Visualization of stress wave propagation via air-coupled acoustic emission sensors

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Abstract
We experimentally demonstrate the feasibility of visualizing stress waves propagating in plates using air-coupled acoustic emission sensors. Specifically, we employ a device that embeds arrays of microphones around an optical lens in a helical pattern. By implementing a beamforming technique, this remote sensing system allows us to record wave propagation events in situ via a single-shot and full-field measurement. This is a significant improvement over the conventional wave propagation tracking approaches based on laser doppler vibrometry or digital image correlation techniques. In this paper, we focus on demonstrating the feasibility and efficacy of this air-coupled acoustic emission technique by using large metallic plates exposed to external impacts. The visualization results of stress wave propagation will be shown under various impact scenarios. The proposed technique can be used to characterize and localize damage by detecting the attenuation, reflection, and scattering of stress waves that occurs at damage locations. This can ultimately lead to the development of new structural health monitoring and nondestructive evaluation methods for identifying hidden cracks or delaminations in metallic or composite plate structures, simultaneously negating the need for mounted contact sensors.

Keywords: sound camera, beamforming, acoustic emission, impact identification

(Some figures may appear in colour only in the online journal)

1. Introduction

In aerospace, civil, and mechanical engineering applications, it is imperative to ensure structural integrity through the detection and characterization of damage and defects. The presence of defects, such as cracks, dents, corrosion, delaminations, or numerous other forms of damage, can significantly reduce the inherit properties and performance of a structure, thereby increasing the chance of premature failure. Therefore, structural health monitoring (SHM) and nondestructive evaluation (NDE) have been subjects of intense studies in recent decades. In particular, increases in the use of advanced materials, sensors/actuators, and manufacturing processes has spurred the development of numerous SHM/NDE techniques. These methods include—but are not limited to—thermography, shearography, X-radiography, eddy current, ultrasonic c-scan, scanning laser vibrometry, and guided wave-based ultrasound techniques [1–5]. They are based on thermal, electromagnetic, acoustic/mechanical, and other multi-physical feedback, and each technique offers unique advantages and shortcomings.

Using acoustic emissions for purposes of detecting and localizing damage has been one of the widely adopted methods in the SHM/NDE community [6–9]. Acoustic emissions are manifest when a material is subjected to extreme stress conditions due to external loads, such that a local point source within the material suddenly releases irreversible energy in the form of stress waves. The released stress waves are transmitted to the surface of the material and then propagate outwards from the epicenter of the release source.
Previous studies involving acoustic emission techniques have focused largely on the onset of such acoustic emissions to locate their release sources [10–13]. However, more useful applications can be derived from the susceptibility of acoustic emissions to attenuation, scattering, or reflection by discontinuities present in the material [8]. We identify that it is this particular property of acoustic emissions that can be exploited in order to detect and localize pre-existing damage in an inspection medium.

In this study, we experimentally demonstrate the feasibility of visualizing stress waves in an aluminum plate using acoustic emissions. The focus is whether acoustic emission techniques can capture the scattering of stress waves due to the presence of damage resulting from an applied impact on the plate. For recording and subsequent visualization of such transient events, we employ a device referred to as an acoustic or sound camera. This device embeds an optical lens at the center and arrays of microphones around the optical lens in a helical pattern [14]. Note that arrays of microphones have been used in previous studies to identify the locations of vibration sources [15], but it has not been thoroughly explored yet to visualize stress waves in structures via air-coupled microphone sensors to the best of the authors’ knowledge. This is because of a short characteristic time—on the order of micro-seconds—of stress waves propagating in solids and also due to the difficulty in post-processing measured raw data to visualize the wavefronts of these stress waves.

To address the challenges associated with stress wave visualization, we implement time-domain delay-sum beamforming techniques [16] based on acoustic emission information collected from the arrays of microphones. To enhance the accuracy of the diagnostic scheme, we conduct parametric studies on various post-processing conditions, including the temporal resolution of the sensor data and the spatial resolution of the inspection plate. Finally, the developed technique is evaluated for SHM/NDE purposes with capabilities assessed for detecting the defect location simulated with a mass placed in the path of the wave propagation on the inspection plate.

