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THE CONCEPT OF ENERGY IN ACOUSTIC EMISSION MEASUREMENTS

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THE PROBABLE BANDWIDTH OF EMISSIONS AT SOURCE

It is only comparatively recently that consideration has been given to the possibility of determining the total energy in an acoustic event, but such an approach has obvious attractions since, if successful, it opens up the prospect of direct comparison with the work of fracture and with standard fracture mechanics parameters. The first stage in the chain of energy conversions is the conversion of that part of the stored strain energy released by a failure event into a stress wave. Stephens and Pollock (1) considered possible models of the emission source waveform and concluded that there is a step change in displacement giving rise to a simple pulse for the stress waveform. For analytical purposes they used a Gaussian pulse shape, generated by an event of duration 2T, and derived an energy spectral distribution function.

$$A(f) = \frac{y_0^2 E}{c} \exp\left[-\tfrac{1}{2}(2\pi fT)^2\right] \qquad (1)$$

where y_0 is the amplitude of the associated displacement step. E and c are the elastic modulus and stress wave velocity respectively of the medium.

This model does enable us to calculate, for a given duration of source event, the relative energy content at different frequencies. Take, for example, a matrix crack joining two fibres in a carbon fibre composite; the duration of this event is about 10ns. Using the above equation the energy may be shown to vary very little with frequency and even at 14MHz has only fallen to about 90% of its value at zero frequency. Thus the energy distribution will be more or less uniform over the frequency bands of any of the currently available instrumentation systems which are mostly limited to about 2MHz. There will, however, be a large amount of the total energy contained in components with frequencies above 2MHz, and this will be ignored by the instrumentation. The percentage of the total energy released available as measurable stress waves will depend on the effective duration of the source event. This loss of energy at high frequencies is, however, inevitable in many practical situations, where the transducer is located some distance from the event, because during the passage of the wave to the transducer the higher frequency components are attenuated much more than the lower frequency ones.

THE RELATIONSHIP BETWEEN THE ENERGY RELEASED AND THE ENERGY IN THE STRESS WAVE

Let us now examine the energy content of the Fourier components of a given stress wave pulse. For simplicity we shall consider a longitudinal wave. The energy density of a component having a frequency $f = \omega/2\pi$ may be expressed in terms of the acoustic pressure p , the particle displacement ξ or the particle velocity $\dot{\xi}$,

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$$\mathcal{E} = \frac{p^2}{2\rho c^2} = \tfrac{1}{2}\rho\omega^2\xi^2 = \tfrac{1}{2}\rho\dot{\xi}^2 \quad : \tag{2}$$

and it should be noted that there is a $(\text{frequency})^2$ term introduced if $\mathcal{E}$ is expressed in terms of particle displacement.

Take any linearly elastic system which is under a stress σ and which on the release of stored strain energy from U to $(U - \delta U)$ to create a stress wave suffers a slight drop in stress $\delta\sigma$. The released strain energy per unit volume may be shown to be

$$\delta U = \frac{\sigma}{E} \tag{3}$$

and the acoustic pressure amplitude may be taken as proportional to $\delta\sigma$ so that from equation (2)

$$\mathcal{E} = \frac{(k_1\delta\sigma)^2}{2\rho c^2} \tag{4}$$

and

$$\frac{\text{energy density of each component of the wave}}{\text{stored strain energy released}} = \frac{\mathcal{E}}{\delta U} = k\frac{\delta\sigma}{\sigma} \tag{5}$$

where $k = k_1^2 E/2\rho c^2$.

Thus the energy density of each component of the stress wave is not a constant proportion of the stored energy released, but is governed by the ratio of the small drop in stress $\delta\sigma$ to the stress at which this drop occurs. It is interesting to note that same conclusion can be reached by a development (2) of a spring mass model proposed by Pollock (3).

