Virtual Frequency Data Fusion for Localization of Multiple Damages from Broadband Lamb Wave Velocity Field

M. KANNUSAMY, SAPTARSHI SASMAL
and SANTOSH KAPURIA

ABSTRACT

In this article, a new damage indicator called reciprocal root mean square (*r*RMS) index is proposed for the localization of multiple damages in plate-like structures from the velocity field of guided wave propagation measured using Scanning Laser Doppler Vibrometer (SLDV). The Lamb waves are induced by applying voltage excitation to piezoelectric patch transducers pasted on the top of the plate. It is found that the velocity field measurement from one narrowband pulse excitation of a given central frequency may not be adequate in identifying the locations of all damages. To overcome this difficulty, a new methodology is proposed for a combined damage index that fuses measurement data of different excitation frequencies. However, obtaining the velocity field data at multiple narrowband frequencies from SLDV required for frequency fusion can be tedious, time consuming and expensive. To address this issue, velocity fields at various narrowband frequencies are virtually derived by utilizing the one-time physical velocity field measurement from a broadband excitation. The efficacy of the proposed method for damage localization using frequency fusion is experimentally tested. It is found that the proposed technique using *r*RMS index and frequency fusion is able to localize multiple damages of different types with high sensitivity.

INTRODUCTION

An efficient and robust structural health monitoring (SHM) technique is extremely important to prevent catastrophic failure of civil, mechanical, and aerospace structures during their service life. Owing to the specific advantages and alluring scopes, noncontact measurement techniques are gaining huge traction in recent times. The noncontact methods are advantageous over the conventional contact measurements due to the flex-

Kannusamy M, Senior Scientist, Email: kannusamy@serc.res.in. CSIR- Structural Engineering Research Centre, Taramani, Chennai-600113, India and PhD Scholar, Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India
Saptarshi Sasmal, Senior Principal Scientist, Email: saptarshi@serc.res.in. CSIR- Structural Engineering Research Centre, Taramani, Chennai-600113, India and Professor, Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India
Santosh Kapuria, Professor, Email: kapuria@am.iitd.ac.in. Department of Applied Mechanics, Indian Institute of Technology Delhi, New Delhi 110016, India

ibility in choosing the measurement resolution, no need for affixing physical sensors at the measurement points and the ease of focusing the measurement in any particular area(s) of interest. The scanning laser Doppler vibrometer (SLDV) is an advanced noncontact measurement instrument which can produce maps showing the propagating waves and their interactions with any obstruction during travel [1,2]. Any defect in the scanned area causes a disturbance in the propagating waves, but detection of the exact location and form (size/shape) is not straightforward. Thus, additional signal processing is necessary to provide a helpful defect map.

Sohn et al. [3] could detect delamination and disbond in composite plates using a standing wave filter and Laplacian image filter on SLDV maps. Another technique for imaging damage utilizes the vibration energy distribution and includes computations of the root mean square (RMS). It has been effectively used to identify damages in various structures [4–7]. Saravanan et al. [4] carried out a damage detection study on aluminium plates having missing bolts, added masses, and holes, using 50 kHz narrowband tone burst excitations. Radzienski et al. [6] examined the missing bolts in a stiffened aluminium plate with different excitation frequencies (5, 35, and 100 kHz). Marks et al. [8] used the three-dimensional SLDV measurement to detect disbonds in stiffened aluminum plates, considering narrowband excitation frequencies of 100, 250, and 300 kHz and concluded that the excitation frequency has a major role in Lamb wave energy that is either reflected or transmitted through an adhesive disbond. Similarly, other studies showed that for structures with multiple damages, measurements with one narrowband excitation frequency could not identify the different types of damage [9,10].

The current study presents a new damage indicator known as the reciprocal RMS (rRMS) index for the localization of different defects in plate-like structures from the guided wave propagation velocity field obtained using SLDV. It is observed that determining the locations of all damages is not possible using the velocity field measurement from a single narrowband pulse actuation of a specific central frequency. To resolve this issue, a new technique is put forward here where the fusion of RMS/rRMS maps obtained from several narrowband frequencies is used for the detection/localization in a multi-damage scenario. However, acquiring the velocity field data from SLDV at numerous narrowband frequencies needed for frequency fusion can be laborious, expensive, and time-consuming. To address this problem, a single physical velocity field measurement from a broadband actuation is used to virtually derive velocity fields at multiple narrowband frequencies.

