Numerical Approach to Absolute Calibration of Piezoelectric Acoustic Emission Sensors using Multiphysics Simulations

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Abstract

In this paper, the absolute calibration of piezoelectric Acoustic Emission (AE) sensors is developed using multi-physics numerical and experimental models. In this process, two common excitation approaches including laser and pencil lead break (PLB) are used to generate the simulation sources because of their excellent reproducibility and well-established analytical expressions of their source functions. The numerical models include source function, steel plate and piezoelectric sensor model with the details including adhesive layer, wear plate, piezoelectric ceramic, and backing material. The experimental results of four types of AE sensors (true wideband sensor, low and high frequency conventional sensors and low frequency unpackaged sensor) are compared with the numerical results. The numerically obtained calibration curves show good agreement with the calibration curves provided by the manufacturer. The influences of adhesive layer, backing material and sensor size on the sensor response are studied. The uncoupled piezoelectric sensor models indicate that there is no single displacement history that the sensors can be used for calibration. It is shown that the quantitative AE analysis requires the coupled structural and electrical models of structural medium and piezoelectric sensor.

Keywords: acoustic emission, calibration, piezoelectric

1. Introduction

The Acoustic Emission (AE) method relies on detecting propagating elastic waves released by newly formed fracture surfaces. The AE method has been successfully implemented to detect the initiation [1–3] and the location of damage in coupon samples and large-scale structures [4,5]. The damage initiation is typically identified using the cumulative energy graph of AE signals [6]. The damage location is determined using the time of flight differences of sensor arrays strategically positioned on the structure [7]. However, understanding the quantitative meaning of damage, such as source mechanism from the transient AE signals, is still a challenging research problem. The challenge is caused by the complexity in the process of detecting AE signals generated by active flaws. The AE signal is the convolution of source function, structural transfer function and sensor response function. As the final component of the convolution process (assuming that data acquisition electronics have no effect to the sensor output signal), AE sensors, typically piezoelectric types, play a significant role in detecting damage in structures. The characteristics of an AE signal highly depend on sensor types and models, which add further complexity in signal processing and generalizing the AE signal characteristics of damage modes for different test conditions.

There are several approaches to understand the quantitative meaning of piezoelectric AE sensors and calibrate the sensor response with the known input excitation. The absolute calibration of AE sensors is performed by following the guidelines of ASTM E1106 [8]. The test method requires breaking glass capillary on a large steel block to generate displacement normal to the surface, and determine voltage output per unit displacement in comparison to the response of a standard calibrated transducer. Lan et al. [9] proposed the surface-to-surface calibration method to simplify the standard calibration process; however, one reference sensor is required and the compatibility of two paired sensors (transmitter and receiver) is needed [10]. Hatano et al. [11] developed the reciprocity method, which is based on the principal that transducers behave exactly both in sensing and actuation modes, and tested the method on a steel block with different transducer arrangements for surface and bulk waves. Based on the reciprocity method, Kober et al. [12] took the advantage of time reversed acoustics to determine highly accurate reference-free in situ calibration method, and verified the method by testing five transducers on an airplane wing flange section. Mclaskey and Glaser [13] discussed that a sensor with built-in preamplifiers cannot be calibrated by the reciprocity method. The authors utilized glass capillary and ball impact as excitation sources, and found the displacement histories analytically to plot the calibration curve of transducers. They emphasize the importance of separating the response function of AE transducers from other variables in the measurement chain in order to have a physics-based understanding of the AE signals. The calibration approach is based on the theoretical solution of wave motion at the sensor location due to the selected source function, and the experimental output signal. The sensor response is obtained by dividing the AE sensor output to the theoretical input displacement in the frequency domain. Theobald [14] measured normal and tangential

