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Harvesting energy from pavement based on piezoelectric effects: Fabrication and electric properties of piezoelectric vibrator

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This article demonstrates the design of a road piezoelectric transducer (PZT) through a laboratory load test, to utilize the load mechanical energy in road. PZT-5H was selected as the piezoelectric vibrator material. With the combination of the action property of low-frequency forced vibration of the pavement vehicle wheel load, a simple supported disk lap piling piezoelectric vibrator was used as the core component of the road piezoelectricity generating set. The tracking wheel-pressure test of a beam piece was used to determine the piezoelectricity generating capacity of road pavement. The maximum voltage that could be reached is 65.2 V. The primary wheel rolling impact could produce an electric energy of 0.23 mJ. The electric capacity of 0.8 kW/h could be produced per day, which can meet the demand of signal lights. *Published by AIP Publishing.* https://doi.org/10.1063/1.5002731

I. INTRODUCTION

Energy harvesting refers to the collection of various energy sources from the environment and transforming it into electric energy directly for use so as to reach the target of energy recycling and reuse.[1–4] There are various energies available in the living environment of human beings. They are solar energy, thermal energy, wind energy, vibrational energy, etc. Researchers have been doing a lot of work about the utilization of previous three energies.[5,6] However, with the aim of finding out how to transform vibrational energy into electric energy for use, many exploratory research works have been carried out by research scholars from different countries in recent years. At present, the devices that collect environmental vibrational energy can be divided into electromagnetic type, electrostatic type and piezoelectric type according to the difference in transformation principles.[7–9]

The salient feature of the piezoelectricity generating set is its high energy density. It is not necessary to put initial voltage, but it still produced appropriate voltage directly. The structural design is unrestricted and there is no electromagnetic interference and others.[10–12] Based on these advantages, piezoelectric power generation technology has been developed rapidly. However, the majority of piezoelectric transducers (PZT) is used to collect the vibrational energy of fixed mechanical equipment, tidal and wind energy. The utilization of road is still in its research stage. At present, some effects have been achieved in the theoretical research of piezoelectric road, but generally it is still in the starting stage.

Alexander[13] used[1] the piezoelectric effect to develop a system that is used to collect vibrational energy produced by the walking of pedestrians by the thunder piezoelectric device used for the study. Takefuji[1,2,11] developed an energy harvesting device that was built on the pavement of the sidewalk to collect energy produced from walking on the sidewalk. Besides, tests were conducted at the entrance of the subway and on the market aisle.

Jiang *et al.*[15] studied a two-degrees-of-freedom electromechanical model of the piezoelectric harvesting unit that was developed to characterize its performance in generating electrical energy upon external excitations. The result shows that the output power properties of the harvesting unit in the laboratory had good agreement with the theoretical analysis. Cafiso[16] have validated the use of piezoelectric transducers in road asphalt pavement in terms of effectiveness and production of energy. But, the test results show that the energy produced by the piezoelectric transducer within the pavement is very low.

Roundy[17] had performed a theoretical analysis aiming to determine the power produced from the transducer model of a piezoelectric cantilever beam. 60 Hz vibration produced from a microwave oven was used as the driving source to design a cantilever beam piezoelectricity generating set and it was calculated that the maximum output power was around 125–975 μW. Dutoit and Wardle[18] studied the harvester material selection and optimization harvesters with a scheme for chip-level assembly of harvester clusters to meet node requirements.

Platt *et al.*[19] fabricated a cylinder-shaped piezoelectric transduction structure with an area of 1 cm^2 and a height of 1.8 cm with 145 piezoelectric patches in series mechanically and circuits in parallel connection. Under the action of 800 N sine force, the capacitance of 1–10 μF and an open-circuit voltage of 30 V can be produced. Sodano *et al.*[20] studied power generating shoes. The peak electrical power produced from piezoelectric crystals was measured to be 80 mW. But, that does not automatically solve the self-generated electricity's difficulty in road transport; we are still faced with the question if the composites or structures consisting of piezoelectric materials can facilitate the conversion between mechanical and electric energies under load behavior.[21,22]

