Application of Piezoelectric Rubber Sensor for Rolling Stock

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Piezoelectric materials are used as sensors because they convert mechanical energy to electrical energy. However, piezoelectric ceramics made with conventional piezoelectric materials, are very brittle. Instead of brittle ceramics, flexible piezoelectric rubber is preferable for engineering use. Therefore, the authors investigated the applicability of flexible rubber for pinching sensors to detect foreign objects between the edges of closing doors and for defect detection on rolling stock axle bearings. It was found that the sensors were able detect foreign objects not usually detected with ordinary systems. Similarly, the newly developed sensors were able to detect axle bearing defects in simplified system.

**Keywords:** piezoelectric rubber, particle alignment, sensors, door-end, axle bearing

1. Introduction

Piezoelectric materials can convert mechanical energy, e.g. vibration and impact forces applied to materials, to electric energy, e.g. electric voltage and electric current, and vice versa. Therefore, piezoelectric materials are used as sensors which can detect applied forces, and as actuators which can vibrate in response to loaded electric signals. More recently, it has been discovered that piezoelectric materials could be applied to noise and vibration reduction devices [1], or to energy generation devices [2].

At present the most conventional piezoelectric materials are piezoelectric ceramics. Piezoelectric ceramics have been used as sensors, actuators, and motors, because they have a high energy conversion performance. On the other hand, the piezoelectric ceramics are very brittle. Therefore, they cannot be used where impact forces are loaded and large deformation occurs. Furthermore, it is difficult to form large and complex shaped product. For these reasons, the areas where piezoelectric ceramics can be used are restricted.

As such, the focus of this paper was placed on piezoelectric rubber which should make it possible to overcome the problem of piezoelectric ceramics. This paper explains the method used to produce piezoelectric rubber and means used to improve its piezoelectric performance. Then the paper presents some examples of actual application of piezoelectric rubber to rolling stock.

2. Piezoelectric rubber

2.1 Ordinary piezoelectric rubber

2.1.1 Method for producing ordinary piezoelectric rubber

Piezoelectric rubber is a composite of rubber and particles of piezoelectric ceramics.

Ordinary Piezoelectric rubber is made by mixing rubber and the particles of piezoelectric ceramics using a mixing machine, e.g. roller mill. Piezoelectric rubber was made by mixing EPDM (ethylene propylene rubber) and PZT (Lead zirconate titanate) piezoelectric ceramic. The product with a concentration of PZT particles of 50 Vol% was molded into piece measuring 150 mm in length, 150 mm in width and 1 mm in thickness. The appearance and flexibility of the produced piezoelectric rubber is shown in Fig. 1.
2.1.2 Piezoelectricity of ordinary piezoelectric rubber

The piezoelectricity of piezoelectric rubber was evaluated using the piezoelectric strain constant $d_{33}$. $d_{33}$ is a piezoelectric index, and indicates the electric charge generated per unit of force applied. The front subscript 3 of $d_{33}$ indicates the direction of the electric field loaded to the piezoelectric rubber during the manufacturing process, while the rear subscript 3 of $d_{33}$ indicates the direction of applied force during the process for measuring its piezoelectric strain constant. In the case of the piezoelectric rubber made in this study, both the directions are vertical; therefore, in this paper, it is written as $d_{33}$. In cases where the direction of the applied force is horizontal, it is written as $d_{31}$. The $d_{33}$ by the generated electric charge when force was applied to the piezoelectric rubber using a vibration machine was measured. As the measurement condition, a sine wave with a frequency of 100 Hz and a vibration of 2 kN ± 1 kN were given.

As a result of the measurement, the $d_{33}$ of the piezoelectric rubber was 1–5 pC/N. This value was low as compared with the 80–600 pC/N of the $d_{33}$ of conventional PZT. Piezoelectric rubber which has low $d_{33}$ can be used as sensors if amplifier of electric charge is available. On the other hand, $d_{33}$ should be increased when the amplifier is unavailable or electric signal have to be detected directly.

Therefore, the $d_{33}$ of the conventional piezoelectric rubber was investigated. As a result, it was confirmed that the conditions of the PZT particles in rubber influence the $d_{33}$ of piezoelectric rubber. Figure 2 shows the result of magnifying observation of samples. The samples have different $d_{33}$ although they have the same concentration of PZT particles of 50 Vol%.

The $d_{33}$ of the piezoelectric rubber shown in Fig. 2(A) was 5 pC/N and the piezoelectric rubber shown in (B) was 1 pC/N. The piezoelectric rubber shown in Figure 2(A) had a mass of PZT composed of submillimeter sized particles while Fig. 2(B) shows isolated PZT particles of approximately 1 μm. It was confirmed that the piezoelectric rubber shown in Fig. 2(A) can easily take an electric charge because of interconnectivity between the larger PZT particle masses. Therefore, the $d_{33}$ of this piezoelectric rubber was higher than that shown in Fig. 2(B).

