Impact localization in complex structures using laser-based time reversal
Byeongjin Park, Hoon Sohn, Steven E Olson, Martin P DeSimio, Kevin S Brown and Mark M Derriso
Structural Health Monitoring 2012 11: 577 originally published online 1 July 2012
DOI: 10.1177/1475921712449508

The online version of this article can be found at:
http://shm.sagepub.com/content/11/5/577
Impact localization in complex structures using laser-based time reversal

Byeongjin Park, Hoon Sohn, Steven E Olson, Martin P DeSimio, Kevin S Brown and Mark M Derriso

Abstract
This study presents a new impact localization technique that can pinpoint the location of an impact event within a complex structure using a time-reversal concept, surface-mounted piezoelectric transducers, and a scanning laser Doppler vibrometer. First, an impulse response function between an impact location and a piezoelectric transducer is approximated by exciting the piezoelectric transducer instead and measuring the response at the impact location using scanning laser Doppler vibrometer. Then, training impulse response functions are assembled by repeating this process for various potential impact locations and piezoelectric transducers. Once an actual impact event occurs, the impact response is recorded by the piezoelectric transducers and compared with the training impulse response functions. The correlations between the impact response and the impulse response functions in the training data are computed using a unique concept of time reversal. Finally, the training impulse response function, which gives the maximum correlation, is chosen from the training data set and the impact location is identified. The proposed impact localization technique has the following advantages over the existing techniques: (a) it can be applied to isotropic/anisotropic plate structures with additional complex features such as stringers, stiffeners, spars, and rivet connections; (b) only simple correlation calculation based on time reversal is required, making it attractive for real-time automated monitoring; and (c) training is conducted using noncontact scanning laser Doppler vibrometer and the existing piezoelectric transducers that may already be installed for other structural health-monitoring applications. Impact events on an actual composite aircraft wing and an actual aluminum fuselage are successfully identified using the proposed technique.

Keywords
impact localization, time reversal, laser Doppler vibrometer, laser ultrasonics, complex structures

Introduction
Composite materials are widely used for aircraft applications, thanks to their high strength with low weight. However, composite parts of an aircraft are vulnerable to delamination, which can pose serious problems compromising aircraft safety and integrity. To avoid such problems, tremendous time and efforts are spent performing ground inspections such as vibration testing, static testing, and fatigue testing. Since delamination is often caused by foreign object impacts, information regarding impact events and their locations can be useful for effective inspection of delamination. There has been a large volume of literature on impact localization based on acoustic and ultrasonic wave propagations generated by an impact event and sensed by surface-mounted transducers such as lead zirconate titanate (PZT) transducers.1–10

Among various impact localization techniques, a time-of-arrival triangulation technique, known as Tobias algorithm,1 has been most widely accepted. It predicts the impact location as the intersection of three circles, centered around each transducer location with radii calculated by the time-of-arrival at each transducer. The applicability of this algorithm is limited to simple isotropic plates because the wave velocity is...
assumed to be known and constant for all directions. Although several studies have attempted to extend this technique to anisotropic or inhomogeneous materials by using elliptic group velocity patterns, they still require a priori knowledge of angular group velocity patterns and their applicability to complex geometries is still limited.\textsuperscript{2-4}

Several research groups have focused on impact localization in anisotropic and complex structures. The Delta-T method\textsuperscript{5,6} estimates the impact location by comparing differences in the time of flight for each sensor pair between a training data set and an actual impact event. Hiche et al.\textsuperscript{7} identified impact location based on the relative placement of sensors and maximum strain amplitude measured by each sensor. Also, a technique using piezoelectric rosettes was suggested.\textsuperscript{8,9}

This technique identifies the impact location by measuring the directional information of the impact-induced waves using piezoelectric rosette transducers rather than investigating their arrival times. This method can identify impact locations in complex structures without a priori knowledge, but requires the use of specialized rosette transducers.

Recently, a new impact localization algorithm based on time reversal was proposed.\textsuperscript{10,11} This method works in the following steps: (1) collects a training data set by mechanically impacting multiple points within a target structure and measures the corresponding impulse response functions (IRFs) at a surface-mounted sensor; (2) records an actual impact event at the sensor in a similar manner; and (3) identifies the IRF in the training data set, which gives the maximum correlation with the IRF generated by the actual impact event, and determines the corresponding mechanical impact point. This technique is shown to be very powerful particularly because it does not require the knowledge of the wave velocity or the structural geometry. One problem is that repeated training, which can take a long time to cover a large area, needs to be conducted by manual impacts or by employing robotic devices and the training.

