CHAPTER 3 THEORY AND MODEL FORMULATION

This chapter introduces and explains the principles that are important and applied in this dissertation. The AE testing system, the PZT material, theories of electromechanical and calibration method of AE sensor are explained here. The model formulation for the relationship between mechanical energy released from source and AE signal is described and created based on theoretical method. The important details of each principle are described in the following sections.

3.1 Acoustic Emission Testing

3.1.1 Principle of AE

Formally defined, "Acoustic emission (AE) is the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized source within a material, or the transient elastic waves so generated" (ASTM, 2011). Clearly, from the description, there are two distinct phenomena, namely, the generation of stress waves within the material or structure and the propagation of these waves from the AE source location throughout the structure. This means that the strength of the AE sources is affected by the wave propagation path.

AE is generally termed a nondestructive testing (NDT) technique although in most cases AE does depend on some damage occurring in the material or structure. AE is a useful tool in the NDT in structure in service using either continuous monitoring or during routine in-service inspection. Materials "talk" when they are in trouble. The AE equipment can "listen" to the sounds of active damage in the stressed material (LOCAN 320 User's manual, 1990). The main advantage over conventional ultrasonic or radiographic testing is that large areas or volumes can be tested at once with a small number of AE sensors. The diagram of phenomena of transient elastic waves and AE testing system is show in figure below.

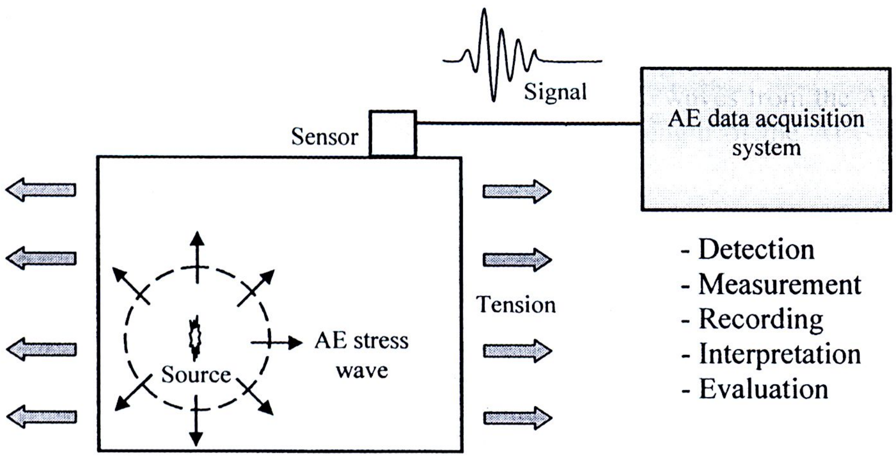

Figure 3.1 A diagram of phenomena of transient elastic waves and AE testing

Small-scale damage is detectable long before failure, so AE can be used as a NDT technique to find defects during structural proof tests and plant operation. AE also offers unique capabilities for materials research and development in the laboratory.

Finally, AE equipment is adaptable to many forms of production QC testing, including corrosion monitoring and leak detection.

The mostly common AE sources are caused by mechanical processes such as fracture, impact and corrosion process. There are other mechanisms that are contained by AE and can be detected using the same equipment such as plastic deformation, leaks in piping and valve, liquefaction/solidification of material and chemical phase transformations in solid (McIntire, 1987; Evans, 1997). These mechanisms are referred to as secondary sources to distinguish them from the standard mechanical deformation sources. All AE generation mechanisms are active, in other words they require an external load in order for the source to generate stress waves. For example, crack growth will only occur if the structure or material is sufficiently loaded. All common sources of AE produce an elastic wave that propagates and can be detected by appropriate AE sensors and analyzed.

The signal generated by an AE source can be roughly divided into two categories, discrete (burst) and continuous (McIntire, 1987; Evans, 1997). A crack growth or corrosion process is an excellent example of a discrete AE generation mechanism, being characterized by individual events of energy separated by periods of apparent inactivity. The events were shown to be related to minute increments of crack growth (Hanato, 1975). The example of burst AE signal is shown in figure 3.2. Continuous AE signals are generated by such sources as fluid leaks and the plastic deformation of solid. The example of continuous AE signal is shown in figure 3.3.

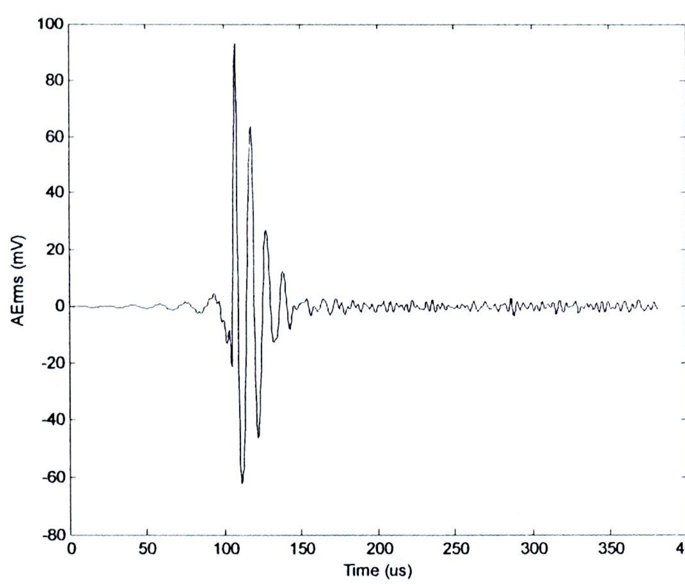

Figure 3.2 The example of burst AE signal

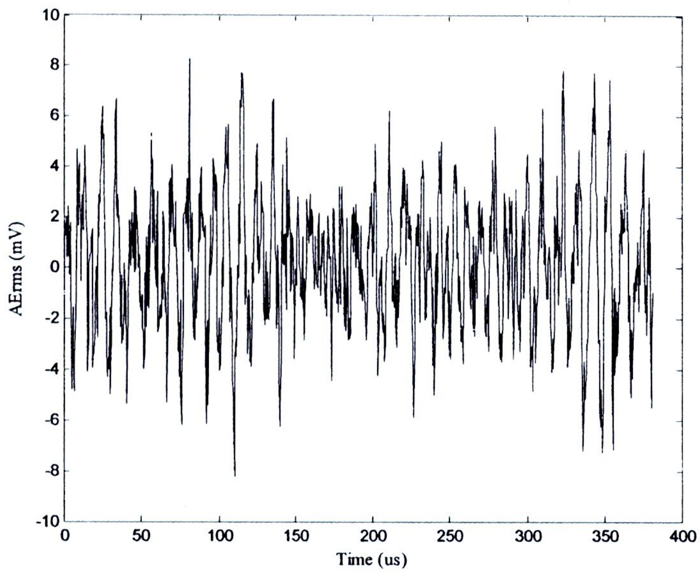

Figure 3.3 The example of continuous AE signal

3.1.2 AE Parameters

Discrete AE source are individual bursts of energy with amplitudes well above the noise floor and well separated in time. The AE parameters were explained in time domain. The individual events are complex, usually rising in amplitude rapidly until a maximum is reached and decaying exponentially to the background noise level. The character of AE signal is dependent on the AE source. When using a highly resonant sensor the resulting signal can be approximated to a damped sinusoidal function. In order to identify events, a threshold level is set. This level must be higher than the background noise level but lower than the even amplitudes as shown in figure 3.4.

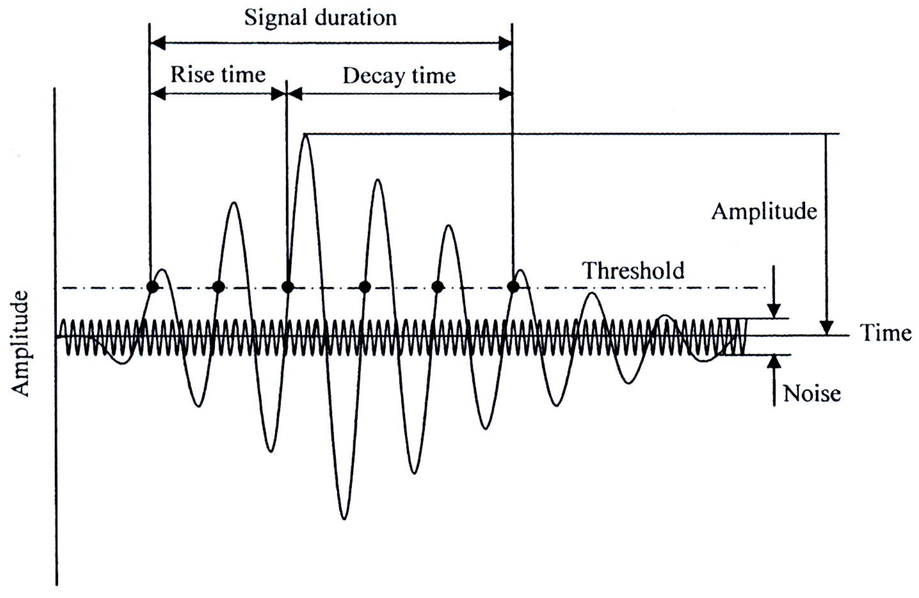

Figure 3.4 The definition of AE waveform parameters

The waveform parameters most commonly measured are as follows (McIntire, 1987; Evans, 1997):

Hits or Evens: The hit is a signal that exceeds the threshold and causes a system channel to accumulate data. It is frequently used to show AE activity with counted number for a period (rate) or accumulated numbers. One waveform correspond one "hit". This parameter is used in many practical applications such as corrosion monitoring.

Ring-down count: The severity of an AE event may be estimated by counting the number of cycles in each event that pass above the threshold level. The complicated AE events may be represented by a single number or count (for example, the count for the signal shown in figure 3.4 would be 6). The numbers of count per unit time depend on the AE sensor frequency, the damping characteristics of the AE sensor, the damping characteristics of the structure and the threshold level. The idealized signal can be given by

$$V = V_0 \exp(-Bt) \sin \omega t \qquad (3.1)$$

where V is the output voltage of AE sensor, V_0 is the initial signal amplitude, B is the decay constant (greater than 0), t is the time, and ω is the angular frequency. When the time required for the signal to decay to the threshold voltage V_t is long compared to the period of oscillation, the number of counts (N) can be given by

$$N = \frac{\omega}{2\pi B} \ln \frac{V_0}{V_t} \qquad (3.2)$$

where V_t is the threshold voltage of the counter.

