Known and unknown phenomena of nonlinear behaviors in the power harvesting mat and the transverse wave speaker

Yoshiyasu Takefuji†

† Faculty of Environment and information studies, Keio University
5322 Endo, Fujisawa, 252-0816 Japan
Email: takefuji@sfc.keio.ac.jp

Abstract– Known and unknown behaviors of three nonlinear systems are described in this paper. The power harvesting project is mentioned where the power generation mat using piezoelectric elements was experimented and demonstrated in Tokyo station of Japan Railways east (JR-east) company in 2006 and 2008 respectively. The commuters and passengers generate electric power by passing the power generation mats through SUICA (RFID) gates which can provide enough electric power for operating the RFID gate system. The system is composed of the power generation circuit and the super capacitor circuit to store the generated electric power. Thermoelectric power generation project is also proposed in this paper where peltier elements are used for generating the continuous power harvesting. Unknown phenomena of the transverse acoustic waves from a new speaker are depicted in this paper. The new speaker under development is useful in railways stations and trains where we can hear the transverse acoustic sound clearly in noisy places. The transverse wave speaker does not generate reverberant sound and the sound attenuation in distance is much smaller than 6dB.

1. History of power harvesting mat in JR-east

In 2003, one of my undergraduate students (Mr. Kohei Hayamizu) for senior project developed a power generation circuit using human voices where a piezoelectric element was used [1]. In 2003, then, I have proposed a new power harvesting project to Mr. Mutsutake Ohtsuka at the JR-east party who was the president of JR-east railway company [2]. Instead of using human voices, my idea is that a variety of vibrational energy in railways can be converted to electronic power. Because JR-east railway company in Tokyo is infamous for trains jampacked with commuters, vibrational energy by commuters walking or foot steps can be utilized for electric power generation. In July 2006, we have experimented the first power generation mat in the headquarter building of JR-east railway company in Shinjuku [3]. Based on the result of the first experiment in Shinjuku, from October to December 2006 for two months, we have tested the second power generation mat in Tokyo station at the north gate of Marunouchi where the mat was laid down at the automatic IC card SUICA ticket gate [2]. The durability of the power generation

mat and the performance and deterioration of the piezoelectric elements were evaluated through the experiment. The third experiment was performed again in Tokyo station in January 2008 where the total of 90 m^2 power generation mat were laid down in the stairs, in front of the convenience store, and the SUICA ticket gate [4]. In the second power generation mat, the conventional piezoelectric elements (speaker elements) were used while the third power generation mat uses piezoelectric elements which are specially tailored and dedicated for generating electric power. The new piezoelectric device should be able to generate electric power 10 times better than that of the second generation mat. Since it is a single-layered piezoelectric element, it is expected to generate more electric power by multiple-layered piezoelectric element. The size, thickness, and shape of the piezoelectric elements are keys for better performance. The durability is also considered in our project.

2. Principle of power generation mat

Piezoelectric effect was discovered by Jacques and Pierre Curie in 1880 when a mechanical force was given to certain crystalline minerals, the crystals became electrically polarized. The converse effect was mathematically deduced by Gabriel Lippmann in 1881. "Piezo" is a Greek word which means pressure. Best known piezoelectric application is a barbeque or cigarette lighter that uses a piezoelectric element to create a spark to ignite a gas. Best known converse application is a piezoelectric speaker used in mobile phones or laptop computers to create acoustic sound. Piezoelectric ceramic element is widely used in our society and called PZT. The piezoelectric element is the mixed solid solution of lead zirconate ($PbZrO_3$) of ferroelectric and lead titanate ($PbTiO_3$) of anti-ferroelectric.

The piezoelectric element is a bidirectional energy transformation transducer: mechanical energy to electrical energy and electrical energy to mechanical energy. Fig. 1 (a) (b) (c) depict current piezoelectric power generation models respectively: (a) neutralized ions in unpoled ferroelectric ceramic, (b) unbalanced ions in poled ferroelectric ceramic when compressed, and (c) unbalanced ions in poled ferroelectric ceramic when expanded. Electrical dipoles in Fig. 1 (a) tend to be

