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Non-Contact Measurement of Acoustic Emission Signals in the 100 MHz Frequency Range Using an Acoustical Microscope

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Non-Contact Measurement of Acoustic Emission Signals in the 100 MHz Frequency Range Using an Acoustical Microscope

Summary

Many papers on the detection and analysis of acoustic emission (AE) signals have been reported in the frequency range below a few megahertz using ordinary AE sensors. This paper describes experiments on non-contact measurements of AE signals in the VHF range using an acoustic microscope with a point-focus beam (PFB) lens. When the surface of a glass specimen with a notch is set at the focal plane of the PFB lens, the AE signals radiated from the crack can be detected during a conventional three point bending test. The output signal of the PFB lens transducer is amplified and A/D converted at a sampling rate of 200 MHz. By comparing the power spectrum of the wave detected when a static load was applied with that of the wave detected without a load, it was experimentally confirmed that the resultant waves radiated by static loads have frequency components in the frequency range above a few megahertz. The new AE measurement system in the VHF range developed here can be applied in a new research field to be called "micro-AE spectroscopy" for the diagnosis of micromachines.

Berührungsfreie Messung der akustischen Emissionssignale im Bereich von 100 MHz mit Hilfe eines akustischen Mikroskops

Zusammenfassung

Über die Detektion und Untersuchung von akustischen Emission-(AE)-Signalen im Frequenzbereich unter einigen MHz und bei Verwendung normaler AE-Sensoren sind zahlreiche Arbeiten veröffentlicht worden. In dieser Arbeit werden Versuche der berührungsfreien Messung von AE-Signalen im VHF-Bereich beschrieben unter Benutzung eines akustischen Mikroskops mit einer Punktfokuslinse. Wenn die Oberfläche einer Glasprobe mit einer Kerbe in die Fokalebene der Linse gebracht wird, können die AE-Signale detektiert werden, die von der Kerbe während eines konventionellen Dreipunkt-Biegetests ausgehen. Das Ausgangssignal des Linsenwandlers wird verstärkt und mit einer Samplingrate von 200 MHz analog-digital gewandelt. Durch Vergleich des Leistungsspektrums nach Aufbringung einer statistischen Last mit dem ohne Last erhaltenen Spektrum wurde experimentell bestätigt, daß die bei einer statischen Last erzeugten AE-Wellen Frequenzkomponenten im Frequenzbereich oberhalb einiger MHz aufweisen. Das hier entwickelte neue AE-Meßsystem im VHF-Bereich kann in einem neuen Forschungsfeld angewandt werden, welches als "Mikro-AE-Spektroskopie" für die Diagnose an Mikromaschinen bezeichnet werden könnte.

Mesure sans contact d'émissions acoustiques dans la bande des 100 MHz à l'aide d'un microscope acoustique

Sommaire

Il existe de nombreuses publications sur la détection et l'analyse d'émission de signaux acoustiques, dans le domaine des fréquences inférieures à quelques MHz, à l'aide de capteurs ordinaires. Le présent article fait état de mesures d'émissions acoustiques dans la bande VHF, effectuées sans contact à l'aide d'un microscope acoustique équipé d'une lentille de focalisation (PFB). Si l'on dispose la surface d'un échantillon de verre rayé dans le plan focal de la lentille, on peut détecter les émissions acoustiques rayonnées par la fissure, au moyen d'un test classique de flexion et en utilisant trois points de mesure. Le signal de sortie du transducteur à lentille PFB est amplifié puis numérisé à une cadence d'échantillonnage de 200 MHz. Par comparaison des spectres de puissance des signaux détectés, sans charge d'abord puis avec charge statique, on a pu confirmer expérimentalement que les ondes rayonnées lors d'applications de charges statiques avaient une fourniture spectrale qui dépasse les quelques mégahertz. Ce nouveau système de mesure d'émissions acoustiques dans la bande VHF peut être appliqué dans un nouveau domaine de recherche que l'on pourrait appeler «spectroscopie de micro-émissions acoustiques» pour l'examen de micromachines.

