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ACOUSTIC EMISSION SPECTRAL CALIBRATION AND ANALYSIS.(U)
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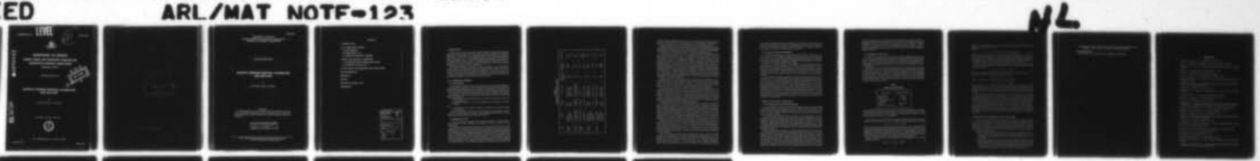

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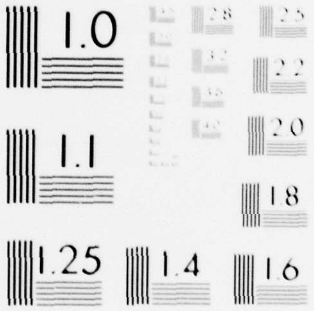
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ACOUSTIC EMISSION SPECTRAL CALIBRATION AND ANALYSIS

by

C. M. SCALA and I. G. SCOTT

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ACOUSTIC EMISSION SPECTRAL CALIBRATION AND ANALYSIS

by

(10) C. M. SCALA and I. G. SCOTT

(11) Jun 78

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SUMMARY

A detailed description is given of an acoustic emission (AE) calibration system based on the use of a helium jet. Reasons for the choice of the helium jet are given and various other simulated sources of AE are discussed in terms of their suitability for calibration of AE systems.

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1. INTRODUCTION

Acoustic emission (AE) is a rapidly developing technique for non-destructive inspection (NDI) which utilises the detection of sounds usually of ultrasonic frequency. It has numerous applications to proof-testing, in-service testing and materials research studies. The AE signal can be processed in various ways to yield threshold crossing or event counts, RMS voltage and energy measurements, and/or to permit amplitude distribution and frequency spectral analysis to be conducted. Whereas event counting is an established method for determining AE activity, spectral analysis has been proposed as a means for identifying AE sources and for gaining an insight into the operation of source mechanisms (1).

The spectral distribution of AE from a source in any specimen is convoluted with the transfer functions of the propagating medium, specimen geometry, transducer and couplant, and signal-processing equipment. Consequently, calibration of the *complete* AE system is required. In this paper, system calibration is considered and a number of simulated sources are evaluated, including the recently developed use of a helium jet. A description is given of the instrumentation required for spectral analysis of random AE events.

2. AE CALIBRATION METHODS

2.1 System calibration

In any physical measurement system, there is the need to (a) verify the reproducibility of data from particular equipment, both in the laboratory and in the field, and (b) compare and evaluate data from different laboratories. The impetus for calibration of an AE system is also based on the additional requirement to characterise an AE source, independent of the AE system.

The sequence of analysis of AE signals is illustrated in Figure 1. Elements which constitute source and system are given. Three main problems associated with the analysis of the detected signal can be defined (2):

(i) determination of the relationship between the physical event and the elastic waves that are produced,

(ii) quantitative description of the wave propagation process throughout the material structure,

and

(iii) characterisation of the transducer response to a simulated AE source and eventually to a real source.

The first problem relates to the source and the remainder to system calibration. Since AE sources are not well understood at present, a variety of methods has been used to simulate acoustic emision and to calibrate the system shown in Figure 1.

2.2 Simulated sources of AE

A list of simulated sources, together with their principal characteristics, is given in Table 1. Each technique has certain advantages and limitations, but none has achieved universal acceptance (3).

The spark-bar calibration method (4) utilises an electric spark formed between two high voltage (500 V to 15 kV) electrodes to induce a pulse of mechanical stress in a bar or specimen. The associated stress waves then propagate to the transducer which is to be calibrated. Parker (5) asserts that large variations in both the voltage applied to the electrode and in the air gap spacing result in only small changes (5 dB) in measured AE; this result has yet to be confirmed by other AE workers. Spark excitation has been successfully applied to a range of specimens of varying shape, size and material. However, consideration needs to be given to the modes propagated in various geometries. From our experience, the major disadvantage of the spark-bar technique is its non-reproducibility. A very similar technique (5) involves passing a heavy current (up to

