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"Moonie Type" of Piezoelectric Transformer as a Magnetic Field Detector

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Abstract

The present study proposes a new method for determining magnetic field intensities from a composite piezoelectric – magnetostrictive transformer response. In contrast to the previous detector models, which utilize more popular piezoelectric transformer geometries, in the present method the authors introduce the high voltage amplification effect of the "Moonie" transformer. An increased inherent voltage response to the magnetic field is an added value of this almost unknown piezoelectric transformer structure. The new device overcomes several deficiencies of previous detectors. Such drawbacks include the inability to use conventional multimeters instead of lock-in amplifiers due to the low signal to noise ratio. Consequently, the presented device provides low cost and is undisturbed by the noise magnetic field measurements, taking advantage of the "resonant personality" of this disk-type transformer and its exclusively high voltage gain.

To summarize, the paper introduces an efficient method of magnetism sensing based on Moonie piezoelectric transformer geometry within which the force of magnetic field changes its performance. The voltage gain characteristics confirmed the excellent sensitivity and linearity of the composite to magnetic field.

Keywords: Piezoelectric transformer, magnetic field sensor, magnetoelectric effect, measurement techniques

I. Introduction

Superconducting Quantum Interference Devices (SQUIDs) are the world's most sensitive magnetic field sensors, which have a maximum sensitivity limit of 5×10^{-18} T when operated below 77 K, with noise levels as low as 3×10^{-15}T·Hz$^{-½}$ [1]. However, the next best method for ultralow magnetic field detection is constituted by optical magnetometry offering sensitivity limits of 10^{-11} T [2], and also an ultrahigh magnetic field sensitivity of $< 4 \times 10^{-11}$ T has been recorded by Shuxiang Dong *et al.* in magnetoelectric (ME) composites [3]. Therefore, the magnetoelectric effect, with cross coupling between magnetic and electric fields, is regarded as very promising for sensors application [4].

However, the real usefulness of a magnetic detector is determined not only by the output signal absolute value, but also by the reduction of equivalent magnetic noise in the absence of an incident field [5]. The resonant measurement technique is one of the most efficient in a noisy environment and allows us to dispense with costly lock-in amplifiers, but use conventional meters [6].

On the other hand, resonance detection is the most effective technique for detecting any physical properties. Taking advantage of the resonant technique and magnetoelectric effect, an ultra-high-sensitivity sensor of pico Tesla resolution, with its electromechanical resonance frequencies at 215 kHz, has been recently demonstrated [7]. It is also worth mentioning that the Atomic Force Microscope also works according to this principle with demonstrated resolution in the order of fractions of a nanometer, more than 1000 times better than the optical diffraction limit [8].

Piezoelectric transformers (PTs) are solid-state devices that transform primary electrical energy into secondary electrical energy by means of mechanical vibration, but the most important property for the above-mentioned reasons is that they are driven at resonance [9]. Additionally, the most important PT operational factor for detector application is constituted by very high voltage gain, defined as an output to input voltage ratio [10]. Consequently, the high voltage amplification effect of PT increases inherent voltage response to the magnetic field in detector applications so that there have been several implementations of piezoelectric transformers with incorporated magnetostrictive part for efficient magnetic field sensing [11]. The magnetostrictive layer is sensitive to the external magnetic field and it damps the PT's vibration to suppress the PT's voltage output signal. The published papers demonstrates, however, only the most known geometries of piezoelectric transformers like Rosen [12, 13] or bar longitudinal type [14], but not the most effective. Although Rosen PT has a high voltage gain (above 100), it generates a lot of electric noise and spurious vibrations, due to the mixed $k_{31} – k_{33}$ vibration mode, resulting in acoustics wave reflections and in-

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terferences (acoustics mismatch). The longitudinal transformer type is reverse: though it has no spurious vibrations due to $k_{33}-k_{33}$ mode, unfortunately, it has a very low voltage gain of 30, despite the use of PMN-PT single-crystal material [15]. The situation is much worse with the implementation of hard PZT ceramics to this PT structure – in such a case the voltage gain drops to the value of 2.27 [16].

