Chapter 6

Acoustic Emission

6.1 Introduction

- **Acoustic emission (AE) is high frequency elastic waves (discrete acoustic packets) produced in a material *under load* by the rapid release of strain energy during crack propagation, plastic deformation or phase transformation.**
- **These waves travel to the surface where thy can be *listened* to (detected).**
- **Signals of significance in metal and brittle materials produce between 30 kHz to 5 MHZ waves (Audible limit = 20 kHz).**
- **Technique also called Stress Wave Emission. "Cry of tin" 1938, the noise due to the twining experienced by fine tin when deformed.**
- ***Key words*: under stress, under load, solids, crack propagating (not stationary).**
- **AE can be considered as an extension of ultrasonic testing, except that the source is internally generated (passive) and the produced signal may be continuous.**
- **Technique is also passive in the sense that one *listens* to defects rather than looks for them.**
- **AE can give indications on the location as well as the relative severity of a defects and can detect many defects simultaneously. AE can be used to measure degree of stress (strain) of a material.**

Source: Acoustic wave (passive).

Modification: stress induced dislocation, producing source.

Detector: Piezoelectric transducers of amplified signals.

Indication : Oscilloscope, tape recorder.

Interpretation: will study here.

Kaiser Effect, 1950: If materials (most solids) are stressed while emissions are being monitored and the stress is then relaxed, *no new* emissions will occur until the previous *maximum* stress has been exceeded.

6.1.1 Advantages

AE Testing:

- nondestructive, useful for quality assurance or safety reasons.
- can detect very small flaws (1μ to 50 μ).
- responds only to stress levels which are greater than those which have previously, and in many cases, safely maintained.
- is essentially non-localized, i.e. receiving transducer does not have to be particularly near the source of emission (less number of probes are required, large volumes can be examined).
- can provide continuous in-service monitoring.

6.1.2 Disadvantages

- Detected signal has low energy, requires sophisticated and expensive electronics.
- Background noise (pumps, moving machines) is difficult to separate from signals.
- At present, AE is applied to some heavy walled pressure vessels in the nuclear and petroleum refining industry, but is not in general use as an inspection tool.

6.1.3 Ability

AE can detect:

- Nature and severity of change occurring.
- May locate the position of formation by using 3 or more transducers.

AE is used for detecting:

- Steady load beyond the elastic limit (crack growth or failure).
- Fatigue: fluctuating loads.
- Stress-corrosion fatigue: environmental stress.
- Crack growth in adverse gaseous conditions, e.g., hydrogen growth in metals (Candu pressure tubes).

6.2 Source and Modification

- Deformation occurring on the onset of plastic flow is caused by dislocation motion of atoms.
- This leads to burst-type emission.
- Of too many locations are occurring in the same time, a continuous-type emission is produced.
- Continuous emission is thought to be a collection of pulses (bursts), rather than sinusoidal emission with imposed noise.

Therefore, *stressing* a metal produces two distinct acoustic signals:

1. Burst: caused by crack growth.
2. Continuous signal: due to movement of dislocations.

Detection Piezoelectric transducers, as in Ultrasonics, AE pressure on a the transducers generates an electric signal (voltage).

- Transducer transforms the amplitude of the signal (after amplification and shaping) to some *voltage* signal.

- The signal has the ideal form:

$$V = V_0 e^{-\beta t} \sin \omega t \tag{6.1}$$

where

$$\begin{aligned} V_0 &= \text{reference voltage} \\ \omega &= 2\pi f \text{apparent frequency} \\ \beta &= \text{decay constant} \end{aligned}$$

6.3 Indication

1. Ring-down Counting: signal transformed into counts.
2. Energy: integrate signal with time.
3. Root-Mean Square Value.
4. Amplitude Distribution.
5. Frequency Analysis.

6.3.1 Ring-Down Counting

- A threshold voltage V_{th} is defined and a count is given every time the signal crosses this voltage.
- the number of counts obtained is given by:

$$n = \frac{\omega}{2\pi\beta} \ln \frac{V_0}{V_{th}} \tag{6.2}$$

Note that n depends on frequency, medium (β), in addition to V_0 and V_{th} which must remain constant.

- For a continuous signal:

$$\frac{dn}{dt} = \frac{f \exp(-V_{th}^2)}{\alpha (V_{rms}^M)^2} \tag{6.3}$$

where α is a calibration constant (typically =2), and V_{rms}^M is the measured root-mean-square voltage.

- In general, n can be related to the stress intensity factor K_I by:

$$n = AK_I^m \tag{6.4}$$

where A and m are material-dependent.

- For fatigue:

$$\frac{dn}{dt} = \beta(\Delta K_I)^m \tag{6.5}$$

where ΔK_I is the change in the stress intensity.

- Ring-Down Counting is used in stress corrosion, stress cracking, hydrogen embrittlement and mechanical and fracture behaviour of ceramics and composites.

