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Effect of Nickel Wire Gauze on Coupling Factor, Conductance and Efficiency of PZT-Steel Unimorphs

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Abstract

In this study, electromechanical coupling factor, conductance and their effect on performance of PZT-steel circular unimorph transducers were investigated. Two approaches had been followed for developing piezoelectric unimorphs. In the first approach, PZT unimoprhs were developed by directly joining the PZT ceramic element to the steel circular plate. In the second approach, Ni gauze was incorporated between PZT ceramic element and steel disc as an intermediate electrode. Transducer analyzer and LCR meter were used to measure these electromechanical parameters while transmit and receive sensitivities were measured by reference method. PZT unimorphs with Ni wire gauze showed higher values of coupling coefficient, conductance and better transmit & receive sensitivities compared to unimorphs prepared without Ni wire gauze. These unimorph transducers find a wide range of applications in energy harvesting, underwater surveillance, medical and commercial products.

Keywords: PZT; Transducer; Unimorph; Nickel gauze**.**

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1. Introduction

The use of piezoelectric materials in different fields and applications has been increased significantly in recent years. Piezoelectric material, Lead Zirconate Titanate (PZT) is of particular importance and broadly classified into two main categories; soft and hard ceramics. The term soft and hard refers to the dipole movement, polarization and depolarization behavior of the material. These materials are used in broader range of applications such as actuators, sensors, benders, extenders, generators and transformers [1-3]. Since, piezoelectric element converts one form of energy into another form, two types of piezoelectric effects can be observed. One is direct piezoelectric effect which is also called generator or sensor effect, converts mechanical energy into electrical energy. The second is indirect piezoelectric effect, also called motor action, converts electrical energy into mechanical energy [4-6]. These transducers can be compressed or stretched depending upon the configuration used for the desired application. Instead of above general categorization, some soft ceramics are prepared in such a way that their characteristic properties also approach to hard ceramics. These ceramics are used in applications that require dual function e.g. as transmitter and receiver.

Flexural and flextensional piezoelectric transducers are low frequency transducers. Flexural transducers consist of ceramics joined together or with central metal plate. In these transducers, flexural motion of the ceramic element is used [7]. In contrast to flexural transducers, flextensional transducers employ the flexural motion of the metal shell instead of ceramic element. They are constructed by joining the active layer/unimorph transducer to the central metal shell. The purpose of using the metal shell is to convert the small extensional motion of the disc into large flexural motion of the shell. Flextensional transducers have gained popularity because of their increased interest in low frequency and medium to high acoustic power output [8-10]. Furthermore, displacement produced by flextensional transducer is higher than extensional transducer. Displacement produced by flextensional mode transducer would be in mm, whereas extensional mode transducer only generates a strain of the order of 10^{-4} [11].

A piezoelectric unimorph transducer is constructed by joining the active PZT element to a passive layer of elastic material. Active layer expand or contract on applying electric voltage, whereas passive layer resist the change. Due to difference in strain developed, contracting and stretching occurs along the length or thickness direction. The conversion of electrical energy into mechanical energy by unimorph actuators is used for various purposes. Single layer / unimorph PZT transducers can be tailored into different configurations like disc type or strip type transducers. The working principle of all these types is the same. The passive element layer/metal amplifies the radial displacement and vibrational velocity of piezoelectric element into larger axial displacement. Whereas, the cap can mechanically convert and amplify an axial incident stress even a weaker pressure wave into a much larger radial direction stress causing a large value of electric charge generation on the piezoelectric electrodes [12, 13]. These simple geometrical structures have many competitive features like low pricing, lower power consumption, high sound pressure and simple geometry.

Numerous research works have been carried out in order to investigate the behavior of PZT unimorph and bimorphs transducers. A comprehensive review on PZT unimorph and bimorph configurations of PZT element bonded to different metallic layers and thickness modeled and studied in [11, 14-16]. These unimorph finds applications in pressure and acoustic sensing, watch alarms, precision position control, push button devices, and low frequency vibration damping. These can also be employed as end caps in flextensional type transducers[17].

The parameters like frequency, coupling factor, conductance, capacitance and charge coefficient play an important role in the performance of transducer. In this article experimental results of electromechanical coupling factor and conductance of PZT unimorph transducers with and without Ni gauze were presented and compared. Further, the effect on coupling factor and conductance validated by measuring transmit and receive sensitivities of the transducers.