The "Ring dot" disc-type of piezoelectric transformer is also frequently used for magnetic sensing. This PT operates in the uniform planar k_p vibration mode without spurious vibrations, and also it has a low voltage gain of 30 [17]. The disk-type "Moonie" PT (called also "180° wedge" or "half to half" PT design) is an almost unknown structure of a piezoelectric transformer, but it also works in the uniform planar mode of vibrations and the most important feature is that it has a twice larger voltage gain than the "ring dot" and longitudinal transformer [18].

Thus, the present work aims to examine the "Moonie" structure of a disk-type piezoelectric transformer in magnetic field sensing applications and presents the effectiveness of magnetic field measurements with two different layers of magnetostrictive Metglas and Terfenol D. However, comparison of the response from the magnetostrictive layer of Terfenol-D and Metglass is questionable, while their planar strain influence on PZT disc in the composite structure depends on layer thickness (quite different for Terfenol-D and Metglass) as well as different material properties, but such information is interesting from the application point of view.

II. Experimental Procedure

A set of two "Moonie" disk piezoelectric transformers with "half to half" electrode design was prepared from the commercially available APC 841 hard PZT ceramics (manufacturer APC International Ltd., Mackeyville, PA, USA). Disks having a diameter D = 20 mm and a thickness T = 0.8 mm were used (Fig. 1a). Firstly, the electrode patterns, separated by narrow 1-mm insulating gaps, were deposited with the air-dry Ag-paste on the top surface to create PT's input and output parts (Fig. 1a). Secondly, the samples were poled in the electric field of 2 kV/mm at 130 °C for 5 min. The poling direction is indicated in Fig. 1a by red arrows. The piezoelectric parameters and material properties of the PZT discs were measured in compliance with the European Committee for Electrotechnical Standardization standard EN 50324 – 2:2002 [19], listed in Table 1 (density ϱ, elastic stiffness c, the electromechanical coupling factor k, mechanical quality factor Q_m).

The high voltage gain of "Moonie" PT was confirmed by measuring the no-load transformation ratio with two Agilent 34401a multimeters and an HP 3325a function generator. As shown in Fig. 1b, the voltage step-up ratio of the pure "Moonie" transformer is as high as 68.

Finally, piezoelectric transformers, constituting the components of the hard PZT and 2605SA1 Metglas (Hitachi Metals Europe GmbH) or Terfenol-D (Suzhou A-one Special Alloy Co., Ltd), were fixed by means of the 8331 - Silver Conductive Epoxy (M.G. Chemicals Ltd). The fusion process was performed at the curing temperature of 65 °C. The aspect ratio of the applied magnetostrictive layer from Metglas and Terfenol D is r/R = 10/10 (Fig. 1a). The thickness of magnetostrictive layer is equal to 25 μm 2605SA1 in the case of Metglas foil and 1 mm for Terfenol-D material.

Impedance frequency spectra were measured using an Agilent 4294A impedance analyzer in the frequency range from 100 kHz to 1 MHz as a function of DC magnetic field intensity. The magnetic field induced impedance changes in the range of the resonance/anti-resonance frequencies, generated by a symmetrically moving pair of neodymium magnets (Fig. 2). The magnetic field in a measurement chamber was controlled before and after every testing procedure and no bias effect was observed. The Hall Effect sensor that directly measures the magnetic field is 0.5 % accurate and is permanently fixed, because it is sensitive to misalignment in three dimensions.