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1. Introduction

Acoustic emission (AE) techniques are powerful methods for detecting the dynamic deformation and fracture of materials with a high sensitivity. To date, many papers have considered the detection and analysis of the AE signals using ordinary AE sensors directly attached to materials or structures [1–3]. Almost all the previous papers on the detection of AE have been concentrated in the frequency range below a few megahertz. It has not been clarified experimentally whether higher frequency components (above 10 MHz) are emitted or not during fracture processes. If AE signals with VHF frequency components are observed, a new non-destructive testing method for micro-mechanical components will be developed to cultivate new research fields in micro-mechanics.

Recently, we have measured AE signals for the first time in the 100 MHz frequency range with thin-film piezoelectric transducers fabricated in our laboratory. By analyzing the output signals detected by the transducers attached to the end surfaces of rectangular glass specimens notched for bending tests, we measured AE signals with components in a 100 MHz frequency range during the fracturing process [4].

In the previous experiments, however, it was necessary that the transducers were kept in contact with the specimens. Moreover, the size of the fabricated transducers is not small enough to locate the AE sources in this high frequency range. In a short letter [5], therefore, we have introduced an acoustical microscopic technique with a PFB lens for non-contact measurement of the AE signals.

This paper describes the measurement system using an acoustical microscope in detail and confirms that AE signals detected by this system during conventional three point tests have frequency components in the frequency range from a few megahertz to 100 MHz. Finally, by removing the transfer characteristics of the acoustic PFB lens transducer, the power spectrum of the AE components radiated from the cracks is calculated from the power spectra of the output signals detected with and without application of the load.

2. Apparatus for experiments

Fig. 1 shows the measurement system using an acoustical microscope. Figs. 2 and 3 show a glass beam specimen (a slide glass, 26 mm × 76 mm × 1.3 mm) with a single-edge notched for a three-point bending test. The specimen has been notched using a diamond cutting machine in the middle of the longer side of the specimen. The initial size of the notch was 0.4 mm in width and 0.5 mm in depth.

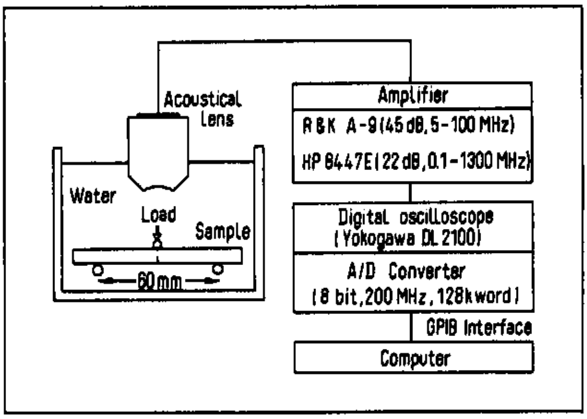

Fig. 1. Non-contact measurement system for detection of AE signals in the 100 MHz frequency range using an acoustical microscope with a PFB lens and a slide-glass specimen used in the static three-point bending test.

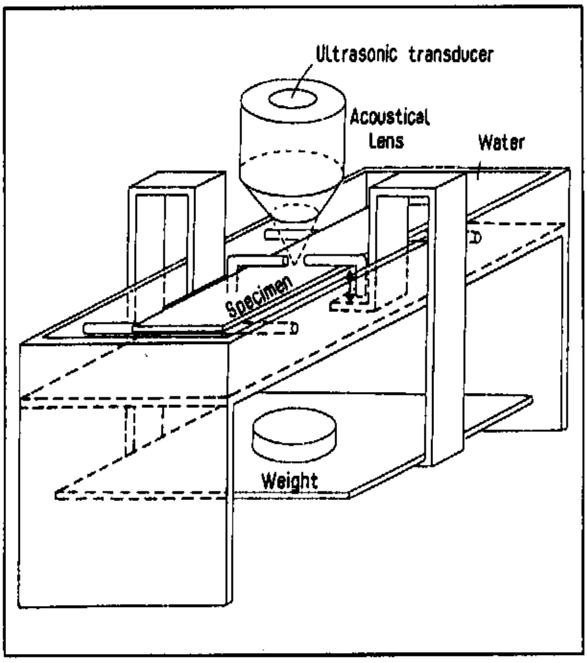

Fig. 2. Acoustical lens and notched slide glass specimen with a notch mounted on the apparatus for a static three-point bending test (made in the laboratory).