In this article, the training has been automated and expedited using a scanning laser Doppler vibrometer (SLDV), which can measure out-of-plane velocity based on the Doppler effect.\textsuperscript{12,13} The IRF previously obtained by mechanical impacts and PZT transducer sensing is now replaced and approximated by the IRF excited by the surface-mounted PZT transducer and sensed by SLDV based on the reciprocity between these IRFs. The proposed impact localization technique has the following advantages over the existing techniques: (a) it can be applied to complex structures with additional structural features such as ribs, stringers, stiffeners, spars, and rivet connections; (b) only simple correlation calculations are required for impact localization, making it attractive for real-time automated monitoring; and (c) a high spatial resolution of impact localization is achieved using SLDV for sensing. Actual impacts in a composite aircraft wing and an aluminum fuselage were successfully localized in spite of the anisotropic and complex nature of test articles.

**Laser-based impact localization technique**

In Figure 1, an overview of the proposed impact localization technique is provided. Step 1: A pulse input is generated by a surface-mounted PZT transducer, and the corresponding IRF is measured by SLDV at a single point within the target scan area. Here, the duration of the pulse input is adjusted to approximate that of the expected actual impact event. Step 2: The same pulse excitation is repeated by the PZT transducer, and additional IRFs are obtained and stored by scanning the SLDV over the entire target scan area. Steps 3 and 4: Once an actual impact event occurs, the impact response is recorded by the PZT transducer. Steps 5 and 6: Based on the time-reversal concept,\textsuperscript{11} the correlations between the actual impact response and the IRFs in the training data are computed and visualized. Then, the training point, whose IRF has the maximum correlation with the actual impact response, is identified as the most likely impact location.

As previously mentioned, the impact location is identified by finding the IRF in the training data set, which has the maximum correlation with the IRF generated by the actual impact event. Let $f(t)$ and $g(t)$ represent actual and training IRFs, respectively. Then, the correlation between two IRFs is defined as follows

$$\langle f \star g \rangle(\tau) = \int_{-\infty}^{\infty} f(t)g(\tau+t)dt \quad (1)$$

where $\star$ denotes the correlation operation. On the other hand, the convolution of two functions is defined as

$$\langle f \odot g \rangle(\tau) = \int_{-\infty}^{\infty} f(t)g(\tau-t)dt \quad (2)$$

where $\odot$ is the convolution operation. Comparison of equations (1) and (2) reveals that the correlation and convolution are related to each other as follows $\textsuperscript{14}$

$$f \star g = f(-t) \odot g \quad (3)$$

Equation (3) shows that the correlation between two IRFs is mathematically equivalent to the convolution between one IRF and the time-reversed version of the other IRF.
This equivalent mathematical representation of the correlation using the convolution provides an interesting insight. Suppose a pulse input, \( x(t) \), is applied to point A and the corresponding response, \( y(t) \), is measured at B. Then, \( y(t) \) can be represented using \( x(t) \) and the IRF between points A and B, \( f(t) \), as

\[
y(t) = f(t) \otimes x(t) \tag{4}
\]

If the response at point B is time-reversed and applied back to point B, then the response at an arbitrary point C, \( z(t) \), becomes

\[
z(t) = g(t) \otimes y(-t) = g(t) \otimes f(-t) \otimes x(t) \tag{5}
\]

where \( g(t) \) is the IRF between points B and C. As stated by the time-reversal theory,\(^{11}\) focusing of this time-reversed and reemitted signal is maximized when point C is equal to point A, that is, when \( f(t) \) and \( g(t) \) are identical. In other words, the maximum correlation is obtained when impact excitation point A is equal to the training point C. Thus, the impact location can be identified utilizing this technique.

In the previous studies, a training IRF is obtained by manually or mechanically introducing an impact\(^ {15} \) and measuring the corresponding response at a fixed PZT transducer. In this study, the IRF is replaced and approximated by exciting the PZT transducer and measuring the response using the SLDV at the previous impact point. Based on the linear reciprocity theorem, a response at point A caused by excitation at point B should be identical to a reciprocal response at point B caused by excitation at point A. However, this linear

---

**Figure 1.** Overall scheme of the proposed laser-based impact localization technique: In Steps (1) and (2), IRFs for training are obtained by exciting the surface-mounted PZT transducer and measuring responses using SLDV, covering the entire target area. In Steps (3) and (4), the impact response is recorded when an actual impact event occurs. In Steps (5) and (6), the correlations between training IRFs and the actual impact event are computed, and the training point with the maximum correlation value is identified as the most likely impact location.