TABLE 1
Simulated Sources of Acoustic Emission

Class	Examples	Source size	Type of signal	Wide range frequency	Reproduc-ibility	Recurrent
Thermal pulse	Spark bar	Point	Single transient	Yes	Poor	Yes
	Current contact	Point	Single transient	Yes	Poor	Yes
	Laser pulse	Point	Single transient	Yes	—	Yes
Ultrasonic wave	Transducer pulser	Extended	Controlled multiple	Yes	Fair	Yes
	Capacitive pulser	Extended	Controlled multiple	Yes	Fair	Yes
Change of state	Chemical reaction	Extended	Continuous	No	Poor	Yes but random
	Transformation	Extended	Random multiple	Yes	Poor	
Particle impact	Falling ball	Small	Single transient	No	Poor	No
	Sand or silicon carbide blast	Small	Multiple transient	Yes	Poor	Yes
	Helium jet	Small	Multiple transient	Yes	Good	Yes
Fracture	Silicon carbide particles	Extended	Multiple transient	Yes	Poor	Yes
	Glass capillary	Small	Single transient	Yes	Good	No
	Lead pencil	Small	Single transient	Yes	Good	No

100 amp) through a reproducible point contact to the specimen. The contact is formed by pressing a steel ball bearing of 3 mm diameter against the specimen and is standardised by its D.C. resistance. Thereby, some control of generated stress wave amplitude is achieved.

Preliminary studies have been conducted into the use of a laser pulse impinging on a specimen and creating a simulated AE source (6, 7). Studies are needed to evaluate both the reproducibility of this thermal source in different materials and the possibility of an absolute energy calibration. The pulsed laser may then be found to provide a calibrated reproducible source (7, 8).

A commonly used simulated AE source is a pulsed piezo-electric transducer (9). Recent authors have also considered the use of a related device—the capacitive pulser (5, 10). The advantages of a piezo-electric transducer as a simulated source include control of the duration and waveform of the stress waves generated, verification of the mode of propagation of the stress wave, and simplicity and convenience (6). Bentley and Green (8) used the formulation described in section 3·2 for the helium jet, to obtain system-independent AE spectra for the pulsed piezo-electric transducer. However, the piezo-electric transducer has some disadvantages—in particular, difficulties have been reported in reproducing transducer coupling, especially in the field. Problems are also associated with the production of identical transducers, whereby the requirement of a transferable standard for comparison of data (e.g. between laboratories) is not easily fulfilled. Absolute calibration of piezo-electric transducers as primary standards can be achieved using reciprocity techniques. Most commonly, the standard is only calibrated for longitudinal waves (9), although approximations have recently been developed for reciprocity calibration in a Rayleigh wave field (11).

Attempts to use the AE spectra generated by corrosion reactions have failed to yield a reproducible calibration standard. Similarly, the AE spectra generated by martensitic transformations in an Au-47% Cd alloy (12) and in a Fe-29·5% Ni alloy (13) depend upon thermal history and are therefore inappropriate for calibration standards. However, the copious uncontrolled emissions are very useful for verifying the operation of AE instrumentation.

In concept, dropping a ball onto a transducer or specimen appears a likely basis for a very simple absolute calibration method. However, in practice, there are serious problems: the rise-time of the simulated AE signal is slow compared with signals from real AE sources (14) and damage is incurred by the transducer or specimen surfaces. In addition, at ARL, it has proved necessary to constrain the ball to move in a tube before impact and after impact to pass through a window, before reproducible bounces could be achieved. Stephens and Pollock (15) showed that the spectra obtained by dropping a steel ball on their specimen were essentially low frequency and thus quite different from their observed emission spectra.

A logical extension of the concept of the dropped ball is the use of sand or silicon carbide blast. A transducer is mounted on a 'standard' specimen which is subjected to the impact of numerous high speed particles. Continuous emission is simulated. This technique is suitable for spectral studies of transducer response but it is of little value as a standard because reproducibility is poor; the output depends significantly on air pressure and the size of grit or sand. An analogous technique uses a helium jet directed onto a specimen to simulate a continuous source of AE which is claimed to be reproducible; the use of the helium jet for the excitation and spectral calibration of AE systems was postulated by McBride and Hutchison (16). A jet of helium at a specified pressure is applied through a glass capillary tube situated normal to, and at a fixed distance from, the surface of the specimen. This technique is discussed in detail in section 3.2.

Fracture of materials in any form generally provides copious AE and the fracture of silicon carbide particles has been used in various studies to simulate an AE source. Graham and Alers (1) used a steel plate having a depression on one face in which fine particles of silicon carbide were fractured continuously under the rotary action of a fused silica rod. The 'white noise' generated by this method (and related methods like the use of carborundum paper) is again useful in verifying the operation of equipment e.g. a location system, but it is not sufficiently reproducible for system calibration.

Two basic, but elegant, techniques recently reported are the fracture of selected glass tubing by means of a screwed indenter (2, 10) and the mechanically controlled fracture of selected pencil lead (2). Both techniques are founded on the concept of a well-defined stress pulse, a step function, which is said to resemble a real AE source. Hsu et al (2) obtained good agreement between theory and experiment for a system incorporating both a capacitive displacement-sensitive transducer and a plate for which an exact solution to the wave propagation problem was available. Substituting a piezo-electric transducer for the capacitive one showed that the response from the piezo-electric transducer was predominantly velocity sensitive. Extension of this study should ultimately allow more complete characterisation of a transducer, particularly with respect to its response to displacement, velocity and stress.