2. Materials and methods

2.1 Materials

The essential components of a unimorph transducer are piezoelectric (ceramic disc), non-piezoelectric (steel-disc) and conductive adhesive. Commercially available piezoelectric ceramic discs Navy type 1 (PZT 400 series) were used for our study. The ceramic discs were coated with silver, making it an electrode on both sides and polled in the thickness direction. Steel discs were fabricated using commercially available standard Mild Steel rods. The material specifications of PZT and Steel are given in (Table 1). Dielectric and electromechanical properties of PZT discs were measured by LCR meter and Transducer analyzer (TA/2000/M2) and piezometer (Piezometer PM 300/d_{33}). PZT and steel discs were joined by using conductive adhesive.

Table 1: Properties of PZT (Navy type-1) and steel

PZT						
Diameter (mm)	Thickness (mm)	Capacitance @ 1 kHz (nF)	Resonance frequency (kHz)	Planer coupling factor (k_p)	Dielectric Loss factor (Tan δ)	Charge Coefficient d_{33} (C/N)
38	1	11	60	0.48	0.001	266
Steel						
Steel Type		Diameter (mm)		Thickness (mm)		
Mild Steel		38		1.45		

2.2 Fabrication Method

Two approaches have been followed for fabricating unimorphs. Details of the manufacturing processes are illustrated below:

Approach 1: The surfaces of the PZT and steel discs were properly cleaned with a cloth soaked in toluene. The surfaces should be free from any dirt, oil residue and other contamination. A thin layer of adhesive was applied on one face of the steel disc with the help of a brush in two passes. The thickness of the adhesive layer was approximately 8µm. The negative poled surface of the ceramic disc is properly pasted on the glued steel surface. Then the unimorph assembly is pressed at 0.05 MPa and placed in a vacuum oven at 70 °C for 2 hour for curing. The schematic of unimorph assembly without Ni wire is shown in (Figure 1). After curing electrical wires are soldered to the steel substrate and PZT for electrical connection. One electrical wire is soldered to positively polled surface of the PZT and other to the thickness side of the steel disc. The resonance frequency ($f_{r)}$, coupling factor (k) and conductance value (G_r) were measured by using Transducer analyzer and LCR meter.

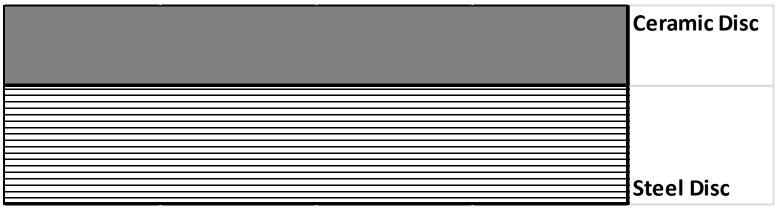

Figure 1: Unimorph without Ni Gauze (Not to scale)

Approach 2: Second type of PZT unimorph differs from first type with respect to Ni wire electrode/mesh. Commercially available Ni wire gauze with mesh size of 200 and wire diameter of 0.05 mm was outsourced for incorporating in unimorph. In this type Ni wire gauze is glued to the cleaned surface of the steel disc. After pasting Ni wire gauze, adhesive is uniformly applied to the surface of the gauze equal in thickness to the wire of the mesh. Then negative poled side of the ceramic is placed symmetrically on wire mesh. The whole assembly is pressed at 0.05 Mpa and placed in the oven at 70 °C for 2 hour for curing. The schematic of unimorph with Ni wire incorporated between ceramic disc and steel disc is shown in figure 2. Then electrical wires are soldered in the configuration as described in method (Approach 1). Measurements for resonance frequency (fr), coupling factor (k) and conductance value (Gr) were taken by using transducer analyzer and LCR meter. Effect of k and G on performance was evaluated by measuring transmit and receive sensitivities of the transducer in water by comparison method using the Reson hydrophone 4042(5Hz-85 kHz).

