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# Characteristics of Piezoceramics Sensors for Vibration Detection

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**Abstract** : Early detection of an internal malfunction of machinery plays a very important part in all condition monitoring programs. Sensors to detect amplitude, velocity and acceleration are widely used in vibration detection and control. Piezoceramic materials are largely used in sensors and actuators for vibration monitoring and control due to their relatively large output from an induced strain and their arguable self powering characteristics. In this paper a cheap and yet reliable sensors/actuators were developed to detect vibration. The results show that low cost PZT can be designed for optimum detection of bearing vibration. This paper presents the experimental results of a number of piezoceramics characteristics in terms of resonant frequencies and variation of PZT constants with temperature.

**Key words** : Condition Monitoring, Vibration, Piezoceramics, Sensors, Detection

## 1. Introduction and background

Condition monitoring is widely used in industry to assess internal malfunctions of machines. An experienced operator can detect changes of machine condition by listening to the sound of the machine or sensing the vibration of the machine. This subjective approach requires years of experience to develop. In most cases, failure has already occurred and may not provide enough time to take remedial action. In order to detect a small growing defect at its infancy and also in the present of severe background noise, it is essential to detect the impendent failure at an early stage. An efficient and sensitive sensor is the heart of the detection process. A problem with high sensitive sensor is that it will also detect the corrupting background noise as well. Consequently, advanced signal enhancement techniques are essential to remove the background noise hence detecting the desired signal. Regardless of whatever technique being used, the very first step in the detection process is the sensing of the overall signal and noise.

It is well known that noise and vibration from the machine carries

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important information on the health of the machine. For its detection, it is essential to have highly sensitive and efficient sensors and advanced signal processing algorithm to detect the desired signal. Sensors for vibration detection basically consist of three types, namely displacement sensors, velocity sensors and acceleration sensors[1], [2].

Increasingly, more of the fundamental research on active control using piezoelectric sensors and actuators is finding practical applications. These sensors are used in research focusing on the suppression of vibrations in simple structures such as beams, plates and trusses[3], [4]. These studies are predominantly numerical in nature and only present limited experimental results. Additionally, most of this work has been conducted with a limited set of operating temperatures. Interest is more recently being shown in the use of these devices for complex structures operating in more demanding environmental conditions such as in the aerospace and automotive industries[5], [6].

Further novel applications have recently been developed with the use of these devices as sensors in bearing failure detection and condition monitoring [7]. In all these applications, the operating conditions can be extreme especially when the integrity of these bearings starts to fail. The sensors can be subjected to large temperature fluctuations, immersion in fluids such as oils and broad band vibration.

Piezoelectric devices can be modelled simply as a voltage proportional to the induced strain of the sensor and piezoelectric constant[8], [9]. Based on the principle of piezoelectricity a number of specially designed sensors to measure machine vibration or acoustic emission are now widely reported[10]-[12].

Sensors and actuators need to be reliable, repeatable and accurate for use in vibration detection under all expected operating conditions. As temperature is a dominant influence on the variation of electrical and mechanical properties of PZT, this study examines the effect temperature has on a set of key piezoceramic sensors characteristics. The results provide some insight into the required compensation and design considerations for utilising these devices in real-life vibration detection applications.

## 2. Sensor design for optimum vibration detection

Piezoceramics are a self-sensing material and has a relative large output for their size. It has a very wide frequency range, from a few kHz to MHz. The material has low mechanical impedance and with a proper ageing and curing technique, the material produces excellent stability. The material used in the manufacture of these sensors is lead zirconate titanate (PZT) ceramic. The material properties include high electro-mechanical coupling coefficient, high charge sensitivity and is 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. When the material is deformed, it produces an output proportional to the electric charge as shown in Eq. (1).

$$Q = d_{xx} \sigma A \quad (1)$$

where Q = crystal charge, coulombs, $d_{xx}$ =piezoelectric coefficient (coulombs/Newton), = stress (N/m) and A = surface area of the crystal ($m^2$).

To overcome signal attenuation through the propagation mediums, the bolt type sensor was designed with the sensing element located at the back surface of a stainless steel tip that can be inserted into the hollow bolt. The bolt can be screwed through the housing touching the test bearing. Due to the close proximity of the sensor to the rotating bearing, it is anticipated that strong signal will be detected during shaft rotation.

## 3. Experimental set-up for testing of PZT characteristics

The effective use of piezoceramic sensors requires the need to consider a variety of factors. This investigation performs some simple tests to examine and verify the influence of temperature on the piezoceramics sensing characteristics. Whilst there are a large number of properties describing the properties, these experiments are setup to investigate those most commonly mentioned by authors such as $d_{31}$, $g_{31}$. Experiments were conducted in an environmental chamber. The temperature inside the chamber was monitored by platinum Resistance Temperature Device (RTD) and stable temperatures could be maintained from room temperature to 90℃ to within 1℃ of the desired value during a test run. Temperatures below ambient were more difficult to achieve with the current chamber design due to refrigeration requirements. Nonetheless, temperatures above ambient are sufficient to provide an insight into this investigation.