- Ring-down counting is sensitive to threshold value and system gain (amplification).

- It is difficult to find a direct correlation between the count rate and event rate.

- In general, increased weighting is given to large signals (to reduce effect of noise). Large counts are associated to severe material damage.

6.3.2 RMS Value

- RMS voltage is reported to be a measure of the AE activity

$$V_{rms}^2 = \frac{1}{T}\int V_i^2\, dt \tag{6.6}$$

where T is signal's period.

- measures all emissions generated (+ve, or −ve) with equal weight.

- Can be related to the energy of emission or area under the signal curve.

- Generally:

$$\text{Energy} \propto V_{rms}^K \tag{6.7}$$

where K is a system-dependant constant.

- RMS itself (no need for ring-down counting) can be used to measure AE activity and hence size of dislocation and severity of damage.

6.3.3 RMS and Energy

Electrical Energy present in a signal:

$$E = \frac{1}{R}\int_0^{\infty} V^2(t)\,dt = \frac{1}{R}V_{rms}^2 \tag{6.8}$$

R= Resistance of measuring device.

$$\begin{aligned} E &= \frac{1}{R}\int_0^{t^*} V_0^2 e^{-2\beta t}\sin^2\omega t\,dt \\ &= \frac{V_0^2}{4R(\omega^2+\beta^2)}\left[\frac{\omega^2}{\beta}(1-e^{-2\beta t^*})\right] \\ &- \frac{V_0^2}{4R(\omega^2+\beta^2)}\left[2e^{-\beta t^*}\sin\omega t(\beta\sin\omega t^* + \omega\cos\omega t^*)\right] \end{aligned} \tag{6.9}$$

where

$$\begin{array}{rcccl} t^* & = & \frac{1}{\beta}\ln\frac{V_0}{V^*} & \approx & \text{duration} \\ V^* & = & V_0 e^{-\beta t^*} & = & \text{decayed voltage} \end{array} \tag{6.10}$$

If $\exp(-2\beta t^*) << 1$, signal decays rapidly

$$E \approx \frac{V_0^2\omega^2}{4R\beta(\beta^2+\omega^2)} \tag{6.11}$$

Counts to reach V^*

$$n^* = \frac{\omega}{2\pi\beta}\ln\left(\frac{V_0}{V^*}\right) \tag{6.12}$$

Then

$$V_0 = V^* e^{\frac{2\pi\beta n^*}{\omega}} \tag{6.13}$$

$$E = \frac{(V^*)^2\omega^2}{4R\beta(\beta^2+\omega^2)}e^{\frac{4\pi\beta n^*}{\omega}} \tag{6.14}$$

IF β and ω are constants:

$$E \propto e^{\frac{4\pi\beta n^*}{\omega}} \tag{6.15}$$

1. n^* provides some indication of energy of signal (intensity).

2. Also $V_{rms}^2 = RE$ provides an energy dependant indication (activity).

3. To measure energy directly, one needs to digitize and integrate waveform signal (Analog-to-digital convertor).

- RMS is related to heating power.
- A device to measure heating power is used.
- RMS response is *slow* as compared to electrical energy.
- RMS is indicative of average acoustic power.
- In ring-down counting, V_{th} and V^* must be high enough to avoid noise (only high level bursts are counted).
- RMS is not sensitive to short duration noise fluctuations, therefore one can measure signals close to the background level and detect smaller dislocations.

6.3.4 Energy Analysis

1. Signal voltage is measured.
2. Area under curve of voltage is squared against time is measured.
3. Area is $\propto$ signal energy.

- Need to digitize and then integrate waveform signal; suitable analog-to-digital converters are not currently available for this frequency resolution.
- Alternatively, a design to perform integration electronically need to be developed.
- Actual energy of signal $\propto$ mechanical energy in the emission event $\propto$ size of displacement.
- Energy signal yields substantially the same information as ring- down counting, except if there is a frequency change in dislocation emission.

6.3.5 Event & Amplitude Distribution Analysis

- Counter is only triggered when upper window is reached.
- Trigger is reset only after the signal ring-down duration is passed to avoid counting signal twice.
- Then, count signals greater than V_{up} and between V_{up} and V_{th}.

- A series of events counter.
- One can distinguish between magnitude and type of dislocation, e.g., small crack growth v.s. rapid crack growth.
- Can check for multi-cracks and change in crack size.

6.3.6 Frequency Analysis

- Commercial spectra analysis are expensive but readily available.
- Digital methods, via Fast Fourier Transform, are more expensive.
- Frequency distribution may be identified with a particular type of fractures.
- Useful when signals are continuous, as in leak testing, or large plastic deformation.
- May identify strain rate.
- Still under development.