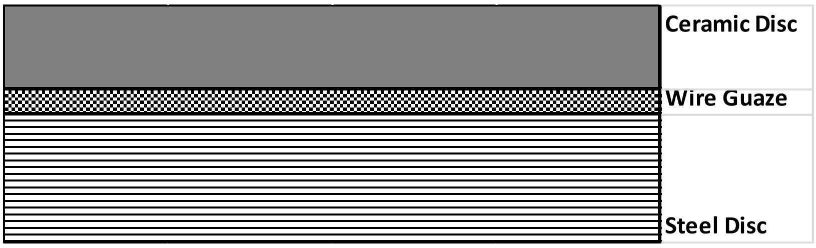

Figure 2: Unimorph with Ni Gauze (Not to scale)

3. Results and discussion

Piezoelectric properties include material, electrical and mechanical parameters. In this research two important parameters coupling factor and conductance were studied. Coupling factor K is measure of effectiveness of piezoelectric material with which it converts electrical energy into mechanical energy and vice versa. The formula for k_{eff} is given by the following expression:

$$K_{eff} = \sqrt{\frac{Energy\ converted}{Input\ Energy}} \qquad (1)$$

The expression holds for both electrical to mechanical and mechanical to electrical conversion [5, 18]. Practical transducers have lower value of k_{eff} than the theoretical values. Coupling factor k when described, carry subscript with it to indicate the direction of applied field and mechanical vibrations. For example k_{33} describes the mechanical vibrations in longitudinal direction for a long rod having length /diameter ratio >10 with longitudinal electric field. For transversal mode coupling factors is indicated by k_{31} with longitudinal vibrations and transversal electric field. Planer coupling factor of thin disc is represented by k_p with electric field in the direction 3 and mechanical vibrations in radial direction. This is also called radii coupling factor.

For efficient transducer, a higher value of k_{eff} is desirable. Since efficiency of a transducer is the ratio of the useful converted energy to the total energy input. So a well-constructed, tuned and adjusted transducer could be highly efficient >90% at its resonance frequency. However, outside resonance region its efficiency could be lower [19, 20]. In this research, planer mode coupling factor k_p was investigated for a unimorph transducer. The trend of k_p values with and without Ni electrode has been plotted at constant frequency (Figure 3) for various samples. It is clearly evident from the graph that k_p values are higher for transducer with Ni gauze as an electrode. The purpose of using the Ni gauze as an intermediated layer is to increase the uniformity of glue, providing a network of electrical connection for efficient transfer of electric charge and strain developed by the transducer. The thickness of layer of glue is same for both transducer fabrication types.

Also when external electric field is applied to the metal electrode, conduction current and bias is generated in the polar insulator. The ratio of both type of currents determine the electromechanical coupling factor in the PZT transducer.

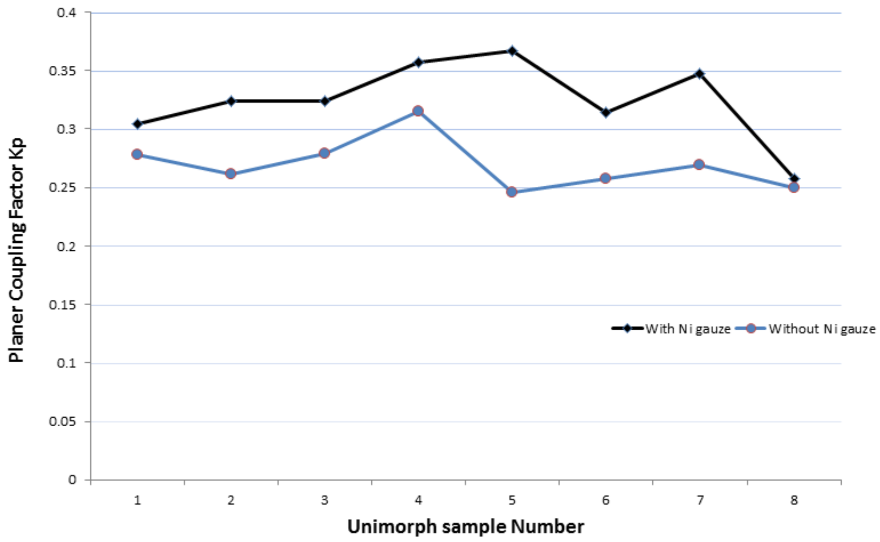

Figure 3: Comparison of Kp for unimorphs with and without Ni gauze

Optimal value of PZT excitation depends upon the bias and conduction currents in the metal-PZT structure under the effect of external electric field. Also the polarization and distribution of dielectric constant is determined by the electric field strength or electron density by the influence of external field.

