SCREEN-PRINTED PIEZOELECTRIC GENERATOR FOR HELICOPTER HEALTH AND USAGE MONITORING SYSTEMS

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Abstract: This paper presents a piezoelectric vibration energy harvester fabricated using screen printing. The formulation of a novel tungsten based polymer ink enables the deposition of an inertial mass enabling the entire structure to be fabricated by the printing process. The devices have been designed for use on an aircraft Health and Usage Monitoring System (HUMS). Initial devices produce a peak power of 117µw at 6.9m/s^2 and 70Hz with an optimum load of 140kΩ and an output voltage of 2.9V.

Key words: vibration energy harvesting, piezoelectric thick-films, screen printing

1. INTRODUCTION

The localised generation of electrical energy from environmental vibrations is an attractive approach for powering wireless systems in applications where suitable vibrations are present. Numerous practical examples exist including industrial machinery, automobiles, rolling stock, rail infrastructure, ships and aircraft. This paper presents an initial investigation into the design and fabrication of vibration energy generators for use in aircraft health and usage monitoring systems (HUMS). This work is performed as part of an EC framework 7 research project TRIADE which is concerned with the development of structural HUMS for aeronautical applications. HUMS are widely used in helicopters and some fixed wing aircraft for monitoring components and systems in order to provide effective maintenance and reduce accidents [1].

A key part of the TRIADE project is the development of long lasting embedded energy harvesting solution which, coupled with ultra low power electronics and sensors, will provide a self powered wireless sensing solution. These systems can be powered by the vibrations present in the aircraft, which can be quite substantial depending upon location. Ideally, the assembled system should be a planar structure which enables it to be combined with composite manufacturing processes. The project includes several aircraft manufacturers and represents an exciting opportunity to develop and test energy harvesters designed for aeronautical applications in real operating scenarios.

The energy harvesting solution presented in this paper is based entirely upon screen printed piezoelectric materials. The screen printing process deposits the piezoelectric material, developed in the form of a paste, onto the substrate. The paste is dried and fired, forming a high quality bond to the substrate. The process provides a straightforward, low cost, rapid manufacturing process that can accurately manufacture planar devices compatible with the requirements of the project. This approach has been demonstrated previously with a triangular piezoelectric generator that delivered 3µW from 9m/s^2 acceleration levels at 80Hz [2]. The work presented in this paper builds upon this work by exploiting the improved piezoelectric properties of the ink which has subsequently been optimized [3]. Furthermore, to enable the devices to be fabricated completely using the screen printing process, a novel high density printable paste has been developed to form the inertial mass. Finally, the generator has been designed using actual helicopter vibration data.

2. VIBRATION DATA

Figure 1 shows a frequency spectrum taken from the vertical stabilizer on a PZL SW-4 helicopter. The helicopter was flying horizontally at 200km/h and at an altitude of 1000m with an outside air temperature of 10.5^{o}C. The main rotor rotational speed was 103% where 100% = 7.288Hz. The plot shows a variety of frequencies and vibration levels; we have identified modes at 30, 45 and 90Hz which exhibit 15.4, 8.6 and 1.5 m/s^2 vibration amplitudes respectively. This range of frequencies and amplitudes were selected to enable evaluation of a variety of generator dimensions in order to identify the important design variables and achieve a practical solution.

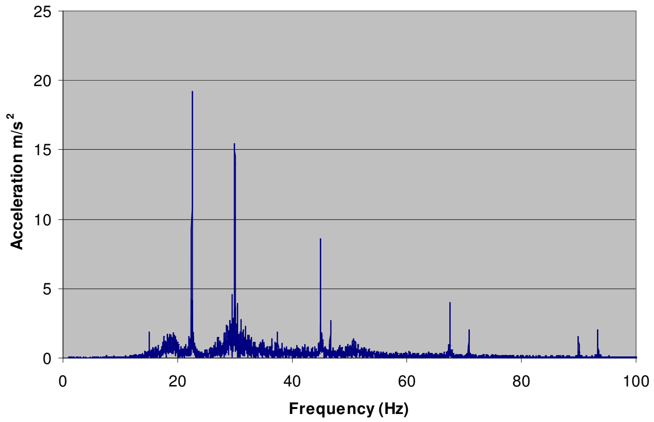

Fig. 1: Vibration frequency spectra on a helicopter vertical stabilizer.