Amplitude: The peak signal amplitude is a peak voltage of the AE signal waveform that is usually assigned. Amplitudes are expressed on a decibel scale instead of linear scale where 1 μV at the AE sensor is defined as 0 dB_{AE}. The amplitude is closely related to the magnitude of AE source event. As mentioned the AE signals are detected on the basis of the voltage threshold, the amplitude is also important parameter to determine the sensitivity of testing system. The detected amplitude shall be understood as the value does not represent the AE source but the AE sensor response after losing the energy due to propagation. The magnitudes of amplitudes are often analyzed in relation with frequency distribution as the amplitude distribution.

Signal duration: The signal duration is given by the time between the first and last level crossings (see figure 3.4). This parameter is also affected by the threshold level and the overall damping (attenuation) in the structure or material. The duration of a burst signal, such as would be measured by a highly resonant AE sensor, is linearly related to the ring-down count and is given by

$$\delta = Nt \qquad (3.3)$$

where δ is the signal duration, N is the number of counts, and t is the period of each cycle.

Rise time: The rise time is a time interval between the triggering time of AE signal and the time of the peak amplitude is assigned (see figure 3.4). The rise time is closely related to the source-time function, and is useful to classify the type of fracture or eliminate noise signals.

Energy: The definitions of energies are different in AE system suppliers, but it is generally defined as a measured area under the AE waveform. The electrical energy (E_{AE}) present in a transient event can be defined as

$$E_{AE} = \frac{1}{R}\int_{t_0}^{t_0+T} V^2(t)dt \tag{3.4}$$

where R is the electrical resistance of the measuring circuit, and T is the integration time of the signal. Direct energy analysis can be performed by digitizing and integrating the waveform signal or by special devices performing the integration electronically.

The energy is preferred to interpret the magnitude of source event over counts because it is sensitive to the amplitude as well as the duration, and less dependent on the voltage threshold and operating frequencies.

The advantage of energy measurement over ring-down count is that energy measurements can be directly related to important physical parameter without having to model the AE signal. Energy measurements also improve the AE measurement when AE signal amplitudes are low, as in the case of continuous emission.

Squaring the signal for energy measurement produces a simple pulse from a burst signal and leads to a simplification of even counting. In the case of continuous signal, if the signal is of constant amplitude and frequency the energy rate is the root mean square voltage (AE_{rms}). The AE_{rms} can be given by

$$AE_{rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0+T} V^2(t)dt} \tag{3.5}$$

The AE_{rms} measurement is simple and without electronic complications. However AE_{rms} meter response is generally slow in comparison with the duration of most AE signal. Therefore, AE_{rms} measurements are indicative of average AE energy rather than the instantaneous energy measurement of the direct approach. Regardless of the type of energy measurement used, none is an absolute energy quantity. They are relative quantities proportional to the true energy.

3.1.3 AE Sensor

Formally defined, "AE sensor is a detection device, generally piezoelectric, that transforms the particle motion produced by an elastic wave into an electrical signal." (ASTM, 2011). The sensors are generally of the narrow band (resonant) type, designed to give maximum sensitivity in the bandwidth of interest. Resonant sensors are highly sensitive to a very narrow frequency range, which must be carefully selected depending on the application. If the bandwidth of interest is unknown, the wide band (broad) is generally applied. The details of AE sensors are as follows.

1. Type of AE sensors

There are several ways how this transduction can be achieved. The PZT effect, capacitance methods and optical interferometers are common techniques used for detection of AE in industry and research (Keprt and Benes, 2007; Keprt and Benes, 2008). PZT sensors offer the greatest sensitivity and thus they are the most widely used type of sensor in AE applications. The PZT element is easy to fabricate in circular shape and other shapes. When broad bandwidth measurement is of primary importance then interferometer and capacitive techniques are employed. Interferometers and capacitance sensors have the capability to perform very high fidelity measurements over a broad frequency range far beyond that of conventional PZT sensors. Interferometers also provide very good spatial resolution, which is ideal when measurements of small changes in surface displacement are required (surface wave). However the interferometers and capacitance sensors are relatively insensitive, being orders of magnitude less sensitive than a typical AE PZT sensor. In addition, these devices can be very delicate and are commonly limited to laboratory use where measurement conditions can be controlled. Interferometers and capacitance sensors are often used to calibrate PZT AE sensors.

Table 3.1 Typical sensitivities of AE sensors (Keprt and Benes, 2007)

Type of sensor	Sensitivity (m)	Bandwidth (MHz)
Piezoelectric resonant	10^{-13}	0.1 to 0.3
Piezoelectric wideband	10^{-12}	0.1 to 2
Capacitance	10^{-11}	DC to 50
Laser interferometer	10^{-10}	0.05 to 100

The most widely used type of a sensor in AE testing systems is a PZT sensor. The main components of PZT AE sensor are described in next subsection.

2. The main components of PZT AE sensor

The components of PZT AE sensor is shown in figure 3.5. Four main components are described here: the PZT material or active element, the backing material, the wear plate and the housing.

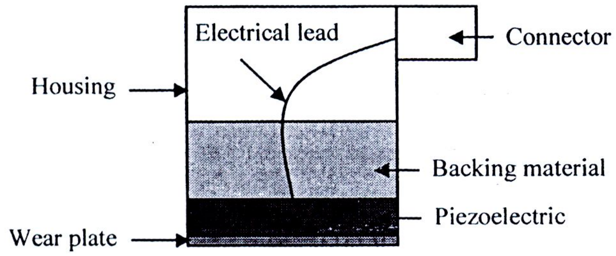

Figure 3.5 The components of PZT AE sensor

PZT material is the certain crystalline material to generate electrical charges on the application of mechanical stress. Conversely, if the crystal is placed in an electric field, it will experience a mechanical strain. The definition and detail of PZT material are described in section 3.2. The theorems for design and analysis of output voltage of PZT AE sensor are described in section 3.3 to 3.5.

The backing material is usually a highly attenuative, high density material that is used to control the vibration of the sensor by absorbing the energy radiating from the back face of the PZT material. Thereby the any unwanted noise is reduced (Jomdecha and Prateepasen, 2006; Noipitak et al., 2007). When the acoustic impedance (Z) of the backing material matches the acoustic impedance of the PZT material, the result will be a heavily damped sensor. The acoustic impedance can be given by

$$Z = \rho \times c_o^{'} \tag{3.6}$$

where ρ is the density of the backing material and $c_o^{'}$ is the longitudinal velocity of the backing material.

The basic purpose of the sensor wear plate is to protect the PZT material from the testing environment. In the case of contact sensors, the wear plate must be a durable and corrosion resistant material in order to withstand the wear caused by use on materials such as steel. It is also insulated to prevent short circuit. This is accomplished by selecting a matching layer that is 1/4 wavelength thick($\lambda/4$) (Jomdecha and Prateepasen, 2006).

The housing is normally used to protect and hold the PZT material and all components, respectively. The housing is usually made of a stainless steel.

3. Aperture Effect

The AE sensors are traditionally fabricated in circular shape of finite dimensions (typically 0.5 to 2.5 cm diameter). Although these sensors are easy to manufacture and they provide strong and well-directed signals, there are some disadvantages associated with their relatively large dimensions with respect to the wavelengths (Rayleigh wave) (Keprt and Benes, 2007). The main disadvantages of a large sensor include signal distortion, the fact that certain frequency components may be cut off, which are generally referred to as aperture effects (Evans, 1997).

Based on Breckenridge model (Breckenridge, 1982; Breckenridge et al., 1984), assuming the sensor output is proportional to the average displacement over the sensor face with uniform sensitivity across that face, the sensor response can be written as

$$U(t) = \frac{1}{A}\iint_S u(x,y,t)r(x,y)dydx \tag{3.7}$$

where the $x-y$ plane is the material surface, S is the surface of the sensor face, A is the area and $u(x,y,t)$ is the out-of-plane surface displacement.

Assuming that the incoming waves have a plane wave front, traveling in the x direction, incident on a circular sensor having radius a and with a wave of the form

$$u(x,t) = B\cos(kx - \omega t) \qquad (3.8)$$

where k is the wave number and is given by $k = \omega / c$, where ω is the angular frequency, and c is the Rayleigh wave velocity.

The AE sensor sensitivity may be written as

$$U(t) = \frac{2J_1(ka)}{ka} B\cos(\omega t) \qquad (3.9)$$

where J_1 is the Bassel function of the first type.

The importance of aperture effects of AE sensors to AE measurements depends on the structure that is propagating the AE wave. If the propagating AE wave that the AE sensor detects can be described as diffuse, aperture effects can be ignored (A diffuse wave field is an enclosed area in that the wave energy is evenly distributed. It is to say that the amplitude and directional distribution of the waves throughout the enclosure is random and the waves are uncorrelated with respect to phase. A diffuse field is guaranteed to occur if all boundaries within the enclosure are diffuse reflectors (Evans, 1997). On the other hand, if the AE wave propagation arrives as a plate wave, aperture effects are critical.

For example, if the AE sensor is in the near vicinity of the AE source and multiple reflections of the AE signals occur within the structure or material, a diffuse acoustic field is produced. The frequency content of the AE signal is very broad and therefore very high frequency response sensors can effectively record the data. For this case the aperture of the sensor is of no significance due to the diffuse acoustic field. Test coupons used in the laboratory, such as fracture toughness specimens, are examples where the diffuse field can be assumed and aperture effects can be ignored (Dunegan, 2003).

When monitoring for damages in structures or material, the diffuse field will not develop and sensor response will depend on the aperture size. There are two key differences from the diffuse field case that change the situation: propagation distance (AE source to sensor) and the thickness of structural or material members. In many applications sensors can be several meters away from the AE source. The displacements activate the PZT crystal contained in the sensor, producing the AE signal. If the aperture of the sensor coupled to the surface is small compared to the wave length of the traveling wave, the frequency content and amplitude of the signal can be accurately measured. If the aperture of the sensor is large compared to the wave length the efficiency of the sensor is compromised.

In the equations 3.7 to 3.9, the aperture effects are calculated for Rayleigh velocity in steel of 3,000 m/sec. The calculation is shown in figure 3.6.

