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Signal Processing Techniques of Lamb Waves for Structural Health Monitoring System- A Review

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ABSTRACT

The structural health monitoring (SHM) system using Lamb wave approach has drawn a lot of interest because of its outstanding performance in terms of accuracy and adaptability. The implemented signal processing techniques in the diagnostic analysis are specifically reviewed in this work. The primary factors of the wide range of applied signal processing techniques are due to the multimode and dispersive behaviour of the Lamb waves. Several Lamb modes occur simultaneously, and because they have different dispersive characteristics, they can produce complicated superimposed signals. To effectively diagnose the observed signals, several mode separations approaches have been proposed. Generally, time-frequency representation is applied for signal processing techniques. The findings demonstrated that the proposed procedures were successful in decomposing the superimposed mode into individual modes for further analysis. All these works have shown how SHM systems based on Lamb waves have evolved over time to control and monitor the condition of the structure.

1. Introduction

Lamb Waves (LW) is a promising and commonly used SHM-based technology, has been shown to be a promising approach in a variety of fields. LW were used to identify both internal and external damage because of their special characteristics that allowed them to travel into the thickness of the plate [1]. As a result, the detected waves are able to be used to extract significant information on structural integrity. Its capability to conduct inspection for a huge structure from restricted access has contributed to the rapid growth of this technique [2].

The actuator and the sensor are used in the active LW approach. Generally, the measured LW signal comprises energy components from all the propagating modes which are resulted from the dispersive nature of the LW. When a Lamb wave interacts with defect, it scatters in all directions. That scattered wave can be investigated for damage determination. In many cases, there are multiple

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modes and reflections that are superposed on each other. As a result, determining the source of each feature in a time domain response, as well as detecting and interpreting minor scatters in complicated Lamb wave signals, is difficult. Superposition of all modes leads to the difficulty for the post-processing analysis of the signals. Tracking a particular mode became more complicated and eventually affected the accuracy and reliability of the SHM process. Thus, the ability of the proposed signal processing to accurately separate into individual mode would significantly enhance current SHM applications.

2. Signal Processing Technique

2.1 Fast Fourier Transform

By converting the observed amplitude-time record at evenly spaced positions to amplitude-wavenumber records at discrete frequencies, 2D FFT solves the multiple mode and dispersion issues, allowing individual Lamb waves to be resolved [3]. Some researchers successfully implemented 2D FFT analysis for the dispersion mode separation. Eisenhardt *et al.,* [4] demonstrated the effectiveness of 2D FFT by determining the dispersion curves in a flat plate. It was performed by applying the laser ultrasonic technique. The resulting frequency-wave number (*fk*) spectrum indicates that certain k-f components can be detected from the amplitudes (peaks), and these components are solutions to the dispersion equations of the plate (individual modes). Ruzzene [5], Tian and Yu [6] and Michaels *et al.,* [7] improved the multi-dimensional FFT method by applying a filtering technique for the broadband excitation signals. This technique makes various wave modes separable and distinguishable for the ease of analysis as presented in Figure 1. The technique is also able to highlight the presence of reflections associated with damage and enabling for their identification and interpretation. However, Niethammer *et al*., [8] claimed that the need for exact, spatially sampled data and preferably along a long range of distance in order to avoid aliasing when Fourier transforming from the spatial domain restricts the practicality of the 2D-FT especially for small size or irregular inspection applications. Other than that, this method is suitable for stationary signals which is obviously not suitable for the non-stationary Lamb waves [9]. In these cases, the time-frequency based techniques have a better advantage.

