

CHAPTER 4 FABRICATION OF AE SENSOR AND AIR JET SYSTEM CALIBRATION

This chapter presents the experiment procedure, results and discussions of design and fabrication of AE sensor (home-built) using PZT material and the air jet system for calibration the sensitivity of AE sensors. Then, the home-built AE sensors and the model formulation for the relationship between mechanical energy released from source and AE signal (subsection 3.7) are applied in two practical applications: the internal valve leakage rate measurement in the laboratory and in the field work (presented in chapter 5) and uniform corrosion monitoring in the laboratory (presented in chapter 6).

4.1 Design and Fabrication of the AE Sensor

The objective of this dissertation is to study and fabricate an AE sensor and create the model formulation for the relationship between mechanical energy released from source and AE signal. The model formulation is created and explained based on theoretical method as shown in the subsection 3.7. So this subsection is only provided the experiment procedure of design and fabrication of the AE sensor, the detail is shown follow.

4.1.1 Design of AE Sensor

Three main components of the home-built AE sensor are described here: the PZT material, the backing material and the wear plate.

The PZT material, in general, the aperture effect is an important concern. In this dissertation, the aperture effect for the home-built AE sensor is not a significant concern due to the multiple reflections of the AE signal occurring within the specimen; these reflections diffuse the acoustic field when the AE sensor is near the vicinity of the acoustic source (in case of the internal valve leakage rate measurement). In case of uniform corrosion monitoring, the AE wave propagation arrives as a longitudinal wave. The aperture effect is not a significant concern also. On the other hand, if the AE wave propagation arrives as a plate or surface wave, the aperture effects are critical.

This study attempts to design the natural frequency of the PZT material to correspond with the natural frequency of the AE source. From the theories, the resonance frequency of the PZT material can be expressed by

$$\omega = \frac{\pi(2n-1)c_0'}{2h}$$

and

$$h = (2n-1) \frac{\lambda_n}{4}$$

where $\lambda_n = c_0' / f$ and λ_n are the wavelengths of natural frequency (which are propagated along the AE sensor), f is the natural frequency, c_0' is the velocity of wave

propagation, n is a positive integer of $\lambda_n/4$, $n=1,2,3,\dots$, and h is the thickness of piezoelectric material.

The equation implies that natural oscillations of the AE sensor occur if h is equal to an odd multiple of $\lambda/4$.

For the backing material is usually made of an acoustically-absorbent material. Thus, the sound transmitting from the backside of the piezoelectric material will be absorbed, thereby reducing any unwanted noise. From the theories, the crucial factor for the backing material is acoustic impedance, which is governed by

$$Z = \rho \times c_o$$

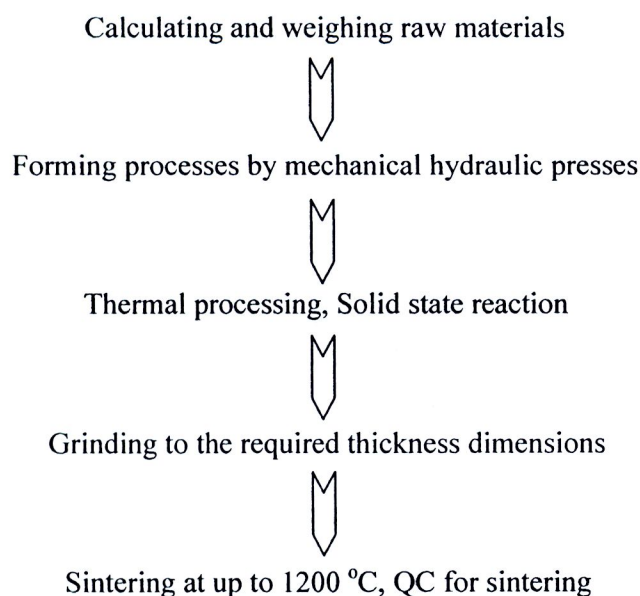
where Z is the acoustic impedance, ρ is the density and c_o is the longitudinal velocity of the backing material.

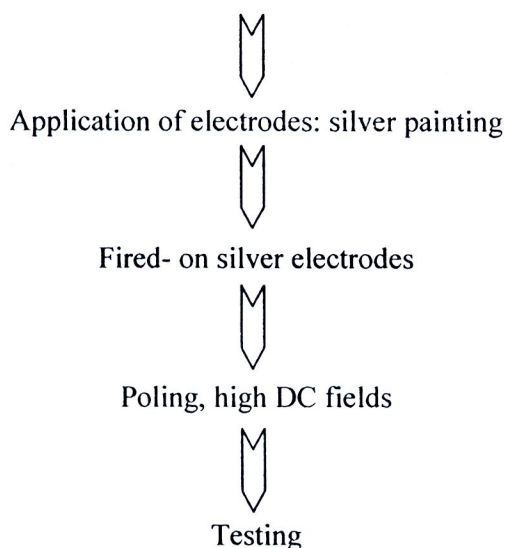
The wear plate is normally a thin plastic plate used to cover the exposed face of the piezoelectric element. The thickness of the wear plate generally is designed to be equal to one quarter of the wavelength of the sound wave to reduce the attenuation effect. However, the effect of matching layer is maximizing the transmission energy to the media.

