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DAMAGE STUDY BY ACOUSTIC EMISSION: THE ROLE OF THE TRANSDUCER

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ABSTRACT

Acoustic emission is a powerful tool to study damage in materials. However, if in literature, reference is made to the energy released during the failure mechanisms, little attempts have been made to take into account the local time-varying discontinuities involved in the fracture processes. The objective of this study is to have an approach of the contribution of the source-event dynamic characteristics, and of their influence on the amplitude values of acoustic emission signals.

SOMMAIRE

L'émission acoustique est une technique largement utilisée pour l'étude de l'endommagement des matériaux. Si, dans la littérature, un intérêt particulier est porté sur l'énergie libérée durant les mécanismes de rupture, force est de constater que peu d'attention est accordée à la variation dans le temps des discontinuités locales créées lors de ces mécanismes. L'objet du présent travail est de dégager l'influence des caractéristiques dynamiques des processus de rupture sur l'amplitude des signaux d'émission acoustique.

1. INTRODUCTION

Failure processes create local strain and stress discontinuities that generate strain waves within materials. These signals propagate to the surface of the structure where they can be detected by one or an array of sensors.

If waves carry initially information about fracture mechanisms, there is a tendency for this information to be weakened through features resulting from their propagation, multiple reflections on the structure boundaries, their combinations, and also by transducers. While industrial acoustic emission (AE) applications and instrumentation developments have progressed well in recent years, the interpretation of AE signals still remains empirical and qualitative. The difficulty lies in the fact that the influence of the different parameters involved in the AE process has not yet been clarified. In this paper, the different types of AE transducers used in geotechnical applications and problems relating to their calibration will be reviewed. Then, the response of resonant transducers to a discontinuity created during microcracking will be considered.

2. ACOUSTIC-EMISSION PROCESS

Fracture mechanisms induce local mechanical discontinuities in materials. These discontinuities are responsible for a sudden release of energy stored in the cracked area. Part of the total strain energy is dissipated as transient waves that propagate from discontinuities through the medium. Acoustic emission can be considered as a system in which the input is the acoustic-emission event and the output is the acoustic-emission signal (Fig. 1).

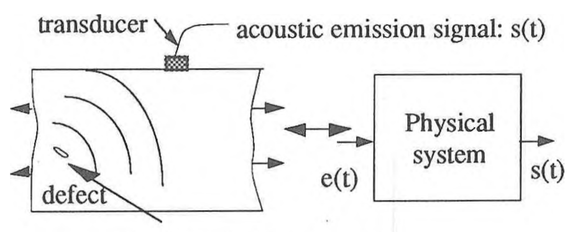

Figure 1: Acoustic emission process

It is generally known today that many materials emit AE when they are stressed or deformed. Discovery of this phenomenon led to the realization that it could be a powerful tool for detecting an AE event, localizing it and getting information on the nature of the source (crack creation or propagation). Most AE applications involve monitoring manufacturing and other dynamical processes, the integrity of structural components as well as fundamental investigations of the failure process in engineering and geological materials (Sachse et al.,1991)

The basis of AE measurement system consists of AE signal detection, conditioning, and analysis (Fig. 2). Since the problem with AE techniques is extracting from all information gathered those that are related to failure process, the role of the transducer is of a prime importance. However, many kinds of problems concerning AE transducer sensivity still remain; in particular, the precise physical meaning of the transducer mechanical-electrical conversion process makes interpretation of AE test results difficult. In the following paragraphs, a review of AE transducers used in geotechnical applications is given and the problem of their calibration is discussed.

3. ACOUSTIC EMISSION TRANSDUCERS AND THEIR CALIBRATION

The transducer converts the mechanical energy associated with an AE event into a suitable electrical signal. The detected AE signals typically range from low kHz values in geological materials to over 10 MHz in some laboratory specimens. Different types of transducers are used in geotechnical applications to detect AE activity at a specific point in the structure (Drnevich and Gray, 1981). Displacement gages are conveniently used to detect low frequency signals ($f < 1$ Hz), while accelerometers are usually employed when higher frequency signals ($f > 2000$ Hz) are involved. Signals between these extremes are picked up using velocity transducers (geophones). Hydrophones are generally not suitable as AE transducers, because they are ultra-sensitive pressure transducers and must be installed in a fluid-filled borehole. In this case, AE source location is difficult due to the composite media (fluid / rock) involved.