displacements on a cylindrical aluminum block with interferometer. Normal displacement and tangential displacements are results of wave generation by normal and shear wave transducers, respectively. Griffin [15] identified the behavior of piezoelectric AE sensors using experimental results. Although there are several calibration methods used in literature, each method has its own drawbacks. For instance, the theoretical approach relies on obtaining the displacement history from the Green's function solution, which is based on the assumptions of point source and receiver, and limited by simple geometries. The reciprocity approach requires nearly identical transducer design and specifications. The absolute mechanical quantities (e.g. displacement, velocity and pressure) on the structure surface are difficult to measure experimentally. Laser interferometry provides point displacement while the presence of sensor may influence the true displacement history. The selection of transfer medium may also affect the calibration result. While the face-to-face calibration removes the influence of transfer block, the method requires the proper selection of actuating sensor.

There are recent studies in literature that combine structural wave propagation problem and electrical piezoelectric sensor model into a multi-physics numerical model [16,17]. The interaction of sensor and structure can be better described using the numerical simulations. In our study, the experimental results of four types of AE sensors (true wideband sensor, low and high frequency conventional sensors and low frequency unpackaged sensor) are compared with numerical results. Numerically obtained calibration curves of conventional piezoelectric sensors show good agreement with the calibration curves provided by the manufacturer. The influences of adhesive layer, backing material and sensor size on the sensor response are studied. The uncoupled piezoelectric sensor models indicate that there is no single displacement history that the sensors can be compared for calibration. Laser ultrasound and pencil leak break (PLB) are selected as the simulation sources because of their excellent reproducibility and well-established analytical expression of source functions. Fig. 1 shows the approach for absolute calibration of piezoelectric AE sensors. Section 2 describes the structures of piezoelectric AE sensors studied in this paper. The source functions are described in section 3. The numerical and experimental results of piezoelectric AE sensors are presented in section 4. The conclusions of this study are presented in section 5.

Fig. 1 The factors influencing the absolute calibration of piezoelectric AE sensors.

2. Background Literature

2.1. Piezoelectric Acoustic Emission (AE) Sensors

Piezoelectric AE sensors are made of wear plate, electrodes, active element, backing material and protecting case [18]. Wear plate, typically made of silicon oxide, protects the active element and provides easy removal of sensor after adhesively bonded to the test structure. Active element converts dynamic surface displacement into electrical signal. Backing element reduces the vibration of active element to design wideband response. The type and size of active element and backing material establish the sensor response as resonant or broadband, frequency bandwidth and sensitivity. Felis et al [19] optimized the PZT sensor by tuning the piezoelectric materials, geometries, matching layers and backing. Álvarez-Arenas [20] designed, constructed and characterized air-coupled piezoelectric transducers by stacking up the piezocomposite disk and polypropylene foam ferroelectric film with low impedance value. The transducer frequency response is controlled by the thickness of the polypropylene foam ferroelectric film. In the aspect of piezoelectric sensor design, special emphasis is therefore put on the optimization of different components (e.g. active element and auxiliary elements) inside of the sensor. Therein, the most common active element used in the design of AE sensors is lead zirconate titanate (PZT). Lee and Kuo [21] design a miniature acoustic transducer with two conical PZT elements to measure the surface wave velocity by using PZT ceramic (PZT-5H) as the sensing element. Other piezoelectric elements reported in literature for AE sensing are polyvinylidene fluoride-trifluoroethylene (PVDF-TrFE) copolymer [22], embedded polyvinylidene fluoride (PVDF) [23], PTCa/PEKK piezo-composites [24,25], piezoelectric polymer-ceramic composites [26], macro-fiber composite (MFC) film [27].

