

CHAPTER 2 THEORETICAL BACKGROUND

2.1 Overview

This chapter presents the theoretical background concerned with sound and acoustic emission. Firstly, fundamentals of sound, especially basic sound source, consists of monopole, dipole, and quadrupole are described in a concept. Secondly, pressure-recovery processes related with sound generation of valve are explained. Thirdly, sound sources such as mechanical source and fluid source are described as sound sources from valve leakage. Finally, acoustic emission subject of the phenomena of acoustic emission, acoustic emission measurement system, and AE signal analysis techniques, are also presented.

2.2 Fundamentals of Sound Sources

Sound is a pressure wave that propagates through a medium at some characteristic speed. For fluid medium, sound wave can be generated by the vibration of any solid body in contact with fluid medium, or by vibratory force directly-acting on the fluid, or by the fluctuated motion of the fluid itself, as from turbulence. In each case, energy is transferred from the source to the fluid. Naturally, any motion of one portion of the fluid medium is transmitted to other parts of the medium. The motion in the frontal region of a sound wave at one instant may be regarded as the “source” of the subsequence motion, further along in the medium [52]. This section is devoted to the description of fundamental sound sources.

As previously mentioned in Chapter 1, the AE signal power was a function of the sound power radiated by valve leakage, thus, the sound sources can be considered in three different categorizes; monopole, dipole, and quadrupole sources when the physical mechanisms of fluid dynamically-generated sound and its sound power are discussed [53]. Their main features are explained below.

2.2.1 Monopole Source

A monopole can be considered as simple point source of a fluctuating mass flow, which radiates uniformly in all directions and the size of which is very much smaller than the

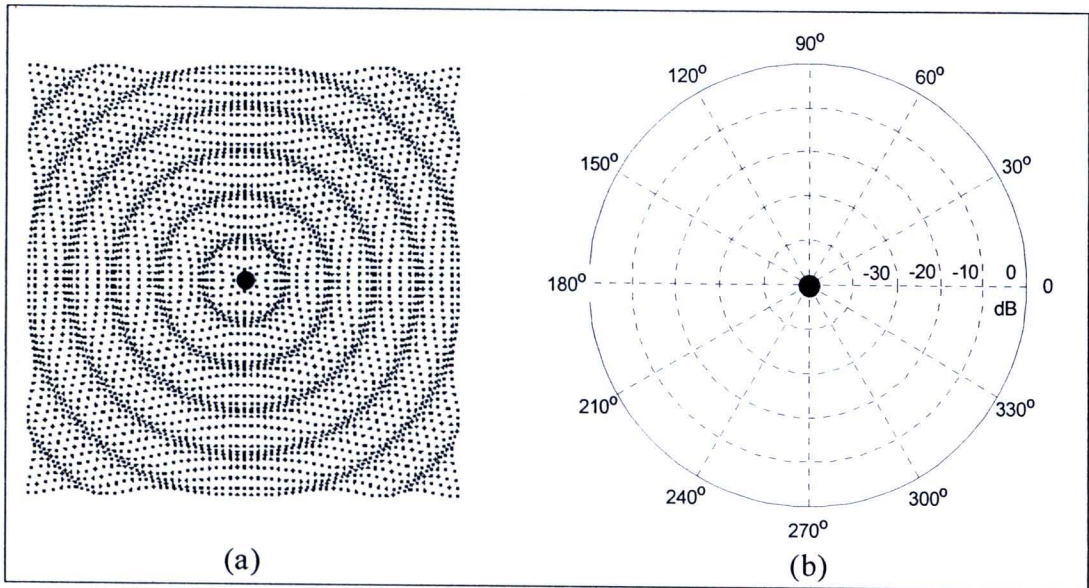


Figure 2.1 Monopole source (a) source motion and (b) sound field [55].

wavelength of the radiated sound. The example of this source would be a sphere whose radius alternately expands and contracts sinusoidally, as shown in Figure 2.1 [54, 55]. The source creates a sound wave by alternately introducing and removing fluid into the surrounding area, for example, boiling or cavitations causing an outward explosion of the fluid, a small pulsating sphere, a small speaker in a small rigid box, and engine exhaust [55, 56, 57].

2.2.2 Dipole Source

A dipole source can be considered as two monopole sources of equal strength but out of phase by 180 degrees and separated by a small distance compared with the wavelength of sound. A fluctuating force is produced due to this opposite phase oscillation [54]. While a monopole source expands the other source contracts, consequently, the air near the two sources moves back and forth to produce the sound. A sphere oscillating back and forth acts like a dipole source. A dipole source cannot radiate sound in all directions equally [55]. The directivity pattern is shown in Figure 2.2. There are two regions where sound is radiated very well, and two regions where sound cancels. There are many real sources of sound that behave like the idealized dipole source, for example, pure-tone fan noise, vibrating beam, un baffled loudspeaker, and sound due to vortex shedding [56, 57].

2.2.3 Quadrupole Source

Quadrupole may be considered to compose of two opposite dipole or equivalently four monopoles [56]. In a Quadrupole arrangement, the two dipoles do not lie along the same line (four monopoles with alternating phase at the corners of a square). The directivity pattern for a quadrupole looks like a clover-leaf pattern; sound is radiated well in front of each monopole source, but sound is canceled at points equidistant from adjacent opposite monopoles, as shown in Figure 2.3 [55].

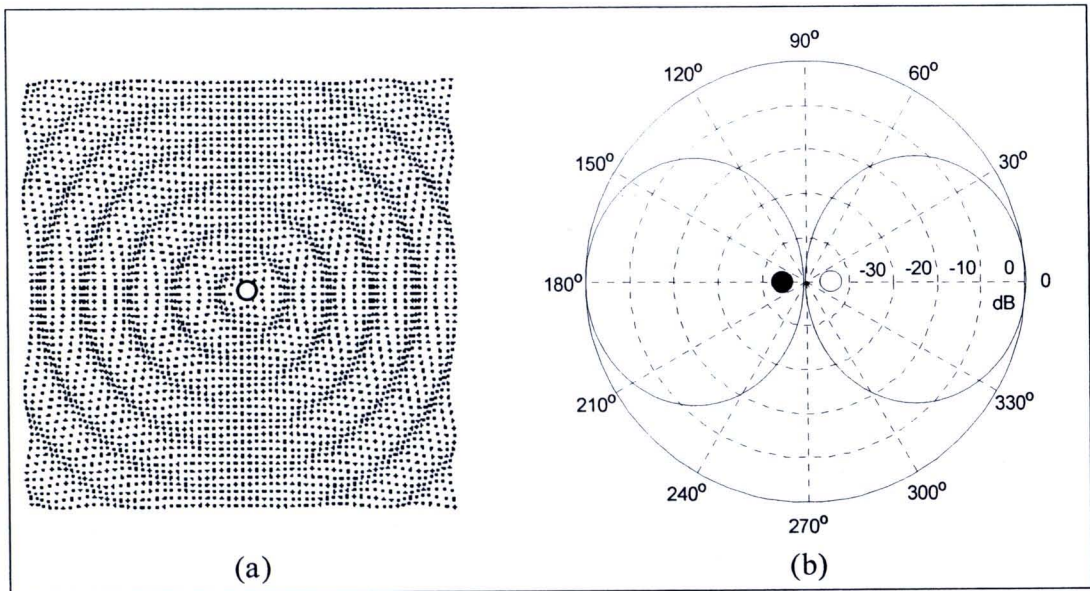


Figure 2.2 Dipole source (a) source motion and (b) sound field [55].