EXPERIMENTAL STUDY

The experimental setup consists of an aluminium plate with 1500 mm $\times$ 1200 mm $\times$ 3 mm dimensions. As shown in Figure 1, the experimental instruments include a function generator, a signal amplifier, and an SLDV. We considered four defects in the study, a notch-type damage, and three masses (circular block mass and two sharp stiffeners with different lengths) bonded to the aluminium plate (Figure 2). A Gaussian broadband signal (Figure 3) was generated using the function generator. Then, the signal was amplified up to 70 V using a power amplifier and sent to the lead zirconate titanate (PZT) wafer (SP-5H type) mounted on the surface of the plate to generate Lamb waves. The SLDV (Polytec PSV-500-3D-HV) was employed to acquire the out-of-plane velocity response at a pre-selected scan area of the plate. The scan area consists of 21516 scan points, with 132 points in the horizontal grid and 163 in the vertical grid. The sampling frequency of 6.25 mega samples per second is used. To reduce the signal-to-noise ratio (SNR), at least 70 repetitive measurements were carried out and averaged. Also, a band-pass filter with lower and higher cut off frequencies as 23 kHz and 320kHz respectively, was applied to reduce the noise outside the excitation frequency range.

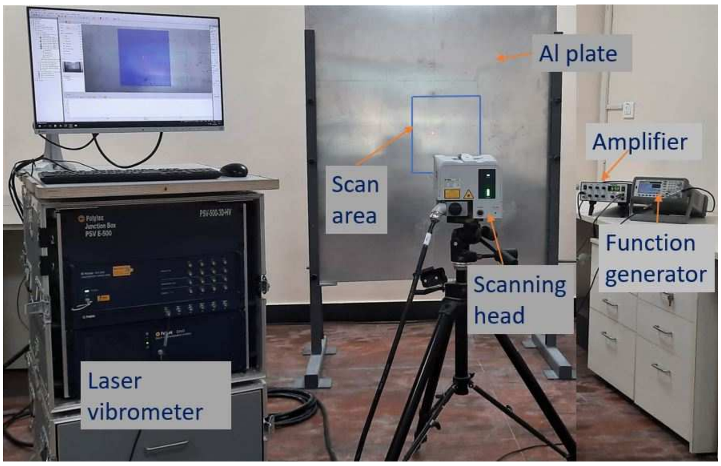


Figure 1. Experimental setup

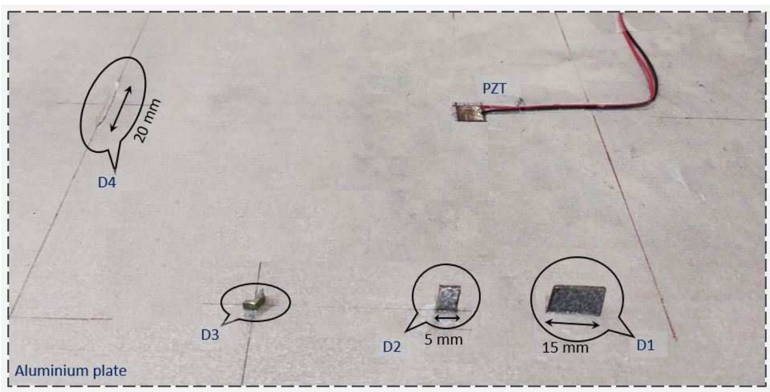
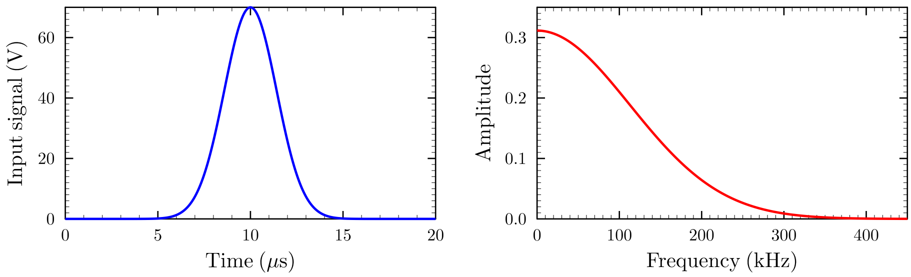