6.4 Interpretation

Some Facts:

- Uncoordinated motion of individual dislocations cannot be detected, except perhaps during the formation of high-purity single crystals.
- The nearly simultaneous motion of many dislocations within a small volume of material is generally required (packet or avalanche of moving dislocation).
- The packet must glide far enough at high enough velocity, otherwise the elastic wave produced will not be large enough to be detected.
- These conditions are often not satisfied simultaneously, so only a small fraction of the dislocation within the object produces AE.
- Equipment limitations (sensitivity of sensors, frequency within which measurements are made, etc.) may substantially influence the AE observation.

- Strain rate is generally proportional to rate of AE (except in a very few cases).

- Test temperature, like strain rate, can alter significantly the amount of AE.

- Material purity and volume is important, since signal has to travel form source to sensor (calibration is needed).

- Cold or warm working prior to AE testing generally reduces observed AE.

- Calibration standards are not available (not reproducible), however pulsed laser has been reduced to simulate elastic waves.

6.5 Applications

6.5.1 Flaw Location

- Need at least two transducers for locating a flaw.

- For flaws in vessels need more than two transducers.

- Need burst emissions to localize a signal.

- Source volume (flaw) must be small in size.

$$x = \frac{K(t_A - t_B)}{2} \qquad (6.16)$$

where x = distance form source to mid-point of line and K is a constant describing the speed of wave and its attenuation in material. Note that, if $t_A = t_B$, $x = 0$.

- For three sensors, solve the equations:

$$\begin{aligned} r_3 - r_2 &= k_2 = v(t_3 - t_2) \\ r_2 - r_1 &= k_2 = v(t_2 - t_1) \\ r_1 - r_3 &= k_3 = v(t_1 - t_3) \end{aligned}$$

v = velocity of sound in material, r_1, r_2, r_3 define a hyperbole, the intersection of which determines the location of the source.

6.5.2 Leak Detection

- Leaks generate acoustic noise due to the pressure difference between the fluid and the atmosphere.
- Two detectors placed on opposite sides of the leak can be used to determine leak location.
- Relative strength of AE signal depends on location of transducer from leak.
- Relative intensity of signal can be used to determine leak location.

6.5.3 Other Applications

AE can be used for:

- Study of behaviour of metals, ceramics, composites, rocks and concrete, to obtain information on rupture, fatigue, corrosion, yielding, creep, stress corrosion, plastic zone, head of crack tip, and discontinuities in crack propagation.
- In-service monitoring in drilling platforms, mines, aircraft, pressure vessels, pipelines, bridges, cables, loose parts.
- AE is of special interest in petrochemical, chemical equipment, electric utilities (nuclear reactors), aerospace and electronics industries.

6.6 Work Problems

1. In AE testing, what is applied and what is detected?
2. In AE, once a discontinuity is detected, what other information about the flaw can be found?
3. What is the difference between AE signals obtained from crack growth and those obtained from deformation? Draw schematic of each signal.
4. Why is AE testing important during hydrostatic testing?
5. Ring-down time is an important performance parameter of a piezoelectric transducer. Ring-down time can be defined by the number of oscillations within the probe that is required to reduce a pulse to a specific lower magnitude (a threshold value). Let $x = 0$ defines the

boundary between the ceramic material of the transducer and the back material, and $x = X$ defines the boundary between the ceramic and the load material. If A_0 is the amplitude of the leftward travelling wave at X and A_1 is the amplitude of the pulse at $x = 0$ after being reflected by the backing material:

(a) Determine the relationship between A_0 and A_1 in terms of the acoustic impedance of the ceramic, Z_0, the backing material, Z_2, and the load material Z_1.

(b) The magnitude of the nth travelling wave from the ceramic to the load material is given by:

$$\frac{A_n}{A_0} = R_0^n R_X^{n-1}$$

Define R_0 and R_X in the above expression in terms of acoustic impedances.

(c) Verify mathematically or physically the validity of the above expression for A_n/A_0.

(d) For a lead-zirconate-titanate, PZT, ($Z = 33.0 \times 10^6$ kg/m^{2}s) transducer with no backing material, calculate the number of oscillations required to reduce A_n to ten percent (10 %) of A_0.

(e) For a backing material with $Z = 18.8 \times 10^6$ kg/m^{2}s, calculate the number of oscillations required to reduce A_n to ten percent (10 %) of A_0.

(f) Based on the above calculations, elaborate on how the higher acoustic impedance of the backing material would affect probe performance in ultrasonic testing.

(g) Based on the above calculations, elaborate on how the higher acoustic impedance of the backing material would affect probe performance in acoustic emission testing.