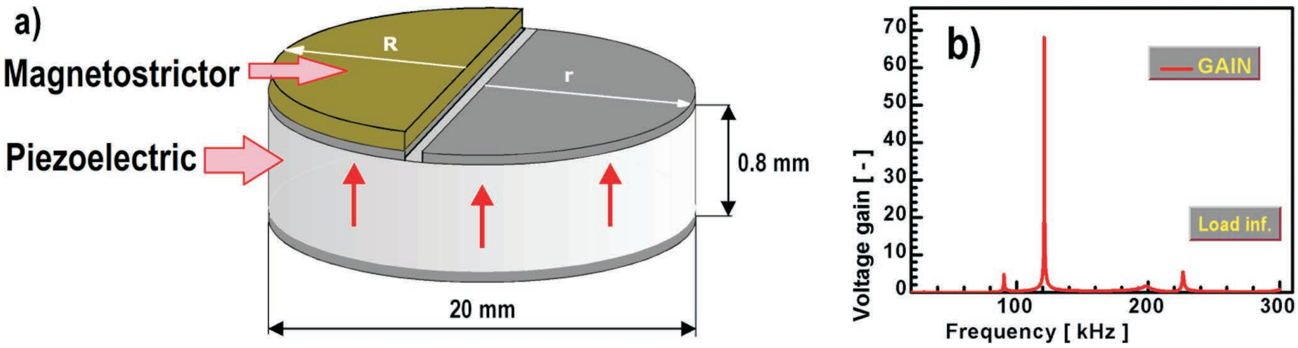

Fig. 1: Schematic illustration of the ME composite with disc "half to half" PT design (a) and frequency dependence of the voltage gain of the pure transformer (b).

Table 1: Measured material parameters of PZT ceramic discs (American Piezo Ceramics Int., Ltd., USA).

PZT type	D [mm]	h [mm]	Q_m [-]	tan δ [%]	$[e_0]$	d_{33} [pC/N]	k_p [-]	$[10^{10}Pa]$	ϱ $[kgm^{-3}]$
APC 841	20	0.8	1400	0.4	1375	300	0.6	10.1	7600

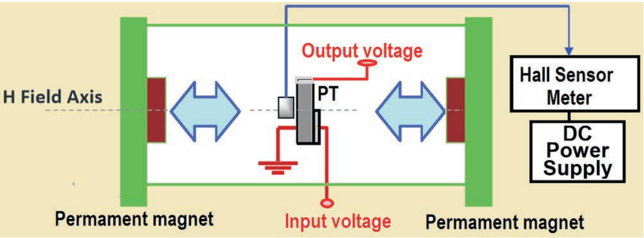

Fig. 2: Scheme of the measurement chamber with changing distance of the permanent magnets, which generates a magnetic field stimulating the sample. A Hall Effect sensor is inserted into the volume next to the sample to measure the field directly.

III. Impedance Analysis Results

(1) Impedance analysis results for Metglas magnetic active part

The shape of the impedance modulus Z maximum value obtained in the present study appears to be a strongly magnetic field dependent on piezoelectric transformers with Metglas magnetostrictive layer (Fig. 3). The influence of the magnetic field on the variability of the impedance modulus can be easily seen in Fig. 3a, which shows a 33-% increase from the value of 7.4 to 11.1 kΩ that corresponds to the impedance maximum frequency value with the increasing magnetic field intensity from 0 to 500 Oe (Fig. 3a). For the higher overtone, the amplitude increase was also significant and it changes in 30 % from the value of 5.8 to 8.3 kΩ (Fig. 3b).

In addition, there was an increase in the frequency value of impedance maximum, strongly dependent on the magnetic field intensity. Under the same conditions, with the increasing magnetic field intensity from 0 to 500 Oe, the Δf = 1200 Hz, the maximum frequency offset of the impedance modulus and phase of the impedance were recorded (Fig. 3a and c). In the case of higher resonance the shift was smaller and equal only to Δf = 200 Hz (Fig. 3b and d).

(2) Impedance analysis results for Terfenol-D magnetic active part

The shape of the complex impedance spectra obtained for the “Moonie” piezoelectric transformers with Terfenol-D magnetic active part appeared to be only slightly dependent on the magnetic field (Fig. 4). The influence of the magnetic field on the variability of the impedance modulus can be observed in Fig. 4, which shows a very small 3 % decrease with the increasing magnetic field intensity from 0 to 500 Oe (Fig. 4a).

Moreover, there was also a small frequency offset of these maxima, equal to the Δf = 20 Hz with the increasing magnetic field intensity from 0 to 500 Oe. Under the same conditions, no shift in resonant frequency of the impedance phase was recorded (Fig. 4b).