In this paper, a road piezoelectric transducer that is suitable for the road service environment was developed according to the practical application of a piezoelectricity generating set. In addition, piezoelectric materials that met the performance requirements were selected to achieve structure optimization for the piezoelectric structure design and the piezoelectric transducer. Second, the proper laying scheme of the piezoelectricity generating set was selected according to the generation condition of the piezoelectric device and the structural response of asphalt pavement. The road piezoelectricity generating effect was studied through theoretical calculation and laboratory tests. In addition, the feasibility of this road piezoelectricity generating scheme was discussed.

II. DESIGN OF THE PIEZOELECTRIC PATCH ENERGY HARVESTER

A. Geometric dimensions

The vibration of the pavement structure is mainly produced by running vehicles. Usually, when the vehicles run on the road at a certain speed, it is very short for the wheels to run over a certain size of the piezoelectric vibrator. Take two-axle vehicles with a 2.5 m wheel base and when the running speed was 80 km/h, the frequency of the front and rear wheels was 10 Hz. And, when the wheel pressure is involved, the standard load axle is usually 70 Mp. Suppose that the length of the piezoelectric vibrator was 2 cm and the duration of the wheel load effect on the piezoelectric vibrator was around 0.1 ms. Thus, it can be approximately considered that the effect of wheel load on the piezoelectric vibrator is a single instant shock, which is a forced vibrating excitation. Thus, a round or rectangular piezoelectric patch can be used to fabricate the piezoelectric vibrator. Since the pavement layer contains mineral aggregates at various corner angles, considering the complexity of the environment in the pavement structure, a disc-shaped piezoelectric patch was used as the core component for the transduction of the piezoelectric vibrator in this task.

B. Vibration baseplate

Compared with simple piezoelectric materials, piezoelectric vibrators predominantly have mechanical properties. They can bear huge deformation quantity without any damage. In addition, the response speed is also very fast. Phosphor bronze (density = 8900 kg/m^3) has the advantages of appropriate hardness and specific resistance. After overall considerations, phosphor bronze was used as a metal base. To avoid the damage to mineral aggregates on breakable piezoelectric patches, the size of the base plate is slightly greater than the geometric dimension of piezoelectric patches. It was planned that the size was 4 cm and the thickness was 0.3 mm.

C. Adhesive materials

The bonding layer of a metal base and piezoelectric ceramics should not only have conductivity, but also enough adhesive force. However, the majority of materials are hard to meet requirements on these aspects in the market. Therefore, the method of two glue mixtures was used in this task about the bonding layer. The DB2011 copper powder conducting resin was used as the main conductive material. It not only has excellent conductivity, but also some stretching strength, shearing strength and bonding strength. However, the strength could still not meet the requirements of this task. To ensure that the adhesive strength between the metal base and the piezoelectric ceramics is strong enough, super glue that is not conductive was used to achieve supplementary bonding, so that the structure can meet the requirements of strength.

D. Light-emitting diode

As the direct recognition mode on piezoelectric power in this task, light-emitting diodes should take full consideration of the performance parameters of visual acuity, luminance, specified working condition and service life, of which the visual acuity of red light and green light in emitting colors is good. The directivity of highlight and ultra-brightness is strong. In this task, a highlight red light 3 mm diode was selected in this task. Highlight light-emitting diodes have the advantages of high illumination intensity, low drive current, short response time, and a colorless and transparent epoxy resin package. The rated current of the red light 3 mm highlight diode is 15 mA during normal illumination.

E. Fabrication of piezoelectric vibrator

To make sure that the piezoelectric vibrator can have some piezoelectricity generating capacity under small excitation action and a wider excitation frequency range, a double-crystal piezoelectric vibrator structure was used in this task and two crystals were bonded to the sides of the metal base. To reduce the complexity of the lead circuit, a series connection was used for two crystal plates. It was prepared by polarity relativity and mechanical series connection. Afterwards, a guide line was drawn from the edge of two crustal plates. In addition, it was fixed with soldering tin on the end and connected with a light-emitting diode on the other end to form a self-closed loop circuit so as to collect piezoelectric power.