The acoustical PFB lens employed in the acoustical microscope has a concave surface with a radius of curvature of 11 mm on one end of a fused-quartz rod of 39 mm length. The half aperture angle is 8.6° in water. To the other end of the rod, a piezoelectric transducer of a thin $LiNbO_3$ plate is attached.

The specimen is set in water and is located at the focal plane of the PFB lens. The AE signals radiated around the notch are detected by the transducer conventional three-point bending tests [6] with a static load applied as shown in Figs. 1 and 2. After amplifying the output signal of the transducer with a total amplification of about 67 dB, the resultant signal is A/D converted with an 8 bit A/D converter in a digital oscilloscope (Yokogawa DL 2100) with a sampling period of 5 ns. The maximum length of each signal is about 128×10^3 points ($= 640\ \mu s$) and the signal is transferred via a GPIB interface to a computer and processed using digital signal processing techniques. To measure the displacement of the glass specimen due to the static load, the output of a laser-doppler velocity-meter (Ono Sokki, LV-550) is A/D converted simultaneously using the digital oscilloscope.

In the experiments, the oscilloscope was set to trigger when the output level of the amplifier reached 200 mV. In this way, A/D conversion of the acoustical microscope and laser-doppler velocity-meter signals starts at the moment of fracture of a glass specimen due to a static load of 490 g. Using the above digital oscilloscope, the output signals before and just after the moment of fracture are obtained. By integrating the output digital signal of the laser-doppler velocity-meter, the displacement is obtained. The available frequency range of the velocity-meter is from DC to 100 kHz. Although there is a delay of about several micro-seconds in the output, the delay is negligible in these experiments.

When the ultrasonic transducer of the acoustical lens was excited by RF burst pulses, the acoustical waves, which propagated through the acoustical lens and water, and back to the lens from the specimen at the focal plane, were received by the same transducer. From the power difference between the input RF pulses and the output ones received, the two-way insertion loss $P_{\rm Loss}(f)$ of the transducer was obtained for each frequency f as shown in Fig. 4. The insertion loss of the transducer is about 34 dB at 40 MHz.

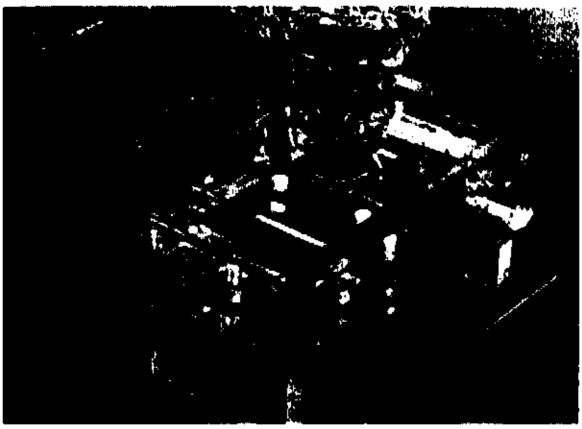

Fig. 3. Photograph for explaining the acoustical lens and slide-glass specimen.

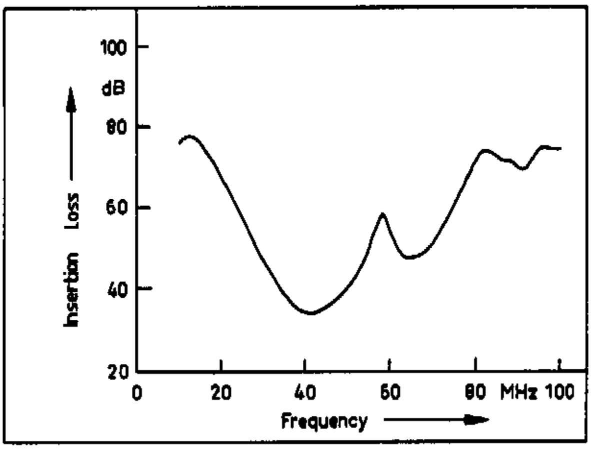

Fig. 4. Characteristics of the insertion loss $P_{\rm Loss}(f)$ in transmission measured for the acoustical lens with a $LiNbO_3$ transducer.

