selected as floating and ground potentials respectively, while all other faces of piezoelectric layer were kept as zero charge [13].

The standard meshing tool was used with the mesh setting at physics – controlled mesh and element size set to “finer”. Figure 1 shows the meshed geometry of the device under study where a total 2509 tetrahedral elements and 988 triangular elements were used. The width of the device was set to 2 mm while the length was set to 10 mm throughout the simulations. The thickness of the substrate material (t_s) was fixed at 1 mm while the thickness of the piezoelectric material (t_p) was varied from 0.1 to 2 mm.

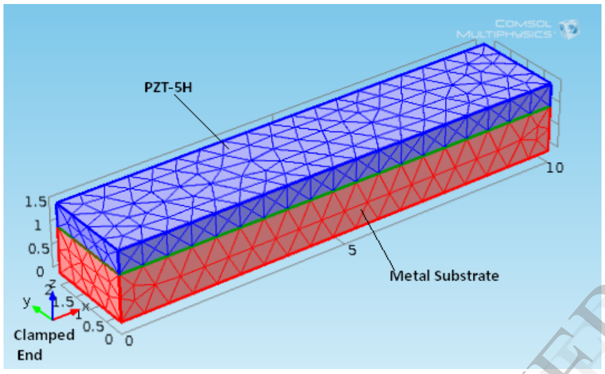

Figure 1. 3D Geometry of unimorph sensor

3. Results and Discussion

3.1 Voltage and tip displacement under a body load

The first study was a parametric analysis of the effect of piezoelectric thickness on both the open circuit voltage output and the tip displacement of the sensor. This was performed with a total body load of 1000 N/m^2. Figures 2 and 3 show the results of the effect of piezoelectric thickness on the voltage output of the sensor using aluminium and structural steel substrates. These results show that for a fixed substrate thickness, there is generally an increase in output voltage. However, this increase is not linear for the thickness ratio beyond 0.5. Beyond thickness ratio of 0.5, there is a monotonic increase in the voltage output. Figures 2 and 3 show that the sensor employing aluminium substrate has no marked increase in voltage output beyond a thickness ratio of 1.5. In fact, any increase in thickness ratio beyond 1.5 lead to a decrease in voltage output. When structural steel is employed, the sensor device exhibit no drastic saturation of the output voltage compared to the case where aluminium is used (see Figure 3).

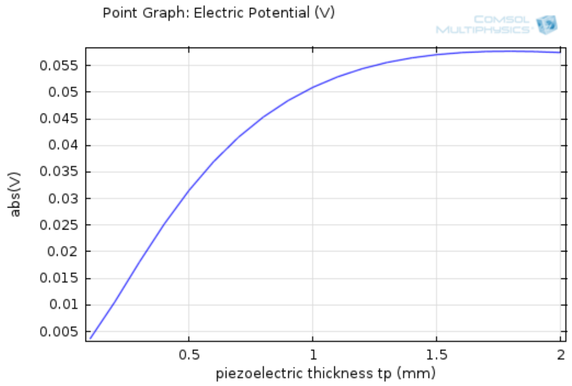

Figure 2. Variation of voltage output with piezoelectric thickness using aluminium substrate

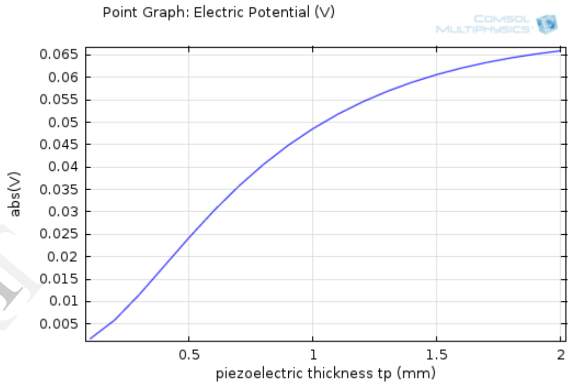

Figure 3. Variation of voltage output with piezoelectric thickness using structural steel substrate

The effect of tip displacement of the beam to a body load of 1000 N/m^2 was investigated. The results are shown in Figures 4 and 5.

The sensor device employing an aluminium substrate showed a high displacement compared to the one employing structural steel. This may be expected since aluminium is less stiff compared to structural steel.