6.7 Graphs

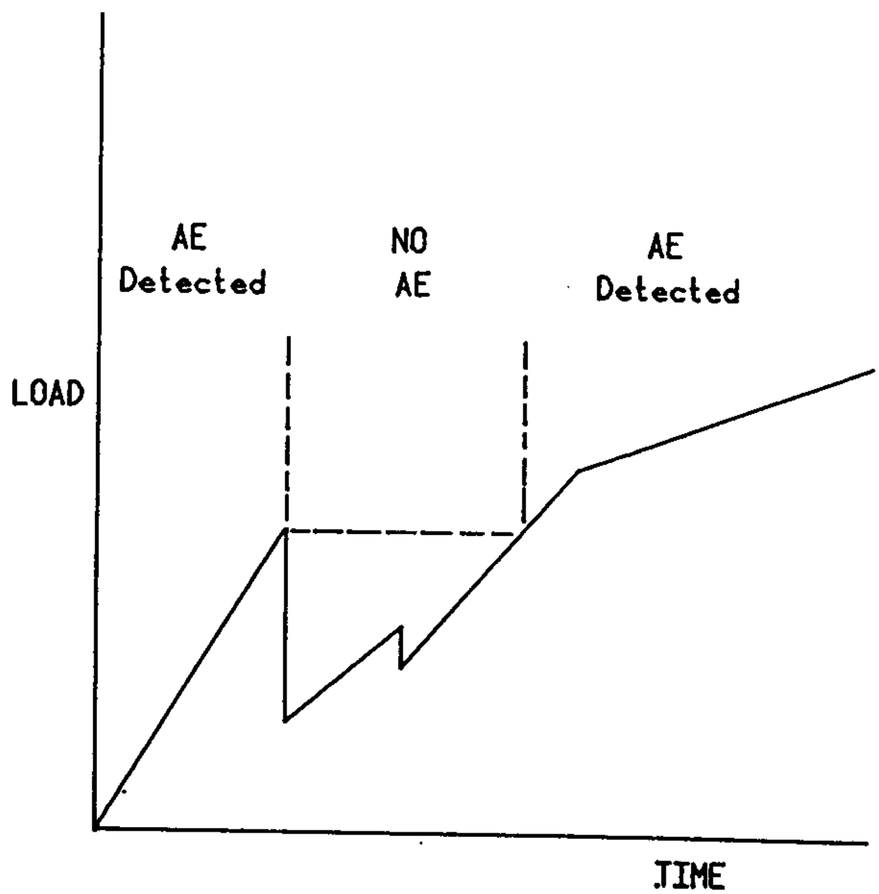


Figure 1. Kaiser effect.

