

Development of a Valve Leakage Detector**A.Prateepasen*, S.Channarong**

Department of Production Engineering

King Mongkut's University of Technology Thonburi

126 Prachautid, Bangmod, Toongkru, Bangkok, Thailand 10140.

* Corresponding author Tel: +66 24709296, Fax: +66 24709296, Email: iasaasen@kmutt.ac.th**Abstract**

This paper presents the development and realization of a portable Smart Valve Leakage Detector (SVLD). It was equipped with a microcontroller for data acquisition, and an AE sensor was specifically designed to cover the frequency range of valve leakage for cost effectiveness. Models to predict the leakage rate were presented and compared. A method was proposed to calibrate the system in case of AE probe replacement. Characteristics of the AE signal obtained from the air jet were also investigated. The result showed that the signal had comparable frequency characteristics to that from the actual valve leakage especially in the frequency range of 100-300 kHz. A method based on coherence function was also proposed to identify the cause of valve leakage. These make the instrument flexible to be used in practice. The main benefits of the detector are its portability, cost-efficiency, ease of use and its flexibility to change AE sensor.

Keywords: Acoustic Emission, Coherence Function, Leakage Identification, Sensor Calibration, Valve Leakage.**1. Introduction**

Valve leakage problem can cause not only explosion and fire but also other serious threats from fluid degrading owing to fluid mixing [1]. In addition, fluid losses lead to increase in production cost including maintenance parts, labor, and equipment downtime. Therefore, in-line valve leakage instrument is normally applied to evaluate its severity degree to identify the points that are cost-effective to service the valve [2]. The testing costs are usually justified by potential consequences of valve failures. Typically, direct test methods require special test equipment and personnel at each valve. Some approaches even require a shutdown of the process. Therefore, a noninvasive method convenient for valve leakage application is required.

Acoustic emission (AE) technique, a very sensitive noninvasive testing method, can be used in proof testing of valve parts. Although, a general AE data acquisition system is highly sensitive with in-process valve leakage. The disadvantages of this system are large size, complexity of its components, and non-portability. Therefore, a high precision and low cost portable AE instrument is required. In our previous work [3], a microcontroller-based, AE instrument for detecting valve leakage rates has been invented. This paper will summarize this equipment with additional methods to make it practicable. In previous researches, the empirical model between AE signal and various fluid variables was established by multiple regressions. In addition, a mathematical model to predict the valve leakage rate was also investigated. The relations of AE signal to predict the level of leakage using empirical [4] or mathematical models [5] were investigated. To make the instrument practical, there were studies on an AE system calibration, such as the application of comparatively low cost air-jet for tool wear monitoring [6,7]. It was conducted that the frequency spectra of the AE produced by the air jet and the leakage were very similar to each other and it was possible to convert AErms values obtained from AE sensors of

different frequency characteristics. Identifying failure mode of a valve is also important to understand and analyze the leakage. For the past few decades, several researches have demonstrated a systematic approach to identify dynamic responses of AE signatures correlated with typical failure modes of check valves [8,9]. It was found that locations of peak amplitudes in its frequency spectrum of AE signal correlated to local aging and degradation of internal parts of check valves.

In this work, the progression of a microcontroller-based instrument called Smart Valve Leakage Detector (SVLD) is summarized. An appropriate AE sensor was constructed and used in the SVLD. Empirical regression and theoretical modeling were compared and applied to the equipment. A method based on relative air jet calibration to transfer information between different sensors is also implemented. In addition, a new method to identify leakage sources for in-process valves using coherence functions is proposed. The benefits of the paper are to describe the progression of novel low cost valve leakage rate instrument and the capability of the SVLD.

2. Material and Method

2.1 Development of SVLD equipment

Three main components of the sensor are focused: piezoelectric material, backing material and wear plate. Piezoelectric material (PZT) which is the most important component used for converting elastic waves to AE signals. Backing material was usually used for acoustical absorption [10] to reduce unwanted bouncing signals to the PZT. A wear plate is applied for protecting wearing of piezoelectric element when sliding across the specimen surface.

2.1.1 AE sensor

To efficiently convert mechanical energy to electrical AE signal, an attempted is exerted to design a PZT to match the natural frequency band of the AE source. High frequency sound from valve leakage is generated from turbulence of fluid. It is usually released in the range of frequencies 30 kHz-300 kHz. In this paper, PZT was made from soft piezoelectric ceramic with a resonant frequency of 100 kHz approximately.