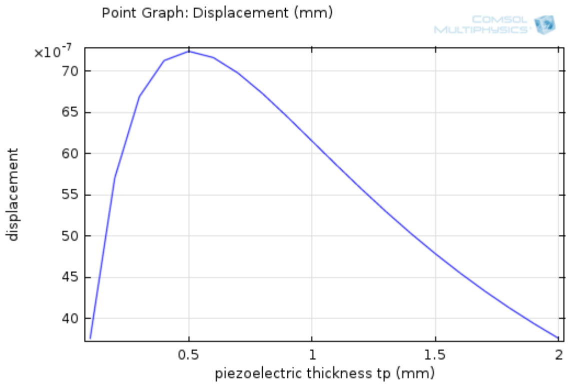

Figure 4. Variation of tip displacement with piezoelectric thickness using aluminium substrate

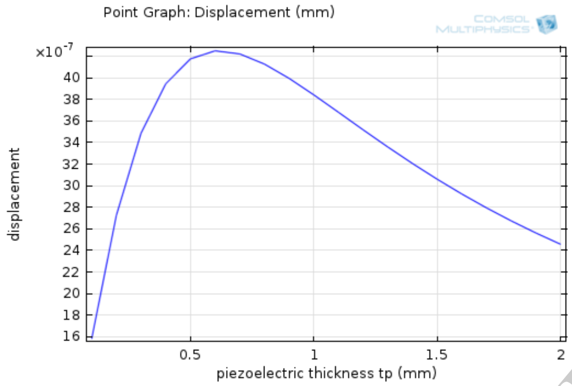

Figure 5. Variation of tip displacement with piezoelectric thickness using structural steel substrate

3.2 Sensitivity

The voltage sensitivity of a cantilever sensor can be defined as the voltage output per unit force applied at the tip of the sensor. With a tip force of 1 N, the sensitivity of the unimorph sensor as a function of the thickness ratio was studied and the results are shown in Figure 6. The voltage sensitivity is very much dependent on the thickness ratio as shown in Figure 6. Aluminium substrate results in a higher sensitivity of over 30 V/N compared to structural steel with around 25 V/N. For both substrates, the results show that there exist an optimum thickness ratio for optimum sensitivity and going beyond optimum will result in loss of sensitivity. For aluminium substrate the optimum thickness ratio is around 0.5 while for steel its about 0.7. However, structural steel shows a higher sensitivity at thickness ratios beyond 1.2 compared to the aluminium substrate.

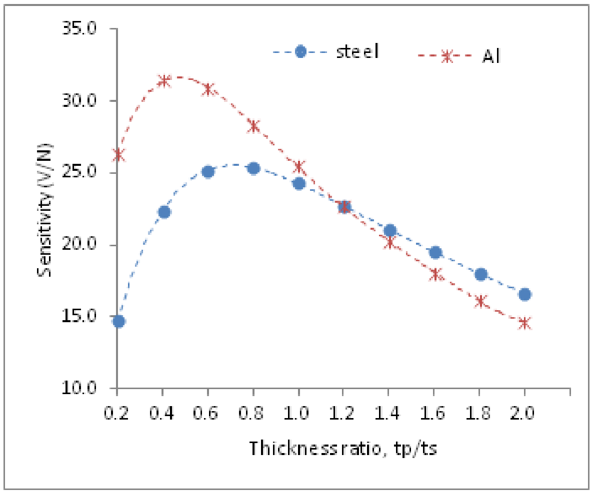

Figure 6. Voltage sensitivity comparison

To explain the relationship between the voltage sensitivity and the thickness ratio, one needs to understand that the voltage output of a piezoelectric material is a function of its capacitance. If the piezoelectric layer is very thin, there is very high capacitance (C) and low charge (Q). Thus from $V = {}^{Q}/_{C}$, the voltage output is low. The other extreme is when the piezoelectric material is very thick, such that the deflection of the beam is significantly reduced and hence very little charge is generated. Hence, the optimum voltage is obtained at values of the thickness ratio between these two extremes. The result can also be interpreted in the context of the effect of substrate material on the dielectric constants of the unimorph device. The dielectric constants of unimorph benders decrease monotonically with the thickness ratio [14-17]. The use of a stiffer elastic substrate leads to lower dielectric constant. A decrease in dielectric constant implies decrease in the electromechanical coupling, k_{31}. Thus the use of steel substrate will result in lower sensitivity compared to less stiff material aluminium.

Another sensitivity figure of merit is the deflection sensitivity, which is hereby defined as the ratio of absolute tip deflection per unit force. The sensitivity of the unimorph sensor to tip deflection is shown in Figure 7. Generally the deflection sensitivity decreases with increase in thickness ratio. As observed earlier, the higher elastic compliancy of aluminium will lead to a higher deflection sensitivity of a sensor employing aluminium substrate compared to steel [14,17].

