TRANSFER FUNCTIONS OF ACOUSTIC EMISSION SENSORS

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Abstract

We have obtained the transfer functions of a wide range of AE sensors commonly available and utilized. These were determined by the excitation of input waves using an ultrasonic transmitter or pulse-laser in conjunction with a transfer block, a laser interferometer and a deconvolution procedure typically in the frequency domain. Sensor responses depend on the wave types; i.e., plane waves, and spherical waves with different radius of curvature. Using typical source waveforms and a convolution procedure, one can then visualize waveforms expected out of these AE sensors. Some sensors showed displacement response, while another gave velocity response. These response types also depended on incident wave types, requiring additional characterization steps in sensor calibration procedures.

Introduction

Acoustic emission (AE) sensors play a crucial part in determining AE behavior of materials and structures. The characteristics of AE sensors control the waveforms of AE signals detected. Manufacturers usually provide the sensitivity and frequency response of an AE sensor in terms of velocity response in reference to 1 V/µbar or 1 V/m/s. Here, 1 V/µbar can be converted (using aluminum dilatational wave velocity of 6.15 mm/µs) to $1.1 \times 10^8$ V/m/s. Typical peak sensitivity values are about $-65$ dB in reference to 1 V/µbar for normally incident waves and correspond to $6 \times 10^4$ V/m/s. Some sensors produce the output proportional to acceleration, while others respond to displacement. These are calibrated differently and reported in mV/Gal or in reference to 1 V/µm, for example [1]. Such information is useful in sensor selection for laboratory work and for field applications, but is inadequate to characterize the input since a sensor response depends on frequency and other conditions. Thus, in order to understand mechanical incident waves that generated AE waveforms, we need the transfer function of an AE sensor.

Let us consider mechanical input, $x(t)$, to a sensor and assume $x$ represents displacement as a function of time, $t$. $x(t)$ is normal surface motion at the epicenter and is generated on the sensing surface of a transfer block by a laser or a piezoelectric transmitter source on the opposite face (at $-X_o$). See Fig. 1. Voltage output from the sensor, $y(t)$, is given by the convolution of the input $x(t)$ and the impulse response of the sensor, $h(t)$, as

$$y(t) = h(t) * x(t)$$

(1)

The Fourier transform of $h(t)$, or $H(j\omega)$ where $j^2 = -1$ and $\omega$ is angular frequency, $2\pi f$, is known as the transfer function or system function and relates the input and output in the frequency domain. Here, we use the time domain representation, $h(t)$, with displacement input as the transfer function. This allows us to simulate expected waveforms corresponding to arbitrary input functions. Furthermore, we limit the input to be displacement of normal incidence to the sensor face.
Fig. 1 Experimental schema. Wave excitation from the bottom surface of transfer block, thickness $X_o$ (100-mm and 25-mm plates used). Sensor placed at the epicenter on the sensing surface side. Relative changes in the radius of curvature for the two plates shown.

Dependence on incident angle is expected and will be examined in the future. It is also possible to define a similar function for velocity or acceleration applied to the sensor face. However, it is not feasible to consider surface-wave input or sensor response at this time even though surface waves are important in AE signal detection and analysis.

In the above definition of the transfer function, $x(t)$ was treated as scalar. In reality, any sensor face has a finite area, typically circular with radius, $r_o$. We must consider spatial dependence and define the surface displacement as $x(r, t)$, where $r$ is the distance from the epicenter assuming circular symmetry (cf. Fig. 1). In turn, $x(r, t)$ is given by the convolution of the impulse response (Green’s function) of the transfer block (of thickness, $X_o$) and forces applied at the opposite face. The forces are dynamic and can be applied at a point (focused laser sources) or distributed over an area (piezoelectric sources). When a point source is used, the waves spread spherically to radius of $X_o$ or larger as they reach the calibration surface where the sensor is located. The thickness of the transfer block is a parameter we need to consider since it defines the radius of spherical waves exciting a sensor. Using a suitable distributed source, plane waves of limited size can be produced in the so-called near-field region, as is well known in ultrasonic testing. It would be convenient to use if a single universal transfer function is obtained for a sensor. At this stage, this is not feasible and we will consider below specific transfer functions for three input wave types, one for plane wave condition and two for spherical wave conditions. The latter two apply to AE signals that travel distances of $X_o$ from source to sensor.

