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Novel piezoelectric structures for sensor applications

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Abstract

Piezoelectric ceramic devices have been formed into the helical spring shapes from tubular extrudates. These structures are shown to possess low compliance and low natural resonant frequencies. Equations are presented allowing the prediction of the resonant frequencies of the devices; these are shown to be in good agreement with measured responses. Using the design criteria a device has been constructed to exhibit a low fundamental resonance and a clear spectrum up to 500 Hz. The frequency response is shown for this device and compared to a conventional electromagnetic geophone. The results show that the device acts as a displacement sensor providing an output charge of 0.427 mC/m with no observed spurious resonances. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Piezoelectric structures; Sensor applications; Helical spring

1. Introduction

Conventional piezoelectric sensors are in the form of blocks or disks of piezoelectric material, measuring pressure waves in the case of hydrophones or utilised in accelerometers. The main purpose in the present investigation is to gain an insight into the advantages of net shape forming of ceramics for sensor applications. For this purpose viscous processing (VP) has been utilised in the formation of the green ceramic compact. The process itself and improvements in the material strength of PZT (Lead Zirconate-Titanate) has been reported in previous work[1], and the possibility of producing bulk electroceramics of a complex geometry has been demonstrated. The driving force behind this research was the concept of producing a highly compliant bulk ceramic device to obtain either large movements as an actuator or act as a displacement sensor at low frequencies. The latter of these is the main focus of the present paper. A mechanical sensor operating below its fundamental resonance has time to react to the stimulus of the signal to which it is exposed. In this region the compression experienced by the device is due to the force acting upon it and is therefore directly related to the acceleration. Above this frequency the device does not have time to react and becomes a displacement sensor. Accelerometers measure force and therefore pressure, and since the directionality of a sound wave is dependent upon the direction of particle movement within the medium, this direction information is lost. It is therefore desirable to use a displacement sensor to gain directionality of seismic waves without the need for an array.

The devices described in this paper are made from a piezoelectric ceramic powder–PZT and take the form of a tube coiled into a helical spring. Some ceramic piezoelectric geometries have been considered by other workers for use as audio transducers[2] and realised in PVDF for applications as an acoustic pressure sensor.[3] Previous work by the authors has shown that tubular PZT helices produce a sizeable charge that may readily be observed on an oscilloscope. The origins of the charge and the mechanics of the geometry have been discussed in earlier work,[4] and a full discussion of the mechanics of the helical spring geometry may be found in Reference.[5] This paper describes the properties of a number of piezoelectric ceramic helical tube devices relevant to operation as seismic sensors.

2. Experimental method

2.1. Formation of the ceramic body

The sensor device requires a ceramic tube to be sintered in the form of a helical spring, with electrodes on both the inner and outer surfaces of the tube. The springs were made through a VP extruded route. PZT powder (Morgan Matroc Transducer Products Ltd, PZT 5A) was mixed with polymer (PVA), water and

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glycerol. This was then mixed on a twin roll mill, extruded through a tube die and wound onto a former. After drying the polymer was burnt out at 600°C prior to sintering at 1200°C for 2 h in a closed crucible to prevent loss of lead. Electrodes were applied using a fritted silver ink, the devices were then poled in a field of 2.5 kV/mm at 130°C.

2.2. Vibration analysis

The experimental set-up is shown schematically in Fig. 1. The vibration analyses were performed using a commercial electromagnetic shaker. A computer-generated analogue signal was output to a linear amplifier driving the shaker. The vibrations were monitored through a calibrated commercial accelerometer, and the output from the computer adjusted accordingly to attain a desired vibration magnitude. The output from the test device was measured using an ADC (analogue to digital converter) after appropriate signal conditioning (amplification and filtering). A computer program controlled the process providing a set magnitude of vibration over the frequency range 10–1000 Hz.

