PIEZOCERAMIC SENSOR for MONITORING of STRUCTURAL VIBRATION

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ABSTRACT: Since their discovery in 1880, piezoelectric devices have found widespread use in engineering applications due to their simplicity and ease of application. High on the list of applications is their versatility in sensor technology applications particularly as the key element in modern day accelerometers. Furthermore, recent advances in piezoelectric crystals have made them even more cost effective for use in low cost sensors for condition monitoring of structure. Traditional methods utilising acceleration and strain gauge signals for detecting an incipient failure in structures suffer from inherent difficulty due to massive damping characteristics of the structures which results in minute fault signals being buried in dominant background signal components. In this paper, common PZT materials such as PZT-5A and PZT-5H were used in the construction of piezoceramic (PZT) sensors. Experimental tests were performed to evaluate the performance of the PZT sensors in detecting a simulated bearing crack operating at low speeds (100 rpm) and comparisons made with a commercial accelerometer and an ultra-sound prob. The results show that the PZT sensor is a more sensitive device compared to a commercial sensors in detecting a minute crack of a rolling element bearing operating at low speeds. Work is in progress in using the PZT sensors for condition monitoring of bridge structures.

KEYWORDS: PZT Sensors, Condition Monitoring, Structure Monitoring, Vibration Detection, Piezoceramic, Civil Structures

1. INTRODUCTION

To ensure structural integrity of civil structures, such as bridges, it is essential to monitor the condition continuously while in operation. Sensors are used to provide advanced warning of impending failure of the machines and structures. Traditionally, the condition of civil structures is maintained by performing periodic maintenance. This is normally carried out at regular intervals by visual inspection and retrofit of parts can be planned in advance. The only drawback with this approach is that the operator/inspector must be well qualified to detect incipient defect and such assessment is based on human judgement.

Sensors play an important role in monitoring the condition of machines and structures. Commercial sensors come in different sizes and are normally attached on the surface of the structure to monitor the internal defects of the structure. The vibration signal generated from a crack initiation is severely attenuated via the propagation paths and its final detection by the sensor located on the surface often fails to detect an impending failure of the structure. Sensors located at the surface are generally effective when the signal to noise ratio is high where the defect has accelerated to an advanced stage.

Vibration sensors basically consist of three types, namely displacement, velocity and acceleration sensors [Endevco 1987, B&K 1992]. Displacement sensors are normally used for low frequency signals with relatively large amplitude. The most common displacement sensor is the electromagnetic proximity sensor and works on the energy dissipation by the eddy currents and is mainly used to detect the motion of shafts relative to the motion of other machine elements. Displacement sensors that utilise the concept of light intensity is presented in [Wilson 1999] and it is claimed that the interference patterns formed by the phase differences can measure displacement down to less than 100 nm. Velocity sensors can measure higher frequency vibration than the displacement sensors. The disadvantages of a velocity sensor are the signal detected tends to be very noisy, prone to wear since it is a mechanical device and produce unreliable output [SKF note]. Acceleration sensors or accelerometers are widely used in vibration measurement. Modern accelerometer operates on a piezoelectric principle and the heart of the sensing process is the piezoelectric crystal. The signal output of the accelerometer after a certain conditioning process produces an output, which is proportional to the acceleration. Coupled with modern electronics, the output of an accelerometer can be integrated to produce a velocity or a displacement signal. The main disadvantage of this sensor is its temperature limitation [Entran 1987].

Recently piezoelectric crystals (PZT) have been extensively used in the design of sensors for vibration measurement and actuators for control of vibration, noise control and precision applications [Ge *et al* 1996, Friswell *et al* 1997, Lach *et al* 1996], control of flexible structure [Dunbabin & Tan 2000, 2002] and NDT studies for railway track vibration detection [Mitra 1996]. Piezoelectric crystals when subjected to stress it will generate a charge proportional to the induced stain. In this process it acts as a sensor. If a voltage is deliberately applied to the crystal it will deform the crystal with a strain proportional to the applied voltage, hence it acts an actuator [Friswell *et al* 1997]. Application of piezoelectric crystal in sensors for machine vibration and acoustic emission can be seen from [Varadan *et al* 1997, Tan *et al* 1992 and 2000] and ultrasonic testing in [Lach *et al* 1996]. Although the usage of PZT in sensor design is widely reported, the choice of a correct sensor is often made difficult due to the lack of understanding of the behaviour of the sensor under certain operating conditions [Lach *et al* 1996].