aligned in regions called Weiss domains. The Weiss domains are randomly oriented. When the piezoelectric ceramic material is pressed by our steps, positive electric charges are generated on top while negative electric charges are on bottom. When releasing our steps from the piezoelectric ceramic material, negative electric charges are generated on top while positive electric charges are on bottom. We don't know how to construct the best Weiss domains for power generation.
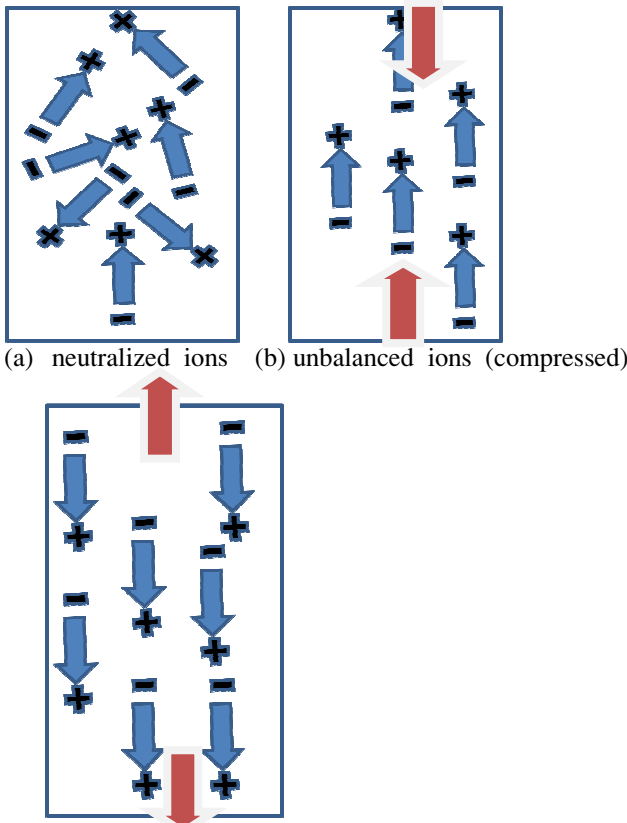

(a) neutralized ions   (b) unbalanced ions (compressed)

(c) unbalanced ions(expanded)
Fig. 1 Unpoled and poled ferroelectric ceramic

3. Power generation mat circuits

Our power generation mat uses piezoelectric elements in parallel. There are two types of circuits to store the generated electric power: one using the full-bridge circuit as shown in Fig. 2 and another using the pump circuit as shown in Fig. 3.
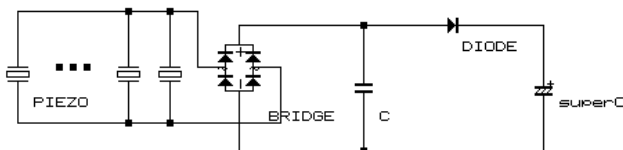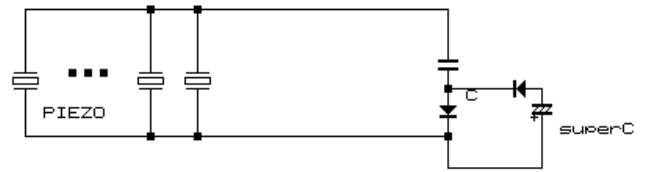

Fig.2 Bridge circuit with a super capacitor

Fig. 3 Pump circuit with a super capacitor

4. Computation of generated electric power

Generated electric energy is given by the following equation:

Energy $=\dfrac{1}{2}CV^2$ (joule) where V is the voltage of the C capacitor (Farad).

In other words, one joule is equivalent to one Watt·second. For example, when 1 F capacitor is charged and the voltage becomes 4V, the energy is 8 Watt·second.

Fig. 4 and Fig.5 show JR-east power generation mat in 2006 respectively. Based on our experiment, a 47uF capacitor is charged to 7.8 Volt by ten times stepping a single piezoelectric element. This means that one step to a piezoelectric element generates 0.14 mWatt·second. Conventional piezoelectric speakers were used in the power generation mat.
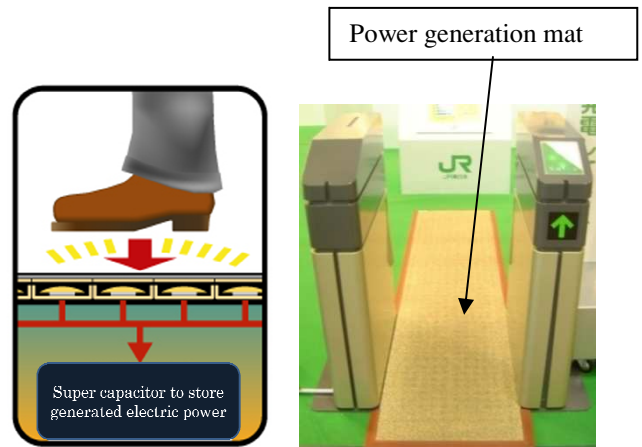