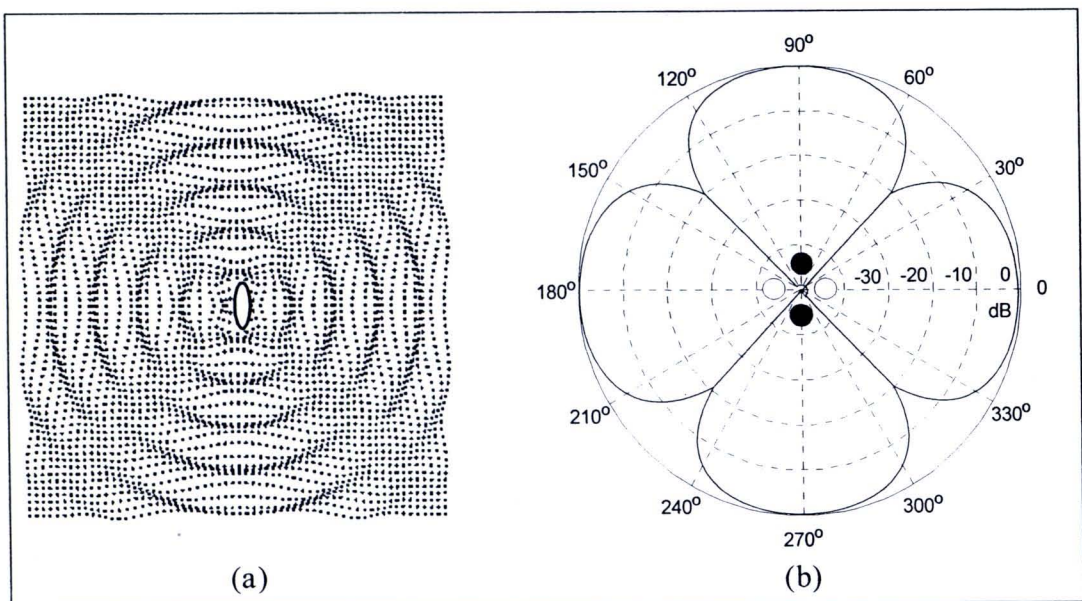


Figure 2.3 Quadrupole source (a) source motion and (b) sound field [55].

Since mechanical stress can be applied to a fluid, fluctuating stresses are often found in areas with large velocity gradients. These can be found in virtually every fluid, but most significantly in turbulence jet flow. It is thought that the sound produced by the mixing process in an air jet gives rise to stresses that are quadupole in nature [57].

In case of sound from fluid motion, especially generated by valve leakage, these sound sources relate with pressure recovery process of valve which described in the next section.

2.3 Pressure-Recovery Processes of Valve

Typically, a valve allows the passage of a fluid from one side of valve to another so that a dynamically-fluid motion is considered. To simplify the understanding, a static pressure can be identified for every point in a fluid flow field. The static upstream pressure (P_1), in inlet side, may be transported or leaked to a fluid at the lower statics or downstream pressure (P_2), in outlet side, by dissipating potential energy stored in the fluid at the higher pressure during the passage of the fluid through the valve. This represents the conversion of potential energy (inlet pressure level) to kinetic energy (velocity), and back to potential energy (outlet pressure level), where a recovery pressure factor, which is a function of pressure drop across the valve, represents energy lost to waste heat and a small fraction to sound.

Therefore, this section will begin with consideration of possible regimes of operation associated with pressure recovery process in a valve, as shown in Figure 2.4. Consideration of the regimes of operation in turn provides the means for determining the sound sources and the sound power entering the valve. In addition, the sound estimation procedure will also be described in this section.

Referring to Figure 2.4, when the fluid at higher pressure P_1 enters the lower pressure P_2 through the valve orifice, a confined jet is formed which is characterized in turn by a vena contracta and minimum static pressure, P_0 , after which the static pressure rises to P_2 . This recovery process allows an increment in pressure from the minimum pressure to the existing downstream pressure P_2 , which is rather than P_0 .

To quantify pressure recovery and sound-generating behavior of incompletely closed valve or leaking valve, a quantity, F_L , is called “pressure recovery factor” has been defined. The definition, which forms the basis for its determination, is given in terms of following relation involving the inlet static pressure, the outlet static pressure and the static pressure in the vena contracta [58]:

$$F_L^2 = \frac{P_1 - P_2}{P_1 - P_0} \quad (2.1)$$

Referring to Figure 2.4 or to Equation 2.1, it may be noted that F_L has the value 1 when $P_2 = P_0$ and there is no pressure recovery. However, in this case sound generation must be maximal because it is always a fraction of the energy dissipated which is maximal here. On the other hand, F_L has the value 0 when $P_2 = P_1$ and there is complete pressure recovery. In this case, no energy is dissipated and thus no energy has been converted to sound.

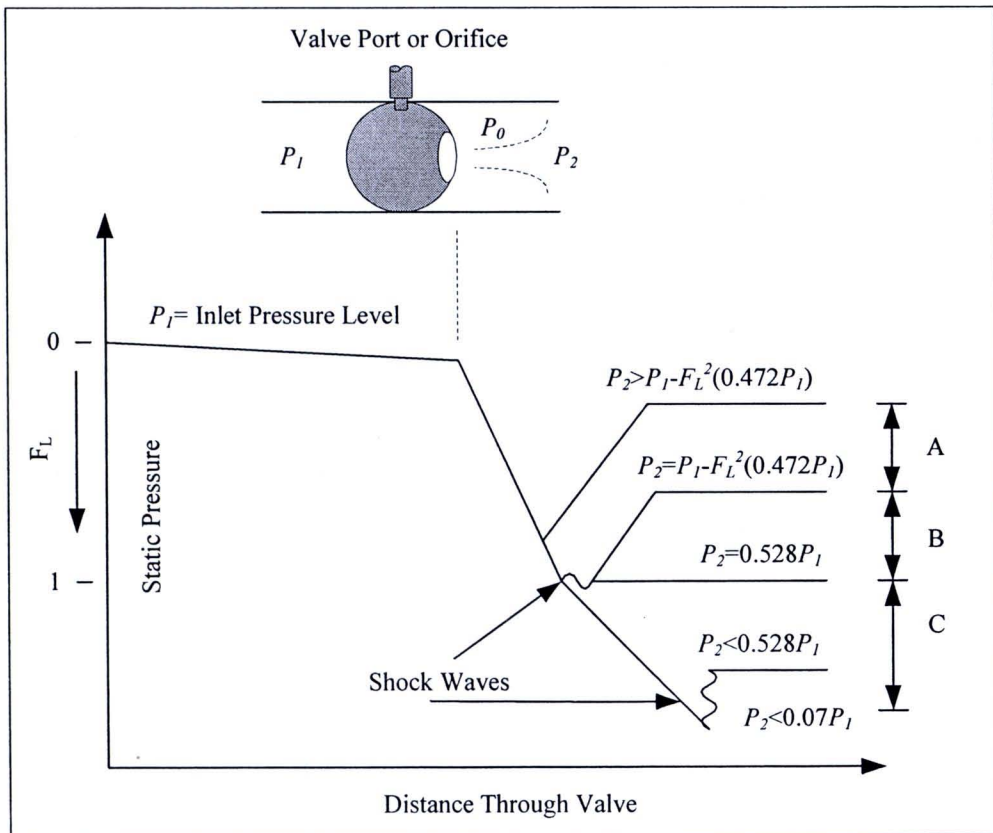


Figure 2.4 Air jet showing mixing regions and sound source from valve leakage [58].

When considering sound generation in a valve using this prediction procedure, three regimes of operation and associated energy dissipation and sound generation mechanisms may be defined. These regimes may be understood by referring to Figure 2.4 during the following discussion where they are defined as A, B, and C. In pressure regime A, the flow through the valve is everywhere subsonic and all energy dissipation is accomplished by large scale turbulence. In this case, sound generation is found to be proportional to sixth power of the stream speed which implies that it is dominated by fluctuating forces acting on the fluid and thus dipolar in nature. When the flow is sonic at the vena contracta and is subsonic in pressure regime B ($P_2 > P_0$), sound generation becomes to be proportional to the eighth power of the stream speed. In this regime, the sound-generation of quadrupoles associated with intense turbulence of the jet through the valve.

The pressure recovery which has been used to establish the bound between two pressure regimes of A and B of operation is seen to be determined by the pressure ratio P_2/P_1 at which the flow in vena contracta becomes sonic, as follows [58]:

$$\frac{P_0}{P_1} = \left(\frac{2}{(\gamma + 1)} \right)^{\gamma/(\gamma-1)} \quad (2.2)$$

For gases, where $\gamma = 1.4$,

$$\frac{P_0}{P_1} = 0.528 \quad (2.3)$$

Solving Equation 2.1 for pressure ratio P_2/P_1 and using Equation 2.2 gives the pressure ratio across the valve, $P_2/P_1 = P_{2crit}/P_1$, at which the vena contracta is sonic. The equation has been used to establish the bounds between pressure regimes A and B in Figure 2.4, as follows [58]:

$$\frac{P_{2crit}}{P_1} = 1 - F_L^2 \left[1 - \left(\frac{2}{(\gamma + 1)} \right)^{\gamma/(\gamma-1)} \right] \quad (2.4)$$

In pressure regime C, the pressure ratio across the valve P_2/P_1 , is less than P_0/P_1 given by Equation 2.3 and the flow is supersonic everywhere in outlet side. In this regime, energy dissipation is dominated by shock formation and sound-generation is maximal. The critical pressure ratio when $P_2 = P_0$ or $P_2 = 0.528P_1$ and flow through the valve is subsonic and supersonic as the bound between pressure regimes B and C and under pressure regimes C, respectively.