This paper describes the use of PZT in sensor design for detecting vibration signals. The design involved the size and location of the piezoceramic element on a specially designed sensor that can be located close source. To validate the effectiveness of a range of sensor designs experimental tests were performed with simulated defects. The results show superior performance of the sensors in detecting a damaged bearing signal corrupted by severe background vibration

2. CHARACTERISTICS OF PZT

The material used for the design of sensors for optimum vibration detection is lead zirconate titanate (PZT) ceramic. The material properties include high electromechanical coupling coefficient, high charge sensitivity and extremely stable with time and temperature. It has Curie temperature of above 300 deg C, making it suitable for use as a sensing element in a variety of applications. The crystals have high thermal and physical stability and can be manufactured in many different shapes. The main disadvantages are the temperature sensitivity and their susceptibility to aging when operates close to their Curie temperatures (193 – 490 deg C).

Piezoelectric crystal is self-sensing material and results in an electrical output when an induced strain is applied to the contact surface of the crystal. The material has low mechanical impedance and has a very wide frequency range, from a few kHz to MHz. With proper ageing and curing techniques the material produces excellent stability. However, the output is dependent on the electromechanical coupling and the placement of the sensor on the structure. The displacement vector is given by,

$$D = d_{xx}\sigma \tag{1}$$

and the charge obtained will be,

$$Q = DA = Ad_{xx}(F/S) = (A/S)\, d_{xx}F \tag{2}$$

where D is the displacement vector, σ is the stress (N/m^2), d_{xx} is the piezoelectric charge coefficient (coulomb/N), A is the surface area of the crystal, S is the cross-sectional area of the crystal, Q is the charge and F is the applied force.

The bonding of the sensing element plays a vital role in transmitting the electromechanical effects and hence the quality of the signal. In an experimental study shown in [Dunbabin & Tan 1999] and it was reviled that the bonding agents to hold the sensing element in position is crucial in case there is a temperature variation. It was reported that at around 60 to 70 deg C, the epoxy adhesive glue used in the bonding of the sensor experienced micro movement which can affect the damping capability if used as an actuator. The resonant frequency suffers a 10% reduction and the d_{xx} constant experiences a 60% variation in value for the temperature range from –25 deg C to 65 deg C. This effect is critical if the PZT is to be used as actuator or sensor.

3. DYNAMICS CHARACTERISTICS OF PZT

The method of model development described above has been shown to be an effective technique to analyse continuous flexible structures [Dundabin and Tan]. However, to accurately represent the controlled dynamics of piezo-actuated flexible structures under the influence of changing temperature, these models were enhanced by including key temperature dependent material and PZT properties in the system equations as described in [Dunbabin and Tan]. The bending moment induced into a structure from a piezoelectric actuator was first described by Bailey and Hubbard. In this investigation, the induced moment was modified to include key temperature dependent properties such that

$$M(T) = -V(x,t)d_{31}(T)\left(\frac{t_b + t_p}{2}\right)\left(\frac{E_b(T)t_b E_p(T)W_p}{E_b(T)t_b + E_p(T)t_p}\right) \quad (3)$$

where T is the temperature, $V(x,t)$ is the distributed control voltage across the piezoceramic, d_{31} is the piezoelectric charge constant, and t_b, E_b, t_p and E_p are the thickness and Elasticity of the beam material and piezoelectric element respectively, and W_p is the width of the piezoelectric element.

