Thick-film strain transducers made using piezoelectric paint

J M Hale

Department of Mechanical Engineering
University of Newcastle upon Tyne
Newcastle upon Tyne, NE1 7RU, UK
e-mail: jack.hale@newcastle.ac.uk

Abstract

This paper describes the manufacture and testing of a novel strain transducer based on piezoelectric paint for use in structural vibration monitoring.

This is a form of thick-film sensor, similar in structure to conventional thick-film sensors based on piezoelectric ink. However, the use of paint avoids two problems associated with the ink based manufacturing process: screen printing and high temperature curing.

The materials selection and application techniques development are outlined for the three principal components of the transducer: the resin binder, the piezoelectric material and the electrode. The final design comprised a sprayable suspension of milled PZT powder in lacquer (the piezoelectric paint) with a gold electrode formed by physical vapour deposition.

The transducers were tested for variability and for dynamic properties (bandwidth and dynamic range). It was found that there is considerable scatter between the output sensitivities of individual transducers, but that the dynamic properties were very consistent.

It is shown that the techniques developed form the basis for a viable low cost vibration transducer in the range 20 - 600Hz.
Piezoelectric materials have many potential applications in strain measurement. However, a serious limitation on these applications is the difficulty of attaching the piezoelectric material to the surface to be tested. A solid ceramic cannot be applied easily to a curved surface, and even a polymer film cannot be applied to a double curved profile or any irregular surface such as a corner or weld.

It has been proposed by Egusa & Iwasawa\(^1\) that it would be easier to apply the ceramic in the form of a paint. This would conform to the surface and adhere well even in the most inaccessible places. Some promising experiments are also reported, in which the mode shape of a vibrating beam is measured.

More recently the technique has been used to make much higher frequency sensors using ceramic piezoelectric paints. Egusa & Iwasawa\(^2\) describe acoustic emission sensors for use up to 1.2MHz and Lukacs et al\(^3\) describe ultrasonic transducers in the range 80-200MHz, both using piezoelectric paints based on PZT ceramic.

The Concept

All piezoelectric strain sensors are based on the same principle. Piezoelectric materials are made up of elemental dipoles which are aligned by some mechanical or electrical process to form a polarised sensor element. When the material is strained in the alignment direction the elemental dipoles are also strained, thus altering the dipole moment (i.e. the effective distance between the poles) of each and thus changing the potential difference across the sensor element.

Paints come in many forms, but all have two basic components: a liquid binder containing a suspension of solid particles (the pigment). The novel idea was to make a paint with piezoelectric properties by replacing the pigment with finely powdered piezoelectric material. When the paint dries, the particles are locked in position and so form a solid piezoelectric composite film. This is the basis of a thick film strain transducer.

The objective of the present work was to establish the viability of the piezoelectric paint concept by making transducers in small batch quantities and testing their performance at the moderate frequencies required for structural vibration work.

The first task was to select suitable materials and develop techniques for applying them. These two items were intimately bound
The piezoelectric material and the binder had to combine to form a paint that would be easy to apply and would cure to form a uniform layer. Similarly, the electrode layer had to be stable for application onto the paint surface without interfering with any of the properties of the paint or the curing (drying) process.

The next task was to develop a process by which the piezoelectric particles may be aligned reliably and permanently. For the ceramic material selected (see below) the conventional technique is electrical poling, by which the material is exposed to a strong constant electric field for a prolonged period. The intensity of the electric field and the duration of application were determined experimentally.

The properties of the transducers thus made were then tested. A large number of specimens was tested to determine quickly the effect of piezoelectric powder concentration in the paint, following which a thorough test of the dynamic response (dynamic range and bandwidth) of three representative transducers was made.

Material Selection and Application Techniques

A paint based piezoelectric sensor requires three main components: piezoelectric material in fine powder form, a resin binder to carry the powder in suspension during application and bind it together on curing, and an electrically conducting surface layer to form an electrode. For most engineering applications the substrate will be metallic and an independent conducting layer beneath the paint is not necessary.

Piezoelectric Material Selection

The effectiveness of a piezoelectric transducer is clearly heavily dependent on the piezoelectric material used. There is a wide range of materials that exhibit piezoelectric properties to a greater or lesser extent, but the most powerful by far are the lead zirconate / lead titanate (PZT) ceramics. Transducer grades of this material are readily available in powder form and an appropriate grade, PZT5A milled powder, was selected with advice from a commercial supplier, Morgan Matroc Ltd.