2.3 Comparison of system-source combinations

It is evident that identification of a standardised calibration method represents one of the more urgent needs of the rapidly developing AE technology (3). However, the requirements (section 2.1) for selection of a standardised method are neither straightforward nor easily achieved; also, in many cases, quantitative comparison of the different calibration techniques is complicated by the limited, and sometimes conflicting, data available.

Initially we will consider only the basic requirements of reproducibility and versatility between laboratory and field applications. It is evident that the only simulated AE sources satisfying both these conditions are (i) the helium jet, and (ii) the related techniques of fracture of glass capillary or pencil lead. While excluding the use of the other techniques given in Table 1, it should be reiterated that, on further study, the laser pulse may prove to be a reproducible standard and the pulsed transducer already provides a viable reference for intra-laboratory calibration.

The third and most significant requirement of a calibration standard is based on the characterisation of an AE source, independent of the AE system. Let us examine the calibration of an AE system (Fig. 1) using the simulated sources which have already fulfilled the basic requirements. Since there has been only limited theoretical analysis of AE sources (15, 17, 18, 19, 20), careful experimental observation has to be used to validate simulated AE sources. The signals produced by the helium jet and the fracture of glass capillary tubing or pencil lead exhibit the wide frequency range normally associated with AE sources, although the helium jet more closely represents continuous emission (1, 20) and the fracture technique, burst emission (1, 19). These sources appear to be well-suited to study the problem of system calibration and to determine the transfer functions for wave propagation in a bounded structure, for the transducer and couplant, and for associated signal-processing equipment. In our laboratory, the helium jet has been selected for detailed study.

3. HELIUM JET SPECTRAL CALIBRATION

3.1 AE monitoring system for transient spectral analysis

The basic requirement for this study of AE spectral calibration and analysis was the recording and processing of spectra in the frequency range 0·1 to 1 MHz. A variety of techniques for the analysis of the transient spectra associated with intrinsically random AE events has been proposed (1, 8, 21). At present, computer methods for spectral analysis appear most promising, but their on-line presentation is difficult.

The spectral analysis recording system used at ARL is shown schematically in Figure 2. The AE signals are detected by a piezo-electric transducer; presently a Dunegan/Endevco S 9201 transducer is used for broad-band spectral analysis. The signals are amplified by a high input impedance preamplifier (gain 60 dB) having a decreasing frequency response above 1 MHz. A Biomation model 610B transient recorder with variable trigger level and gate is used to record the transient AE signals, the analog output being recorded by an Ampex PR-2200 tape recorder for subsequent spectral analysis. Alternatively, analysis can be made directly by the HP 8556A/8552B spectrum analyser.

Restrictions imposed by sampling theory must be considered when using any digital recording device having limited memory. To minimise the effects of aliasing of the spectra, the maximum frequency which can be determined is half the sampling frequency (22). Therefore, a sampling frequency of not less than 2 MHz is required to resolve an upper limiting frequency of 1 MHz. (It is assumed that signals above 1 MHz have been effectively removed by filtering.) In the frequency domain, the AE signal is convoluted with the gate signal. Thus, a lower limit is imposed on the number of signal cycles which must be recorded within the gate period for effective resolution. The memory of the Biomation 610B transient recorder contains 256 words; consequently, once a sample rate of 0·5 μs is chosen, a gating period of 128 μs results. For adequate resolution of 100 kHz signals, a bandwidth of 10 kHz is needed, which corresponds to a minimum gating period of 100 μs. This demonstrates how the restriction of the gating period limits the proportion of the signal analysed and also determines the accuracy of analysis. A transient recorder with larger memory would allow greater flexibility of analysis. Similarly, control of signal processing from the transient recorder to the tape recorder would improve the efficiency and rate of recording.

3.2 The helium jet as a source of AE

The helium jet was briefly described in section 2.2. McBride and Hutchison (16) discussed the use of gases other than helium and found that, to achieve comparable results using nitrogen, pressures of about 550 kPa were needed. At ARL, it was considered that some damage to aircraft surfaces may occur at this pressure so the possible use of nitrogen was never pursued. However, in some preliminary experiments compressed air was used; the AE output then differed from that of the helium jet.

Pressure conditions in the helium jet were monitored close to the jet using a pressure gauge, and a flow meter was used to check perturbations in gas delivery. The capillary tube was mounted on a microscope stage close to the flat end of a standard specimen block 125 mm in diameter and 100 mm in length. Signals generated by the helium jet impinging on one flat face propagated through the cylinder and were detected by a transducer coupled to the opposite face. Both jet and transducer were mounted on the axis of the specimen. A 5 MHz X-cut quartz transducer and the Dunegan/Endevco S 9201 transducer were used. The optimised operating conditions for the jet are summarised in Table 2.

