Active Sensing Using LDV and T-Shaped Arrays in Metallic Plates for Damage Localization

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ABSTRACT

In this work, T-shaped arrays of sensors generated by a single laser Doppler vibrometer (LDV) are used for damage localization in a metallic plate. Previous studies have used a single T-shaped array of piezoelectric patches to estimate the direction of arrival of waves in plate-like structures. Here, by comparing the measurements of two and four T-shaped arrays with baseline information, this technique could be extended for damage localization, resulting in an active sensing application. Instead of piezoelectric transducers, a LDV is used to create the T-shaped arrays, which enables the testing of arrays with different numbers of measuring points and different positions. The difference between test and baseline measurements is used, as it contains information on waves from a known acoustic source that scatter and reflect at a damage site. Beamforming is then applied to these residual signals, and the resulting beamforming maps are transformed into a map of positions in the inspected area. The measurements of each array results in one position map, and combining all maps results in an estimated location of the damage. This is demonstrated in a square metallic plate with a single source of vibration located at its center, while the arrays are located at the boundaries of the inspection area. The tests show that even for low density arrays, increasing the number of arrays enables damage detection with reasonably good results, even when employing simple delay-and-sum beamforming instead of more advanced and complicated processors. This work also serves as a proof of concept that a set of T-shaped arrays can be reliably used for active sensing of damage in plane plates.

INTRODUCTION

In Structural Health Monitoring, phased arrays have found extensive use for damage detection and localization in plate-like structures. It is very common to use piezoelectric transducers as sensors in these arrays, but since the same transducers can also be used as actuators, this allowed the development of not only passive but also active sensing techniques [1]. Some works have also employed non-contact sensors for creating these

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arrays, but to achieve good results with either contact or non-contact sensors, usually a linear or rectangular grid with many sensors is used [2]. However, it was recently shown that for estimation of direction of arrival of waves, a T-shaped array would require less sensors than a linear array to achieve similar results [3], and this works demonstrates that they can also be used for reliably detecting damage.

In this work we present a technique for active sensing in plate-like structures using a laser Doppler vibrometer (LDV) as sensing device, and a piezoelectric transducer as the source of acoustic waves. It uses more than one T-shaped array created by the LDV at the boundaries of the inspection area, and the waves are generated by the transducer placed at the center of this area. The measurements are compared to baseline data, and a simple delay-and-sum beamforming is applied to the residual signals, which requires an estimate of the speed of propagation of the waves. The results of beamforming on each array are transformed into position maps that cover the area of inspection, which can then be combined, and a probable location of damage can be visualized. The next section describes this technique in greater detail, and results of applying it to a specimen are shown in the "Results and Dicussions" section. Final remarks of this work are then given in the last section.

METHOD

The method described here does not require extensive setup, as shown in Figure 1, which depicts a plate-like structure with a source of acoustic waves located inside the region of interest. T-shaped arrays, whose geometry is also shown in Figure 1, are positioned at the boundary of the inspection area. These arrays are created using a laser Doppler vibrometer (LDV) with a mirror galvanometer. For each point of each array, the structure is excited with a tone burst signal, and the LDV measures the response of the structure. The laser point is then moved to a new location by the galvanometer, and the procedure is repeated until all points of all arrays are measured. The responses are continuously stored for further processing.

The method used to detect damage in the structure relies on baseline measurements, which are measurements made in the same structure in a healthy state. The process for measuring a baseline or running an actual test is the same as described above, but the responses recorded by the arrays are clearly different. The baselines will include information on waves that travel a direct path from the source to the arrays and reflections on the boundaries of the structure. However, when the structure is damaged, the measurements will also include responses from waves that scatter and reflect on the damage, as show in Figure 1. By extracting the difference between the test response from the baseline response, the direct path of travel and normal reflection at the boundaries are eliminated, and the residue left will contain information only on the interaction of the waves with the damage. These residue signals are then processed using delay-and-sum beamforming to find the time and direction of arrival of the incident waves from the damage. For more information on the concept and implementation of delay-and-sum beamforming, readers can refer to Reference [4].