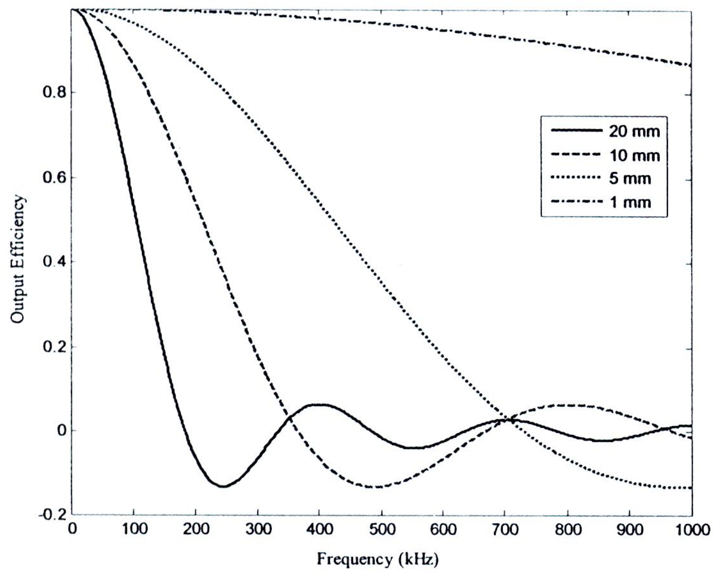

Figure 3.6 Calculated aperture effects based on Breckenridge model

In the figure 3.6, the aperture size of AE sensors 20 mm is a great loss in relative output efficiency in response for frequencies above 100 kHz. The sensor has an aperture size of 1 mm that is calculated to have an efficiency of approximately 95% at the 500 kHz frequency and almost 100% efficiency at 200 kHz frequency. For this study, the aperture size of home-built AE sensors 30 mm is calculated as shown in Appendix A.

3.1.4 Limitations of AE

AE testing systems have a several major limitations, for example:

- There are no measurement standards for estimating the absolute strength of the AE source (Yan and Jones, 2000). The lack of standardization makes it very difficult to compare the results obtained in different laboratories or on different structures and materials, and to obtain meaningful repeatability of measurements. This means that the results can not directly compare between AE testing systems or laboratories.

- The experimental design can affect some or all of the measured waveform parameters in an unpredictable fashion; for example, the relative locations of the AE source and receive can change the maximum amplitude of the resulting waveform. Consequently, tests taken on identical structures may not be directly comparable if the source location is different in each case (the frequency and attenuation are different) (Evans, 1997).

- The effect of the geometry and material properties of the structure under test is not fully understood. The complex signals measured from AE events generally contain multiple reverberations of the initial source waveform within the structure and consequently are affected by the accurate properties of the structure such as attenuation and wave velocity. Therefore, it is not possible to directly compare the AE signal measured from structures of different geometry with any degree of certainty. This means that the AE testing systems must be calibrated to reference the sensitivity of testing systems all tests.

- The measured waveform parameters depend on the AE data acquisition system used, for example the accurate frequency of operation, the sensitivity of the AE sensor and amplifier gains as well as signal processing. If repeat tests on the same structure or material are to be compared quantitatively, all tests must be carried out using identical AE data acquisition system. This usually means permanently bonding AE sensors to the structure or material as repeatable AE sensor response and coupling between tests can not be guaranteed (Evans, 1997). The big influence on uncertainty is the influence of remounting AE sensor and the accuracy in amplitude of the AE data acquisition system (Keprt and Benes, 2007).

Clearly, the mostly current techniques only give a qualitative indication of the change of state of structure or material rather than a quantitative indication of the absolute level.

3.2 Piezoelectric Material

3.2.1 Introduction and Principle of PZT Material

Piezoelectricity from the Greek word "piezo" means pressure electricity (Merhaut, 1981). It is the property of certain crystalline materials to generate electrical charges on the application of mechanical stress. Conversely, if the crystal is placed in an electric field, it will create a mechanical strain. The PZT materials are useful as sensor elements for converting mechanical energy into electrical energy and vice versa. When an AC voltage is applied, it will cause it to vibrate and thus generate mechanical waves at the same frequency of the input AC field. In the same way, it would sense the input mechanical vibrations and produce the proportional charge at the matching frequency of the mechanical input.

The PZT material is a polycrystalline Lead Zirconate Titanate based ferroelectric ceramic materials. These materials are represented by the formula ABO_3, perovskite crystalline structure wherein A-site denotes large divalent metal ion such as Pb and B-site denotes smaller tetravalent ion such as Ti or Zr (APC International, 2002). Under conditions that confer tetragonal or rhombohedral symmetry on the crystals, each crystal has a dipole moment. This material has several advantages such as higher piezoelectric coefficients, ease of fabrication into components of any shape and size, mechanically hard and strong, chemically inert and completely unaffected by atmospheric humidity.

Currently, metal oxide-based PZT ceramics and other man-made materials enabled designers to employ the piezoelectric effect and the inverse piezoelectric effect in many new applications. The composition, shape, and dimensions of a PZT ceramic element can be cut to meet the requirements of a specific purpose. Ceramics manufactured from formulations of lead zirconate / lead titanate show greater sensitivity and higher operating temperatures, relative to ceramics of other compositions.

For fabrication the PZT element, fine powders of the component metal oxides are mixed in specific proportions, and heated to form a uniform powder. The powder is mixed with an organic binder and is formed into structural elements having the desired shape such as discs, rods and plates. The elements are fired according to a specific time and temperature program, during which the powder particles sinter and the material attains a dense crystalline structure. The elements are cooled, then shaped or trimmed to specifications, and electrodes, silver, are applied to the appropriate surfaces.

For the polarization process, above a critical temperature, the Curie point, each perovskite crystal in the fired ceramic element shows a simple cubic symmetry with no dipole moment. At temperatures below the Curie point, each crystal has tetragonal or rhombohedral symmetry and a dipole moment. Adjoining dipoles form regions of local alignment refer to as domains. The alignment gives a net dipole moment to the domain, and thus a net polarization (APC International, 2002). The direction of polarization domains is random and the ceramic element has no overall polarization (figure 3.7 (a)). Then, the domains in a ceramic element are aligned by exposing the element to a strong, DC (direct current) electric field, usually at a temperature slightly below the Curie point (figure 3.7 (b)). Through this polarizing treatment, domains most nearly aligned with the electric field expand at the expense of domains that are not aligned with the field, and the element lengthens in the direction of the field. When the electric field is removed most of the dipoles are locked into a configuration of near alignment (figure 3.7 (c)). Finally, the element now has a permanent polarization and is permanently elongated.

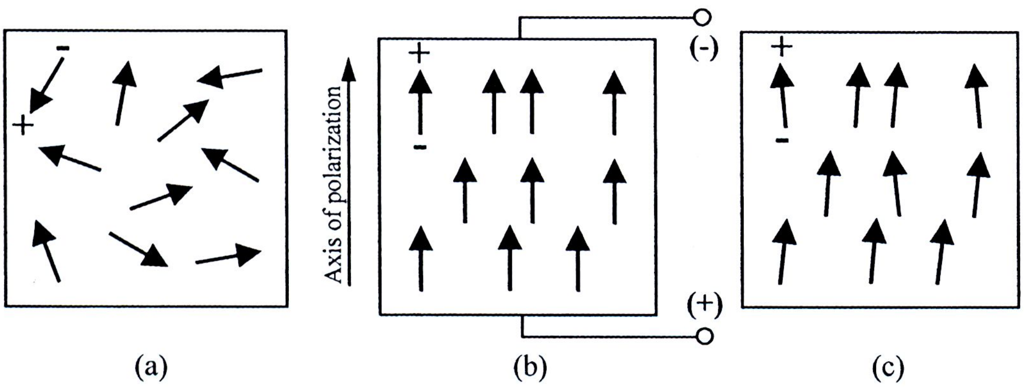

Figure 3.7 Polarizing (poling) a piezoelectric ceramic: a) random orientation of polar domains prior to polarization b) polarization in DC electric field c) permanent polarization after electric field removed

For creating a voltage, mechanical compression or tension on a poled PZT ceramic element changes the dipole moment. Compression along the direction of polarization or tension perpendicular to the direction of polarization generates voltage of the same polarity as the polarizing voltage (figure 3.8 (b)). Tension along the direction of polarization or compression perpendicular to the direction of polarization generates a voltage with polarity opposite that of the polarizing voltage (figure 3.8 (c)). These actions are generator actions. This means that the ceramic element converts the mechanical energy of compression or tension into electrical energy. Values for compressive stress and the voltage generated by applying stress to a PZT ceramic element are linearly proportional up to a material-specific stress. The same is true for applied voltage and generated strain.

In figure 3.8, d_o is the original diameter of ceramic element, and h_o is the original thickness of ceramic element.

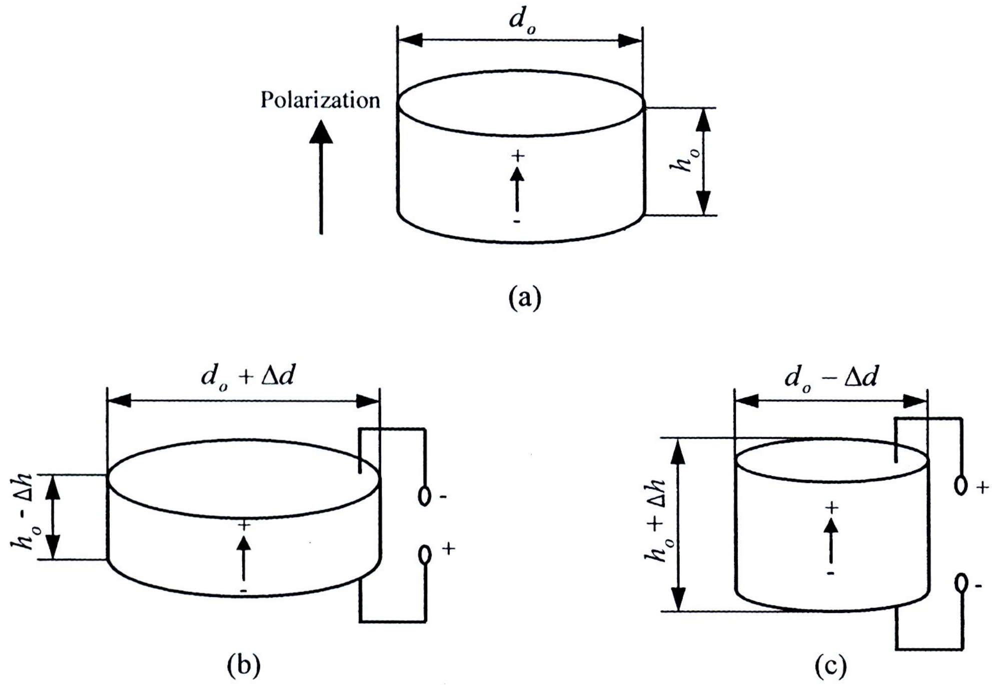

Figure 3.8 Generator action of a ceramic element: a) ceramic element after polarization (poling) b) ceramic element compressed c) ceramic element stretched

3.2.2 Properties and Definitions of PZT Material

Because a PZT ceramic is anisotropic material, physical constants relate to both the direction of the applied mechanical stress and the directions perpendicular to the applied stress. Therefore, each constant generally has two subscripts that indicate the directions of the two related quantities, such as stress (force on the ceramic element / surface area of the element) and strain (change in length of element / original length of element) for elasticity. The direction of positive polarization usually is made to correspond with the Z-axis of a rectangular system of X, Y, and Z axes that the direction is shown in figure 3.9. Direction X, Y, or Z is represented by the subscript 1, 2, or 3, respectively, and shear about one of these axes is represented by the subscript 4, 5, or 6, respectively.

