Fabricated PVDF Acoustic Emission Sensor for Lubricated Bearing Monitoring

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ABSTRACT: A fabricated Acoustic Emission (AE) sensor using polyvinylidene fluoride (PVDF) film and its application for lubricated bearing monitoring on a rotodynamic machine are presented. The advantages of a PVDF sensor are not only flexibility in terms of complex shapes but also low acoustic impedance leading to efficient energy coupling and broad frequency range. The calibrated resonance frequency of the sensor is 38 kHz using an artificial AE source (number E976-84) obtained from American Standard Testing Materials (ASTM). The experiment on a rotodynamic test rig at different machine conditions showed that the fabricated AE sensor can identify different machine operating conditions. Therefore, the fabricated AE sensor offers a potential alternative as a non-destructive monitor lubricated bearings.

Key words: Acoustic Emission, sensor, Non-Destructive Testing, bearing monitoring

INTRODUCTION

Acoustic Emission (AE) is typically a transient elastic wave generated by sudden released energy in materials under stress.(1) Such AE can be naturally generated by, for example, mechanical stress, pressurization, acoustic fields, etc. Recently, the use of AE has been of much interest for its potential in material testing processes. It may be particularly useful in Non-Destructive Testing (NDT) in which damage zones could be easily detected through fabricated AE sensors without damaging the tested materials.(2) NDT consequently offers not only real-time monitoring and overall structural performance checking but also a low cost process.

Generally, frequency ranges of AE lie between 20 kHz to 1.2 MHz.(1) The sensor is the equipment which is used for detection and monitoring of the AE signal. Practically, the AE sensors used in NDT utilize piezoelectric materials as a transducer with high sensitivity and a low response time. Conventional AE sensors are generally fabricated using lead zirconate titanate (PZT), a ceramic type of piezoelectric material. Although the use of PZT has shown excellent detection performance,(1, 3) the PZT, is physically hard and brittle. Therefore the AE sensors are not only difficult to produce in various complex shapes but also vulnerable to mechanical vibrations. In addition, the relatively high acoustic impedance of the PZT may result in a coupling mismatch leading to inefficient energy coupling.(1, 4)

Recently, polyvinylidene fluoride (PVDF) films were introduced as an alternative piezoelectric material for some applications.(5) Unlike the existing PZT materials, PVDF films offer not only flexibility in terms of complex shapes but also low acoustic impedance leading to efficient energy coupling without the mismatch problem. Moreover, PVDF films have a frequency response in the region of the AE signal.

In this paper, a fabricated AE sensor using PVDF and its application to lubrication bearing monitoring on a rotodynamic machine are presented. The measured resonance frequency of the PVDF-AE sensor is 38 kHz with standard deviation of 0-1687(6) using a standard artificial source obtained from American Standard Testing Materials (ASTM) No. E 976-84. The experiment looked at lubricated bearings under three different operating conditions; no lubricant, normal lubricant, and lubricant with graphite, and with the speed of the motor varied at 99, 1,500 and 3,000 rpm.

ACOUSTIC EMISSIONS IN ROLLING ELEMENT BEARINGS

Rolling element bearings are commonly used in all kinds of machines. As defective bearings may result in significant problems, condition monitoring of such rolling element bearings has received considerable attention. Reliable condition monitoring will significantly reduce failures and resulting damage in rotating machines.(7)

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In the case of rotating element bearings, AE signals are generated when a defective roller surface comes into contact with other components. This release of strain energy can picked up by a piezoelectric sensor. Theoretically, the energy of AE signals can be measured in terms of Root-Mean-Square, i.e. AE_{RMS}, and expressed as[8]

$$AE_{RMS} = \sqrt{\frac{1}{T}\int_{-T/2}^{T/2} A^2(t)dt} \qquad \ldots (1)$$

where AE_{RMS} is energy of the AE signals, T is a period of time and A is an amplitude of AE signal.

FABRICATION OF A PVDF AE SENSOR

The schematic diagram and a photograph of the PVDF AE sensor are shown in Figure 1 and Figure 2 respectively. The fabricated PVDF AE sensor is comprised of four major components - PVDF film, epoxy, aluminium housing and BNC connector. The PVDF film was a 2 x 3 cm rectangle with a thickness of 28 μm used as a mechanical stress wave sensor. The PVDF film is limited in terms of operating temperature to a range from 0 to 100°C. The backing material was made of epoxy and used to affix the PVDF film and the aluminium housing. The housing was 2.5 cm in width and 3.5 cm in length. The anode of the PVDF film was directly connected to the BNC connector through an electrical wire while the cathode was grounded. An aluminium protective film with BNC connector was used to cover the open side of the aluminium housing.