Conductance is related to admittance by the formula:

$$Y = G + jB \qquad (2)$$

Where, Y is admittance, G is conductance (real part of admittance) and B ((imaginary part of admittance) is susceptance. G describes the ease with which charge carrier passes through a substance. More easily the charge carriers move in response to the applied electric field, higher will be the conductance[21, 22].

The value of G is determined from the electric field strength or current density generated at the interface. Electric field strength of PZT near the anode is several times than at the cathode [23]. A uniform metal structure with high conductivity is suitable for efficient charge carriers. Pure Ni gauze with flexibility and higher value of conductivity was incorporated for efficient transfer of charge and strain developed at the interface. Ni gauze not only assists in transfer of strain and charge but also provide a medium for optimal excitation of piezo-ceramics.

The conductance of various samples at constant resonance frequency has been plotted for unimorphs fabricated with and without Ni gauze and are shown in (Figure 4) below. It can be seen from the graph that conductance values for unimorph with Ni gauze are higher compared to unimorph without Ni gauze.

Hence coupling factor and conductance related to the phenomena of energy conversion and conduction of these current from the source. Effect of coupling factor and conductance on performance was evaluated by measuring and comparison of sensitivities of the transducers.

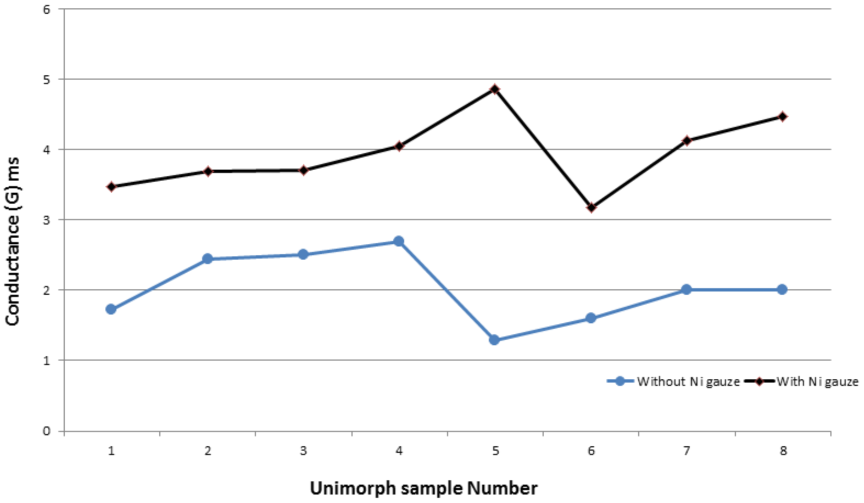

Figure 4: Comparison of G for unimorph with and without Ni gauze

Transducers can perform either as projector, receiver or both transmitter and receiver. Projectors are operated near resonance frequency because they generate maximum output acoustic pressure at that frequency. A projector or transmitter is characterized in terms of transmit voltage response (TVR). Transmit voltage sensitivity is a ratio of sound pressure generated at a distant of one meter in a specific direction with respect to the acoustic center of the transducer to the applied voltage [24].

$$\text{Transmit Response} = P/V \qquad (3)$$

For underwater, transmit voltage response is measured in test tank, where hydrophone is at a distant of 1m and referred in decibel level of 1 μPa/V at 1m.

A Receiver (hydrophone) is usually employed well below resonance frequency in the flat band region. Receive sensitivity is used to characterize a hydrophone and is expressed in following conventions with negative value: dB re 1 V /μPa [22, 25].

When voltage V is applied to a multilayer transducer then electric field developed across each layer is given below:

$$E_N = \frac{V}{t/N} = N.E_{Single} \qquad (4)$$

Where E_{single} is electric field generated across a single layer transducer. Higher the electric field generated across single layer higher will be the output acoustic pressure. For multilayer transducer, transmit voltage is obtained by multiplying the output acoustic pressure of single layer by factor of N.

Receive sensitivity of transducer depends upon the electric field developed due to incident acoustic pressure. Higher generated electric filed results in more sensitive transducer. For this reason a PZT transducer require suitable PZT element, uniformity in assembly and good medium for strain and charge transfer [26].

Receive sensitivities of transducers are measured around range of interest 7-14 kHz. The resonance frequency of transducers is around 12 kHz. Maximum receive sensitivity is obtained in the flat band region well below the resonance. Trend of receive sensitivity of unimorphs fabricated with and without Ni gauze are shown in Figure. Peak value for transducers with Ni gauze is -179.64 dB at frequency 8.19 kHz and for transducers without Ni gauze is -186.31dB at 8.19 kHz. It is clear that unimorphs with Ni gauze exhibit more sensitivity compared to type without Ni gauze.