3. Experimental results

Fig. 5a shows the output signal observed by the system without a load in Fig. 1. This signal, therefore, represents background noise. Its average power spectrum $P_{\rm N}(f)$, which was calculated by averaging 490 periodgrams, is shown in Fig. 5b. Each periodgram is obtained from the fast Fourier transform (FFT) after cutting out the detected signal (32000 points $= 160\ \mu s$ in length) by using a Hamming window which is 256 points in length and overlaps adjacent segments by three quarters the length of the segment. The increase in power of the near DC component in Fig. 5b is due to the characteristics of the amplifier and the digital oscilloscope. A few peaks in the range from 90 MHz to 100 MHz are due to radio waves from television broadcasting.

Fig. 6 shows the displacement of the slide glass specimen obtained when a static load of 490 g was applied. After 400 μs, the amount of displacement increases rapidly, which corresponds to the start of fracture. Thus, so as not to be affected by the vibration components caused by the fracture, the observed signal in the period before 400 μs is analyzed in the following experiments.

Figs. 7a and 7b show the typical AE signals within the two periods (a) and (b), respectively, as shown in Fig. 6. By comparing these signals with the background noise in Fig. 5a, the signals in Fig. 7a and 7b have larger amplitude.

Fig. 7c shows the average power spectrum $P_{\rm LOAD}(f)$ of the 80000-point signal in the period (c) in Fig. 6. The average power spectrum was calculated by averaging 12000 periodgrams of the segments as described previously. By comparing the average power spec-

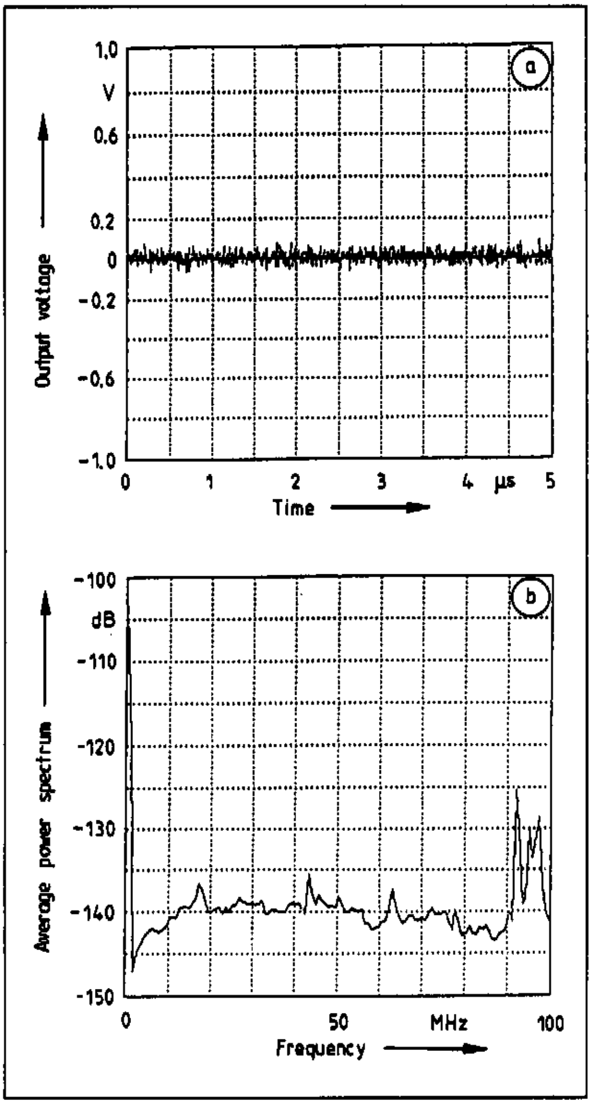

Fig. 5. (a) Output signals detected without load and (b) average power spectrum $P_{\mathrm{N}}(f)$.