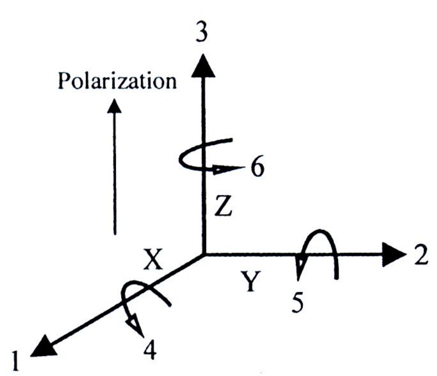

Figure 3.9 Directions of forces affecting a PZT element

The definitions and constants of PZT element are summarized in this subsection. The piezoelectric charge constant (d), the piezoelectric voltage constant (g) (see Appendix B), and the permittivity (ε) are temperature dependent factors (APC International, 2002).

The permittivity or dielectric constant (ε) for a PZT ceramic material is the dielectric displacement per unit electric field. ε^T is the permittivity at constant stress and ε^S is the permittivity at constant strain. The first subscript to ε is the direction of the dielectric displacement. The second is the direction of the electric field.

ε_{11}^T is the permittivity for dielectric displacement and electric field in direction 1 (perpendicular to direction in which ceramic element is polarized), under constant stress.

ε_{33}^S is the permittivity for dielectric displacement and electric field in direction 3 (parallel to direction in which ceramic element is polarized), under constant strain.

The relative dielectric constant (K^T) is the ratio of ε. The amount of charge that an element constructed from the ceramic material can store, relative to the absolute dielectric constant (ε_0), the charge that can be stored by the same electrodes when separated by a vacuum, at equal voltage ($\varepsilon_0 = 8.85 \times 10^{-12}$ farad / meter). The relative dielectric constant given by

$$K^T = \frac{\varepsilon_{11}^T}{\varepsilon_0} \tag{3.10}$$

The electromechanical coupling factor (k_p) is the factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and radial vibrations in direction 1 and direction 2 (both perpendicular to direction in which ceramic element is polarized).

Lastly, the static capacitance (C_S) of the PZT material can be given by

$$C_S = \frac{K^T \varepsilon_0 \pi r^2}{h} \tag{3.11}$$

where r is the radial of PZT material, and h is the thickness of PZT material.

The analysis of the out put voltage of PZT and AE sensor is described in subsection 3.3 to 3.5. The Mason's equivalent electrical circuits of electromechanical sensor are used to explain the analogies between electrical and mechanical systems.

3.3 Translational Mechanical Systems

In order to explain the analogies between electrical and mechanical systems, some fundamental theorems of mechanics must be reviewed in this section.

The motion of a point mass, m is described by Newton's second law of motion. If the effects of friction and elasticity are neglected, the force, F acting is equal to the rate of change of linear momentum, mv; the force and the velocity, v have the same direction (see Appendix C). The equation can be expressed by (Merhaut, 1981),

$$F = \frac{d(mv)}{dt} \tag{3.12}$$

and

$$v = \frac{dy}{dt} \tag{3.13}$$

where y is the displacement from the equilibrium position.

From equations 3.13 can obtain

$$v = j\omega y \tag{3.14}$$

Similarly, the acceleration

$$\frac{dv}{dt} = j\omega v \tag{3.15}$$

where $\omega = 2\pi f$ is the angular frequency, f is the frequency, and $j = \sqrt{-1}$.

From equations 3.12 and 3.15 can be written as

$$F = j\omega mv \tag{3.16}$$

There is an analogy between the mechanical and the electrical systems with the force (F) playing the same role as the voltage (u), and the velocity (v) playing the same role as the current (i). The mass (m) in this analogy, has a similar significance in mechanical systems as inductance (L) has in electrical circuits.

According to this analogy, in a mechanical system the power, P is given by

$$P = \frac{1}{T}\int_0^T Fv\,dt \tag{3.17}$$

A formula analogous in electrical circuit theory is

$$P = F_{ef} v_{ef} \cos\varphi \tag{3.18}$$

where φ is the phase difference between the force and the velocity, and T is the integration time.

3.4 Oscillations of Plates

In this section, the simple oscillations of solid bodies are presented. They are presented in each case only one kind of oscillation propagated in a single direction. This approach will be adequate for most cases occurring in practice.

When oscillations are propagated in a solid, the medium is in a state of tension, where the strain and stress are mutually dependent. The stress is given as the ratio of force acting on an element of surface to the area of the element. Generally, the stress is a tensor, which has six components (T_{ij}), each component being the ratio of a force acting in the direction (i) to an area of a surface element perpendicular to the direction (j). The components can be written in cartesian coordinates as (Yarovikov and Bazheno, 1998; Merhaut, 1981)

$$T_{xx} = T_1 \qquad T_{yz} = T_{zy} = T_4$$

$$T_{yy} = T_2 \qquad T_{xz} = T_{zx} = T_5$$

$$T_{zz} = T_3 \qquad T_{xy} = T_{yx} = T_6$$

The strain, a relative deformation ($\Delta l / l$) of the original length (l), is also a tensor with six components (σ). If the displacement along the directions x, y and z were defined as η_x, η_y and η_z respectively, the components can be written as

$$\sigma_1 = \frac{\partial \eta_x}{\partial x} \qquad \sigma_4 = \frac{\partial \eta_y}{\partial z} + \frac{\partial \eta_z}{\partial y}$$

$$\sigma_2 = \frac{\partial \eta_y}{\partial y} \qquad \sigma_5 = \frac{\partial \eta_z}{\partial x} + \frac{\partial \eta_x}{\partial z}$$

$$\sigma_3 = \frac{\partial \eta_z}{\partial z} \qquad \sigma_6 = \frac{\partial \eta_x}{\partial y} + \frac{\partial \eta_y}{\partial x}$$

The components σ_4 to σ_6 are represented a shear deformation.

The tensors T and σ are related by Hooke's law within the limits of elastic deformation. This law can be written in a matrix as

$$\begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} = \begin{bmatrix} \varsigma_{11} & \varsigma_{12} & \varsigma_{13} & \varsigma_{14} & \varsigma_{15} & \varsigma_{16} \\ \varsigma_{21} & \varsigma_{22} & \varsigma_{23} & \varsigma_{24} & \varsigma_{25} & \varsigma_{26} \\ \varsigma_{31} & \varsigma_{32} & \varsigma_{33} & \varsigma_{34} & \varsigma_{35} & \varsigma_{36} \\ \varsigma_{41} & \varsigma_{42} & \varsigma_{43} & \varsigma_{44} & \varsigma_{45} & \varsigma_{46} \\ \varsigma_{51} & \varsigma_{52} & \varsigma_{53} & \varsigma_{54} & \varsigma_{55} & \varsigma_{56} \\ \varsigma_{61} & \varsigma_{62} & \varsigma_{63} & \varsigma_{64} & \varsigma_{65} & \varsigma_{66} \end{bmatrix} \cdot \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \qquad (3.19a)$$

so

$$[T]=[\varsigma]\cdot[\sigma] \tag{3.19b}$$

where ς is the Young's modulus for an isotropic medium.

3.4.1 Wave Equation for Thickness Oscillations

Consider a bar of a uniform cross section (S) and of density (ρ) (figure 3.10), in which mechanical oscillations are propagated in the x direction. The oscillation of the particles of mass also takes place in the x direction, and as the phase is the same in each section it can be described by a displacement $\eta_x(x,t)$ (Merhaut, 1981). For this case, equation 3.19 takes the simpler form of

$$T_1 = \varsigma_{11}\sigma_1 \tag{3.20}$$

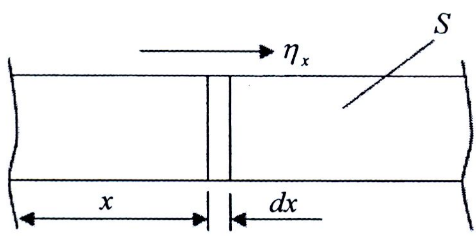

Figure 3.10 The oscillation of the particles of mass in the x direction

The forces acting in the sections x and $x+dx$ are $ST_1(x)$ and $ST_1(x+dx)$, respectively (see Appendix C). The increment of force along the length dx is

$$ST_1(x) - ST_1(x+dx) = -S\frac{\partial T_1}{\partial x}dx \tag{3.21}$$

The wave equation of oscillations propagating in the x direction is

$$\frac{\partial^2 \eta_x}{\partial x^2} = \frac{1}{c_0^2}\frac{\partial^2 \eta_x}{\partial t^2} \tag{3.22}$$

and

$$\frac{\partial^2 \eta_x}{\partial t^2} = -\omega^2 \eta_x \tag{3.23}$$

Where $\omega = 2\pi f$. Then, substituting equation 3.23 into 3.22, for the time-independent part of η_x, the equation can be written as

$$\frac{\partial^2 \eta_x}{\partial t^2} + k^2 \eta_x = 0 \quad (3.24)$$

where $k = \omega / c_0$ is the wave number.