The transfer function concept was utilized in fundamental studies of AE source functions and provided valuable insight to the nature of the origins of AE. A well-characterized sensor, such as a NIST capacitive or conical sensor was used, and sensor outputs were analyzed by a deconvolution procedure, and the AE source functions were deduced. In these studies, the breakage of glass capillary usually provided the calibration source of a step force of a short rise time of $\sim 1$ µs, generating stress waves with a known theoretical basis. See ASTM E-1106, which serves as the primary standard for all AE sensor calibration (for the surface waves) in the US [1]. Some efforts to get the transfer functions via frequency domain procedures were reported [2], but no systematic study is known. Manthei [3] used a procedure similar to one at NIST and obtained experimental calibration response to glass capillary breaks for lab-built sensors and a reference sensor (Panametrics V103). The results were in the form of output peak voltage per unit force for the body waves of normal incidence due to glass capillary breaks. By comparing the predicted
epicentral velocity signal for a glass capillary break with the observed, he concluded these sensors to be of velocity-sensitive type. At this stage, the velocity was not measured, so the result is useful mainly for relative calibration. It is noted that the initial single-sided peak has the half-height width of 1.9 µs (Fig. 5 in Ref. 3). This is comparable to the width expected from the resonance frequency (1 MHz) and a typical glass capillary break of 1 µs [4], though the pulse length may be extended by the use of plexiglas as the transfer block that attenuates the high frequency components. His finding is consistent with the expected velocity response near sensor resonance.

Some AE sensors are referred to have velocity response or resistance controlled. Others may be of displacement response or mass controlled. The third type is acceleration response or stiffness controlled. Such characterization is based on a simple one-dimensional analysis of a damped oscillator, which is used to represent a piezoelectric sensor [5, 6]. In this most simplistic model, a sensor is considered as a mass (m) connected to a Voigt model (a spring (k) and a dashpot (η) in parallel connection). Taking sensor frame displacement as x and frame-mass relative displacement as y, we obtain

\[ m(x + \dot{y}) + \eta \dot{y} + ky = 0 \]  \hspace{1cm} (2)

Applying sinusoidal vibration at f, we obtain the following:

\[ y = \frac{(f / f_o)^2}{1 - (f / f_o)^2 + j(f / f_o)/Q} x \]  \hspace{1cm} (3)

where \( f_o = (1/2\pi)(k/m)^{1/2} \) is the natural frequency and quality factor \( Q = (mk/\eta)^{1/2} \). In approximation, we have

\[ f \ll f_o \rightarrow y = (f / f_o)^2 x = -\ddot{x}/\omega_o^2 \]
\[ f \approx f_o \rightarrow y = -jQ(f / f_o)x = -(Q / \omega_o)\dot{x} \]
\[ f \gg f_o \rightarrow y = -x \]  \hspace{1cm} (4)

Equation (4) then predicts an acceleration response (stiffness controlled vibration) at lower frequencies, a velocity response (resistance controlled vibration) near the natural frequency, while displacement response (mass controlled vibration) is expected at higher frequencies. Note that this analysis was initially applied for a mass-loaded spring seismometer and is useful for a single-mode vibration sensor. We need caution in applying this analysis or results in typical AE sensors, in which cross-coupled modes are commonly exploited for improved sensitivity. Besides, AE signals are transients and the above analysis is for steady state oscillations.

More advanced transducer analyses are given in Mason [7], where equivalent circuit models are developed for various boundary conditions. The simplest case is for a free resonator and is represented by a series of capacitor, inductor and resistor in parallel to a capacitor. This is equivalent to the above mechanical model.