Dosch derived a relationship for the piezoelectric sensor voltage generated when undergoing a dynamic strain. This voltage is used as a feedback signal to indicate the strain at the root of the beam and allows estimation of the tip displacement for vibration suppression. For a single sensing element, the following equation for the sensor voltage is derived.

$$v_s(t) = k_s[y'(t,x_2) - y'(t,x_1)] \quad (4)$$

where $y(t,x)$ is the slope of the beam at the two ends of the piezoceramic sensor, and the sensing constant (k_s) is given by

$$k_s = \frac{g_{31}E_p z_c W_p^2 L_p}{t_p} \quad (5)$$

where $g_{31} = (d_{31}t_p)/(C_p b L_p)$ and z_c and C_p is the distance from the piezoelectric sensor outer surface to the centroid of the beam structure and the capacitance of the sensor respectively.

Extensive experimental results [Dunbabin and Tan] have shown how the piezoelectric voltage constant (g_{31}) can vary with temperature. The parameters that are significantly temperature dependent relate to the actuating and sensing characteristics of the piezoceramic (represented by d_{31} and g_{31} respectively). The percentage deviation of g_{31} from room temperature values from published materials and that observed from experimentation can be seen [Dunbabin].

The basic design of sensor for bearing vibration measurement consists of placement of PZT element for optimum detection and to be located as close as possible to the source. Figure 2 shows the various types of sensor designs developed for the detection of machine vibration. Both types of sensors can be screwed through the housing all the way to the test bearing.

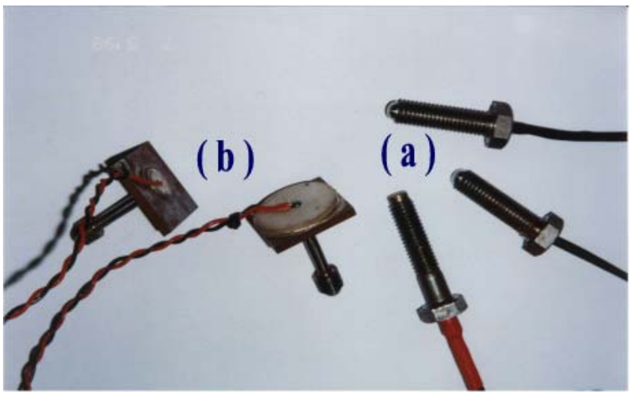


Fig 1. An enlarged view of the sensors used for vibration detection, (a) Bolt type and (b) Probe type.

3.1 Bolt type

The bolt type sensors as shown in Fig 1(a) have the sensing element located at the back surface of a stainless steel piece and inserted at the tip of a hollow bolt where the cables from the sensing element can pass through. The sensing element is a disc of 3 to 4 mm diameter by 0.2 mm thick. With the tip of the bolt touching the bearing ring directly, it will overcome the problem of signal attenuation through the propagation mediums and also corruption by other background noise.

3.2 Probe type

The basic structure of the probe type sensors consists of the sensing element located on the top flat surface of the probe and are shown in Fig 1(b). The probe can be screwed through the housing directly to the bearing ring to maintain contact with the test bearing. Two sizes of sensing elements were used in the design of probe type sensors, namely, 25 mm diameter by 2 mm thick PZT and 8 mm diameter by 0.2 mm thick PZT. The latter sensing element is similar to those used in domestic fire-alarm system and is cheaply available.

4. EXPERIMENTAL TESTS

In this investigation, a number of flexible cantilever beam specimens of varying properties were studied. Specimens consisted of a series of long and short aluminium beams, as well as different types and sizes of PZT actuators and sensors adhered at their clamped ends. Additionally, different types of adhesive used to bond the PZT ceramics to the substructure are investigated. Table 1 lists the main physical and piezoceramic properties of the long and short beams.

Table 1. Beam specimen physical dimensions and attached piezoceramic properties

	Physical dimensions			Piezoceramic Properties			
Ident	**Length (mm)**	**Width (mm)**	**Thickness (mm)**	**t_p (mm)**	**L_p/ϕ (mm)**	**PZT Type**	**Adhesive**
Beam 1	303	26.6	1.0	0.20	20.0	5H	Epoxy
Beam 2	303	27.1	1.0	0.20	20.0	5H	Epoxy
Beam 3	304	27.8	1.2	0.20	20.0	5H	Super-glue
Al Beam	303	25.1	1.0	N/A	N/A	N/A	N/A
Beam 5	302	26.9	1.0	0.20	20.0	5H	Super-glue
Beam 7	303	27.0	1.0	1.01	24.0	5A	Epoxy
Beam 8	303	27.0	1.0	0.27	24.0	5H	Epoxy
Small Beam 1	170	17.0	1.0	2.00	16.2	5A	Epoxy
Small Beam 2	170	17.5	1.0	1.00	16.5	5A	Epoxy
Small Beam 3	170	17.0	1.0	0.27	13.5	5H	Epoxy