The specimens are placed within the chamber and appropriate connections to the outside of the chamber are made to allow various analysers and amplifiers such as oscilloscopes, RCL and Electrometers and signal generators to be attached and accurate measurements taken as shown in Fig. 1. The PZT specimens were constrained to the test bed by various methods as described in subsequent sections. The test bed contains a non-contact proximity probe to monitor displacements and a shaker (oscillating) mechanism for inducing known strain into the elements. The test bed allowed specimens to be tested whilst attached to various configurations of beams which could permit in-situ examination of the ceramics and the host structure.

A number of PZT ceramics specimens were examined. High quality PZT-5A (1.0mm thick) and PZT-5H (0.25mm thick) were examined as well as two ceramics of unspecified properties. One was a relatively cheap commonly available acoustical generator (Buzzer) element whose properties are consistent with PZT-5H, and the other was a large ceramic disc of 25mm diameter and 2mm thick. After the investigation, the discs properties best matched those of PZT-5A.

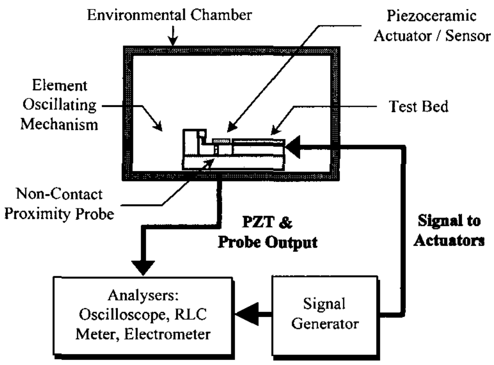



**Fig. 1 Outline of experimental setup.**

## 4. Results and discussions

### 4.1 Piezoceramic sensors in vibration detection

The frequency range of the sensor is dependent upon the element thickness and diameter. The thinner and larger the element, the lower the resonance frequency. However, thicker element generally produces higher sensitivity.

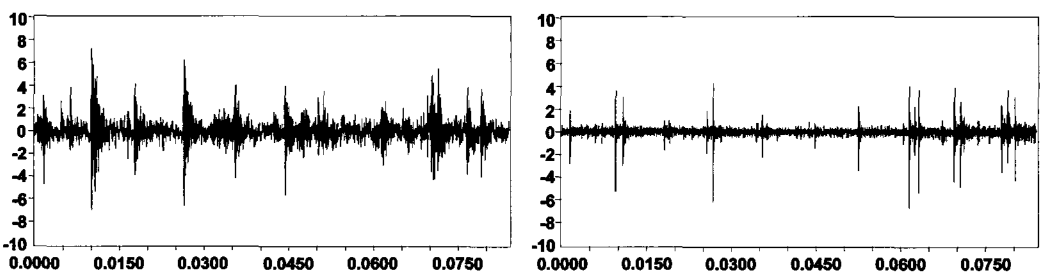
A typical vibration measurement of a defective bearing is shown in Figure 2. The results show the impulsive periodic nature of a rolling element striking a defect on the rolling track. This is made possible only by specially designed sensor that can be located close to the test bearing. It would be hard to detect the bearing signal with a commercial sensor located on the housing surface due to signal attenuation through the housing.

### 4.2 Piezoceramic characteristics

In this paper, only common PZT materials such as PZT-5A and PZT-5H were considered. A number of inherent properties of piezoceramic materials may limit their performance when used as sensors in vibration detection. A significant influence on these key parameters is temperature. As temperature varies, these properties generally exhibit nonlinear behaviour in the sensing and actuating properties some of which are discussed below.

**(a) Capacitance and resonant frequency**

The Resonance method described by ANSI/IEEE Std 176-1987[13] was used to characterise the piezoceramic element properties. The resonant frequency and capacitance were measured at various temperatures. Figure 3 shows the measured change in resonant frequency capacitance (Cp) of the PZT-5H acoustic actuators and the PZT-5A disc with




(a) Measurement with a commercial sensor (b) Measurement with bolt type sensor

**Fig. 2 Samples of a damaged bearing signal by a commercial sensor and the PZT sensor.**

varying temperature. The capacitance was measured a 1kHz using the RCL Meter.