Once the transfer function of an AE sensor is known, a convolution procedure (Eq. (1)) allows one to simulate the sensor output signals using different input signals. This in turn provides the insight to original source mechanisms of AE. In order to obtain the transfer function, one needs a repeatable wave source and a transfer block of adequate size. It is also essential to determine the displacement (or velocity) of the surface on which to install a sensor under test. A classic setup was used at NIST using a glass capillary break and a capacitive transducer [1, 4]. A steel cylinder of 90-cm diameter and 43-cm high was the transfer block. In our initial work previously reported [8], we used a setup, consisting of a pulse laser, an aluminum plate (25-mm thickness) and a laser interferometer. In this work, we added a larger cylindrical aluminum block
(100-mm thickness x 300-mm diameter) and also used a piezoelectric ultrasonic sensor as a transmitter. Despite the block size limitation, this still provides information useful in understanding AE waveforms encountered in many AE studies. Another significant development is the consideration of plane waves and spherical waves from a point source as input. These required separate approach to get the transfer function of AE sensors specific to an input wave type. It was also found that various vibration modes of a sensor are activated over time and depending on the excitation wave types. This necessitates serious reconsideration of sensor calibration methods in the future.

Experimental

The initial source of impulse was a pulsed YAG laser and the output was ~2 mJ, focused on 0.5~1-mm-diameter area. Unfocused laser pulses were also used and a 4~5-mm diameter ring-like zone had high beam intensity. In the previous work, laser pulse impinged on an aluminum plate of 25 mm thickness. This resulted in a sharp displacement pulse on the opposite side, having the peak width of 50 ns at half height and the peak displacement amplitude of 1.4~1.9 nm (Fig. 2a) depending on the laser output. Three additional reflected pulses follow, but these are 11, 20 and 24 dB below the initial pulse height. Two larger blocks were added in this study. These are 300-mm diameter cylindrical shapes of 100-mm or 500-mm thickness. The largest block turned out to be a wrong geometry and produced extended echo-trains almost submerging the primary signals. Thus, the present work mainly utilized the 100-mm thick block. Displacement waveform on the opposite surface is given in Fig. 2b for the focused laser beam. The half-height peak width was 25 ns and was a half that of the 25-mm plate case. The extrapolated base width was 48 ns and the main motion of the waveform can be represented by a symmetrical triangular pulse of 48-ns duration. This shape has wide frequency content, well beyond 10 MHz and frequency at -3 dB point is 13 MHz. Unfocused beam produced similar pulse widths.

Effects of beam spread are examined. Relative changes in the radius of curvature are shown in Fig. 1. From a point source to a typical 13-mm diameter sensor, one expects 35 or 140 ns delay for 100 or 25 mm plate, causing significant changes in the displacements on the sensor surface. Figure 3 shows displacement measured on the 100-mm block from unfocused laser source. Despite the spread at the source, the peak amplitude decreased and arrival time was delayed. At 12 mm off-center, the peak amplitude was ~1/3 and the peak delay was 200 ns. Assuming a circular symmetry, one can simulate the averaged displacement response over aperture area of different diameter. Using the data of the epicenter (marked 0 mm in Fig. 3), 2-, 4- or 6-mm off-center, area-averaged displacement was calculated for 2-mm, 6-mm, 10-mm, or 14-mm diameter aperture. Here, the displacements were summed in proportion to the areas of circular zones of 1-3, 3-5 and 5-7 mm radii. Results are shown in Fig. 4. The peak amplitude increased with larger aperture and resulted in 25-times higher peak value for 14-mm size over the peak value of 2-mm size. Peak width at base also broadened from 50 ns to over 250 ns. While displacement sequence or locations were ignored, the results can approximate averaged displacement response. Thus, capacitance sensors with a given area should produce outputs similar to those in Fig. 4. In piezoelectric sensors, however, arrival phases are expected to affect the sensor output substantially.
In order to enlarge the size of source and to obtain plane waves on the sensing surface, a piezoelectric ultrasonic sensor was used as a transmitter. We used AET FC500, which has nominal resonance frequency of 2.25 MHz and 19-mm aperture size. It was driven by a negative-going step of 1-µs duration (430 V/µs peak slope over 0.7 µs). This produced a displacement waveform on the opposite surface as shown in Fig. 2c. This waveform is much broader than the laser-induced waves. The main motion is a triangular pulse of 240-ns rise and 360-ns trailing times as shown in the insert of Fig. 2c and is limited in its bandwidth. Frequency at -3 dB point is 1.2 MHz. The uniformity of the surface displacement can be seen in Fig. 5, where a PAC Pico sensor was placed at the epicenter (0 mm), 4-mm or 6-mm off-center. Amplitude was within ±1 dB and the phase was essentially identical. 2-mm off-center data was identical to the epicentral one and
not shown. Thus, this source can be utilized for plane-wave input to a sensor of 13-mm diameter or less.