Figure 6.1: Kaiser Effect

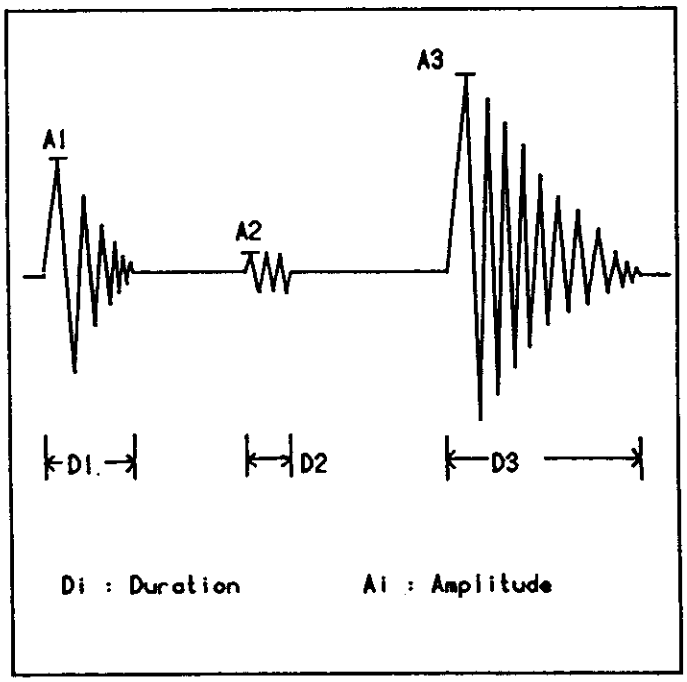


Figure 6.2: Amplitude and Duration of AE Signal

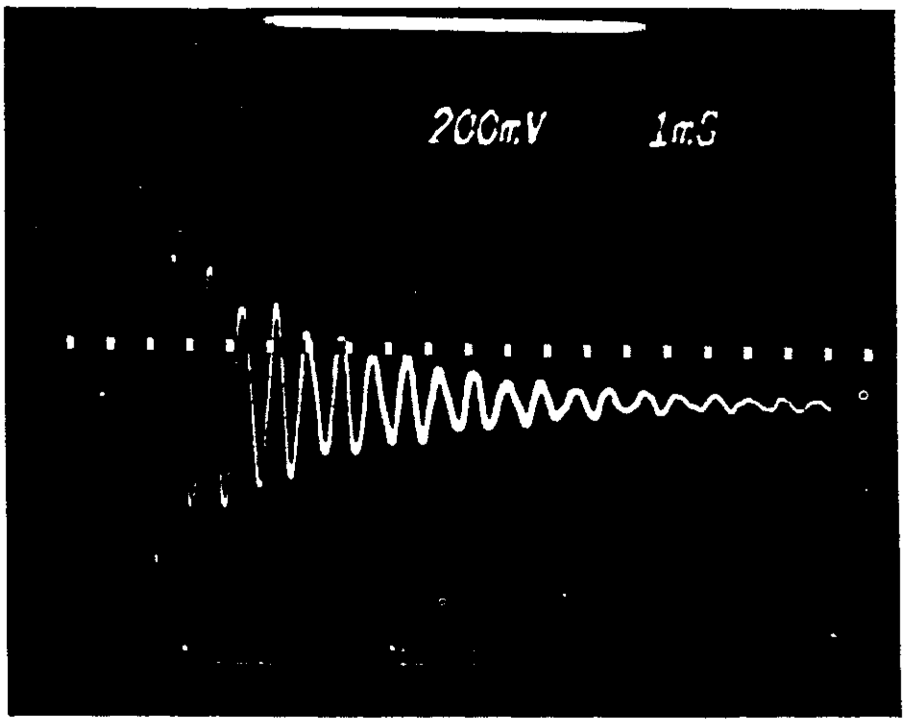
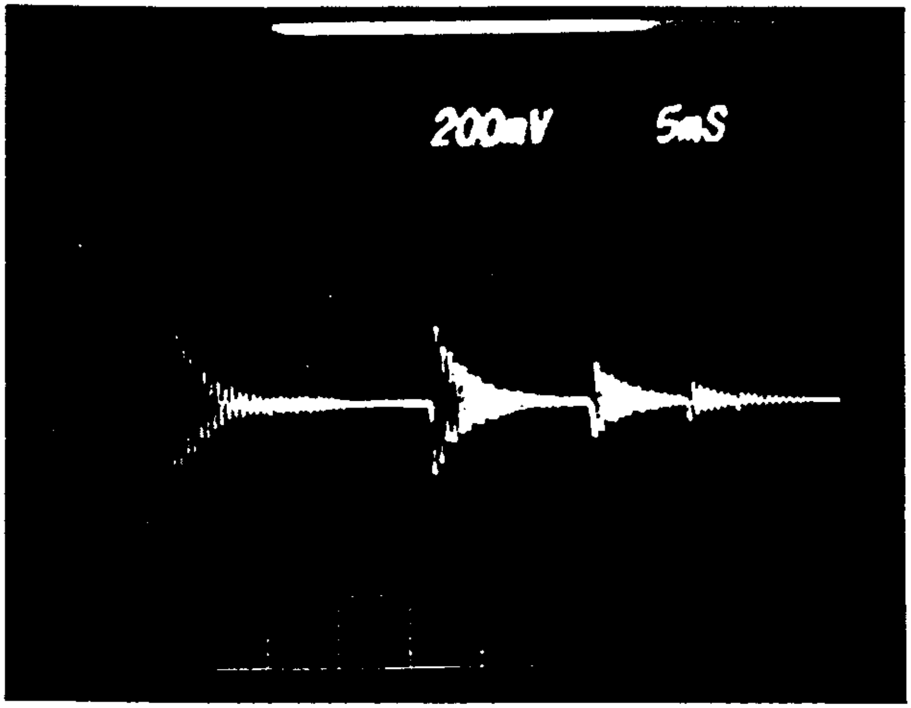
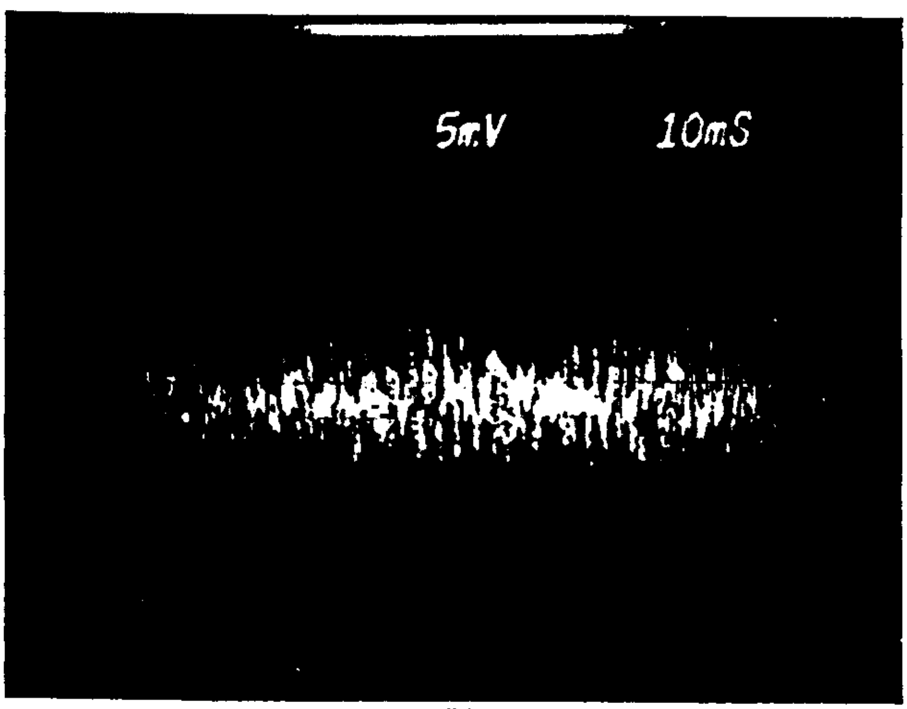