III. INSTALLATION AND EXPERIMENT

A. Testing schemes

Piezoelectric materials have been laid on a road pavement, the road surface vibration energy is used for piezoelectric power generation, and the service environment of piezoelectric materials is utilized to withstand the pressure of traffic and pedestrians on the road, so that the road conditions determine the capacity of the piezoelectric devices. It can be analyzed through impact factors such as the speed, the frequency and the car traffic on piezoelectric devices.

Under actual road conditions, the piezoelectric device is not subjected to continuous pressure, but to certain frequency, so that the traffic frequency of the vehicle is closely related to the loading frequency of piezoelectric materials. The load frequency is associated with the speed of vehicles, according to the JTG D20-2006 highway route design; the design speed of the highway is shown in Table I.

With urban highway as an example, most of the cars are small cars on the road; in terms of two-axle, the wheel base is 2.5 m and the speed is 80 km/h, so the frequency of the front and rear wheels is: $f = 1/(2.5/(80/3.6)) = 8.99\,\mathrm{Hz}$; we take 10 Hz for calculation. The piezoelectric device used is the piezoelectric ceramic wafer and its diameter is 30 mm; so, the time

TABLE I. Level of highway designed speeds.

Highway classification	Expressway	First-class	Second-class	Third-class	Fourth-class
Design speed (Km/h)	120	100	80	40	20
	100	80	60	30	
	80	60			

duration the car went through the piezoelectric material is: t = L/V = 0.03/(80/3.6) = 0.0013 s. The time of transducer loading is too short (1.3 ms), so the effect the car impact has on the piezoelectric transducer can be seen as an instant impact and the vibration impact can be reflected in the simulation experiment. It is known from the analysis of the above calculation that the theoretical loading frequency that traffic went through the piezoelectric device is approximately 10 Hz.

In this paper, a tracking wheel-pressure experiment was used to test the laboratory generating capacity of the piezoelectric transducer. First, the piezoelectric transducer was fixed on the side of the beam test piece to fabricate a beam test piece tracking plate. Since only two beam test pieces installed with the piezoelectric transducer were applied, this difference resulted in a height difference between beam test pieces; wood was required to fill up and keep the upper surface of the beam test piece smooth. The gap around was filled up with bits of wood to make a tight contact with the beam test piece without any waggle.

All the piezoelectric transducers are self-made and the properties of each device may have some difference. Thus, different quantities of piezoelectricity generating sets should be bonded to different beam test pieces to reduce occasional experimental error. The test scheme diagram selected in this task is shown in Fig. 1. In addition, the piezoelectric transducers of a group of test pieces in two were identified for the convenience of marking the test results.

In the experimental process, the tracking testing wheel was set to act on the middle of the beam test piece. Since the length of the beam test piece was limited and it had some rigidity, first suppose that the testing wheel pressure to bear was the same on the piezoelectric transducer of beam test piece. The piezoelectric transducers of the beam test piece were laid along the length direction of the beam. They all had midpoint symmetry about the beam test piece, but considering that the beam body might produce some bending deformation under the vertical load effect, it was theoretically considered that there should be a consistent load effect between 1# and 2#, 3# and 5# in the longitudinal direction. However, the load effect among 4#, 3# and 5# might have slight differences. It can be analyzed and judged from the transduction effect whether there is a difference.

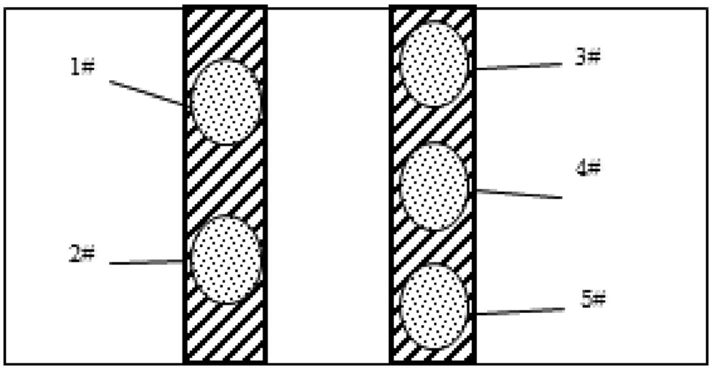

FIG. 1. A group of test pieces and the identification diagram.

