Design and Development of a Tachometer Using Magnetoelectric Composite as Magnetic Field Sensor

Article *in* IEEE Transactions on Magnetics · June 2017

DOI: 10.1109/TMAG.2017.2721900

8 authors, including:

Yang Mujin
Southern University of Science and Technology

Jing Ma
Tsinghua University

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2721900, IEEE Transactions on Magnetics

Design and Development of a Tachometer Using Magnetoelectric Composite as Magnetic Field Sensor

Zhan SHI[1]*, Qun HUANG[1], Gui-Sen WU[1], Yi-Hui XU[1], Mujin YANG[1],
Xing-Jun LIU[1], Cui-Ping WANG[1], Jing MA[2]
[1] College of Materials, Xiamen University, Xiamen 361005, China
[2]Department of Materials Science and Engineering, School of Materials Science&Engineering, Tsinghua University, Beijing 10084, China

A tachometer was designed and developed using magnetoelectric composites as the magnetic field sensor. In the presented design, a simple structure with one permanent magnet and a steel gear was used. Magnetoelectric composites Ni/lead zirconate titanate and Metal-glass/lead zirconate titanate were prepared and their sensitivity-field relationship was measured at the first. The simulation was conducted to determine the optimal size of the permanent magnet and the dimension of the air gap. According to the magnetic field distribution in the air gap, the speed sensor was mounted where the magnetoelectric composites had the highest sensitivity. The practical test results showed that magnetoelectric composites had much higher and more stable output voltage signal than the coil, especially in the low-speed range. This study clearly proved the advantage of the magnetoelectric composites in the application of the tachometer.

***Index Terms*—Magnetoelectric effect, tachometer, speed sensor.**

I. Introduction

THE magnetoelectric(ME) effect achieved by combining ferroelectric materials and ferromagnetic materials is known as a new coupling effect between the magnetic field and electric field with great potential in applications of current sensors, geomagnetic sensors, actuators, tachometer and other novel functional devices[1-10]. ME composites sensors have been applied in measuring AC, DC, or pulse magnetic fields, and the highest sensitive threshold of AC magnetic fields by ME sensors can reach the magnitude of 10^{-12}T[11-14]. The mechanism of magnetoelectric effect in composites can be shown by Equation (1). If we stack ferroelectric materials (PZT, BT) and ferromagnetic materials (Ni, Metal-glass, Fe-Ga) together, the piezoelectric effect and the magnetostrictive effect can be coupled by means of mechanical strain/stress. Compared with the intrinsic magnetoelectric effect in many compounds, the coupled magnetoelectric effect in the composite is much more convenient to achieve and much stronger at room temperature. It is also very convenient to adjust the magnetoelectric effect of the magnetoelectric composite by changing the thickness ratio of the ferroelectric layer and ferromagnetic layer. These merits bring a broad application prospect and bring great opportunities to design novel devices.

$$\text{Magnetoelectric effect} = \frac{\text{Electrical}}{\text{Mechanical}} \times \frac{\text{Mechanical}}{\text{Magnetic}} \quad (1)\ [15]$$

Magnetoelectric composite has obvious advantages to making a tachometer. The first reason is the strain/stress mediated magnetoelectric effect is almost frequency independent. The magnetoelectric coefficient in the magnetoelectric composite is very stable in a very wide frequency range below its intrinsic mechanical resonant frequency(as high as 100kHz). So the sensor made by the magnetoelectric composite is very beneficial for low-speed measurement. Another reason is that magnetoelectric sensor is suitable for high-temperature measurement, for the high Curie's temperature of the constitutive phases. For example, Ni's Curie's temperature is 352°C[16], PZT's Curie's temperature is 325°C-340°C[10], and Metal glass's Curie's temperature is about 400°C[17]. Previously a prototype of tachometer with magnetoelectric sensor has been developed using six rotating Nd-Fe-B permanent magnets as the alternating magnetic field source[10]. Here, we present a much simpler design using one steel gear and one permanent magnet as the alternating magnetic field source, which is very popularly seen in a tachometer.

II. EXPERIMENTAL

A. Structure of the Tachometer

The structure of the tachometer was shown in Fig. 1. A steel gear was chosen and one permanent magnet was placed nearby the gear. Hence during rotating, the magnetic field in the gap will change continuously. A magnetoelectric composite was placed in the gap as the magnetic field sensor. The gear was driven by a DC motor with photoelectric encoder. The rotation speed of the motor can be calculated by analyzing the output signal of the photoelectric encoder. Other parts of the tachometer were made of plastic materials with no magnetism to avoid extra magnetic field leaking.