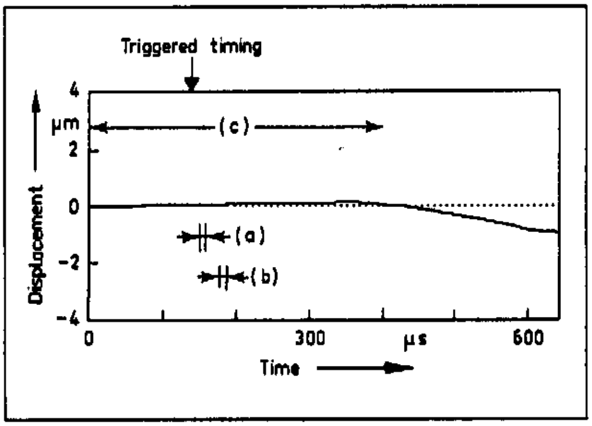

Fig. 6. Displacement of the surface of the specimen during the static three-point bending test.

trum $P_{\mathrm{LOAD}}(f)$ in Fig. 7c with the average power spectrum $P_{\mathrm{N}}(f)$ of the background noise in Fig. 5b, it is found that the detected signal with a static load has definite components in the frequency range between 10 MHz and 90 MHz.

In order to evaluate quantitatively the increased power in the components due to the static load, the power spectrum $P_{\mathrm{LOAD}}(f)$ of the signal with the static load in Fig. 7c was normalized by the power spectrum $P_{\mathrm{N}}(f)$ of the background noise in Fig. 5b. Let $P_{\mathrm{AEOBS}}(f)$ be the averaged power spectrum of the AE components involved in the observed signal detected with the static load. Since the AE components are uncorrelated with the background noise, the average power spectrum P_{LOAD} in Fig. 7c is described by the sum of $P_{\mathrm{AEOBS}}(f)$ in Fig. 7c and $P_{\mathrm{N}}(f)$ in Fig. 5b as follows:

$$P_{\mathrm{LOAD}}(f) = P_{\mathrm{AEOBS}}(f) + P_{\mathrm{N}}(f). \tag{1}$$

By subtracting $P_{\mathrm{N}}(f)$ from $P_{\mathrm{LOAD}}(f)$, the resultant relative power spectrum $P_{\mathrm{AEOBS}}(f)$ of the AE components involved in the observed signal detected with the static load is shown in Fig. 7d.

Fig. 8 shows the power ratio of the signal detected with the static load to the background noise in Fig. 5. The power is compared for the components in the frequency range between 10 MHz and 60 MHz. The length of the signal is 640 µs, which corresponds to the horizontal axis in Fig. 6. There is a large increase at the period (d) near the triggered point in the power of the signal detected with the static load. For this period (d), the average power spectrum is obtained as shown in Fig. 9, which was calculated from the 370 periodgrams of the segments. By comparing the power spectrum in Fig. 9 with that of Fig. 5b, it is seen that there is a notable increase in power for the whole frequency band up to 100 MHz.

Finally, by removing the transfer characteristics of the acoustical PFB lens transducer as described below, we obtain the power spectrum $P_{\mathrm{AE}}(f)$ of the AE signal from $P_{\mathrm{AEOBS}}(f)$ as shown in Fig. 7d. Since $P_{\mathrm{Loss}}(f)$ in Fig. 4 represents the two-way insertion loss of the transducer, the squared amplitude $P_{\mathrm{LENS}}(f)$ of the transfer characteristic of the acoustical lens is obtained as follows:

$$P_{\mathrm{LENS}}(f) = \frac{2}{P_{\mathrm{Loss}}(f)}. \tag{2}$$

Using $P_{\mathrm{LENS}}(f)$, the power spectrum $P_{\mathrm{AEOBS}}(f)$ of the AE components in the observed signal with the static load is described by the power spectrum $P_{\mathrm{AE}}(f)$ of the AE signal radiated from the cracks as follows:

$$P_{\mathrm{AEOBS}}(f) = P_{\mathrm{LENS}} \cdot P_{\mathrm{AE}}(f). \tag{3}$$

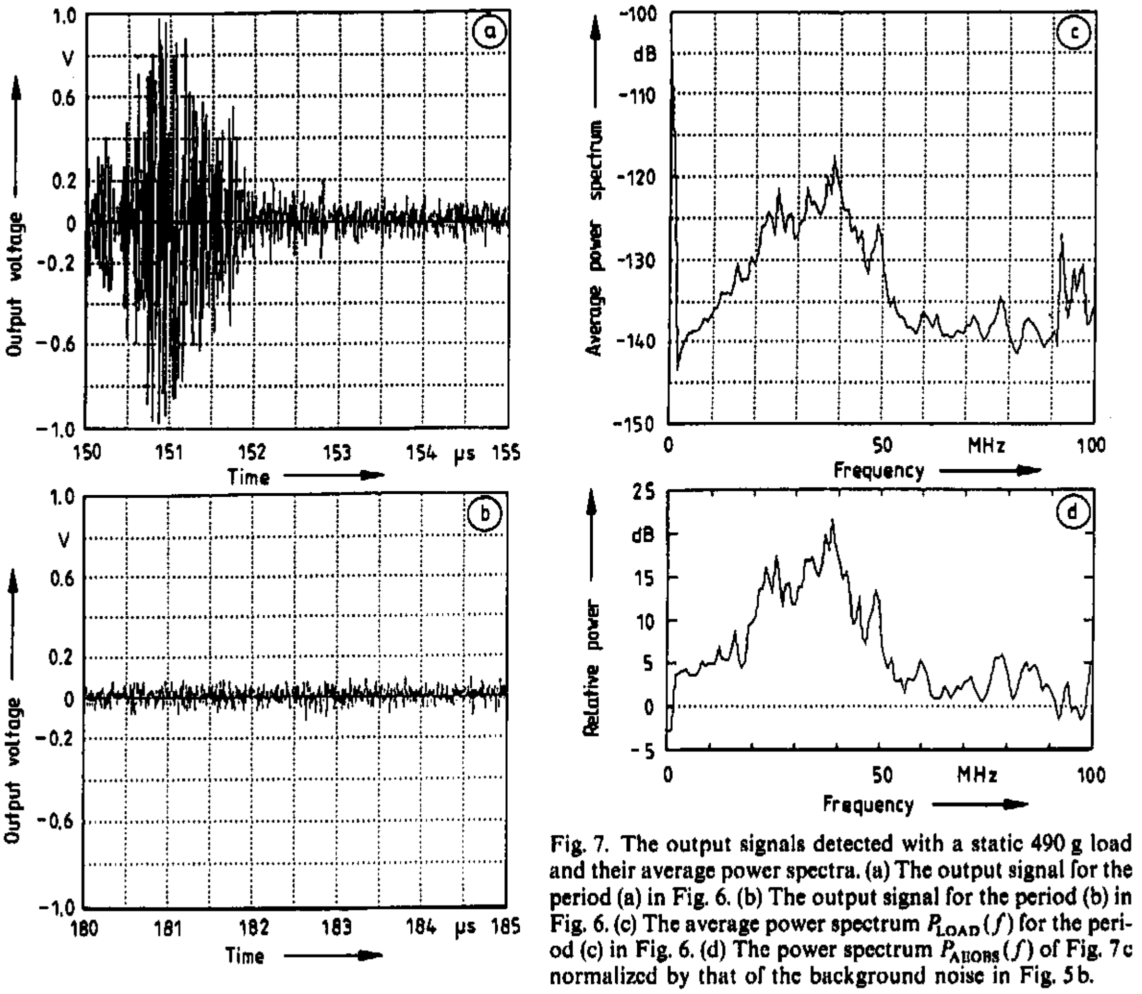

Fig. 7. The output signals detected with a static 490 g load and their average power spectra. (a) The output signal for the period (a) in Fig. 6. (b) The output signal for the period (b) in Fig. 6. (c) The average power spectrum $P_{LOAD}(f)$ for the period (c) in Fig. 6. (d) The power spectrum $P_{AEOBS}(f)$ of Fig. 7c normalized by that of the background noise in Fig. 5b.