For pressure recovery processes, these regimes presented in this section are concerned with the intense turbulence and shock formation in the valve. This agrees with the next section that addressed by the possible sources of sound from the valve leakage, e.g., impingement of the fluid, turbulent mixing, turbulence/boundary interaction, shock/turbulence interaction, flow separation, and vortex shedding.

2.4 Sound Sources from Valve Leakage

This section mainly considers the possible sound source from valve detected by AE measurement system (The details of this system will be described in Section 2.6.2). Typically, valves, which used in fluid lines, have a significant source of sound in transmission systems. Most of relevant researches in the literature review, in the AE field, just have merely mentioned that turbulence is a major source of sound although the mechanisms of sound generation in valves are complex. Moreover, there are not considerate other sources for any modeling. Therefore, before embarking on the model for predicting valve leakage rate, it is worth considering the source of sound that is one of the components of physical sound.

In the field of noise and vibration control, the primary sources of sound generate by valves can be divided into two main categories (i) mechanical source and (ii) fluid source [59]. The first category consists of mechanical vibrations of flexible parts of valve. The second category consist of the sound source caused by turbulent mixing, turbulence/ boundary interaction, shock/turbulence interaction, flow separation, and vortex shedding [60, 61] as described. Some of mentioned sources are illustrated in Figure 2.5. Thus, this section described major source of sound and its mechanism generated by valve leakage as follows.

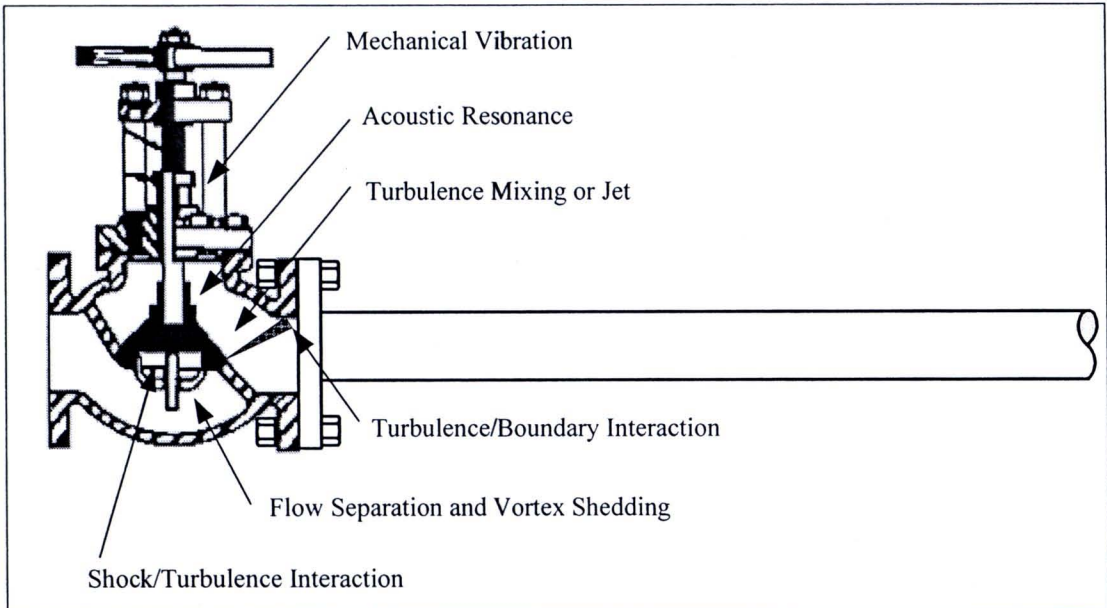


Figure 2.5 Schematic representation of the static pressure distribution through a valve with inlet pressure level (P_1) and outlet pressure level (P_2) [60].

2.4.1 Mechanical Sources

Sound that generated in this case is a by-product of the mechanical vibration of valve components. This vibration results from flow-induced random pressure fluctuations in the fluid within the valve and from impingement of the fluid against flexible parts of the valve. In conventional valve, the main source of noise from mechanical vibration arises from the sidewise motion of valve plug within its guiding surfaces. This sound source usually produces sound at frequencies below 1.5 kHz and are often classified as a metallic “rattling” sound. In fact, sound from valve vibration could be considered beneficial, because the noise warns of conditions in the valve (wear, clearance, etc.) that result in valve failure [59].

Another source of mechanical vibration arises from valve components resonating at their natural frequencies. Resonant vibration of valve components produces a pure-tone component, usually in the frequency ranges between 3 kHz and 7 kHz. This vibration can cause high stress in the component that may lead to fatigue failure [59].

The AE method is not rather sensitive than the vibration method to detect these mechanical sources, because the frequency of sound released from mechanical vibration

fall within the operating frequency range of the vibration method. In practice, however, the use of vibration method may produce the inconclusive results especially when this method is used in noisy environment in industry.

2.4.2 Fluid Sources [60, 61]

Since air is selected as the test subject in this research, a fluid source concerned within this dissertation is an aerodynamic sound. Possible sources of the sound are as follows.

1. Turbulence Mixing or Turbulence Jet

In the fluid system of various plants, valve which is used to start, regulate, and relieve flow, converts kinetic energy not only to heat but also to acoustic and vibration energy. The turbulent mixing are arise by the throttling, radiates an extreme aerodynamic sound in the vicinity of the valve and downstream piping with high frequencies of more than several kilohertz [61].

The simplest example of a turbulence jet is the high velocity of airflow emanating from a reservoir through a nozzle, as illustrated in Figure 2.6. The actual generation of the sound from air jet results from the creation of fluctuation of shearing stresses as the high velocity of air flow interacts with surrounding air. The radiating sources, called eddies, are then formed, with the high frequency sound generated near the nozzle in the mixing or shearing region, and the low frequency sound generated downstream in the region of large scale turbulence [62].

In valve case, high frequency components of the AE signal emitted from the leakage are attributed from mixing region of turbulence jet of fluid flow inside the valve passing the valve seat or seal, as shown in Figure 2.7. This is because the movement directions of fluid particles are in a disorderly manner and there are changes of momentums from one part of the fluid to another non-directionally. As a consequence, shear crashing of particles at high velocities generates the high frequency components. Therefore, the spectral characteristics of air jet sound are generally broadband. The continuous acoustic waves normally have their frequencies ranging from 100 kHz to 1 MHz [63]. Pollock and Pepper [64] reported that the predicted center of quadrupole radiation caused by turbulence mixing was around 130 kHz. In this case, the sound generation process can

be distinctively categorized into the subsonic regions. Additionally, the velocity profile organized by motion of the jet is transformed by a nonlinear process into the heat and acoustic energy, the sound is being generated outward into the other surrounding medium [62].