Piezoelectric sensors operate as direct mode (sensing) or converse mode (actuating). The AE sensors function in the direct mode that piezoelectric element produces current under applied stress. The sensing mode equations are:

$$S_{ij} = s_{ijkl}^D T_{kl} + g_{kij} D_k \quad (1)$$

$$E_i = g_{ikl} T_{kl} + \beta_{ik}^T D_k \quad (2)$$

where T is the stress tensor, E is the electric field, D is the electric displacement field or polarization, S is the strain field, g is the piezoelectric voltage coefficient [28]. The relationship between piezoelectric voltage coefficient g and the piezoelectric charge constant d is:

$$g = \frac{d}{K \epsilon_0} \quad (3)$$

where K is the dielectric constant and ϵ_0 is the permittivity in free space. The sensitivity of AE sensors depends on the piezoelectric voltage coefficient and the shape of piezoelectric element. The stress tensor is augmented in a specific direction (e.g., thickness vibration for thickness-mode transducer); however, complex vibration modes may occur due to the bulky characteristic of piezoelectric element. Better understanding of piezoelectric AE sensor behavior requires combining experimental results with numerical models.

2.2. Source Functions Generated by Laser Ultrasound and PLB

Laser ultrasound is a non-contact method to generate elastic waves in structures. Davies et al. [29] characterized the laser source depending on the power density generated on the surface laser directed. Surface displacements are different for two regimes: thermoelastic and plasma regimes. Hutchins et al. [30] used capacitance transducer to plot the displacement waveforms produced on a metal block in thermoelastic regime. The test is repeated for a constrained surface to see the change in displacement waveforms. Scruby [31] studied the effect of laser power density on the surface displacement, and proposed an equation for determining the volume expansion due to a laser source on the metal surface. Rose [32] solved the surface displacement equation due to thermoelastic laser source and showed that the laser source can be expressed as a point expansion. Hutchins et al. [33] demonstrated the angular dependence of surface displacement in the thermoelastic and plasma regimes. Spicer and Wagner [34] plotted epicenter waveforms on a plate with changing plate thickness, laser diameter and energy. Bernstein and Spicer [35] modified the laser beam to a line source on an aluminum block to compare the directivity results obtained from a small diameter laser source.

The laser source generates rapid heating on the metal surface. If the laser source has power density greater than 10^7 W/cm^2 [29], rapid heating causes surface ablation where vaporization and melting of the surface is encountered. This destructive heating source creates a net force on the surface. However, for power densities less than 10^7 W/cm^2 , the laser source creates thermoelastic distortion on the surface. This is basically the volumetric expansion of the metallic surface where laser heating is absorbed. Force dipoles appear on the opposite sides of the surface while the plane stress condition is present on the surface hit by the

laser beam [36]. In this case, the source thickness is assumed to be zero, and this condition implies that out-plane dipole strength is zero, only the horizontal dipole is considered. The dipole force is given by the product of magnitude of each force and distance separating them. For example, the product of stress and volume is given by:

$$D = B\delta V \quad (4)$$

where, D is the dipole strength ($N \cdot m$), B is the bulk modulus of elasticity, δV is the volumetric expansion (m^3). The analytical solution requires the properties of metal and the value of volumetric expansion on the surface of the plate. The volumetric expansion is calculated using the following equations:

$$\delta V = \frac{3\alpha}{\rho\sigma} \delta E \quad (5)$$

$$\delta E = (1 - R)E \quad (6)$$

where α is the linear expansion coefficient ($1/K$), ρ is the density (kg/m^3), σ is the specific thermal capacity of metal ($J/kg \cdot K$), R is the reflectivity, E is the pulse energy ($J/pulse$) and δE is the energy absorbed in the metal. The laser dipole source model has been validated analytically by Spicer [37]. The force function is a step function as shown in Fig. 4 (a), which has a rise time of 4.5 ns (the same as the laser used in this study), and does not vanish immediately as the heat dissipation takes a certain amount of time. The magnitude of the force function is obtained using Eq. (4). Because the thickness of laser source is zero, Eq. (4) is modified as Eq. (7):

$$D = B\delta V = Fd \quad (7)$$

where F is the magnitude of dipole force (N), d is the diameter of laser beam.