B. Selection of experimental parameters

The piezoelectric effect is known, and since the generated power of the piezoelectric transducer was in direct proportion to the pressure F and the loading frequency ω of piezoelectric patches, the selected piezoelectric materials were identical to the transducer in this paper. Therefore, only the impacts of pressure F and loading frequency ω were considered in this laboratory test. Pressure F was related to the pressure of the wheel on the ground. Meanwhile, considering that piezoelectric transducers might be laid in different pavement structure layers, under the load effect of the standard wheel, the bearing pressure of piezoelectric transducers could also be different in different structural layers. To simplify the testing scheme, only the effect of the standard axle load is considered in this paper.

While preparing the beam test piece in laboratory tests, different quantities of piezoelectric transducers were bonded to simulate the bearing wheel-pressure force of each layer of piezoelectric transducer under standard axle load. In this task, two kinds of beam test pieces were selected. The first kind was that two piezoelectric transducers were bonded at an equal distance. The other kind was that three piezoelectric transducers were bonded at an equal distance, as shown in Fig. 2.

As we all know, the loading frequency ω is related to the traffic flow in unit time. However, the vehicles running on the road had no regularity in the actual running process. For different periods of time, the quantity of running vehicles was changeable, and the difference was large. In addition, since the vehicle models were different, there would also be some difference in the distance between axles. Thus, the active frequency of the axle of various vehicles on piezoelectric transducers could also be different.

C. Data acquisition

The stress applied by the vehicle is about 25 MPa, so that the piezoelectric ceramic material meets the pressure conditions on the road. The loading frequency is set to 10 Hz and the loading load to 700 MPa.

Since the materials used for transducers were the same, dielectric constants ε_r were the same. Moreover, the piezoelectric ceramic area A and thickness h were the same. The level of voltage V_0 in an open circuit could be used to judge the level of transducer efficiency. To accurately measure the voltage and the stored data, a UT2042C-digital storage oscilloscope was used to perform voltage measurements in this task and store waveforms and voltage data. Since the voltage was very high at the moment for exciting piezoelectric materials, 10× attenuation multiplying power was used in the measuring process.

The laboratory test situation is shown in Fig. 3. In the experimental process, a tracking test wheel was maintained at the axle wire of the whole tracking board. Moreover, the beam test

FIG. 2. Beam test piece installed with piezoelectric patches.

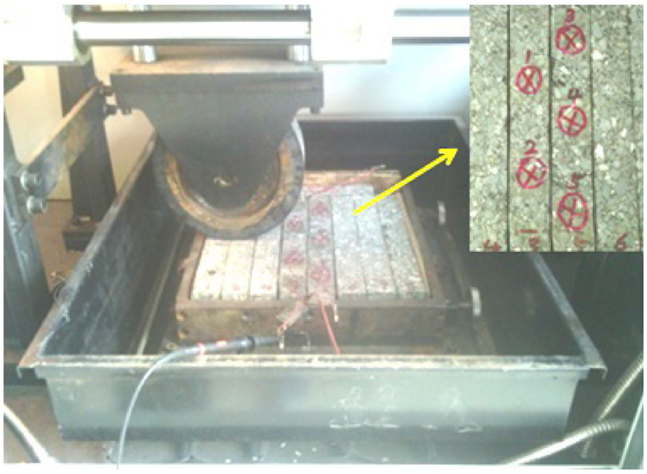

FIG. 3. Test for the generating capacity of piezoelectric transducer.

piece was rolled once along the horizontal direction of the beam test piece. The probe of the oscilloscope was used to clamp the ends of the light emitting diode to collect voltage signals.

