ACOUSTIC EMISSION SOURCE CHARACTERIZATION THROUGH DIRECT TIME-DOMAIN DECONVOLUTION

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ABSTRACT

While detected acoustic emission (AE) signals contain potentially useful information about the deformation source mechanisms of a structure under load, signal processing techniques such as threshold counting, RMS recording, energy measurement, peak detection, and spectral analysis often fail to extract such information unambiguously. The difficulty lies both in the inherent complexity of the deformation mechanism and in the lack of understanding of the source mechanism, the wave propagation details, and the physics of the sensor's mechanical-to-electrical conversion process.

Instead of taking an empirical approach to establish the correlations between the detected AE and the observed possible deformation mechanism, we approach the problem by constructing a simple test system which consists of three main ingredients: a true displacement sensor (capacitive transducer), a simple structure (either a large block or a plate), and known theoretical impulse-response functions for specific sensor-source relative locations. We first establish the validity of these ingredients by testing with simulated AE of known step-function time dependency generated by breaking glass capillaries. Unknown sources are then introduced, one at a time, into the system for determination of their time functions. The time function at the source is determined by a deconvolution process from the known impulse response and the detected displacement. Furthermore, we show the existence of the inverse of the impulse-response function with respect to convolution for at least two extreme cases. Consequently, the source function can be obtained simply by convolving the detected signal with the inverse function. Applications to AE system calibration, sensor characterization, wave propagation studies, and brittle crack opening signature analysis will be demonstrated.

INTRODUCTION

The objective of our study is to determine AE source characteristics at the source by analyzing detected AE signals. As shown in Fig. 1 the evolution of AE signals are rather complex; the evolution can be broadly divided into three steps and associated with them, three analytical problems. The first is the description of the deformation mechanism of generating AE at the source location, second is the transient stress wave propagation through the structure, and third is the sensor transduction process which converts a local disturbance into a measurable voltage signal. The goal of AE signal analysis is to extract the information of the source mechanism from the detected voltage signals.

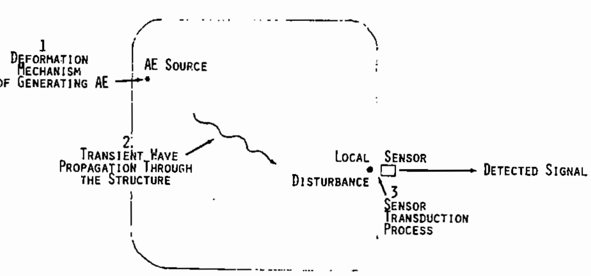

Fig. 1. The evolution of an AE signal and its associated analytical problems.

Our approach to the problem is based upon a simple experimental system consisting of a large plate (or a large block) as the structure and a capacitive displacement transducer as the sensor (Fig. 2).[1,2] The transfer function (impulse response) of the plate in terms of displacements at arbitrary points due to an impulsive force can be theoretically computed; thus is provides a basis for detailed analysis. It has been shown that the capacitive transducer measures true displacement so that the transducer transfer function is trivial. The AE source, for the time being, is modeled as a force-drop whose time dependence is to be determined from the displacement measurements and the known response of the plate.

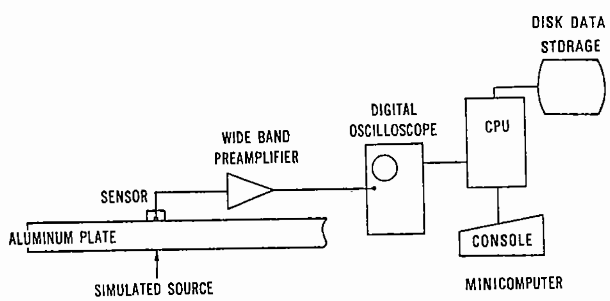

Fig. 2. An experimental system for AE source analysis.

THEORY

The method of time domain deconvolution for AE signal analysis is summarized in Fig. 3. The detected displacement U(t) is the convolution of the system impulse response with the source function. The conceptual solution to the inverse problem, i.e., to find the source function from the detected displacement, can be formulated as a convolution integral of the detected displacement U(t) with the inverse function $G^{-1}(t)$ of the impulse response of the system. Here $G^{-1}(t)$ is defined by the convolution integral so that when $G^{-1}(t)$ convolves with the impulse response G(t), a delta function is produced. If it exists, $G^{-1}(t)$

can be computed numerically. The algorithm for computing $G^{-1}(t)$ is shown in Fig. 4.