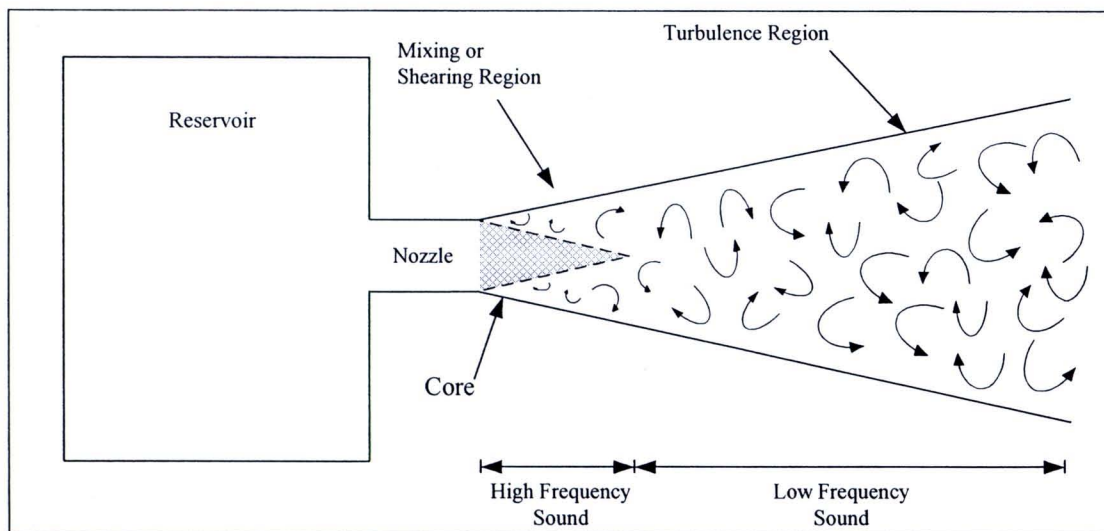


Figure 2.6 Schematic of nozzle sound source [62].

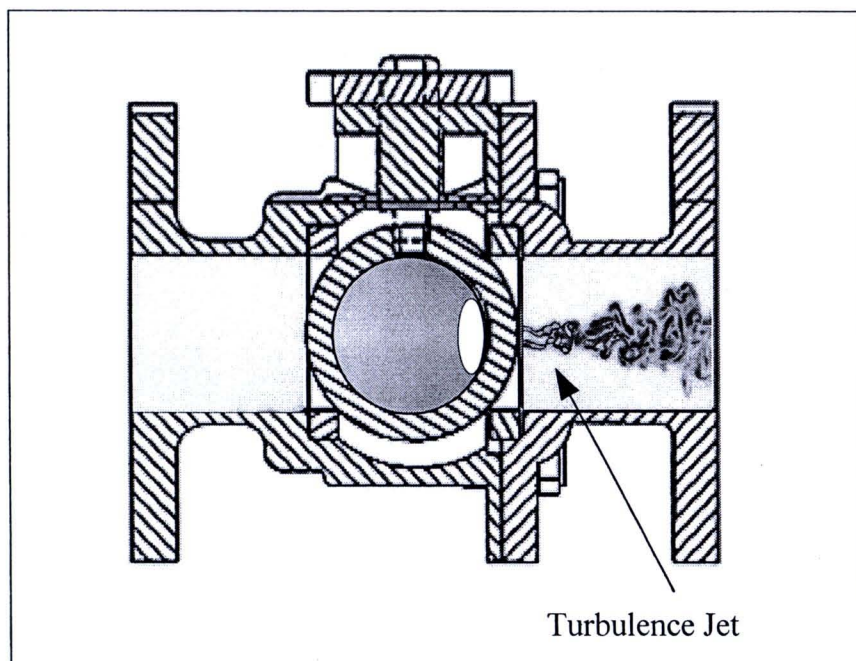


Figure 2.7 Mixing region of turbulence jet generating AE source from valve [62].

2. Turbulence/ Boundary Interaction

Since flows pass the construction and valve seat within the valve, an area or cross section of flow are suddenly changed. As a result, the sound of the valve results from flow instability, which is turbulence, in fluid within the valve. The interaction between random pressure and boundary layer induces the mechanical vibration called turbulence/ boundary interaction [60].

3. Shock/Turbulence Interaction

In this case, the actual sound production mechanisms in a valve are complex. There are primarily two principal sound mechanisms. When the fluid at higher upstream pressure (P_1) changes into a fluid at lower downstream pressure (P_2) through the valve seat, a confined jet is formed. The primary sound mechanism is due to the turbulence downstream of the vena contracta. This is called turbulent shear flow which falls within a mixing shearing region. In case of $P_2 \ll P_1$, the flow gets more powerful due to the higher pressure drop across the valve, and the normal shock initiating to move further downstream and starts to break up into several smaller shock cells. From each of these shock cells, shock waves are formed which travel downstream at some angle on centerline. These shock waves bounce off the wall inside valve and are reflected across to the opposite wall. As these reflected waves go bouncing down the pipeline, they pass through the area of turbulent shear flow creating sound energy. This is called shock/turbulence interaction [60].

4. Flow Separation and Vortex Shedding

Vortex shedding is an unsteady flow that takes place in special flow velocities (according to the size and shape of the cylindrical body). In this flow, vortices are created at the back of the body and detach periodically from either side of the body. Vortex shedding is generated when a fluid flows past a blunt object. The fluid-flow past the object creates alternating low-pressure vortices on the downstream side of the object. The object will tend to move toward the low-pressure zone and vortex shedding can occur [60].

Although this work focuses on the turbulent jet as a source of AE measurement system, the turbulence/ boundary interaction and the shock/turbulence interaction have

complicated to investigate the sound generated by these sources [60, 61]. Thus, the next section addresses the sound power from the turbulent jet based on Lighthill's theory. This leads to the derivation of the model based on assumption (as described in Chapter 3) that the sound power is directly related to AE signal power.

2.5 Sound Power based on Lighthill's Theory

Aerodynamic sound generated by turbulent flow has been treated extensively in the literatures. In general, there are three basic acoustic sources, namely monopole, dipole and quadrupole, which depend strongly on the velocity and pressure fluctuations in the region of turbulence. Although, valve noise generation is a confined jet mixing process, it basically has intrinsic characteristics of a free jet. From dimensional analysis, Lighthill has shown that the sound power output of a subsonic jet consists of quadrupole sources and is proportional to fluid variables, as given by [62]

$$W = \frac{K_0 \rho A v^8}{\alpha^5} \quad (2.5)$$

where W is the sound power (Watt),
 ρ is the density (kg/m^3),
 α is the speed of sound (m/s),
 v is the velocity (m/s),
 A is the area of the jet nozzle (m^2), and
 K_0 is a constant of proportionality (unitless).



2.6 Acoustic Emission

2.6.1 The Phenomenon of Acoustic Emission

Acoustic emission (AE) is a technical term referred to a natural phenomena occurring in wide range of materials and structures and referred to a nondestructive testing (NDT) technique. Formally, AE is defined as a phenomenon where transient elastic waves are generated by the rapid release of energy from localized sources within a material. This is a definition embracing both the process of wave propagation and the wave itself [65].

The application of AE to nondestructive testing of materials in the ultrasonic regime, typically takes place between 100 kHz and 1 MHz, as shown in Figure 2.8. Unlike conventional ultrasonic testing, the major differences between the AE method and other NDT methods are attributed in two significant respects. Firstly, this method is passive that the detected energy is released from within the test object, whereas most others are active. Secondly, the AE method can be applied to detect the dynamic processes associated with the degradation of structural integrity [65, 66]. Since the passive AE waves cannot be recognized by their appearances, these must be analyzed by a various AE signal analysis techniques, as describe in Section 2.6.3.

AE source includes many different mechanisms of deformation and fracture. Sources that have been identified in metals include: crack growth, moving dislocations, grain boundary sliding, and the fractures of inclusion. These mechanisms associate the classical response of materials to applied load. Other mechanisms that fall within the definition are not irreversible in releasing energy from material failure, but they can be detected by AE equipments. These include: leakages, cavitations, impact, and friction in rotating bearing called *secondary source* or *pseudo source* (to distinguish them from the classical AE). Accordingly, all of these research works concern with *pseudo source* [65].