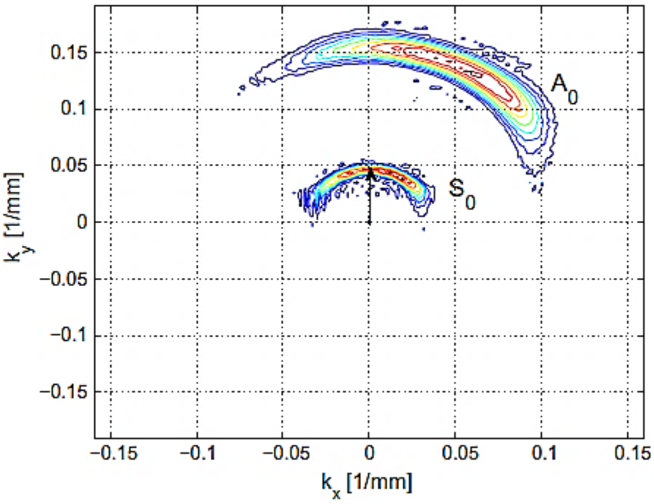


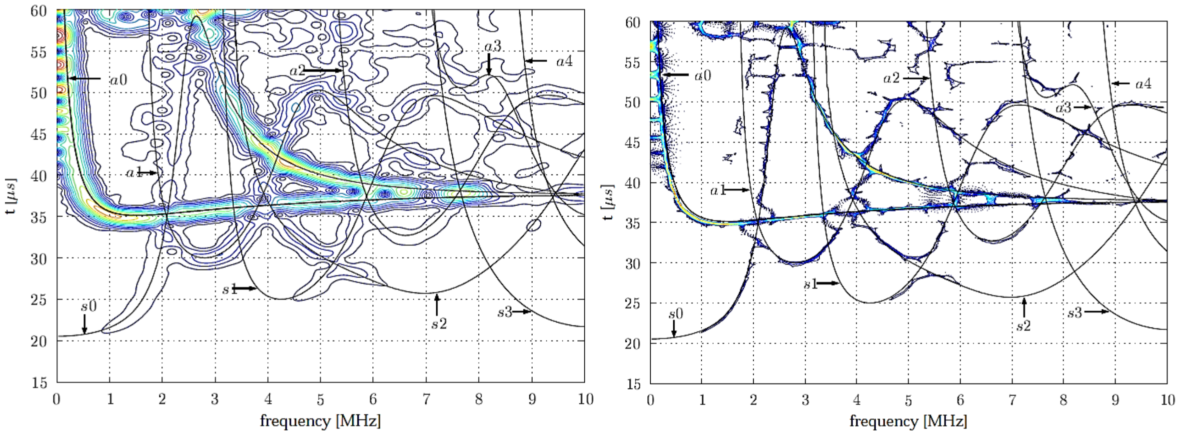
Fig. 1. Results of 2D FFT performed by Michaels *et al*., [7]

2.2 Time-Frequency Representations (TFR)

The dispersive nature of LW means that the frequency content of a received LW signal varies over time and thus this characteristic complicates their analysis in the time-domain. For this reason, time-frequency representation (TFR) is widely employed for better interpretation of a LW signal. The output of these distributions is the energy density or intensity of various frequency components of a signal at given points in time [10]. Detailed review of time-frequency distributions and their numerous applications can be referred to in a study by Cohen [11].

2.2.1 Short-time Fourier transform

Short-time Fourier transform (STFT) is one of the earliest and widely used linear TFR methods. STFT divides the signal into several shorter overlapping segments in the time domain. Each segment is then multiplied with a fixed modulation window. The resulting signals are processed using Fourier transform to obtain the corresponding time-frequency energy distributions (called as spectrogram). Spectrogram displays an image for each point for the time-frequency plane which has been used to isolate the individual mode of detected LW signals in the time domain. Teng *et al.,* [12] adopted STFT to predict the propagation of individual mode in aluminium alloy plate. Unfortunately, the obtained spectral and time of arrival estimations are not accurate enough, leaving a negative effect on the prediction. This is supported by Ho *et al.,* [13] which is claimed that STFT may not provide a good resolution especially at high frequency due to the implementation of a fixed window function. Ajay and Carlos [14] stated in their study that STFT is unable to solve the overlapping reflections. Niethammer *et al.,* [8] had overcome the above and stated limitations by applying reassignment spectrogram to refine the time-frequency resolution of the calculated dispersion curve by using STFT analysis. The finding, as shown in Figure 2 showed that it could distinguish the multiple and closely spaced LW. Niethammer *et al.,* [8] and Valle and Littles [15] also implemented reassigned spectrogram to separate the LW signals for the structural defect detection. However, some lack of definition occurs at the intersection of modes which lead to unwanted distortion of the reassigned spectrogram.