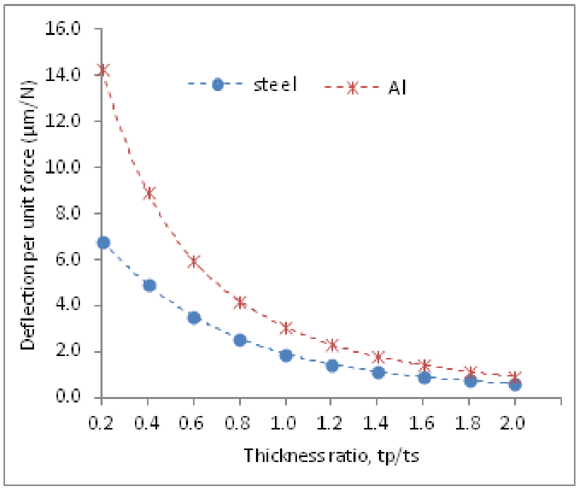

Figure 7. Deflection sensitivity comparison

The performance of the unimorph sensor is generally degraded for very large values of the thickness ratio. If the thickness ratio is large so that the neutral axis of the composite beam lies in the piezoelectric material, then charge cancellation may happen and this reduces the sensitivity of the sensor [14,17,18]. In order to ensure the neutral axis remains in the substrate material, the thickness ratios were set to 0.5 and 1.0 for the substrate materials under study. All other geometrical parameters were maintained as they were in the previous simulations and the tip force was set to 1 N. The results showing the performance of the sensor for the two substrate materials are summarised in Table 2.

Table 2. Effect of thickness ration performance for aluminium and structural steel substrates

	Aluminium		Structural Steel	
Thickness ratio t_P/t_S	0.5	1.0	0.5	1.0
Deflection amplitude (µm)	7.246	3.078	4.176	1.921
Voltage (V)	31.542	25.461	24.257	24.280
E-field norm ($\times 10^5$ V/m)	3.393	2.214	2.587	1.862
Von Mises Stress ($\times 10^7$ N/m^2)	1.806	1.112	1.818	1.090

Table 2 shows that the sensor employing the aluminium substrate has high tip deflection amplitude relative to the sensor employing structural steel. It also has a higher voltage output per unit force. However, the sensor employing structural steel has a very good stability over the thickness ratio range from 0.5 to 1.0 as demonstrated by the voltage output of about 24.3 V. To choose between aluminium and structural steel substrates, the designer also needs to be informed by the environmental conditions where the sensor will be deployed. For operation in high deflection environments, steel may be the ideal choice since it will result in a sensor with adequate sensitivity while offering high durability. Use of aluminium substrate may result in a sensor with higher voltage sensitivity but aluminium has a disadvantage of having a low fatigue stress tolerance compared to steel. The values of the von Mises stress in Table 2 show that the strain transfer from substrate to piezoelectric layer decreases with the increase thickness ratio.

3.2 Effect on first resonance frequency

Sensors based on piezoelectric materials are the most suitable for applications under time dependent mechanical excitations [1,12]. When the mechanical frequency of the sensor matches that of the excitation signal (i.e. resonance), the sensitivity of the sensor is optimum. Figure 8 shows the effect of thickness ratio on the first resonance frequency of the unimorph sensor. For thickness ratio below 1.0, the steel and aluminium substrate based sensors have the same value of first resonance frequency for the same geometry. However, for any thickness ratio beyond 1.0, the sensor employing steel exhibits a higher resonance frequency.

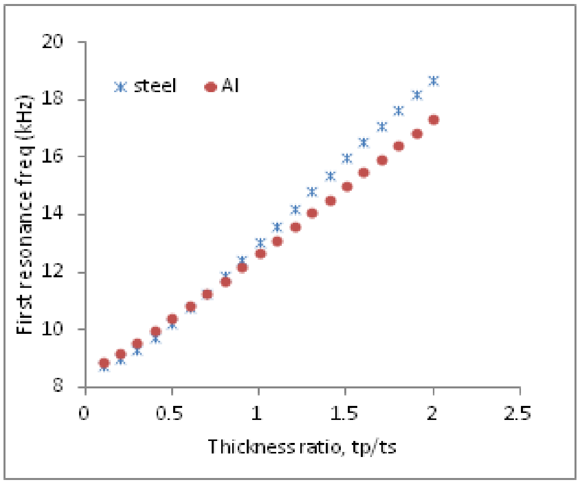

Figure 8. Effect of thickness ratio on first resonance frequency

4. Conclusions

The effect of thickness ratio on the performance of unimorph was studied using the COMSOL Multiphysics® FEM software. Generally, the performance of the sensor is degraded for high values of thickness ratio beyond 1.0. Too small values of thickness ratio below 0.2 will result in low sensitivity due to high capacitance of the unimorph bender. Thus, the results show that there exist an optimum value of thickness ratio for a given substrate material. The results of the study show the use of aluminium as a substrate result in a sensor with sensitivity of above 30 V/N for thickness ratio of 0.5 and the sensitivity reduces to about 25 V/m at a thickness ratio of 1.0. The sensor employing structural steel demonstrated a sensitivity of about 24 V/N at thickness ratios of 0.5 and 1.0. For applications requiring high resonance frequency, structural steel substrate is more applicable than aluminium when thickness ratios around 1.0 are used. The choice of substrate type and substrate ratio is important in optimizing the sensor geometry and hence the performance of the sensor for a specific application.