4.1.2 Fabrication of PZT plate

In this study, the soft PZT (Lead Zirconate Titanate (APCI 850)) made from National Metal and Materials Technology Center (MTEC), Thailand is selected to fabricating the home-built AE sensor. The soft PZT are characterized by large electromechanical coupling factors, large piezoelectric constants, high permittivity, large dielectric constants, high dielectric losses and low mechanical quality factors. The most application of soft ceramics are used primarily in sensing applications.

The bulk forming processes of PZT plate from powder of soft ceramic are shown below.





From the bulk forming processes, soft ceramics powder are calculated the weight from the dimension of PZT plate that required (such as 32 mm of diameter and 1.6 mm of thickness). Next, the weight of soft ceramics powder are weighed and formed by mechanical hydraulic presses using 32 mm of mold size. The 2,000 PSI of pressure is applied and held (20 seconds). Then, the ceramics is heated using oven.

After grinding (using water and silica powder on the glass) to the required thickness dimensions, the ceramics is sintering at temperatures 1200 °C using oven. Then, the silver is employed for thin metallizing layers (electrodes are applied) using paintbrush. The PZT elements are sintering using oven again. The last step is the poling process at electrical fields up to 3 kV/mm (hold 30 minutes). The properties of PZT plate show in table 4.1.

Table 4.1 The properties of PZT plate

Properties	APCI 850
Relative Dielectric Constant; K^T	1900
Dielectric Dissipation Factor (Dielectric Loss (%)); $\tan \delta$	1.4
Curie Point (°C)	360
Electromechanical Coupling Factor (%);	
k_p	0.63
k_{33}	0.72
k_{31}	0.36
k_{15}	0.68
Piezoelectric Charge Constant (10^{-12} C/N or 10^{-12} m/V);	
d_{33}	328 - 365
$-d_{31}$	175
d_{15}	590

Table 4.1 The properties of PZT plate (Continue)

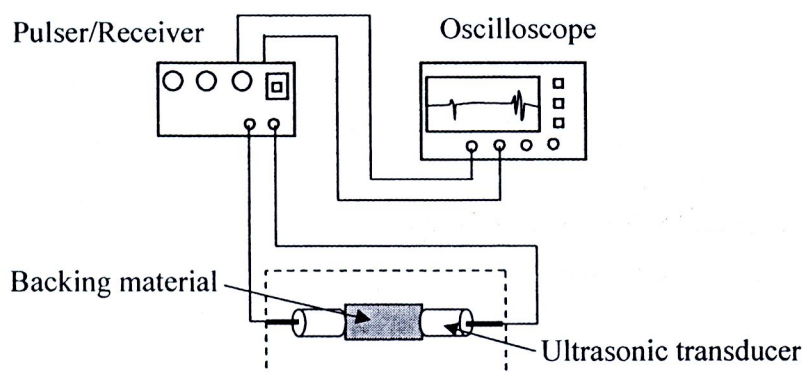
Properties	APCI 850
Piezoelectric Charge Constant (10^{-12} C/N or 10^{-12} m/V;	
g_{33}	26
$-g_{31}$	12.4
g_{15}	36
Young's Modulus (10^{10} N/m ²);	
ζ_{11}^E	6.3
ζ_{33}^E	5.4
Density (g/ cm ³); ρ	7.6
Diameter (mm)	30
Acoustic impedance (kg/m ² s $\times 10^6$)	33

4.1.3 Fabrication of backing material

In the theoretical and literature review, the suitable backing material for AE sensor is the tungsten powder associated with epoxy resin. It is clear that the acoustic impedances of backing material are dependent on density and longitudinal velocity.

In this study, the tungsten powder (the characteristics shown in Appendix D) and epoxy resin are selected to fabricating the backing material. The acoustic impedance of tungsten powder is about $100 \text{ kg/m}^2\text{s} \times 10^6$ while the acoustic impedance of PZT plate is about $32 \text{ kg/m}^2\text{s} \times 10^6$. When the tungsten powder is associated with epoxy resin, the acoustic impedance is reduced. The epoxy resin is fixed by weight (3 grams of resin and 3 grams of hardener) and the tungsten powder is varied from 30 to 60 grams in increments of 10 grams.

