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7–9 May 2012, Dubrovnik, Croatia

Road and Rail Infrastructure II

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THE FEASIBILITY OF PIEZOELECTRIC ENERGY HARVESTING FOR CIVIL APPLICATIONS

Simon C. Bos
Tauw bv, The Netherlands

Background of piezoelectricity

Piezo means pressure in Greek. Piezoelectricity is the generation of an electric field when pressure is applied to a certain material. The piezoelectric effect was first discovered by the Curie brothers in 1880. But this technology wasn't implemented to a product until 1921. Like many inventions there is time between the discovery and practical use. This is mainly because of the advantages of already optimized competing technology. In addition, new technology has to show great benefits before it will be accepted. In 1924 piezo was used for the first time in radio transmitters and at the end of 1930 all transmitters were equipped with piezoelectric crystals. The major introduction of piezoelectric material was by the discovery that the mixed oxide compound barium titanate ($BaTiO_3$) can be made piezoelectric. With an electric poling process the material gains its piezoelectric properties which are much stronger than the natural quartz crystal. In 1947 the first $BaTiO_3$ piezoelectric based phonograph pickups appeared on the commercial market. The strong piezoelectric effect of lead zirconate titanate (PZT) was discovered in 1954 and is until today a leading material for piezoelectric applications. The piezoelectric effect in polymers was first discovered in 1969 on poly vinylidene fluoride (PVDF) [1].

1 Working principle of piezoelectricity

The direct piezoelectric effect is a changing of the shape that gives an electric potential. The converse piezoelectric effect is an electric field that changes the physical shape of the material (see figure 1).

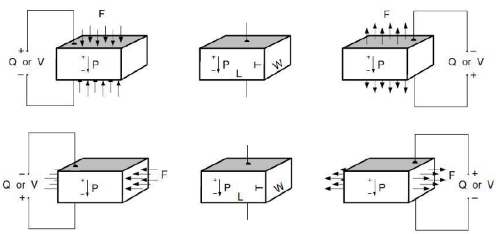


Figure 1 Basic working principle of piezoelectricity

In our opinion the direct piezoelectric effect is most interesting. There are several ways to use the direct piezoelectric effect as you can see in figure 1. In this figure the poling direction is displayed together with the direction of the force. The upper three pictures represent a force applied in the poling direction alongside with the equations for the calculation of the corresponding charge or voltage. The applied force creates direct extension or compression and is best converted with a piezoelectric ceramic (left picture in figure 2). This piezoelectric stack contains multiple layers of piezoelectric material, stacked on to each other to generate a higher energy output.

Figure 2 Examples of piezoelectric material

The lower three pictures of figure 1 show a force applied in the transverse direction. In general this is achieved by attaching the piezoelectric material to another material. When this material is bent, the piezoelectric material will indirectly be compressed or elongated. The flexible polymer material is a suitable material because it can resist high strain (see the middle and the right in figure 2).

There is a relation between electric charge and pressure. This phenomenon is caused by the piezoelectric dipole moment found in some materials [2]. An electric dipole is present in a material when the centers of the positive and negative charges are not matching. When the atomic structure of the material is non–centrosymmetric a dipole can be formed. Without a centre of symmetry the dipoles will not exclude each other and can develop a polarization. Before subjecting a material to external stress, the centers of gravity of each positive and negative charge fit together. The contribution of both positive and negative charge exclude, which results in an electrically neutral material. When subjecting the material to stress, a separation of the gravity centers of the positive and negative molecules is created. This separation creates little dipoles and generates a polarization direction [3]. Some materials that naturally have piezoelectric properties are quartz, rochelle salt and cane sugar. There are also man–made materials with piezoelectric properties like PZT (lead zirconate titanate), barium titanate and the polymer PVDF (polyvinylidene fluoride). A strong electric field is applied to the ferroelectric ceramics when heated for the poling process. After this process groups of dipoles are formed with all more or less the same poling direction. In this way a strong piezoelectric effect is produced (figure 3) [4].