Backing material was placed on the backside of piezoelectric material to absorb unwanted signals. Impedance matching between the PZT and the backing material is very important. It was fabricated from tungsten powder mixing with epoxy resin.

Wear plate is normally a thin plastic plate used to cover the exposed face of the piezoelectric element. The thickness of the wear plate is generally designed equal to a quarter of the wavelength of the sound wave to reduce attenuation. An acrylic layer was selected as the wear plate material in this work since it is scratch resistant. It was prepared by coating spays on the surface of the piezoelectric material.

2.1.2 Signal processor

From the previous research work [3], a low cost portable AE instrument for measuring valve leakage based on microcontroller was invented. The electronic parts were consisted of multiplexer circuit, filter, true RMS circuit, signal processor, keypad, Liquid Crystal Display (LCD) and battery. Multiplexer circuit and filter were designed to acquire AE signals and to separate unwanted signals, respectively. True RMS circuit was used to convert a continuous electrical signal to a root-mean-square (RMS) value. The processor was an Arm7 microcontroller for controlling those circuits and for

displaying the results on LCD. The keypad was used as a mean to enter each value of input variables. The LCD was used to display operation status and results.

2.1.3 Software design

The Software was developed using C programming language for initializing the LCD display and communication ports. Each value of the input variables, i.e., size of the valve (D), inlet pressure (P), temperature (T) and gas constant (R) must be entered to the system before the leakage rate calculation. Before using the instrument, background interference (BGN) from the plant must be determined by mounting the AE sensor to a part of the production line, with no leakage. The AE system then convert the primary background interference signal to an RMS value, usually in mV, and store it in the memory of the microcontroller. In measuring phase, the instrument waits for the signal from the valve passing through the AE sensor and the true RMS circuit converts an analog AE signals to AErms (mV). The microcontroller then compares AErms with the previously stored BGN and if it is found to be greater than BGN, the leakage is computed.

2.1.4 Valve leakage model

Acoustic Emission activity is attributed to rapid releases of energy in the material. It can be detected and analyzed using the energy content of the AE signal. For continuous AE signal in time and frequency domains, the most frequently used AE parameters to refer the average energy is the RMS value of the AE signal (AErms). It can be defined as:

$$AErms = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} v^2(t) dt} \quad \dots\dots\dots 1$$

Where v is the voltage signal from an AE sensor, t_0 is the initial time and T the integration time of the signal. To implement an SVLD, the relation between AErms extracted by the true RMS circuit and the valve leakage rate (Q) was developed using two models empirical and mathematical models:

A. Empirical model

From our previous work [4], the empirical model was created by multiple regressions. A design of experiment (DOE) was employed to plan and study significance between AErms and each of various fluid variables. The study was concluded that the main parameters which effect AErms were valve inlet pressure, valve size and the leakage rate. A detailed experiment had been conducted using three sizes of ball valves of diameters 1, 2 and 3 inches, inlet pressures between 1-5 bars and various leakage rates. Then, those parameters were used to create an approximate model to predict the valve leakage rate by multiple regression analysis as:

$$\log(Q) = 1.78 \log(AErms) - 0.54 \log(P_1) + 0.32 \log(D) - 3.60 \quad \dots\dots\dots 2$$

where Q is the volume flow rate (m³/s), AE_{rms} the rms of AE signal value (in mV), D the valve size (m), R the gas constant (N.m.kg⁻¹.K⁻¹), and P₁ the inlet pressure (kg/m.s²).

B. Theoretical model

Although, the empirical model can be applied effectively for the instrument, its generalization is limited. A theoretical investigation into the relationship between the leakage rate (Q) and those significant variables was performed in our previous work [3]. The finding in that work is that the leakage rate is an exponential function of the other variables. A mathematical model for predicting the leakage rate in our portable instrument was found to be

$$Q = 0.31e^{2 \times 10^{-5} \left[\frac{\alpha^5 AE_{rms}^2 D^{14} RT}{R} \right]^{\frac{1}{8}}} \dots\dots\dots 3$$

Apart from the variables used in Eq. (2), AE_{2rms} is the AE signal power (mV²) obtained by experiment, α the sound velocity in the fluid (m/s), R the gas constant (N.m.kg⁻¹.K⁻¹), and T the temperature (K).