![Fig. 3 Displacement measured on the 100-mm block from unfocused laser source. At epicenter (0 mm) the peak is the sharpest and highest, broadening and lowering with offset of 2, 4, 6 and 12 mm. With larger offset, peak arrival was also delayed. (x-axis length: 0.6 μs)](image)

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![Fig. 4 The averaging of displacement response for larger aperture-size receivers. The epicentral response is used for 2-mm aperture, while displacements measured at larger offset were proportionately summed. (x-axis length: 0.6 μs)](image)

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The normal displacement was detected by a laser interferometer (Thales Laser S.A., SH-140; dc-20 MHz). A sensor under test was placed opposite the laser impingement or FC500 transmitter and its output recorded by a digitizer with 100x signal averaging. Typical sampling frequency was 250 MHz, but was also at 100 MHz or 1 GHz. Acoustic couplant was silicone grease (HIVAC-G, Shin-etsu).
Fig. 5 Similarity of surface displacements produced by AET FC500 on 100-mm block and detected by a PAC Pico sensor placed at the epicenter (0 mm), 4-mm or 6-mm off-center.

Fig. 6 The transfer function of a PAC Pico sensor (s/n 3804) calculated from the epicentral data of Fig. 5 and surface displacement produced by AET FC500 on 100-mm block (Fig. 2c).

Results

1. Transfer functions

The transfer function of a sensor was obtained from its response to excitation and the corresponding displacement waveform using a frequency-domain deconvolution procedure. Noise in the sensor response before the arrival of excitation signals was eliminated and cosine taper window was applied first. Note also that digital data was 5-MHz low-pass filtered before the deconvolution was applied. A Butterworth low-pass filter (<30 MHz) was applied on the deconvoluted transfer function. Some high-frequency noise still remained in some results, making several of them irrelevant. The amplitude of transfer functions is in the unit of V/m·s. The results given in various figures in this work are in terms of V/m·(time step), with 10-ns time step. In taking the
convolution integral, this time step is multiplied; thus, the values given here must be reduced by $10^8$ in using them with the standard unit of V/m·s.

**a. Pico sensor:** The waveform due to FC500 excitation taken by a Pico sensor (PAC, ser. 3804) given in Fig. 5 indicates initial oscillations of 0.7 µs duration (1.4 MHz) followed by 5 cycles at ~2.2 µs period. The latter corresponds to the main resonance of this sensor at 450 kHz. Shown in Fig. 6 is the transfer function of this sensor, which shows a bipolar pulse of 0.74 µs duration. Two additional cycles can be discerned in noise. Thus, both the sensor output and the transfer function exhibit velocity response to unipolar displacement input at 1.4 MHz. The main 450-kHz resonance of this sensor is, however, difficult to recognize in the transfer function, partly because of large high-frequency noise remaining after low-pass filtering. It is also impossible to assign response type at 450 kHz.

![Fig. 7 (a) Waveform and (b) transfer function of a Pico sensor (s/n 3804) obtained using focused laser and 100-mm transfer block. (x-axis length: 10 µs)](image)

It is also possible to define a transfer function even when the acoustic input waves are spherical. Figure 7 shows the waveform and transfer function obtained using 100-mm transfer block. Since the displacement input (Fig. 2b) has a narrow pulse width (25 ns at half height), the waveform and transfer function resemble each other well except for higher noise in the transfer function. The shape is closer to the velocity response with the first negative peak being 3/4 height of the first positive peak. The main 450-kHz resonance of this sensor is also clearly visible. Since this was obscure in the plane-wave input case above, this may be due to the spherical nature of incident waves. This may also cause the broadened first peak (0.45 µs) that has 4–5 times the half height peak width shown in Fig. 6b. These two effects are difficult to rationalize on the basis of spherical waves, however.

Effects of the radius of curvature of spherical incident waves are substantial. Previously, we reported a transfer function using 25-mm thick block [8]. This is shown in Fig. 8. The highest peak is the third one and it is obvious that multiple incident modes contributed to this complex transfer function. The main 450-kHz resonance of this sensor is most evident and the first bipolar pulse can be considered to exhibit velocity response.
From the three transfer functions of a single Pico sensor, it is evident that the nature of incident waves strongly affects the sensor response. It also shows that the type of sensor response, velocity or displacement, for example, must identify the input condition.