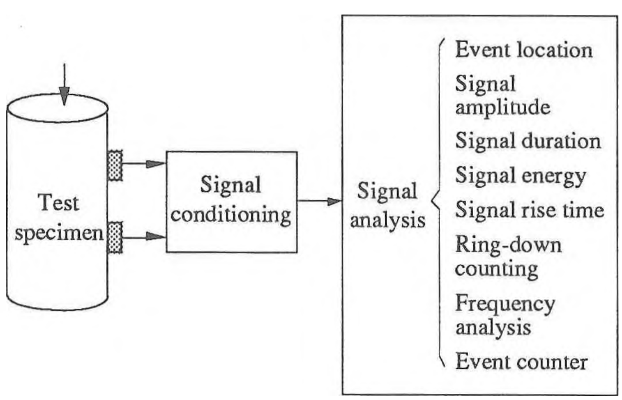

Figure 2 : Typical acoustic emission measurement system

While a number of new sensors, such as non-contacting optical and capacitance sensors as well as novel electromagnetic and embedded fiber-optic sensors, have been developed in the last decade, most laboratory studies on rupture mechanisms are still carried out with piezoelectric sensors. Ideally, the response obtained by the transducer would be the same as that obtained if the transducer were not present. This is not the case with piezoelectric transducers, so calibration is required.

AE transducer characterization has not yet been totally solved, mainly because there is no real standard event of known characteristics. Kim and Sachse (1986) and Yuyama et al (1988) indicated that the source function during the formation of a crack may be simulated by a step function with about one microsecond of rise time. Therefore, piezoelectric-transducer calibration generally consists of applying a step unloading force (glass capillary break, ball impact, pencil-lead fracture...) on the surface of a specimen and digitizing the corresponding transient response from a piezoelectric transducer located at a point on the surface of the specimen. Calibration results show that piezoelectric transducers respond both to displacement and velocity in a complex manner. Some authors (Hsu et al.,1981) have noted subjectively that piezoelectric transducers seem to respond primarily to velocity, while others (Maji et al.,1990) indicated that this assumption is valid only for the duration of the first P-wave.

It appears from this brief review of AE transducers that some questions concerning their characterization deserve more attention. Any success in accurately describing source mechanisms depends on an understanding of AE transducer functioning. The next section presents a study of the influence of transfer function of a resonant piezoelectric sensor on the AE signal characteristics.

4. IMPULSE RESPONSE OF A RESONANT TRANSDUCER

Ohtsu et al (1981 and 1982) reported a study on the source mechanisms of AE in concrete. These authors considered a transducer with a flat frequency response. In practice, acoustic-emission transducers are piezoelectric sensors with high sensivity along a narrow frequency band. The frequency response functions of the transducers are not well-defined, depending particularly on the type and incidence of the wave reaching the transducer. Another important problem lies in modelling the input of the acoustic-emission system. Ohtsu assumed that the input was the acceleration of the discontinuity created during microcracking. Previous study (Berthelot and Rhazi,1990) shows that the energy released during a fracture process depends on the type of fracture process (values of Young's modulus (E), and the average ultimate stress, σ_u, of the cracked area), on the fracture surface created (S) and on the interaction after rupture between the cracked area and the surrounding area (R_t). On the basis of these results, the case of a transducer sensitive to variations in time of the discontinuity $\Delta F(t)$ of the load in the cracked area (Fig. 3) is considered herein. The transducer input e(t) (Fig. 4.1) is therfore, except for one multiplicative factor, the derivative function of the load function (Fig. 3.1) of a duration approximately equal to the transfer time (duration of the discontinuity).

As a first approximation, this function can be represented by a rectangular time window of height a_0 and width T_f (Fig. 4.2), having the same energy as the real impulse. This approximation is equivalent to describing the discontinuity $\Delta F(t)$ as a linear function of the form (Fig. 5.1) :

$$\Delta F(t) = F_0 - \frac{dF_0}{dt} \cdot t \qquad (1)$$

of a duration $T_f = F_0 / \frac{dF_0}{dt}$. The input of an acoustic-emission system is then a window with a width T_f and a height $a_0 = \alpha \frac{dF_0}{dt} T_f$, with $\frac{dF_0}{dt}$ and T_f being the dynamic characteristic parameters of the input. Setting aside the influence of the propagation, the response function of an acoustic-emission system is identical to the transducer response.