5. References

[1] J. Tichy, J. Erhart, E. Kittinger and J. Privratska, *Fundamentals of piezoelectric sensorics*, Springer, New York, 2010.

[2] P. Muralt, “Ferroelectric thin films for micro-sensors and actuators: a review,” *Journal of Micromechanics and Microengineering*, vol. 10, no. 2, 2000, pp. 136–146.

[3] J. F. Tressler, S. Alkoy, and R. E. Newnham, “Piezoelectric sensors and sensor materials,” *Journal of Electroceramics*, vol. 2, no. 4, 1998, pp. 257–272.

[4] E. Aksel and J. L. Jones, “Advances in lead-free piezoelectric materials for sensors and actuators,” *Sensors*, vol. 10, no. 3, 2010, pp.1935–1954.

[5] J. L. San Emeterio and A. Ramos, “Models for piezoelectric transducers used in broadband ultrasonic applications,” in *Piezoelectric Transducers and Applications*, A. A. Vives, Ed., Springer, New York, NY, USA, 2nd edition, pp. 97–110, 2008.

[6] Y. Sugawara, K. Onitsuka, S. Yoshikawa, Q. C. Xu, R. E. Newnham, and K. Uchino, “Metal-ceramic composite actuators,” *Journal of the American Ceramic Society*, vol. 75, no. 4, 1992, pp.996–998.

[7] M. S. Azzouz, C. Mei, J. S. Bevan, and R. J. Jong, “Finite element modeling of MFC/AFC actuators and performance of MFC,” *Journal of Intelligent Material Systems and Structures*, vol. 12, no. 9, 2001, pp. 601–612.

[8] C. Kennedy, T. Usher, J. Mulling, and A. Kingon, “Modeling and simulation of THUNDER actuators using ANSYS finite element analysis,” in *Proceedings of the International Conference on Modeling and Simulation of Microsystems (MSM’01)*, Nanotech 2001, Hilton Head Island, SC, USA, March 2001, pp.330–333.

[9] S. X. Xu, T. S. Koko, Finite element analysis and design of actively controlled piezoelectric smart structures, *Finite Elements in Analysis and Design*, vol.40, no. 3 2004, pp. 241-262.

[10] COMSOL Multiphysics 4.3 Documentation, COMSOL, http://www.comsol.com/, 2012.

[11] R. W. Pryor, *Multiphysics modelling using Comsol v. 4*, Mercury Learning & Information, Virginia, 2012.

[12] D. Popovici, F. Constantinescu, M. Maricaru, F. I. Hantila, M. Nitescu, and A. Gheorghe, “Modeling and simulation of piezoelectric devices,” in *Modeling and Simulation*, G. Petrone and G. Cammarata, Eds, Intech, Rijeka, Croatia., pp. 472–500, 2008.

[13] S. N. Jagtap and R. Paily, “Geometry Optimization of a MEMS-based Energy Harvesting Device” *Proceeding of the 2011 IEEE Students' Technology Symposium*, (2011), IIT Kharagpur, 2011, pp. 265 – 69.

[14] Q-M. Wang, X-h. Du, B. Xu, and L. E. Cross, “Theoretical analysis of the sensor effect of cantilever piezoelectric benders,” *Journal of Applied Physics*, vol. 85, no. 3, 1999, pp 1702-1712

[15] B. Zhang, J. Zhang, Electromechanical Interaction Behaviors of Piezoelectric Sensor and Actuator on Elastic Substrate, *J. Intelligent Material Systems and Structures*, no. 16, 2005, pp. 589-596.

[16] A. K. Jha, D. J. Inman, Optimal Sizes and Placements of Piezoelectric Actuators and Sensors for and Inflated Torus, *J. Intelligent Material Systems and Structures*, no. 14, 2003, pp 563-575.

[17] B.N. Zhang, J.Q. Zhang and J.H. Fan, ‘‘A Coupled Electromechanical Analysis of a Piezoelectric Layer Bonded to an Elastic Substrate: Part II, Numerical Solution and Applications,’’ *International Journal of Solids and Structure*, vol. 40, no.24, 2003, pp. 6799–6812.

[18] Ng T H and Liao W H, “Sensitivity analysis and energy harvesting for a self-powered piezoelectric sensor,” *J. Intell. Mater. Syst. Struct.* 16, 2005, pp.785–789.