This indicates that in order to increase the $d_{33}$ of piezoelectric rubber, the PZT particles need to be in contact each other and connected from the top to the bottom surface. Therefore, the Piezoelectric Rubber with Aligned PZT particles called PRAP was investigated.

2.2 Piezoelectric rubber with alignment PZT particles in Rubber (PRAP)

2.2.1 Fabrication method of PRAP

PRAP is produced using a method to align ferroelectric material particles containing PZT by means of an electric field in a liquid dielectric [3]. Under this method, the particles of ferroelectric materials are aligned in the direction of the electric field because of interaction between the particles which is caused by the inducing electric dipole moment of ferroelectric materials in the electric field.

Investigations into the production method confirmed that PRAP could be produced by combining PZT particles and thermosetting silicone rubber. First, uncured liquid silicone rubber and PZT particles were mixed, and then the silicone rubber was cured by heating it in an electric field. Figure 3 is a cross-sectional view of the PRAP with PZT particles 0.6 mm in size, and concentration of 10 Vol%.

Figure 4 shows the appearance of the PARP of size 50 mm in diameter and 2 mm thick. While, the PZT particles in the PRAP which are produced without an electric field could not be aligned, PZT particles in the PRAP produced by applying an electric field of 2 kV/mm were aligned in the direction of the electric field. The PRAP thus produced was flexible [4].

Fig. 2 Result of magnifying observation of ordinary piezoelectric rubber which have the same concentration of 50 Vol% of PZT particles.

Fig. 3 Cross-sectional observation of PRAP with PZT particles with a size of 0.6 mm, the concentration of which is 10 Vol%.

Fig. 4 Appearance of PRAP
2.2.2 Piezoelectricity of PRAP

Figure 5 shows the relationship between the $d_{33}$ and the electric field of the PRAP with PZT particles 0.6 mm in size, at a concentration of 10 Vol%.

$d_{33}$ increases as the value of the electric field rises, and then decreases after reaching the maximum value at 1.5 kV/mm. Results indicate therefore that PRAP has an optimal electric field when $d_{33}$ is at its maximum. Figure 5 shows that the maximum $d_{33}$ of PRAP was approximately 10 pC/N. This $d_{33}$ value is twice as large as for ordinary piezoelectric rubber although PRAP had a PZT particles concentration of only 10% Vol, which is a fifth of ordinary piezoelectric rubber. This confirmed that the particle alignment is an effective means to increase the $d_{33}$ of piezoelectric rubber.

Figure 6 shows the relationship between the $d_{33}$ and the PZT particle size. The samples shown in the figure were produced under the following conditions: applied electric field 2 kV/mm and PZT particles concentration of 10 Vol%. The $d_{33}$ rose as the particle size was increased, reaching a maximum value of 13 pC/N for a particle size of 1 mm.

Figure 7 shows the relationship between the $d_{33}$ and the concentration of PZT particles. Production conditions were as follows: applied electric field 2 kV/mm and PZT particles concentration of 10 Vol%. The matrix of the PRAP whose $d_{33}$ is shown in Figure 7 was silicone gel. The Young’s modulus of silicone gel is approximately 4 MPa. This value is near to that of silicone rubber, which is approximately 70 MPa.

As shown in Fig. 7, the $d_{33}$ is approximately 110 pC/N at a concentration of PZT particles of 40 Vol% [5]. This value is near to that of the $d_{33}$ in PZT ceramics. In addition, the Young’s modulus of PRAP with a $d_{33}$ of 110 pC/N is approximately 40 MPa. This value was less than 1/100 of that of PZT ceramics.

These results confirmed the following key conditions for increasing the $d_{33}$ of PRAP [5].

- PZT particle size: large
- Young’s modulus of matrix: low

The PRAP which was made under the above conditions had a large $d_{33}$ because the force applied to align the PZT particles was large.

When silicone gel was selected as the matrix however, the material failed to maintain piezoelectricity when a large force was applied to the PRAP. This is because the particle alignment was broken under the low load bearing capacity of the silicone gel. Therefore, PRAP produced with silicone gel should be applied in consideration of the magnitude of forces to be applied.

3. Application of piezoelectric rubber to sensors on rolling stock

3.1 Application to a pinching sensor for foreign objects trapped by rolling stock doors

3.1.1 Door-end rubber with piezoelectric rubber

Rolling stock door-edges create a pinching hazard for foreign objects when passengers are boarding and alighting. Rolling stock is normally prevented from running by an installed system for detecting if foreign objects have been trapped. However, small objects, e.g. of less than 15 mm, cannot be detected because of deformation in the rubber of the door seals. Rubber deformation is used to dampen the force exerted on the foreign object. Therefore, if a small object was caught in doors, e.g. fingers, a sticks, the detection mechanism may not be triggered, allowing the train to move.