PZT: lead zirconate titanate; IRF: impulse response function; SLDV: scanning laser Doppler vibrometer.
reciprocity is not completely satisfied in this study because different excitations and sensing mechanisms are used when this reciprocal pair of signals is obtained. Nevertheless, it will be demonstrated that the proposed technique can still successfully locate impact events.

Because the computation of convolution is typically very time consuming, its computation is often performed in the frequency domain based on the convolution theorem. By applying the Fourier transform, the convolution in the time domain is transformed into a simple multiplication in the frequency domain

\[
\mathcal{F}\{f \otimes g\} = \mathcal{F}\{f\} \cdot \mathcal{F}\{g\}
\]

where \(\mathcal{F}\) denotes the Fourier transform operator. The convolution is reconstructed by taking the inverse Fourier transform of equation (6)

\[
f \otimes g = \mathcal{F}^{-1}\{\mathcal{F}\{f\} \cdot \mathcal{F}\{g\}\}
\]

Since this new formula involves only Fourier and inverse Fourier transforms and point-wise multiplications, the correlation or convolution can be computed effectively

\[
f \star g = f(-t) \otimes g = \mathcal{F}^{-1}\{\mathcal{F}\{f(-t)\} \cdot \mathcal{F}\{g\}\}
\]

Using equation (8), the maximum correlation value, designated here as MAX(CC), is obtained from the given training IRF and the impact IRF. Then, it is normalized with respect to the highest value of MAX(CC) among all scanning points. A correlation map over the entire scanned area is created using MAX(CC), the normalized value of MAX(CC). The point with the highest MAX(CC) is identified as the most likely impact location.

So far the concept of the proposed technique is described assuming a single PZT transducer. In reality, multiple transducers can be installed on the target structure. In such a case, the aforementioned steps are repeated for each transducer, and the correlation maps from all transducers are combined together to generate a single correlation map. The employment of multiple transducers can enhance the localization performance, although it is not a necessary requirement of the proposed technique.

\section*{Impact localization in a composite aircraft wing}

\subsection*{Description of the composite aircraft wing specimen}

The applicability of the proposed impact localization technique to an anisotropic composite structure has been demonstrated using a composite wing segment from an actual aircraft as shown in Figure 2. The test article is approximately 1730 mm in length and the width varies from 450 to 770 mm. Six square PZT transducers (Piezo Systems PSI-5A4E, 10 mm × 10 mm × 0.267 mm) are installed on the outer surface of the wing skin around the perimeter of the scanning area. The proposed impact localization technique has been tested over the testing region (400 mm × 385 mm) shown as a rectangular box in Figure 2. The test article is composed of a composite wing skin, three vertical ribs fixed by rivets, and a horizontal spar inside the article. The test article has been provided by the Agency for Defense Development (ADD) in Korea, and additional details such as material properties are unknown to the authors due to the proprietary nature of the airplane structure presented here.

\subsection*{Experimental setup}

The hardware systems used in this study are shown in Figure 3. For impact testing, an instrumented impact hammer (PCB Piezotronics 086C03, 2.2 mV/N sensitivity) is utilized and in-plane strains from six PZT transducers are simultaneously collected using a multichannel National Instrument (NI) PXI-5105 digitizer. For training, each PZT transducer is individually excited, and out-of-plane velocities over the target area are scanned using a Polytech PSV-400 SLDV. A pulse excitation is generated using a Rigol DG2042A waveform generator, and a Brüel & Kjær 2712 power amplifier was used to amplify the peak input to 22.5 V. A grid array of 3M Scotchlite retroreflective tapes (26 × 27 grid points) has been placed over the scanning region, achieving a spatial resolution of 16 mm and improving the quality of the responses measured by the SLDV.

\subsection*{Measurement of training and test data}

Actual impacts have been applied to 25 random points to verify the effectiveness of the proposed technique.
Corresponding responses are simultaneously collected by six PZT transducers for 32 ms at a 512 kHz sampling frequency.