TABLE 2

Helium jet operating conditions

Jet parameter	Operating conditions
Bore diameter	0·8 mm
Length of bore	80 mm
Stand-off distance from specimen	3·5±0·1 mm
Pressure	145±7 kPa
Angle of jet to surface	90±1°

The parameters listed above were largely chosen for convenience; the tolerances shown can be easily attained and, provided they are maintained, it is found that different workers can obtain essentially the same results. The various parameters are inter-related and the effects of varying separate parameters are likely to be unpredictable.

Now consider the use of the helium jet as a source for transducer calibration. The measured output R_{THB} of the transducer as a result of the helium jet impinging on the block is given by

$$R_{THB} = [J + B + T + C_T]\ dB \qquad (1)$$

where J is the energy input associated with the helium jet, B and C_T are propagation factors associated with the block and couplant respectively, and T is the input/output characteristic of the transducer. Each component described in Equation (1) and in subsequent equations is a function of frequency and is expressed in logarithmic terms. Thus, the transducer/couplant system can be calibrated relative to the jet/block system. Such an evaluation of the AE transducer response may be of considerable value in selecting a transducer for a specific application.

Again, consider the response of the 5 MHz X-cut quartz transducer, whose measured output R_{QHB} is given by

$$R_{QHB} = [J + B + Q + C_Q]\ dB \qquad (2)$$

where C_Q is the propagation factor associated with the couplant and Q is the input/output characteristic of the quartz transducer.
Whence,

$$(T + C_T) = [(R_{THB} - R_{QHB}) + (Q + C_Q)]\, dB \tag{3}$$

Clearly $(T + C_T)$ results once $(Q + C_Q)$ is known. To a first approximation, $C_T = C_Q$. Nevertheless differences in couplants can produce large differences in transducer output (Fig. 3), associated with the predominance of particular transducer modes. Furthermore, attempts to use handbook values of piezo-electric constants for Q have not been successful. Hence the use of the quartz transducer as a standard to replace the helium jet is not satisfactory.

Finally, consider the helium jet standard as applied to a structure close to an anticipated AE site and with the transducer appropriately located. The measured output R_{THS} of the transducer is given by

$$R_{THS} = [J + S + T + C_T]\, dB \tag{4}$$

where S is a transfer function, for the structure, which incorporates propagation effects. The measure output R_{TAS} arising from a source of AE is

$$R_{TAS} = [A + S + T + C_T]\, dB \tag{5}$$

where A is the input associated with the acoustic emission, whence

$$R_{TAS} - R_{THS} = [A - J\,]\, dB \tag{6}$$

Thus a measure of the unknown AE source referred to the helium jet has been made in terms of measured responses. As a result of using this procedure, the effects of the specimen in conditioning AE signals has been eliminated. This procedure implicitly assumes that the signal from the unknown AE source in the specimen is truly analogous to the signal from the helium jet probe.

The procedure described above has been applied to the AE obtained from a loaded double cantilever beam (23) specimen of 7039 aluminium alloy. A typical measurement of AE from cracking in the specimen is shown in Figure 4, together with the corrected AE spectrum relative to J. In Figure 5 the spectrum relative to J for cracking is compared with corresponding spectrum for corrosion in the 7039 alloy. The two processes are seen to yield significantly different spectra.

Various approaches have been proposed to compare spectra such as those in Figure 5. Woodward (24, 25) characterised an AE spectrum by a single frequency, its median frequency, and thereby identified dominant source mechanisms in a series of spectra. Pattern recognition techniques (26) may also assist the rapid analysis and sorting of AE signals. These approaches will enable spectral analysis to be used more efficiently in the determination of the nature of AE sources.

4. CONCLUSIONS AND PROPOSALS FOR FUTURE WORK

A variety of AE simulated sources has been assessed for application to spectral calibration of an AE system. The helium jet has been validated as a reproducible simulated AE source while the use of the fracture of glass tubing or pencil lead appears to hold promise. A method for the analysis of transient spectra has been described and system-independent AE spectra have been presented. The application of the helium jet calibration procedure provides a method for transducer and system calibration which allows the exchange of data between laboratories.

A series of problems remain, viz

(i) The lack of understanding of the response of a transducer to displacement, velocity or stress. This aspect of transducer characterisation is being examined by Hsu *et al.* (2), while Hutchison and McBride (27) have recently calibrated the helium jet in terms of displacement.

(ii) The possible excitation of system resonances (and in particular specimen resonances) which may differ from those excited by AE pulses because of the continuous nature of the helium jet. The results of some preliminary tests suggests that this may not be as troublesome as expected. Among other things, it is implied that the transfer functions for the transducer obtained under steady state and transient conditions are the same.

(iii) The highly non-linear nature of almost any of the transfer functions requires that calibration be carried out using a wide range of variable amplitude signals.