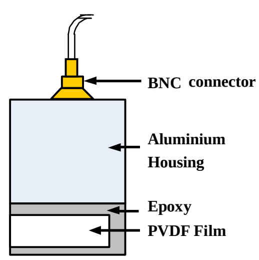

Figure 1. Schematic diagram of the fabricated PVDF AE sensor.

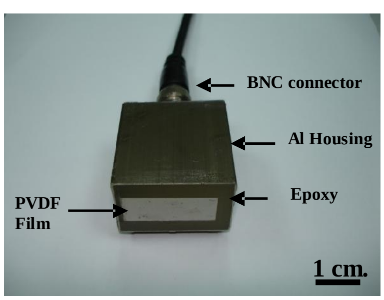

Figure 2. Photograph of the fabricated AE sensor used in the experiments.

CALIBRATION OF THE PVDF-AE SENSOR

Practically, sensors are calibrated in terms of an AE_{RMS} voltage and its operating frequency. Consequently, the fabricated PVDF sensor was calibrated using the standard pencil lead break according to an artificial source, ASTM Standard No. E976-84.[9] In addition, a low-noise pre-amplifier was used for amplifying the AE signals with a voltage gain of 20 dB and a high-pass filter was used for filtering the unwanted low-frequency noise. The data acquisition system consists mainly of a PC computer and a digital oscilloscope with a sampling rate of 4 MHz. The AE signals were processed through a Fast Fourier Transformer (FFT) using MATLAB in order to investigate the signals frequency domain. Figures 3 and 4 show burst waveforms and the resulting power spectral density of the detected AE signals using the fabricated PVDF-AE sensor. It can be seen from Figure 3 that the AE signal is detected within 1.2 ms to 1.5 ms., resulting in a period of 0.3 ms decay time. This is because the AE activities generated from the burst source. Generally, the artificial source produces a wide range of frequencies and the fabricated PVDF sensor can detect the frequency only in the region of approximately 20 kHz – 60 kHz. The resonance frequency shown in Figure 4 that of the PVDF sensor is approximately 38 kHz. Therefore, the PVDF sensor is readily capable for detecting the AE signals in a specific frequency range.

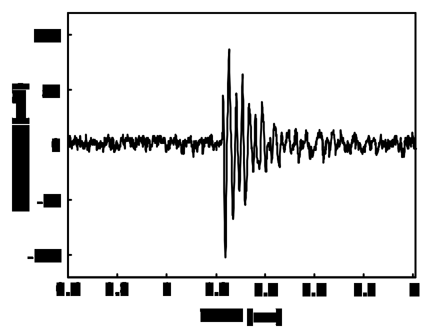

Figure 3. The burst waveforms of the detected AE signals using the PVDF sensor.[6]

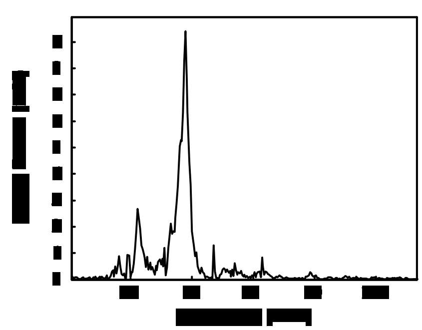

Figure 4. The power spectral density of the detected AE signal using the PVDF sensor.[6]

EXPERIMENT SETUP

The systematic diagram of the experiments for lubrication monitoring system is shown in Figure 5. The rotodynamic test rig consists of motor, spindle and bearings. The test rig can facilitate multi-fault operating conditions. The bearings were monitored under three different lubrication conditions; normal lubrication, no lubrication and lubrication contaminated with graphite. The spindle was driven at different speeds by an inverter at 99, 1,500 and 3,000 revs per minute (rpm). The PVDF-AE sensor was mounted on the bearing housing using a grease coupling medium. When the motor was running, the AE signals produced by the bearings were converted from mechanical energy to electrical energy by the PVDF-AE sensor. As mentioned earlier, the amplitude of AE signals is relatively low and therefore a pre-amplifier with a voltage gain of 20 dB and a high-pass filter at 4.83 kHz[10] were used for amplifying the AE signals and filtering the unwanted low-frequency noise, respectively. This was to ensure that the PVDF-AE sensor captured all AE-activities in terms of high frequency stress-waves due to the different lubricating conditions. The experiments were performed at room temperature. The AE signals were analyzed by using MATLAB. Figure 6 is a photograph of the equipment used in the AE monitoring system on the workbench.