Fig. 1

According to the sensitivity-field relationship of the magnetoelectric composite, there is an optimal magnetic field at which the magnetoelectric composite achieves the highest magnetoelectric effect. To achieve a high sensitivity, the dimension of the gap between the gear and the permanent magnetic should be chosen carefully. The output signal of the magnetic sensor was observed by a digital oscilloscope. For the output of magnetoelectric sensor is a charge signal, a charge amplifier with the filter (YE5852, SINOCERA PIEZOTRONICS. INC.) was used to amplify the signal before the signal entered into the digital oscilloscope. The signal of the coil sensor was amplified by the voltage amplifier. By the digital oscilloscope, the frequency of the magnetic field sensor's signal can be easily measured. The gear's speed can be calculated according to the Equation (2) :

$$n(\text{rpm}) = \frac{60f}{Z} \tag{2}$$

where n is gear's speed, f is the frequency of the signal, Z is the teeth number of the gear（Z=32）.

B. Magnetoelectric Composites

The magnetoelectric composite was prepared by stacking ferromagnetic layer and the piezoelectric layer using instant adhesive, as shown in Fig. 2. In this design, Metal-glass and Ni were chosen as the ferromagnetic layer, respectively, because they have a relatively low price. The PZT/Ni was made from PZT-5 plate(10mm×5mm×1mm, d_{33} = 300pc/N) and Ni plate(10mm×5mm×0.5mm). The Metal-glass/PZT was made from PZT-5 plate(5mm×3mm×0.2mm) and Metal-glass foil (5mm×3mm×0.03mm, λs=27 ppm). For comparison, a coil sensor was made, which has 25 turns around an iron core(Φ2.5mm, 5mm in height). Firstly, the basic sensitivity-field relationship of the magnetoelectric composite was measured by a self-build test system using a dynamic method. In the dynamic method, an electromagnet provides a DC scanning magnetic field applying on the composite and a Helmholtz coil driven by the functional signal generator provides a small and continuous perturbation magnetic field which is applied to the composite at the same time. This method can avoid the quick decay of the DC electric field generated by DC magnetic field. The addition of the perturbation magnetic field ensures a continuous electric output, which can be easily measured by an oscilloscope or a lock-in amplifier. Figure 3 gives the typical sensitivity-field relationship of Metal-glass/PZT and Ni/PZT. The perturbation magnetic field ΔH is 1.25Oe@1 kHz. As shown in Fig. 3, the magnetoelectric coefficient varied strongly with changing external magnetic field, which is because of the non-linear magnetostrictive behavior of the ferromagnetic layer. In Fig. 3, with increasing DC magnetic field, the ME voltage increased first. After reaching the maximum, the ME voltage decreased with increasing DC magnetic field, which is because the magnetostrictive strain tends to be saturated at the high DC magnetic field. When the magnetostrictive strain became saturated, the perturbation magnetic field could not induce magnetostrictive strain anymore, resulting in very small ME voltage. For the tachometer, to ensure high output voltage, it is important to put the ME composite in proper bias DC magnetic field.

Fig. 2

Fig. 3

The Ni/PZT composite had been studied clearly before[18]. To investigate the optimal structure, for Metal-glass/PZT, seven different samples was prepared. From Table 1, it was found that, with increasing Metal-glass layer's number, the optimal magnetic field increased, and maximum magnetoelectric coefficient generally increased too. That is because with increased Metal-glass's layer number, the effective aspect ratio of total magnetic layer will decrease, which make the magnetic layer become harder to be magnetized. So the optimal magnetic field will increase. With increasing Metal-glass layer's number, the ability to extend the PZT layer will increase. For the output terminals directly connected with PZT layer(see Fig. 2), the increasing volume fraction of magnetostrictive layer will increase magnetoelectric coefficient, which has been clearly calculated in many previous researches[19]. For the sample with the same number of Metal-glass layer (like No.3 and No.5), the distribution of the Metal-glass layers affected the maximum sensitivity. According to previous analysis[18,20], the asymmetric distribution will induce flexural deformation, which results in lower magnetoelectric coupling effect. In Table 1, the symmetric distribution (like No.4, No. 7) achieved the highest sensitivity, which is in agreement with previous calculations. Finally, No. 7 was chosen as the magnetic field sensor in the tachometer.