A general solution of equation 3.24, where k is always positive, can be written as

$$\eta_{xm} = A \sin kx + B \cos kx \quad (3.25)$$

where A and B are constants which can be determined from boundary conditions.

3.5 Analysis of AE Sensor

From subsection 3.1.3, AE sensor is a device that is used for converting the mechanical vibrations in to electrical signal and vice versa. The most important quantities of the signal on the electric side are the voltage (u) and the current (i). On the mechanical side it is the force (F) and the velocity (v) (Merhaut, 1981; Jomdecha and Prateepasen, 2006). All these quantities are alternating and in case of a harmonic signal they are given as a sinusoidal function of time. They are interrelated via equations that follow from physical laws applicable to the relevant sensor. It can be shown that each of the quantities u, i, F and v can be expressed as a function of two other quantities of the set. For example, if the values of the electric signal u and i are given, the mechanical values F and v are determined by function

$$F = f_1(u,i) \quad (3.26)$$

$$v = f_2(u,i) \quad (3.27)$$

and

$$dF = \frac{\partial F}{\partial u} du + \frac{\partial F}{\partial u} di \quad (3.28)$$

$$dv = \frac{\partial v}{\partial u} du + \frac{\partial v}{\partial i} di \quad (3.29)$$

In case of linear systems, it may designate them as

$$\frac{\partial F}{\partial u} = a_{11}, \qquad \frac{\partial F}{\partial i} = a_{12}$$

$$\frac{\partial v}{\partial u} = a_{21}, \qquad \frac{\partial v}{\partial i} = a_{22}$$

Substituting these constants into equation 3.28 and 3.29 and integrating, they can be written as

$$F = a_{11} u + a_{12} i \quad (3.30)$$

$$v = a_{21}u + a_{22}i \tag{3.31}$$

These equations are analogous to the relations between signal quantities of four-terminal electrical networks, and according to the electromechanical analogy (see section 3.3 and Appendix C) they can be written in the form of the matrix equation

$$\begin{bmatrix} F \\ v \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \cdot \begin{bmatrix} u \\ i \end{bmatrix} \tag{3.32}$$

The matrix in equation 3.32 is a cascade matrix of an AE sensor, which, if the first analogy from section 3.3 is applied, can be diagrammatically illustrated as shown in figure 3.11.

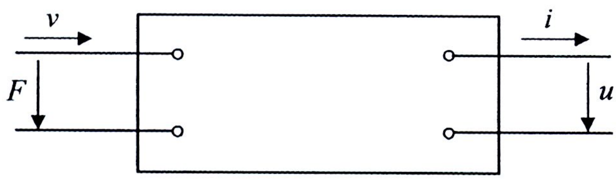

Figure 3.11 A relationship diagram between mechanical and electrical system

3.5.1 Equations of State for PZT Materials

The AE sensor, the operating principle is based on the interactions between electric field and deformations of the active material (PZT). The forces, deformations and electric field intensities are distributed throughout the active part of the sensors. The some theories of this sensor from the equations of state for the active material are explained in this section.

There is a simple relationship between the intensity of the electric field (E) and the displacement (D). The PZTs have D depending not only upon E but also upon the state of mechanical stress. This state can be described either by the strain (σ) or by the stress (T) (see section 3.4). The four quantities, E, D, T and σ, are described the state of the material (Merhaut, 1981). The relationship between them can be written in a similar way to those of four-terminal networks as

$$D = f_1(E, \sigma) \tag{3.33}$$

$$T = f_2(E, \sigma) \tag{3.34}$$

where two of the quantities are always expressed as functions of the other two.

Since PZTs are anisotropic materials, it is necessary to consider equations 3.33 and 3.34 as tensors. The vectors E and D are each defined by three components E_x, E_y, E_z and D_x, D_y, D_z, respectively, x, y, and z being Cartesian coordinates. The stress and the strain are tensors of six components (from T_1 and σ_1 to T_6 and σ_6, respectively; (see section 3.4). PZT materials are linear for small strains (Bolin, 1979). Thus equation 3.33 can be written

$$D_j = \sum_{i=x,y,z} \varepsilon_{ji} E_i + \sum_{k=1}^{6} e_{jk} \sigma_k \tag{3.35}$$

Equation 3.35 represents three equations, for $j = x, y, z$. In a similar way, equation 3.34 becomes

$$T_l = \sum_{i=x,y,z} e_{li} E_i + \sum_{k=1}^{6} \varsigma_{lk} \sigma_k \tag{3.36}$$

And

$$D_j = a_{11} E_j + a_{12} \sigma_i \tag{3.37}$$

$$T_j = a_{21} E_j + a_{22} \sigma_i \tag{3.38}$$

It is clear that $a_{11} = \partial D_j / \partial E_j$ is the permittivity ε_j along the direction of the lines of force of the electric field and $a_{22} = \partial T_j / \partial \sigma_j$ is the appropriate modulus of elasticity ς_i. The coefficients $a_{12} = \partial D_j / \partial \sigma_i$, $a_{21} = \partial T_i / \partial E_j$ express the relationship between the electrical and mechanical quantities of the sensor. The common relation between a_{12} and a_{21} follows from this consideration. The increment of the energy per unit volume, dU, is given as a sum of increments of the energy of the electric field, mechanical work, and heat dQ. Thus

$$dU = E_j dD_j + T_i d\sigma_i + dQ \tag{3.39}$$

and

$$\frac{\partial D_j}{\partial \sigma_i} + \frac{\partial T_i}{\partial E_j} = 0 \tag{3.40}$$

Therefore $a_{12} = -a_{21}$ and this equation can be written

$$a_{12} = e \tag{3.41}$$

and

$$a_{21} = -e \tag{3.42}$$

The coefficient e can be determined for each particular case from the equations of state and the relevant boundary conditions.

Equations 3.37 and 3.38 can be written as

$$D_j = \varepsilon_j E_j + e\sigma_i \quad (3.43)$$

$$T_i = -eE_j + \varsigma_i \sigma_i \quad (3.44)$$

3.5.2 Thickness Vibration of PZT Element

This type of PZT element is shown in figure 3.12. The PZT element has a surface area (S), thickness (h), and its faces, at $x = 0$ and $x = h$, which are silver-coated, serve as the electrodes of the sensor. This study assume that when the AC voltage is applied to the electrodes, the PZT element vibrates only in the x direction (the direction of its thickness) so that a whole cross section of the area exhibits the same displacement $\eta(x,t)$. Displacements in other directions than the x direction are neglected (Merhaut, 1981; Jomdecha and Prateepasen, 2006).

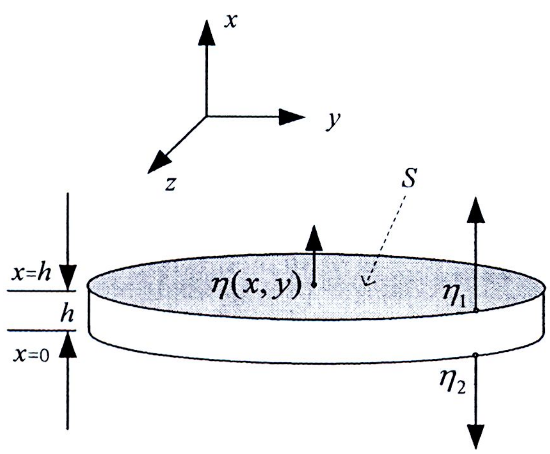

Figure 3.12 Thickness vibration of PZT element

In this case, the equation from previous subsection can be written

$$D_x = \varepsilon_x E_x + e\sigma_x$$

$$T_x = -eE_x + \varsigma_x^D \sigma_x$$

In case of harmonic vibrations, the wave equation can be written as show below. Its solution, for the boundary conditions are

$$\eta = -\eta_2 \qquad \text{for} \qquad x = 0 \quad (3.45a)$$

$$\eta = -\eta_1 \qquad \text{for} \qquad x = h \quad (3.45b)$$

So

$$\eta(x,t) = \frac{\sin k^{'}x}{\sin k^{'}h}\eta_1 - \left(\cos k^{'}x - \frac{\sin k^{'}x}{\tan k^{'}h}\right)\eta_2 \tag{3.46}$$

where

$$k^{'} = \frac{\omega}{c_0^{'}}$$

and $c_o^{'}$ is the velocity of wave propagation.

The charge on the electrodes (q) for this boundary conditions can be written as

$$q = \frac{\varepsilon_x S}{h}u + e\frac{S}{h}(\eta_1 + \eta_2) \tag{3.47}$$

When the static capacitance of the PZT element is

$$C_S = \frac{\varepsilon_x S}{h} \tag{3.48}$$

and the electromechanical coupling factor,

$$k_p = e\frac{S}{h} \tag{3.49}$$

are introduced, equation 3.47 becomes

$$q = C_S u + k_p(\eta_1 + \eta_2) \tag{3.50}$$

Differentiating with respect to t, assuming a harmonic signal, this equation can be written

$$i = j\omega C_S u + k_p(v_1 + v_2) \tag{3.51}$$

where $v_{1,2} = d\eta_{1,2}/dt$ are the velocities of the sensor faces.

The expression for the force $F_x(x,t)$ acting on a cross section at a position x can be derived and the formula $F_x = ST_x$, Using $D_x S = q$

So

$$F_x = -\frac{e}{\varepsilon_x}q + \varsigma_x^D S\frac{\partial \eta}{\partial x} \tag{3.52}$$

The forces F_1 and F_2, which act in the outward direction on the sensor gates, are in equilibrium with F_x for $x = 0$ and $x = h$

So

$$F_1 = -F_x(h) \tag{3.53}$$

$$F_2 = -F_x(0) \tag{3.54}$$

Differentiating equation 3.46 with respect to x and substituting in equation 3.52, putting $x = h$ and $\eta_{1,2} = v_{1,2} / j\omega$, the equation can be written

$$F_1 = -\varsigma_x^D S \frac{k'}{\omega}\left(\frac{1}{j\tan k'h} v_1 + \frac{1}{j\sin k'h} v_2\right) + \frac{e}{\varepsilon_x} q \tag{3.55}$$

This equation can be modified by substituting equation 3.50 for q and by introducing k_p as defined by equation 3.49.