For the convenience of analyzing the produced voltage signal and reducing the selected area to improve the extension so that the window extension could be used to magnify a certain part of the waveform and observe the transduction effect of piezoelectric transducers under the direct action of force, the contrast test of the direct testing wheel rolling on piezoelectric transducers was conducted. The test piece number of this group of tests was 6# piezoelectric transducer. First, the piezoelectric transducer was bonded to the cement slab to ensure that the cement slab surface would be flat and smooth to facilitate deformation for the piezoelectric transducer due to rolling. Afterwards, the test pieces were placed on the wheel tracking tester to load directly to observe the difference in the electrical signal produced under this circumstance and the electrical signal produced on beam test piece.

IV. RESULTS AND DISCUSSION

A. Wheel-pressure experiment

Figures 4 and 5 show the relationship curves of piezoelectric components under different loading frequencies with voltage and current signals. It can be seen that the current generated

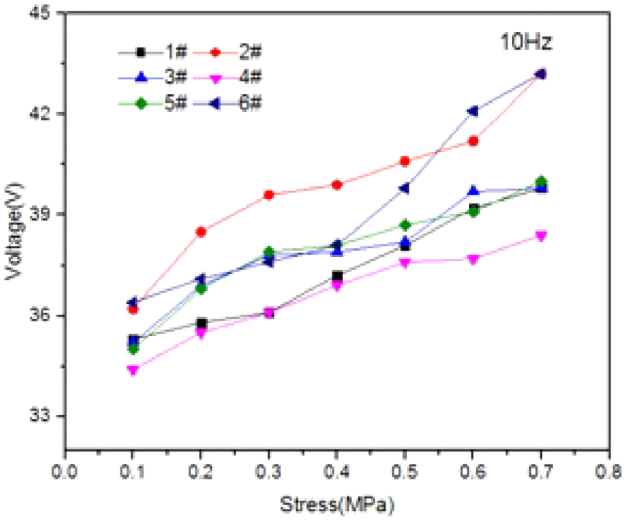

FIG. 4. Loading-voltage curves at 10 Hz.

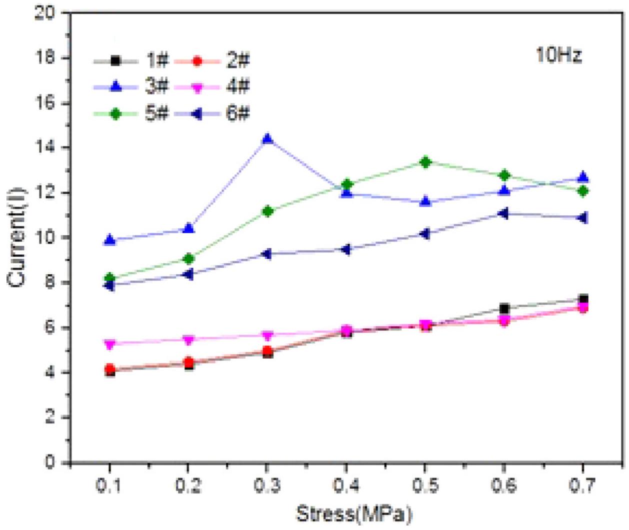

FIG. 5. Loading-current curves at 10 Hz.

by the piezoelectricity generating device increases with the increase in the loading frequency and increases with the increase in the loading load. The voltage signal increases with the increase in the load and decreases with the increase in the loading frequency. Piezoelectric materials are able to generate electricity, because it has a positive piezoelectric effect; when there is a positive piezoelectric effect, the piezoelectric crystal produced charge is proportional to the stress imposed on it; therefore, when the load increases, piezoelectric materials generating voltage current signal will also increase. Based on the current and voltage calculation formulas (1) and (2), it can be seen that the current and the load frequency are positively proportional to the load frequency; so the current signal increases significantly with the loading frequency. Voltage has nothing to do with the loading frequency in the formula given by the theory, and so when the loading frequency increases, voltage change is not very big, but in the process of simulation load fluctuations, the voltage signal changes under different frequency fluctuations.