3. Results and discussion

A typical spring possesses a complex frequency spectrum, containing longitudinal, flexural, rotational and transverse vibrations, as shown in Fig. 2, for a spring comprising eight turns with a major diameter of 20 mm made from a tube of 1.5 mm OD, 0.6 mm ID. The fundamental longitudinal resonance is the most prominent. Calculations of the fundamental resonances predicted values of 57.3 Hz for the compressive mode and 50.7 Hz for the flexural mode. Since the spring was of a close-coiled type the compressive mode would be the more prominent, as the stresses involved are in torsion, whereas the flexural mode stresses are in bending. From simple spring analysis it can be shown that the stresses in torsion vary in proportion to the cosine of the pitch angle, while the bending stresses vary with the sine of the angle.[6] At low angles therefore the torsional stresses are much greater. This prediction is confirmed by the two resonances observed at 48.9 and 56.2 Hz (B and C) in Fig. 2, likely to be the flexural and torsional resonances respectively. The predicted frequencies, as well as the relative amplitudes, are in line with those measured. The rest of the frequency response becomes increasingly difficult to interpret. The low frequency resonance, at 33.4 Hz (A), is likely to be a shearing mode, generated by imperfect alignment of the spring to the vertical axis of vibration. Above the fundamental resonances are many separate and overlapping harmonics, though the resonances at 149 and 168 Hz (D and E) can be confidently attributed to 3× multiples of the flexural and torsional fundamentals. The more complex behaviour above these frequencies arises from the many modes that a spring possessing a significant self-mass appears to be able to generate.

To utilise a piezoelectric spring as a seismic sensor it is necessary to provide a sufficient bandwidth devoid of resonances. In order to do so the spring itself must be stiff compared to its mass, the spring used for the results presented in Fig. 2 had a spring constant of 205 N/m and a mass of 5.2 g. The frequency response of a device with a higher spring constant (5992 N/m) and lower mass (4.5 g) is shown in Fig. 3. The major spring dimensions were chosen to make the natural frequency of the unclamped spring high, a major diameter of 16 mm and consisting of three turns fabricated from a

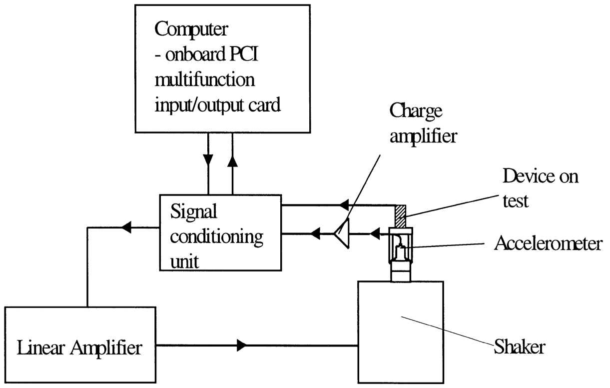

Fig. 1. Schematic diagram of the experimental set-up to analyze the spring vibration responses.

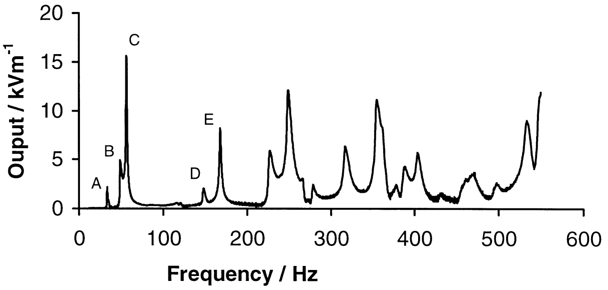

Fig. 2. Typical response of a piezoelectric spring to axial vibration.

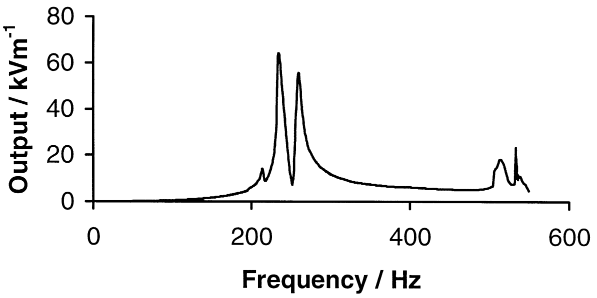

Fig. 3. Frequency response of a piezoelectric spring with a large spring constant compared to its mass.

tube with a thin wall section (0.5 mm) but relatively large inner diameter (1.7 mm). The capacitance of the spring was measured as 56.97 nF at 1 kHz. At the lower frequencies this structure has an output proportional to the acceleration (force) upon the device, this was measured at 1.4 mV/ms^{-2} at 100 Hz. This relates to 17.7 nC/N, and expressing in terms of pressure, 88 μC/Pa.