Next, the steel mold is used to forming the backing material. The 1,000 PSI of pressure is applied and held (50 minutes). The backing material is stored overnight at the room temperature. Then, backing material is cut according to the required length dimensions (5 mm) using handsaw. Lastly, the backing material is grinded by sandpaper and measured the longitudinal velocity by ultrasonic transducer. A diagram of the acoustic impedance measurement of backing material is shown in figure 4.1.

**Figure 4.1** A diagram of the acoustic impedance measurement

In figure 4.1, the pulser/receiver (panametrics-NDT model 5077 PR square wave) and oscilloscope (agilent 54624A) are employed to measuring the time of longitudinal velocity that travel though the backing material. Through-transmission method is applied to measuring due to high attenuation of backing material. Next, the longitudinal velocity of backing material is calculated by this time (that travels though the backing material). The density of backing material can be calculated from its weight and volume. Lastly, the acoustic impedance is calculated from the density and longitudinal velocity of backing material.

4.1.4 Assembly of home-built AE sensor

After fabrication PZT plate and backing material, in next step, the housing is fabricated from stainless steel by machine (turning and boring). A female BNC connector is selected for the home-built AE sensors. The wear plate is fabricated using an acrylic spray. The assembly procedure is shown in figure 4.2.

The PZT plate with 1.55, 1.60 and 2.40 mm thickness and 30 mm diameter are selected for fabrication home-built AE sensors. The label of each home-built AE sensors is specified as:

- AE1: PZT of 1.55 mm thickness.
- AE2: PZT of 1.60 mm thickness.
- AE3: PZT of 2.40 mm thickness.