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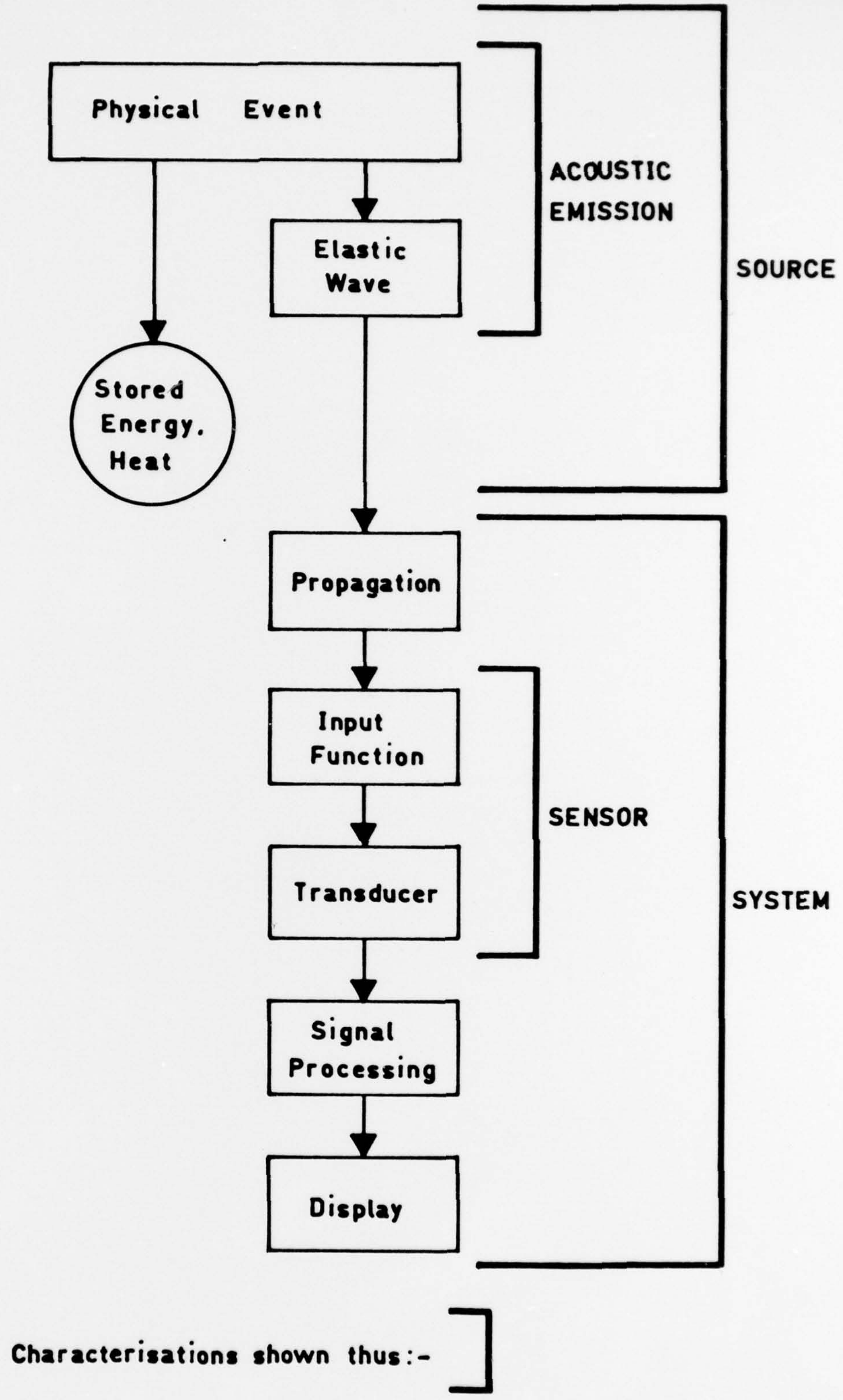