After beamforming, a map of the intensity of the signal arriving at a given array as a function of time of arrival t and angle of arrival θ is obtained. From these maps,

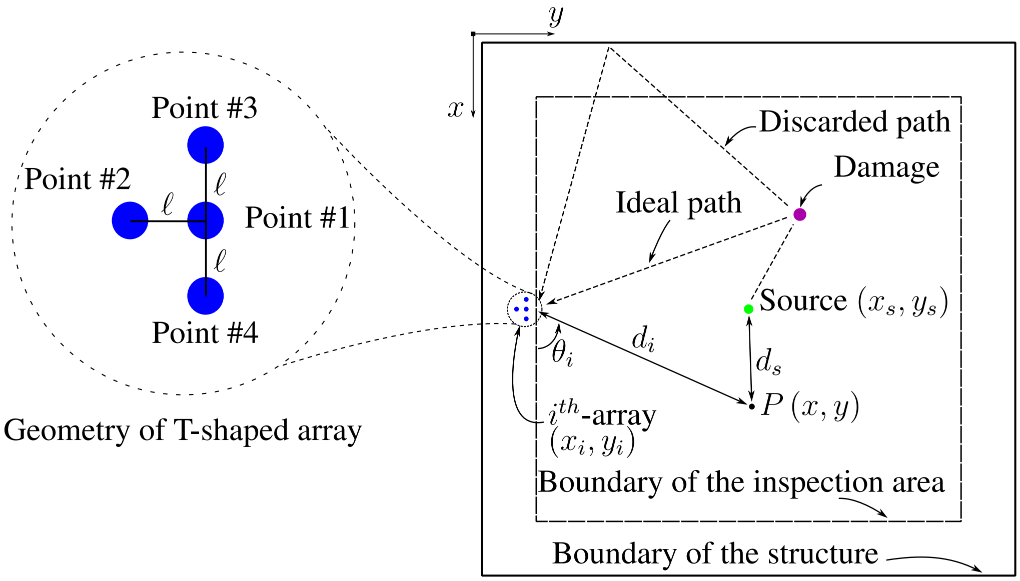

Figure 1. Illustration of the experiment setup showing the inspection area, the source of vibration, the damage, a T-shaped array and its geometry, and possible path of propagation for waves that interact with the damage.

the waves arriving below a certain time threshold could be identified. Waves that go from the source, interact with the damage, and go to the arrays travel a path shorter than waves that also interact with the boundaries of the plate before reaching the arrays. Each array used in the test will produce one beamforming map, and these maps can be converted into position maps. Referring to Figure 1, for every point P at (x, y) inside the inspection area, its distance to the source is $d_s = \sqrt{(x - x_s)^2 + (y - y_s)^2}$, where (x_s, y_s) is the position of the source, and the distance from P to the i^{th}-array at (x_i, y_i) is $d_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$. Therefore, for a wave propagating at a speed c, the time of arrival at the i^{th}-array following the ideal path is

$$t_i = \frac{d_s + d_i}{c},$$

and the angle of arrival is

$$\theta_i = \arctan\left(\frac{y - y_i}{x - x_i}\right).$$

Each position (x, y) can then be mapped to a single (t, θ) pair in a given beamforming map, and with N arrays there will be N position maps. These position maps can be combined to form one single for the inspected area by simple multiplication [5]. The following section showcase the use of this technique in a thin metallic plate.