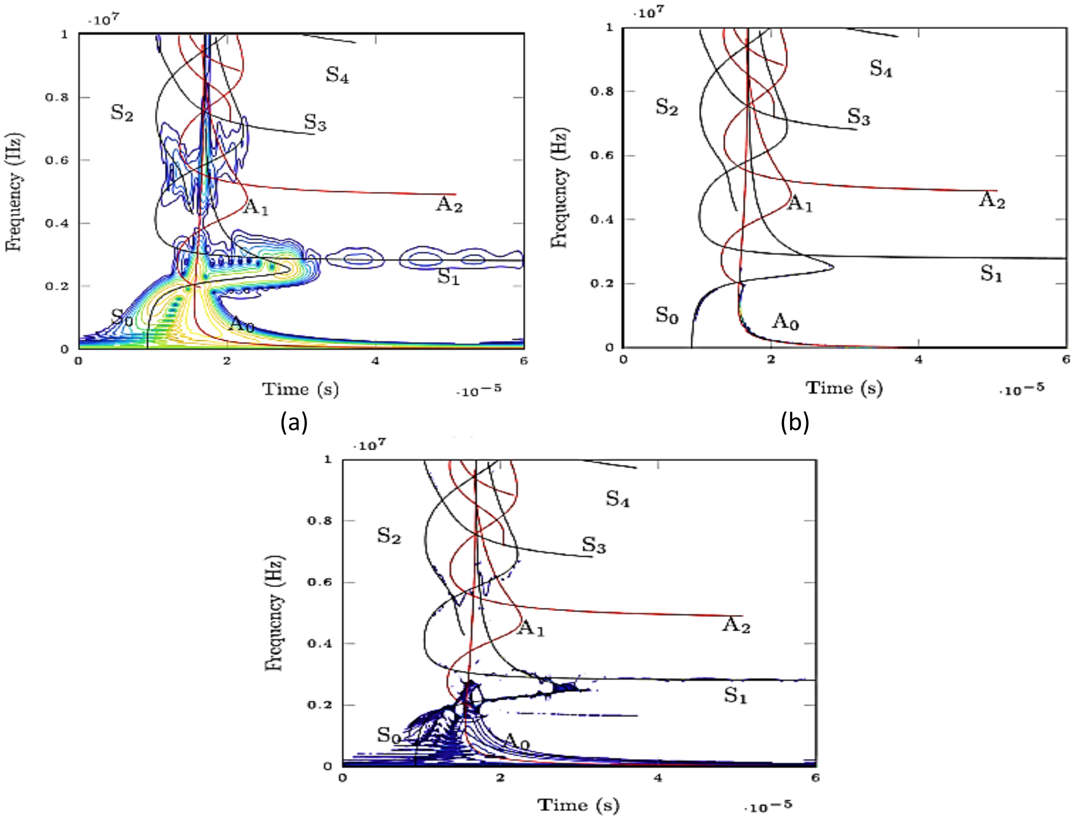
(a) (b)

Fig. 2. A contour plot obtained by Niethammer *et al.* [8] (a) original spectrogram from STFT analysis and (b) reassigned spectrogram

2.2.2 Wavelet transform (WT)

Another linear TFR that is introduced for the extraction of the interest mode is Wavelet transform (WT). WT is a powerful tool for signal analysis by decomposing them into a set of basic vector components [16]. The basis vectors are acquired through a family of functions that depend on scale coefficient and the translation step [17]. The mother wavelet plays an important role for the harmonic component extraction of dispersive waves. The desired frequency component in the output signal can be extracted using the peak of the magnitude plot of wavelet coefficient by applying the appropriate scaling and shifting [18]. Veroy [19] implemented WT to extract the individual mode of the laser generated broadband signals. Image of wavelet coefficient clearly reveals the exist modes in the dispersion curve form. The modes were easily distinguishable for the lower frequency and illustrated difficulties for the higher frequency especially when encountered with the intersection of the dispersion curve. Hyunjo and Young-Su [20] and Jeong and Jang [21] utilising the peak magnitude of the WT to extract the mode of the waves. The extracted mode was then used to detect the arrival time for locating AE sources. Li *et al.,* [22] and Zamen *et al.,* [23] also applied the wavelet transform to distinguish the LW modes. The mode of interest was then used for further analysis.

Wang *et al.,* [24] performed squeezed WT for the mode identification using synthesised and simulated broadband LW signals. It is noted that the overall time and frequency resolutions are determined by Gauss function and the centre frequency. Carefully choosing that parameter should improve the performance of the squeezed WT that will lead to the well modes separation and minimising the interferences between the modes. From the obtained results as shown in Figure 3, it should note that the squeezed wavelet transform shows the applicability as an alternative tool for the LW modes extraction with an added value that is permitting reconstruction of the original signals which is not possible for the reassigned TFRs. However, there is no improvement for the signal analysis performance compared to the reassigned scalogram.