2.1.5 Comparison of prediction models

The leakage rate prediction algorithms obtained from our empirical regression and mathematical models were compared. Table 1 shows the mean-square-error (MSE) value of each model. A high MSE value accounts for the lack of fit between the predicted and the reference data. It can be seen that the theoretical model had better accuracy and generalization and it is used in our instrument for predicting the valve leakage rate.

Table 1

The MSE of the each model.

Model	MSE
Empirical	356.25
Theoretical	257.73

Table 1 The MSE of the each model.

A photograph of the instrument is shown in Fig. 1. The instrument was easy to use, convenient and only requires a short lead time during initial measurement. The instrument returns a volumetric flow rate of the leakage in within 3 seconds after mounting AE sensor to an under-test valve. Before performing measurement, the valve must be fully shut off

temporary. Couplant must be applied to the AE sensor before mounting to the valve. The appropriate position for mounting the AE sensor is around the valve flange area or on a flat surface of valve in the downstream side.



Figure 1: Photograph of the instrument.

2.2 Supplementary Functions

2.2.1 Relative calibration approach

In practice, some parameters of AE acquisition system such as AE sensor, instrument gain, reference voltage, and signal attenuation etc., can change from one system to another. To make it possible to apply the instrument in the field, a calibration technique is required. We therefore proposed a relative calibration technique using air jet as the calibration reference source. Air jet was used as an artificial source instead of the actual valve leakage system in our calibration method. This calibration technique can be used to transfer information between systems especially those with different characteristics of sensors.

2.2.2 Identification of Leakage Source using Coherence-based approach

The location of peak amplitudes in its frequency spectrum of AE signal was previously used to identify the source of failures in check valve [8]. However, due to the resonant AE sensor used in our design, the peak amplitude in frequency domain generated from each case can not be easily identified. We therefore proposed an approach based on coherence functions to identify the cause of failure and to improve our portable machine.

In this paper, coherence function had been studied to investigate similarity of two different AE signals [11]. These works applied the function to locate damages in the material by finding a time difference of signals obtained from a pair of sensors. The coherence function was used to determine if the detected signal was adequately similar and to compute the time difference of the similar signals. In valve leakage, various causes such as actual leakage, incomplete closing and loose part of valve generate different magnitude and phase coherence characteristics of AE signals. Since this coherence function can identify similarity of a pair of different AE signals, it is possible to distinguish AE signals generated from different cases.

Coherence-based method applied the ordinary coherence function to indicate the similarity of any pair of signals. Coherence is a function of frequency band (f). It can be used to determining how linearly related a pair of signals are. It can be represented in form of magnitude-squared (γ^2) and phases (ϕ). In the valve leakage, Fig. 2 shows $x_n(t)$ and $y_n(t)$ signals which were the input AE signal and the AE signals from various leakage cases in a library, respectively. The magnitude-squared and phases coherence can be determined by Eq. (4) and (5) respectively [12].

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_{xx}(f) \cdot G_{yy}(f)} \quad \text{..... 4}$$

Where $G_{xy}(f)$ is the averaged cross-spectrum function of the two signals, and $G_{xx}(f)$ and $G_{yy}(f)$ are their averaged auto-spectra.

$$\phi = 2 \times \tan^{-1} \frac{\text{im}(G_{xy}(f))}{\sqrt{\text{Re}(G_{xy}(f))^2 + \text{im}(G_{xy}(f))^2 + \text{Re}(G_{xy}(f))}} \quad \text{..... 5}$$

The similarity of both AE signals from valve leakage can be decided by an averaged value of magnitude-squared throughout their frequency band and linearity of phases coherence. However, the γ^2 is a real number between 0 - 1. In our work, if the value γ^2 were greater than 0.9 and the phase (ϕ) is linearly decreasing along the frequency axis, the two signals were similar. An overview of the method is represented in form of a block diagram as shown in Fig. 2.

