SELF-POWERED SMART SENSOR MATERIALS

Harvesting electricity from mechanical vibrations

Earlier this year, part of the fuselage of a Southwest Airlines 737 failed, resulting in an emergency landing. If aircraft could be made with smart materials that are equipped with distributed sensing elements, these types of incidents can be avoided and ground time for structural inspection can be reduced. Distributed sensors can also provide detailed feedback about many parts of the aircraft, from pressure distributions across control surfaces to friction information of landing gear tires on the runway. By harvesting energy from the environment to power all these sensors, the need for connecting wiring or (replacing!) batteries is eliminated and the monitoring system becomes truly autonomous.

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SELF POWERED SENSORS USING ENERGY HARVESTING TECHNIQUES

A significant amount of research effort has been spent in the last decades on developing systems that can sense (upcoming) structural damage. These monitoring systems are often based on electrical measurement of the mechanical structure, measurements which can potentially be performed in flight [1]. Other systems, such as MEMS (Micro-Electro-Mechanical Systems) based integrated airspeed sensors for real-time airflow monitoring across control surfaces are also under development. All these sensors have to be present in a large number of places and with a greater number of sensing elements comes added complexity of the system architecture. Aircraft are already suffering from wiring issues [2] and a distributed network of many hundreds of sensor elements would lead to even more wires going out to every remote part of the aircraft. So the sensor elements have to be able to gather, process and transmit their data to the central system wirelessly and they will need to be powered locally. It would be impractical as well as extremely expensive to fit each sensor with a battery, so the sensors have to be self-powered. That means constantly extracting its energy from the environment, which acts as a continuous source of power. This upcoming technology is called energy harvesting [3]. The energy harvesting technology for powering wireless sensor nodes in large area sensor networks is also applicable in many other fields, from monitoring of industrial plants and (urban) environments to embedded sensors in human clothing (body area networks) and smart automobile tires [4]. Present small scale harvesting systems are most often aimed at harvesting energy from solar, thermal or vibration sources. Depending on the sensor type and operating environment, a suitable energy harvesting source can be selected to power the sensor node, where the aim is that in all operating conditions the harvested energy is enough to power the electronics and periodically transmit a sensor signal to a central receiver. Of these techniques vibration energy harvesting is a versatile option in aerospace environments, where vibrations are omnipresent. A vibration energy harvesting system can for instance be used to power embedded sensors in a wing or around the engines. Usually vibrations are nothing but a nuisance but for a vibration energy harvester they are its source of power.

VIBRATION ENERGY HARVESTING MATERIALS

A class of materials that has a “built-in” vibration to electricity energy conversion are piezoelectric materials. In these materials electrical and mechanical domains are directly coupled and therefore mechanical deformation of the material will cause an electrical signal to be generated (and vice versa). This interesting property has lead to widespread use of piezoelectric materials, from accurate sensors (such as very low power strain gages) to preci-
sion actuators. When a piezoelectric material is placed in a vibrating environment it will constantly produce an electrical signal, which can be temporarily stored and used as a power source for the sensor electronics and periodical transmission of a wireless signal to the central electronics system of the aircraft. The recent interest from the microelectronics industry has resulted in very low power chips which now make it possible to operate a wireless sensor with only 100µW of power. The massive potential of this technology has attracted the attention of the likes of NASA, Boeing and Airbus, who all have a program on energy harvesting devices and wireless monitoring systems.

However, reliability of the materials is an issue. Because only a limited number of material classes are piezoelectric at all (e.g. Quartz glass and some ceramic materials), the range of other material properties, such as toughness or maximum operating temperature is also limited. At present there is not one commercially available piezoelectric material that is strong, tough and temperature resistant at the same time. By combining the piezoelectric materials with high-performance polymer, a piezoelectric composite can be manufactured which is both strong and tough as well as having the capability to provide power to the sensors in the structural health monitoring system. At the Novel Aerospace Materials (NOVAM) group a research program is ongoing which focuses on improving the properties of piezoelectric materials, both for sensing and energy generating purposes, while also making the material more mechanically and thermally resistant. The key to having the best of both worlds is to make the material contain a piezoelectric "active" phase which is embedded in a tough and resilient matrix. It is critical for the piezoelectric properties of the material to ensure good electrical connection between the active particles. By simply mixing piezoelectric ceramic powder into the matrix it is hard to achieve a high enough signal. One promising way of increasing the electrical output of the composites is a processing technique called "dielectro-

Figure 2. In tire energy harvesting experimental setup. The power is generated by the piezoelectric composite energy harvesters during the time when the part of the tire to which the energy harvester is attached touches the ground.

Figure 3. Prototype of a CFRP panel with a piezoelectric element attached for energy harvesting tests in a four point bending test setup. The energy harvesting materials are strained when the plate is bent and generate power accordingly.

phoresis" or electric-field-structuring. This processing technique is a versatile way of manipulating the microstructure of materials while these are being processed. By applying an alternating voltage on the composite mixture of particles in a liquid polymer matrix during the curing of the polymer the particles align themselves into chains along the direction of the applied voltage (see figure 1). The alignment increases the electrical output in this direction compared to simply randomly filling the composite with the sensitive piezoelectric particles [5]. This technique is recently attracting much attention because it is a useful technology for controlled processing of micro- to nano-sized particles.

By applying this technique sensitive but robust films can be made with a relatively high energy output as a function of strain while still being able to survive the challenging conditions that are present inside, for example, an automobile tire. Moreover, by changing the type of polymer which is used as the encapsulating matrix, the material properties can be tailored to the specific application.

**PROTOTYPES AND OUTLOOK**

Several composite prototypes have been manufactured and tested as energy harvesting elements inside an automobile tire for feasibility in a "smart tire" application. The in-plane sensitivity of the composites is maximised by applying an alternating electrode structure on a substrate foil and applying a mixture of piezoelectric particles in an uncured polymer resin on top of the electrode structure. The piezoelectric particles in between the electrodes are then aligned by using the dielectrophoresis technique and the polymer is cured to fix the particles into place. When using short piezoelectric fibres instead of particles, the electrical connectivity can be increased considerably without compromising robustness of the composite material.

Several prototypes we manufactured are tested in a rolling tire test setup (see figure 2). They are already capable of producing 3µW/cm² per tire revolution which translates to over 100µW continuous output power at a modest driving speed of 50km/h for a small 10cm² foil device. The typical power output currently is a little lower than existing commercial materials. However, after simulating tire operating conditions the output of the piezoelectric composites remains steady while the output of the existing materials degrades. In other situations vibration energy can be harvested from smaller higher frequency vibrations, such as those which occur near aircraft engines. In these situations lower strains of the vibrations are compensated by the higher frequency, leading to more charge/discharge cycles in one second. A prototype of this kind of energy harvester is shown in figure 3. A piezoelectric composite is attached to a composite panel and will generate power when the laminate is flexed. In the future, the piezoelectric composite material can be miniaturised and integrated in a CFRP (Carbon Fiber Reinforced Polymer) laminate. Compared to state-of-the-art materials these novel materials have several advantages, such as mechanical and thermal properties which can be tailored to suit the specific application and processing compatibility with structural fibre composite processing techniques. If the output of the piezoelectric composite materials can be increased even more these materials may be a serious candidate to provide many wireless sensor systems with power.

**If you are interested in smart materials and/or energy harvesting technologies, please do not hesitate to contact Daan van den Ende (D.A.vandenende@tudelft.nl) or prof. Sybrand van der Zwaag (S.vanderzwaag@tudelft.nl)**

**References**