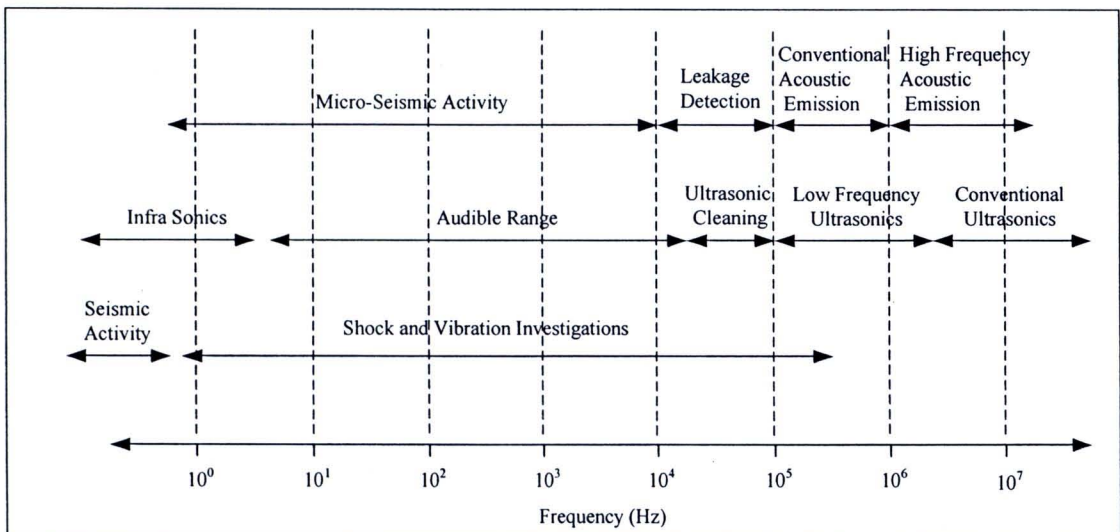


Figure 2.8 Acoustic emission, sonic, and ultrasonic spectrum [66].

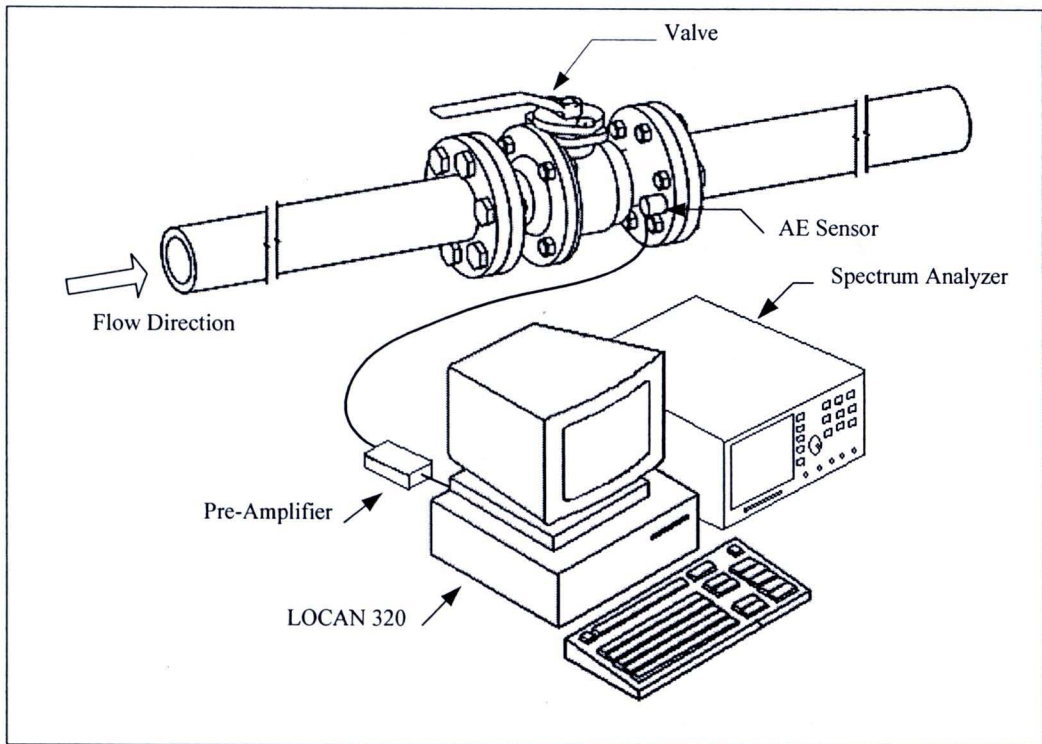


Figure 2.9 AE measurement system.

2.6.2 Acoustic Emission Measurement System

Many studies of valve leakage apply the AE technique in their investigations with various AE equipments. Although the processes involved in these applications are quite different, the basic equipment required for the measurements is the same for all the applications. Figure 2.9 illustrates the schematic representation of the AE measurement system in valve leakage applications.

1. AE Sensor

The AE sensor is an important and fundamental element for the efficiency of the AE wave detection. In an ideal case, an AE sensor should have small size, flat response, wide frequency range, and high sensitivity. Nevertheless, these do not generally come together in an AE sensor. There are a variety of AE sensors, produced by different companies (Only Physical Acoustic Corporation: (PAC) has more than 40 different models) [67] and adequate for most applications; because the different sensors are available from AE manufacturer corresponds to the variety of demands and applications. The most important characteristic of AE sensor for valve leakage detection is its operating frequency range.

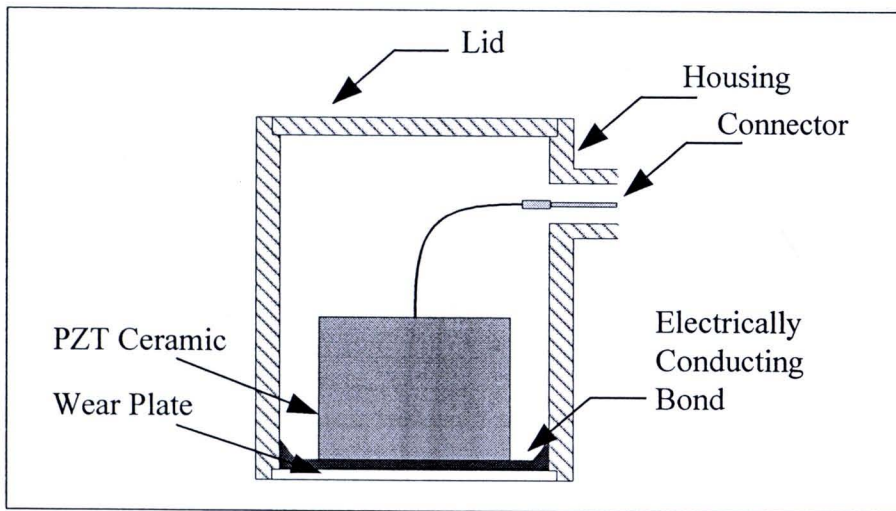


Figure 2.10 Structure of AE sensor [67].

AE sensors, having the sensing element based on lead zirconate titanate, piezoelectric (PZT) ceramic, are commonly used due to its ease of use, low price, and sufficient sensitivity. The capture process depends upon the piezoelectric effect, which converts small surface displacements into electrical signals that can be amplified and recorded. The basic components of an AE sensor are constructed as shown in Figure 2.10.

Traditionally, there are two types of AE sensor based on PZT disc: (i) wideband sensor and (ii) resonant sensor. Wideband sensors are usually selected when waveform analysis is desired because of its bandwidth flattened over the frequency range. In the other word, they are used in analyzing the frequency characteristics of the detected AE signals. A bandwidth of wideband sensor is simply increased by mass loading/damping the PZT disc, but sensitivity of AE sensor becomes poor [68].

Resonant sensor is employed to improve the sensitivity. The frequency response of this sensor type dominates around its natural frequency, depending on its thickness. The resonant sensors are useful in applications where unwanted acoustic noises are present outside the frequency response region [68].

In this application, peak amplitude is raised by increasing leakage rate at frequency around 150 kHz. Thus, the narrow band resonant sensor operating with this peak is recommended for practical valve leakage detection. The resonant type of AE sensor,

model (R15), manufactured by Physical Acoustic Corporation (PAC) were mainly chosen for AE measurements, as shown in Figure 2.11(a). R15 sensor has a resonant response center on 150 kHz, and operating frequency range of the sensor is from 50 kHz up to 200 kHz. Since the major objective of this dissertation aims to model and predict the leakage rate quantitatively, the AE signals received by a resonance AE sensor have better sensitivity than those by the wideband type.

The wideband sensor, model (WD), was also used to measure the AE waveforms, as shown in Figure 2.11(b). Because of its wide operating frequency range, signals obtained from a WD sensor are suitable for signal characterizations. Thus, the spectrum analysis of these signals is meaningful. The operating frequency range of WD sensor is from 100 kHz up to 1,000 kHz.

2. AE Coupling and Mounting

Couplant is essential to fill the air gap between sensor and structure, to achieve an efficient coupling of the AE wave energy from valve body into the sensor. Ultrasonic gel was generally used as a couplant to improve sensitivity. It is easy to apply and clean off after use and it has high viscosity. Consequently, Ultrasonic gel is suitable for vertical mounting of AE sensor.