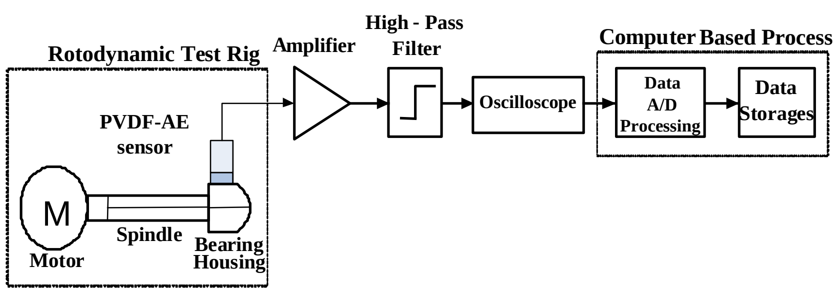

Figure 5. The systematic diagram of the experiment setup in lubrication bearing monitoring.

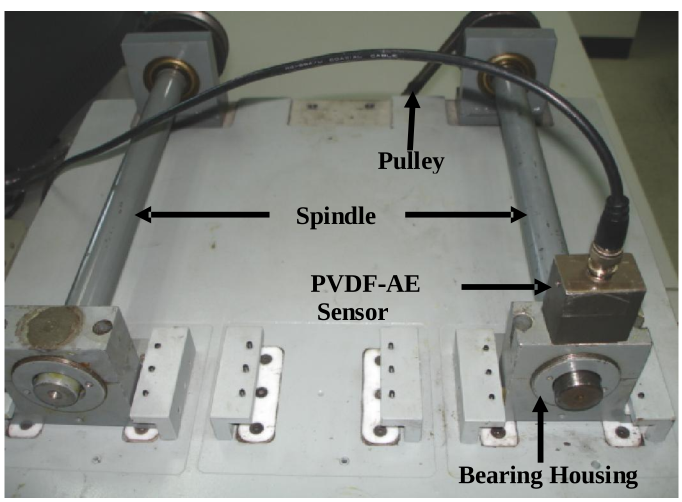

Figure 6. The test rig for lubrication bearing monitoring.

RESULTS AND DISCUSSIONS

The AE signals generated from the bearings of the rotodynamic test rig were examined at different speeds and operating conditions. The recorded amplitudes were calculated to obtain AE_{RMS} values using equation 1. Table 1 summarizes the resulting AE_{RMS} values collected from ten AE signals of each machine condition. With reference to Table 1, when considering only the operating speed, the rolling element bearing operating at the speed of 3,000 rpm has the highest AE_{RMS} value followed by that at the speed of 1,500 rpm and then 99 rpm respectively. When different bearing conditions are considered, the rolling element bearing operating under the case of lubrication contaminated with graphite has the highest AE_{RMS} values. This is because of the impact occurring between the contaminated graphite and the bearing surfaces. It is evident that the proposed fabricated AE sensor can effectively be used for detection of the AE signal even at different operating conditions and speeds. Figure 7 shows the trends of AE_{RMS} values from different bearing lubrication conditions.

Table 1. Measured RMS values of the AE signals at different bearing conditions and speeds.

Bearing conditions	Measured RMS values of the AE signals (AE_{RMS})		
	99 rpm	1,500 rpm	3,000 rpm
No lubricant	2.94	3.23	3.89
Normal lubricant	2.66	3.08	3.50
Contaminated lubricant	3.28	4.06	4.83

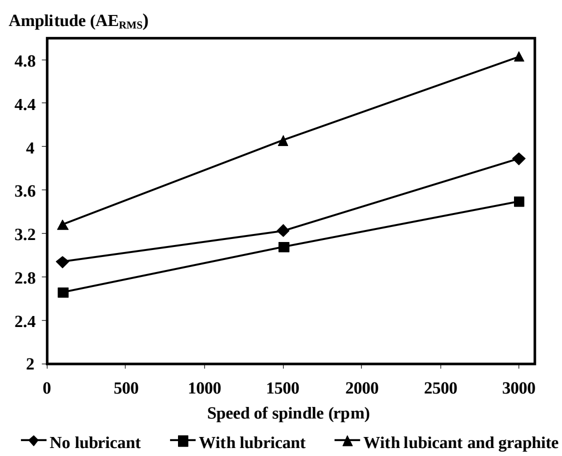

Figure 7. Comparisons between AE $_{RMS}$ of the bearing conditions and speed of the motor.

CONCLUSIONS

The fabricated PVDF-AE sensor for lubricated bearing monitoring applications has been presented. The measured resonance frequency of the PVDF-AE sensor is 38 kHz using a standard artificial source obtained from ASTM No.E976-84. The rotodynamic test rig allowed use of different speeds and operating conditions for investigation using the PVDF-AE sensor. The experimental results show that the PVDF-AE sensor can detect AE signals and identify different machine operating conditions in terms of AE_{RMS} values. As a result, the PVDF-AE sensor offers a potential alternative for use in applications of a Non-Destructive Test in industry.

ACKNOWLEDGMENT

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