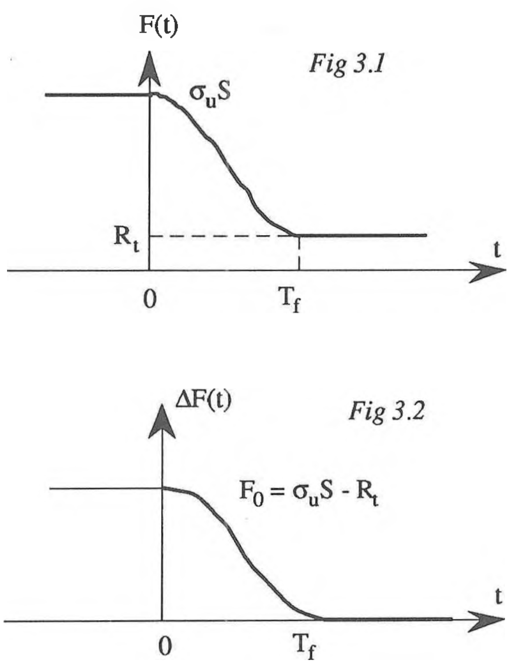

Figure 3: Variation of the local load during microcracking process

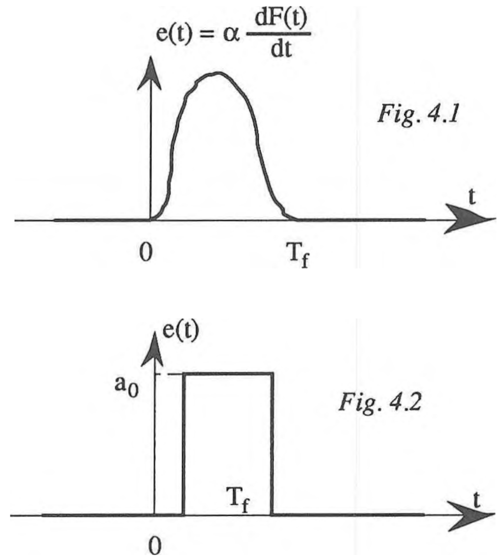

Figure 4: Input of the acoustic emission system

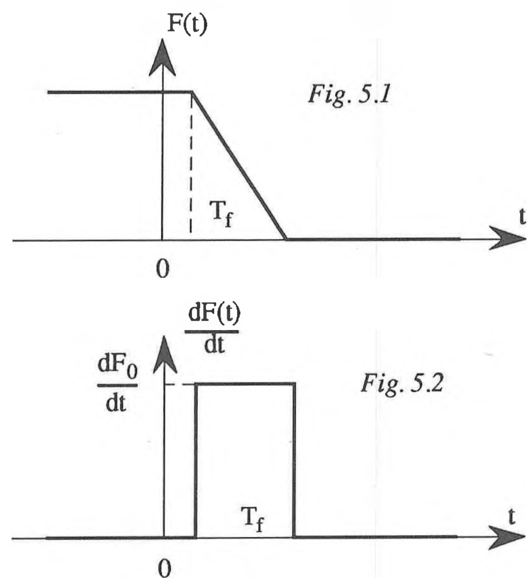

Figure 5: Variation of the load in the cracked area

The acoustic-emission transducer can reasonably be considered a resonant transducer characterized by its resonant frequency f_0, its gain factor (H_0) at frequency f_0, and its quality factor Q. The case of an ideal transducer of rectangular bandpath (Fig. 6), of height H_0, and width $\Delta f = f_0/Q$, centered on the resonant frequency is considered. To simplify calculations, it is assumed that the signal input is a rectangular window of width T_f centered on t = 0 (Fig. 7.1), and that the frequency response of the transducer is real, and composed of two symmetrical parts (Fig. 7.2).