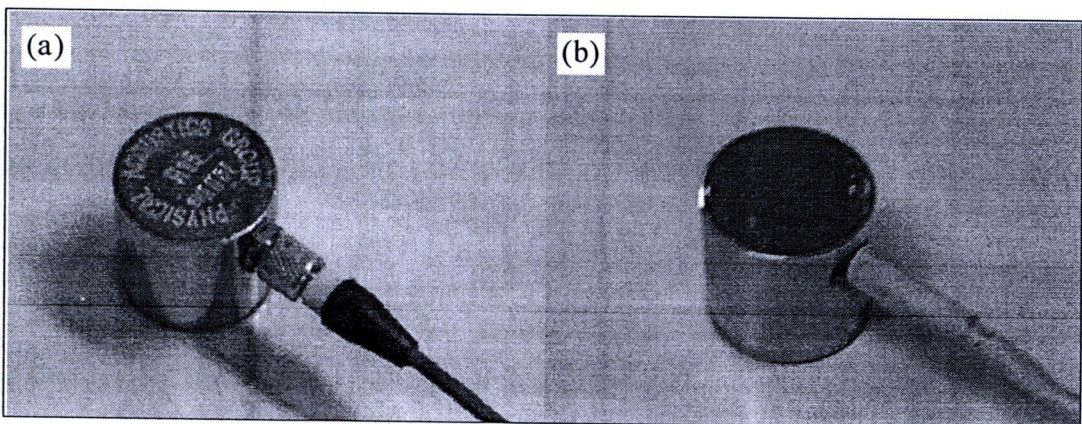


Figure 2.11 AE sensor (a) resonant type; model R15 and (b) wideband type; model WD.

To maximize energy transmission, the chosen surface of valve should be prepared by cleaning and smoothening. The mounting position of the AE sensor was on the smooth surface of valve flange with an application of a couplant to improve sensor sensitivity and signal attenuation due to impedance mismatch at the interface between AE sensor and the valve body. The most common mounting is to press the sensor to the surface with tape or magnet. To maintain good reproducibility, standard pencil-lead-breaking was performed every time prior to recording the AE signals. [68]

3. AE Preamplifier and Filter

Most of AE measurement systems use preamplifier between the AE sensor and the other instrumentation, typically as close to the AE sensor as possible; to minimize signal loss in the connecting cables. The preamplifier must have a low input noise and a large dynamic range to scale amplitude without saturation. The suitable preamplifier level is based on the signal source level and the saturation limits of the data acquisition system.

First, the AE preamplifier receives the AE signals and then drives them to other components. The main function of preamplifier is not only to amplify but also to match the sensor impedance to the signal cable and electrical component impedance. A low output impedance (usually about 50Ω) of AE preamplifier is required to drive a long cable [69]. A small preamplifier may be embedded into the AE sensor for reducing equipment costs and decreasing set-up time for field applications. In addition, filter may be included to reject undesirable signals. Since such AE preamplifiers unavoidably generate electrical noise, their signal-to-noise ratios should be large to enhance the AE measurement [69].

In this dissertation, a preamplifier, model 1220A, by PAC was used as a signal conditioner, as shown in Figure 2.12. It was set at the gain of 60 dB and was connected to an analogue band-pass filter with a cut-off frequency between 100 kHz and 1200 kHz to eliminate mechanical and background noises that prevailing outside this range. In order to eliminate background noise, a band-pass filter operated in the range of 100 kHz to 400 kHz is normally used.

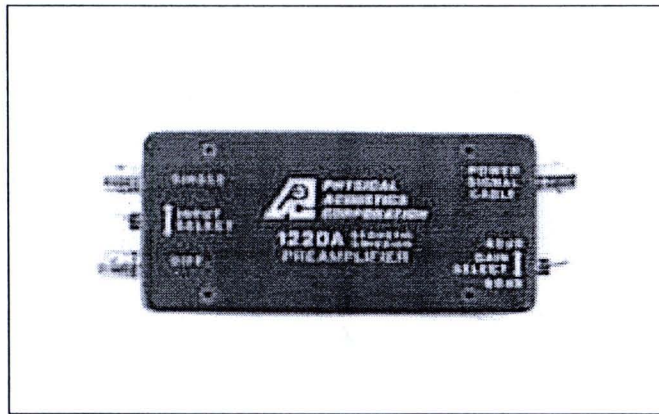


Figure 2.12 Preamplifier; model 1220A.

4. AE Data Acquisition

The voltage signal received from the AE sensor and the preamplifier is analog and continuous. This signal can be sampled and converted to a digital signal and displayed on devices such as AE multi-channel workstation (LOCAN320), spectrum analyzers and PC. The LOCAN 320 from PAC was employed for this study, as shown in Figure 2.13. The LOCAN 320 is a model of computerized acoustic emission system from PAC that performs AE signal measurements, stores, displays, and analyzes the AE data such as AE parameters. Each channel requires its own AE sensor, preamplifier, and connecting cables [68].

In this study, the LOCAN320 was proposed to amplify AE signals to useable voltage levels with a gain of 20 dB. A spectrum analyzer, HP 89410A, (with a maximum sampling rate of 10 MHz) was also used to record the AE waveforms in both time and frequency domains, as shown in Figure 2.14. The AE waveform was recorded and converted to AE parameter, AE_{RMS} , by a PC.

5. AE Signal Processing Program

The AE signals digitalized in the HP 89410A was processed by PC to extract relevant information from the AE arbitrary waveforms. This was done in MATLAB (version 2008a).

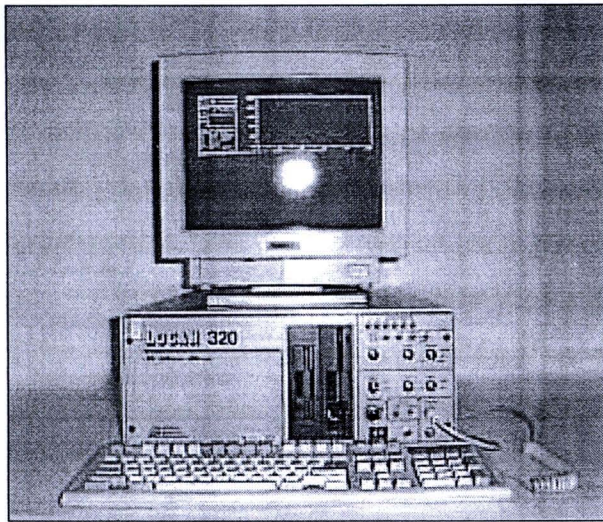


Figure 2.13 LOCAN 320 AE data acquisition.

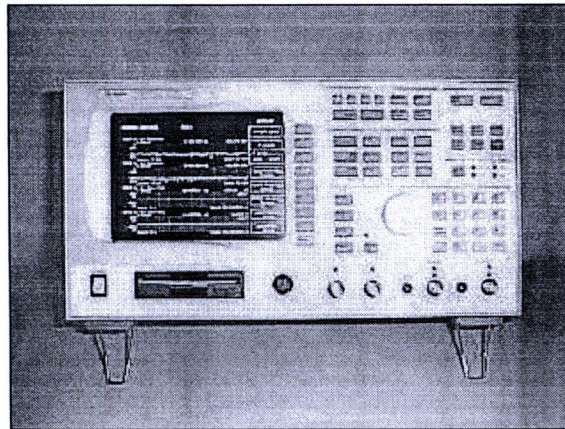


Figure 2.14 HP 89410A spectrum analyzer.

2.6.3 AE Signal Analysis Techniques

After the preamplifier, the AE signal is transmitted to the AE data acquisition system by a cable. The data acquisition system can filter (eliminate unwanted signals or frequencies), or amplify the signals. It can also record, and organize the AE data. Most of the time data acquisition software can instantly plot graphs and analyze the data, which is helpful for inspectors to understand what is happening during the test. In general, the signal analysis techniques are used to analyze the AE signals and extract features related to AE signal types. Typically, the AE signals generated by an AE source can roughly be divided into two categories, (i) discrete or burst and (ii) continuous.