For the training process, a pulse excitation with a duration of 1 ms is applied to each PZT transducer. The duration of the PZT excitation signal is designed to approximate that of the impact hammer excitation such that the training data can be a good representative of actual impact events (Figure 4). The duration of an actual impact varied between 1 and 2 ms, and double hammer impacts are occasionally observed.

For each scanning point, 16,384 samples are collected over 32 ms by the SLDV at a sampling rate of 512 kHz, and 40 time signals are averaged to improve the signal-to-noise ratio. Approximately, 50 ms intervals are provided between two consecutive pulse excitations to allow signals to decay close to a background noise level before a new data collection. Measurement of all time signals from 702 scanning points takes approximately 40 min.

The PZT transducer response due to the hammer excitation and the SLDV response at the hammer excitation point due to the PZT excitation are compared in Figure 5. As the consequence of the input signal difference between the hammer and PZT excitations shown in Figure 4, the corresponding PZT and SLDV responses are quite different. The SLDV response has more high frequency components than the PZT response does. This difference can be partly attributed to the fact that the PZT transducer measures in-plane strain, while the SLDV traces out-of-plane velocity. In addition, the hammer mainly exerts vertical force to the structure in contrast to the PZT transducer, which applies in-plane forces. To reduce noise outside the signal bandwidth of interest, a band-pass filter with lower and upper cutoff frequencies of 1000 and 2000 Hz is used.

**Experimental results**

In Figure 6, impact localization results corresponding to 25 different impact events are summarized. The image corresponds to the scanning region shown in Figure 2. The black dots denote the actual impact locations, while the crosses indicate the impact locations estimated by the proposed technique. The values listed near each impact location represent discrepancies between the actual and estimated location in millimeter.

Since six PZT transducers are used in this test, localization results obtained from each PZT transducer are combined to produce a single impact location estimation. The calculated correlation values from each PZT transducer are normalized with respect to the maximum correlation value among all correlation maps before they are combined into a single map.

In general, the actual impact location is well identified. Only 3 out of the 25 cases tested yield an error larger than a single grid size (16 mm). For 11 cases, the

![Figure 3](image3.png)

**Figure 3.** Description of the hardware systems used in this study. For impact testing, an impact is introduced by (a) an impact hammer and (b) the corresponding responses are measured by the installed PZT transducers using the NI digitizer. For training, the PZT transducers are excited by the (c) waveform generator and the responses are measured by (d) SLDV.


![Figure 4](image4.png)

**Figure 4.** Comparison between the (a) hammer excitation and (b) PZT excitation signals. The pulse duration of the hammer impact varied approximately between 1 and 2 ms each time and the duration of the PZT pulse excitation was fixed to 1 ms. PZT: lead zirconate titanate.
actual impact locations are estimated within 5 mm accuracy. The average estimation error is 8.36 mm. Considering that the reciprocals of SLDV and PZT responses shown in Figure 5 are quite different, the presented localization results are quite impressive.

Figure 7 investigates the effect of the number of PZT transducers used on the impact localization performance. In a correlation map, scanning points with a high probability of being an actual impact location are marked in red (dark). The black circle and the white dot represent the actual and estimated impact locations, respectively. Even a single PZT transducer can precisely identify the actual impact location (Figure 7(a) to (c)). However, there is a variation in the localization performance by each PZT transducer due to the imperfect bonding conditions and different structural geometry at each location. When six PZT transducers are used simultaneously (Figure 7(d)), the localization performance is further improved and it is expected to yield more consistent result.

In Figure 8, the effect of the length of the measured time signal on the localization performance is investigated. Figure 8(a) shows the distribution of the correlation values at different scanning points. As the length of the measured signal becomes longer, the correlation value at the actual impact location (Grid 20) increases, but the correlation values at other locations decrease. Ideally, all correlation value should be zero except for the actual impact location. For a more quantitative comparison, a localization error index (LEI) is defined as follows

\[
LEI = \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left( \frac{x_k - y_k}{d} \right)^2} + \sqrt{\frac{1}{N} \sum_{k=1}^{N} \left( \frac{1}{n-1} \sum_{i=1, i \neq m}^{n} \left( \frac{\text{MAX}(CC)_{ki}}{\text{MAX}(CC)_{km}} \right)^2 \right)}
\]

where \(N\) is the number of impact cases; \(d\) is the length of the grid spacing; \(x_k\) and \(y_k\) are the actual and the estimated impact location for the \(k\)th impact event, respectively; \(n\) is the total number of scanning points; and \(m\) indicates the index of the scanning point with the highest normalized correlation value. In other words, the first term on the right-hand side of equation (9) indicates how well the estimated impact position approximates the actual impact location, and the second term specifies how large the background noise level is.