Vibration testing comprised of the beam specimens being attached to a custom built test bed inside an environmental chamber as used in [Dundabin]. The beam and environmental chamber temperature was monitored to ensure the temperature within the chamber is increased quasi-statically and that uniform beam temperature is achieved.

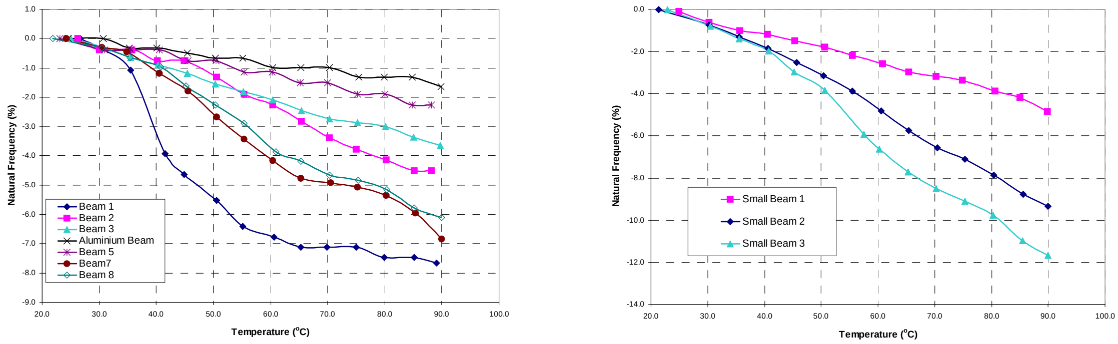
The beams were remotely given an initial displacement and released to initiate vibration. A non-contact proximity probe was used to monitor the beams transverse displacement. Once the beam vibration has settled, the recorded displacement data is written to file. This data was then processed off-line using the Matlab software package to determine dynamic properties such as damping, settling times and natural frequencies. The novelty of this method arises from the automated algorithms developed to rapidly process and extract key dynamical features from recorded time histories.

4.1 Natural Frequency

The free-vibration test results of all beams were examined to determine the variation of the natural frequency with temperature. Fig 2 shows the percentage deviation of the first natural frequency of the beams with temperature relative to the ambient laboratory temperature ($26^{o}C$).

The general trend evident in Fig 2 is that the systems natural frequency decreases as the temperature increases. This decrease is likely due to reductions in material stiffness as temperature increases. The aluminum beams natural frequency drops relatively linearly with increasing temperature. This can be explained from the change in elasticity of aluminum which varies roughly linearly with temperature for the range considered here. Beams 3 and 5, using the cyanoacrylate adhesive, show a similar trend to the aluminum beam. Beams 1 and 2, using an epoxy adhesive, show a marked decrease in natural frequency at 35 and 50^{o}C respectively. Beams 7 and 8, also using an epoxy adhesive, show a similar change around 70^{o}C.

Comparison of the natural frequency of the aluminium beam to the other beams indicates that there is some other mechanism present, be it piezoelectric or adhesive, which is capable of altering the system dynamics. This change is not evident with the cyanoacrylate (Super-glue) adhesives.