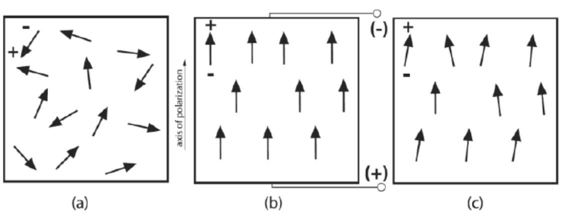


Figure 3 Polling of piezoelectric material [4]

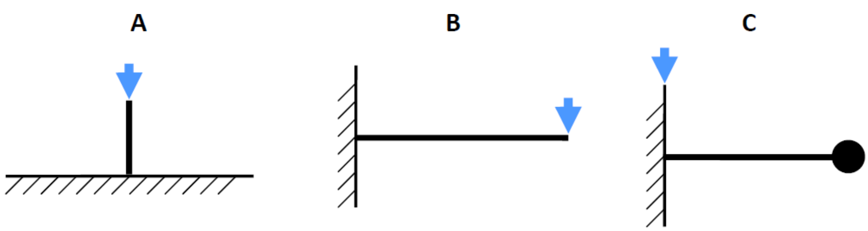
2 Applications of piezoelectricity

Piezoelectric material can be used as a sensor, actuator or as a transducer, which acts both as sensor and actuator. Piezoelectricity is used in many products both using the direct and converse piezoelectric effect. Products using the direct effect act as a sensor, for instance as a strain, pressure or acceleration sensor. Good everyday examples are the electronic drum pad, guitar pick–up or electric lighters. When using the converse piezoelectric effect, the material is functioning as an actuator. Everyday examples of actuators are found in buzzers used in smoke detectors and ejecting ink with inkjet printers. Piezoelectric actuators are also useful in accurate positioning systems. Because of the small changes in dimension when using a strong electric field, these actuators are for example suitable for the focusing of lenses of cameras. Figure 4 gives an overview of applications of piezoelectricity in different areas.

Communications and control	Industrial	Health and consumer	Newer applications
Cellular radio Television Automotive radar	Transducers Sensors Actuators Pumps Motors	Transducers Sensors Actuators Pumps Motors	Smart Structures High Displacement Transducers Mixed-effect Devices
○ Signal processing ○ Oscillators ○ Frequency control and timing ○ Correlators ○ Convolvers ○ Filters ○ Delay lines	○ Ultrasonic cleaning ○ Vibration damping ○ Sonar ○ Liquid level sensors ○ Non-destructive evaluation (NDE) ○ Material properties determination ○ High temperature sensors ○ Chemical/biological sensors	○ Non-invasive medial diagnostics ○ Hypothermia ○ Lithotripsy ○ Wristwatches ○ Subcutaneous medications ○ Camera focusing/ steadying/ ranging ○ Computer timing / printing/ modems ○ Ignition of gases (“spark pump”)	○ Microelectromechanical (MEMS) devices ○ Microoptomechanical (MOMS) devices ○ Biomimetic devices ○ Rainbow devices ○ Acousto-photonic-electronic devices ○ Composite and functionally graded devices

Figure 4 Applications of piezoelectric materials in different areas

Three basic principles can be recognized in which the energy harvesting concepts can be categorized as shown in figure 5. Those basis concepts help to generate concepts and help to understand the working principle of the energy conversion. Several concepts can be created from each category of vibration sources. Minor variations in the three models can be applied to adjust the principle to create the best suitable solution for the specific vibration. The goal is to look for opportunities for piezoelectric energy harvesting in the civil world. The input for harvesting energy is a vibration which can be found everywhere as seen in figure 6.



a). Direct extension or compression of an element when subjected to a periodic acting external force like a vibration.

b). Bending of a cantilever beam subjected to a periodic acting external force at the tip of the beam.

c). Bending of a cantilever beam subjected to an external force excited as an impulse at the base.

Figure 5 Basic principles of energy harvesting concepts

Figure 6 Examples of vibrations in a city

3 Pilot project on the N34, the Netherlands

3.1 The goal of 'Mooi Nederland'

One of the policy goals of the Dutch government stimulated with subsidy, is 'Mooi Nederland' (Beautiful Holland). The achievement for this initiative is in the scope of sustainability and alternative energy. For this master project, this is an interesting initiative to exhibit the use of piezoelectricity. The goal of 'Mooi Nederland' is that people from The Netherlands should appreciate the landscape more. The Dutch Ministry has started a subsidy arrangement for innovative projects to invest in spatial quality. In 2010 one of the three themes is Identity of energy landscapes. The Ministry is especially searching for actual projects on a local and regional scale where renewable energy is combined in a nice way with other functions.