COMPARISON WITH THE ELECTRICAL ENERGY IN THE TRANSDUCER OUTPUT

Now, as shown by equation (2), the energy density may be expressed in a number of ways and, since our only means of measuring this energy is by examining the output voltage from the transducer, it is necessary to know to which of the acoustic parameters the transducer responds. Evidence has been presented to support either the hypothesis that the output voltage is proportional to particle displacement $(V = C_1\xi)$, or that it is proportional to particle velocity $(V = C_2\dot{\xi})$. A comparison between the acoustic and electrical energies may, however, be made for either proposition.

The output energy (per cycle of period τ) of a transducer feeding an impedance Z is

$$U_E = \frac{I^2 Z\tau}{2} = \frac{V^2\tau}{2Z} \tag{6}$$

and this may be compared with the total acoustic energy per cycle of each Fourier component

$$U_A = \mathcal{E}\tau \quad . \tag{7}$$

Substituting for the two hypotheses in equation (2) and comparing with equation (6) gives

$$\frac{U_E}{U_A} = \frac{C_1^2}{Z\rho\omega^2} \qquad \text{(voltage} \propto \text{displacement)} \tag{8}$$

or

$$\frac{U_E}{U_A} = \frac{C_2^2}{Z\rho} \qquad \text{(voltage} \propto \text{velocity)} \quad . \tag{9}$$

The ratio between the two energies may thus be seen to exhibit a frequency dependence if the voltage is proportional to displacement; there is, however, no such dependence if the voltage is proportional to velocity. It should be noted that a similar conclusion may be demonstrated for transverse waves and Rayleigh waves. It is therefore most important to know exactly how the parameters of the stress wave in a component govern the output of a transducer attached to it.

Consideration of transducer calibration techniques is beyond the scope of this paper, but current evidence indicates that the output voltage of a transducer is not simply proportional to either displacement or velocity, independent of frequency. The above conclusion is therefore largely of academic interest and we must assume that either constant of proportionality varies as a function of frequency, say

$$V = g(f)\xi \tag{10}$$

or

$$V = h(f)\dot{\xi} = 2\pi f h(f)\xi \quad . \tag{11}$$

Substitution of either expression into equation (2) results in an expression of the form

$$\mathcal{E} = g_1(f)V^2 \quad . \tag{12}$$

At present we are unable unambiguously to determine $g(f)$ or $h(f)$ and practical considerations limit the range over which this will be possible in the future. If, however, a sharply resonant transducer and narrow band instrumentation is used then $g_1(f)$ may be replaced by a constant g, giving

$$\mathcal{E} = gV^2 \quad . \tag{13}$$

Only a small fraction of the total energy available is now being measured, but the difficulty of determing the function $g_1(f)$ is avoided. Calibration of a transducer at a single fixed frequency is clearly much simpler, but factors such as the loading of the front face by the component and its alignment with respect to the wave-front still have to be considered. Equation (13) does, however, justify the use of $\Sigma N_i V_i^2$ or $\int V^2 dt$ as a measure of energy.

SOME PRACTICAL CONSIDERATIONS

For simplicity we have so far considered only a plane wave in which the energy density does not vary with distance; in many practical situations, however, the wave-fronts in regions near the source will be cylindrical or spherical and $\mathcal{E}$ will vary with r or r^2, because the total energy transmitted from the source has to be shared over an increasing area of wave-front. In addition the ratio $\xi/\mathcal{E}$ or $\dot{\xi}/\mathcal{E}$ may also be shown to decrease with r. Thus not only does the ratio between the transducer output and the energy density depend on its distance from the source but so also does the ratio of the energy density of the wave to the energy originally released at the source.

In many cases the direction of wave propagation is normal to the axis of the transducer and, when the transducer diameter is an integral number of wavelengths there will be zero output induced by this component. The bounded nature of most practical components means that multiple reflections of the original pulse will occur and, unless logic is incorporated in the instrumentation to avoid it, the same event will be counted several times. The energy recorded by a given system will therefore be governed not only by the nature of an event and its location with respect to the transducer, but also by the geometry of the component in which the event occurs.

REFERENCES

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