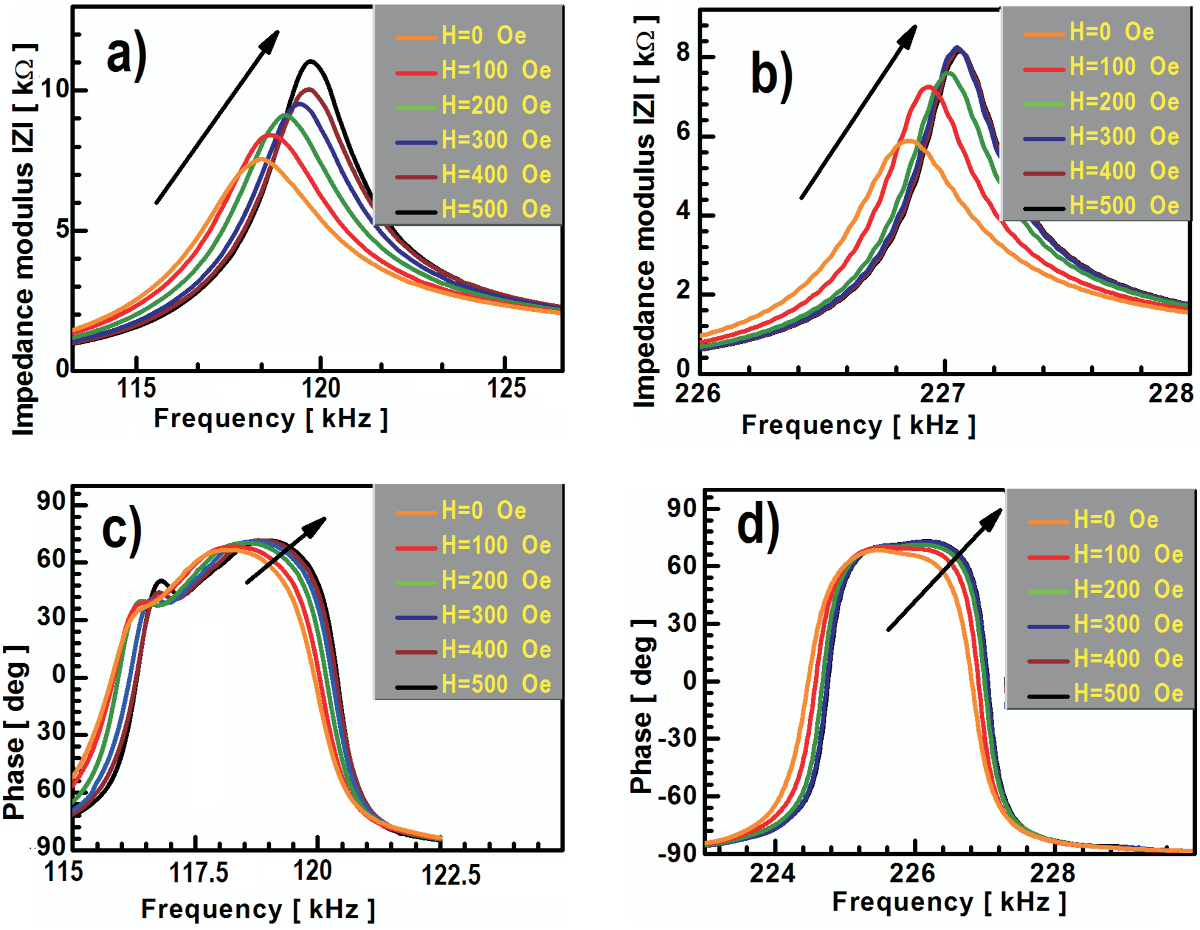

Fig. 3: The influence of the magnetic field intensity on the variation of the impedance maxima for the most effective PT “moonie” disc piezoelectric transformer with Metglas magnetic active layer. Increase of the impedance modulus maxima for lower (a) and higher (b) resonant frequency and phase for the respective frequency ranges (c and d).