Fig. 8 Transfer function of a Pico sensor (red), which accounted for three reflected laser pulses. First-peak only (blue) curve is essentially same as measured waveform for t<30 µs. [8]

Fig. 9 (a) Waveform and (b) transfer function of a V1030 sensor (10 MHz) obtained using FC500 transmitter and 100-mm transfer block.

b. V1030 sensor: This sensor from Panametrics is a damped ultrasonic transducer and we mis-identified it previously as V103 [8]. Current Panametrics V103 has nominal resonance frequency of 1 MHz, while our V1030 has 10 MHz/0.5” inscription. Using the plane-wave input with FC500 transmitter through 100-mm block, we obtained the waveform and transfer function as shown in Fig. 9. The waveform is a typical bipolar pulse, indicative of the velocity response with 0.68 µs duration. This is much longer than the 10-MHz inscription implies, but the rise time was faster than 0.15 µs (which is shorter than the incident wave rise time of 0.24 µs). The transfer
function also shows the main feature to be a bipolar pulse of 0.27 \( \mu \text{s} \) duration, i.e., the velocity response. However, it is followed by a 5.5-MHz wave train. The origin of this trailing vibration is still obscure.

![Graph](image)

Fig. 10 Waveform of V1030 sensor obtained using focused laser and 100-mm transfer block.

![Graph](image)

Fig. 11 Waveform of V1030 sensor obtained using focused laser and 25-mm transfer block. [8]

Using spherical incident waves and 100-mm block, V1030 sensor produced the output shown in Fig. 10. The main pulse is a negative-going narrow peak having half-height duration of 0.25 \( \mu \text{s} \). It is followed by lower amplitude oscillations. The transfer function contained strong noise at 35 MHz and meaningful features could not be deduced. The previous result of transfer function obtained using 25-mm radius spherical waves also showed the main peak to be a unipolar pulse, followed by numerous oscillations (see Fig. 11 [8]). For this large aperture sensor, both spherical incident waves resulted in apparent displacement response. In spite of a simple structure of averaged displacement for larger aperture shown in Fig. 4, real sensors must be sensitive to the phase distribution of incident waves. The averaged displacements may be applicable for capacitive sensors only.

From the present results, the conventional wisdom of using well-damped sensors for high-fidelity waveform acquisition needs to be reexamined carefully. Depending on the types of waves being detected, appropriate sensor calibration has to be conducted considering the source types and propagation distances.

c. B-1080 sensor: This is a broadband sensor from Digital Wave. This is twice more sensitive compared to V1030, in part due to the addition of FET input stage on the sensor. This sensor
output indicates the acceleration response to a displacement pulse input, although the two positive-going pulses are not quite symmetric in shape. However, the peak heights are almost identical and the peak positions were symmetric. The transfer function calculation was not successful, again with strong high-frequency noise that could not be eliminated.

Fig. 12 Waveform of a Digital Wave B-1080 sensor excited by FC500-generated plane waves.

d. WD sensor: This is a popular wide-band sensor from PAC with multiple resonances having multi-element sensing design. Its sensitivity is higher than broadband sensors (V1030 and B-1080). Because it has a disc and two ring elements, its response is expected to be complex.

Fig. 13 Waveform of a PAC WD sensor excited by FC500-generated plane waves.

Fig. 14 Transfer function of a PAC WD sensor excited by FC500-generated plane waves.
Under the plane-wave excitation with 100-mm block, the waveform and transfer function were obtained as shown in Figs. 13 and 14. The first three peaks of the waveform are indicative of the acceleration response (also for transfer function plot albeit with strong high-frequency noise) as in B1080 above. In this case, many oscillations follow without any definitive pattern. The two initial positive peaks have a 1.4-µs period while many pairs of peaks have 1 to 1.8 µs duration. However, the main resonances of WD sensor are at 200 to 500 kHz range and 2 to 5 µs periods are not discernible in Fig. 13. Periods corresponding to 1 to 1.6 MHz are present for the transfer function plot, but again no indication of low-frequency resonances can be found.