The acoustic emission beamforming technique coupled with the sound camera device has unique advantages compared to the conventional techniques such as ultrasonic or laser based testing methods [6]. Many of the conventional testing methods are founded on the principle of imparting external stimuli or excitations on the inspection material and measuring differences in the received signal in order to detect whether damage is present and where it is located. While such methods generally provide highly accurate results, they often involve slow and expensive processes to operate equipment. Conversely, acoustic emission beamforming methods can be conducted in situ and in real time, without necessitating permanently mounted contact sensors or baseline data.

Recently, laser Doppler vibrometry has gained significant attention as a means to visualize stress waves in solids and structures with an unprecedented resolution [17–19]. However, this method requires synchronization and reconstruction of data measured from every single discretized spatial point of an inspection medium in order to compose the propagation development. This is not practical given the difficulties in exciting structures in a repeated, identical fashion. Digital image correlation techniques can also visualize extremely dynamic motions, but they require speckle patterns on specimens and their field of view can be often narrow for recording high speed events [20]. In contrast, the proposed acoustic emission beamforming technique is capable of conducting non-contact—yet full-field—stress wave visualization across an inspection medium in a single shot measurement. Consequently, we envision that this method can open new avenues to diagnosing the existence of damage in structures in a time- and cost-efficient manner by conducting simple tests.

The contents of this manuscript will address the following topics. Section 2 contains an introduction to the time-domain delay-sum beamforming theory and a discussion of how this concept is incorporated into the study contained herein. Section 3 describes the experimental setup used for monitoring inspection plates and tracking stress waves using the sound camera. Section 4 provides an analysis of parametric studies performed on pristine plates that are used to determine temporospatial resolutions necessary for capabilities-centric analyses. Finally, section 5 concludes the study with an analysis of the acoustic emission beamforming method for identifying varying impact locations and detecting simulated damage on the inspection plate.

2. Theoretical background

Traditional methods of source localization via air-coupled acoustic emission rely on the assumption that the recording device is pointed at or aimed in the general vicinity of the emission origin. Acoustic beamforming is an attractive alternative for use in acoustic feedback NDE as it provides the opportunity to detect the direction of unknown acoustic emissions associated with failure events across a large spatial domain [21]. While acoustic beamforming is a relatively new concept for applications related to damage localization, beamforming using microphone arrays is a standard practice for spatial isolation of sound sources. The beamforming method—also known as microphone antenna, phased array of microphones, acoustic telescope, or acoustic camera—is used extensively for localizing sounds on moving objects and to filter out background noise in acoustically active environments with stationary sound sources [22].

Figure 1 gives a visual representation of the basic delay-sum beamforming method. This process can be expressed mathematically by equation (1) in terms of the time-domain delay-sum beamforming output [16]:

$$B(t, \vec{X}_P) = \sum_{n=1}^{N} a_n s_n [t - \tau_n (\vec{X}_P)],$$

(1)

where $N$ is the total number of microphones, $t$ is time, and $\vec{X}_P$ represents an inspection position on the plate with respect to
the reference position (e.g., center of the microphone arrays as shown in the figure). \( a_n \) is a spatial shading or weight coefficient that can be applied to the individual microphones to control mainlobe width and sidelobe levels \([16]\). In many instances, the weighting coefficients are set to unity. \( s_n(t) \) represents the acoustic emission received by the \( n \)th microphone emitted by an arbitrary sound source.

After receiving the signal, a specified delay, \( \tau_n \), is imposed to the signal for each individual microphone based on the spatial domain. Figure 1 shows the operation used for calculating the microphone delays. First, the spatial domain of interest is discretized into 'pixels' rendering a superimposed grid onto the spatial domain. Second, for each point on the spatial domain the position vector \( \vec{X}_p \) from the predetermined reference point is calculated. Then, the position vector of that same spatial pixel from the \( n \)th microphone whose position relative to the reference point is given by \( \vec{M}_n \) is determined as \( \vec{X}_n = \vec{X}_p - \vec{M}_n \). Finally, the difference of flight time of the acoustic signal between the two vectors is found by calculating the difference in vector magnitudes and dividing the speed of sound \( c \). That is, the time delay for each point on the inspection plate and each \( n \)th microphone is defined by

\[
\tau_n(\vec{X}_p) = \frac{1}{c}(|\vec{X}_n| - |\vec{X}_d|).
\]