Fig. 4 Power generation mat in 2006

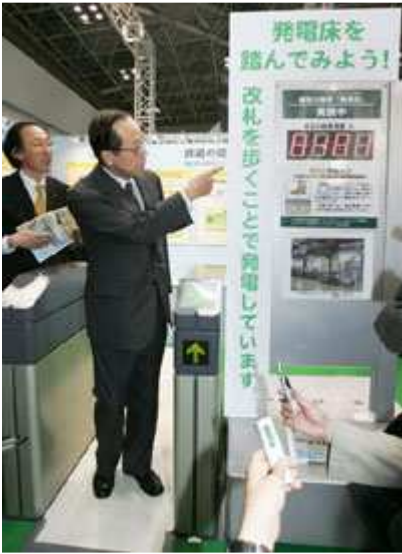Fig. 5 Power generation mat at Marunouchi North gate of Tokyo station in 2006

Fig. 6 Prime minister visited the power generation project at Ecology show in 2007
(http://www.kantei.go.jp/jp/hukudaphoto/2007/12/15eco1.html)

Power generation mat project has been conducted at Yaesu North gate of Tokyo station from January 19 in 2008 for two months. The goal of the current project is that one passenger can generate 1 mWatt second per gate. The goal is about 7 times better performance than that of 2006 project. The total of 90 m^2 power generation mat were laid down in Tokyo station. The total generated electric power, 500 kWatt second is expected a day. The piezoelectric elements were tailored by Kyocera for electric power generation. Fig. 7, Fig. 8, and Fig. 9 show power generation mat laid down at stairs, that at SUICA ticket gate, and that in front of convenience store respectively. Based on the observed result, the goal was achieved where more than 500 kWatt second energy was generated a day except Saturday and Sunday. In the peak day, 766kWatt second energy was generated. The result indicates that it is now possible to provide enough electric power to operate the SUICA ticket gate system. In the near future, without external power supply, SUICA ticket gates may be operated using power harvesting devices with a large number of commuters.
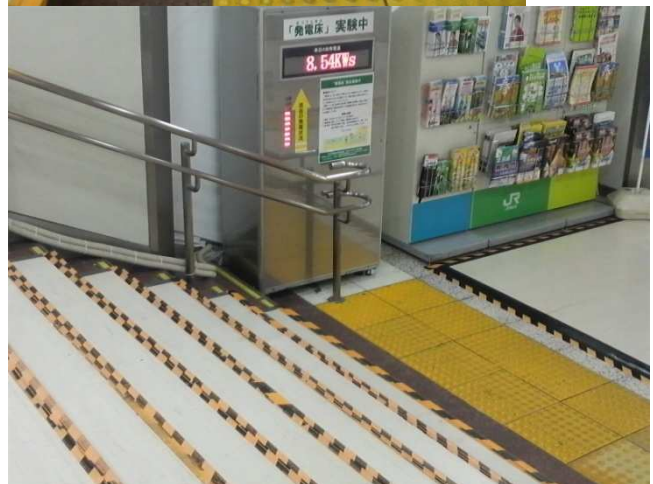

Fig. 7 Power generation mat laid down stairs at Tokyo station in 2008

Fig. 8 Power generation mat at SUICA ticket gates in 2008

$$I(r) = \frac{W}{4\pi r^2} \qquad \textbf{Eq. 1}$$

Where I= acoustic intensity (watts/m^2)

r=distance from the source in meters

W=sound power (watts)

Therefore, sound levels decay by 6 dB per doubling of distance from a point source as long as the sound is a longitudinal wave.