TABLE I

THE OPTIMAL MAGNETIC FIELD OF DIFFERENT SAMPLES

C. Simulations

To determine the size of the permanent magnet and the dimension of the gap between the gear and the magnet, we used a commercial finite element method(FEM) software to calculate the magnetic field distribution. Two Nd-Fe-B permanent magnets (Type: N30, dimensions: 20mm×15mm×18mm and 3mm×6mm×14mm), and three gap distance (D = 16mm, 25mm, 34 mm) were simulated. According to the results of the simulation, we chose the magnet with 20mm×15mm×18mm and D = 25 mm to produce the tachometer. As shown in Figure 4, compared to the experimental results, the simulation results are in good agreement.

Fig. 4

III. RESULTS AND DISCUSSION

By changing the driving voltage of the DC motor (1V-24 V), the rotation speed of the gear can be controlled in the range of 2.6 rpm-180 rpm. The output voltage of different kinds of magnetic sensors can be seen in Fig. 5 The output voltage of coil is quite speed-sensitive. The output voltage of the coil decreased quickly with decreasing speed. According to Faraday's Law, the coil's output voltage is due to the change of the magnetic flux in the coil. The lower speed, the lower change rate of the magnetic flux, resulted in lower induction voltage in the coil. For comparison, it can be seen in Fig. 5 that the output voltage of the ME composites keep very stable when the speed changes. This is because the ME sensors work under the totally different mechanism. According to the magnetoelectric effect as introduced in Equation (1), the output voltage induced by the ME composite comes from the coupling effect between the magnetostrictive effect and the piezoelectric effect. Because magnetostrictive strain is mainly influenced by the magnitude of the magnetic

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2721900, IEEE Transactions on Magnetics

field, not the change rate of the magnetic field, the ME effect is almost frequency independent if the operation frequency is far away from the mechanical resonant frequency (usually as high as about 100kHz). This is an obvious advantage for ME composite when measuring a low speed.

Fig. 5

Fig. 6 presents the practical waveform of the output voltage under two different speed 2.6 rpm and 10.4 rpm. From Fig. 6 (a) (b), it can be seen that, for the very low sensitivity in the low-speed range, the output voltage of the coil is nearly as weak as the noise. The performance of the ME composites, by contrast, is much better than that of the coil. Although there was some noise accompanying with the voltage signal, the output voltage of the ME composite is much higher than that of the noise. The frequency of the output signal can be measured by the digital oscilloscope. In addition, according to Equation (2), it is very easy to calculate the rotation speed of the gear using the frequency of the output voltage of the ME sensors.

Fig. 6

Fig. 7 gives the comparison of the measured speed and the reference speed given by the photoelectric encoder of the DC motor. The solid line in Fig. 7 is linear regression result. As shown in Fig. 7, the linearity is about 0.999 for both two ME sensors, which means measured speed agrees very well with the reference speed.

Fig. 7

IV. Conclusion

A tachometer using ME composites was designed and developed. The coil, Metal-glass/PZT, and Ni/PZT magnetoelectric composite materials were used as the speed sensor to measure the gear's rotation speed. Comparing with the coil, Metal-glass/PZT, and Ni/PZT showed very stable and very high sensitivity under low-speed range. This job will give a very typical framework for designing tachometer using ME composites.

Acknowledgment

This work was supported by National Natural Science Foundation of China(51402164).

References

[1] N. Cai, C. W. Nan, J. Y. Zhai, and Y. H. Lin, "Large high-frequency magnetoelectric response in laminated composites of piezoelectric ceramics, rare-earth iron alloys and polymer," *Appl. Phys. Lett.*, vol. 84, pp. 3516-3518, May 2004.

[2] S. X. Dong, J. R. Cheng, J. F. Li, and D. Viehland, "Enhanced magnetoelectric effects in laminate composites of Terfenol-D/Pb(Zr,Ti)O-3 under resonant drive," *Appl. Phys. Lett.*, vol. 83, pp. 4812-4814, Dec 2003.