The present result differs drastically from the transfer function obtained using 25-mm radius spherical waves [8]. The previously obtained function is shown in Fig. 15, where two strongest peaks of opposite signs seem to imply the velocity response. (The velocity response is confirmed on the basis of source wave convolution, as discussed later.) The origin of many oscillations observed in Fig. 15 was not elucidated. Again, the type of incident waves affected the basic character of the transfer function.

e. R15 sensor: This utilitarian sensor from PAC and others of similar designs with 140-175 kHz resonance have been used widely during the past four decades. This is usually not intended for waveform acquisition, but its waveform and transfer function are obtained as the representative of widely used resonant sensors. See Figs. 16 and 17 for the plane-wave input case. The observed waveform shows well-separated pulses corresponding to the front-face arrival of the incident wave (marked A), the back-face arrival (B), the return of reflected wave at the front face (C) and the second arrival to the back face (D). These are spaced at 1.40 µs and the amplitude of B-pulse is 1.7 times that of A-pulse. Other peaks are more irregularly spaced and it is hard to identify its main resonance frequency of 150 kHz from period observation. Broad peaks at ~12, ~20 and ~28 µs may possibly correspond to the main resonance. On the other hand, the first 10 µs (see Fig. 16 insert) contains 13-14 peaks, implying that this sensor has a high-frequency sensitivity and can be used in the same way as a WD sensor above to detect AE activities at different frequency ranges. The transfer function shown in Fig. 17 has a similar pulse sequence, with a – d peaks corresponding to A – D peaks in Fig. 16. The pulse sequence A-B-C with the strongest B suggests acceleration response. However, these three peaks are separated by two-cycle oscillation and the transfer function sequence a-b-c has a large positive peak following b-pulse, making acceleration designation tenuous.
The transfer function calculated from 25-mm radius spherical wave input is given in Fig. 18 and has less discernible structures under 10 µs, but ~7-µs period becomes visible at longer duration. Its FFT is shown in the lower plot and clearly shows the presence of expected resonance structures at 155, 250 and 366 kHz, as indicated in the figure. However, two higher resonance frequencies had no corresponding peaks with a usual face-to-face testing method. The resonance oscillation in the transfer function appears to need spherical incident waves since it was invisible in the case of plane-wave input (in both the time and frequency domains).

f. PZT elements: Three PZT discs were similarly excited by plane or spherical waves. These are PZT-5 elements of 11.0-mm φ (diameter) x 5.4-mm thickness (designated as 375), 18-mm φ x 5.35 (400) and 10-mm φ x 14.4 mm (100), respectively. Disc 375 was taken out of AET AC375 sensor with nominal 375-kHz resonance. Disc 400 and 100 were ordered as 400-kHz or 100-kHz element. The waveform (left plot) and transfer function (right plot) of Disc 375 with plane-wave input are shown in Fig. 19. Those of Disc 400 were very similar, while we failed to get the trans-
Fig. 18 Transfer function of a PAC R15 sensor (top) and its FFT (bottom) with peak frequencies in kHz. FFT used Noesis software.

Fig. 19 Waveform and transfer function of Disc 375 PZT-5 element excited by plane waves using FC500 and 100-mm block. (x-axis length: 8 μs)
When these same discs were excited by spherical waves, the response was quite different as shown in Fig. 20. Here, 100-mm block and a laser source were used. Left plot is for Disc 375, while right plot is for R15. In both cases, sharp spikes are followed by decaying output corresponding to the arrival of incident waves at the front or back surface. After a few cycles, these are replaced by smoother oscillations of respective resonance frequency. In the un-damped Disc 375, sudden rise-and-fall cycles lasted longer and these can be seen even after 12 µs. In R15 with backing material in the sensor construction, these disappeared after the third cycles. When sharp steps are smoothed out (by filtering), this response gives rise to velocity-response at the thickness resonance as expected. However, when the main resonance frequency develops from cross-coupling effects (e.g., between thickness and radial modes), it is not possible to interpret the response mode.

2. Source wave convolution
When the transfer function of a sensor is known, we can construct the output signals from input displacement waveforms by performing convolution operation [8]. In order to show the utility of this procedure, we conducted a series of model computation. The transfer functions used were those obtained using 25-mm radius spherical waves.