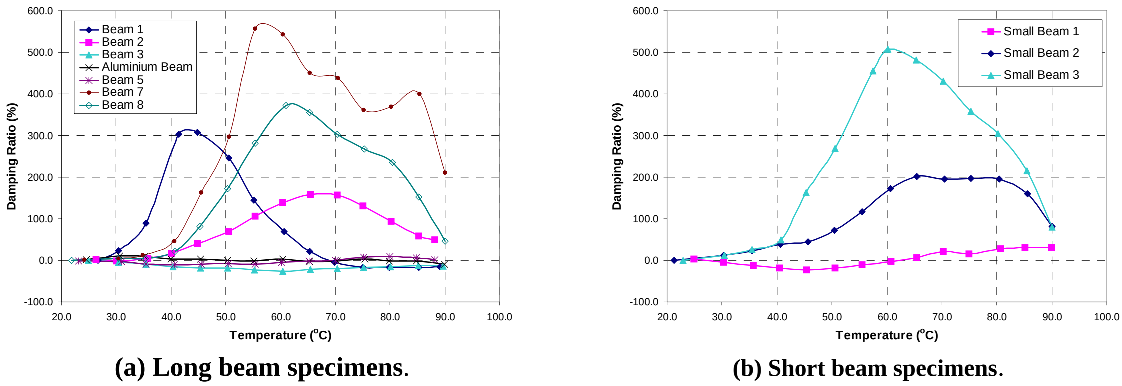


(a) Long beam specimens. **(b) Short beam specimens.**

Fig 2. Percentage deviation in first natural frequency of beam specimens with temperature (Ref 26^{o}C).

4.2 Intrinsic Damping

The damping characteristics of the beam specimens are considered with respect to their temperature. The damping ratio was calculated from the time histories using logarithmic decrement. Fig 3 shows the percentage deviation of the calculated free vibration damping ratio of each individual beam with temperature. The percentage variation of the damping ratio is referenced from the individual beams room temperature damping ratio.



(a) Long beam specimens. **(b) Short beam specimens.**

Fig 3. Percentage deviation in free-vibration damping ratio with temperature (Reference 26^{o}C).

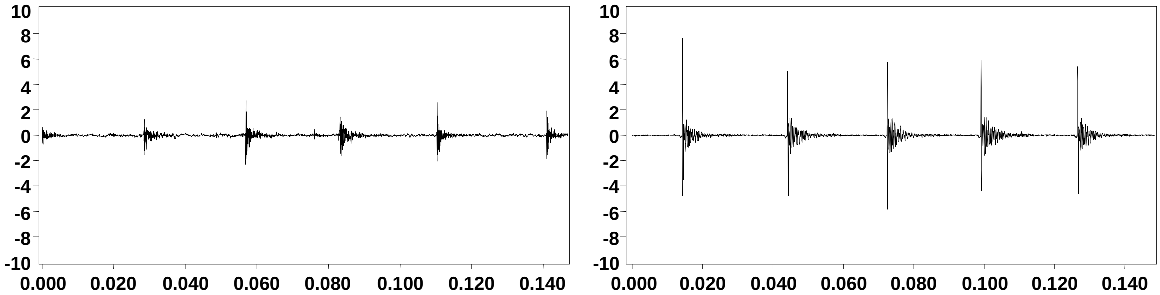
A number of interesting observations are made from this analysis. Firstly, Beams 1, 2, 7 and 8 showed a sharp increase in free-vibration damping ratio around 42^{o}C , 68^{o}C , 55^{o}C and 62^{o}C respectively. Beams 3 and 5 as well as the Aluminum beam do not show this property. After an investigation into the cause of these peaks in damping ratio, it appears most likely that it is due to the epoxy adhesive passing through its glass transition temperature.

Small-Beams 2 and 3 show a similar increase in damping ratio with temperature with peaks at 65 and

$60^{o}C$ respectively. Although all the Small-Beams used epoxy adhesives, each used a different brand of epoxy to each other and that used on the Long Beams. Therefore, it appears that the increase in damping ratio experienced here is not only temperature dependent, but also adhesive chemical composition dependent. It should be noted that these beams were tested a number of times and all results were repeatable in closed-loop and free-vibration tests.