METHOD OF TIME DOMAIN DECONVOLUTION

• DESCRIPTION OF A LINEAR SYSTEM:

$$U(t) = \int_0^t F(\tau)\; G(\tau - t)\, d\tau$$

G = IMPULSE RESPONSE
U = OUTPUT
F = INPUT

• CONCEPTUAL SOLUTION TO THE INVERSE PROBLEM:

$$F(t) = \int_{-\infty}^{\infty} U(\tau)\; G^{-1}(\tau - t)\, d\tau$$

G^{-1} IS DEFINED BY

$$\int_{-\infty}^{\infty} G(\tau)\; G^{-1}(\tau - t)\, d\tau = \delta(0)$$

Fig. 3. Method of time domain deconvolution

• NUMERICAL METHOD:

DISCRETIZE:

$$\begin{aligned} U(I) &= u(I\Delta t) \\ F(I) &= f(I\Delta t) \qquad I = 0,1,2,\ldots \\ G(I) &= g(I\Delta t)\Delta t \end{aligned}$$

WRITE IN MATRIX FORM:

$$\begin{bmatrix} U(0) \\ U(1) \\ U(2) \\ \vdots \\ \vdots \end{bmatrix} = \begin{bmatrix} G(0) & 0 & 0 & 0 \\ G(1) & G(0) & 0 & 0 \\ G(2) & G(1) & G(0) & 0 \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} F(0) \\ F(1) \\ F(2) \\ \vdots \\ \vdots \end{bmatrix}$$

$$\mathbf{U} = \mathbf{G}\,\mathbf{F} \longrightarrow \mathbf{F} = \mathbf{G}^{-1}\mathbf{U}$$

or

$$U(I) = \sum_{k=0}^{I} F(k)\; G(I-K)$$

$$F(I) = \left[U(I) - \sum_{K=0}^{I-1} G(I-K)F(K)\right] / G(0)$$

Fig. 4. An algorithm for computing the inverse function $G^{-1}(t)$. If G^{-1} exists, the unknown force function may be computed directly by the last two equations.

RESULTS

We have computed explicitly $G^{-1}(t)$ for two cases. One is when the sensor is on one side of a large plate and the source is at the other side of the plate directly opposite the sensor location (the epicenter). The other is when the sensor and the source are on the same side of the plate (or a large block) but reflected rays from the opposite free surface, which arrive at a later time, are not included. Shown in Fig. 5 through 8 are the impulse responses and their inverses for the two cases.

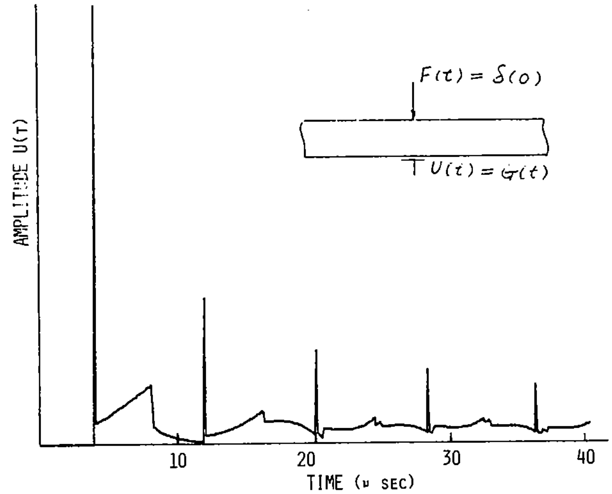

Fig. 5. Impulse response at the epicenter of a large plate. Physically the curve is the vertical displacement as a function of time at the epicenter due to a vertical force function of delta function time dependency.

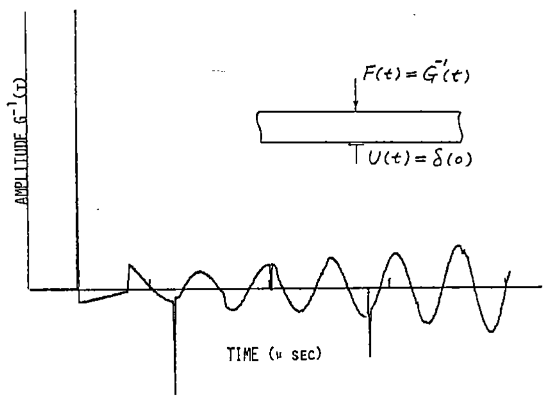

Fig. 6. Inverse function $G^{-1}(t)$ at the epicenter of a large plate. The curve is obtained by direct inversion of the function shown in Fig. 6. Physically the curve is the force function required to produce a displacement at epicenter of delta function time dependency.

The signatures of many simulated AE sources have been determined in terms of a force time function for the source. These signatures were obtained by direct convolution of the detected displacement at the epicenter with the inverse impulse response function G^{-1} shown in Fig. 6. The breaking glass capillary signature is a step function with a rise time of less than 0.5 μ sec. The breaking pencil lead source has a small yet noticeable dip before the step; its rise time is less than one μ sec and the magnitude of the step has been calibrated from 1 to 7 newtons depending on the particular size of lead used. The dropping ball contact force function also compares well with elasticity theory (Fig. 9-11).