3. SCREEN PRINTABLE PASTES

The screen printing process requires materials to be mixed into a paste form. The printing process then squeezes the paste through openings in a patterned screen thereby depositing the material in the pattern required onto the substrate. The deposited film is then dried and fired to leave a sintered thick-film on the substrate. The lead zirconate titanate (PZT) piezoelectric film used in the original screen printed generator had a d_{33} coefficient of approximately 40pC/N. The materials used in this work were based upon a revised piezoelectric ink formed by blending PZT-5H powders of different particle size. The blend of sizes results in an improved film density which, when combined with optimized processing parameters, give a substantially improved d_{33} coefficient of 131pC/N. The d_{31} coefficient was not measured but was assumed to be approximately -60pC/N given a typical d_{33}/d_{31} ratio for PZT materials of -2.2. The Young's modulus (Y) and dielectric constant (ε) of the sintered piezoelectric film were previously found to be 26GPa and 8 x 10^{-9}F/m respectively [4]. These values can be used to calculate the electromechanical coupling coefficient, k, using equation 1. The k_{33} and k_{31} coefficients were therefore 0.25 and 0.11 respectively.

$$k^2 = \frac{d_{coeff}^2 Y}{\varepsilon} \qquad (1)$$

The other pastes used in the devices (supplied by Electro-Science Laboratories Inc.) are an insulating dielectric (ESL4924), gold conductor for the bottom electrode (ESL8836) and a silver polymer for the top electrode (ESL1901-S). Also, a high density tungsten paste was formulated at Southampton specifically for this work. Tungsten particles were obtained in two nominal sizes: 1µm and 4-6µm. As with the PZT paste, the different particle sizes were blended so as to maximise the density of the film. The basic tungsten powder blend was based on the PZT formulation and consisted of a 2:1 mix of small particle to large particle size powders by weight. Two versions of the paste were evaluated. The first used a glass binder and involved the addition of a percentage of CF7575 lead borosilicate glass powder and a quantity of ESL400 vehicle. Initial tests involved mixing the blend of tungsten powder with different percentages of glass. This paste type proved largely unsuccessful with only the 60% glass formulation bonding suitably to an alumina substrate and forming a mechanically robust film. This film had a low density of only 3360kg/m^3. The second approach was to mix the tungsten with a dielectric polymer paste. The blend of tungsten particles was mixed with 15% ESL 240-SB polymer ink by weight. This formulation yielded a film density of 10,000kg/m^3 which is 52% of the bulk value. A cross section of the cured material is shown in figure 2. The polymer tungsten ink was therefore used to fabricate the devices.

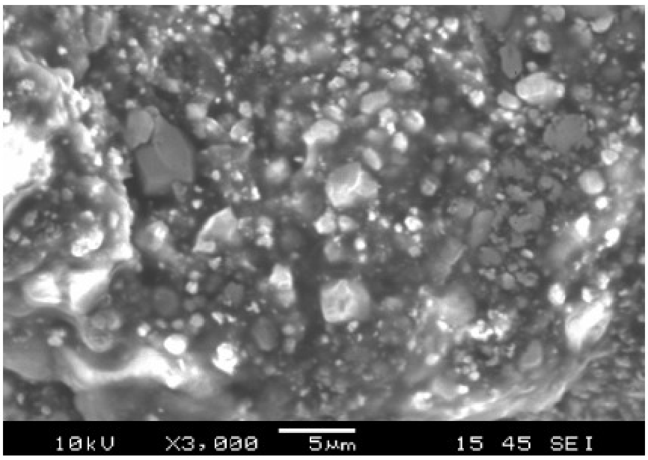

Fig. 2: SEM photo of cured polymer tungsten film

4. GENERATOR SIMULATION

The generators were designed using ANSYS finite element analysis (FEA) in order to match the application frequency and predict voltage outputs. FEA was used to identify the device size and shape, and a coupled field piezoelectric analysis enabled the output from the planar electrode structure to be identified.

The initial modelling involved a modal analysis using purely mechanical elements (shell99 for 2D model, solid45 for 3D). Basic cantilevers were investigated since this structure can achieve the low resonant frequencies required and also enable validation with analytical models. The models assumed a substrate thickness of 100µm, dielectric thickness of 20µm, PZT thickness of 50µm, electrode thicknesses of 10 µm and mass thickness of 200µm. Material properties were obtained from the literature. The cantilever dimensions arising from the analysis are given in table 1. The beam width was 20mm in all cases and the printed mass extended along 50% of the beam length. The coupled field piezoelectric analysis applied the application acceleration levels to the generator and calculated the static deflection and resulting voltage. Dynamic amplitudes and voltage levels can be estimated by multiplying the static values by the Q-factor of the generator.