The LEI for the 25 impact cases has been computed by varying the sampling time duration from 1 to 32 ms as shown in Figure 8(b). Note that the behavior observed here concurs with the time-reversal theory. According to the time-reversal theory, energy focusing
The correlation value is enhanced as the length of the time signal to be reversed increases. Next, the effect of the sampling frequency is examined in a similar way. With a higher sampling frequency, a better spatial resolution is achieved for impact localization (Figure 9(a)). The LEI for 25 impact cases is computed with six different sampling frequencies (16, 32, 64, 128, 256, and 512 kHz) as shown in Figure 9(b). For the signal measurement, better resolution in the time domain can be obtained with a higher sampling frequency. The high resolution makes the digitized signal more similar to the original response and leads to more accurate calculation of correlation values. However, its effect is not dominant as the effect of the sampling time duration. As shown in Figure 9(b), LEI values for sampling frequencies above 16 kHz do not decrease significantly.

In practice, the time duration of a signal and the sampling frequency have to be compromised due to limited memory storage and high computational cost.

**Figure 6.** Impact localization results corresponding to 25 different impact tests. The rectangle corresponds to the scanning region shown in Figure 2. The black dots denote the actual impact locations and the crosses indicate the estimated impact locations. The numbers represent the differences between the actual and estimated locations in millimeter.

**Figure 7.** Impact localization results using (a) PZT 1, (b) PZT 3, (c) PZT 5, and (d) all six PZT transducers. The actual impact location has the highest correlation value within the correlation map regardless of the PZT transducer used, but the localization performance is improved when all six PZT transducers are used simultaneously. The black circle and the white dot represent the actual and estimated impact locations, respectively. Larger correlation values are shown in red (dark).

PZT: lead zirconate titanate.

**Figure 8.** The effect of the sampling time duration on impact localization performance: (a) as the time duration of the measured signal becomes longer, the correlation value at the actual impact location (grid number 20, which is indicated by a dashed line) increases, but the correlation values at the other positions decrease. (b) The LEI defined in equation (9) is computed as a function of sampling time duration, while the sampling frequency is fixed at 512 kHz. A lower LEI value is observed with a longer sampling time duration.

LEI: localization error index.
This trade-off issue is investigated in Table 1, which compares LEIs obtained for 25 impacts with the same number of sampling data points (4096 points) but with different combinations of sampling time durations and frequencies. Although the number of sampling points is the same, the localization performance is much better with a longer sampling time. As previously mentioned, having a sufficiently long time duration is an important factor for achieving successful energy focusing using a time reversal concept.

To examine the robustness of the proposed localization technique to varying impact excitations, additional impact tests have been performed by changing the hammer tips. Four types of hammer tips have been used in this examination: a metal tip, a plastic tip, a hard rubber tip, and a soft rubber tip. Impact excitation signals with these tips are shown in Figure 10. The localization results for these different impact signals are shown in Figure 11. Although the introduced excitation signals are different from each other, the impact location is well identified for all four cases.

### Table 1. LEI with a fixed number of sampling points (4096 points) but with different combinations of sampling time durations and sampling frequencies

<table>
<thead>
<tr>
<th>Sampling time duration (ms)</th>
<th>Sampling frequency (kHz)</th>
<th>LEI</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>512</td>
<td>12.41</td>
</tr>
<tr>
<td>16</td>
<td>256</td>
<td>1.544</td>
</tr>
<tr>
<td>32</td>
<td>128</td>
<td>1.029</td>
</tr>
</tbody>
</table>

LEI: localization error index.
introduced impact signals are quite different from each other and, more importantly, they are very different from the training data sets.

The effect of additional structural features on wave propagation can be shown from the root-mean-square (RMS) energy image of the propagating guided waves (Figure 12). In Figure 12, the red (dark) dot represents an area of higher RMS energy, and the black dot indicates the location of the PZT transducer used for elastic wave excitation. It can be seen that the wave propagation is blocked by the ribs and the spar, complicating the wave propagation.