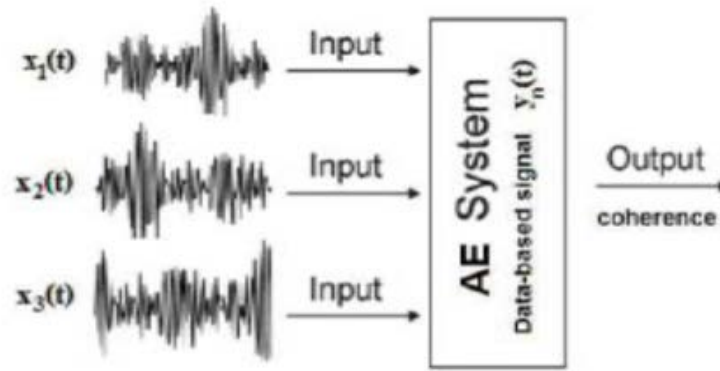


Figure 2: Source identification problems

3. Results and Discussion

3.1 SVLD

3.1.1 Frequency characteristics of proposed AE sensor

In this section we investigate our AE sensor (AE1) and compare it with commercial AE probes: (from Physical Acoustic Corporation or PAC). Air jet is used as an artificial AE source since it produces a wide range of frequency spectrum. The air jet at various pressures was applied to each of the sensors. The frequency responses of each sensor had similar shape but different scales. However, different sensors produced different shapes and resonance frequencies of frequency spectra. AE sensor (AE1) was built and used as a sensing component of the Smart Valve Leakage Detector (SVLD). High-response sensor operating in a frequency range of valve leakage is necessary for AE detection. Typical AErms spectra of the air jet at the pressure of 5 bars obtained from the sensor is shown in Fig. 3. It illustrates the sensor responses in frequency range 30-300 kHz and a resonant frequency at 100 kHz approximately. Since the sensor response agreed with natural frequency band of fluid turbulence, it could be used for valve leakage inspection.

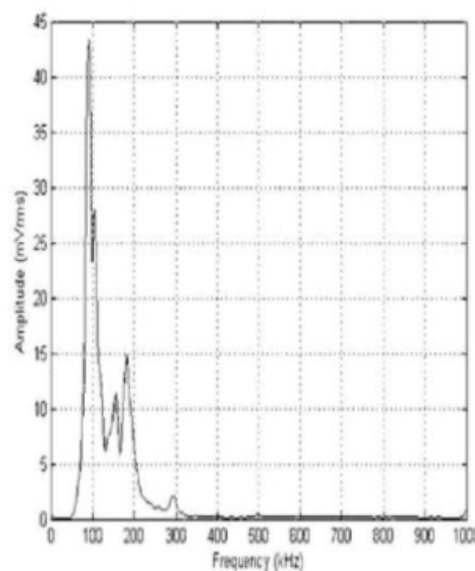


Figure 3: AErms spectra of the sensor (AE1) from applying air jet at 5 bars.

The sensitivities of responses from commercial (R15) and build (AE1) sensors were also examined. An air jet as the artificial AE source was applied to both sensors using the pressure level between 3 to 5 bars. The AErms values were computed from the received AE signals using Eq. 1. The results are presented in Fig. 4. It can be seen that the AErms and air pressure were linearly related. The sensitivities of the two sensors were 20.70 and 8.03 mV/bar when R2, the square of the correlation coefficient between the two observed data values, were 0.99 and 0.98 respectively. Although, the sensitivity (mV/bar) of the AE1 sensor was lower than that of the commercial sensor, it could still be used with an increase in the instrument gain of the signal conditioner. This experiment also justified the application of the air jet as an artificial AE source.

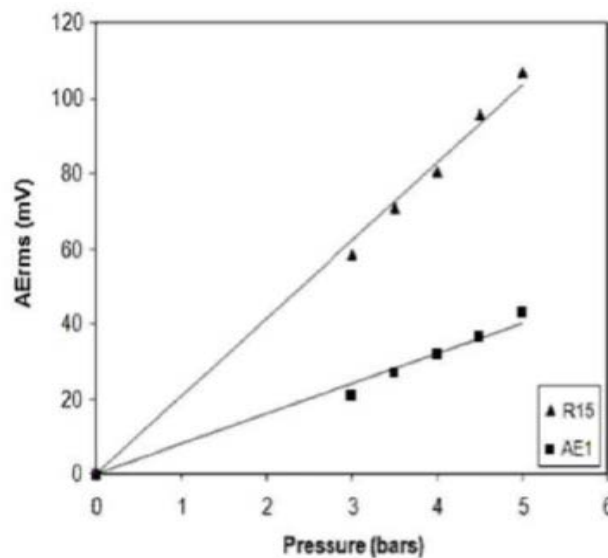


Figure 4: Relation between AErms and air jet pressure from the both sensors.