In this research, the voltage oscillograms of two groups (10 pieces) of piezoelectric transducers excited under a standard vehicle wheel load were measured through laboratory tests. The sampling method was based on peak-peak value measurements. It can be found by comparing the difference in the voltage values produced due to different load effects that the magnitude of force can have some impact on the voltage excited by piezoelectric transducers, but the difference is very small. It was analyzed that the acting frequency was constant on the beam test piece because the testing wheel was running at a fixed speed. Therefore, the piezoelectric voltage signals excited by piezoelectric transducers were only related to the coupling effect of the deformation quantity of the piezoelectric patch itself. However, since the piezoelectric patch was very thin, it did not have the ability to resist deformation due to external force. Moreover, the height of the supporting point below the prepared piezoelectric transducer was limited. Thus, it can be considered that the piezoelectric vibrator produced full deformation under any of the above-mentioned load effect and the deformation quantity reached the limit. In other words, the contact between the crooked metal base surface and the bearing surface below the piezoelectric vibrator made the deformation quantity reach the maximum value. Therefore, the voltage signal produced by a piezoelectric transducer did not have significant fluctuation under a large change in external force.

B. Instant finger compression test

To compare the impact of the wheel rolling effect and the simple finger strike or the compression effect on the vibration effect of the piezoelectric transducer, an oscilloscope was also used to test the voltage signal excited by a piezoelectric transducer under finger compression and strike in this laboratory test. The voltage values are summarized in Table II.

The experimental results showed that the piezoelectric transducer could produce 61.6 V peak-peak voltage under finger compression. Under finger strike, 59.2 V peak-peak voltage could be produced. The test results were close to the voltage values under testing wheels, of which 61.6 V peak-peak voltage could be produced by finger compression, indicating that the piezoelectric transducer could also produce deformation quantity identical to testing wheel rolling under finger compression. This also indicated that the hypothesis of ultimate deformation quantity produced by a piezoelectric transducer analyzed above was correct. However, 59.2 V peak-peak voltage could be produced under finger strike, indicating that it weakened the effect of vibrational deformation somewhat compared with the support mode of a simply supported structure and a cantilever structure. This is because that the piezoelectric transducer is bonded with a beam test piece, but not all about the impending cantilever support structure. Under the external impact effect, it is more difficult for the piezoelectric transducer to have vibration together with beam base. Thus, it is not good for the extension of vibration. However, a piezoelectric patch can only present better piezoelectric effect under free vibration, where the efficiency is the highest under resonance oscillation. In addition, this vibration effect will not be significant due to the low acting frequency of the testing wheel, which causes the piezoelectric transducer to excite voltage signals only because of the deformation that resulted from stress in the transduction process.

C. Generating capacity

The performance indexes of piezoelectric vibrators are mainly voltage (V), current (I), output power (P), and power (U_E). Based on the static analysis of the ceramic piezoelectric sheet, the electrical energy generated by the excitation of the piezoelectric vibrator (U_E) was calculated. In the following analysis, the diameter and the thickness of the piezoelectric plates and the size of the external excitation are considered, and the influence of the adhesive is not considered.

As the key element of the piezoelectricity generating device, it is necessary to analyze whether their generation capacity meets the requirements of use. The structural parameters of the piezoelectric vibrators are different; the size of the voltage is different; this PZT-5H piezoelectric vibrator with a diameter of 30 mm and a thickness of 0.2 mm was used for analysis theoretically.

For the d_{33} piezoelectric element, only the axial displacement under the action of the external excitation ability, its piezoelectric charge from the top and bottom surfaces of the piezoelectric element is equivalent to a capacitor, capacitance in polar charge after that fire is equal to the stored energy. The current in the direction of piezoelectric plate thickness is given by

$$I = \frac{dQ}{dt} = d_{33} F \omega. \tag{1}$$

The voltage in the direction of piezoelectric plate thickness is given by

$$V = \frac{Q}{C} = \frac{d_{33} F h}{\varepsilon A}. \tag{2}$$

Therefore, the power P of the d_{33} piezoelectric element is expressed as

TABLE II. Voltage signals excited under finger compression and strike.