From eqs. (1), (2), and (3), the estimated $\hat{P}_{AE}(f)$ of $P_{AE}(f)$ is calculated by

$$\hat{P}_{AE}(f) = \frac{P_{AEOBS}(f)}{P_{LENS}(f)} = \frac{(P_{LOAD}(f) - P_N(f)) \cdot P_{LOSS}(f)}{2}. \quad (4)$$

The resultant power spectrum $\hat{P}_{AE}(f)$ of the AE signal is shown in Fig. 10. It is found that the radiated AE signal has definite components in the whole frequency band below 100 MHz, and it seems that the AE signals even have frequency components greater than 100 MHz.

4. Concluding remarks

In this paper we described in detail a new system for non-contact measurement of AE signals in a 100 MHz frequency range together with experimental results. The AE signals radiated during bending tests of thin notched glass specimens were successfully detected by the acoustical microscope system with a PFB acoustical lens in the frequency range up to 100 MHz.

The new AE measurement system developed here can be used to analyze micro-deformation and microfracture of materials to promote research in micromechanics. Research on the non-destructive testing of micro-machinery can also be developed with this high-frequency, non-contact AE measurement system. It can be expected that a new scientific field of micro-AE spectroscopy will be cultivated soon.

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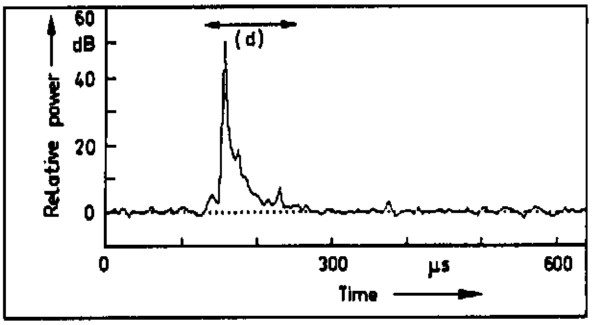

Fig. 8. Power ratio of the signal detected with the static load for the period in Fig. 6 to the background noise in Fig. 5.

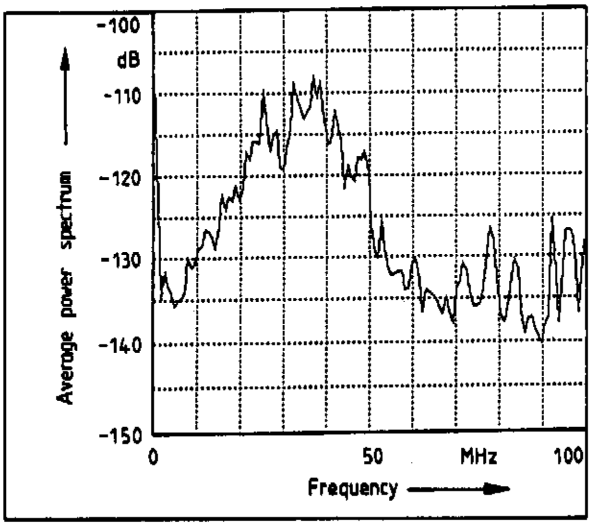

Fig. 9. Average power spectrum of the signal detected around the moment of fracture of the glass specimen. The period (d) analyzed in this figure is indicated in Fig. 8.

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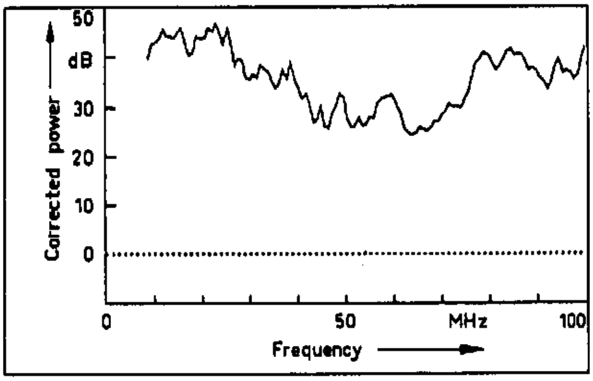

Fig. 10. The power spectrum $\hat{P}_{AB}(f)$ of the AE signal radiated from the cracks which is calculated from eq. (4) by taking account of the insertion loss $P_{\mathrm{Loss}}(f)$ of the acoustical lens.

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