So

$$\varsigma_x^D \frac{k'}{\omega} = \frac{\varsigma_x^D}{c_0'} = \frac{c_0'^2 \rho}{c_0'} = c_0' \rho$$

and

$$F_1 = k_p u - \left(Z_b' - \frac{1}{j\omega c_b}\right) \cdot (v_1 + v_2) - Z_a' v_1 \tag{3.56}$$

where

$$c_b = \frac{\varepsilon_x h}{e^2 S}, \qquad Z_a' = jc_0' \rho S \tan\frac{k'h}{2} \quad \text{and } Z_b' = c_0' \rho S \frac{1}{j\sin k'h}$$

Similarly, the equation for F_2 can be written as

$$F_2 = k_p u - \left(Z_b' - \frac{1}{j\omega c_b}\right) \cdot (v_1 + v_2) - Z_a' v_2 \tag{3.57}$$

3.5.3 Mason's Equivalent Electrical Circuits of AE Sensor

The analogy diagram of thickness vibration type of PZT element follows from equation 3.51, 3.56 and 3.57. The diagram is illustrated in figure 3.13 and it is clear that c_b is the already known negative compliance. It is easy to show that

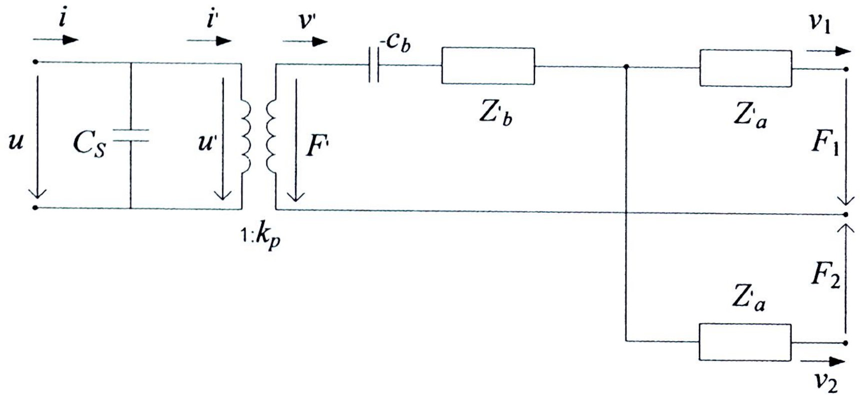

Figure 3.13 Equivalent electrical circuits of PZT (thickness vibration)

where

$$c_b = \frac{C_S}{k_p^2} \tag{3.58}$$

Then the PZT material was assembled with backing material, wear plate and housing. When the AE sensor was used to capture the acoustic stress wave, the AE sensor was mounted on the surface of test structure. In this reason, one active face ($x = 0$) is fixed and the gate with F_2, v_2 is loaded by a mechanical impedance ($Z_2 = \infty$ or free) that is practically $Z_2 = 0$ (Merhaut, 1981; Jomdecha and Prateepasen, 2006).

In this case, when $Z_2 = \infty$ the part of the circuit in figure 3.13 that leads to the gate 2 is disconnected, and the diagram of the sensor can be drawn as indicated in figure 3.14.

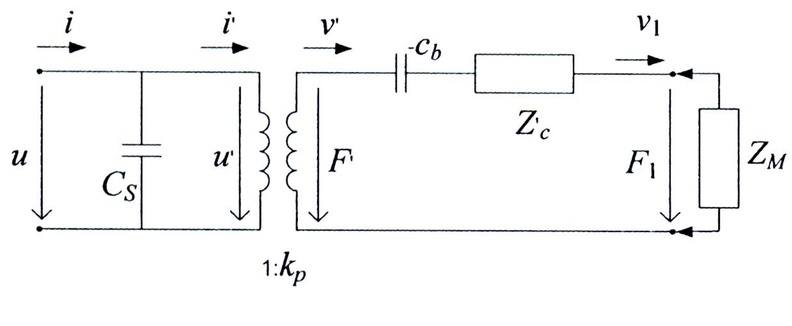

Figure 3.14 Equivalent electrical circuits of AE sensor

where Z_M is the impedance of backing material.

The sum of impedance ($Z_c^{'}$) can be calculated as

$$Z_c^{'} = Z_a^{'} + Z_b^{'} = c_0^{'} \rho S \frac{1}{j \tan k^{'} h} \tag{3.59}$$

For power series, the equation 3.59 can be written as

$$\frac{1}{Z_c^{'}} = \sum_{n=1}^{\infty} \frac{1}{j\omega m_e + (1/j\omega c_n^{'}} \qquad (3.60)$$

where

$$m_e = \frac{\rho S h}{2} \qquad (3.61)$$

and

$$c_n^{'} = \frac{8h}{\pi^2 (2n-1)^2 \varsigma_x^D S} \qquad (3.62)$$

This equation can be modified by putting $\varsigma_x^D = \varsigma_x (1 + \chi^2)$, so

$$\frac{1}{c_n^{'}} = \frac{\pi^2 (2n-1)^2 S \varsigma_x}{8h} (1 + \chi^2) = \frac{1}{c_n} + \frac{1}{c_{nx}} \qquad (3.63)$$

where

$$\chi = \frac{e}{\sqrt{\varepsilon_x \varsigma_x}}$$

$$c_n = \frac{8h}{\pi^2 (2n-1)^2 S \varsigma_1} \qquad (3.64a)$$

and

$$c_{nx} = \frac{c_n}{\varphi^2} \qquad (3.64b)$$

The compliances c_n refer to the sensor as if it were made from a non-piezoelectric material. The compliances c_{nx} are additional compliances which are related to the piezoelectric properties of the material (if $e = 0$ and $\chi = 0$ then c_{nx} would vanish).

It follows from equation 3.60 that $Z_c^{'}$ can be replaced by a parallel arrangement of series resonant circuits which consist of m_e and $c_n^{'}$. Equation 3.63 indicates that $c_n^{'}$ can be replaced by c_n and c_{nx} connected in series. The losses in c_n can take into account by incorporating the resistances r_n into the circuit. Hence the analogy diagram of AE sensor in figure 3.14 can be modified in case of mounting on the surface of test structure. The analogy diagram is shown in figure 3.15.

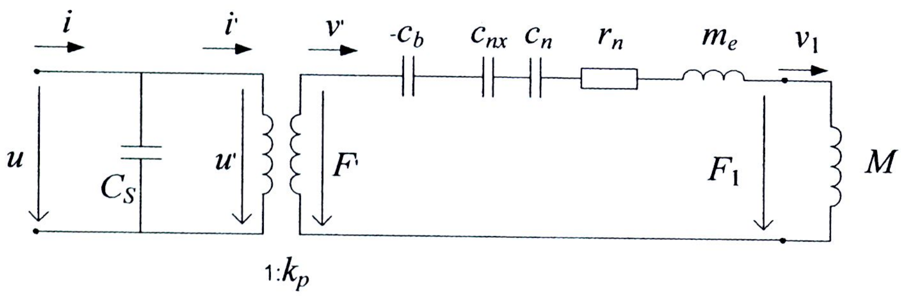

Figure 3.15 Equivalent electrical circuits of AE sensor (mounted on the surface of test structure)

The resonant frequencies of this system ω_n can be obtained as

$$\omega_n = \frac{\pi(2n-1)c_0^{'}}{2h} \tag{3.65}$$

Substituting $\omega_n = 2\pi f_n$ into equation 3.65, it follows that

$$4h = \frac{(2n-1)c_0^{'}}{f_n}$$

Since $\lambda_n = c_0^{'} / f_n$ is the wavelength corresponding to the natural frequency f_n,

so

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

This means that natural oscillations of the sensor occur if h is equal to an odd multiple of $\lambda / 4$.

3.5.4 Out Put Voltage of AE Sensor

The electro-acoustic receiver is essentially an AE sensor that transforms an incident sound wave into an electric signal. The voltage produced by this signal is approximately proportional to one of the parameters of the incident acoustic wave (Merhaut, 1981; Jomdecha and Prateepasen, 2006).

In this case, there is no direct relation available for the output voltage. The output current (i) corresponds to the velocity (v), since the voltage (u) of the external source is zero. The relationship can be written

$$i^{'} = k_p v \tag{3.66}$$

A receiver incorporating a sensor of this system is shown in figure 3.16.

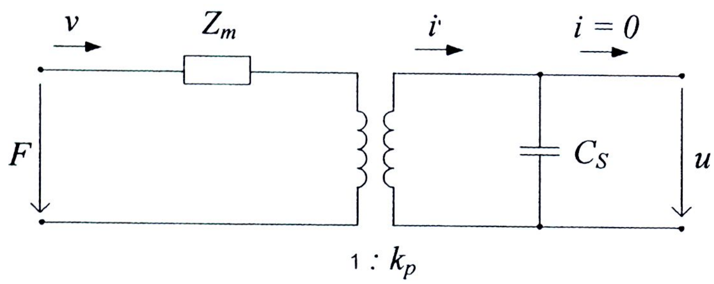

Figure 3.16 System of a receiver incorporating

The negative compliances (c_{na} and c_{nb}) are omitted in order to simplify the diagram. These compliances are usually negligible in comparison with Z_m and for some sensors they vanish completely.

The output voltage (u) of an AE sensor, which is used in a receiver, is given as the product of the output current from the sensor and the reactance of the capacitance C_S (assuming that there is no external load on the electrical side of the sensor). In the figure 3.16, the relationship can be written

$$u = \frac{i'}{j\omega C_S} \quad \text{or} \quad u = \frac{k_p v}{j\omega C_S} \tag{3.67}$$

Hence, the output voltage (u) of AE sensor that are used in electro-acoustic receivers is proportional to the displacement y ($y = v / j\omega$: see section 3.3 and Appendix C) for these sensors.

In the figure 3.16, the velocity (v) is directly proportional to the force (F) that acts upon the active part of an AE sensor and is inversely proportional to the mechanical impedance (Z_m) as seen from the side of the force

$$v = \frac{F}{Z_m}$$

where

$$Z_m = j\omega m$$

The force is equal to the product of the sensor surface area (S) and the pressures (p) acting upon this area:

$$F = S\sum p \tag{3.68}$$

From equation 3.67, the output voltage of a receiver can be expressed as

$$u = \frac{k_p F}{C_S \omega^2 m} \quad \text{or} \quad u = \frac{k_p S}{C_S \omega^2 m} \sum p \tag{3.69}$$

In order to be able to describe the individual type of receiver and derive the property, this dissertation will assume that the receiver is in an acoustic field of a spherical sound wave. The equation of acoustic pressure can be given by

$$p = \frac{p_m}{x} e^{j(\omega t - kx)} \tag{3.70}$$

where p_m is the peak value of the acoustic pressure at the unit distance from the source and x is the distance.