RESULTS AND DISCUSSION

The setup used to demonstrate the proposed technique using T-shaped arrays is shown in Figure 2:

- a thin aluminum plate of size 1.20 m $\times$ 1.20 m $\times$ 1.00 mm,

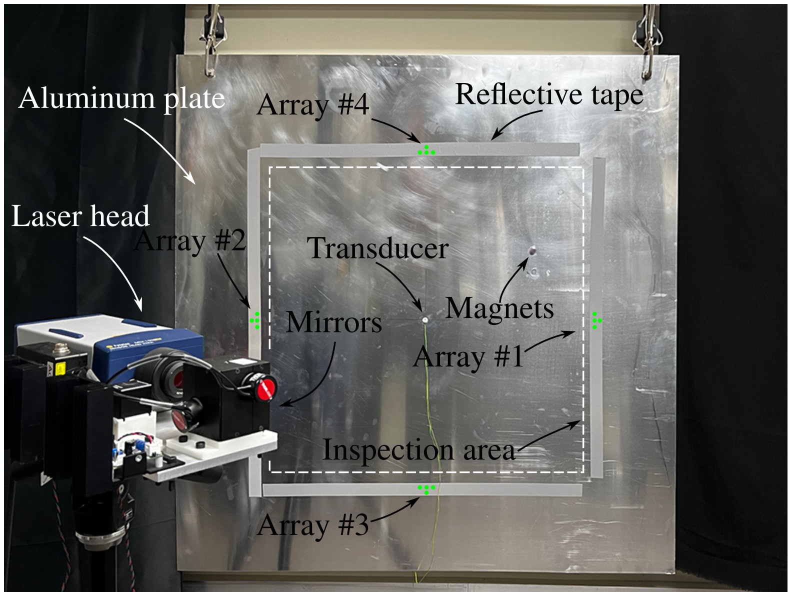

Figure 2. Test bench used in this study. The arrays shown in this photograph are the approximate locations of the arrays created by the laser point.

- a Polytec OFV-5000 Xtra laser vibrometer with a Polytec MLV-100 Xtra laser head to measure the out-of-plane velocity response of the plate,
- a Thor Labs GVS112 pair of controllable mirros to move the laser point,
- a APC D-.500”-.020”-850-WFB circular piezoelectric transducer at the center of the plate as source of waves,
- small, round magnets with diameter of 1.5 cm, weighting 20 g in total to emulate damages in the plate.

To reduce noise in the measurements, reflective tape was used. A National Instruments USB-6363 device for measuring and generating signals, a power amplifier to drive the transducer, and a computer were also used but are not shown in the photograph.

The plate was excited with a Hanning-windowed tone burst with center frequency of 50 kHz, and consisting of 5.5 cycles. At this frequency and for this plate, the S_0 propagation mode of the Lamb waves was found to be of negligible amplitude, while the group velocity of the A_0 mode was estimated at 1300 m/s. The LDV was used to measure the out-of-plane response of the plate at each location for 0.5 s, and these recordings were later trimmed down to 2 ms. The experiments were carried out using 4-point T-shaped arrays, and to prevent issues with spatial aliasing during the beamforming process, the separation ℓ shown in Figure 1 was of 2 cm, which is less than half of the predicted wavelength of the tone burst. Two and four arrays were used in the following tests, and they were placed at the boundary of the inspection area of 70 cm $\times$ 70 cm with the transducer positioned at its center. The arrays were oriented to “look inside” the inspection area, with their linear parts parallel to the side of the area, and Point #2 pointing outwards, similar to the arrays shown in Figures 1 and 2.

We now present some results of our tests. Figure 3 shows the results for Array #1 in Figure 2 up to the beamforming step: in Figure 3a, the tone burst and signals for one of the baselines; in Figure 3b, the residual signals, which is the difference between the signals of a damaged state and the baseline; and in Figure 3c, the resulting map after applying the beamforming processor on the residual signals. Figure 4 shows the individual position maps for each of the four arrays, and the result of combining two maps and four maps can be seen in Figure 5. This last figure shows that combining only two maps may not be enough to give accurate results, but the combination of all four maps resolved left over ambiguities.