[3] X. Zhuang, M. L. C. Sing, C. Cordier, S. Saez, C. Dolabdjian, J. Das, *et al.*, "Analysis of Noise in Magnetoelectric Thin-Layer Composites Used as Magnetic Sensors," *Ieee Sens. J.*, vol. 11, pp. 2183-2188, Oct 2011.

[4] Y. J. Wang, D. Gray, D. Berry, J. Q. Gao, M. H. Li, J. F. Li, *et al.*, "An Extremely Low Equivalent Magnetic Noise Magnetoelectric Sensor," *Adv. Mat.*, vol. 23, pp. 4111-4114, Sep 2011.

[5] L. Chen, P. Li, Y. M. Wen, and D. Wang, "Magnetoelectric Transducer Employing Piezoelectric Ceramic/Ferromagnetic Alloy/High-Permeability FeCuNbSiB Composite," *IEEE Trans. Magn.*, vol. 47, pp. 4437-4440, Oct 2011.

[6] Z. Fang, N. Mokhariwale, F. Li, S. Datta, and Q. M. Zhang, "Magnetoelectric Sensors With Directly Integrated Charge Sensitive Readout Circuit-Improved Field Sensitivity and Signal-to-Noise Ratio," *Ieee Sens. J.*, vol. 11, pp. 2260-2265, Oct 2011.

[7] D. Cahen, G. L. Frey, and A. Zaban, "Human resources for future alternative-energy research," *Nature Mater.*, vol. 7, pp. 93-93, Feb 2008.

[8] M. Zucca, O. Bottauscio, C. Beatrice, and F. Fiorillo, "Modeling Amorphous Ribbons in Energy Harvesting Applications," *IEEE Trans. Magn.*, vol. 47, pp. 4421-4424, Oct 2011.

[9] C. L. Zhang, J. S. Yang, and W. Q. Chen, "Low-frequency magnetic energy harvest using multiferroic composite plates," *Phys. Lett. A.*, vol. 374, pp. 2406-2409, May 2010.

[10] R. Myers, R. A. Islam, M. Karmarkar, and S. Priya, "Magnetoelectric laminate composite based tachometer for harsh environment applications," *Appl. Phys. Lett.*, vol. 91, pp. 122904, Sep 2007.

[11] S. X. Dong, J. F. Li, and D. Viehland, "Ultrahigh magnetic field sensitivity in laminates of TERFENOL-D and $Pb(Mg_{1/3}Nb_{2/3})O_3$-$PbTiO_3$ crystals," *Appl. Phys. Lett.*, vol. 83, pp. 2265-2267, Sep 15 2003.

[12] S. X. Dong, J. G. Bai, J. Y. Zhai, J. F. Li, G. Q. Lu, D. Viehland, *et al.*, "Circumferential-mode, quasi-ring-type, magnetoelectric laminate composite - a highly sensitive electric current and/or vortex magnetic field sensor," *Appl. Phys. Lett.*, vol. 86, pp. 182506, May 2, 2005.

[13] S. X. Dong, J. Y. Zhai, J. F. Li, and D. Viehland, "Small dc magnetic field response of magnetoelectric laminate composites," *Appl. Phys. Lett.*, vol. 88, pp. 082907, Feb 20 2006.

[14] J. Y. Zhai, Z. P. Xing, S. X. Dong, J. F. Li, and D. Viehland, "Detection of pico-Tesla magnetic fields using magnetoelectric sensors at room temperature," *Appl. Phys. Lett.*, vol. 88, pp. 062510, Feb 2006.

[15] C.-W. Nan, "Magnetoelectric effect in composites of piezoelectric and piezomagnetic phases," *Phys. Rev. B.*, vol. 50, pp. 6082, 1994.

[16] F. Nix and D. MacNair, "The thermal expansion of pure metals: copper, gold, aluminum, nickel, and iron," *Phys. Rev.*, vol. 60, pp. 597, 1941.

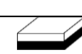
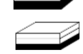
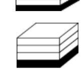
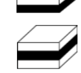
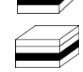
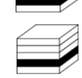
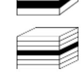
[17] F. S.-y. LI Hong, "curie temperature determination of amorphous alloy by differential scanning calorimetry," *Chin. J. Iron Steel Res.*, vol. 28, pp. 74-78, 2016.