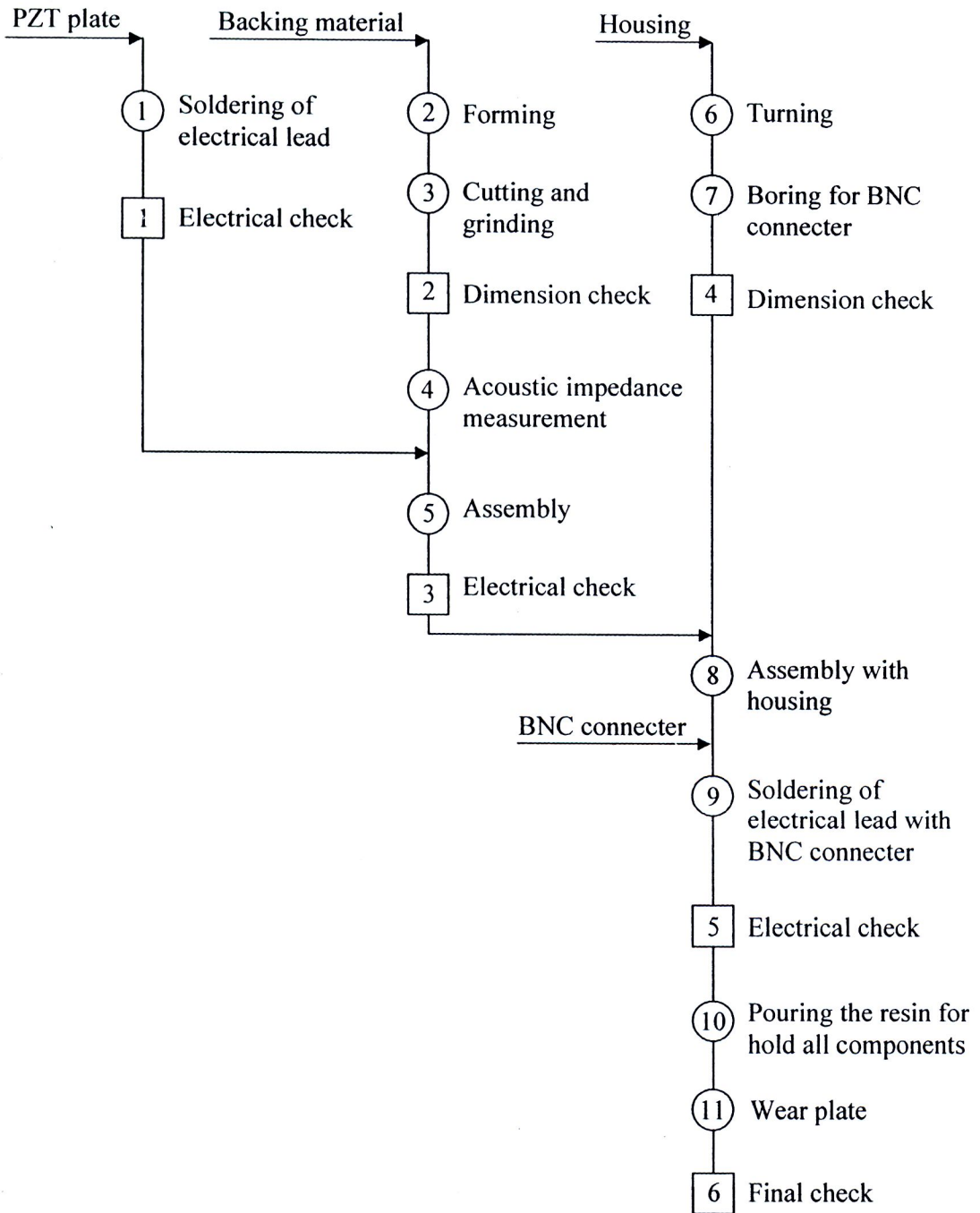


Figure 4.2 An assembly diagram of home-built AE sensor

4.2 The Air Jet System Calibration for Reference the Scale of AE Sensors Sensitivity

Before the home-built AE sensors are applied in the internal valve leakage rate measurement and uniform corrosion monitoring. The home-built AE sensors must be calibrated to check the frequency and sensitivity respond.

To check the frequency and sensitivity response of home-built AE sensors, an air jet, a relatively low-cost AE energy source, is used. Each home-built AE sensor presents a different sensitivity due to its PZT thickness. Besides the linearity of home-built AE sensors must be tested. The linearity between the measured energy in an AE signal and the mechanical source energy is very important in AE measurement systems. The AE signals from AE sensor are employed to forecast the severity of damage. If the sensitivity of home-built AE sensor responds to nonlinearity, the AE signal from home-built AE sensor can not be used to forecast the severity of damage.

From analysis of AE sensor (section 3.5), the output voltage (u) of AE sensor is proportional to acoustic power or acoustic pressure (p). The magnitude of the output voltage can be obtained as in from

$$|u| = \frac{k_p S}{C_s \omega^2 m} |p|; \quad 0 \leq u \leq 8 \text{ Volts}$$

The maximum of output voltage of the soft PZT (APCI 850) is about 8 volts.

In this study, the home-built AE sensors from section 4.1 are calibrated using an air jet and according to ASTM E-976. For the air jet, the air supply system that drives the air jet calibration rig is shown in the block diagram of figure 4.3.

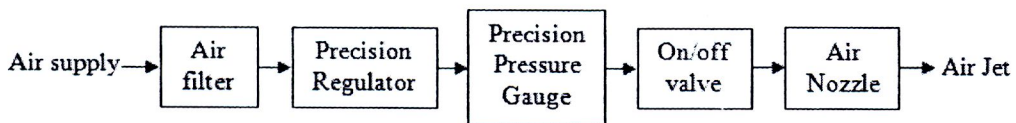


Figure 4.3 A block diagram of the air jet equipment

The air pressure is varied from 200 to 500 kPa in increments of 50 kPa. The home-built AE sensors are mounted on the surface of test block as illustrated in figure 4.4. The distance between air jet (nozzle) and AE sensor is 250 mm. The application of appropriate couplant, which minimises energy loss at the interface of the test block and the home-built AE sensors, is one of the most important factors in applying an AE measurement. A couplant is applied using a standard procedure. The signals are amplified by 40 dB using pre-amplifiers fitted with a 100 kHz – 1 MHz band-pass filter. Output signals from the pre-amplifier are fed into the amplifier and analyser, a LOCAN 320, set at a gain of 20 dB (see Appendix E), and recorded by a real-time signal analyser HP 89410A (with a sampling rate of 10 MHz) (Agilent Technologies, 2000). The spectrum in the frequency span from 0 to 1 MHz is recorded using 401 sample points and is averaged over 500 samples (see Appendix F).

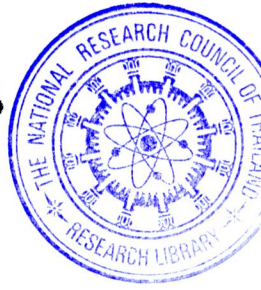
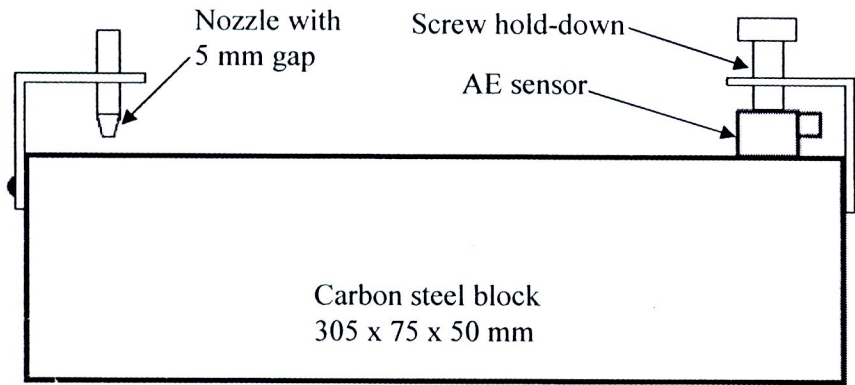