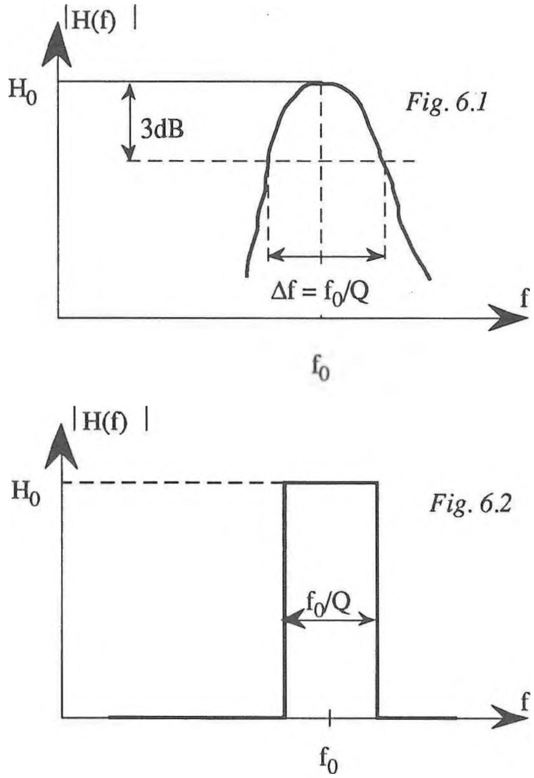

Figure 6: Real and ideal response of the transducer

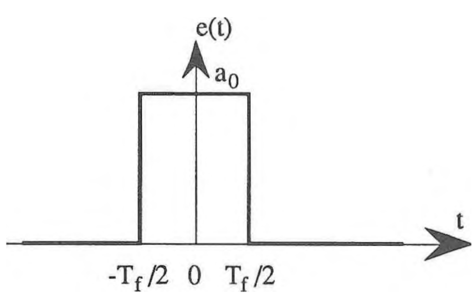

Figure 7.1: Signal input

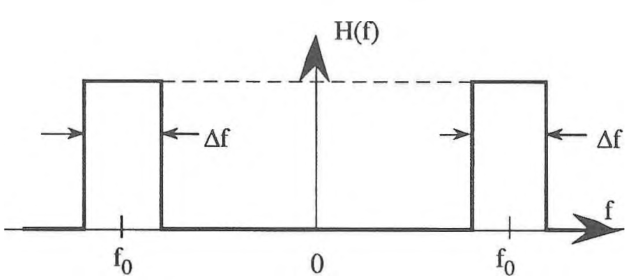

Figure 7.2: Frequency response of transducer

The Fourier transform $E(f)$ of the signal is (Fig. 7.3):

$$E(f) = a_0\,T_f\,\frac{\sin \pi T_f f}{\pi T_f f} \qquad (2)$$

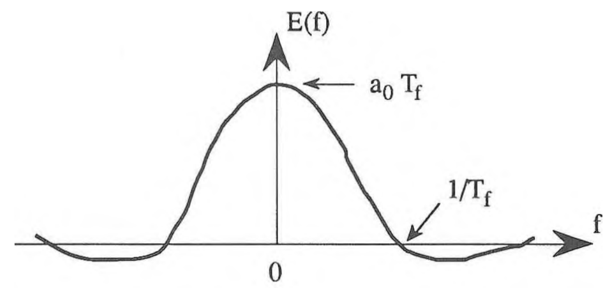

Figure 7.3: Fourier transform of signal input

The Fourier transform of the output signal can thus be expressed as:

$$S(f) = H(f).E(f)$$

and depends on the respective values of T_f and f_0 .

- If $1/T_f < f_0 - \Delta f/2 \sim f_0$, practically $H(f)\,E(f) \cong 0$. The output signal is null.

- If $1/T_f > f_0 + \Delta f/2$, the Fourier transform of the output signal comprises (Fig. 8.1) two windows of width Δf, centered on f_0 and $-f_0$, and practically equal in height to:

$$H_0 = a_0\,T_f\,\frac{\sin \pi T_f f_0}{\pi T_f f_0} \qquad (3)$$

The output signal (Fig. 8.2) is then obtained using the inverse Fourier transform, that is:

$$s(t) = \alpha\,H_0 \frac{dF_0}{dt} T_f \Delta f\,\frac{\sin \pi T_f f_0}{\pi T_f f_0}\,\frac{\sin \pi t \Delta f}{\pi t \Delta f}\,\cos 2\pi f_0 t \qquad (4)$$

This result shows that the signal amplitude detected by the transducer depends on the variation of F_0 by unit of time, on its duration T_f, on the resonant frequency f_0, and on the bandwidth Δf of the transducer.

- For events of long duration, such as practically $T_f > 1/f_0$, no signals are detected by the transducer.