FIG. 1 SEQUENCE OF ANALYSIS OF AE SIGNALS

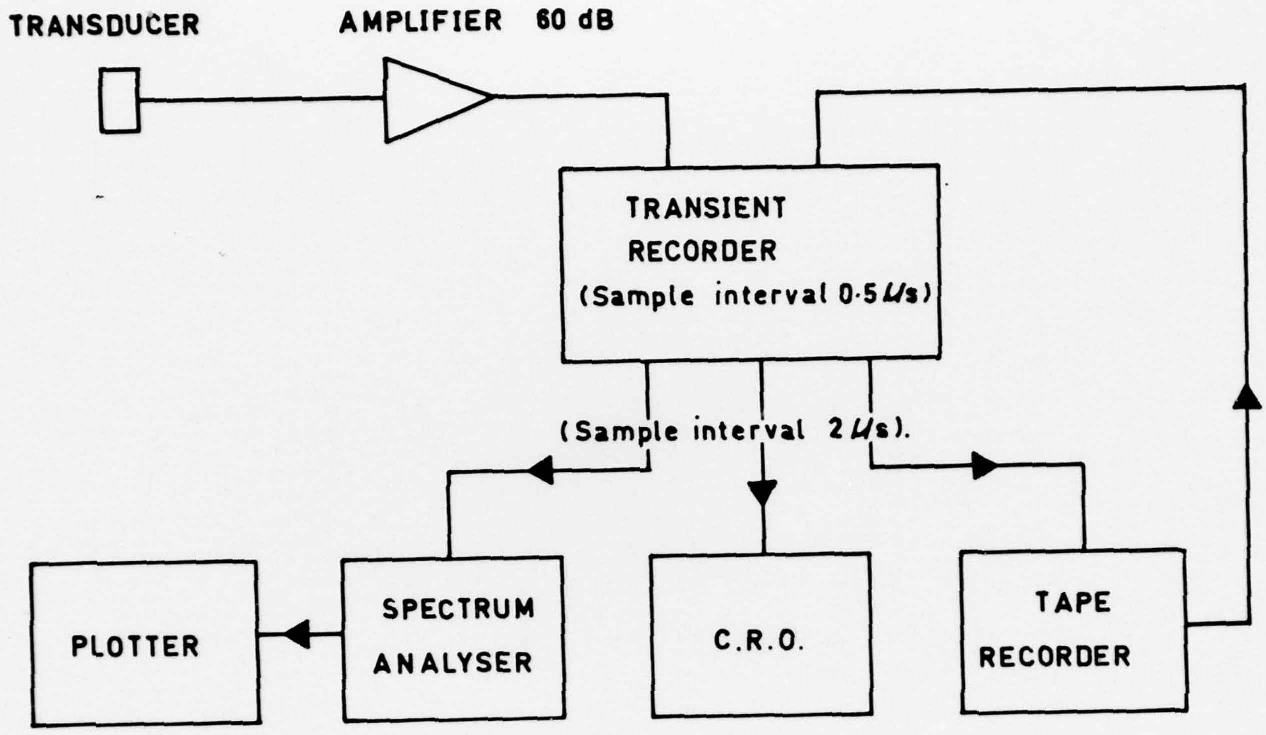

FIG. 2 BLOCK DIAGRAM – TRANSIENT SPECTRAL ANALYSIS

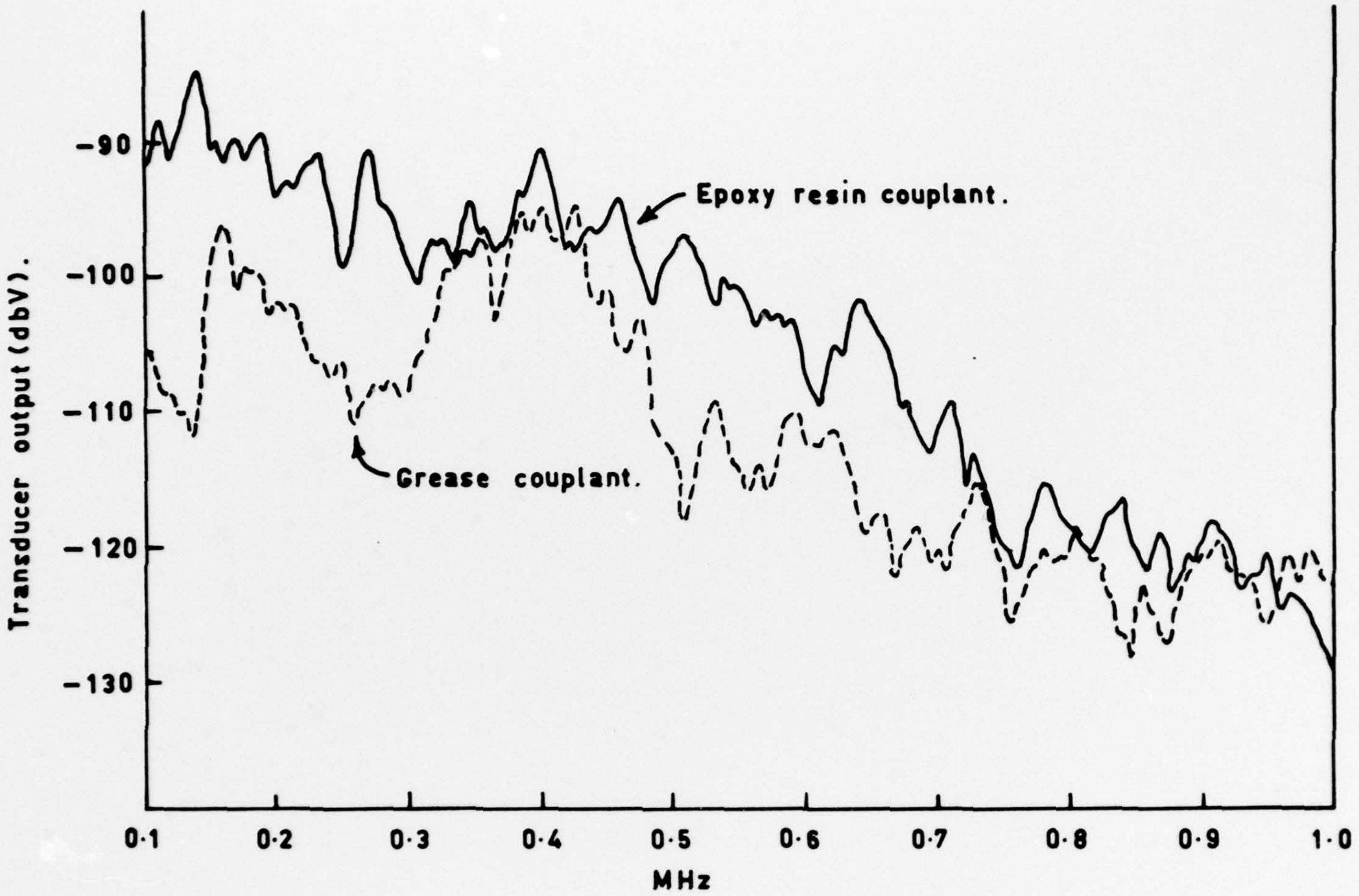

FIG. 3 EFFECT OF COUPLANT ON THE RESPONSE OF THE QUARTZ TRANSDUCER