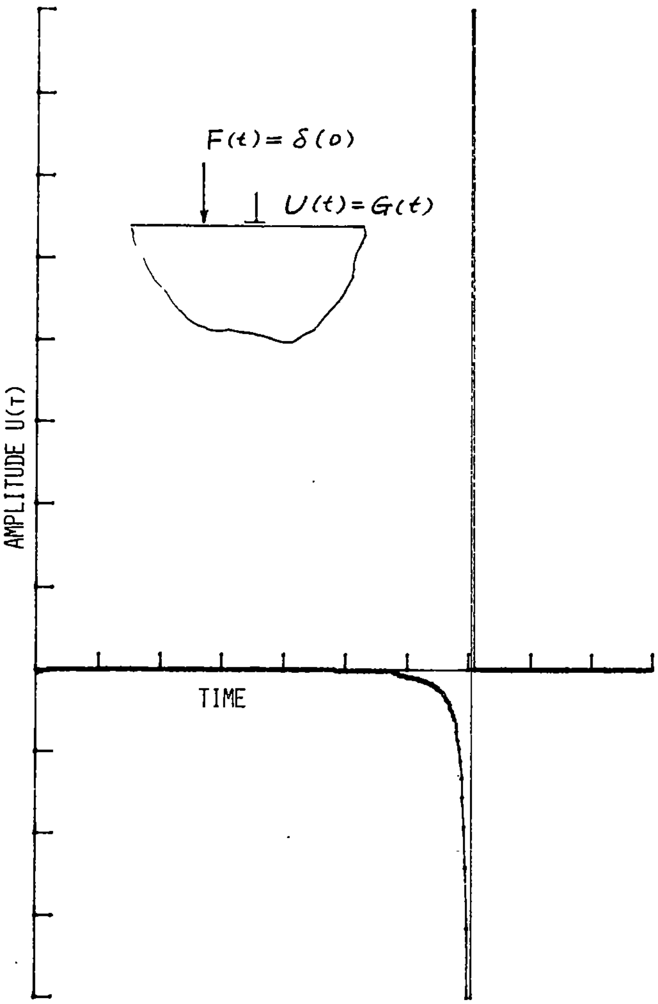

Fig. 7. Impulse response of a surface pulse. The curve shows the vertical displacement on the surface of a large block due to a vertical force of delta function time dependency applied on the same surface.

AE signals induced in glass plates by dynamic impact have also been recorded using a capacitive transducer located at the epicenter. The signals are very reproducible. The source signatures of such brittle fracture resembles a step-function at least at the initial part of the waveform (Fig. 12).

In addition to the examples given, the simple test system has many potential applications. Many unknown elements in an AE system such as sensors or structure transfer functions may be substituted into the controlled system, one at a time, and be analyzed in detail.

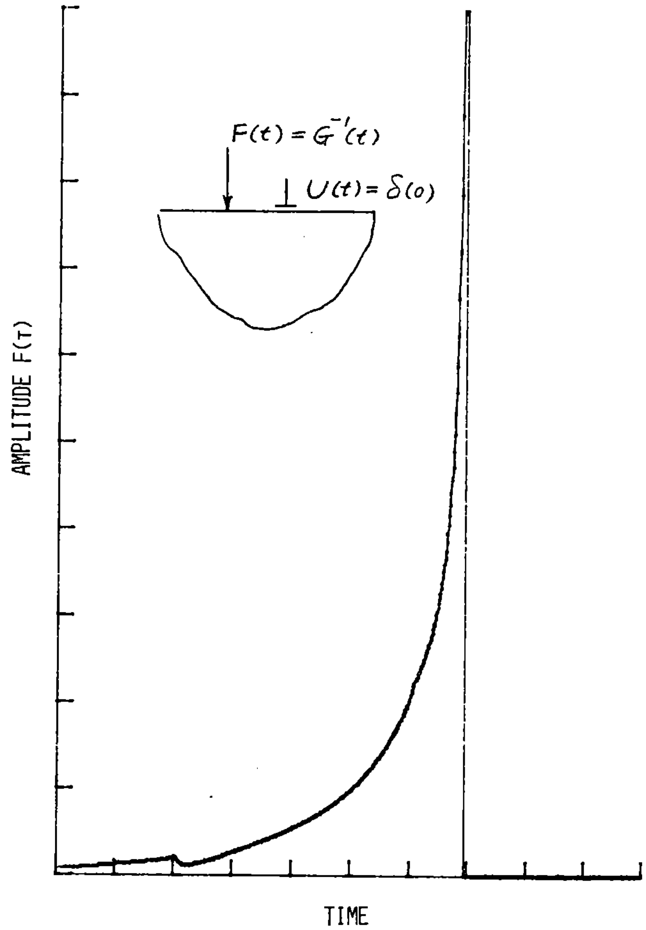

Fig. 8. Inverse of the function shown in Fig. 7. Physically it is the vertical force required to generage a vertical displacement of delta function time dependency.