A receiver gives a voltage corresponding to the acoustic pressure at a given point in space. The active surface of the AE sensor is influenced only by acoustic pressure of the external acoustic field. For this receiver, the equation can be written

$$\sum p = p$$

Thus the output voltage of a receiver of the sensor is

$$u = \frac{k_p S}{C_S \omega^2 m} p$$

The pressure sensitivity (ψ) of a receiver is defined as the ratio of the output voltage to the acoustic pressure. Hence

$$\psi = \frac{|u|}{|p|}$$

so

$$\psi_s = \frac{k_p S}{C_S \omega^2 m}$$

It is clear from this equation that the sensitivity of receiver of the AE sensor is independent of both the distance (x) from the source of the acoustic stress wave and the angle (α) at that the acoustic wave is incident upon the receiver. The directional characteristic of a receiver is given by a polar diagram of the sensitivity as a function of the angle.

The voltage (u) is again proportional to the acoustic pressure. However, it is also proportional to ω^2.

The theory that this dissertation has just discussed is valid only for an ideal receiver, the dimensions of which are negligible in comparison with the wavelength. The theory would hold only for a point receiver.

After the analysis of out put voltage of PZT and AE sensor is describe. In next subsection, the calibration methods of AE sensor are described as follows.

3.6 Calibration Method of AE Sensor

The aim of AE sensors calibration is to find a characteristic of the sensor. A frequency response of specific sensor on the mechanical input quantity (velocity, displacement) is the most common result of calibration as well as the sensitivity of AE sensor. The equipment for waves propagation is called testing block. It is usually a high homogenous steel block with block or cylinder shape. Size of testing block has to be sufficient to get response of direct wave, not reflected wave. The size of testing block is dependent on the type of wave such as longitudinal wave or surface wave. A defined source (simulated source of AE) affects surface of testing block. Waves spread in block and are detected by AE sensor mounted on the surface. Simulated source can be fall of steel ball, helium jet or air jet, spark discharge, pencil lead break, capillary break, generation by piezoelectric sensor, laser etc (Keprt and Benes, 2007; Keprt and Benes, 2008).

3.6.1 Absolute Calibration (Primary Calibration)

Primary calibration has to know absolute value of input signal. A mechanical source of input signal with defined parameters (shape of waveform and duration) is important features (Keprt and Benes, 2007; McIntire, 1987). In case of calibration with step or impulse input signal, the transfer function is defined by comparison of known spectrum of input signal with spectrum of sensor. The method of calibration with step function and reciprocity calibration are described in this subsection.

1. Step Function Calibration

The basis for the step function force calibration is generated a plane surface on a testing block. A step function force applied to a point on one surface of the testing block (standard block) initiates an elastic disturbance that travels through the block.

This method uses a standard reference capacitance sensor and the step-force is generated by the fracture of a glass capillary. The response of the AE sensor being calibrated to the step-force source is then compared with the reference sensor (capacitance sensor) that measures the surface displacement due to the elastic surface waves only. The displacement at the reference sensor can be calculated using elastic theory. The surface motion on the transfer block, determined using either technique, is the free motion of the surface and not the loaded surface displacement, under the sensor being calibrated. The measured data are used to calculate a fast Fourier transform to determine values of the spectra from unknown (AE sensor) and reference sensor (Keprt and Benes, 2007).

The calibration method is described in ASTM standard (ASTM, 2007). A cylindrical steel test block 0.9 m in diameter 0.43 m long with optically polished end faces is used in this method. According to ASTM E 1106, the diagram of the apparatus setting for the step function force calibration is shown in figure 3.17.

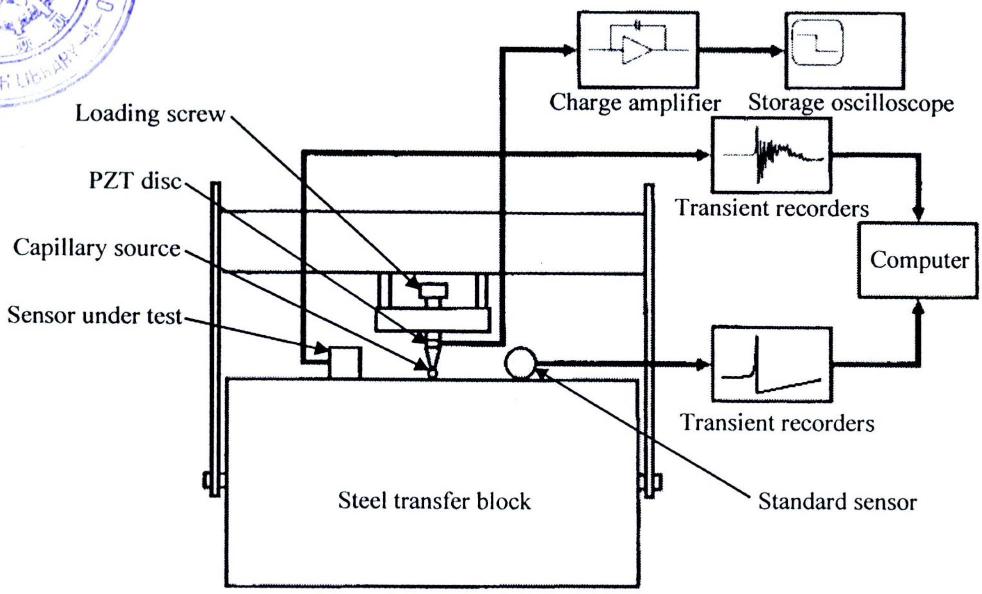

Figure 3.17 Diagram of the apparatus setting for the step function force calibration (ASTM, 2007)

2. Reciprocity Calibration

Reciprocity calibration method works on reciprocity theorem that is known from electrical circuits (Keprt and Benes, 2007). This principal can be use for electromechanical system and makes relation between transition of the sensor acting as source and later as receiver. This method requires three reversible AE sensors that are mounted on a transfer medium. One is used solely as a receiver, one a transmitter and the third is used as a transmitter and a receiver.

Three measurements are necessary for a reciprocity calibration. Each measurement requires two sensors, one transmitter (input current) and one receiver (signal voltage for bursts of varying frequency) that are coupled together through a transfer medium with the reciprocity parameter (Evans, 1997). Each sensor is to be calibrated by measuring electrical signals only. The sensor characteristics are defined as the transmission voltage response in the transmitter configuration and the free-field voltage sensitivity in the receiver configuration.

The advantage of the reciprocity calibration method is that it avoids the necessity of measuring or producing a known mechanical displacement or force. All of the basic measurements made during the calibration are electrical. The mechanical transfer function or Green function for the transmission of signals from the source location to receiver location must be known. This function is equivalent to the reciprocity parameter. It describes a transfer function of a surface wave and it takes into account the frequency of the surface wave as well as the material properties of the propagating medium. This function is the frequency domain representation of the elasticity theory solution (McIntire, 1987). The diagram of the apparatus setting for the reciprocity calibration is shown in figure 3.18.

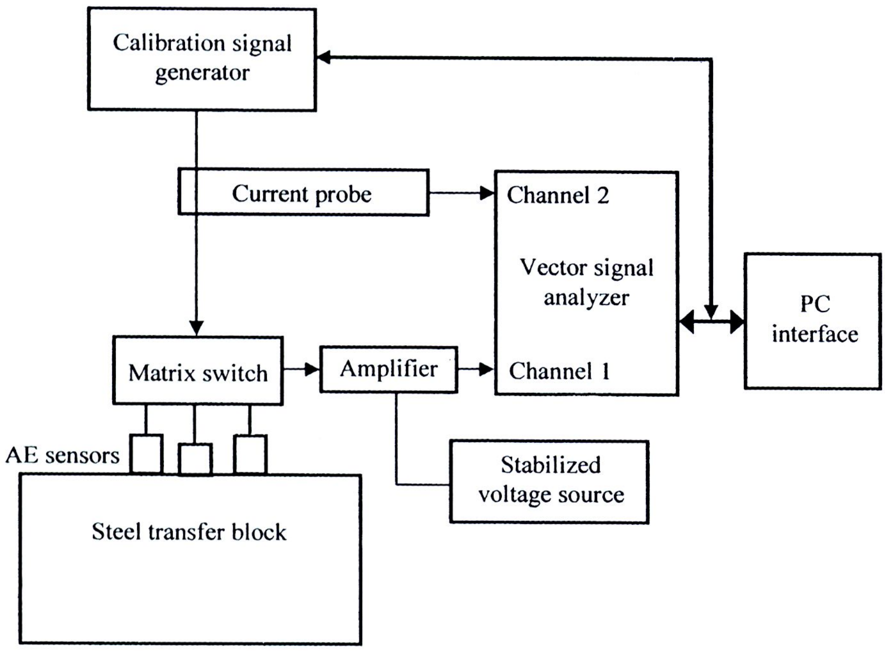

Figure 3.18 Block diagram of the apparatus setting for the reciprocity calibration (Keprt and Benes, 2007)

3.6.2 Relative Calibration (Secondary calibration)

Secondary calibration requires reference sensor with known the characteristics. Calibration is done by comparison of results of reference and tested sensor. Data from secondary calibration are the same type as from primary calibration, but are more limited such as frequency, absence of shift characteristics and greater error of calibration. The method of secondary calibration is standardized by ASTM E 1781 (ASTM, 1998) and ASTM E 976 (ASTM, 2005). Recommended configuration includes tested sensor, reproducible reference source, medium for wave propagation, steel cone with cut off top in an oblique surface and a measuring device.

According to ASTM E 976, the most relative calibration defines simple economical procedure for testing or comparing the performance of AE sensors only. The methods allow the user to check for degradation of a sensor or to select sets of sensors with nearly identical performances. The methods can be summarized as follows:

Ultrasonic transducer: Repeatable acoustic waves can be produced by an ultrasonic transducer permanently bonded to a testing block or structure, or attached face-to-face to the AE sensor under test. The pulse or sweep generator can be used to excite the ultrasonic transducer. The transducer should be heavily damped to provide a broad frequency response and have a center frequency in the 2.25 to 5.0 MHz range. The diameter of the active element (PZT) should be at least 1.25 cm. The ultrasonic transducer should be checked for adequate response in the 50 to 200 kHz region before permanent bonding to the testing block or structure.