3.1.2 System Performance

Accuracy of our SVLD was determined by a system calibration. In the calibration, an inline flow meter was used as the reference meter. Leakage rate obtained from the SVLD was compared with that from the flow meter. The experiment was conducted using valve size 1 inch at inlet pressure 1 and 3 bars at various leakage rates. Fig. 5 (a) and (b) show the calibration curves at the inlet pressures of 1 and 3 bars respectively. It can be seen that output of the instrument has a linear relationship to the conventional inline flow meter reading. The R2 of the curves are 0.97 and 0.98, respectively. The overall accuracy is approximately $\pm 8\%$ full scale.

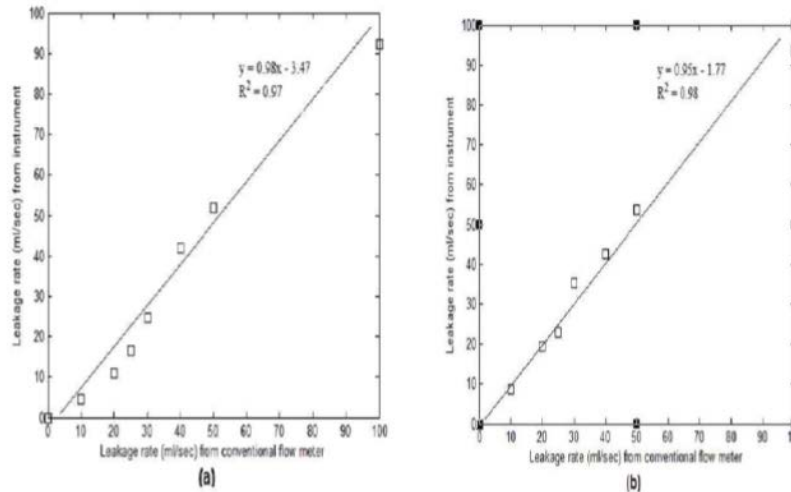


Figure 5; Correlation of leakage rate obtained by SVLD and by conventional flow meter: (a) at inlet pressure 1 bar; (b) at inlet pressure 3 bars.

The sensitivity and repeatability of the SVLD were calculated using data obtained from 5 runs of the experiment, carried out within a short period. The tests were performed using a two-inch ball valve at the inlet pressure of 1 bar. The sensitivity of this instrument was found to be 8.44 mV/l/min. The repeatability can be presented in term of R^2 obtained from the curve fitting. It was 0.93 in our experiment.

3.2 Results of supplementary functions

3.2.1 Relative calibration

In this section, we present results from the proposed method to transfer data between different AE sensors. In our first experiment, a nozzle with a 0.5 mm diameter was placed to the internal side of 1 inch ball valve at a fixed distance of 5 mm. AE1 and WD sensors were installed close to each other on the valve body. The pressure of air jet was varied from 3 to 5 bars. Frequency ratio spectra Gy1/Gy2 of the two AE sensors (AE1/WD) from the air jet at different pressures were plotted in Fig. 6(a). Another experiment was conducted using actual leakage of pressurized inlet air through the valve in stead of the air jet. This was done by varying the valve opening to generate the leakage rate from 6-9 ml/sec. The ratio spectra from different leakage rates were shown in Fig. 6(b).

It can be seen that the shapes of the ratios are similar for each of the results. The average ratio spectra of Gy1/Gy2 (AE1/WD) obtained from the air jet and the valve leakage are shown in Fig. 7. The curves showed that ratio of AE spectra obtained from the air jet were similar to that obtained from the actual valve leakage especially in the frequency range of 100-300 kHz [13]. Similarity coefficient of the curves (obtained from the Pearson coefficient [14]) was found to be 0.81.