The scanning algorithm of the microphone array will perform the delay calculation operation for the entirety of the spatial domain which it is monitoring. After the time delays for all microphones are imposed on the signal for a given spatial pixel, the transformed signal from each microphone is summed as shown in figure 1(b). The location of the sound source is determined by the delays for a specific spatial location which produced the maximum beam output, \( B(t) \). It is important to note that the microphone delays are time independent and therefore will remain constant for a given microphone to a given spatial pixel throughout the monitoring period assuming the geometry of the test setup remains constant. While figure 1 and equation (1) illustrate the basic delay-sum beamformer in the time-domain, there exist many variations and modifications to this algorithm, see reference \([16]\).
For the study presented herein, we used a commercial acoustic emission sensing device equipped with microphone arrays and a motion camera (SeeSV-5205 Sound Camera, SM Instruments) [14]. Specifically, the sensing device consisted of a high resolution optical camera with a sampling rate of 25 frames per second located in the center of the device. The optical camera is surrounded by 30 high sensitivity digital micro-electric mechanical system (MEMS) microphones with a sampling frequency of 25.6 kHz arranged in five helical arrays of six microphones each as shown in figure 2(a). The figure inset shows a digital image of embedded microphones along with the optical lens. The locations of microphones shown in the inset are flipped horizontally (in x-direction) to make the microphones see the inspection plate corresponding to the coordinate configuration shown in figure 1(a).

Figure 2(b) shows the experimental setup used in this study to induce and track the transient waves in the aluminum plate. The images show the 1.2 m × 1.2 m × 1.02 mm 6061-T6 aluminum plate mounted to an optical table using a rail system to create a fixed boundary condition around the plate. The plate was secured between the angle bars and the square tube with fasteners placed every 15.24 cm that went through all components to effectively fix the boundary of the plate and suspend it above the optical table.

Once the plate was installed, the acoustic camera was mounted above the center of the plate at a height of 0.52 m as shown in figure 2(b). Impacts were introduced into the plate via manually tapping the plate using the tip of a hexagonal wrench while simultaneously capturing the acoustic signal recorded by the 30 microphones. This manual tapping is similar to the conventional pencil lead break (PLB) test [25] in a sense that all initiate stress wave propagation in an inspection medium. However, the PLB approach mimics the generation of stress waves due to the initiation of cracks or similar types of internal/external damage, while our manual tapping simulates external impact events, e.g., bird and hail impact or inspecting crew’s manual tapping. Since the PLB test generates very low-level acoustic signals it requires a highly sensitive contact-type acoustic emission sensor to record the low amplitude signals. In our study, we focus on visualizing stress waves via non-contact microphone arrays, and thus, the manual tapping is highly efficient for generating tunable, high amplitude acoustic emission signals. Based on the pressure waves initiated by the manual tapping and measured by the microphone arrays, post-processing was performed to calculate the time delays and beamforming output by using equations (1) and (2) in order to produce the acoustic images.

4. Parametric studies on pristine plates

In this study different parameters were systematically varied to investigate and assess the wave propagation tracking capabilities of the sound camera in addition to determining post-processing parameters used in subsequent analyses. These parameters included the temporal and spatial resolutions in post-processing. This section discusses the results from these parametric studies given pristine plates. For all images shown of the wave propagation tracking, the area presented in the image represents that of the entire inspection plate.

4.1. Effects of temporal resolution

The temporal resolution was investigated with the goal of achieving a smooth propagation of the transient wave front. In this study, the sound camera MEMS microphones imposed a hardware limitation on the sampling frequency restricting it to 25.6 kHz. This meant the time between individual samples was slightly greater than 39 μs. Figure 3 shows an exemplary signal captured by microphone 1 (see the location in figure 2(a)) immediately following a top left impact on the plate. Figure 3(a) shows the time history of sound pressure up to 8 ms post-impact, while figure 3(b) plots the frequency spectrum of the same signal. In the temporal signal, the maximum pressure measured is around 2.5 Pa (the saturation threshold of each microphone sensor). Note that in experiments, the manual
tapping was practiced carefully in a way that the peak amplitude of the sound pressure is kept around 2.5 Pa. In figure 3(b), we observe that a peak frequency is located at approximately 850 Hz and that very little acoustic activity occurs at high frequencies, i.e., above 6 kHz.