Figure 6.3: Idealized AE Signal



(a)



(b)

Figure 6.4: Burst (Top) and Conitnious Emissions (Bottom)

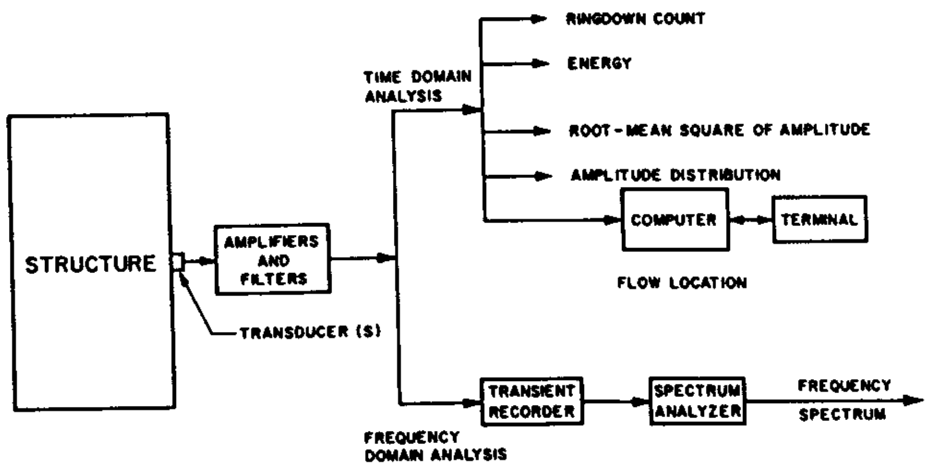


Figure 1. Block diagram showing the different parameters measured in the time and frequency domains.