	Voltage value (V)		
Excitation type	V_a	V_b	ΔV
Finger compression	−28.0	33.6	61.6
Finger strike	−4.00	55.2	59.2

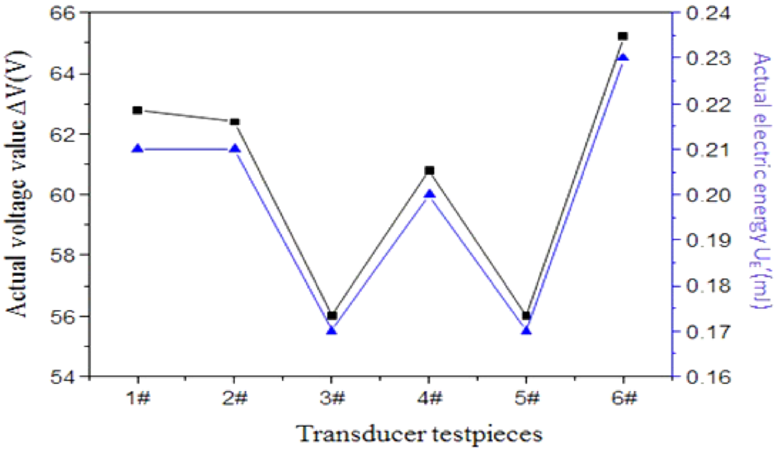

FIG. 6. Relationship of V and U_E' of different piezoelectric transducers.

$$|P| = |V| \times |I| = \frac{d_{33}^2 F^2 h\omega}{\varepsilon A}. \tag{3}$$

In this formula, F is the bearing pressure of the piezoelectric element, h and A are the thickness and the size of the piezoelectric element, respectively. ω is the loading frequency. ε_0 and ε_r are the vacuum dielectric constant and the dielectric constant, respectively. d_{33} is the piezoelectric coefficients. For the piezoelectric transducer embedded within the pavement, assuming that the electrical energy converted by the transducer is all output and stored, the conversion electrical energy U_E of the transducer can be calculated according to the following equation after a standard axle load:

$$U_E = \frac{1}{2} q V_0 = \frac{1}{2} DAE\mathrm{h} = \frac{1}{2} E^2 \varepsilon A\mathrm{h} = \frac{1}{2} V_0^2 \frac{\varepsilon_r \varepsilon_0 A}{\mathrm{h}}. \tag{4}$$

q is the quantity of the electric charge on the surface and V_0 is the potential difference at the ends of the transducer in an open circuit. A and h are the area and the thickness of piezoelectric ceramics, respectively. ε_0 and ε_r are the vacuum dielectric constant and the dielectric constant, respectively. The theoretical voltage value V and the theoretical electric energy U_E of various piezoelectric transducers were obtained under the conditions of open circuit voltage. The relationship of the actual voltage and the actual electric energy of various piezoelectric transducers is shown in Fig. 6. According to it, the calculated actual electric energy U_E' is produced under the once rolling action of the single piezoelectric transducer in the laboratory tracking testing wheel and the actual electric energy value is the one that can be collected in the actual using process of a single piezoelectric transducer with the combination of actual application of road.

Suppose that the service environment is only bi-directional and is a four-lane road, and the annual average daily traffic volume is 25 000–55 000 by converting vehicles into passenger cars, which is on the basis of 40 000, the energy per day to be produced by various piezoelectric transducers are shown in Table III.

Since the size of the piezoelectric transducer is small, multiple piezoelectric patches can be laid on the wide range of wheel load effect on the road surface to improve the piezoelectricity generating capacity.

TABLE III. Energy calculation table of each transducer per day.