[18] Z. Shi, Y. S. Tong, Z. B. Zheng, H. Xue, S. Y. Yang, C. P. Wang, *et al.*, "The Influence of Flexural Deformation on the Static Magnetoelectric Coefficient of a Bilayered Magnetoelectric Composite," *Mater. Res. Lett.* , vol. 1, pp. 45-50, 2013.

[19] S.X. Dong, J. Y. Zhai, "Equivalent circuit method for static and dynamic analysis of magnetoelectric laminated composites," *Chin Sci. Bull.*,vol.53, pp2113-2124,2008

[20] M. S. Guo, S.X. Dong, "A Resonance-Bending Mode Magnetoelectric-Coupling Equivalent Circuit," *IEEE Trans. Ultrason. Ferroelectr. Freq. Control.*, vol.56, pp2578-2586,2009

TABLE I
THE OPTIMAL MAGNETIC FIELD OF DIFFERENT SAMPLES
（White layer: Metal-glass; Black layer: PZT）

Sample No.	Structure	Optimal magnetic field (Oe)	Maximum Sensitivity (mV/Oe)
1		68	0.402
2		120	0.718
3		158	0.462
4		123	1.00
5		147	2.01
6		249	1.216
7		329	2.12

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2721900, IEEE Transactions on Magnetics

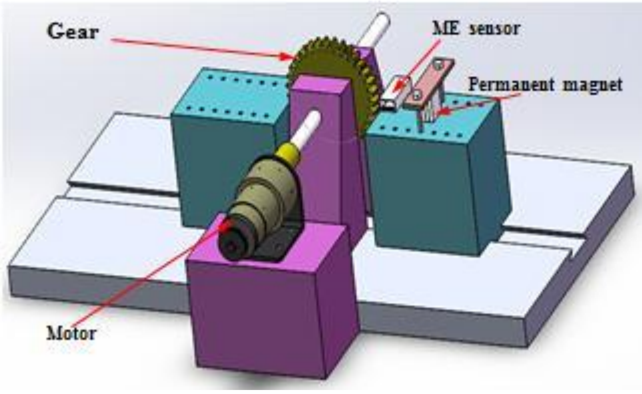


Fig. 1. The mechanical diagram of the designed tachometer.

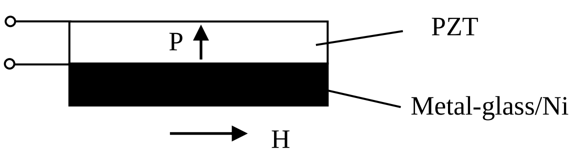


Fig. 2. The schematic diagram of the magnetoelectric composite. The utilized couple mode of the ME composite is longitudinal-transversal mode.

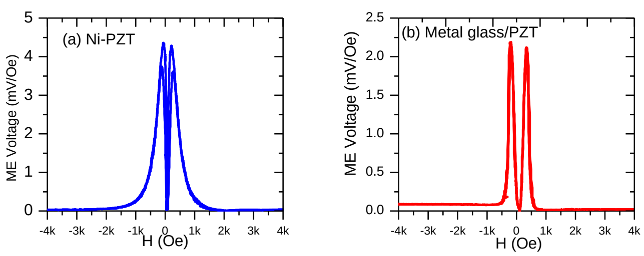


Fig. 3. The magnetoelectric loop of (a) Ni/PZT and (b) Metal glass/PZT.

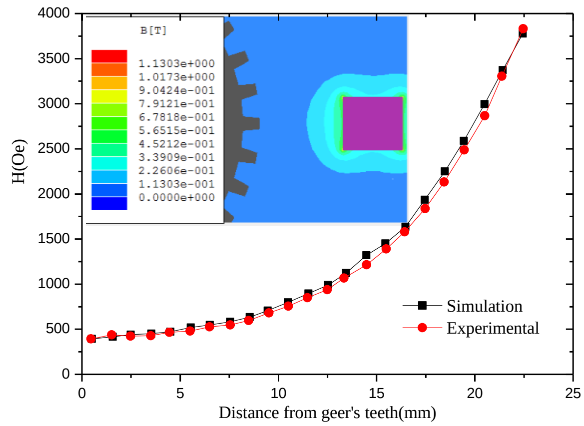


Fig. 4. The magnetic field intensity as the function of the distance from the gear's teeth. The size of the permanent magnetic is 20×15×18mm^3, the gap distance is 25 mm. The inset is the screenshot of the calculated magnetic field distribution by FEM simulation.