Pencil lead break (PLB) known as Hsu-Nielson source [38] is widely used as an artificial AE source. The lead of a mechanical pencil is pressed firmly on the surface until it breaks. The theory of PLB test is well-established and the expression of source function has been validated.

3. Methods

3.1. Sensor Models

Fig. 2 shows the components and pictures of four piezoelectric AE sensors modeled in this paper. Three resonant types of AE sensors, including micro30s and R6 sensor manufactured by Mistras Group Inc. and an unpackaged PZT sensor, referred herein as cut-PZT [39] are tested. Additionally, wideband piezoelectric AE sensor manufactured by Acoustics Technology Group is used for validating the numerical models. Table 1 shows the material properties used for each sensor component. The components of micro30s and R6 sensors modeled in the simulations include adhesive layer, ceramic wear plate, and piezoelectric element. R6 has an

additional brass backing. The couplant influence is considered as adding a bonding layer between wear surface and steel plate.

Table 1 Materials properties of structural steel and piezoelectric element [40].

Property	PZT-5A (micro30s / R6 / cut- PZT Sensor)	Structural steel (Plate)	Couplant/Epoxy(micro30s / R6 sensor)	Brass backing material(R6)	Ceramic (wear plate of micro30s/ R6)
Elastic modulus (GPa)	$C_{11} = C_{22} = 121,$ $C_{12} = 75.4,$ $C_{13} = 75.2, C_{33} =$ $111.2,$ $C_{66} = 22.6, C_{44} =$ $C_{55} = 21.1$	200	2.7	105	300
Density (kg/m^3)	7750	7850	1700	8000	3200
Poisson ration	0.3	0.33	0.45	0.34	0.28
Piezoelectric constants (C/m^2)	$S_{31} = S_{32} = -5.4,$ $S_{33} = 15.8,$ $S_{24} = S_{14} = 12.3$

Fig. 2 Piezoelectric AE sensors; (a) commercial sensors, (b) unpackaged piezoelectric sensor, and (c) wideband displacement sensor.

Isotropic damping ξ is considered in each of the sensor model. The damping ratio is calculated according to the mechanical quality factor Q_m , and Q_m is measured by the ratio of the equivalent reactance to the equivalent resistance of the losses in vibrating element using the following equation [39]:

$$Q_m = \frac{f_n^2}{2\pi f_m Z_m C (f_n^2 - f_m^2)} \quad (8)$$

$$\xi = \frac{1}{2Q_m} \quad (9)$$

where f_m and f_n are frequencies at the minimum and maximum impedance of element (Hz), respectively. Z_m is the minimum impedance of the element (Ω) and C is element capacitance (F) measured at 1000 Hz. All of the parameters are measured by an Agilent 4294 A Precision impedance analyzer as shown in Fig. 3 and listed in the Table 2. The damping ratios of micro30s, R6 and cut-PZT are measured as 0.048, 0.017 and 0.020, respectively. The transducers are numerically modeled and their frequency response analyses are conducted. The resonant frequencies obtained by the numerical and experimental frequency response results show good agreement as shown in Fig. 3. It is important to note that the numerical results are presented using the electrical flux density. Therefore, the numerical and experimental values in the vertical axis do not match.

Fig. 3 The comparison of admittance (experimental) and absolute electric flux density (numerical) of three sensors (a) micro30s, (b) R6, and (c) cut-PZT.

Table 2 The measured quantities from the Agilent 4294 A Precision impedance analyzer

Sensor	f_m (kHz)	f_n (kHz)	C (pF)	Z_m (Ω)	Frequency sweep range (kHz)
micro30s	218.66	236.72	340	1416	1~500
R6	92.36	98.12	550	936	1~200
cut-PZT	60.20	84.76	240	1104	1~150

3.2. AE Source Models

In this paper, the laser system is made of Polaris II, Nd-Yag Q-switched laser, which has 50 mJ/pulse energy, 4.5 ns rise time and 3 mm beam diameter at 1064 nm wavelength. The dipole strength is calculated using Eq. (4), and then the magnitude of the force function is obtained using Eq. (7). The magnitude of dipole force is calculated as 2.258 N. The source function of PLB is represented as a point load (see in Fig. 4 (b)) with a linear ramp function, which has a rise time of 1 μ s, and the maximum magnitude as 3 N [41,42].