4.3 Detection of Bearing Faults

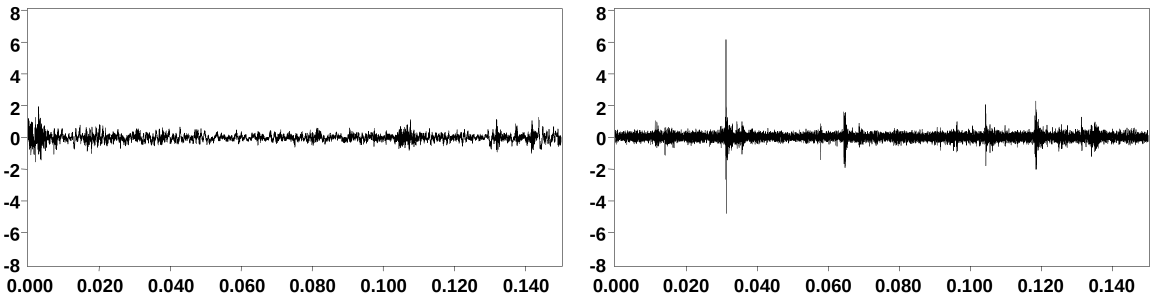
The discrete frequency of a damaged bearing due to a fault at the outer race and with a rotating speed of 800 rev/min, worked out to be 0.025 sec. In the time domain plots the discrete bearing frequency will produce a series of periodic impulsive signal occurring at the defect frequency with a slight variation in the time interval due to the inconsistency of the shaft speed. The signal shows a typical response of a ball striking a defect at a regular interval.



(a) Commercial accelerometer
(b) The bolt type sensor

Fig 4. Defective bearing signals

In Figs 4(a) and 4(b) the signals show a relatively clean impulsive bearing signal occurring at the frequency corresponds to a damaged bearing. The B&K accelerometer is a standard commercial sensor and is normally located on the machine surface close to the test bearing and consequently the signal is severely attenuated by the time it is detected by the accelerometer. While as the bolt type sensor, the sensing element is located at the tip of the bolt and has direct contact with the test bearing. This sensor design allows strong impulse amplitude of the signal to be detected as shown in Fig. 4(b). The result shows similar impact frequency as those detected using an expensive commercial sensor. The cost of this sensor is about 10% of that of the commercial sensor.



(a) A commercial sensor
(b) The bolt type sensor

Fig 5. Damaged bearing signals via a commercial and the bolt type sensor.

Since the bolt type offers superior detection capability, a further test was performed to evaluate the capability of the sensor to detect an actual crack on a rolling element bearing. The impulsive vibration signal due to a defective bearing is as not as consistent as that of the ball bearing due to the motion of the rolling elements coming into contact with the defect crack intermittently. The results from a commercial sensor and the bolt type sensor are shown in Figs. 5(a) and (b), respectively. In Fig. 5(a), it is not possible to identify the impulse response of the rolling element impacting on the crack. The signal of the bolt type sensor shows a couple of inconsistence impacts and the period of the first two impacts corresponds to the discrete frequency of a damaged bearing.

6. CONCLUSIONS

Piezoelectric materials have excellent electromechanical coupling property and with proper polarisation it can be effectively used as a sensor for vibration detection or as an actuator for vibration control. In sensor design, lead zirconate titanate (PZT) ceramic can be shaped to allow optimum location of the sensing element for vibration detection.

This paper presents results from selected experimental methods to determine and evaluate key mechanical properties of piezoceramic sensors/actuators. The experiments are designed to aid in improving vibration suppression techniques through greater understanding of flexible structure temperature dependant properties. The properties investigated for temperature dependence were the dynamic characteristics of the flexible structures and adhesive.

Key observations from this investigation are that material and adhesive properties of the PZT ceramics can vary significantly with temperature. These variations in properties alter the dynamic characteristics of the structure in terms of damping and natural frequencies. Results from this unique form of testing provide valuable insight into the influence of temperature on the dynamic behaviour of flexible structures.

For optimum detection of vibration signal it is essential to locate the PZT element as close as possible to the source to avoid signal attenuation through the propagating mediums and avoidance of corruption of severe background vibration. Experiment studies involving various sensor designs revelled that the bolt type sensors offer excellent detection capability and are just as effective as the commercial accelerometer. With the availability of cheap PZT there is a great potential for its application in machine diagnostic and monitoring.

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