- For events of short duration, such as $T_f < 1/f_0$, the transducer detects signals (Fig. 8.2) for which the peak amplitude is given by:

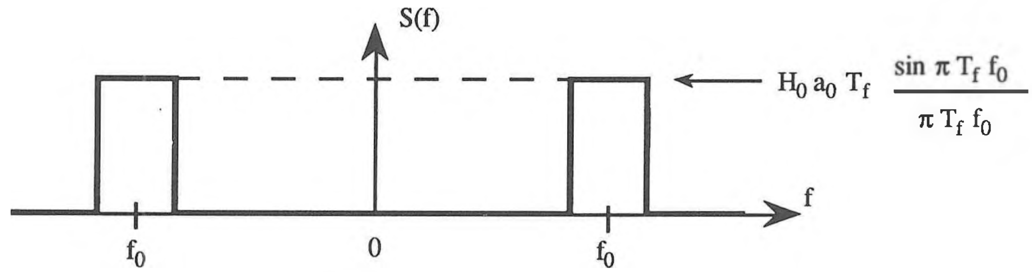

Fig. 8.1

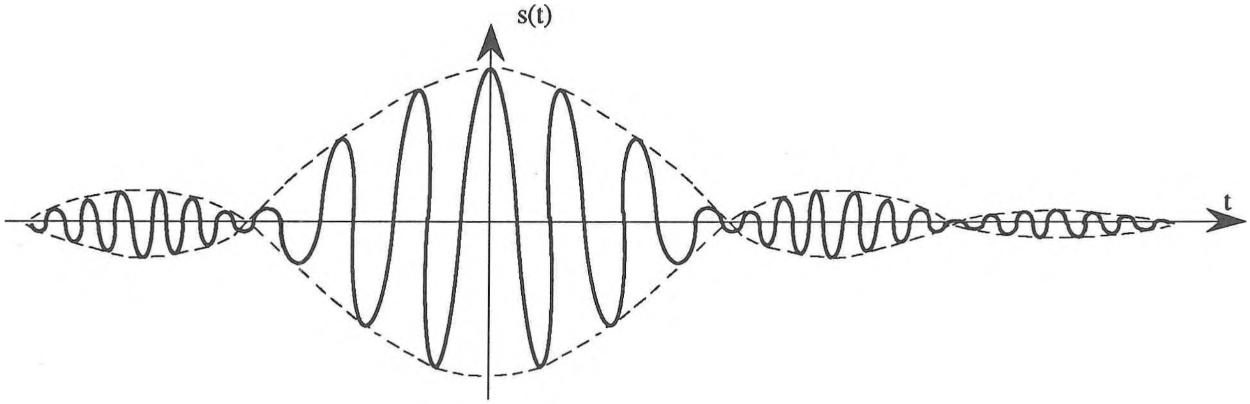

Fig. 8.2

Figure 8: Acoustic emission signal

$$s_0 = \alpha\, H_0 \frac{dF_0}{dt} T_f \Delta f \frac{\sin \pi T_f f_0}{\pi T_f f_0} \qquad (5)$$

The peak amplitude goes to a maximum for a duration $T_f = {}^1/_2\, f_0$ of the input signal, then decreases as does T_f.

In the preceding discussion, the transducer response s(t) exists for $t < 0$. This is a result of choices made for the input signal and the response function in order to simplify calculations. In reality, the input signal begins at $t = 0$ (time of the rupture event), and the transducer response introduces a phase factor, which produces a supplementary temporal shifting t_0, that is a global shifting of the preceding output signal of $t_0 + T_f/2$. Moreover, there is no signal before $t = 0$.

5. INFLUENCE OF DYNAMICAL CHARACTERISTICS

The determining influence of an event duration can explain some experimental results published in the litterature. A few examples are given in this paragraph.

Rhazi (1987) used acoustic emission to monitor damage in five types of industrial composites: unfilled polyamide, polyamide with 0.40 mass fraction of mineral fillers and polyamide with 0.20, 0.30 and 0.50 mass fraction of glass fibres. He found that only composites of mass fraction 0.20 and 0.30 show significant acoustic activity. This result can be explained by assuming that the matrix rupture process proceeds by jumps, the average distance of which and hence the duration depends on fibre fraction. Thus, the dynamic characteristics of matrix cracking processes are adapted to those of the transducer, in the case of 0.20 and 0.30 fibre fractions.

A similar explanation can be advanced for the experimental results obtained by A.G. Benz et al (1983) in the case of particulate epoxy composites and by V.M. Malhotra (1976) in the case of concrete. These autors have studied the failure processes as a function of reinforcement size and dimension. It was observed that the acoustic activity goes to a maximum for a volume fraction which depends on the dimensions of reinforcements, but which corresponds to the same average distance between reinforcements.