Fig. 11 indicates conflicts against Eq.1. As shown in Fig. 11, many observed points at the longer distance have higher sound intensity than those at the shorter distance.
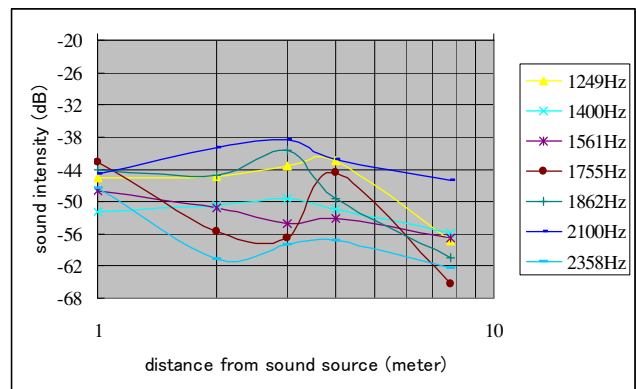

Fig. 9 Power generation mat laid down in front of convenience store at Tokyo station in 2008

5. Transverse wave speaker

I have been intrigued by the speaker invented by Mr. Takeshi Teragaki since July 7, 2004. It was my first experience that Mr. Teragaki showed the principle of his speaker using a tiny music box and a piece of paper or an elastic pencil board. The original sound intensity from the music box was 30dB amplified by the strained paper or the elastic pencil board. As of today, nobody knows the mechanism of 30dB amplification.

Fig. 10 Strained elastic pencil board with the music box

The experiment was performed in a hemi-anechoic room at a temperature of 20 degrees Celsius and at a humidity of 50 % on June 17, 2006. In our experiment, an experimenter holds an 18-note standard musical movement which is perpendicularly attached to the strained elastic pencil board (18cm x 25cm x 0.5mm) as shown in Fig. 10. The sound intensity from four directions: front, back, side, and up of the pencil board was observed respectively. Fig. 11 shows the result of observed sound intensity from side. Other observed sound intensities show the similar result. Crests and troughs in sound waves were found in Fig.11.

The longitudinal sound intensity for a point source in a loss-less medium with no reflections is depicted by the following equation:

Fig. 11 Sound intensity decay versus distance:1m, 2m, 3m, 4m, and 7.8m respectively

Assume that the observed sound wave is a transverse wave. Then, the frequency of the transverse sound wave should determine crests and troughs in sound waves like solitary waves. The speed of sound in air V(T) is given approximately by

$$V(T) = 331.4+0.6T \qquad \text{Eq.2}$$

where T is the Celsius temperature. If observed sound waves were transverse waves, then sound intensity I(r) (dB) of transverse waves compared to Eq. 1 can be computed by Eq.3:

$$I(r) = k_1 f(r) SIN\left(\frac{100r}{\left(\frac{\lambda}{2\pi}\right)} - k_2\right) - k_3 \cong k_1 SIN\left(\frac{200r\pi f}{V(T)} - k_2\right) - k_3$$

$$\text{Eq. 3}$$

where r is distance from the sound source, f(r) is the decay function of the solitary waves, and k_1, k_2, and k_3 are constant parameters. Fig. 12 shows an example of comparison between the observed sound intensity at 2100Hz as shown in Fig. 11 and computed transverse wave based on Eq. 3 where parameters: k_1=5.5, k_2=0.55, k_3=45 are given. For short distance of solitary wave propagation, f(r)=1 is satisfied.
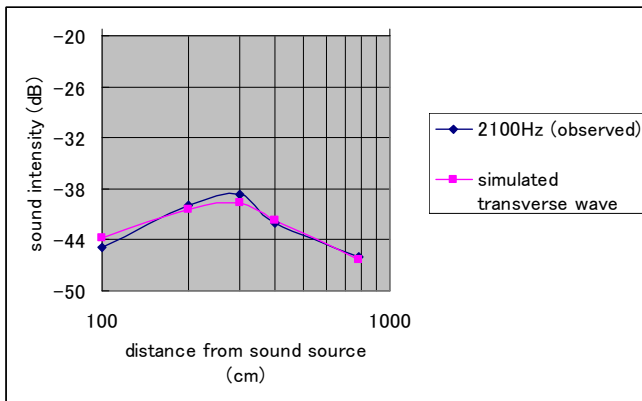