Figure 6.5: Measurement in Time and Frequency Domains

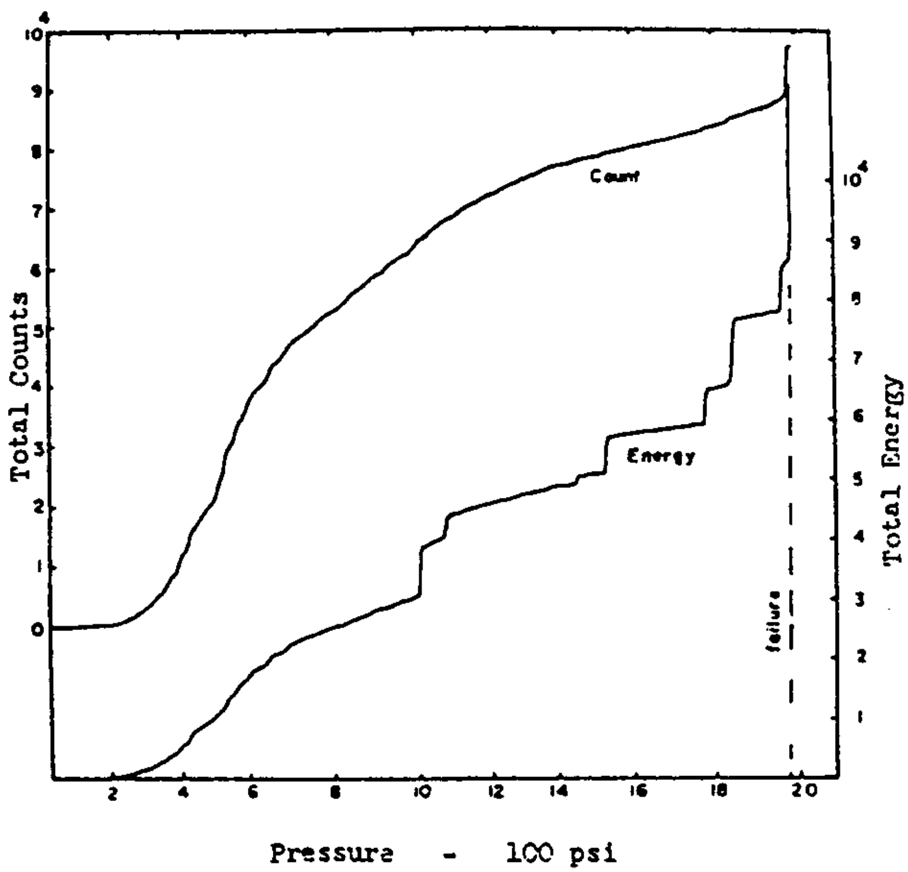
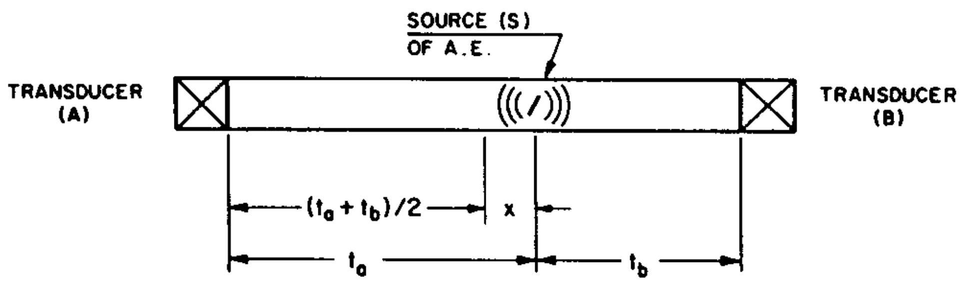
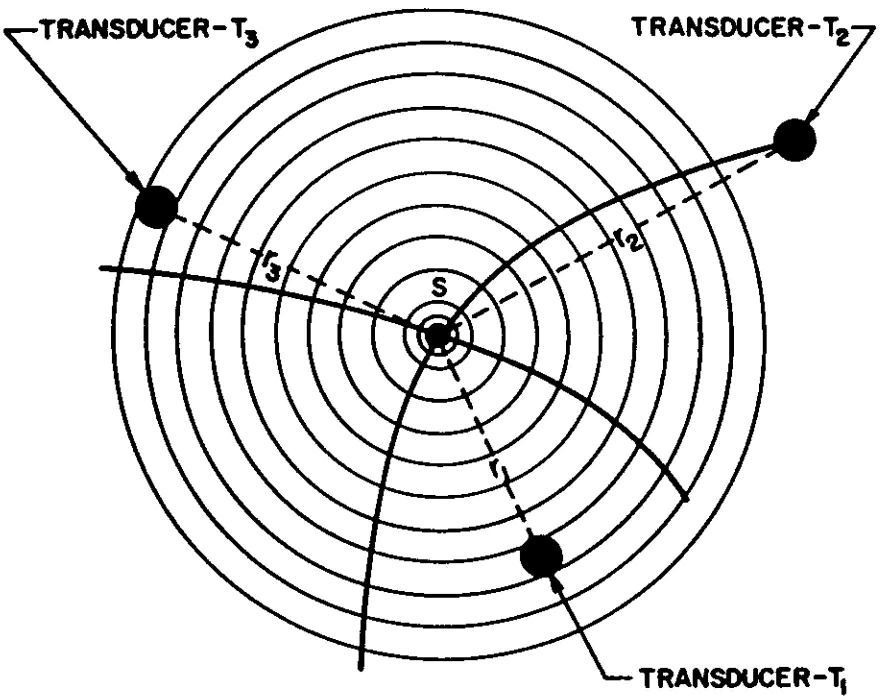