Figure 4.4 Air jet test block according to ASTM E-976

4.3 Home-built AE Sensors

The home-built AE sensors are fabricated from soft piezoelectric ceramic of 1.55, 1.60 and 2.40 mm thickness and 30 mm diameter. The backing material is fabricated from tungsten powder associated with epoxy resin. The maximum of acoustic impedance of the backing material is about 14.7 ($10^6 \text{ kg/m}^2\text{s}$). Its sensitivity is high, and its natural frequency is approximately 100 kHz. The characteristics of home-built AE sensors are shown follow.

4.3.1 Backing Material

The backing material is analyzed in terms of the microstructure, chemical composition and measurement of acoustic impedance. The all results show below.

1. The Microstructure Testing

The composition of backing material in the figure below is 60 grams of tungsten powder and 6 grams of epoxy resin (3 grams of resin and 3 grams of hardener).

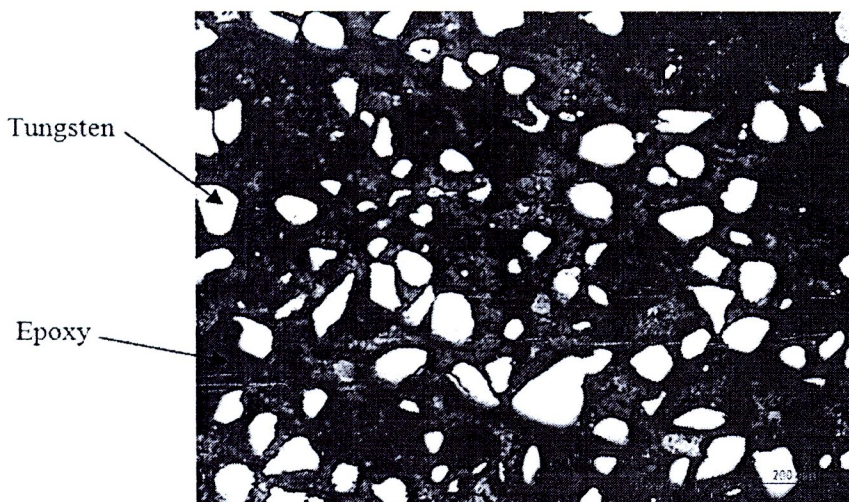


Figure 4.5 The microstructure testing of backing material

In the figure 4.5, the white area is tungsten powder and black area is epoxy resin. The result of microstructure testing shows that the distribution of tungsten powder and epoxy resin is uniform.

2. The Chemical Testing

The chemical testing of backing material is analyzed using the X-ray diffraction method. The result is shown in figure 4.6.