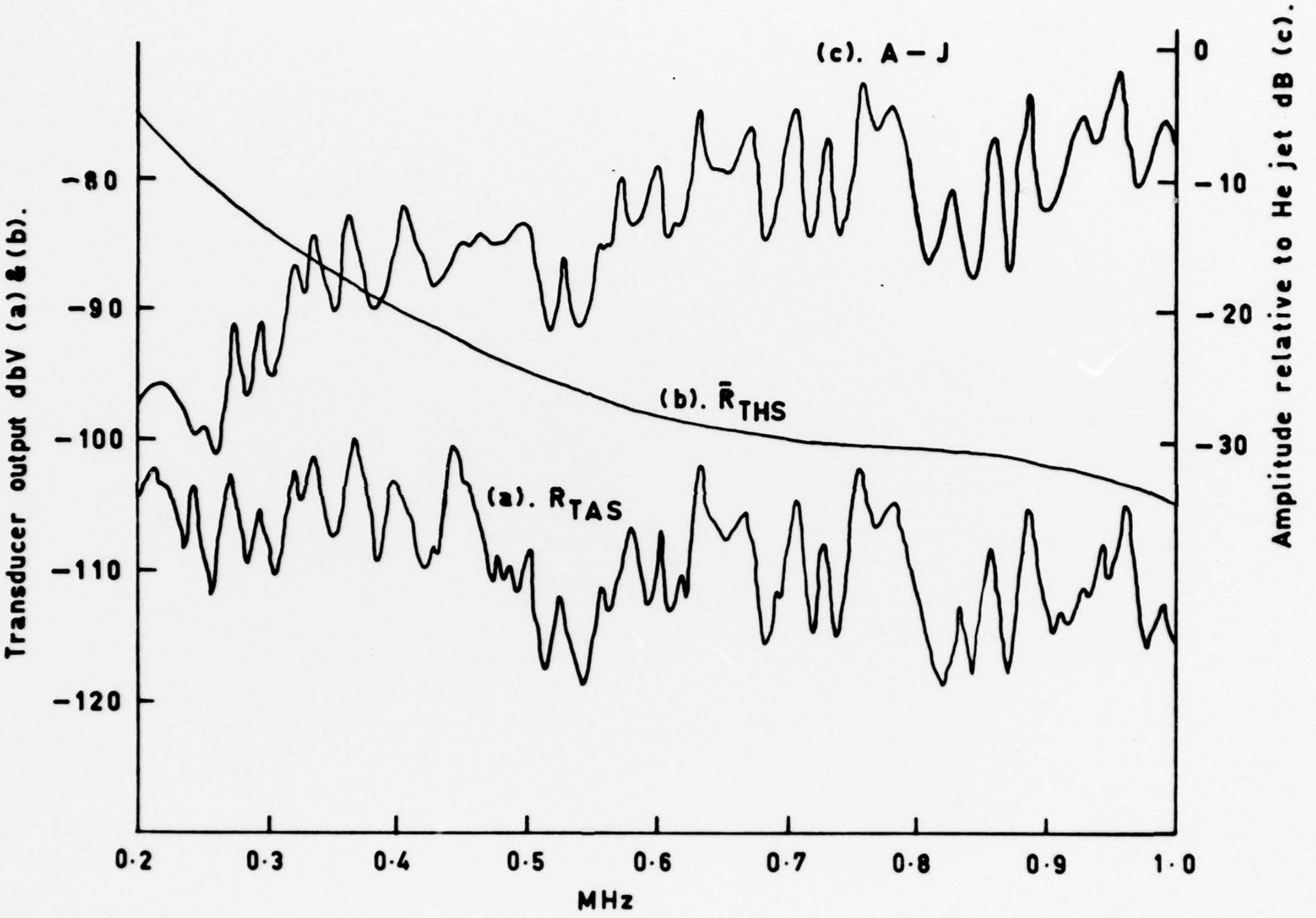

FIG. 4 (a) AE SIGNALS FROM CRACKING IN A DOUBLE CANTILEVER BEAM SPECIMEN
(b) He JET CALIBRATION OF DOUBLE CANTILEVER BEAM SPECIMEN (Averaged)
(c) A–J