Resin “Binder” Selection and Development of Paint Application Technique

Selection of a suitable resin to act as a binder for the paint formed a significant part of the work. It was necessary to identify a material that
would hold a high fraction of the PZT powder in suspension but still flow freely during application, would cure quickly at room temperature, would prevent significant settling out of the powder during the curing process and would dry to a smooth, even finish.

Testing the resins for suitability was subjective, based on the difficulty the researcher experienced in mixing large concentrations of PZT powder into the resin, the ease with which the paint could then be applied by brush and spray, and the quality of the finish obtained. After several commercial paints and resins were investigated, a lacquer was found that was easy to apply by spraying, even with powder concentrations up to 75% by weight.

Spraying was found to be far superior to brushing for producing a void free paint layer with a good surface finish. Once some skill had been achieved this process was found to be very reliable and no voids were found in the five batches of specimens made.

Cross sections of the paint layers were cut, set into epoxy and polished to form microscope specimens for examination under the scanning electron microscope. It was clear from the micrographs that the piezoelectric particles were distributed evenly across the matrix with no tendency to settle out during the early stages of the cure.

Electrode Material Selection and Development of Deposition Technique

There are two separate requirements for the electrode: to provide a pickup for the finished transducer and to facilitate the high voltage poling process that aligns the piezoelectric dipoles.

In previous work, the electrode was produced by applying conductive ink onto the paint by screen printing. This approach was not followed here because of the perceived problems of printing onto complex curved surfaces, which is seen as an important application. Various materials were evaluated for the electrode, of which only one, vapour deposited gold, was found to be entirely satisfactory.

Vapour deposition of gold and aluminium is a well established technique used in the preparation of electron microscope specimens. A metal vapour is produced inside a vacuum chamber by heating a bar of the metal to an appropriately high temperature. In the absence of any significant atmosphere, the vapour radiates away from the source until it encounters a body on which it condenses and deposits the metal. By this means a very thin, even layer of metal can be produced on an even
care needs to be taken to ensure line of sight between source and target.

The use of aluminium was not investigated because it would oxidise rapidly and so give rise to problems making electrical contact. The use of gold was found to be ideal. It adhered to the paint without difficulty with no tendency to delaminate, provided a very low resistance layer with no electrical connection problems, worked well both during poling and as a transducer pickup and has negligible mass and stiffness due to the extremely thin layer obtainable using this process. Finally and importantly, this use of high purity gold is not expensive because it is only used in minute quantities.

Vapour deposited gold was thus adopted for the electrode.

**Manufacture of Specimens**

The tests were carried out on short steel cantilever beams 200mm × 40mm × 1.25mm, each with a rectangular sensor deposited on one face near the free end as shown in Figure 1.

Five batches of specimens were made, differing only in the PZT powder content, ranging from 45% to 80% by weight.

The transducers were made using the following procedure, except only for the batch with 80% PZT content which could not be sprayed due to the high solids content and was applied by brush.

1. The surface was cleaned using a commercial degreasing agent.
2. Most of the surface was masked off leaving an area 50 × 35mm exposed in the position required for the transducer.
3. A batch of paint was mixed in the proportion of resin to PZT required for the specimen.
4. The paint was sprayed onto the surface, care being taken to ensure even coverage, and allowed to cure at room temperature.
5. The edges of the dry paint were masked off, leaving an exposed area of 40 × 25mm to form the final size of the transducer.

![Figure 1. The test specimens.](image-url)
The beam was placed in the vacuum chamber and the gold layer deposited onto the surface.

7. The masking was then removed, leaving the transducer exposed on the surface of the beam, surrounded by a rim of exposed paint to ensure no contact between the gold electrode and the beam.

The final stage in the manufacture of each transducer was to align the piezoelectric particles electrically by high voltage “poling”. The field strength and exposure time had to be established by experiment. It was found that poling for one hour at 600 volts gave an effect that was stable over a period of five months, and appears to be permanent.

This poling regime was thus adopted for all specimens.

Testing Effectiveness of Sensors

Having established a technique for manufacturing piezoelectric paint strain transducers, it was necessary to investigate their effectiveness by measuring the effect of PZT concentration in the paint. Thirty specimens were prepared in five batches, using paints with four different concentrations of PZT powder in the resin binder.

A simple test procedure was devised by which the transducer outputs at various strains could be compared without the need to measure the actual strain causing it. For each test the beam was mounted as a cantilever in a heavy block. The beam was bent by deflecting the tip a given distance and then released and allowed to vibrate freely in the first bending mode. The voltage output of the sensor was monitored directly using a digital oscilloscope.