Methods were therefore investigated for detecting small objects being trapped in the door seals using piezoelectric rubber, hereafter referred to as “door-end sensors.” Figure 8 schematically illustrates the door-end sensor and Fig. 9 shows the appearance of the piezoelectric rubber used for the door-end sensor. The piezoelectric rubber used for the door-end sensor was 1500 mm in length, 5 mm in width and 1 mm in thickness. This size was determined in consideration of the space inside the door-end rubber and the difficulty in pinpointing where pinching could occur. Contrary to piezoelectric ceramics, piezoelectric rubber has
the advantage that it can be molded. PRAP however was difficult to mold into the shape required. Therefore, the door-end sensor was produced using ordinary piezoelectric rubber by mixing 1 mm PZT particles with EPDM at a concentration rate of 50 Vol%. The $d_{33}$ of the piezoelectric rubber used was approximately 2.5 pC/N.

3.1.2 Bench test

A bench test was carried out to measure the generated electric charge from the door-end sensor when an object is pinched. Figure 10 shows the bench test set up.

In the test, a jig simulating the door-end was mounted on the rig. The door-end sensor cut 150 mm long was affixed to the lower part, while ordinary door-end rubber cut 150 mm long was affixed to the upper part. When the rig was set up, the gap between the upper and lower rubber edges was set at 20 mm, and then the upper part was moved down to make a gap of 0 mm, pinching metal rods which were placed between the two edges to simulate foreign objects being trapped.

Figure 11 shows an example of the results obtained: the time wave of the electric charge generated from door-end sensor and force applied to it when a metal rod with a diameter 8 mm was pinched.

The time wave of the electric charge was similar to that of the force. The maximum value of the force and the electric charge were approximately 35 N and 150 pC, respectively.

Figure 12 shows the relationship of the contact speed with the maximum value of the force and the electric charge when a metal rod with a diameter of 8 mm was pinched.

Figure 13 shows the relationship between the size of the metal rod and the maximum value of the electric charge when the contact speed was 1000 mm/min.
Both the electric charge and force rose as the size of the metal rod was increased.

It was considered that a larger electric charge would be generated between the closing train doors on a real train because the contact speed exceeded the 1000 mm/min used in the bench test. However, the target size of foreign objects for the detection of the pinching was larger than 5 mm because the bench test indicated that only a small amount of electric charge was generated when metal rod with a diameter of less than 5 mm were pinched.

3.1.3 Tests on full-size rolling stock

Tests for the evaluation of pinching detection performance of the door-end sensor were carried out on rolling stock owned by RTRI and using a door-end sensor with a length of 1800 mm. Figure 14 illustrates the test set up.

The control device was also validated during these tests. This device has the function of reopening the door when it receives an electric signal from the door-end sensor which exceeds the set threshold. The electric signal was electric voltage obtained by amplifying the electric charge with an amplifier.

As an example of the test results, Fig. 15 shows the time wave of the signal when no object was pinched and a metal rod of φ10 mm was pinched at the height of 1000 mm from the bottom. Here, the range of the amplifier to change from the electric charge to electric voltage was 0.01 V/pC, and the threshold of the control device was 8 V.

While the door did not reopen when no object was pinched because the signal did not reach the threshold, it reopened when a metal rod of 10 mm was pinched because a signal of 10 V which is more than the threshold was generated. At present, objects with a size of less than 10 mm cannot be detected by the installed system in rolling stock. In this test, it was confirmed that the new device did not interfere with systems already installed, and it could detect metal rods of 10 mm or finger tips, in places where the piezoelectric rubber was embedded into the door-end sensor. On the other hand, metal rods with smaller than 5 mm or objects in lower positions remain difficult to detect. These smaller object can form the subject of future research.

3.2 Application to a sensor for detecting axle bearing defects on rolling stock

3.2.1 Vibration-isolating rubber for axle bearings with piezoelectric rubber

Axle bearings on rolling stock bogies are important components because defects in axle bearings can lead to serious accidents. Therefore, a method was studied for detecting axle bearing defects using piezoelectric rubber.

In order to protect the axle bearing and to isolate the bearings from vibration, axles bearings are housed in axle boxes with vibration absorbing rubber. One method studied for detecting axle bearing defects is to incorporate piezoelectric rubber into the vibration-absorbing rubber to make an “rubber axle bearing sensor.” The inside of the rubber axle bearing sensor is shown in Fig. 16. The rubber axle bearing sensor detects abnormal vibrations caused by defects in the axle bearings. The force applied to the piezoelectric rubber inside the rubber axle bearing sensor was 1/10 of the total force. Therefore, PRAP with 0.7 mm sized PZT particles and a concentration of 30 Vol% was used because it was considered that a high d33 would increase the effectiveness of the detection. The value of the d33 of the PRAP used for the rubber axle bearing sensor was approximately 20 pC/N.