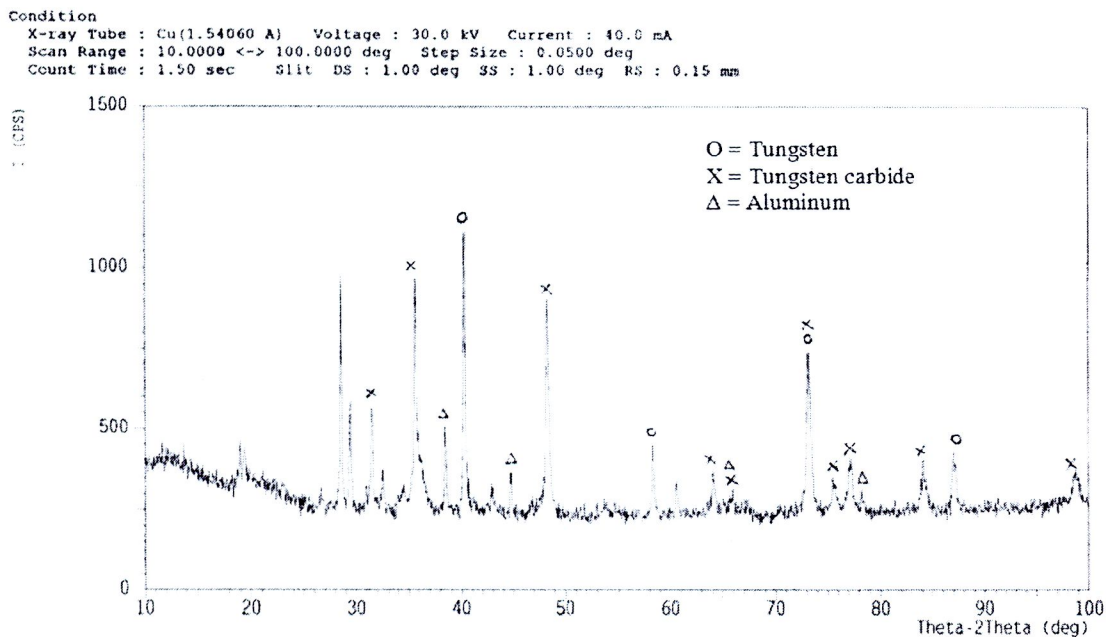


Figure 4.6 The chemical testing of backing material

In the figure 4.6, the base material is epoxy resin and the main composition is tungsten and tungsten carbide. Besides, the composition includes a little aluminum.

3. The Acoustic Impedance Measurement

The result of acoustic impedance measurement is shown in table 4.2. The density of backing material is calculated and longitudinal velocity of backing material is measured using the ultrasonic testing method.

Table 4.2 Composition of backing material and acoustic impedance

No.	Tungsten powder (g)	Epoxy Resin/Hardener (g)	Density (kg/m ³)	Longitudinal velocity (m/sec.)	Acoustic impedance (kg/m ² s × 10 ⁶)
1	30	3/3	6,445	1,748	11.3
2	40	“	7,195	1,734	12.5
3	50	“	7,860	1,705	13.4
4	60	“	8,405	1,754	14.7

In the table 4.2, the result shows that their density of backing material increased as tungsten powder increased. The longitudinal velocities of backing material are quite constant. The relationship between densities and acoustic impedances of backing material is shown in figure 4.7.

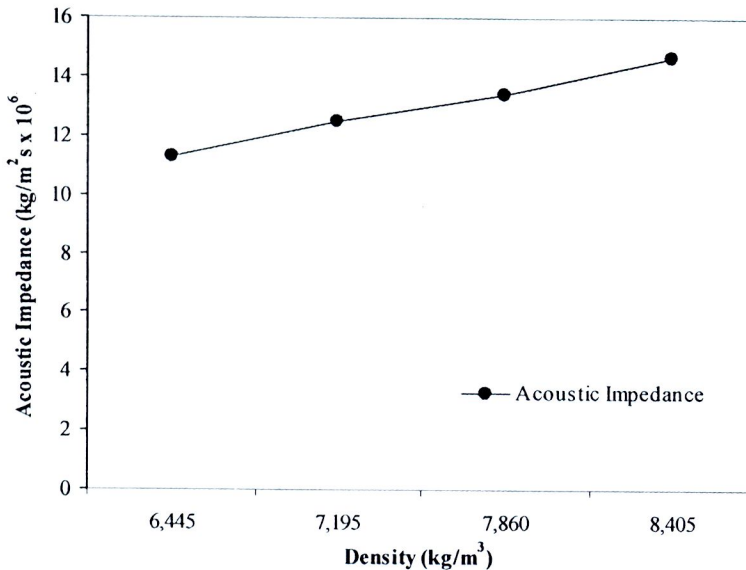


Figure 4.7 Acoustic impedance of backing material

From table 4.2 and figure 4.7, it can be seen that the acoustic impedances of backing material are dependent on density and longitudinal velocity. If the longitudinal velocity of backing material is quite constant, the acoustic impedance is dependent on the volume of tungsten powder only.

4.3.2 Appearance of the Home-built AE Sensors

In previous subsection, the backing material is fabricated from tungsten powder associated with epoxy resin and is analyzed. In this subsection, the wear plate is fabricated using an acrylic spray, the housing is fabricated from stainless steel, and a female BNC connector is selected for the home-built AE sensors. The appearance of home-built AE sensors is shown in figure 4.8 and 4.9.

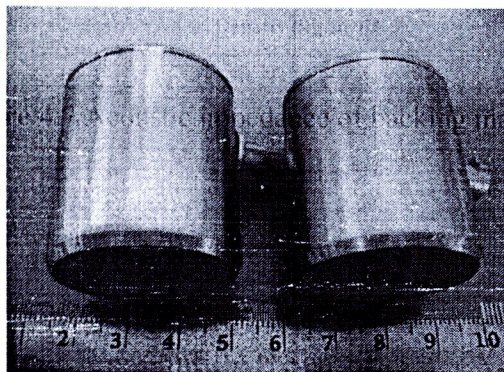


Figure 4.8 Home-built AE sensors (side of BNC connector)