Figure 2. Damage scenario

VIRTUAL NARROWBAND RESPONSE FROM BROADBAND MEASUREMENT

Figure 4 schematically depicts the procedure for obtaining the virtual narrowband response from the broadband measurements. As established in our prior research [11], a Gaussian broadband signal (Figure 3) V_A^b is employed in the actuator to generate Lamb waves, and the velocity response at each SLDV scanning point P (v_P^b) is measured. The



(a) (b)

Figure 3. (a) Gaussian broadband signal, and (b) its frequency spectrum

transfer function is then evaluated at each scan point in the frequency domain as

$$G_P(\omega) = v_P^b(\omega)/V_A^b(\omega) \tag{1}$$

The narrowband frequency domain response at point P ($v_P(\omega)$) can be evaluated using the transfer function $G_P(\omega)$, as

$$v_P(\omega) = G_P(\omega) * V_A(\omega) \tag{2}$$

where $V_A(\omega)$ is the narrowband input signal in the frequency domain whose frequency band lies within the broadband signal excitation frequency. The time domain response is then evaluated by applying an inverse Fourier transform (IFFT) on $v_P(\omega)$.

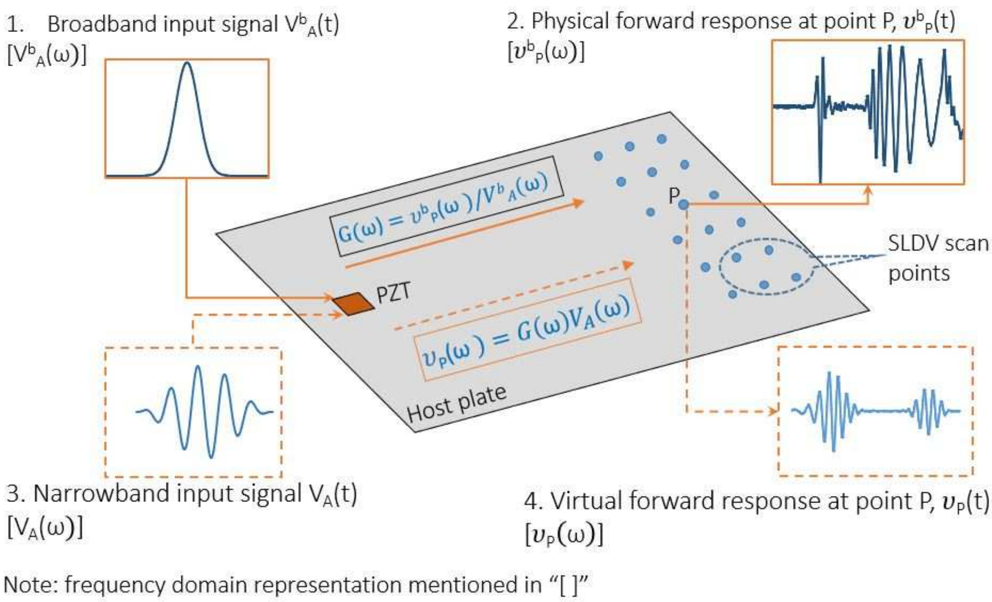


Figure 4. Schematic diagram of the proposed virtual technique for extracting narrowband response from SLDV broadband measurement

RESULTS AND DISCUSSION

The velocity field acquired from SLDV is processed for damage imaging. One of the most common methods is to use the basic root-mean-square (RMS) of the velocity signal, representing the wave energy at each scan point (x, y), given by

$$RMS(x,y) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(s_i(x,y,t))^2} \tag{3}$$

where N is the number of sample in the time domain signal $s_i(x, y, t)$ and s_i is the i^{th} sample amplitude at the scan point (x, y).