3.2 Project implementation

The initiative of 'Mooi Nederland' was very interesting, so we decided to send in one of the concept directions in an attempt to obtain subsidy. Together with the University of Twente and the province of Overijssel a project will be set up. The main objective of the project is to harvest useful energy, by means of undesirable vibrations in the civilian world. This will be done by using piezoelectric materials. This method of renewable energy production has not yet been applied in the civilian world. Tauw and the University of Twente are investigating the possibility to reuse the energy lost in vibration on roadways. With the help of a pilot project the feasibility will be tested. The project started as a graduation project to examine the feasibility of piezoelectric energy harvesting into the civil world. Piezoelectric material can convert strain into an electric charge. With high alternating strain a significant amount of energy can be generated to power small electric circuits. In other words, the energy of a vibration is partly needed to produce electric energy. Traffic loses a part of its energy in friction of the tires and the road. This lost energy is dissipated as heat into the ground. A fraction of this lost energy can be used to generate electricity for a better use. In a pilot project piezoelectric ceramics will be positioned below the road surface. A vibration will be produced when traffic past the installation and as a result generating energy. The goal of the pilot project is to acquire information about the energy output and the performance of the product subjected to environmental factors. The key is to produce energy at locations where unwanted vibrations already exist. An example of this could be at places with seams in the road or with bridges. Since piezoelectric material is behaving as a damper, the supports of bridges can be equipped with piezoelectric material to generate electric energy. The energy can be used to power sensors, road signs or lighting. In the pilot project the energy will be monitored and used to power a sign to inform people about the project or the energy production. After a few months the gained knowledge will be used and the project viability will be assessed.

3.3 The first results

This project has been rewarded with a subsidy in the past of 2010 to run a pilot. The pilot was tested at the N34 in 2011. The province of Overijssel wants to change this road and wants to improve the safety. Sustainability is an important part of the reconstruction. And piezoelectric energy harvesting may contribute to realise this goal.
For the pilot, it's important that we are looking for the connection between energy and traffic. Therefore, we also collected data from the traffic on this road as 1) how many cars passed, 2) what types of cars passed, 3) what is the speed of the cars passing the pilot, etcetera. In future, the speed of the cars on the 'new' N34 may be 100 km per hour. Therefore it was decided to do the pilot on a section, where the maximum speed of cars on this moment is 100 km per hour.
The chosen location on the N34 (the east of the Netherlands) is nearby a measurement for traffic information. Figure 7 gives an overview of the location.

Figure 7 Location of the pilot

The construction consists of a beam, which is build in the road, as you can see in the photo of figure 7. When a car drives over the beam, it presses a threshold of 3 mm with its wheels. The height of 3 mm is related to the thickness of the stripes on the Dutch roads. They are about 3 mm high as well. The car driver doesn't feel the threshold as an extra hurdle. If a car drives over the beam, the beam will be declined and the piezoelements will be vibrated. When the beam comes back of the pressure, the piezoelements will be vibrated again and they generate energy.
The first interpretation gives good results [5]. There is a good connection between the traffic and the generated energy. Figure 8 shows the results of two beams on Friday, 4 November 2011. The most energy is harvested between 5 an 20 o'clock, with elevated peaks around 6 to 9 o'clock and around 15 to 18 o'clock. Those times are the peak hours on the roads.

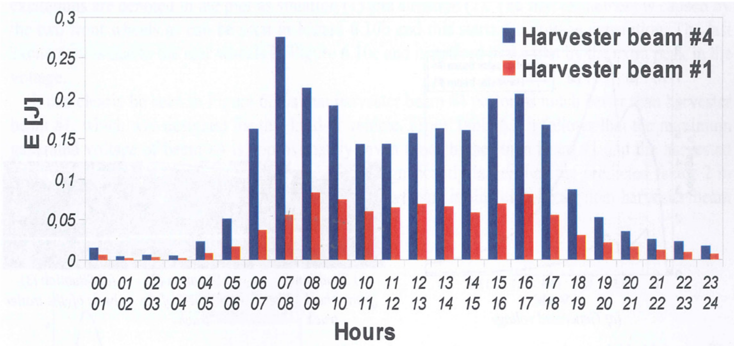


Figure 8 Power distribution for Friday, 4 November 2011

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