1. Discrete AE Signal

Type Crack growth is an excellent example of a discrete AE generation mechanism. It is characterized by individual events or bursts of energy. These events can show initial and final time relating the individual crack growth [70]. Typically, various signal-processing techniques are used to analyze discrete or burst AE signals and to extract features related to defects. Usually, a threshold level is defined to segregate the signal from the background noise. The AE threshold needs to exceed this value before further analysis. An AE event is an individual signal burst produced by local material change as shown in Figure 2.15. Basics AE parameters are designed to identify defects:

Threshold (Voltage Threshold)

“A voltage level on an electronic comparator such that signals with amplitudes larger than this level will be recognized. The voltage threshold may be user adjustable, fixed, or automatic floating.” (ASTM E 1316). The threshold is set for eliminating electronic background noise, which normally has low amplitude.

Count (AE count)

“The number of times the acoustic emission signal exceeds a preset threshold during any selected portion of a test” (ASTM E 1316).

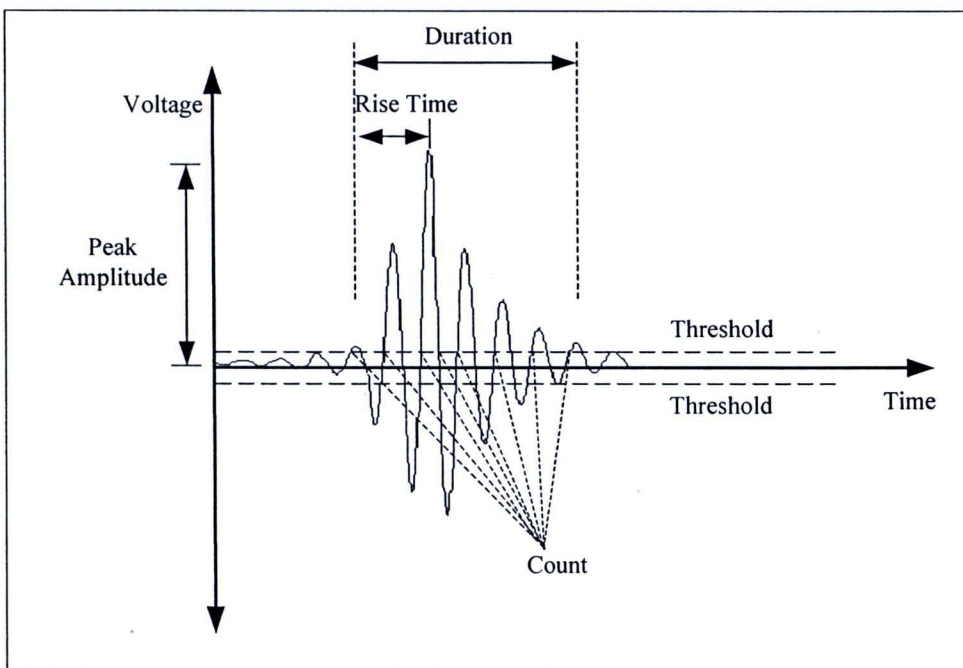


Figure 2.15 Basic AE parameters of burst AE signal type [70].

Peak Amplitude (AE Signal Amplitude)

“The peak voltage of the largest excursion attained by the signal waveform from an emission event” (ASTM E 1316). In other words, peak amplitude is the highest point of the signal. It is the absolute value on either positive or negative side of a waveform.

The peak amplitude is usually reported in decibels (dB) due to its wide range of typical values in voltage unit. Voltage is converted to decibels using the following equation:

$$A_i = 20 \log \frac{V}{V_{ref}} \quad (2.6)$$

where A_i is the amplitude in decibels (dB_{AE}),
 V is a voltage of peak (V), and
 V_{ref} is a reference voltage, typically 1 μV.

Duration

“The time between AE signal start and AE signal end” (ASTM E 1316). It is the time from the first to the last threshold crossing and is typically displayed in microseconds.

Rise Time (AE Signal Rise Time)

“The time between AE signal start and the peak amplitude of that AE signal” (ASME E 1316). Rise time is also measured in microseconds.

Energy (AE Signal Energy)

“The energy contained in a detected acoustic emission burst signal, with units usually reported in joules and values which can be expressed in logarithmic form (dB, decibels)” (ASTM E 1316). Specifically, energy is defined as:

$$E = \frac{1}{R_0} \int_0^{\infty} V^2(t) dt \quad (2.7)$$

where E is the electrical energy (V²),
 $V(t)$ is the voltage of signal (V), and

R_0 is a resistance of measurement device (Ω).

Hit (AE Hit)

“The detection and measurement of an AE signal on a channel” (ASTM E 1316).

Event (AE Event)

“A local material change giving rise to acoustic emission” (ASTM E 1316).

Frequency

Frequency is the number of cycles per second of the pressure variation in a wave. Commonly, an AE wave consists of several frequency components.

2. Continuous AE Signal

Type Continuous AE signals are generated by such sources as fluid leakages, cavitations in flowing liquids and the plastic deformation of solids. These signals cannot distinguish the initial and end time certainly, as show in Figure 2.16, but these can be separated by determining periods to consider [71]. The AE sources of interest for this current work are predominantly associated with leakage and so only continuous signals are considered. From review of literature, many researches [32, 33, 34, 35] illustrated that the leakage waveforms detected by AE was continuous and random. Figure 2.17 shows the different types of random signals. It can be classified in two categories: (i) stationary signal and (ii) non-stationary signal [72]. When the generating sound from turbulence flow presents, statistical methods can be used to describe the character of the sound. Thus, an AE signal processing technique concerned with a random signal are described as follows:

For random stationary signals, generally, the signals do not repeat itself and is hardly described by an explicit mathematical relationship [72]. The word “stationary” implies that the mechanisms producing the signals are independent with time (time-invariant). Thus, the statistical properties of the signal are not changed with time. In addition, the spectrum distributions of the signal are continuously with frequency and are the same as different distributions recoded by the same process.

For non-stationary signals, the signals spectra and statistical properties vary with time. They require signal processing techniques that can quantitatively provide changes in frequency content as a function of time. They can generally be broken up into smaller quasi-stationary segments or into transient segments as procedures are used in the speech analysis. This characteristic of signal is not concerned with the AE signal detected in this work. The signal analysis of this technique is excluded deliberately in this dissertation.

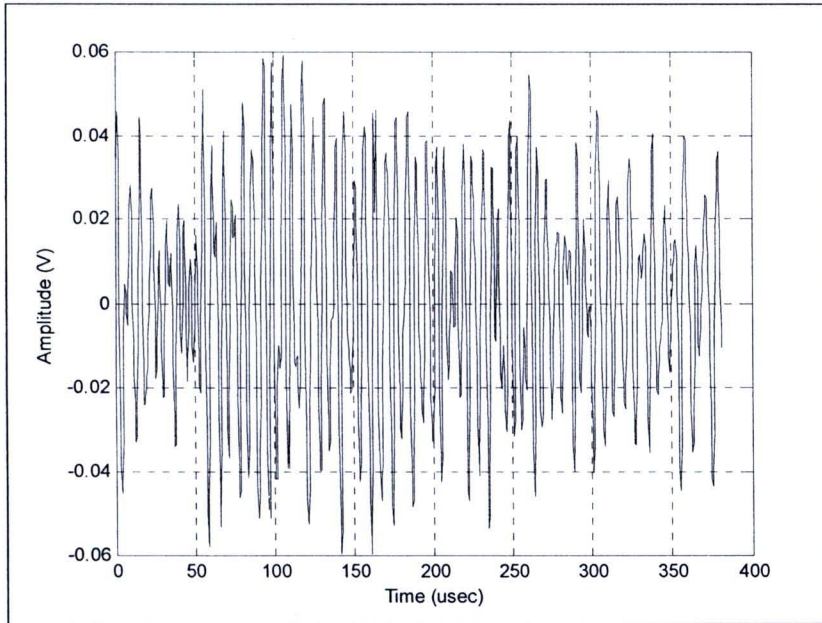


Figure 2.16 Continuous type of AE signals [71].