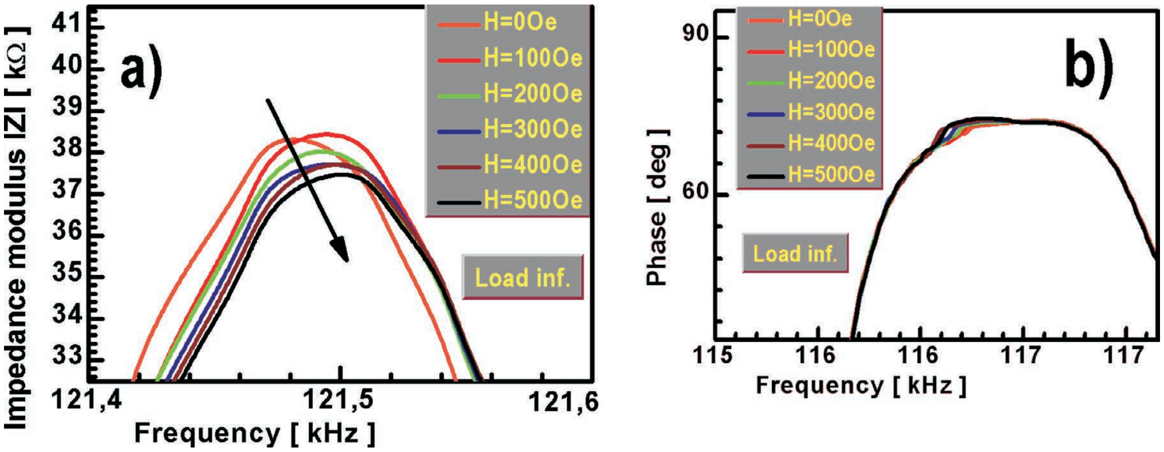

Fig. 4: The influence of the magnetic field intensity on the variation of the impedance maxima for the bar "Moonie" type of piezoelectric transformer with Terfenol D magnetic active layer. Decrease of impedance modulus and (a) no recorded change in the impedance phase (b).

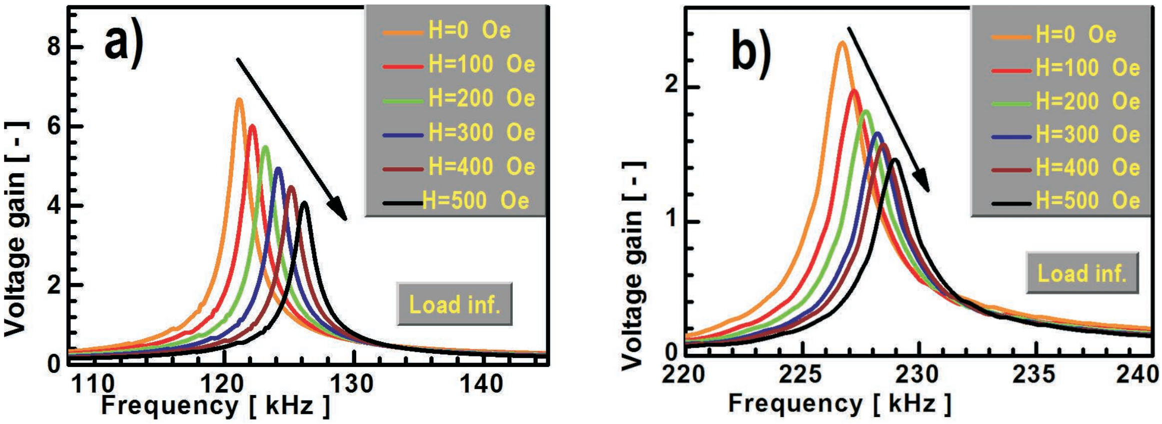

Fig. 5: The influence of the magnetic field intensity on the variation of the voltage gain for the most effective PT "moonie" piezoelectric transformer with Metglas magnetic active layer. Decrease of voltage gain for lower (a) and higher (b) frequency range.

Explanations of the recorded changes in the impedance spectra are connected with the change in the lattice arrangement, due to the application of a force to the lattice from an external magnetic field via the fixed magnetostrictive layer.