Fig. 4 The schematic of artificial AE source functions; (a) laser source, (b) PLB source.

3.2. Experimental and Numerical Designs

The AE sensors are mounted on a steel plate with the dimensions of 254 mm x 254 mm x 12.7 mm using epoxy. Each sensor is positioned at the center of the plate as shown in Fig. 5. The AE signals are recorded using MSO2014 oscilloscope (100 MHz sampling frequency) manufactured by Tektronix.

The numerical models include 3D structural module for steel plate, and piezoelectric module for the AE sensors, Fig. 5. Two physical domains are coupled using Eqs. (1) and (2) in COMSOL. The steel plate is partitioned with different mesh sizes to reduce the computational effort. A convergence study was conducted to the mesh size and time step. The central part between the excitation source and the AE sensors has the mesh size of 3 mm using tetrahedral elements. The other parts of the plate have the mesh size of 30 mm. The mesh size for the components of AE sensors is 0.75 mm. The time step is selected as 10 ns, which corresponds to 100 MHz frequency resolution. The laser and PLB excitations are generated on the plate epicenter (denoted as OOP_{ext}) as shown in Fig. 5.

Fig. 5 The numerical models of (a) micro30s sensor, (b) R6 sensor, and (c) cut-PZT sensor (unit: mm).

4. Results

4.1 The validation of numerical models with experiments

The displacement history obtained from the 3D numerical model is compared with the experimental result of wideband piezoelectric AE sensor manufactured by Acoustics Technology Group. The sensor has a nearly flat response spectrum in the frequency range of 10 kHz - 1 MHz. The voltage output is linearly proportional to the surface displacement in this frequency range [13]. The piezoelectric sensor as shown in Fig. 5 is placed on the centroid of steel plate and coupled using vacuum grease.

Fig. 6 and Fig. 7 show the normalized numerical displacement and experimental voltage histories using the laser and PLB sources, respectively. The band pass filter of 10 kHz-1 MHz is applied to the numerical results as the piezoelectric sensor has linear response within this frequency range. The time histories and frequency spectra of numerical and experimental results agree with each other for two simulation sources. The influence of rise time of source function on the output signal is clearly observed by comparing the laser source (rise time as 4.5 ns) and the PLB source (rise time as 1 μ s) waveforms.

Fig. 6 The numerical and experimental results of wideband displacement sensor using the laser source; (a) time domain histories, (b) frequency spectra, (c) frequency spectra in logarithmic scale.

Fig. 7 The numerical and experimental results of wideband displacement sensor using the PLB source; (a) time domain histories, (b) frequency spectra, (c) frequency spectra in logarithmic scale.

4.2 The structure-coupled response of AE sensors

Once the source function and the numerical model are validated using the wideband displacement sensor, the epicenter experiments are repeated for three resonant type piezoelectric AE sensors to obtain their calibration curves, and understand their wave conversion characteristics. In COMSOL, a local coordinate system is built to define the poling direction. The poling direction of cut-PZT is z-direction. When the direction of excitation is changed, the piezoelectric effect refers to a change in the electrical polarization using Eqs. (1) and (2). The surface displacement components and poling direction directly influence the voltage output of the sensor. In this section, the numerical models include fully coupled structure and piezoelectric models.