The virtual response for the narrowband five-cycle tone burst excitation of 50 kHz frequency was derived for each scan point by following the procedure given in the previous section. Then, the RMS for each scan point was evaluated using Equation (3). The RMS value of each scan point is normalized with respect to the maximum RMS value of the scan area, which is shown in Figure 5(a). The visual assessment of the RMS map shows that while added masses are identifiable, the notch-type damage is not identifiable (Figure 5(b)). Further, there are ripples accompanied with the detectable defects due to reflection from the defect. They may lead to a false identification of defect locations. Also, the RMS amplitude at the actuator location overshadows the peaks or valleys at the defect location.

To overcome these issues, we propose a new index called reciprocal RMS (rRMS) and a combined index (CI) that fuses the normalized RMS/rRMS maps obtained at multiple narrowband frequencies as follows:

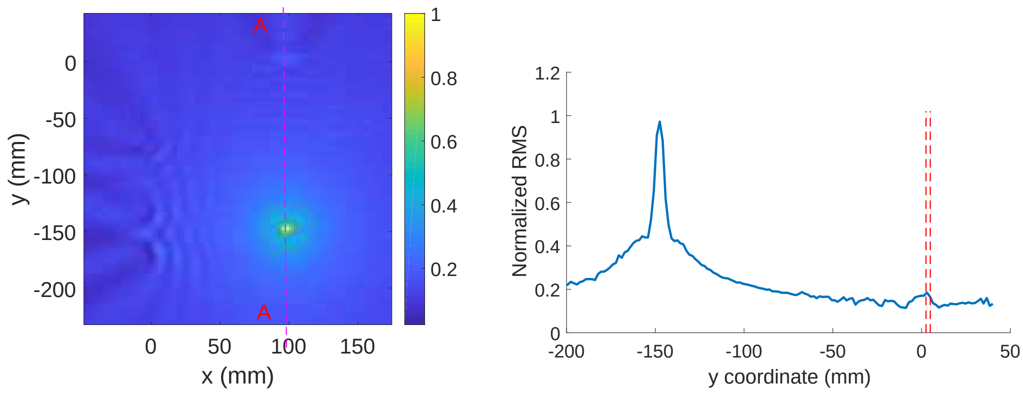
$$rRMS(x,y) = \frac{1}{RMS(x,y)} \tag{4}$$

$$CI_{RMS} = \sum_{f=f_l}^{f_u} RMS_f(x,y) \tag{5}$$

$$CI_{rRMS} = \prod_{f=f_l}^{f_u} rRMS_f(x,y) \tag{6}$$

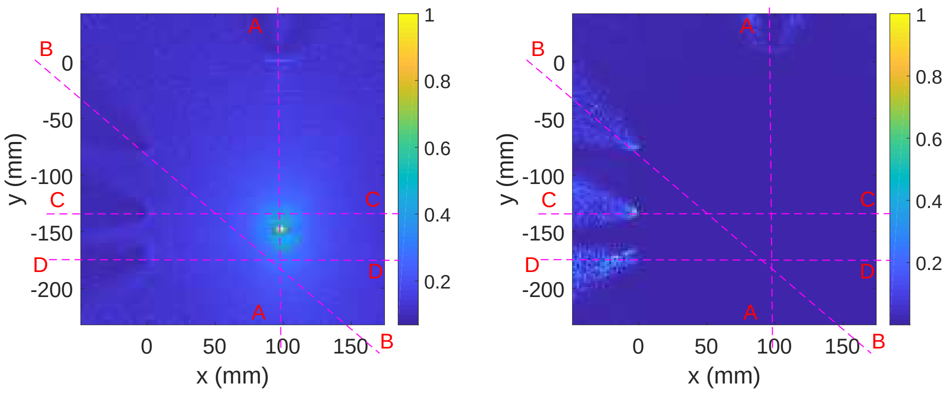
where f_l and f_u are the lower and upper limit frequencies, respectively. The RMS/rRMS maps are obtained for various narrowband central frequencies between f_l and f_u at an interval of Δf. In the present study, we calculate virtually the out-of-plane velocity at each grid point (x, y) for the 5-cycle narrowband excitation from lower bound frequency f_l = 50 kHz to upper bound frequency f_u = 190 kHz with Δf =20 kHz from the SLDV measurement under the Gaussian broadband signal given in Figure 3.