Table 1: Simulated cantilever properties.

	Length (mm)	Mass (g)	Freq. (Hz)	Volts Out	Disp. (µm)
1	4.68	2.8	30.3	0.168	389
2	3.84	2.3	45.5	0.058	97
3	2.68	1.6	94	0.005	5

A simple indication of the maximum electrical power that might be obtained from a generator can be obtained by calculating the maximum mechanical power captured by the generator and multiplying by the maximum possible transmission coefficient, λ_{max}. This is shown by the relationship $P_{avelec}=\lambda P_{avmech}$ where λ is given by equation 2 [5] and P_{avmech} is given by equation 3 where m, ω_n, A and z_{max} are mass, resonant frequency, acceleration and maximum inertial mass displacement respectively. The λ_{max} for the d_{31} mode used in this device is 0.003.

$$\lambda_{max} = \frac{k^2}{4-2k^2} \qquad (2)$$

$$P_{avmech} = \frac{m\omega_n A z_{max}}{2} \qquad (3)$$

4.1 Fabrication

The substrate material was a 100 µm thick stainless steel type 430S17 sheet. The three cantilever designs were formed by etching through the sheet metal using wet double sided etching (photo chemical machining). The inks were then printed on both sides of the substrate in order to cancel out the stresses that arise from the unequal material thermal expansion coefficient (TEC). The dielectric film was printed first with 2 separate deposits giving a fired film thickness of 70µm. A single print was sufficient for the bottom electrode giving a film thickness of 15µm. The PZT ink was deposited in two steps giving a film thickness of around 70µm. These inks were all dried at 140°C and fired at 850°C immediately after printing. Next, the polymer top electrode was deposited with one print yielding a film thickness of 20 µm. Finally the polymer mass film was printed with 3 deposits yielding a mass thickness of around 200 µm. A final printed cantilever is shown mounted on the test rig in figure 3.

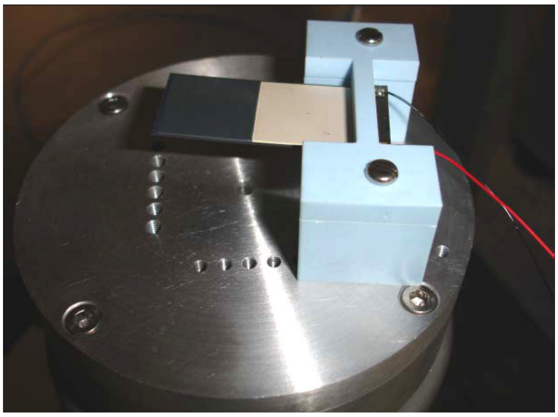

Fig. 3: Photograph of finished printed generator mounted on the vibration platform

Polarisation of the PZT layer was achieved by simultaneously heating the devices and applying an electric field across the two electrodes. An electric field of 4 MVm^{-1} was applied and the samples were heated to 200°C. The field was maintained for 50 minutes comprising 30 minutes poling at 200°C and 20 minutes cooling down with the field maintained.

There were some issues with the fabrication process that reduced the yield and affected repeatability between devices. The TEC mismatch caused the dielectric film to crack in places which also affected the PZT layer. These cracks, the severity of which varied between devices, caused the majority of devices to short circuit through the PZT layer during poling and as a result only devices with a single active layer were realised. The cracking also had a detrimental effect on the mechanical and piezoelectric properties of the materials leading to variable performance.

5. RESULTS

The generators were mounted on the vibration platform using a plastic clamp (shown in figure 3) and connected through the wires to a programmable resistance. The platform and resistance load was controlled by a PC running Labview software interface. This set up enables the automated collection of voltage and power readings from a range of frequencies, acceleration levels and load conditions. The experiments run were a frequency sweep at 1 m/s^2

whilst varying the resistance, a frequency sweep with the optimum load resistance varying amplitude of acceleration and a frequency sweep at 0.5 m/s^2 open circuit load (5MΩ). Due to the printed film thicknesses being greater than the values used in the FEA, the experimentally observed frequencies are higher than predicted. These values were 59, 67 and 145Hz for the three geometries. Useful electrical results were only obtained from one side of the lower frequency devices. The power versus frequency plot for different acceleration levels for the 59Hz and the 70Hz generators are shown in figures 4 and 5.