Impact localization in an aluminum aircraft fuselage

Description of the test specimen and experimental setup

The effectiveness of the proposed technique has also been examined using an aluminum fuselage section from an actual aircraft as shown in Figure 13. The test article is composed of a curved fuselage skin, four horizontal ribs, and two vertical stiffeners, which are all connected by rivets, as well as two supporting structures. The test article is approximately 775 mm in height, 680 mm in width, and 2 mm in thickness. Seven PZT disk transducers, 6.35 mm in diameter and 0.25 mm in thickness, are placed on the inner surface of the fuselage skin using M-Bond 200 cyanoacrylate strain gage adhesive. Detailed experimental setup and finite element simulations of elastic wave propagations through this test article are reported in the authors’ previous study.17,18

The configuration of the data acquisition system is similar to the one used for the composite wing specimen examination. For PZT transducer excitation during the training process, a pulse excitation with a duration of 0.6 ms has been generated using an Agilent 33120A waveform generator, and a Krohn-Hite 7500 power amplifier is used to amplify the peak input to 150 V. A 20-mm grid spacing is utilized to achieve high spatial resolution, resulting in 575 scanning points. At each grid point, 40 measurements are averaged to improve
the signal-to-noise ratio. A 100 ms interval is used between two consecutive pulse excitations to allow signal to decay close to a background noise level before new data collection. IRFs during the training have been collected at a sampling rate of 256 kHz, and a band-pass filter with lower and upper cutoff frequencies of 500 and 1300 Hz is used to reduce noise outside the signal bandwidth. For each scanning point, 16,384 time sample points are collected over 64 ms.

**Experimental results**

Figure 14 summarizes the impact localization results corresponding to 25 different impact tests. The rectangle corresponds to the scanning region shown in Figure 13. The black dots denote the actual impact locations, and the crosses indicate the estimated impact locations. The numbers represent the differences between the actual and the estimated locations in millimeter.

Overall, the actual impact locations are well identified. However, for a few impact cases close to the leftmost and rightmost edges, the discrepancies between the actual and the estimated impact locations are above two grid spacing (40 mm). This can be attributed to the larger spacing between two PZT transducers, PZTs 5 and 7 for the leftmost edge and PZTs 4 and 6 for the rightmost edge, is larger than other PZT pairs.

In Figure 15, the effect of the number of PZT transducer used for impact localization is examined. When PZT 1 or 2 is individually used for impact localization, the actual impact location is still properly identified. However, due to the symmetric placement of PZTs 1 and 2 with respect to the test article and the symmetric nature of the test article, the resulting correlation maps become almost symmetrical as shown in Figure 15(a) and (b). On the other hand, when PZT 7 is employed alone, the impact location is clearly identified and a symmetric correlation map is no longer produced. When all seven PZT transducers are used simultaneously, the localization performance is further improved.

The sampling time duration and the sampling frequency also affect the localization performance. As discussed in the composite wing specimen examination, the performance of impact localization improves with a longer sampling time duration and a higher sampling frequency (Figure 16). It is also investigated that with the same number of data samples, a better impact localization is obtained when all seven PZT transducers are used. PZT: lead zirconate titanate.
Localization performance is achieved with a longer sampling time duration than with a higher sampling frequency (Table 2).

**Conclusion**

In this study, a new impact localization technique is developed using SLDV and surface-mounted PZT transducers. The proposed technique is able to locate the impact events simply by comparing an actual impact response with IRFs obtained from a grid of training points. The training data are collected by individually exciting PZT transducers and scanning the corresponding responses over the target area using the SLDV. The effectiveness of the proposed localization technique is examined using the data obtained from a composite aircraft wing component and an aluminum fuselage section. It has been demonstrated that the locations of most test impacts are successfully identified in spite of the complex geometry of the specimens and additional structural features attached to the specimens. However, special surface treatment with retroreflective tapes is necessary to obtain strong laser return signals for SLDV measurement, and the training time can increase as more PZT transducers are used for training. The possibility of the laser excitation and PZT sensing is being explored by the authors to overcome the limitations of the current PZT excitation and laser sensing configuration. Additional tests are also warranted to examine the robustness of the proposed localization technique under temperature variations.

**Funding**

This study was supported by the Nuclear Research & Development Program (grant number 2011-0018430) and the Leap Research Program (grant number 2011-0016470) of National Research Foundation (NRF) of Korea funded by the Ministry of Education, Science & Technology (MEST).

**Acknowledgments**

The authors would like to thank the Agency for Defense Development in Korea and Air Force Research Laboratory in Dayton, Ohio, for providing the test articles. Also, valuable comments by Prof. H.W. Park at Dong-A University are appreciated.

**References**