Moreover, transmit sensitivities for transducers are recorded in the frequency range 8-16 kHz. Receive sensitivity is minimum and transmit sensitivity is maximum at the resonance frequency ~12 kHz. Peak value for transmit sensitivity for transducers with Ni gauze is 123.35 dB at frequency 11.78 kHz and for transducers without Ni gauze is 119.32 dB at the same frequency as shown in the figure . Thus unimorphs with Ni gauze have more transmit sensitivity than transducers without Ni gauze.

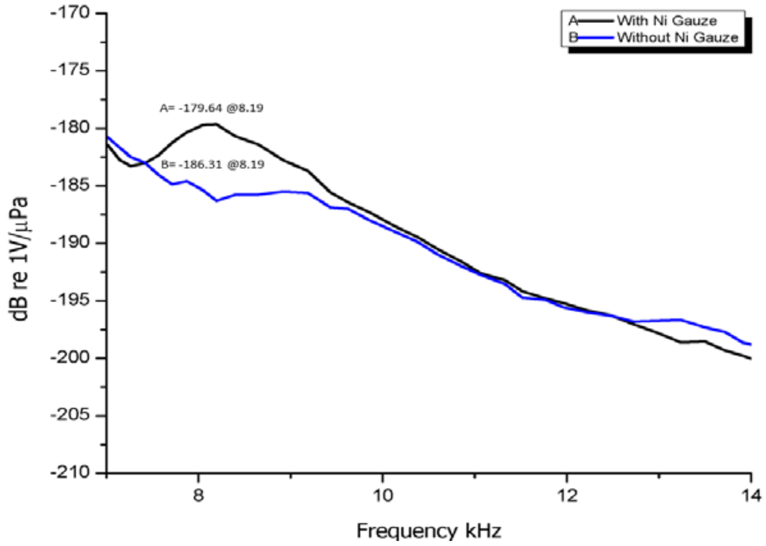

Figure 5 (A): Receive sensitivity of transducers with Ni gauze and **(B)** receive sensitivity of transducers without Ni gauze

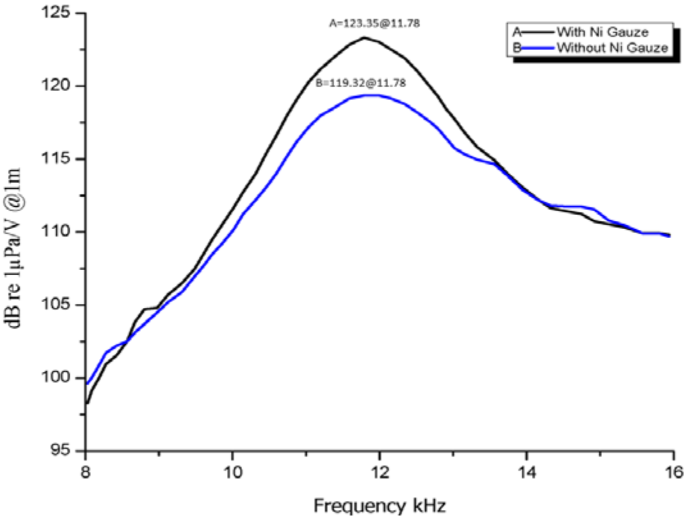

Figure 6 (A): Transmit sensitivity of transducer with Ni gauze and **(B)** Transmit sensitivity of transducer without Ni gauze

4. Conclusion

In summary, behavior of PZT-steel unimorph was investigated experimentally with and without Ni wire gauze. Two important parameters, coupling factor and conductance effect on performance were evaluated. By using Ni gauze, an increase of 1.5 – 2 times in coupling factor and conductance was observed. These results were further validated by measuring receive and transmit sensitivities of both types. Transducers with Ni wire gauze showed higher values of sensitivities. Higher values of transmit and receive sensitivities make these single layer / unimorph transducer more efficient and versatile in many piezoelectric application as sensor and / or actuators. This research further raises many aspects like uniformity, thickness of bonding layer using various techniques &

materials, providing a suitable media for controlling & transferring of electric charge and strain of unimorph transducers need to be investigated.

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