Fig. 8 and Fig. 9 show the numerical and experimental results of different sensors excited by laser and PLB, respectively. All the data (numerical and experimental) are exposed to the band pass filter of 20 kHz - 1000 kHz frequency range. There are slight differences in the time and frequency domain responses; however, in general, the numerical and experimental results agree with each other. Slight differences are attributed to the influence of couplant and the variations in sensor details and input signal amplitude due to the surface texture. The agreement between experimental and numerical response of cut-PZT sensor is better than the commercial sensors as the cut-PZT has simple design.

The influences of couplant, backing material and sensor size on the sensor response are illustrated by the parameter analyses using the R6 sensor model. The parameters include adhesive thickness, the size of backing material, and the height of PZT material. Fig. 10 (a) shows the influence of adhesive thickness on the sensor response. The adhesive thickness leads to a shift of peak frequency. Fig. 10 (b) shows the influence of backing material on the sensor response. The backing material influences the waveform shape and frequency response. The increase of backing material weight causes a shift of frequency components as well as an increase of the peak frequency bandwidth. Fig. 10 (c) shows the influence of slight change in the height of PZT ceramic on the sensor response. Higher frequencies are observed when the size of PZT

ceramic decreases. In general, the first wave arrival has similar signature for all the simulations. The sensor details influence later wave arrivals, which also explain the differences observed in Fig. 8 and Fig. 9.

Fig. 8 The numerical and experimental results of AE sensors due to the laser source; (a) micro30s, (b) R6, and (c) cut-PZT.

Fig. 9 The numerical and experimental results of AE sensors due to the PLB source; (a) micro30s, (b) R6, and (c) cut-PZT.

Fig. 10 Parametric study based on numerical models; (a) adhesive thickness, (b) backing material, and (c) the height of PZT ceramic.

In addition to the comparison of time and frequency domain responses, the calibration curves of micro30s and R6 sensors are developed numerically and compared with the calibration curves provided by the manufacturer. R6 sensor is calibrated using ASTM E1106 [8], and micro30s sensor is calibrated using ASTM E976 [43] by the manufacturer. Fig. 11 shows the numerical calibration curves of the sensors using the laser and PLB excitations. In general, the frequency bandwidths of numerical calibration curves show good agreement with the calibration curves provided by the manufacturer. It is important to note that similar calibration curves are obtained using two simulation sources. R6 and micro30s sensors have the frequency

response ranges as 35 kHz – 100 kHz and 150 kHz – 400 kHz, respectively, which agree with their specifications. Fig. 11 (b) shows the calibration curves of three R6 sensors provided by the manufacturer. Even for the same type of sensor, the calibration curve of each design shows differences due to variations in details (e.g., amount of epoxy coating, wear plate thickness).

Fig. 11 Calibration curves obtained using numerical approach and provided by the manufacture of (a) micro30s, and (b) R6 sensors.

The differences in the measured and calculated waveforms and calibration curves can be attributed to experimental and modeling variables that introduce error and uncertainty in the data. Table 3 summarizes the variables that introduce deviations in the measured and calculated AE waveforms. In the numerical model, the time step and mesh quality introduce approximations to the true data. Additionally, the exact details of internal components are unknown. In the experimental measurement, surface condition, sampling rate, vertical resolution and the control of adhesive thickness are the major variables.

Table 3. Numerical and experimental variables introducing variations into AE waveforms

Numerical Model		Experimental Model	
Factor	Influence	Factor	Influence
Mesh size	Wavelength resolution	Surface condition	Laser/PLB input energy
Time step	Frequency resolution	Sampling rate	Frequency resolution

Materials properties	Waveform amplitude and signature	Vertical effective bit	Amplitude resolution
Internal composition of sensor	Wave reflections in time domain and frequency response	Adhesive thickness	Peak frequency response

As there is no single quantity obtained from the results, it is difficult to quantify the uncertainty. Instead, the correlation coefficients of measured and numerical waveforms are calculated to determine the similarity in addition to visual comparison. The experimental data are considered as true values. The correlation coefficient indirectly shows that the measured and computed waveforms have high similarity. In statistics, the correlation coefficient measures the strength and direction of a linear relationship between two variables. The correlation coefficients between numerical and experimental results are presented in Table 4. The value close to 1 indicates high similarity between two waveforms.