To sum up, the air jet can be used as an artificial source for calibrating different AE sensors. The ratio spectra method enables information transferring of system with different sensors. Sometimes there is a requirement for replacing the AE probe; the ratio spectra can be used to transfer information between the two without a great deal of work for retraining the prediction model of the leakage rate. We demonstrated this by applying the air jet at various pressure levels and observing

the AErms from AE1 and WD sensors. The result is illustrated in Fig. 8. It can be seen that the responses has a linear relationship and can be represented by a scaling factor.

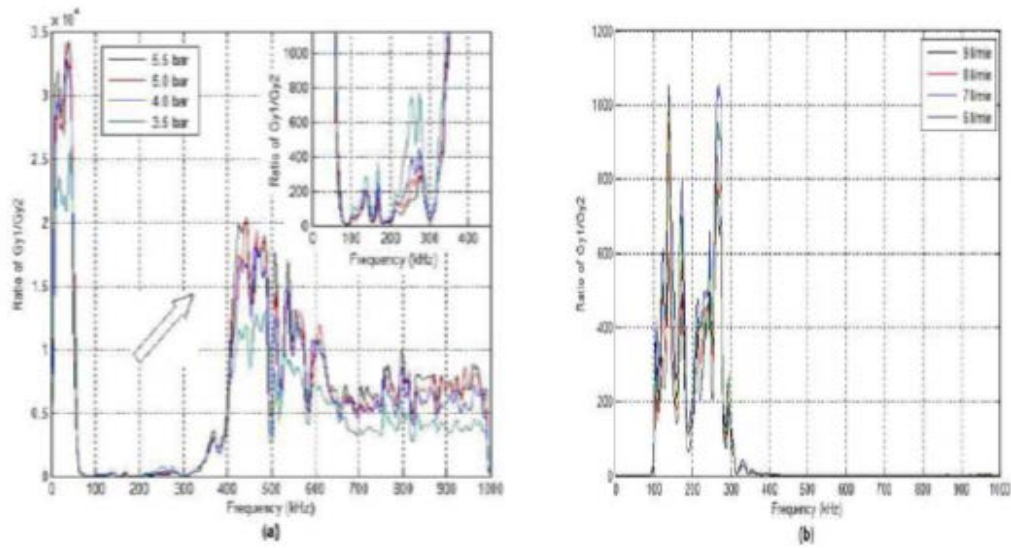


Figure 6: The ratio of Gy1/Gy2 (AE1/WD) of: (a) air jet at pressure from 3 to 5 bars; (b) valve leakage at leakage rate from 6-9 ml/sec at fixed pressure 3 bars.

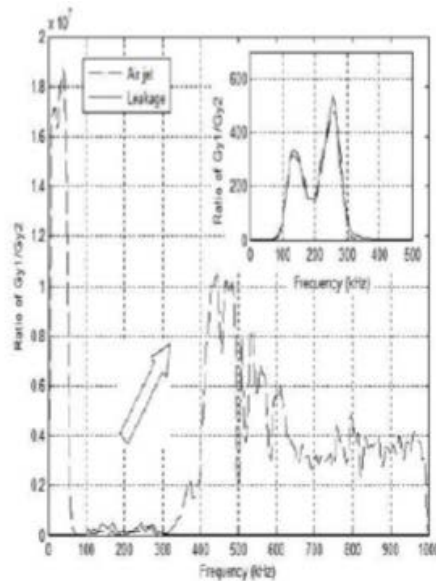


Figure 7: The average ratio of Gy1/Gy2 (AE1/WD) between air jet and valve leakage at various conditions.

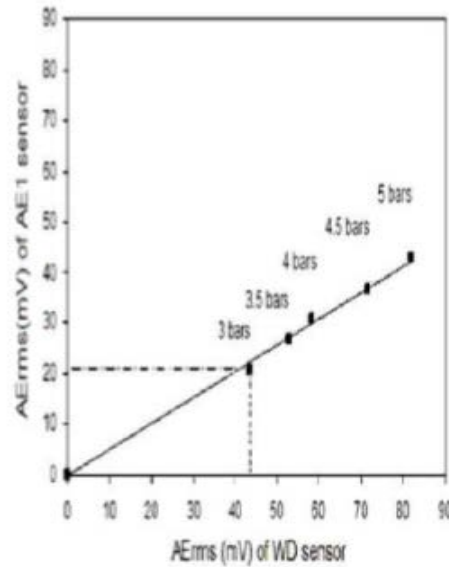


Figure 8: Calibration curve of reference AE sensor (AE1) and another sensor (WD).