Figures 6(a) and 6(b) show the summation RMS fusion and product rRMS fusion map of the multi-frequency normalized RMS/rRMS maps, respectively. It is seen for both the summation RMS fusion and the product rRMS fusion that all four damages are identifiable. However, in the case of RMS fusion, the higher peaks near the actuator affect the sensitivity of the damage localization. Figures 7(a)-(d) shows the profile plots along the damage lines. A sharp and distinct peak in the rRMS value at the front edge of each damage indicates the clear identification of the damage with greater sensitivity, whereas the RMS value at the damage is overshadowed by a higher RMS value at the actuator location, which hinders the damage sensitivity.



(a) (b)

Figure 5. (a) Normalized RMS map for five-cycle 50 kHz narrowband tone burst excitation, and (b) profile plot along path A-A. The width of the damage along the path is marked by the dotted vertical lines



(a) (b)

Figure 6. Frequency fusion at probing frequencies ranges from 50 kHz to 190 kHz with interval of 20 kHz by (a) summation of normalized RMS maps, and (b) product of normalized rRMS maps

CONCLUDING REMARKS

An aluminium plate with multi-damage of different types was experimentally tested using SLDV for localization of damages. It was found that the RMS map obtained at

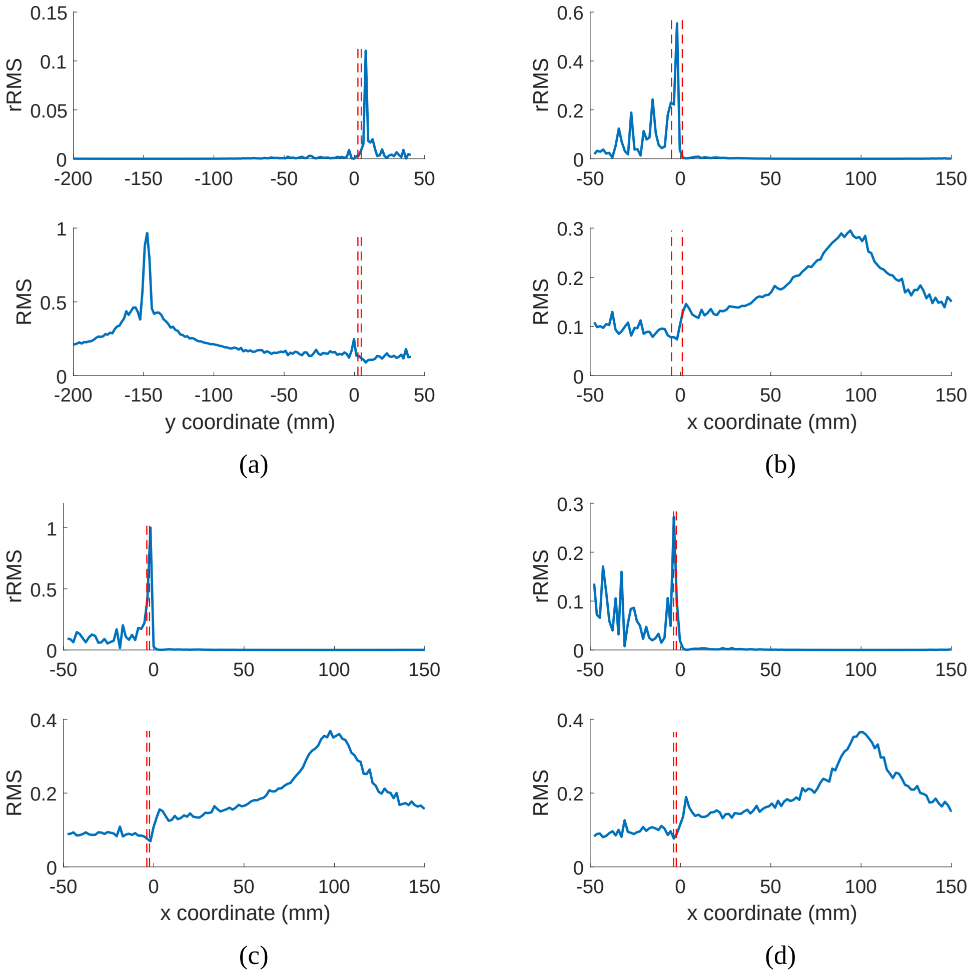


Figure 7. Profile plots at section (a) A-A, (b) B-B, (c) C-C, and (d) D-D. The width of the damage along the path is marked by the dotted vertical lines

one narrowband frequency of excitation cannot identify all the damages. The summation fusion of RMS maps at multiple narrowband frequencies was able to identify all the damages; however, the higher RMS amplitude at the actuator overshadows the damage location, which hinders the damage detection sensitivity. In comparison, the newly proposed reciprocal RMS (rRMS) index and the product fusion technique could identify all the damages with greater accuracy. It shows the sharp increase in rRMS amplitude at the front edge of each damage provides enhanced sensitivity to the damage localization.

REFERENCES