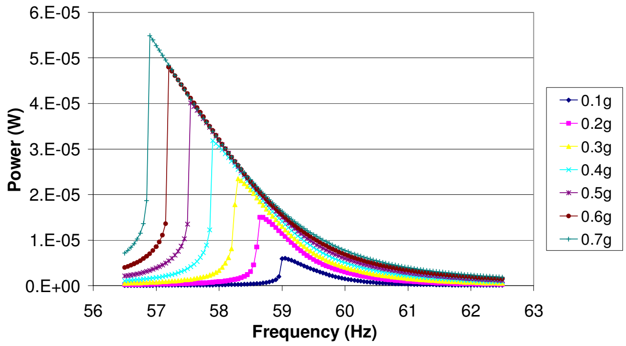

Fig. 4: 59Hz generator (30Hz design) power output

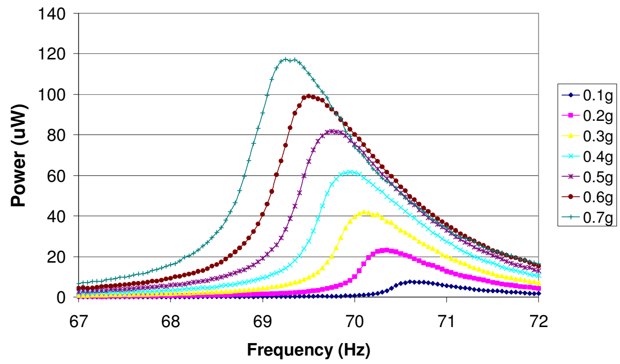

Fig. 4: 70Hz generator (45Hz design) power output

The maximum power for the 59Hz device was 55 µw at 0.7*g* (6.9m/s^2) and this increased to 117µw at 0.7*g* for the 70Hz generator. The optimum loads for the generators were found to be 80kΩ and 140kΩ whilst the output voltage was 2.1V and 2.9V respectively. In both cases the generators show a clear soft nonlinear behaviour where the peak resonant frequency falls with increasing amplitude. This could be due to the plastic clamp used in the experiment which might not be sufficiently rigid. The open circuit Q-factors for the generators were found to be in the region of 100, again this could be improved with a more rigid clamp.

6. DISCUSSION

The power and voltage levels obtained are promising and useful even at acceleration levels as low as 1 m/s^2 (7.5µW, 1V for the 70Hz generator). However, this work has highlighted some important areas for improvement. The fabrication process requires optimisation to prevent cracking and improve yield. This will require modification of the firing profile and could also benefit from a re-design of the devices and a reduction in the area of dielectric deposited. The piezoelectric film used here is clearly superior to the ink used by Glynne-Jones et al [2], but further development to improve the coupling coefficient would also benefit device performance. The use of interdigital electrodes could also benefit performance by exploiting the d_{33} coefficients of the material. Future testing will also be carried out using a more rigid clamp to reduce parasitic damping and potentially improve the level of nonlinear behaviour.

7. CONCLUSION

This work has demonstrated the benefits of the improved piezoelectric paste in energy harvesting applications compared to previous thick-film devices. The development of the screen printable mass paste is a novel development that enables the entire generator to be fabricated using screen printed techniques and avoiding any manual assembly or adhesive bonding. The planar fabrication process is compatible with the requirements of the application but optimum designs still need to be identified.

REFERENCES

[1] Larder B D 2003 Assessing the Benefit of Helicopter Health and Usage Monitoring Systems *IEE Seminar on Aircraft Airborne Condition Monitoring (Gloucester, UK, 14th May 2003)* 6/1 -6/6

[2] Glynne-Jones P, Beeby S P, White N M 2001 Towards a piezoelectric vibration-powered microgenerator *IEE Proc. Sci. Meas. Technol..* **Vol. 148 No. 2** 68-72

[3] Torah R, Beeby S P, White N M (2005) An Improved Thick-Film Piezoelectric Material by Powder Blending and Enhanced Processing Parameters *IEEE Trans on Ultrasonics, Ferroelectrics, and Frequency Control* **52(1)** 10-16.

[4] Torah R 2004 *Optimisation of the piezoelectric properties of thick-film piezoceramic devices* PhD Thesis, University of Southampton

[5] Roundy S (2005) On the effectiveness of vibration based energy harvesting. *J. Int. Mat. Sys and Struct.* **16** 809-823