During investigations of wave propagation velocities, the speed of major flexural waves propagating in the 1.02 mm thick plate was approximately 1700 m s$^{-1}$ (to be further discussed below). At this wave speed and the given sampling frequency, the wave front propagated approximately 66.4 mm between each sample or 5.4% of the total plate width, resulting in a very coarse propagation tracking ability. To reduce the effective propagation distance between sequential samples and to improve the resolution of the wave propagation tracking, an interpolation of the raw acoustic signal was performed. Figure 4(a) shows a window of the raw signal with no interpolation applied (left panel), in which we observe the drastic amplitude changes of pressure measured from a microphone between subsequent samples. The beamforming results of the stress wave propagation for the raw signal without interpolation are shown in the three images to the right of the signal. The inset image at $t = 0$ ms in figure 4(a) represents the top left impact induced in the inspection plate. Note that we used the beamforming power to present the acoustic images, by summing the microphone signals of 30 microphones with the calculated delays as in equation (1). So the maximum possible value of beamforming shown in the acoustic images should be in the range of 60 $\sim$75 Pa, assuming the peak amplitude of each microphone is around 2 $\sim$2.5 Pa.

Figure 4(b) shows the same raw signal as the one above it, but with a frequency-domain fast fourier transformation interpolation applied to reconstruct the signal. An upsample factor of 10 was chosen for the interpolation in order to decrease the time between samples to $3.9 \mu$s. This meant that the propagation distance between samples was reduced to 6.6 mm and only 0.5% of the total plate width. Comparing the two sets of images presented in figure 4, we find that both approaches successfully identify the impact location with a reasonably high accuracy (to be further discussed in the later section). However, the results from the raw signal do not show clear boundaries of wave front while the second set of images associated with the interpolated data show the increased definition of the wave front. Thus, the effects of the interpolation are evident in the smoothing of the wave propagation and acoustic features.

While an improved image quality was achieved by increasing the upsample factor, a computational penalty was incurred. Based on parametric studies utilizing different upsample factors, the upsample-computational time relationship was approximately linear with an increase in computational time. Specifically, for the upsample factor of $n$, the beamforming computational time is increased by a factor of $(1.044 \pm 0.014) \times n$ times compared to the original raw signal. The reduced computational efficiency was deemed an acceptable cost for the increased image quality gained using the reconstructed signal and necessary for identifying and localizing masses. For all subsequent simulations, we used an upsample factor of 10. We also note that it is ideal that we obtain a higher sampling frequency via hardware, i.e., an improved sampling rate of the microphone. However, despite
the limitation of the sampling frequency of the microphone used in this study (25.6 kHz), our investigations of the interpolation (reconstruction of data) enables us to get clear acoustic images in a simple and cost efficient manner without further increasing the hardware specifications.

4.2. Effects of spatial resolution

Now we investigate the effect of spatial resolution in an attempt to further refine the wave front throughout the propagation time. Figure 5 shows the results of the spatial resolution study. Here the spatial resolution was systematically halved for each simulation throughout the parametric study. Figure 5(a) and subsequent beamforming images show the results for a spatial resolution ($\Delta X$) of 80 mm between pixels. While the impact point in the surface map is well localized (compare with the actual impact location as shown in the inset image), the wave front definition dissipates as it begins to propagate into the far-field as seen at times $t = 0.21$ ms and $t = 0.32$ ms.

Figures 5(b)–(c) and associated images show spatial resolutions of 40 mm and 20 mm between pixels, respectively. Both sets of images show an accurate impact localization and increased definition of the wave front as the spatial resolution increases. Figure 5(d) and corresponding wave propagation images represent the case of $\Delta X = 10$ mm between pixels. Compared to all previous results, these images show a very definitive wave front at $t = 0.21$ ms. The image at $t = 0.32$ ms for a spatial resolution of 10 mm validates that increased spatial resolution can maintain the

![Figure 5](image_url)
desired and necessary wave front definition into the far-field of the plate while post-impact saturation behind the wave front clearly emanates from the impact location.