3.2.2 Results from Leakage Source Identification

As mentioned previously, valve failure mode can be identified by the frequency at the peak amplitude in the frequency spectrum. However, a high sensitivity of measurement is also needed and it is normally achieved by a resonant-type AE sensor. This prevents us from using the peak amplitude as the indicator of leakage causes.

Fig. 9 shows the frequency response of different leakage causes of valve of size 1 inch at the pressure level 5 bars and leakage rate 9 l/min. It can be seen that locations of the peak amplitudes of both signals are hardly discernable.

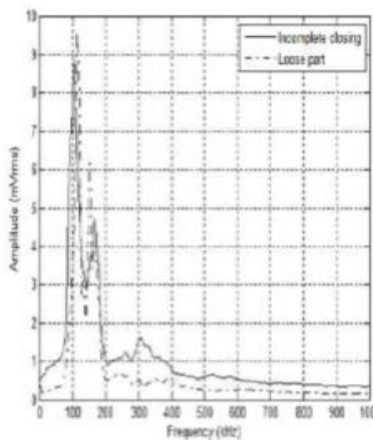


Figure 9: Frequency responses of different leakage causes (incomplete closing and loose part).

To resolve the problem, the coherence function is considered as a tool to identify the causes. Magnitude-squared (γ^2) and phase of the coherence function can be used to identify the failure mode. In our work, if the γ^2 is greater than 0.9 and the phase (ϕ) is linearly decreasing along the frequency axis, the two signals are similar. We conducted experiments on the

source identification for different failure modes and operating conditions. The mode included incomplete closing and loose part. The conditions were a combination of various pressure levels (3-5 bars) and leakage rates (5-9 l/min). The results (details not shown here due to limited space) showed high values of magnitude squared and linear phase shifts along the frequency axis for signals from the same failure mode while those of different modes had low magnitudes and nonlinear phase shifts. Fig. 10 shows an example of the phase coherence (G_{xy}) of responses from unrelated sources of incomplete closing and of loose part. The experiment was conducted using valve size 1 inch at pressure 5 bars and leakage rate 9 l/min. The result showed that the phase was not a linear function. On the other hand, a linear phase function of the signals from loose parts at different pressure levels (4 and 5 bars) is shown in Fig. 11. It was found that the phase linearly decreased over the frequency band 0-1MHz. It can be seen that the coherence function can be used to identify leakage causes accurately; however, the method requires a high sampling rate acquisition and processing system to store, convert the AE signal to a frequency response representation and compute the coherence function.

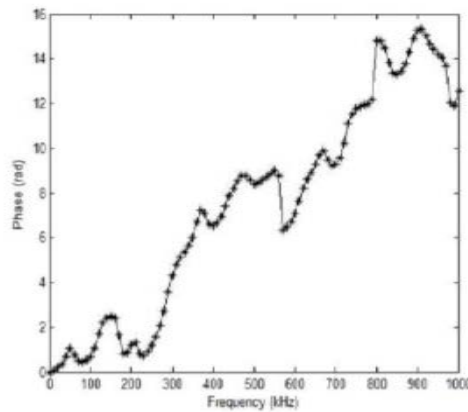


Figure 10: Phase coherence of different leakage causes (incomplete closing and loose part).

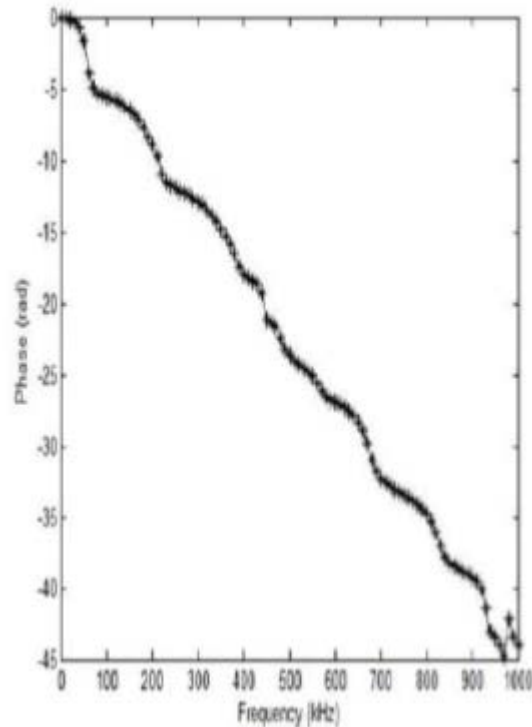


Figure 11: Phase coherence of same leakage causes (loose parts).