1. Staszewski, W., B. Lee, L. Mallet, and F. Scarpa. 2004. “Structural health monitoring using scanning laser vibrometry: I. Lamb wave sensing,” *Smart Materials and Structures*, 13(2):251.
2. Kudela, P., T. Wandowski, P. Malinowski, and W. Ostachowicz. 2017. “Application of scanning laser Doppler vibrometry for delamination detection in composite structures,” *Optics and Lasers in Engineering*, 99:46–57.
3. Sohn, H., D. Dutta, J. Yang, M. DeSimio, S. Olson, and E. Swenson. 2011. “Automated detection of delamination and disbond from wavefield images obtained using a scanning laser vibrometer,” *Smart Materials and Structures*, 20(4):045017.
4. Saravanan, T. J., N. Gopalakrishnan, and N. P. Rao. 2015. “Damage detection in structural element through propagating waves using radially weighted and factored RMS,” *Measurement*, 73:520–538.
5. Radzieński, M., M. Krawczuk, A. Żak, W. Ostachowicz, et al. 2011. “Application of RMS for damage detection by guided elastic waves,” in *Journal of Physics: Conference Series*, IOP Publishing, vol. 305, p. 012085.
6. Radzieński, M., Ł. Doliński, M. Krawczuk, and M. Palacz. 2013. “Damage localisation in a stiffened plate structure using a propagating wave,” *Mechanical Systems and Signal Processing*, 39:388–395.
7. Rucka, M., E. Wojtczak, and J. Lachowicz. 2018. “Damage imaging in Lamb wave-based inspection of adhesive joints,” *Applied Sciences*, 8(4):522.
8. Marks, R., A. Clarke, C. Featherston, C. Paget, and R. Pullin. 2016. “Lamb wave interaction with adhesively bonded stiffeners and disbonds using 3D vibrometry,” *Applied Sciences*, 6(1):12.
9. Zak, A., M. Radzienski, M. Krawczuk, and W. Ostachowicz. 2012. “Damage detection strategies based on propagation of guided elastic waves,” *Smart Materials and Structures*, 21(3):035024.
10. Kang, T., S.-J. Han, S. Moon, S. Han, J. Y. Jeon, and G. Park. 2019. “Lamb-wave sparse-frequency interdigital-transducer-based scanning laser Doppler vibrometry for quantitative depth-wise visualization of defects in plates,” *NDT & E International*, 107:102137.
11. Kannusamy, M., S. Kapuria, and S. Sasmal. 2022. “An efficient Lamb wave-based virtual refined time-reversal method for damage localization in plates using broadband measurements,” *Ultrasonics*, 124:106767.