It was found that the transducer signal did not exhibit a simple decaying sinusoidal waveform as might superficially be expected for a freely vibrating system excited with an initial displacement. Superimposed on the first two or three cycles of the underlying first mode vibration was a high frequency transient which quickly died away. This transient is due to the difference between the deformed shape taken up by the beam under single point end loading and the first resonance mode shape that the beam takes up after release. This difference excites higher vibration modes which quickly damp out.

It may be shown that the amplitudes of the periodic components of both the underlying damped first mode vibration and the bending strain at a point on the surface of the beam after any given number of cycles are proportional to the initial tip displacement once the transient components of the vibration have damped out. For comparative purposes, it is thus sufficient to measure the amplitudes of the piezoelectric transducer
Figure 2 shows the scatter of output levels obtained from transducers prepared from paints with PZT powder concentrations of 45%, 60%, 75% and 80% by weight respectively.

It is clear that the output sensitivity of the transducers is dependent on PZT concentration in the paint, at least up to 75%. A concentration of 80% does not show any apparent increase in sensitivity, possibly due to the less uniform film obtained by brush application rather than spraying.

It is clear from these results that PZT concentration of 60% or less gives poor results, yielding very insensitive sensors (i.e. sensors that provide only a small signal for a given strain). Conversely, PZT concentrations greater than 75% make manufacture difficult without any evident improvement in sensitivity. Subsequent work thus concentrated on the specimens made using 75% PZT paint.

The most likely cause for the scatter of results is variation in the thickness of the paint film. It is demonstrated clearly by Egusa & Iwasawa† that piezoelectric activity of PZT paint is related to the field intensity (voltage per unit distance) under which it is poled. Although the poling potential was held constant at 600v for all the transducers used in this work, the thickness of the hand sprayed paint film would have varied considerably, both between specimens and from point to point within an individual transducer. This will have caused a significant variation in the poling field intensities which could easily account for the observed variation in transducer sensitivities.

Figure 2. Scatter of output levels from transducers containing various concentrations of piezoelectric powder.
Detailed Dynamic Testing

More detailed dynamic tests were carried out on three specimens, all made with paint containing 75% PZT by weight.

Full tests for dynamic range and bandwidth requires measurements to be taken with the sensor excited sinusoidally in the steady state over a range of frequencies and amplitudes. To achieve this the specimens were mounted on an electromagnetic vibrator as shown in Figure 3. In order to relate the sensor signal to the true strain it was measuring, a strain gauge was mounted on the reverse side of the beam and connected to a commercial carrier amplifier (Fylde 641CA) in quarter bridge configuration.

In the initial series of tests above, the output of the piezoelectric transducer was measured simply as a voltage. Piezoelectric transducers are more sensitive when charge, rather than voltage, is measured. In order to enable the sensors to work down to the very low strain levels required for a good estimate of dynamic range, charge was monitored using a commercial charge amplifier (Kistler 5001), the voltage output of which was in turn measured using a digital oscilloscope.

In each case the limits of the tests were defined by the piezoelectric signal dropping to the noise threshold, except for the high end of the dynamic range test which was defined by the maximum power available to drive the vibrator.

The bandwidths and dynamic ranges of the three specimen transducers are shown in Figure 4. The signal level in each case is the ratio of the piezoelectric signal to the strain gauge signal (i.e. piezoelectric output per unit strain). These levels are presented in dB relative to a value near the middle of the working range.

It may be seen that the form of the response curves are very similar for each transducer. The response curves over the measured dynamic range of two decades was quite flat in all three cases,
never deviating from the nominal value by more than 1.5dB. In fact, apart from one specimen at low strains, all the responses were within ±0.5dB of the reference sensitivities over the full two decade range. The frequency response is characterised in each case by a flat region of about one and a half decades centred on 100Hz with a rapid rise in sensitivity at the high and low frequency extremes. The ±3dB ranges are approximately 20 - 600Hz, 15 - 600Hz and 30 - 650Hz respectively.
1. Suitable materials and application techniques have been identified for the three principal components of a piezoelectric paint strain transducer: the resin binder and piezoelectric material forming the paint, and the surface electrode.

2. The optimum concentration of piezoelectric material in the paint has been established.

3. Poling conditions have been determined under which the piezoelectric paint strain transducers have been shown to retain their properties for more than five months.

4. The dynamic range for the transducers is good, with no more than 1.5dB deviation from a flat response over two decades of strain magnitude.

5. The bandwidth for the transducers is less good, with a ±3dB bandwidth of less than one and a half decades of frequency. However, the useful range is between 30Hz and 600Hz, which is the most important for many structural vibration applications.

6. The concept of a strain transducer based on piezoelectric paint clearly works. Further development is required to make the fabrication process more repeatable.

References

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