4. Conclusions

The objective of this paper is to propose the Smart Valve Leakage Detector (SVLD), based on acoustic emission method. The advantages of SVLD are its portability, cost-efficiency, ease of use and its flexibility to change AE sensor. Progression of our resonance-type AE sensor, data acquisition based on microcontroller and supplementary functions of the detector were summarized. The results from our study suggested that the sensor was highly sensitive for valve leakage inspection. The theoretical model for leakage prediction, used in our instrument, had better accuracy than that of the empirical model. An air jet was selected as a reference source for probe calibration. It can be used to calibrate internal valve leakage and to perform relative calibration for transferring information between different AE sensors. Moreover, magnitude and phase coherence can be used to identify the causes of valve leakage.

5. Acknowledgement

This work is financially supported by the National Research University (NRU) of King Mongkut's University of Technology Thonburi.

6. References

- [1] G. Thompson and G. Zolkieski, An experimental investigation into the detection of internal leakage of gases through valve by vibration analysis, *Proc. IME. E. J. Process. Mech. Eng.* 211 (1997) 195-207.
- [2] T. Juvik and T. Hermansen, Online valve monitoring systems used on off-shore platforms in the north sea, *Proceedings of OMAE 2002: 21st International Conference on Offshore Mechanics and Arctic Engineering*, Oslo, Norway, June 23-28, (2002) 1-5.

- [3] A. Prateepasen, W. Kaewwaewnoi, P. Kaewtrakulpong, Smart portable noninvasive instrument for detection of internal air leakage of a valve using acoustic emission signals, *Measurement*. 44 (2011) 378-384.
- [4] W. Kaewwaewnoi, A. Prateepasen and P. Kaewtrakulpong, Measurement of valve leakage rate using acoustic emission, *ECTI 2005*, Pattaya, Thailand , May 12–13, (2005) 412-416.
- [5] W. Kaewwaewnoi, A. Prateepasen, P. Kaewtrakulpong, Investigation of the relationship between internal fluid leakage through a valve and the acoustic emission generated from the leakage *Measurement*. 43 (2010) 274-282.
- [6] A. Prateepasen, Y.H.J. Au, B.E. Jones, Comparison of artificial acoustic emission sources as calibration sources for tool wear monitoring in single point machining. *J. AE*. 18 (2000) 196-203.
- [7] A. Prateepasen, Y.H.J. Au, B.E. Jones, Calibration of AE for tool wear monitoring, *XVI IMEKO*, Vienna, Austria, September 2000, 255-260.
- [8] M.-R. Lee, J.-H. Lee and J.-T. Kim, Condition monitoring of a nuclear power plant check valve based on acoustic emission and a neural network, *J. Press. Vess-T. ASME* 127 (2005) 230-236.
- [9] J. Dickey, J. Dimmick and P.M. Moore, Acoustic measurement of valve leakage rates, *Mater. Eval*. 36 (1978) 67-77.
- [10] C. Jomdecha, A. Prateepasen, A Resonance Acoustic Emission Sensor using Single Piezoelectric Ceramic (Characteristic and Performances), *KMUTT Research and Development Journal* 29 (2006) 483-498.
- [11] A. Murillo, L. Thorel and B. Caicedo, Spectral analysis of surface waves method to assess shear wave velocity within centrifuge models, *J. Appl. Geophys*. 68 (2009) 135-145.
- [12] U. Grosse, F. Finck, H. Kurz and W. Reinhardt, Improvements of AE technique using wavelet algorithms, coherence functions and automatic data analysis, *Constr. Build. Mater*. 18 (2004) 203-213.
- [13] M. Noipitak, A. Prateepasen and W. Kaewwaewnoi, A relative calibration method for a valve leakage rate measurement system , *Measurement*. 44 (2011) 211- 218.
- [14] R.J. Harris, *A Primer of Multivariate Statistics*, Academic Press, Inc., New York, 1975.