We used three types of displacement waveforms to represent a source function. Type 1 is a single full-cycle sinewave, Type 2 a half-cycle sinewave from −90 to +90° (a smoothed step-function) and Type 3 a half-cycle sinewave from 0 to +180°, respectively. The frequency of the waves was chosen at 100, 200, 500 kHz, 1 or 2 MHz. Zero-padding was applied as needed to avoid edge effects. Down-slope was also added for Type 2. For Types 1 and 3, the displacement waveforms are continuous, but their derivatives or velocity waveforms had discontinuities at the beginning and end. The velocity waveforms for Type 2 are of a half-cycle sinewave.

a. Pico sensor: The convolved waveforms are given in Fig. 21. For Type 2, a half-cycle sinewave is the prominent feature indicative of possible velocity response, but Types 1 and 3 waveforms indicate oscillations at input frequency. These Pico waveforms thus give no clear correspondence to displacement or velocity input. Considering the findings reported earlier in this work, this is not surprising. This sensor responds initially at a higher frequency (Fig. 8), followed by the main resonance frequency of 450 to 500 kHz. In the plane-wave excitation case, a velocity response is expected at 1.4 MHz at the beginning according to Fig. 5. Thus, we cannot assign
response type for the slowly developed vibration mode. Amplitude of convoluted waves is given in arbitrary unit, although the output values are given as obtained. When a sinewave of unity amplitude is given as source input, it represents ±1-m displacement. However, the output is not necessarily proportional to displacement and further evaluation is needed to establish a proper unit to use.

![Graphs showing Pico-sensor and WD-sensor responses](image)

Fig. 21 Pico-sensor responses to 3 input types. Fig. 22 WD-sensor responses at 200 kHz.

Pico sensors have been used to evaluate crack-induced AE through source simulation analysis [9-11], where the signal rise time is an important parameter. Thus, we examined the linearity with respect to the source-function rise time. For Type 2 signals, nominal displacement input rise times are 0.25, 0.5 and 1 µs for 2, 1 and 0.5 MHz; the corresponding rise times of the convolved waveforms were 4.60, 4.71 and 4.91 µs, indicating proportional increments with a delay. Similar relations are observed for Types 1 and 3 signals. This implies that Pico sensors can be used for comparative rise time studies. However, this sensor appears to have a mixed response to input displacement and velocity and may cause difficulties in characterizing the nature of source events. We also need to clarify the origin of the rise time stretching of about 4 µs.

b. **WD sensor:** The convolved waveforms for 200-kHz sources are given in Fig. 22. Type 1 shows a large dip between two sharp peaks. This waveform resembles the velocity source wave of Type 1 or the derivative of a full-cycle sinewave displacement. The base duration is extended to 6.64 µs compared to 5-µs input. Type 2 corresponds to a half-cycle sinewave, with an extrapolated base width of 4.0 µs (1.5 µs longer than 2.5 µs input width). Again, this corresponds to the derivative of Type 2 displacement input. Type 3 is the initial part of Type 1, with the base width shortened to 4.48 µs (still ~2 µs longer than the input width). The rise time to the first peak was 1.28, 2.30 and 1.28 µs for the three types. Here, the rise time of 1.28 µs for Types 1 and 3 results from 10 ns effective rise time, while 2.30 µs for Type 2 is due to the smoothed step rise time of 1.25 µs duration. Thus, the WD sensor contributed 1~1.3 µs to the observed rise time at 200 kHz.

Type-2 waveforms using five different source frequencies are shown in Fig. 23. The lower frequency signals are closer to a half-cycle sinewave, while effects of additional peaks are more visible at 2 MHz, especially at the trailing part beyond the main peak having minor oscillations.
The main features of Fig. 22 were also observed at 100 kHz to 2 MHz. In all cases, the WD sensor gives consistent velocity response in the three types of source waves. This finding needs further tests at more frequencies that differ from the sensor resonances (100, 230, 480 kHz) [12], but WD responds basically to velocity signals of spherical wave input. Note that it is difficult to reach this conclusion from visual inspection of the transfer function (Fig. 15).