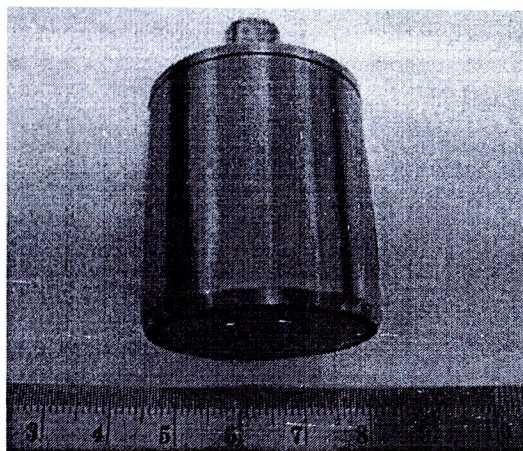


Figure 4.9 Home-built AE sensors (top of BNC connector)

Then, the home-built AE sensors are calibrated for the sensitivity of each sensor using the air jet system calibration. Lastly, the home-built AE sensors are applied in the internal valve leakage rate measurement and uniform corrosion monitoring, respectively.

4.4 Calibration of the Home-built AE Sensors

In this study, the AE sensors are calibrated using an air jet and according to ASTM E-976. Since the AE_{rms} spectra of each sensor at the pressure level between 200 and 500 kPa have a similar shape, their amplitude is increased as air jet pressure increased. The typical AE_{rms} spectra of the air jet at 200 kPa pressure obtained from AE1-AE3 sensors are shown in figure 4.10 - 4.12.