(a) (b)

(c)

Fig. 3. Result for simulated broadband signals obtained by Wang *et al* [24] using (a) scalogram (b) reassigned scalogram and (c) squeezed WT

2.2.3 Chirplet transform (CT)

The chirplet transform (CT) is a generalisation of both the WT and the STFT. It enables the components of a signal to be extracted of with a particular instantaneous frequency (IF) and group delay. CT was initially used to improve the spectrogram results by combining the additional degrees of freedom of the CT with the dispersion relationship model. The shape of the chirplet was adopted based on the dispersion model to fit the known group delay of each individual mode. The group delay will provide information about the frequency content at particular time. The energy of the individual modes is extracted by implementing this procedure. This is accomplished by shifting chirplets onto the dispersion curve, and then shearing them to locally match the slope of the dispersion curve. The chirplet should be better in resolving closely spaced modes because this method offers additional control over the location, shape and orientation of the time-frequency atoms [25]. However, based on the study performed by Ming *et al.,* [26], there is poor agreement between the chirplet-based and theoretical solution in the frequency ranges where two dispersion curves intersect or close to each other. This phenomenon is due to improperly assigned of a large portion of particular modes' energy to the related mode at particular frequency ranges. Due to the issue, Kuttig *et al.,* [27] proposed an adaptive chirplet analysis algorithm to overcome the interferences problem by exploiting another degree of freedom of CT operations called as the scale parameter, s. The s value of basic functions could be adjusted to adaptively match the measured signal at each analysis window. Alternatively, Ming *et al.,* [26] and Zeng *et al.,* [28] integrated the adaptive chirplet algorithm with time–varying filter called as Vold-Kalman filtering (VKF) for the LW modes separation. The study utilised the chirp rate, c parameter to suppress the interferences of the CT spectrogram. A coarse-fine instantaneous frequency (IF) estimation method was used to determine the c value. The values of the parameters have to be chosen carefully in order to clarify the ridge of the mode of interest. Vold-Kalman filtering (VKF) was then employed to extract the individual mode based on the IF bandwidth of each mode component. VKF work principal extraction is based on the centre frequency of the interested mode and its process can be referred to Figure 4. The extraction process of the individual is accomplished by choosing a wide bandwidth mode while excluding the closest component. The wide bandwidth would make certain the interested signal component falls into the passband of the filter. Nevertheless, increment in the bandwidth leads to the noisy extracted waveform.

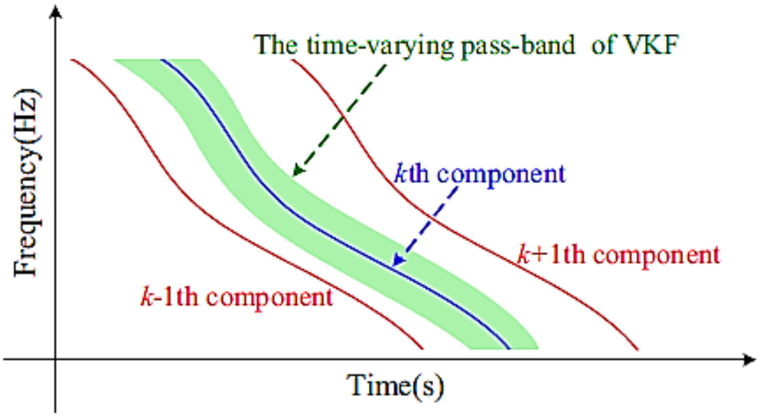
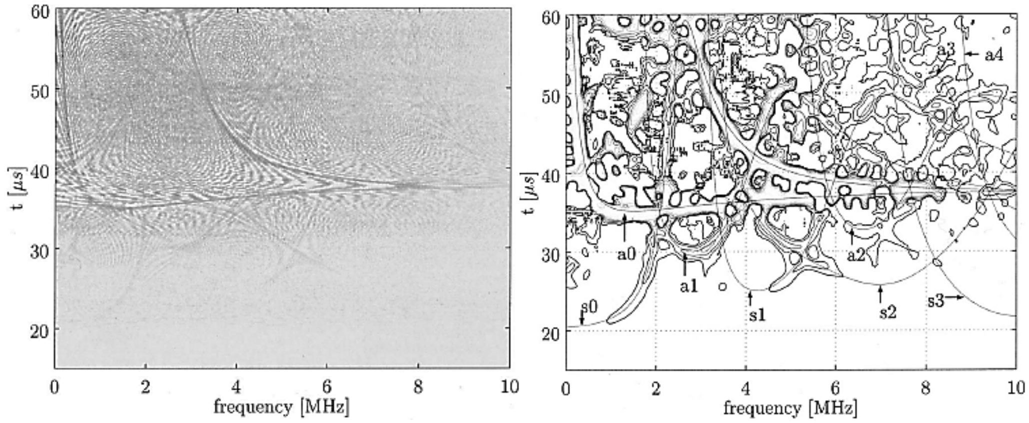


Fig. 4. Work principle of VKF for the waveform's extraction [28]