It is also possible to detect multiple damages at different locations using the proposed technique, as can be seen in Figure 6. However, our tests had some limitations. In Figure 6a, we found the approximate locations of two damage sites, but adding more

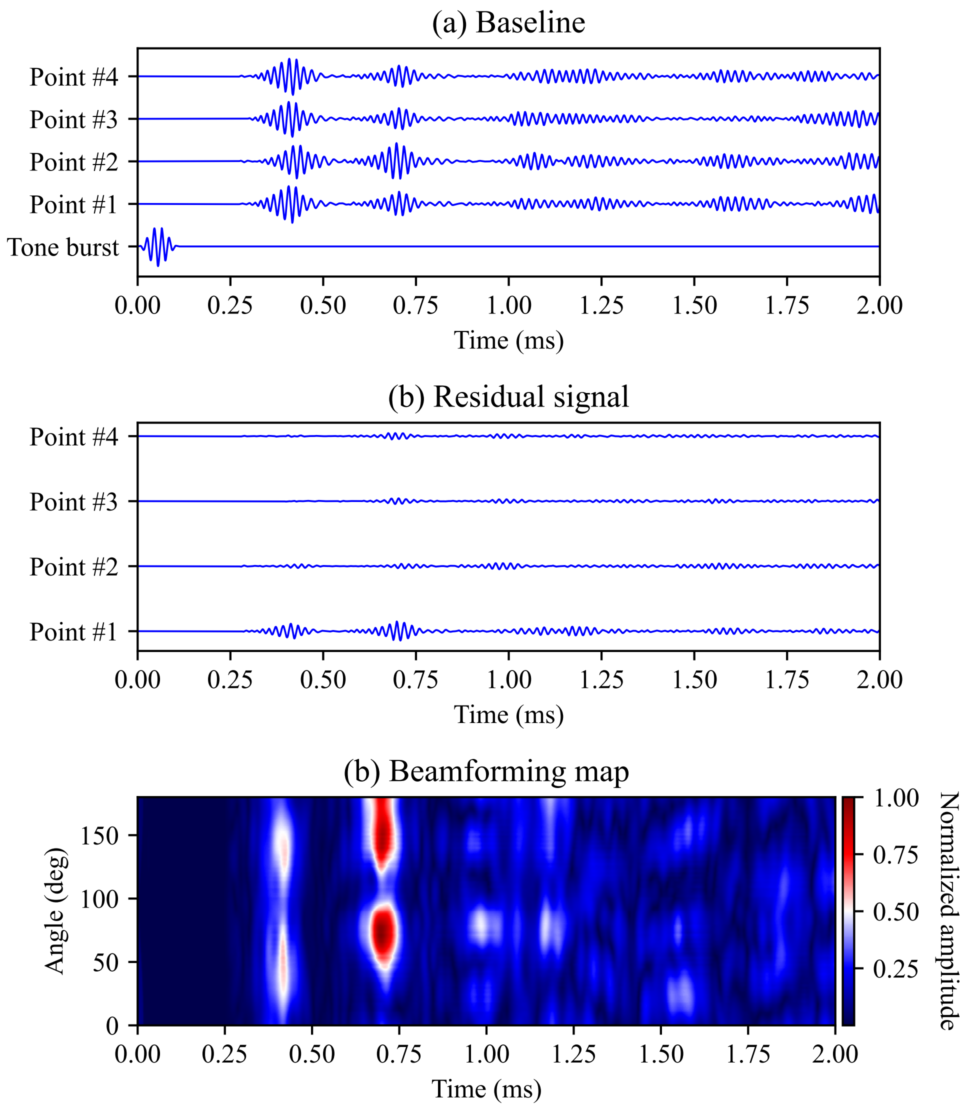

Figure 3. Results of processing the signals from Array #1 in Figure 2. The amplitude of the signals in (a) and (b) have the same scale, except for the tone burst.