While a 10 mm displacement between adjacent pixels may be excessive by creating ripples, it increases the chance of detecting artificially created damage (to be discussed in section 5) and accurately determining its location. However for each halving of the spatial resolution, the computational time is increased by a factor of approximately 4.25, thereby resulting in an approximately power-law relationship equal to $n^{(-2.08 \pm 0.042)}$ where $n$ is the reduction factor with respect to $\Delta X$ (e.g. 80 mm to 20 mm, $n = 1/4$). The power-law relationship is due to the spatial resolution affecting both dimensions of the inspection plate meaning that the increase in spatial resolution is squared with each iteration. While this leads to a significant increase in computational time, the increase was again considered as an acceptable trade-off for the gained wave propagation resolution. This would prove necessary for detecting and localizing artificially created damage on the plate in subsequent analyses. Following the temporal and spatial resolution studies, a temporal upsample factor of 10 and a spatial resolution of 10 mm were selected for use in all following analyses.

### 5. Feasibility studies on the applications to NDE/SHM

In this section, we assess the feasibility of using the beamforming-based sound camera technique for (i) identifying impact location for real-time SHM applications and (ii) detecting artificial damage location for real-time NDE applications.

#### 5.1. Identification of impact location

Once simulation parameters were determined, tests were performed to characterize detection and localization capabilities of the sound camera. Prior to masses being placed on the plate, it was necessary to determine if different impact locations could be identified since a single impact location in the top left corner of the plate had been used for all previous parametric studies. Additionally, these tests would serve as the first quantitative indication of the detection and localization capabilities.

Figures 6(a)–(d) show the beamforming images at the moment of impact for impacts located in the four corners of the plate. With the center of the inspection plate above which
the camera is suspended defined as the origin of the plate, the actual measured impact locations are given in table 1. For each of the impact locations shown, the images suggest that the impact location is properly identified and localized using the sound camera and beamforming algorithm. The images shown were used to identify the point of maximum amplitude at the instant of impact which was defined as the impact location. These identified locations are given as the identified locations in table 1.

We quantify the normalized error between the actual and identified impact locations as below

\[
\text{Normalized Error} = \frac{\sqrt{(X_{\text{actual}} - X_{\text{identified}})^2 + (Y_{\text{actual}} - Y_{\text{identified}})^2}}{\Delta X},
\]

where \(\Delta X\) represents the pixel size. Looking at actual and identified positions in table 1 (i.e., \((X_{\text{actual}}, Y_{\text{actual}})\) and \((X_{\text{identified}}, Y_{\text{identified}})\)), it is observed that all impacts were located relatively accurately with regards to identified positions being in the general vicinity of the actual known position of the impact. Using equation (3), the normalized error in terms of number of pixels between the actual and identified impact locations with respect to the spatial discretization was calculated. The calculated errors are given in table 1. Given the \(\Delta X\) of 10 mm used for this study, the normalized error between the actual and identified impact locations represent differences ranging from 1.45 to 5.15 pixels as shown in table 1. The largest error was calculated for the top right impact location and found to be 5.15 pixels or approximately 4.22% of the plate width. This means that, with respect to the total spatial domain in this case, the localization was still relatively accurate. The larger errors could be attributed to not a fine enough spatial resolution which leads to a larger error between the actual and identified locations. Additionally, the larger error values could be due to human error when initiating the impacts on the plate. Despite some seemingly large error values between actual and identified impact locations this study indicates the sound camera and beamforming algorithm were able to fairly accurately localize different impact locations and track the resultant transient wave across the plate.

### 5.2. Identification of pre-existing artificial damage

Once it was established that the sound camera could detect and sufficiently track the transient wave, the impact location was fixed and masses were added to the plate. This is to determine the capability of the sound camera and beamforming algorithm to detect the discontinuities which represented pseudo-damage cases. Note that if we successfully visualize stress wave scattering at these damage sites, this means that our technique can be used for NDE purposes. That is, assuming damage is present in a plate-like structure, an inspection crew can conduct tapping tests on the plate, and by visualizing the attenuation or reflection of stress waves at this damage site, he/she will be able to detect the damage in an efficient manner. For the feasibility study, we applied impacts in the top left corner of the plate as shown in figures 7(a)–(b). The mass used for this study was a 0.615 kg, 0.0635 m \(\times\) 0.0635 m \(\times\) 0.0196 m stainless steel block. The mass was affixed to the inspection plate using silicon sealant tape that was applied to the entire contact surface of the mass. The use of masses to simulate damage has been used on many occasions to assess the capabilities of different SHM/NDE techniques [23, 24]. Figure 7(b) shows the mass was placed

![Figure 7](image-url)
halfway between the impact location and the center of the plate meaning the mass was approximately 0.215 m from the impact location. Figure 7 shows the wave propagation results for the inspection plate without and with mass present.