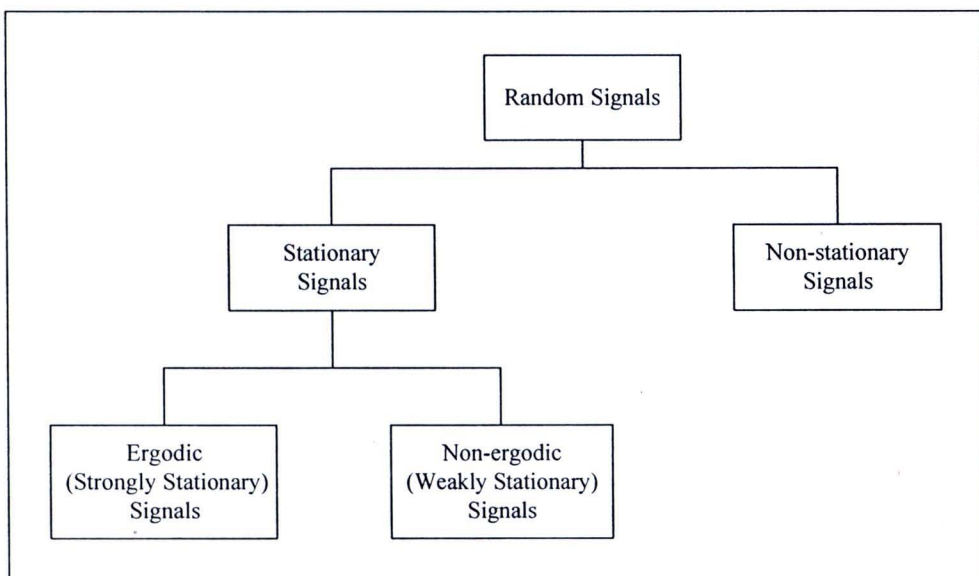


Figure 2.17 Flowchart of the different types of random signal [72].

The signal analyses techniques, which are commonly used to quantify a random stationary measured signal, are summarized in Figure 2.18.

1. Magnitude Analysis

Probability Density Function

In principle, each physical phenomenon has individual probability density function (PDF). Fortunately, stationary random processes are generally Gaussian in nature and constant when the measured system is stationary or invariant with time. Thus it has the well known Gaussian probability density distribution given by [73]

$$p(x) = \frac{1}{\sigma(2\pi)^{1/2}} e^{-(x-m_x)^2/2\sigma^2} \quad (2.8)$$

where m_x is the mean value of the signal and σ is its standard deviation.

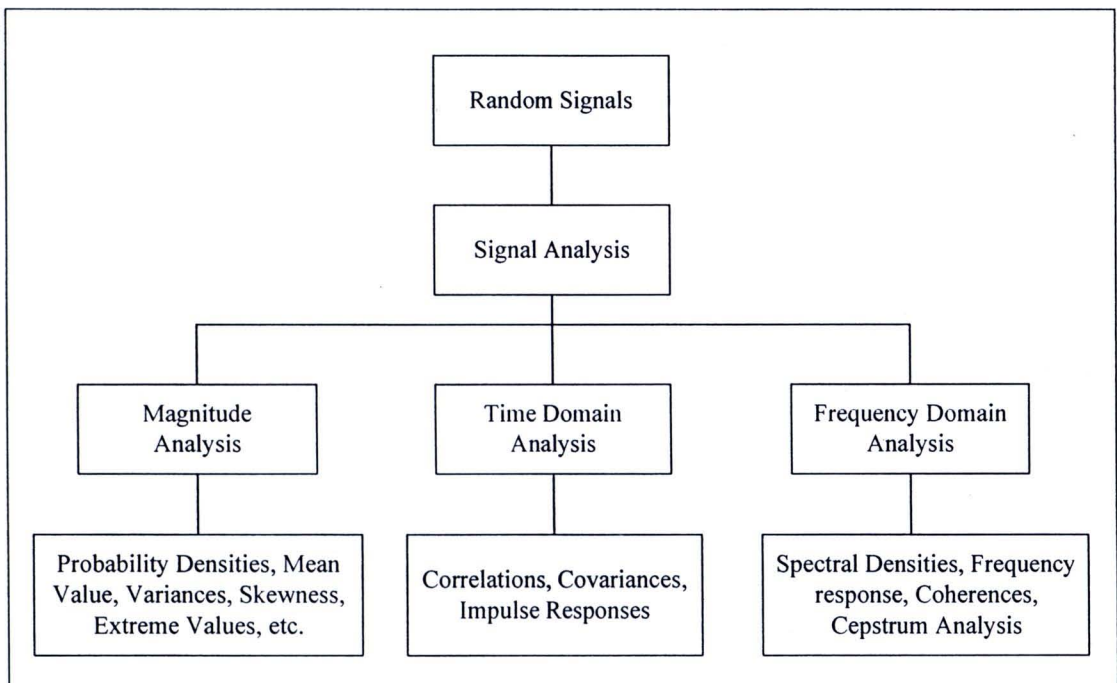


Figure 2.18 Commonly used signal analysis techniques [54].

RMS Value

The square root of the mean square (RMS) value conducting the average energy is a measurement of the total magnitude of a stationary random signal. It is defined as [73]

$$V_{RMS} = \sqrt{\frac{1}{T_0} \int_{t_0}^{t_0+T} v^2(t) dt} \quad (2.9)$$

where T_0 is a period of time (μs),

t_0 is an initial time (μs), and

$v(t)$ is a voltage signal from an AE sensor in continuous-time system (mV).



Signal magnitude analysis such as Root-Mean-Square (RMS) value of AE signal and probability density function (PDF) were utilized in this dissertation.

2. Frequency Analysis

Power Spectral Density

The power spectral density (PSD) is intended for continuous spectra distribution. It represents the distribution of the signal power over frequency bands of raw AE signals. PSD could be computed using the following equation [74].

$$P[k] = \frac{T_0}{N} |X[k]|^2 = \frac{T_0}{N} \left| \sum_{n=0}^{N-1} x[n] \exp(-j2\pi kn/N) \right|^2 ; 0 \leq k \leq N-1 \quad (2.10)$$

where $P[k]$ is the power spectral density (mV^2/Hz),

$X[k]$ is a discrete Fourier transform (DFT) of an AE signal,

N is a number of discrete AE data within the period of time (T_0), and

$x[n]$ is an AE signal voltage in discrete-time system (mV).

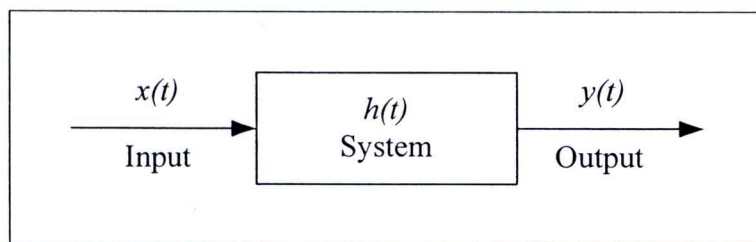


Figure 2.19 A single-input and single-output system [72].

Frequency Response Function

Most analysis in the frequency domain considers features, such as the peak frequency, magnitude of the dominant frequency component within frequency bands. In addition, the frequency response function (also called transfer function) is a frequency-domain function. Consider the input-output relationship depicted as in Figure 2.19, which describes a linear time-invariant system characterized by an impulse response function $h(t)$, with input $x(t)$ and output $y(t)$.

Thus, the frequency response function defines the linear relationship as a function of frequency $H(f)$ between two stationary random signals. It is given by [72]

$$G_{yy}(f) = |H(f)|^2 \cdot G_{xx}(f) \quad (2.11)$$

where G_{xx} and G_{yy} is autospectral density function of two-input signal and two-output signal of a system, respectively. This autospectrum or power spectrum is a frequency domain function that defines the spectral content of stationary process signal. It is given by [71]

$$G_{xx}(f) = \lim_{T \rightarrow \infty} \frac{2}{T_0} E \left[|X_T(f)|^2 \right] ; f > 0 \quad (2.12)$$

where the magnitude of Fourier transform of $x(t)$ over time interval is T_0 , as defined in Equation 2.13, and $E[\]$ denotes the expected value operator, which implies an averaging operation.

$$X_T(f) = \int_0^{T_0} x(t)e^{-j2\pi ft} dt . \quad (2.13)$$

Equation 2.11 describes how the power spectrum density of the input is shaped by the frequency response characteristic of the system.

In practice, the application of AE can usually estimate qualitatively when damage occurs within the material or approximately how long the component will last [66]. Some applications are required to do more thorough examination to provide quantitative results. Thus, this dissertation attempts to correlate the AE feature and valve leakage feature and to model that of features for predicting the leakage rate as derived in the next chapter.