To the same device, a seismic mass of 270 g was then applied, and the resulting frequency spectrum is shown in Fig. 4. This shows a relatively flat output with displacement, slightly noisy at the higher frequencies, with only the compressional, flexural and rotational resonances observed in the frequency range 10–600 Hz. This design is predicted to give the first natural frequency at 30 Hz, and if the ends were clamped a resonance at about 1000 Hz. There is no observable coupling at 500 Hz with the longitudinal mode at 1000 Hz. The results were taken at a constant velocity vibration of 5×10^{-3} ms^{-1}, therefore at 500 Hz the device was measuring a displacement of 1.6 μm, producing an output of 11.8 mV. The noise is therefore more prominent at the higher frequencies. The fundamental frequency of the device is determined by the stiffness of the ceramic component and the seismic mass applied. Below this fundamental frequency the device acts as an accelerometer, above as a displacement sensor. A large seismic mass also acts to increase the output of the device. Previous work[7] has shown that the output of the piezoelectric spring is proportional to the square of the displacement, therefore the greater the precompression due to the seismic mass the greater the output.

Comparing this response to that of an electromagnetic geophone, shown in Fig. 5, it is clear that this approach indicates a potential way forward for utilising piezoelectric springs as vibration sensors. One important point to be noted, however, is that the results for the piezoelectric spring are given in terms of displacement, whereas the geophone results are given in terms of velocity. This is due to the fundamental differences in operation of piezoelectrics, being displacement sensitive, compared to electromagnetic sensors, being velocity sensitive. It is however possible to calculate the charge available, as although the voltage output from the geophone is velocity dependent the amount of current flowing is dependent upon the total flux change through the coils and thus the overall displacement. The resistance of the windings in the conventional geophone was measured as 400 Ω and the measured sensitivity was 30 V/ms^{-1}. From these two figures the charge produced can be inferred as 75 mC/m. For the spring shown Fig. 4, a capacitance of 57 nF and a sensitivity of 7.5 kV/m relates to 0.427 mC/m, considerably less.

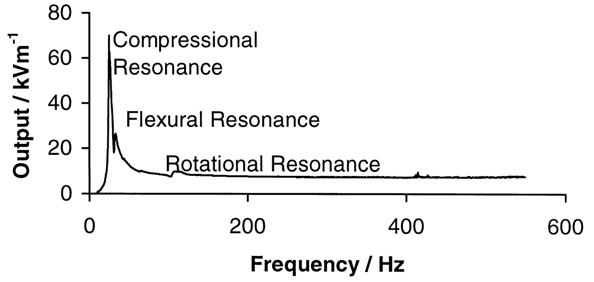

Fig. 4. Frequency response of a piezoelectric spring with a large seismic mass applied.

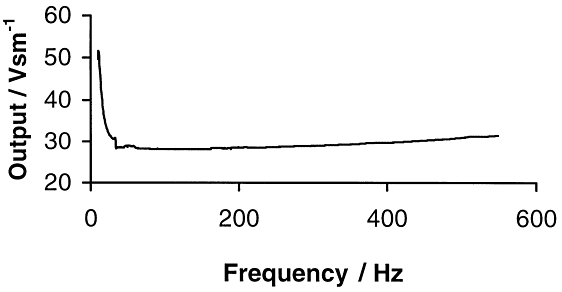

Fig. 5. Typical frequency response of a conventional geophone. Data taken at a constant velocity of 5 mm/s, the geophone is a velocity sensor. The primary resonance is at 10 Hz.

4. Conclusions

Through many measured observations of the voltage output and frequency response of various geometries of piezoelectric springs, the main features of such devices have been recorded and understood. The results shown present a picture of how these springs behave in real vibration situations, which has uncovered many features of their operation. Piezoelectric springs behave in a completely different way to conventional geophones, and as such require different design rules. The effects of the self mass of a spring is one which demands the most attention, since it appears to be the dominant feature in causing the crowded frequency spectra observed to date. Methods to minimise this effect are, however, proposed, which do appear to point towards a more useable device in terms of response to vibrations over a wide frequency range. These will however necessitate the use of a substantial seismic mass, greater than the mass of the active material.

The complex frequency responses of the springs has made the work more difficult, but the predicted fundamental behaviour of the devices has been proven. Accurate measurements of distortion have yet to be taken on the devices, but the equipment described above is capable of carrying out these measurements to an acceptable degree of precision.

The piezoelectric spring provides substantially less charge output when compared with existing geophones. Although optimisation of the device would improve the output it would seem unlikely that it could provide the same magnitude as the moving coil geophone.

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