Table 4. Numerical and experimental correlation coefficient

Excitation Source	Sensor	Correlation coefficient between numerical model and experimental model
Laser excitation	Micro30s	0.80
	R6	0.85
	Cut-PZT	0.86
PLB excitation	Micro30s	0.86
	R6	0.89
	Cut-PZT	0.86

Fig. 12 compares the experimental results of micro30s, R6 and cut-PZT sensors under the laser source excitation. While the medium (steel plate), the excitation source and the couplant are the same, significant differences are observed in the time and frequency domain results. The frequency response of AE sensor controls the characteristics of output signal. The waveform and frequency spectra signatures of different sensors have different shapes and magnitudes. The selection of sensor shows profound influence on the output signal. As shown in Fig. 12, the peak frequency and frequency centroid (two common AE features used in the literature) are controlled by the sensor type selected, which negatively affects the development of generalized pattern recognition methods using the resonant type AE sensors.

Fig. 12 The experimental AE signals of micro30s, R6 and cut-PZT sensors due to the laser source; (a) time domain histories, (b) frequency spectra, (c) frequency spectra in logarithmic scale

4.4 Uncoupled response of piezoelectric sensors

It is important to understand what wave motions the AE sensors convert into electrical signals. For this purpose, the piezoelectric sensors are uncoupled from the structure, and the average surface displacement histories under the sensors are applied as surface load to the wear plate. The uncoupled sensor responses are compared with the coupled responses presented in the previous section. All the sensor details modeled in the coupled simulations are included in the uncoupled response models.

(a) Displacement histories under piezoelectric sensors

The first step is to determine the sensor influence on the surface displacement when the sensor is present on the surface or not. Fig. 13 shows the numerical results of the averaged displacement histories over the area of micro30s. The comparison of results with (W) and without (WO) sensors on the structure shows that the influence of sensor on the surface motion is negligible. There is a slight decrease in the displacement magnitude in y direction (u_y). The sensor introduces additional mass, and influences the surface motion. While there are differences with and without sensor cases in the displacement histories in z (u_z) and x (u_x) directions, displacement amplitudes are low as compared to u_y , and their frequency spectra have components higher than 1 MHz where the piezoelectric AE sensors are not sensitive to. The averaged displacement histories and their frequency spectra over the area of cut-PZT are shown in Fig. 14 (a) and (b), respectively. As compared to the micro30s sensor, the displacement magnitude of u_y is smaller when the sensor is present on the surface as the cut-PZT sensor has larger mass and surface area than the micro30s sensor. Therefore, using the surface displacement without sensor to compare with the voltage output (typically measured with laser interferometry [12]) may cause incorrect calibration result (i.e., V/m or V/(m/s)).

Fig. 13 The influence of micro30s sensor on the surface displacement based on numerical models; (a) time domain histories, (b) their frequency spectra.

(a)

(b)

Fig. 14 The influence of cut-PZT sensor on the surface displacement based on numerical models; (a) time domain histories, (b) their frequency spectra.

(b) The change of displacement histories along the sensor line

The AE sensor outputs are generally compared with the displacement histories at a single point to find the sensor transfer function [13,14]. As the AE sensors have a finite size, the distribution of displacement on the sensor surface should be determined whether comparing the sensor output with the point displacement is accurate or not. The displacement distribution along the sensor surface is studied for the smallest and the largest sensors tested in this study.

Fig. 15 The displacement histories along the centerline of AE sensors due to the laser source based on numerical models; (a) micro30s, (b) cut-PZT.