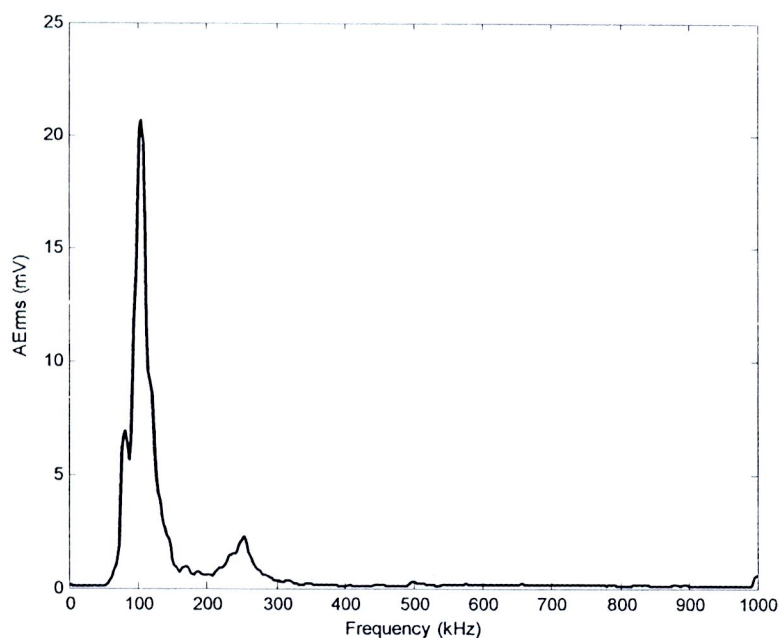


Figure 4.10 AE_{rms} spectra of air jet at 200 kPa pressure for AE1 sensor

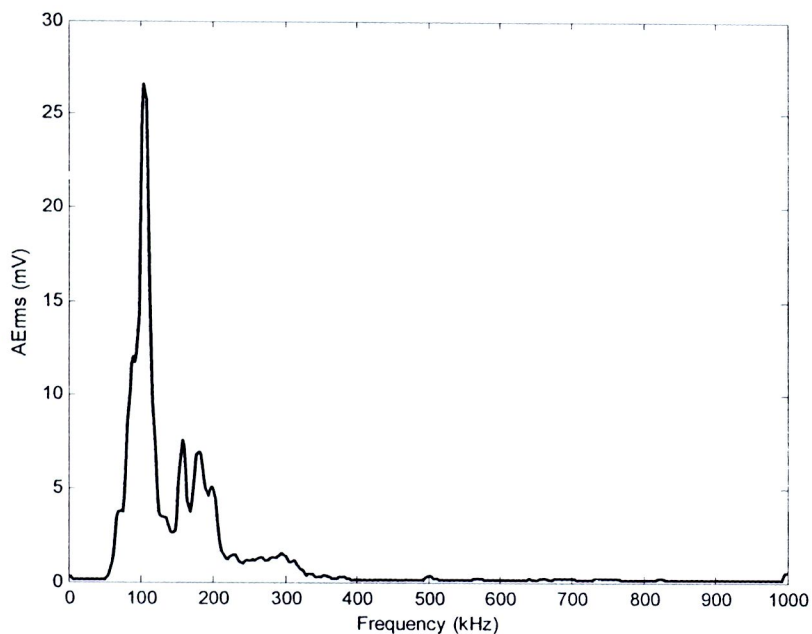


Figure 4.11 AE_{rms} spectra of air jet at 200 kPa pressure for AE2 sensor

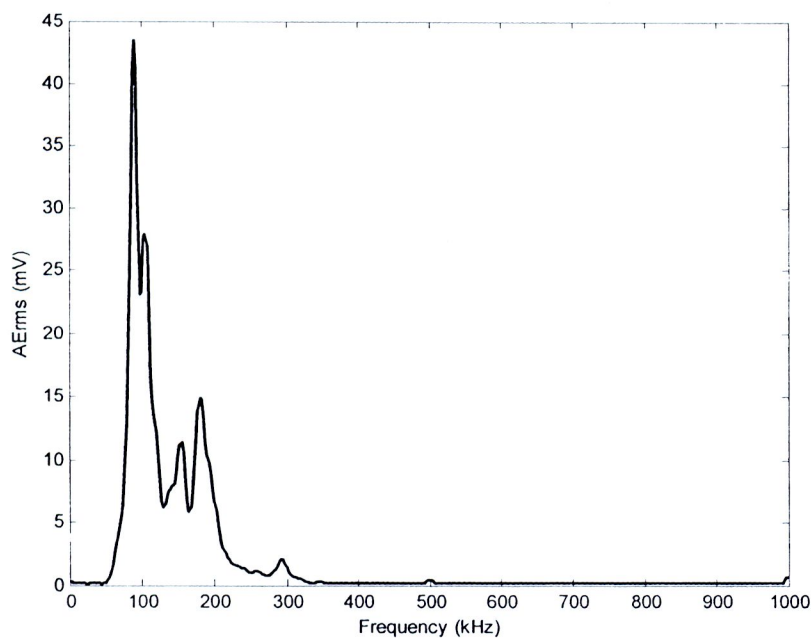


Figure 4.12 AE_{rms} spectra of air jet at 200 kPa pressure for AE3 sensor

In figure 4.10 - 4.12, the frequency responding of each sensor is about 100 kHz and has a similar shape.

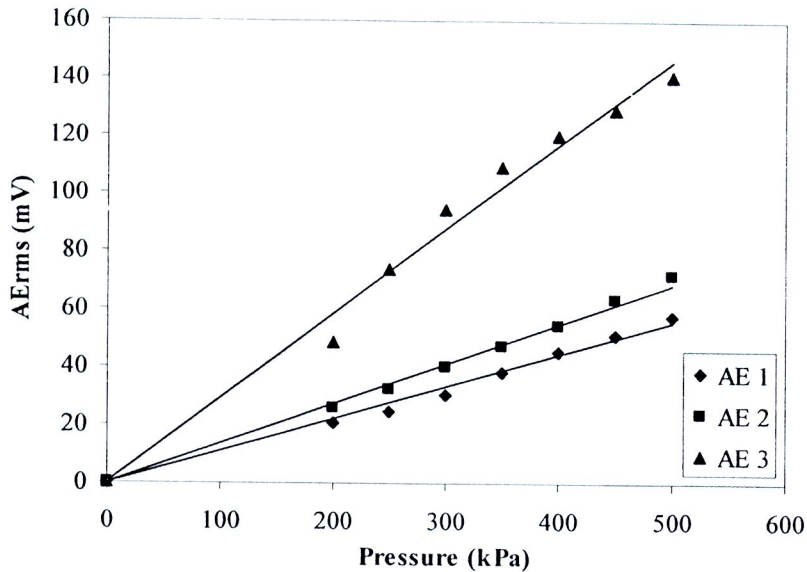


Figure 4.13 The sensitivity of the each sensor

The calibration results of AE1-AE3 sensors are plotted in figure 4.13. It can be seen that the AE_{rms} and air pressure are linearly related, and the gradients for the AE1-AE3 sensors are 0.29, 0.13 and 0.11 mV/kPa. The R^2 , simply the square of the sample correlation coefficient between the outcome (AE_{rms}) and the values being used for prediction (pressure), are 0.98, 0.99 and 0.98, respectively. These values represent the sensitivity of the three sensors.

4.5 Summary

From the results, the backing material made from tungsten powder associated with epoxy resin and the soft PZT made from National Metal and Materials Technology Center (MTEC), Thailand can be fabricated the AE sensor. The home-built AE sensors show that the AE_{rms} and air pressure are linearly related and good frequency responding. The properties of the home-built AE sensor are equivalent to the commercial one. This means that the AE sensor can be fabricated in Thailand for applying into the AE measurement systems. The benefit is to minimize the cost of AE measurement systems for applying in the field work.