Fig. 12   Observed sound intensity of 2100Hz versus computed sound intensity

The transverse wave speaker is composed of two components: vibrator medium(piezoelectric element) and diaphragm. On February 7, 2008, the second experiment was performed in an anechoic room at a temperature of 26 degrees Celsius.
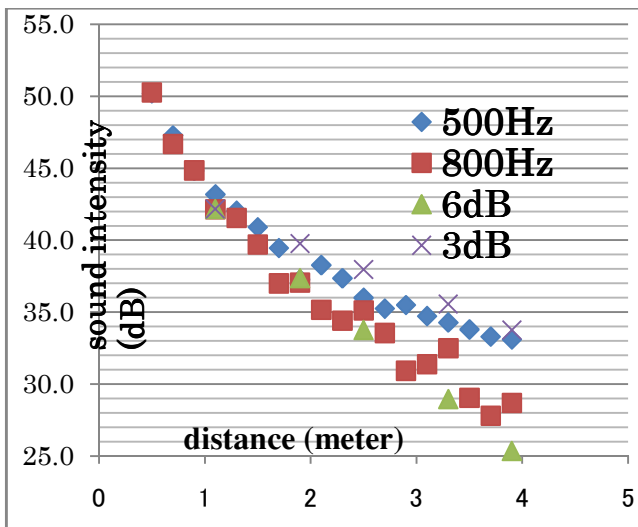

Fig. 13 Observed sound intensity of 500Hz and 800Hz in a distance

Fig. 13 shows the observed sound intensity of 500Hz and 800Hz respectively. Fig. 13 also includes computed 6dB

and 3dB sound intensity model respectively for comparison where 6dB sound intensity decay model is based on the conventional speaker described in Eq.1. The wavelength between a crest and a trough as shown in Fig. 13 becomes longer in the longer distance from the sound source.

6. Unknown behaviors of the transverse wave speaker

We don't know the following behaviors of the transverse wave speaker:

1. Why does the strained pencil board amplify the sound intensity from the music box and the piezoelectric element by 30dB?
2. Why does not the transverse wave speaker generate reverberant sound?
3. Why is the sound attenuation in distance much smaller than 6dB?
4. Why does not the transverse acoustic wave interfere with acoustic waves?

7. Thermoelectric power generator

One of the most promising renewable power generators is the thermoelectric power generator [8] which has been demonstrated by ytakefuji in youtube:
http://jp.youtube.com/watch?v=Rt1BcxJRfmE

This short video has been played back more than 10,579 times as of June 14, 2008.

The system is composed of two serially cascaded peltier elements with heat pipes. The difference between temperature of air and human hands can generate enough electric power to rotate the DC motor.

We will experiment the proposed system in hot springs in order to observe the performance of the system.
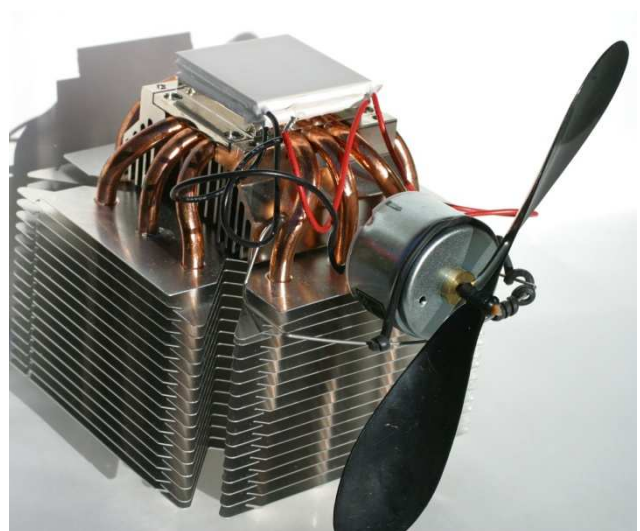

Fig. 14 The thermoelectric power generator

References

[1] "Acoustic sound power generation" published in Nikkei newspaper on Feb. 23, 2004

[2] "Power generation mat" published in Nikkei business on Nov. 13, 2006

[3] "Power generation mat" published in Tokyo newspaper on July 31, 2006

[4] "Power generation mat" published in Asahi newspaper on Jan. 21, 2008

[5] Weiss, P. Single-wave sounds streak through air. Science News 156, 327, 1999.

[6] Hellemans, A. Conjuring a solitary sound wave. Science 286, 2062, 1999.

[7] Physical Review Focus: The sound of solitary wave. Am. Phys. Soc.
    http://focus.aps.org/story/v4/st24, Nov.15, 1999.

[8] Y. Takefuji, "Thermoelectric power generator," Eleki-Jack Magazine, pp156-160, No.5, March 2008