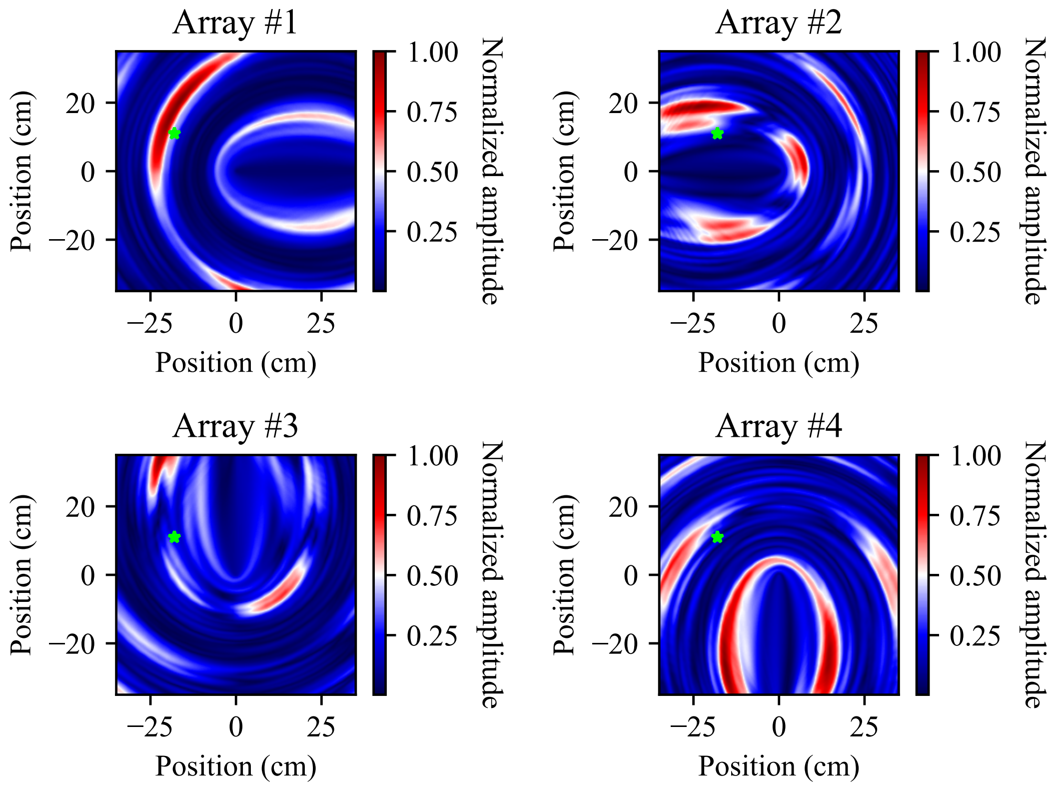

Figure 4. Position maps resulting for each of the four arrays in Figure 2. The green stars indicates the actual position of the damage.

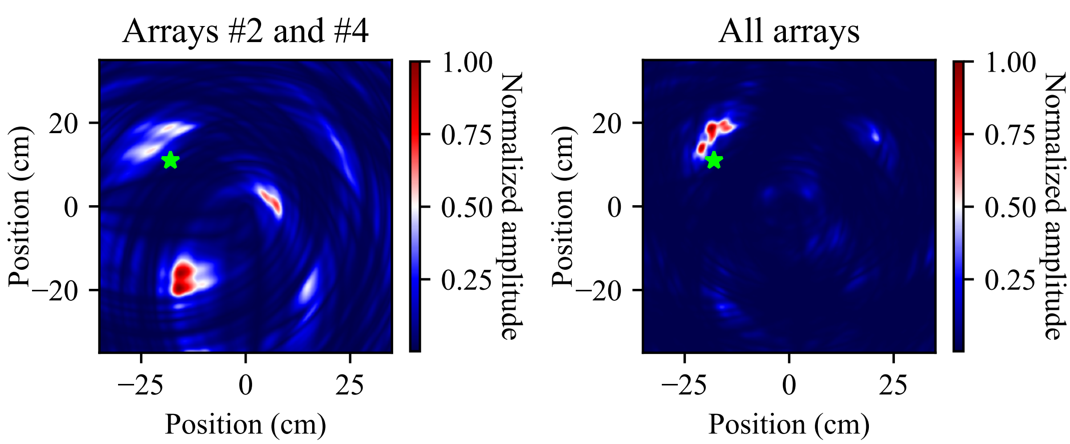

Figure 5. Results of combining only two and all four position maps. The green stars indicate the actual position of the damage.