The observed rise time decreased smoothly with frequency, as shown in Fig. 24, where its values for Type 2 are plotted against nominal (velocity) input rise time. The observed rise time is always larger than the nominal value and the difference ranges from 1.20 µs (100 kHz) to 0.63 µs (2 MHz). Because of multiple resonance characteristics of this sensor, this finding is unexpected and surprising, but WD sensor is useful even for rise time studies.

c. V1030 sensor: The convolved waveforms for 500-kHz sources are given in Fig. 25. For spherical wave input, this sensor gives displacement response, with full or half sinewave output for Types 1 and 3 and a step-down waveform for Type 2. This reflects the nature of its transfer function with the negative-going main peak when excited by 25-mm radius spherical waves. This behavior is expected from its heavily damped construction for ultrasonic testing applications. The waveforms were similar at 200 kHz, but at 1 MHz, an additional peak overlapped and response became a mixed one. The observed width of the first full cycle was 4.91, 2.30, 1.51 and 0.53 µs for 0.2, 0.5, 1 and 2 MHz source, showing anomaly at 1 MHz.

Type-2 response of V1030 sensor is shown in Fig. 25. The anticipated step-down behavior was seen at 0.2 and 0.5 MHz with the “rise” time of 2.33 and 1.25 µs. These compare well with the nominal values of 2.5 and 1.25 µs. At 1 and 2 MHz, a faster rising component (at 0.30 and ~0.6 µs) appears before the main peaks at 0.98 and 0.89 µs (see Fig. 24). The main peak rise times follow a smooth curve, ending at 0.85 µs for zero nominal source rise time. The origin of the fast component is apparently due to the main peak (at 0.30 µs) in the transfer function, whereas the main peak in the convolved waves combines the first two large peaks (at 0.30 and 0.83 µs) in the transfer function. While the overall behavior of V1030 sensor is primarily displacement response, these additional deviations complicate the interpretation and careful waveform evaluation is needed. We obviously cannot assume a heavily damped sensor to be always well behaving.
Discussion

The calibration procedure described here is a straightforward application of current laser-sensing technology in measuring the displacement of elastic waves. In combination with piezoelectric or laser generation of planar or spherical waves, we can characterize AE sensors in a new way; that is, the transfer function of a sensor, which should be available in addition to the customary frequency response characteristics per ASTM E-1106. It also became evident that the transfer function of a sensor depends on the incident wave types as different vibration modes of a sensing element are excited in non-unique manners. This resulted in sensor response characteristics (i.e., acceleration, velocity, or displacement) that are dependent on the incident wave modes.

In light of the present study, we must reevaluate the NIST-developed calibration standard (ASTM E-1106 and ISO equivalent) since it relies on circular waves propagating on a steel block. Depending on the distance from the central glass-capillary break, the wave front changes producing distance- and aperture size-dependent calibration standard. Through-transmission calibration method also faces difficulty of spherical wave propagation.

Because most AE sources can be regarded as a point source, AE sensors must detect spherical waves. We have used two thicknesses for the transfer block. Systematic study of effects of the radius of curvature is needed. Also required is the understanding of how various vibration modes are excited within the sensing element. In this connection, the results reported here on PZT elements must be further examined as to how electrical signals are generated in relation to the position of elastic wave front. Rouby [13] examined long ago how each component of a signal waveform is generated. However, the comparison of R15 and Disc 375 results (cf. Figs. 16, 19 and 20) immediately shows vastly different behavior (input: plane or spherical incident waves; output: bipolar vs. unipolar). Thus, careful model experiments must be conducted to elucidate mechanisms of signal generation as functions of the radius of curvature of incident waves and the degree and types of cross-coupled vibration modes.

Conclusions

The transfer functions of representative AE sensors were obtained using the excitation by an ultrasonic transmitter or pulse laser and displacement measurement using a laser interferometer. Types of incident waves are critically important in defining the transfer functions as different
vibration modes were excited. These also affected the sensor response characteristics (i.e., acceleration, velocity, or displacement). The transfer functions and typical source waveforms were combined by convolution. Results demonstrate the nature of sensor responses and the utility of the approach used here. This study points to the need of reexamining the standard calibration method in terms of wave front radius effects. Wider uses of transfer functions can improve our understanding of various AE sources.

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References