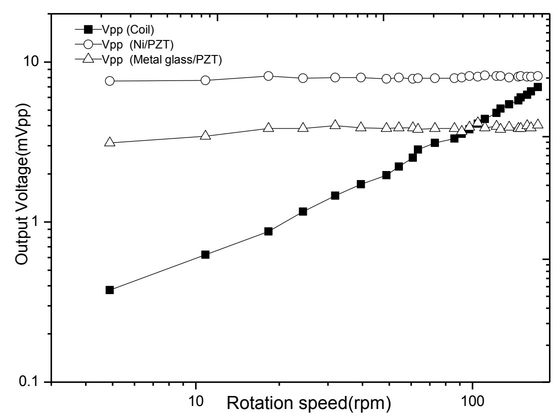


Fig. 5. The relationship between output voltage of the sensor and the rotation speed of the gear.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TMAG.2017.2721900, IEEE Transactions on Magnetics

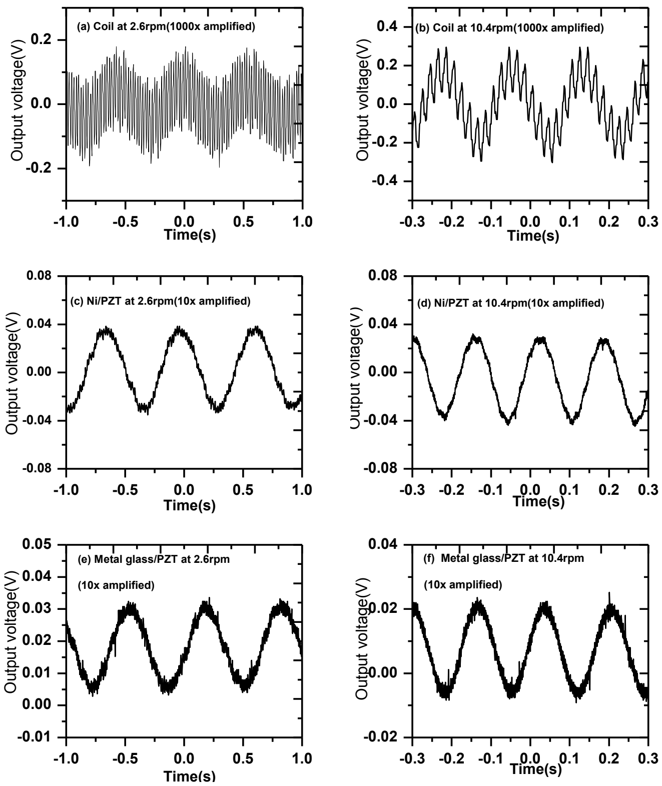


Fig. 6. The output waveform of different sensors at 2.6 rpm and 10.4 rpm.

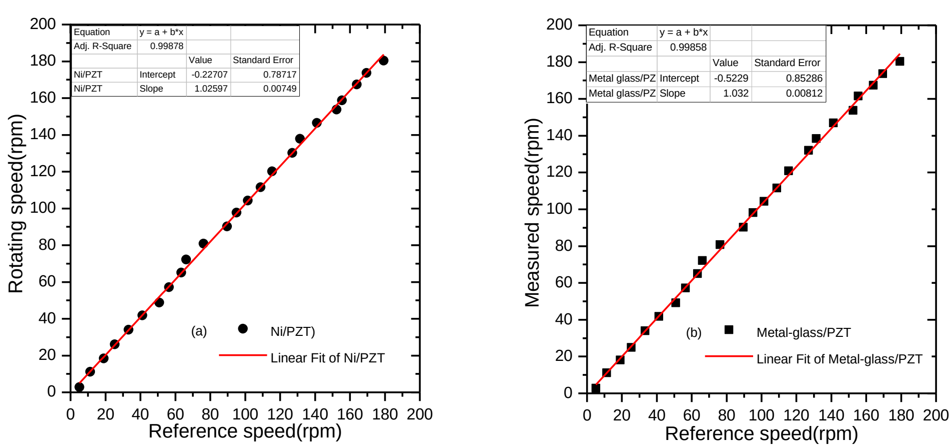


Fig. 7. The comparison between the measured speed and the reference speed. (a) by Ni/PZT sensor, (b) by Metal glass/PZT. The reference speed was given by the photoelectric encoder of the motor.