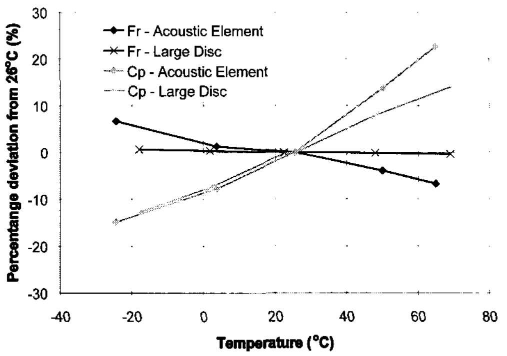


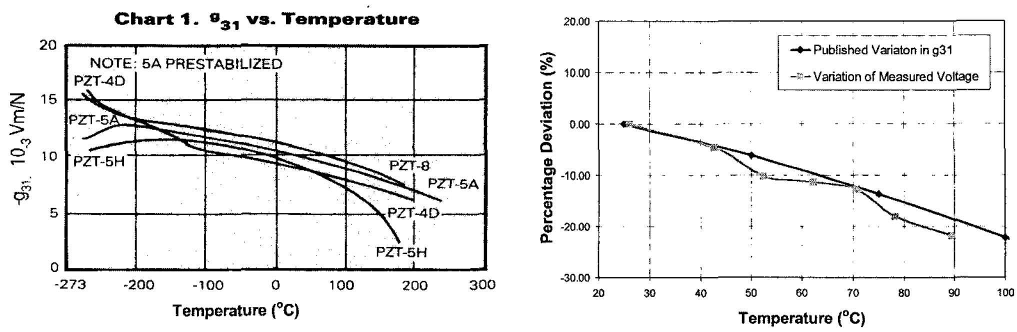

**Fig. 3 Percentage deviation in resonant frequency (Fr) and capacitance (Cp) with temperature of piezoceramic.**

The results shown in Fig 3 for the acoustic actuators closely match the specifications provided by manufacturer. The manufacturer determined a change of 10% and 31% in resonant frequency and capacitance respectively over the temperature range of 20 to 60℃ (These results were obtained from the AVX Kyocera Piezoelectric Acoustic Generators data catalogue). The results above show a change of 12% and 34% change in resonant frequency and capacitance respectively and indicate how the electromechanical properties can vary significantly with temperature and depend on material type.

### (b) Sensing characteristics

When piezoceramics are used as sensors, the output voltage generated by the sensor resulting from a stress is dependent on the piezoelectric charge constant ($d_{31}$) and the capacitance (Cp). The piezoelectric voltage constant ($g_{31}$) can be shown to be dependent on both $d_{31}$ and Cp and describes the output voltage generated by the piezoelectric device to a mechanical stress. Figure 4(a) illustrates the variation of the $g_{31}$ constant of commonly available piezoceramic materials with temperature.

To verify this trend in sensing characteristics, a PZT-5H element was




(a) (b)

**Fig. 4(a) Variation of piezoelectric voltage constant $g_{31}$ with temperature (Extracted from the Morgan Matroc Limited Piezoelectric Ceramics Data Book for Designers).**

**Fig. 4(b) Percentage deviation of published $g_{31}$ and measured output voltage subject to cyclic stress with temperature (Reference at 26℃).**

adhered onto a thin aluminium beam and attached to the test bed and shaker in the chamber. A cyclic stress was induced with the shaker and the voltage measured using an oscilloscope. Figure 4(b) shows the measured percentage variation of output voltage of the element with temperature compared with the published results of Fig. 3 showing good agreement.

Figures 4(a) and (b) indicates a general decrease in sensor voltage would result with increasing temperature when subjected to constant amplitude stress. In a vibration control situation, this could result in reduced performance due to lower than expected feedback voltages describing the magnitude of the stress unless compensation is added to the control algorithm.

**(c) Maximum operating temperature and sensor bonding**

A limiting feature of PZT sensor and actuators for application in real-life systems could be its limiting operational temperature. By virtue of the manufacturing process of PZT, they are polarised above a temperature known as the Curie temperature. Typical Curie temperatures for piezoceramic can range from 190 to 490℃, and is material dependant. Some piezoceramic manufacturers state a maximum operating temperature of 55-70% of the Curie temperature to ensure that excessive depolarisation does not take place. If this temperature is exceeded, then the devices may not perform as intended, or they may completely lose their piezoelectric properties entirely. This limitation may unfortunately reduce the number of possible applications where PZT devices would otherwise be effective.

The adhesives used to bond the ceramics to the structure have been shown to provide a significant source of non linearity in control[9]. The use of commercially available epoxy resins can show an increase in damping around its glass transition temperature about 60℃ for the epoxy.

## 5. Conclusion

The results show that piezoceramic sensor can be shaped and located close to the test bearing to overcome the problem of signal attenuation through the propagating mediums to produce optimum signal detection. The only drawback for its application is that a hole needs to be drilled through the housing, which may not be acceptable. However, this limitation can be overcome during the design stage where the sensor, which is small in size, can be incorporated.

The experimental results show the nonlinear characteristics of PZT and may affect their sensing properties. Not all properties were discussed, such as strong electric fields or large strain effects. It is also shown that inaccuracies may arise from interfacing to external equipment of different impedances and bonding of the sensing element which may be influenced by varying temperatures.

Experimental results show good agreement with published and theoretical predictions of the influence of temperature.

With further understanding of these inherent nonlinearities, these devices will find increasing application in many more real-life systems.

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