Figure 7 uses a red cross and a red square to mark the approximate location of the impact and mass, respectively, on the plate. At \( t = 0 \) ms, the instant of impact is shown for both the without- and with-mass cases. Both images feature similar acoustic characteristics and neither image shows an indication of a mass present on the plate. The images at \( t = 0.25 \) ms show the wave front just after it has propagated past the location of the mass. The first difference is seen in the wave front definition. While the no-mass case maintains a smooth and symmetric wave front, the mass case displays a more turbulent wave front with a significant reduction of the wave front amplitude on the far side of the mass relative to the impact point. Additionally, the widespread saturation behind the wave front seen in the no-mass case is not seen in the with-mass case. In the with-mass case, the area behind the wave front maintains a higher acoustic level compared to the no-mass case contributing to the less defined wave front. Finally, there is much more acoustic noise in the farfield of the plate for the with-mass case compared to the no-mass case where the farfield acoustic level is approximately equal to the amplitude behind the wave front at \( t = 0.25 \) ms.

At \( t = 0.34 \) ms, the most noticeable difference between the no-mass and with-mass cases is the high amplitude acoustic event present at the location of the mass in the latter case. For the no-mass case, the wave front is losing amplitude and definition as it propagates and dissipates into the farfield and the area behind the wave front is becoming saturated with low amplitude acoustic levels. However, the backside of the wave front remains very symmetric with respect to the impact location and there is very little excessive acoustic features seen on the plate. In the with-mass case, the overall wave front condition appears very similar to that for the no-mass case. In terms of dissipation and primary acoustic features, the wave fronts for the two cases display very similar amplitudes and structures at \( t = 0.34 \) ms. However, despite the similarities the with-mass case wave front retains a much less refined wave front at this instance with much more acoustic noise seen in the farfield of the plate. As aforementioned, the most observable and desirable difference is the presence of the acoustic event emanating from the mass location denoted by the red arrow in figure 7 which alludes to the presence of a discontinuity at this location on the inspection plate.

Similar to the impact localization, the maximum amplitude of the acoustic feature near the known location of the mass was used as the identifying location of the mass. This was then compared to the actual location of the center of the mass given in table 2 and using equation (3) the normalized error was calculated between the actual and identified position with respect to the spatial discretization. The calculated error of only 5 spatial pixels represents a fairly high degree of accuracy when identifying the known position of the mass. Given that the mass is 63.5 mm \( \times \) 63.5 mm, the mass itself is 6.35 pixels \( \times \) 6.35 pixels. While the exact coordinates of the actual and identified positions do not necessarily correlate, it is likely affected by the acoustic feedback from the mass not emanating from the center of the block. Therefore, if the maximum amplitude were located at one of the points of the mass as it seems to be in figure 7 (corner nearest top edge of plate), this alone would considerably affect the error value. Given the normalized dimensions of the mass, the identified position of the acoustic emission denoting the location of the mass is likely within the bounds of the mass despite the relatively large normalized error.

### 6. Conclusions

This study demonstrated the visualization of stress wave propagation across an aluminum plate using an air-couple microphone array. The scope of the beamforming method for visualizing stress waves was investigated through various parametric studies that resulted in the establishment of post-processing parameters of upsample factor and spatial resolution for further testing. Subsequent testing revealed the ability of the sound camera to accurately identify various impact locations on the inspection plate. Finally, the beamforming method was used to detect and localize a mass on the inspection plate used to simulate the presence of damage. The sound camera and derived beamforming method were able to locate the position of the mass through the detection of acoustic emission structures indicating the existence of a discontinuity on the inspection plate. This study showed the potential for an acoustic emission beamforming based method to be used for damage detection in SHM/NDE applications. While this study focused on the feasibility of the proposed technique, further studies need to be conducted to assess its sensitivity, to find more sophisticated beamforming techniques, and to optimize their post-processing parameters. Corresponding experiments should be conducted in order to compare results to other experimental techniques, such as laser Doppler vibrometry and digital image correlation techniques. Lastly, the authors plan to perform computational studies of air-coupled acoustic emission events using finite element method and probability of detection analysis.
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