Fig. 15 (a) shows the changes of displacement histories along the micro30s sensor diameter (referred as ‘distance’ in the figure). Under the epicenter excitation, u_y is the major displacement component, and it is considered constant along the sensor line. The AE sensor output is directly related to u_y . Fig. 15(b) shows the displacement histories of the cut-PZT sensor. The distance at the horizontal axis represents the mid-point of the long side of the sensor. As compared to the micro30s sensor, the displacement history varies along the sensor line. It is determined that when the sensor size increases, the comparison of AE sensor output with the point displacement becomes inaccurate.

(c) Voltage outputs of piezoelectric sensors under uncoupled numerical model

In this section, the average displacement histories over the sensor area are applied as boundary load on the uncoupled piezoelectric sensor model either individually or simultaneously to understand the wave conversion characteristics of piezoelectric sensor. The results are compared with the coupled numerical models. Fig. 16 (a) and (b) show the voltage outputs and their frequency spectra of micro30s. The contribution of in-plane displacement to the sensor response is negligible as the amplitude components of in-plane displacements are considerably small as shown as Fig. 13. Micro30s majorly responds to the out-of-plane wave motion. Therefore, comparing the sensor output with the averaged out-of-plane displacement under the sensor is a reasonable assumption for calibrating the micro30s sensor. Fig. 17 (a) and (b) show the voltage outputs and their frequency spectra of R6. The R6 sensor is also sensitive to the out-of-plane wave motion. However, with the increase of the sensor size, a phase shift is observed between the uncoupled and coupled responses. Fig. 18 shows the voltage outputs and their frequency spectra of cut-PZT sensor. The uncoupled and coupled responses have similar patterns while the amplitude difference is lower than micro30s. Though the average displacement over larger contact surface can introduce errors into the input function, larger mass can suppress the surface motion and self oscillation, then the conversion rate between surface motion and electric response is higher. In contrast, micro30s has more differences between coupled and uncoupled models because some of the surface motion is the result of self oscillation (see in Fig. 15). The assumption that the sensor response is linear with the surface displacement obtained by the Green's function solution causes error in the calibration curve. It is concluded that true sensor calibration using numerical approach requires fully coupled sensor-structure model.

Fig. 16 The comparison of uncoupled and coupled micro30s response due to the laser source based on numerical models; (a) time domain histories, (b) their frequency spectra, (c) frequency spectra in logarithmic scale

Fig. 17 The comparison of uncoupled and coupled R6 response due to the laser source based on numerical models; (a) time domain histories, (b) their frequency spectra, (c) frequency spectra in logarithmic scale

Fig. 18 The comparison of uncoupled and coupled cut-PZT response due to the laser source based on numerical models; (a) time domain histories, (b) their frequency spectra, (c) frequency spectra in logarithmic scale.

5. Conclusions

The AE signal is the convolution of source mechanism, medium transfer function, and sensor transfer function. In order to quantify the AE signal in terms of source characteristics independent from the experimental variables, a better understanding of the AE sensor influence on the output signal is needed. In this study, the numerical models are utilized to understand the wave conversion characteristics of three AE sensors with different frequency responses and dimensions. The numerical results are validated with the experimental measurements using the laser and pencil lead break excitations. The numerical and experimental results of three resonant type AE sensors are in good agreement when the sensors are fully coupled to the structure. The experimental results of the sensor with the package have higher differences than the sensor without package; therefore, the complete sensor including active element, package and wear plate should be considered for predicting the sensor response. The effects of adhesive thickness, backing material and sensor dimension on the sensor response are numerically demonstrated. Minor changes in the built sensor can introduce significant differences in the time domain response. The displacement histories under the sensor surface indicate that when the sensor weight increases, the displacement amplitude decreases. Additionally, when the sensor diameter increases, there is non-uniform displacement distribution along the sensor diameter. These two points highlight that the calibration approach by comparing the sensor

response with the displacement history obtained by Green's function solution or laser interferometer introduces error. It is concluded that true sensor calibration using numerical approach requires fully coupled sensor-structure model.

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