Transducer	1	2	3	4	5	6
Power(kJ)	16.8	16.6	13.4	15.8	13.4	18.1

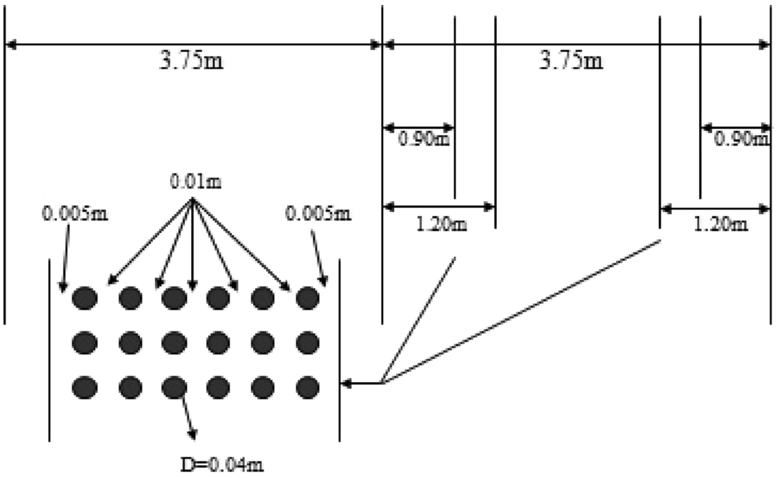

FIG. 7. Vertical view of crosswise pavement.

Take the typical expressway for example, where the lane width calculated is 3.75 m. It is not necessary to lay piezoelectric units on the left overtaking lane because of the efficiency frequency being comparatively low. The service efficiency is higher on the main lane and heavier vehicles are mainly on the main lawn. Thus, the piezoelectric elements should be laid from $3 \times 750/25 = 90$ cm to $4 \times 750/25 = 120$ cm from the edge of the main land where the frequency of the wheel mark is the highest. The width of the piezoelectric transducer is 4 cm and there is a 1 cm gap between two piezoelectric units. One horizontal row of piezoelectric units consists of $2 \times (120–90)/(4+1) = 12$ piezoelectric transducers. The vertical view of the crosswise pavement of the expressway is shown in Fig. 7.

Applying 1 km expressway to have ribbon-like laying along a two-wheeled mark on the main lane, with regard to the group constituted by different numbers of piezoelectric transducers, the daily energy to be produced is shown in Table IV.

It can be seen from the energy value produced by the calculated transducer group that it is the best to lay piezoelectric transducers near the pavement surface. If the piezoelectric transducers are laid between the upper surface course and the middle surface course, around 1.5 kW/h energy can be produced per day, which is equivalent to the above-mentioned sum of conditions.

V. CONCLUSIONS

In this paper, with the combination of self-made series-wound double crystal piezoelectric vibrator elements, the laboratory generating capacity of the developed road piezoelectric transducer was tested and evaluated by choosing a proper experimental scheme and testing technique.

(1) It can be seen from the voltage peak-peak value data obtained by testing that the voltage value of the piezoelectric transducer increases with the increase of external acting force. However, the deformation of the piezoelectric transducer is limited since the rigidity of the metal base is limited, which in turn causes a small difference to the voltage peak values.
(2) The contrast tests of finger compression and strike that simply supported the piezoelectric transducer can produce a voltage signal only because of deformation by force. This will have

TABLE IV. Energy calculation table of each transducer group per day.

Transducer	1	2	3	4	5	6
Power(kJ)	5036	4972	4004	4720	4004	5428

some attenuation of the vibration effect of the cantilever support structure. Thus, it will appear that there is a large difference between the actual voltage value and the theoretical value.

(3) Take expressway, for example, after choosing a proper laying scheme; the calculated piezoelectric transducers can produce around 1.5 kW/h, which meets the demand of the signal indicators to some extent.

(4) The road piezoelectric transduction device is involved in multiple disciplinary fields such as piezoelectricity, machinery dynamics, electricity, road structure, etc. The aspects of improving the piezoelectric property of the piezoelectric material itself, structure optimization and circuit design of the generating set should be taken into comprehensive consideration to further improve the generating efficiency of the piezoelectricity generating set.

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