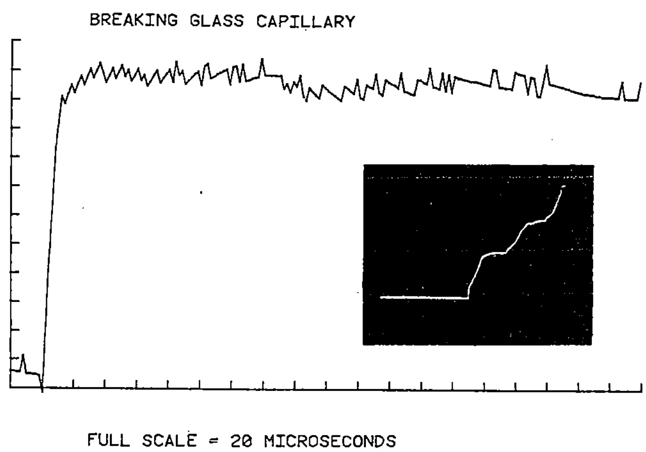

Fig. 9. Source force-time function of breaking glass capillary obtained by time-domain deconvolution of recorded epicenter displacement. Inset trace is the recorded epicenter displacement.

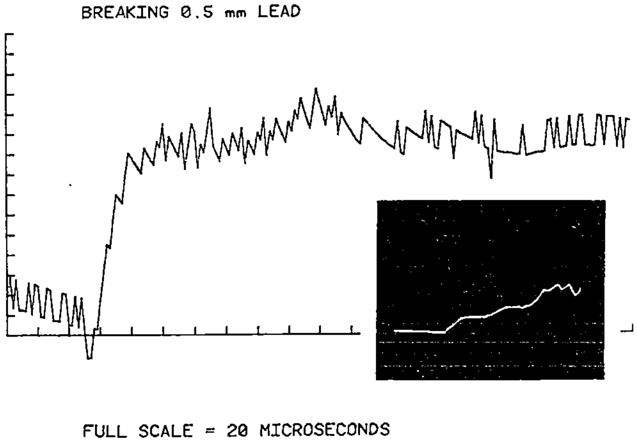

Fig. 10. Source force-time function of breaking 0.5 mm pencil lead. Inset trace is the recorded epicenter displacement.

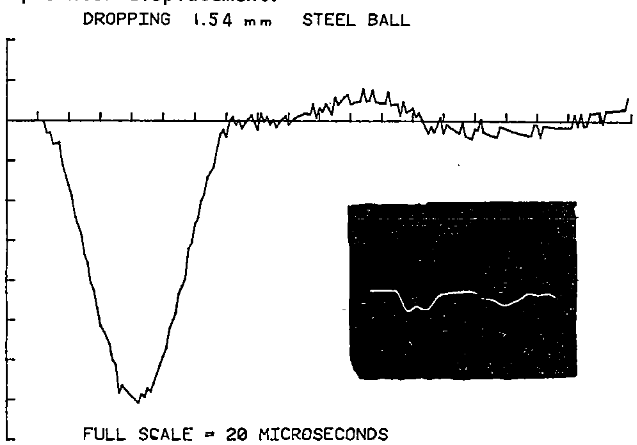

Fig. 11. Source force-time function of dropping ~1.5 mm steel ball from 5 cm height. Inset trace is the recorded epicenter displacement.

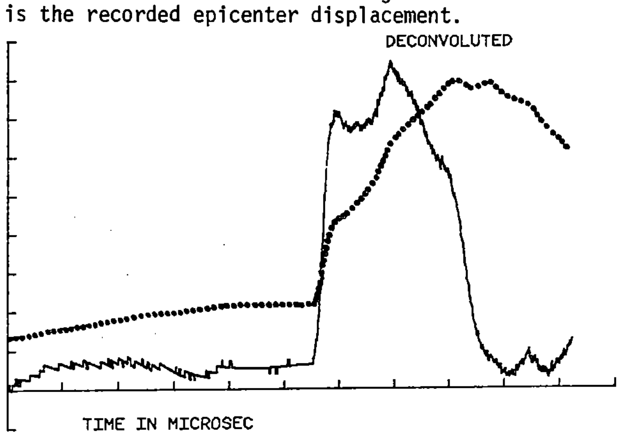

Fig. 12. Source signature of a brittle fracture produced on a glass plate by impact of a diamond indenter. The dotted line is the recorded epicenter displacement. The solid line is the deconvoluted source force-time function. Note that the initial part of the source function resembles a step function.

ACKNOWLEDGEMENT

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