6. CONCLUSION

An attempt has been made in this study to emphasize on the important aspect of the physical process involved in acoustic emission. A simplified study of the response of a resonant transducer shows that the peak amplitude of the output signal depends on the dynamic characteristics relative to the transducer and to the discontinuity created during microcracking. Thus, high fracture energy does not necessarily correlate with high signal amplitude.

It should be noted that only the case of an isolated impulse signal reaching the transducer has been dealt with. In reality, the rupture event creates longitudinal and transverse waves that propagate at different speeds and reflect on the surfaces of the structure. As a result of this, various signals, which can be relatively distorted, attenuated and dephased, arrive at the transducer. According to these phase differences, there may be a distinct modification of the amplitude of the initial impulse signal. This aspect must be kept in mind, and may help explain the relatively frequent anomalies observed in acoustic emission signals.

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COMMENTS ON "COMMON MISCONCEPTIONS ABOUT HEARING" by Marek Roland-Mieszkowski [*Canadian Acoustics*, 21(1), 27-28 (1993)]

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No doubt there are many misconceptions about human hearing that need to be clarified. This has been the object of the above Technical Note and, for that purpose, the author has used 'non-technical' language. However, most probably because of that, some not completely correct concepts have been expressed. This letter is to expand on some of them, so that a non-specialized reader would not be left with wrong concepts.

To avoid repeating the whole 'wrong' statement and its correction, I will only show the beginning of the statement and then expand over the answer:

1. **"Loud sound is not dangerous..."** - The threshold of pain can be used as a reference for instantaneous sounds. It is not related to (occupational) hearing losses resulting from long-term exposures to high-level noise. The quoted noise-level limit of 85 dBA (the 'A' should be included as well as the reference that it is for 8 hr/day exposure, 5 days a week, 40 years work life) is correct;

2. **"Hearing loss after sound exposure is temporary"** - The term "most of the hearing loss..." is incorrect. Noise-induced hearing loss is a function of the sound level and the duration of the exposure. One can be exposed to levels well in excess of 90 dBA for short times without any permanent hearing loss. One may also suffer temporary threshold shift (TTS) and will recover in no time. That is so true, that the preferred laboratory method for assessing effects from noise (that has been and is still used) involves exposing subjects to loud noises of different characteristics and measuring the resulting TTS. Therefore, the original statement regarding hearing loss is only true in certain circumstances;

3. **"Hearing loss can be repaired..."** - First of all, a loss cannot be 'repaired', because it is an effect from a damage to a part of an organ. The damage, itself, can or cannot be repaired. Surgery can today solve or ameliorate problems in the outer and middle ear. Noise-induced hearing loss results in most cases from damage of the cilia or the basilar membrane located in the inner ear. In general, damage to the inner ear cannot be repaired.

   With respect to hearing aids, conventional devices act basically as amplifiers, increasing the sound level at the tympanic membrane. However, new devices, called cochlear implants, 'replace' the cilia, sending filtered electrical signals to the terminals of the acoustical nerve. Although still in the experimental stage, they do promise a solution to the person suffering from hearing loss;

4. **"Most people like their music loud."** - A sound-level difference of 5 dB is generally perceived as twice as loud. Therefore, a difference of 15 dB will certainly be detected. Besides, at 85 dBA one can keep a conversation almost without straining one's voice. At 100 dBA, one has to virtually yell in order to be heard. Therefore, the statement that "most audiences note little perceptible difference between sound levels of 85 dB SPL and 100 dB SPL" is not correct;

5. **"Intensity range"** - Presumably, the author means 'sound-level range'. This is a common misconception; intensity is the ratio of energy flowing through an unit area. It is expressed in joule/m^2. Sound level is the logarithmic ratio of two pressures and it is expressed in dB.

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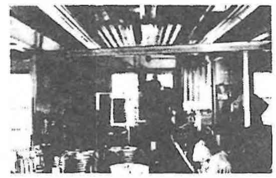

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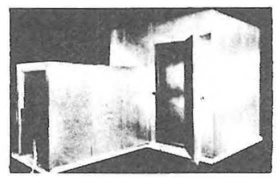

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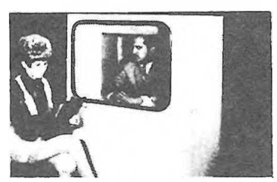

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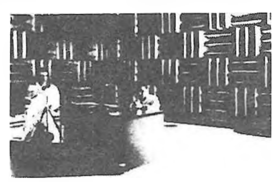

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