In order to evaluate the sensor’s detection performance, rotation tests with the rubber axle bearing sensor were carried out using a fatigue test machine for axle bearings owned by RTRI. In the rotation tests, both a normal axle bearing and a damaged axle bearing with defects were used. The electric signals generated by the PRAP in the rubber axle bearing sensor was measured.

The axle bearing used in the test was a double-row cone roller bearing, the bearings on the axle-end side being called row A and those on the other side, row B. Two sheets of PRAP called P-A and P-B in the rubber axle bearing sensor were placed above row A and row B respectively. The defective bearing was given an artificial defect approximately 35 mm in width on the outer ring of row A and was set in such a way that the artificial flow was placed at the top of the bearing. The test set up is shown in Fig. 17.

Figure 18 gives an example of the test results and shows the measured electric voltage generated from the rubber axle bearing sensor when the rotation speed was 70 km/h. The figure shows the frequency analysis result obtained by measuring electric voltage without using an electric charge amplifier, and compares results of the normal axle bearing and defective one.

Test results indicated that the defective axle bearing generated electric voltage at a given frequency where the normal axle bearing did not. The frequency at which the
defective axle bearing generated electric voltage corresponded to the second and third harmonic frequencies which were calculated by the following equation. In equation (1), $f_s$ was the frequency based on the generated vibration when a defect occurred in the outer ring of the axle bearing.

$$f_s = \frac{Z_n}{60} \left(1 - \frac{D_w}{D_{pw}} \cos \alpha \right)^{1/2}$$

Where, $Z_n$ is the number of rollers of the axle bearing, $n$ is the rotation speed of the axle, $D_w$ is the average diameter of the rollers, $D_{pw}$ is the average pitch diameter of the rollers, and $\alpha$ is the contact angle.

Test results confirmed that defect on the axle bearing could be detected by analyzing the frequency at which voltage was generated by rubber axle bearing sensor. In addition, comparison of the amount of the second harmonic generated electric voltage between P-A and P-B, revealed that the electric voltage from P-A was larger than the electric voltage from P-B. P-A was placed above row A where the artificial defect was made. Therefore, it is considered that defects can be detected through comparison of the generated electric voltage between the two rubber axle bearing sensors. In addition, it was expected that the sensor could be a simple device, because it can measure the electric voltage directly thereby not requiring an electric charge amplifier.

4. Conclusion

Use of conventional piezoelectric ceramics as sensor is limited due to its physical properties, such as brittleness. By concentrating on piezoelectric rubber some of the problems encountered with piezoelectric ceramics have been overcome and methods for enhancing piezoelectricity and the production of piezoelectric rubber were studied. Applications of piezoelectric rubber were then investigated for use in sensors on rolling stock. As a result of the study, the following knowledge was acquired.

1) While conventional piezoelectric rubber produced by mixing rubber and particles of piezoelectric ceramics have flexibility and low piezoelectricity, it was confirmed that the connection of the particles in piezoelectric ceramics in rubber can enhance the piezoelectricity of piezoelectric rubber.

2) The piezoelectricity of Piezoelectric Rubber with Aligned PZT particles in rubber called PRAP, which is still flexible was found to be much higher than other conventional piezoelectric rubbers. It was then confirmed that large piezo ceramic particle size and a rubber matrix with a low Young’s modulus were major factors in enhancing the piezoelectricity of PRAP.

3) A sensor for detecting foreign object being pinched between doors on rolling stock using conventional piezoelectric rubber was able to detect small-sized objects which could not be detected by ordinary detection systems.

4) A sensor for detecting defects in axle bearings using PRAP successfully detected the presence of a defect on the bearings. This was achieved by measuring the electric voltage generated by the PRAP in the sensor directly, which means that the detection device can remain very simple.

This study confirmed that the alignment of particles of piezoelectric ceramics in rubber is an effective way to improve the piezoelectricity of piezoelectric rubber. Tests
were carried out to verify the performance of the pinching sensors and axle bearing defect detection sensors, with a view to practical application on rolling stock. Tests confirmed their applicability. Research into piezoelectric rubber will continue, in order to find more rolling stock applications for this material.

References

[1] N. W. Hagood et al., *Journal of sound and vibration*, Vol.146, pp.243-268, 1991.
[2] Kazuhiro Adachi et al., *Dynamics and Design Conference*, 124, 2009.
[3] Shin Morishita et al., *Mechanics and Mechanical Vibrations of Japan Society of Mechanical Engineers*, No.98-8 242.
[4] Shogo Mamada et al., *Japanese Journal of Polymer Science*, Vol. 65, No.9 pp.579-586, 2008.
[5] Shogo Mamada et al., *Journal of Applied Polymer Science*, Vol.131, 39862, 2014.

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