The stress generated by the magnetostrictive layer under the influence of magnetic field causes a ferroelectric to generate a voltage or a charge or a combination of the two when the sample is exposed to a mechanical stress. The process can be explained in such a way that the sample is transforming some energy of the magnetic field in its lattice, causing a change in the lattice parameters and consequently changing the associated electrical field balance associated with this lattice and finally the impedance. All of the ferroelectric non-linear materials exposed to such an environmental response can ultimately be traced to the changes in the lattice and subsequent impedance alteration.

(3) *Gain results for Metglas magnetic active part*

The experimental data of gain vs. frequency for no-load condition ($Z_L \approx 1$ MΩ) for piezoelectric transformers with Metglas magnetic active part are shown in Fig. 5. It can be clearly seen that the expectation drawn from impedance measurements, concerning the drop in transformation ratio with increasing magnetic field, have been reflected in these experimental data. The presented results show significant lowering of PT transformation ratio with the magnetic field enhancement.

The influence of the magnetic field on the voltage increase can be easily seen in Fig. 5a, which shows an almost 40 % decrease from the value of 6.67 to 4.07 for the low-frequency resonance with the increasing magnetic field intensity from 0 to 500 Oe (Fig. 5a). For the higher overtone the amplitude decreased more significantly and changed in 65 % from the value of 2.33 to 1.46 (Fig. 5b). The respective maxima frequencies shifts are also very distinctive and equal to 6 and 2 kHz (Fig. 5a and b).

(4) *Gain results for Terfenol D magnetic active part*

The experimental data of gain vs. frequency characteristics, for no-load condition, for piezoelectric transformers with Terfenol D magnetic active part are shown in Fig. 6. The expectation drawn from impedance measurements, concerning the small decrease in transformation ratio with increasing magnetic field, have been reflected similarly in the experimental data. The results do not indicate a significant reduction in the coefficient of transformation to the magnetic field increase, which is only 4 % (from the value of 4.75 to 4.58) for the fundamental resonance (Fig. 6).

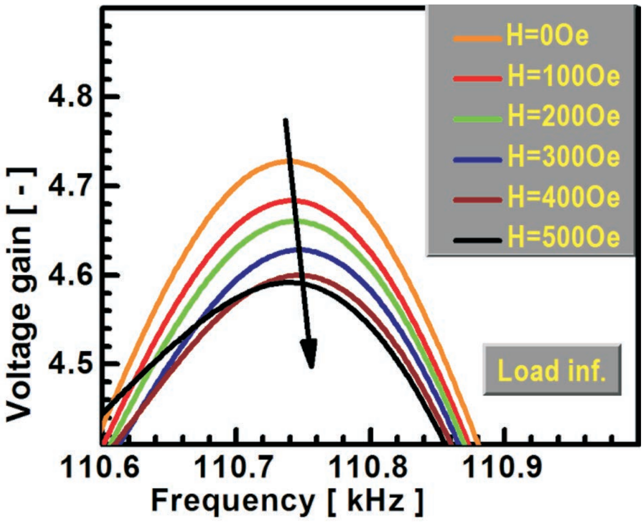

Fig. 6: The influence of the magnetic field intensity on the variation of the voltage gain for the disk piezoelectric transformers with Terfenol D magnetic active layer.

IV. Conclusions

In the present work for magnetic field measurements the high voltage amplification effect of "Moonie" transformer was introduced in contrast to the previous magnetoelectric sensors, using the more common piezoelectric transformer geometries.

The new device overcomes several deficiencies of the previous detectors, including inability to use conventional multimeters instead of lock-in amplifiers owing to the low signal to noise ratio.

The voltage gain characteristic examination confirmed excellent sensitivity to the magnetic field of the disk "Moonie" transformer with Metglas magnetostrictive active layer. A significant drop in the transformation ratio from the value of 6.67 to 4.07 (40 %) with increasing magnetic field intensity from 0 to 500 Oe for fundamental resonance was recorded. For the higher overtone the amplitude decreased even in 65 % from the value of 2.33 to 1.46.

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