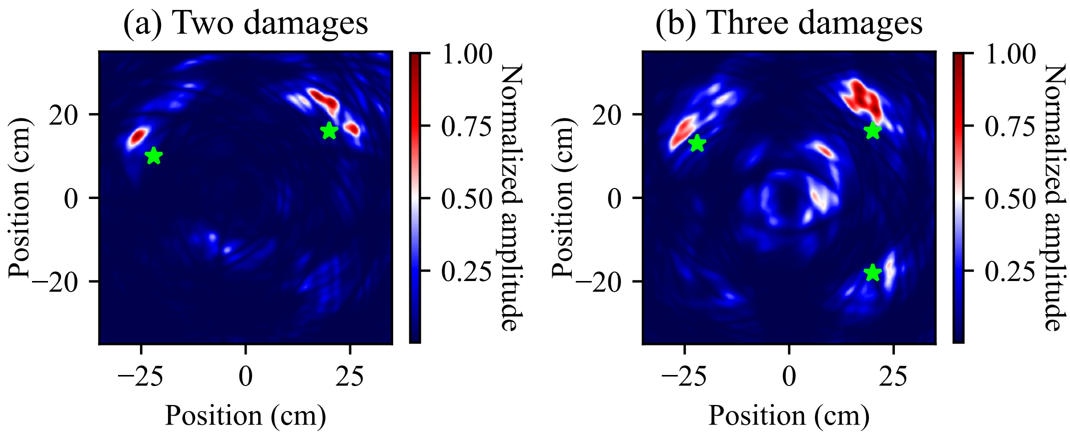

Figure 6. Results when multiple damages are present in the plate. The green stars indicate the actual positions of the damages.

damages, as depicted in Figure 6b, can create ambiguities. Localizing damages relies on identifying distinct and individual peaks on the combined position map, which result from combining high amplitude peaks from the beamforming maps. However, the magnets we used in our tests may not be sufficiently realistic, resulting in lower peak amplitudes when compared to actual damages, for example. Additionally, as the number of damages increases, there is more interaction between scattered waves instead of being reflected only by the boundaries, thus creating greater differences between baseline and test measurements. One possible way to circumvent this is applying an amplitude threshold to the position maps, but it may not always work because it can cause actual damage positions to disappear form the maps while trying eliminating ambiguities.

The technique in this study provided approximate locations of damages, rather than precise pinpoints. Our tests showed that these locations drifted a few centimeters from the actual position of the damages, which is a reasonably good result considering the number of sensors and actuators. There might be several reasons for this difference: the low density of sensors in the arrays (each with only four points, a total of 16 points for the entire plate), and the highly dispersive behavior of A_0 waves in this plate at 50 kHz. Increasing the number of points in the arrays will surely improve the accuracy, as confirmed by other studies [2, 4, 6]. In addition, the issues arising from the dispersive behavior of the waves could be addressed with techniques such as the one presented in Reference [7].

FINAL REMARKS

This work presented a simple approach of active sensing of plate structures using a laser Doppler vibrometer to create T-shaped phased arrays around an inspection area containing a piezoelectric transducer that served as source of acoustic waves. The approach used residual signals, which are the difference between test and baseline data, for delay-and-sum beamforming. The resulting time-of-arrival and angle-of-arrival maps were transformed into position maps covering the inspection area, which were then combined to locate damage sites. This approach showed reasonable accuracy to detect simulated damages in a thin metallic plate, and also confirmed that by increasing the number of arrays, low-density T-shaped arrays can be used for reliable damage location.

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