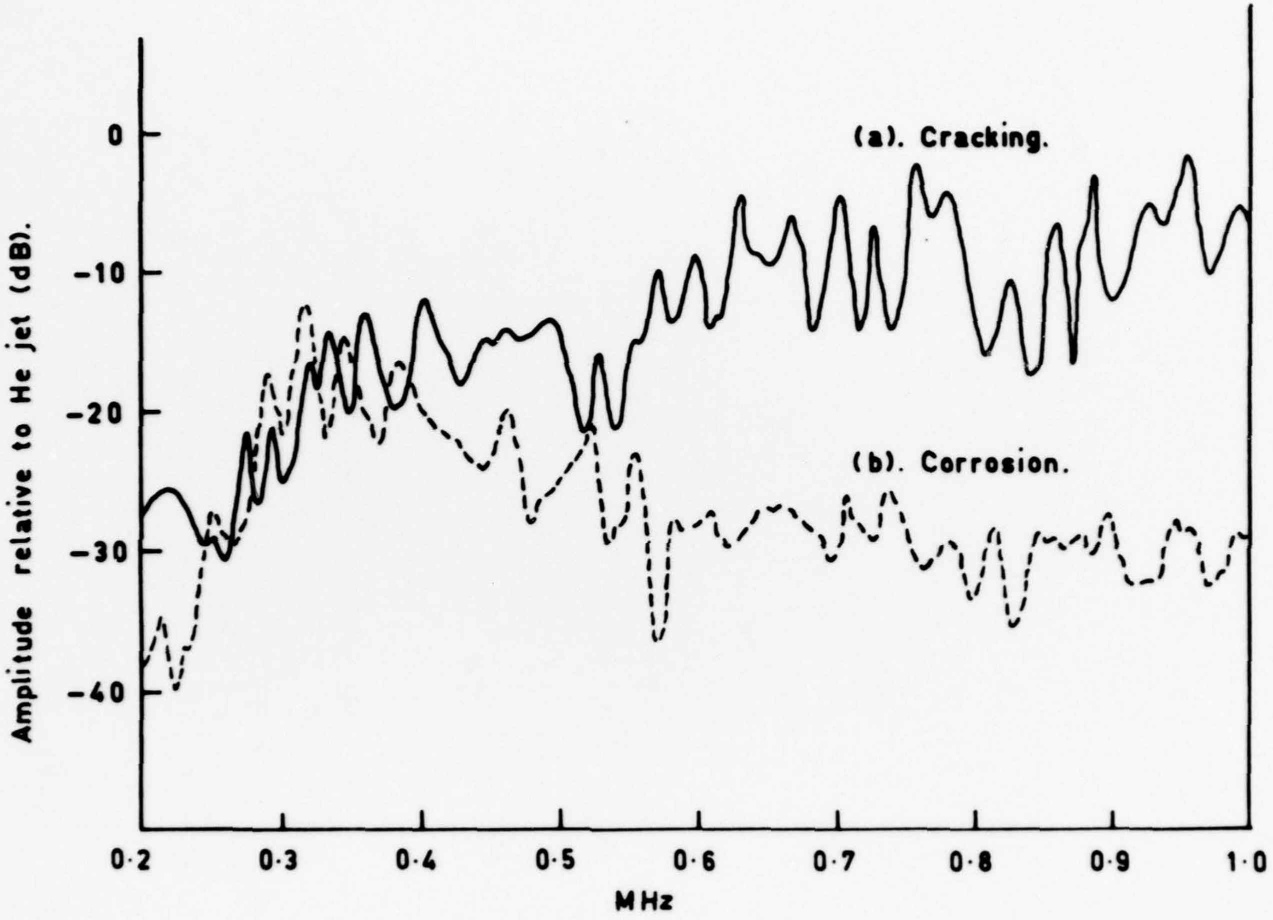

FIG. 5 COMPARISON OF CORRECTED AE SPECTRA RELATIVE TO J IN A DOUBLE CANTILEVER BEAM SPECIMEN FOR (A) CRACKING AND (B) CORROSION.

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    Simulation
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    Spectrum analysis
    Spectra

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16. *ABSTRACT*

A detailed description is given of an acoustic emission (AE) calibration system based on the use of the helium jet. Reasons for the choice of the helium jet are given and various other simulated sources of AE are discussed in terms of their suitability for calibration of AE systems.

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