Gas jet: This method is low cost and simple method that it can be used to calibrate AE sensor. The suitable gases are extra dry air or helium. The recommendation for pressure is between 150 and 200 kPa. Once a pressure and a gas have been chosen, all further tests with the apparatus should use that gas and pressure. The gas jet should be permanently attached to the testing block (see section 4.2). In this study, the gas jet is called the system calibrations (see subsection 3.6.3).

Pencil lead break: This method has been widely accepted for verifying the mounting of the AE sensor and for determining the reproducibility of the AE sensor response in the field work. When the lead breaks, there is a sudden release of the stress on the surface of the testing block or structure where the lead is touching. This stress release generates an acoustic wave. The Hsu pencil source uses a mechanical pencil with a 0.3-mm diameter lead (0.5-mm lead is also acceptable but produces a larger signal). The Nielsen shoe can aid in breaking the lead consistently. Care should be taken to always break the same length of the same type of lead (lengths between 2 and 3 mm are preferred). The lead should always be broken at the same spot on the testing block or structure under test with the same angle and orientation of the pencil. Spacing between the lead break and AE sensor should be at least 10 cm. With distances shorter than that, it is harder to get consistent results.

3.6.3 System Calibration

The system calibration in this dissertation is means that the mechanical energy is input into the system (object, structure or calibration block) and output is AE energy. The mechanical energy must be known such as air jet system calibration and laser system calibration. The system calibration can be provided an absolute sensitivity (a quantitative indication) of the AE sensor in situ of each test. When the AE sensors are calibrated by system calibration, the AE data can be transferred between sensors (see subsection 3.6.4). The block diagram of system calibration is shown in figure 3.19.

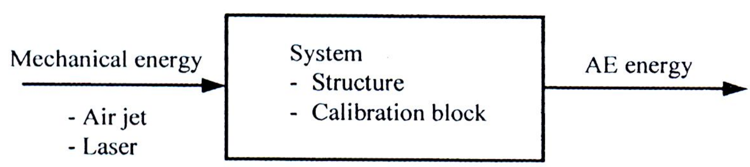

Figure 3.19 The block diagram of system calibration

In figure 3.19, the AE signal energy detected by an AE sensor is directly proportional to the AE source energy (mechanical energy). The relationship between the AE source energy and the AE signal energy can be given by

$$E_S = C_{AE} E_{AE} \tag{3.71}$$

where E_S is the AE source energy, C_{AE} is the constant of system gain, and E_{AE} is the AE signal energy. The material absorption and environmental losses of AE energy in effect decrease the system gain. The existence of a linear relationship between the energy detected by an AE sensor and the AE source energy is very important. Otherwise, the artificial AE sources used for calibration would need to have similar intensities to AE sources that may very significantly in different applications.

Since the AE sensor systems have limited frequency bandwidth, it means that only part of the acoustic energy arriving at the AE sensor will be detected if the frequency bandwidth of the acoustic waves is greater than that of the AE sensor system (Yan and Jones, 2000; Jones and Yan, 2004). The energy calibration of an AE sensor system in situ can be given by

$$E_S = C_1 Q_E E_{AE} \tag{3.72}$$

where C_1 is the system constant to be calibrated and Q_E is the energy measurement coefficient due to the system-source frequency bandwidth effect.

The distribution of the acoustic energy within the frequency spectra of the acoustic waves emitting from an AE source depends both on the type of source and the material and geometry of the structure. The effects of the material and geometry of the structure on the energy transmission of acoustic waves from the AE source to the AE sensor are considered as elements within the system constant to be calibrated.

The effect of limited frequency bandwidth of an AE sensor on the energy measurement of an AE calibration source depends on the spectral energy distribution of the AE calibration source. The effective system measurement bandwidth is determined as the overlap frequency bandwidth of the AE sensor, band-pass filters and the AE source (Yan and Jones, 2000; Jones and Yan, 2004). The energy measurement coefficient can be calculated by

$$Q_E = \left[\frac{W_M}{W_S}\right]^2 \tag{3.73}$$

where W_S is the bandwidth of the artificial AE calibration source and W_M is the effective measurement bandwidth. The energy measurement coefficient (Q_E) is taken to be 1 when the frequency bandwidth of the AE sensor system covers fully that of the AE source

3.6.4 Transferable system

In terms of the spectral density function, the transfer characteristics from the input source to the output of the sensing instrument is governed by (Prateepasen et al., 2000)

$$G_y(f) = |H(f)|^2 \cdot G_x(f) \tag{3.74}$$

where the respective spectral density functions of the input and output are $G_x(f)$ and $G_y(f)$; and $H(f)$ is the frequency response function describing the dynamics of the input signal transmitted through the AE sensors. Notably $G_x(f)$ denotes the AE produced at the source of the AE source. Figure 3.20 shows the different signal propagation paths from a common input to two different sensors.

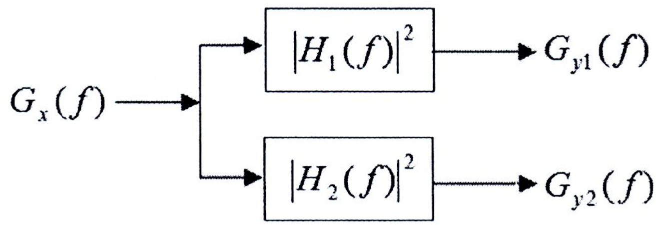

Figure 3.20 Different signal propagation paths with a common input

Because the same input $G_x(f)$ is used for both, their transfer equations can be written as

$$G_{y1}(f) = |H_1(f)|^2 \cdot G_x(f) \tag{3.75}$$

and

$$G_{y2}(f) = |H_2(f)|^2 \cdot G_x(f) \tag{3.76}$$

By dividing equation 3.75 by equation 3.76, we arrive at

$$G_{y1}/G_{y2} = |H_1|^2/|H_2|^2 \tag{3.77}$$

where G_{y1} is the AE output of one of the AE sensors while G_{y2} is that of the other. According to equation 3.77, the ratio G_{y1}/G_{y2} of the AE spectra output represents the transfer function of both AE sensors; these ratios are dimensionless quantities.

3.7 The Model Formulation for the Relationship between Mechanical Energy Released from Source and AE Signal

The main objective of this dissertation is to study and create a model formulation for the relationship between mechanical energy released from source and AE signal. From previous theories, the model formulation is described and created based on theoretical method. The details of model formulation are shown as follow.

From a Mason's equivalent circuit model of a PZT sensor and Newton's second law in harmonic vibration, the equations is

$$u = \frac{k_p}{\omega^2 m C_S}|F|$$

where u is the output voltage of AE sensor, k_p is the electromechanical coupling factor of PZT material (%), ω is the angular frequency, m is the mass of acoustic stress wave, C_S is the static capacitance of the PZT material, and F is the mechanical force of the AE source (N).

Assuming there is no plastic deformation, there are no other mechanical forces present and air resistance is negligible then the mechanical force on the plate by the air jet system calibration can be given by

$$F = pA \tag{3.78}$$

where p is the pressure of air jet and A is the cross section area of nozzle.

And

$$\omega = 2\pi f$$

where f is the resonant frequencies of AE sensor (Hz).

From the properties of PZT material, the static capacitance of the PZT material can be written by

$$C_S = \frac{K^T \varepsilon_0 \pi r^2}{h}$$

where K^T is the relative dielectric constant (at constant stress), ε_0 is the permittivity of free space (8.85 x 10^{-12} farad / m), r is the radial of PZT material (m), and h is the thickness of PZT material (m).

From the AE system calibration, the energy measurement coefficient due to the system-source frequency bandwidth effect (Q_E) can be written by

$$Q_E = \left(\frac{W_M}{W_S}\right)^2$$

where W_M is the effective measurement bandwidth and W_S is the bandwidth of the AE source (air jet)

The model formulation for the relationship between mechanical energy released from source and AE signal is shown below.

$$|F| = \frac{4\pi^3 f^2 K^T \varepsilon_0 r^2 m}{k_p h} K Q_E E_{AE} \tag{3.79}$$

In this case, the mass of acoustic stress wave (m) is omitted.

so

$$|F| = \frac{4K^T \varepsilon_0 r^2 f^2 \pi^3}{hk_p} K Q_E E_{AE} \tag{3.80}$$

where K is the constant of this system (from calibration) and E_{AE} is the AE signal energy.

For the commercial of AE sensor, introducing a new constant, C_{system}

$$C_{system} = \frac{4K^T \varepsilon_0 r^2 f^2 \pi^3}{hk_p} K \tag{3.81}$$

The equation can be written as

$$|F| = C_{system} Q_E E_{AE} \tag{3.82}$$

From model formulation and system calibration, AE sensor systems have limited frequency bandwidths (Q_E). It means that only part of the energy arriving at the AE sensor will be detected if the frequency bandwidth of the acoustic stress wave is greater than that of the AE sensor system. On the other hand, if the frequency bandwidth of the acoustic stress wave is less than that of the AE sensor system, total of the energy arriving at the AE sensor will be detected.

From the system calibration section, the distribution of the energy within the frequency spectra of the acoustic waves emitting from source depends both on the type of source and the material and geometry of the structure. The effect of the material and geometry of the structure on the energy transmission of acoustic waves from the AE source to the AE sensor are considered as elements within the system constant to be calibrated. The effect of limited frequency bandwidth of the AE sensor on the energy measurement of the AE calibration source depends on the spectra energy distribution of the AE calibration source. In these reasons, the energy calibration of the AE sensor system in situ must be calibrated. It is the best and precision if the frequency spectra of the AE calibration source are closed to the frequency spectra of the AE source.

3.8 Summary

AE is one of the NDT methods that can be employed to measure and monitor the internal valve leakage and uniform corrosion, respectively. The main parts of AE system contain AE sensor, amplifier, filters and AE data acquisition systems. The AE sensor is usually made from PZT. When AE testing systems are applied in the measurement and monitoring of structure, the AE testing systems must be calibrated to reference the sensitivity of testing systems. The calibrations of AE testing system need a quantitative indication rather than a qualitative indication. These provide means for traceable measurement of AE testing systems. Since the AE sensors have limited frequency bandwidths and they depend both on the type of source and geometry of the structure, the AE energy source must be used to calibrate in situ AE sensors on the structure under test.