Figure 6.6: Count vs. Energy Analysis

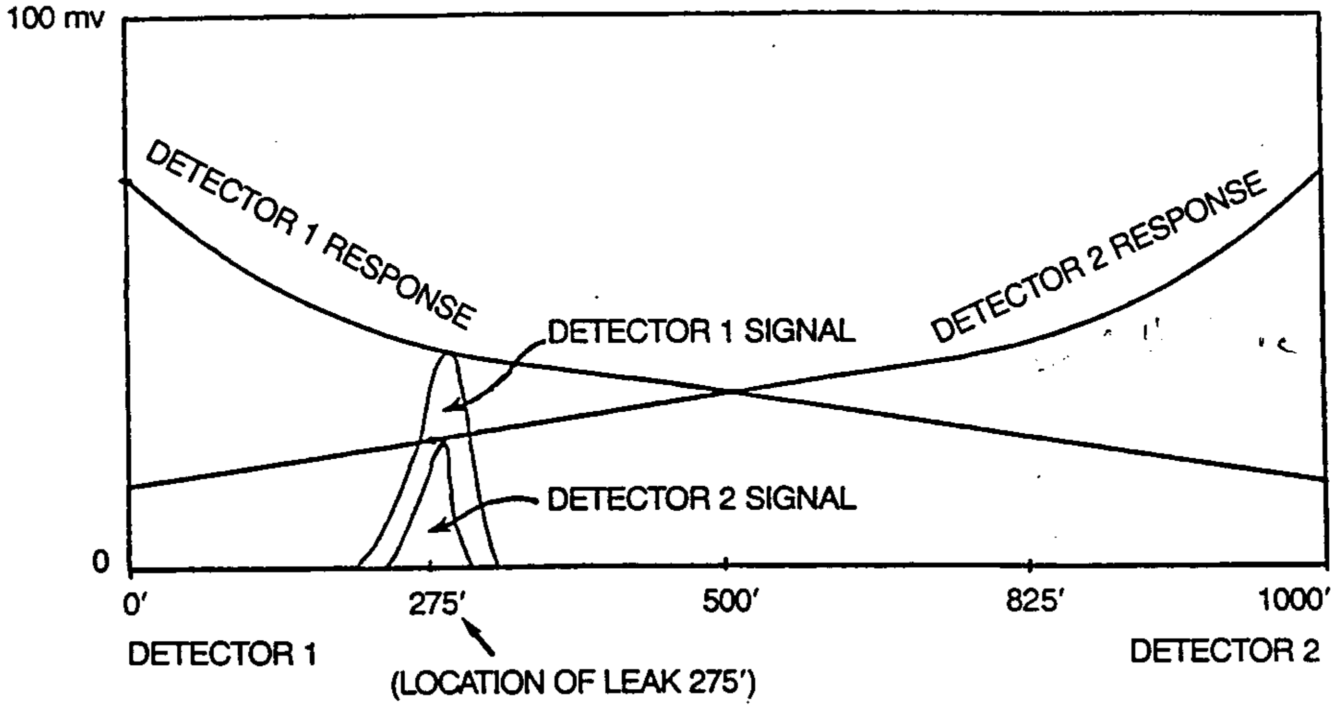


Linear localization using two acoustic emission transducers.



Spacial localization using three transducers. The figure shows the intersection of the two hyperbole defining the source of acoustic emission ′

Figure 6.7: Determination of Position



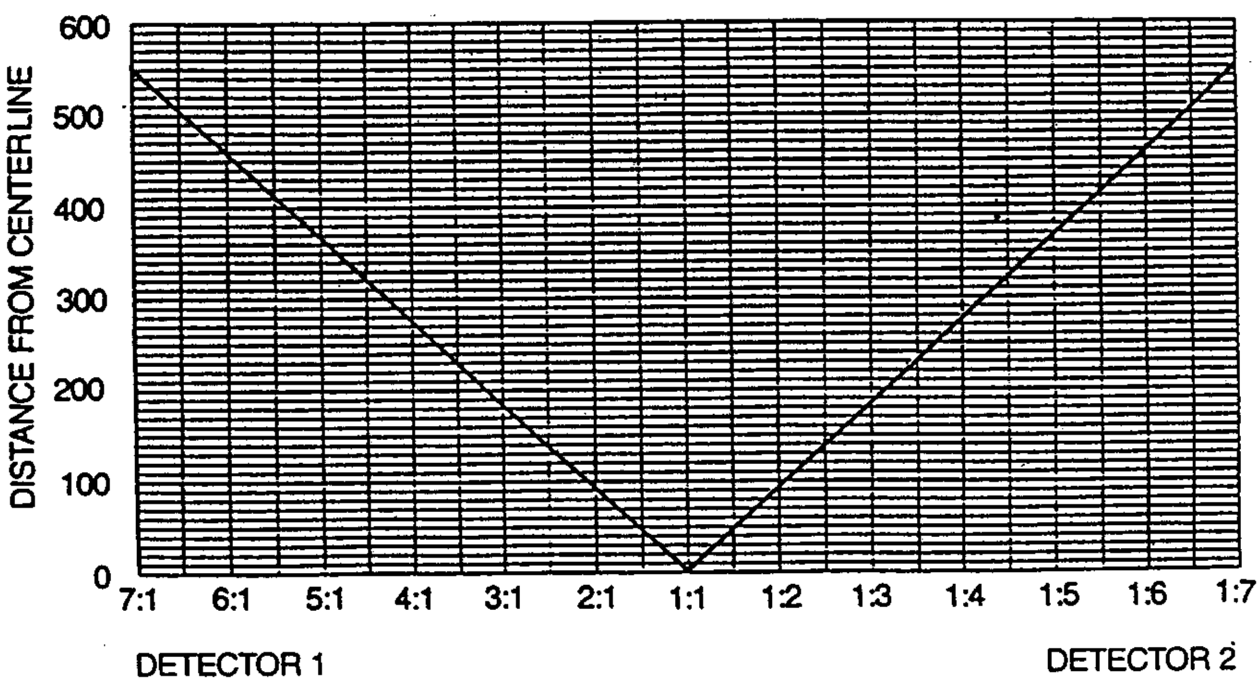


Figure 6.8: Leak Detection