2.2.4 Wigner-Ville distribution (WVD)

Another important TFR that was implemented by scholars is Wigner-Ville Distribution (WVD). The WVD is a measure of the signal's local time-frequency energy. The frequency and time resolutions of the WVD are determined by the selection of desired resolution of the signal itself. It was not determined by the short duration as applied by the other methods. WVD can exactly localise linear chirps, sinusoids and Dirac impulses [29]. Additional interference terms will exist for other types of signals, and it can be reduced by using a smoothing filter in the time–frequency plane, called smoothed WVD or Pseudo-WVD (PWVD). The introduction of time frequency smearing which abolishes the PWVD's property of exact localisation of waveforms is an unfortunate side effect of this smoothing. For example, the difficulty in determining the peak time of each mode due to the limited time resolution is a problem. This affects the accuracy of the prediction of the time of arrival and group velocity. Other than that, many peaks appeared for a particular given frequency which corresponds to the different times of arrival of the different modes. Another problem is higher background noise level in the distribution because of smoothing just reduced not entirely eliminate the noise.

An example for the WVD and smoothed WVD can be referred to in the note reported by Niethammer *et al.,* [29]. They performed the analysis of the broadband LW using both WVD and smoothed WVD to resolve the individual mode. Each of the findings is compared with the analytical solution of the dispersive curve (solid line) as shown in Figure 5. WVD result shows a clear separation just for anti-symmetrical mode, A_0 and symmetrical mode, S_0 only whereas the other modes were unclear because of the interference terms. In contrast with smoothed WVD (by using Gaussian filter) which did a good job in resolving A_0, A_1, A_2, S_0, S_1 and S_2 over a large frequency range. However, there is some lack for the frequency over 5 Mhz and times beyond 50 µs (Figure 5 (b)). It is quite difficult to identify the individual mode at that mentioned range.



(a) (b)

Fig. 5. Time-frequency resolution obtained by Niethammer *et al.* [29] using (a) WVD and (b) smoothed WVD

The same cases go to Prosser *et al.*, [30] which is applied this technique to the simulated and experimentally broadband acoustic signals. The PWVD technique was first demonstrated on a simulated waveform to model propagation in an aluminium plate and the results proved that the PWVD able to separate multiple Lamb modes, as well as a reflection from a boundary which were superimposed in the time domain waveform. It was further demonstrated using experimental waveforms. The data was measured in a graphite/epoxy plate using pencil lead fracture source for propagation both along, and perpendicular to the fibre direction. The fundamental symmetric, S_0 and anti-symmetric, A_0 modes clearly appeared compared to the highest modes because of the higher background noise. Holland *et al.,* [31] utilised the reassignment smoothed WVD to sharpen the features of the time-frequency distributions using synthetic waveforms. Image sharpening was completed by moving energy ‘uphill’ in time–frequency–amplitude space as shown in Figure 6. The reassignment algorithm is able to overcome the clarity problem of the smoothed WVD. Unfortunately, it shows a higher background noise level utilising the real experimental data.

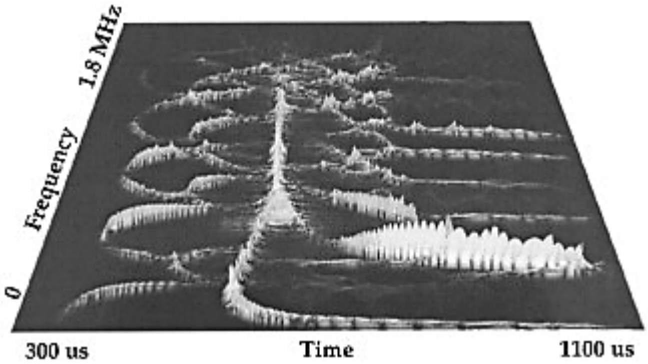


Fig. 6. Time-frequency distribution using reassignment smoothed WVD by Holland *et al.,* [31]

2.2.5 Hilbert-Huang transformation (HHT)

It should be noted that the Hilbert-Huang transformation (HHT) was also implemented by some researchers for the mode discrimination. The HHT method is composed of empirical mode decomposition (EMD) and Hilbert transform. EMD analysis effectively separated the frequency components to the intrinsic mode function (IMF). IMF then produces the instantaneous frequency (IF) that enables the identification of the mode. Finally, Hilbert spectrum was obtained using Hilbert transformation to the IMF sequence. Hilbert spectrum is a 3-D discrete time-frequency spectrum containing time, frequency, and amplitude, which provides very clear time-frequency characteristics with local details. The HHT was also utilised by Niethammer *et al.,* [29] for the mode separation of the broadband laser-generated signals. The findings show that the contour plot of the Hilbert spectrum was far from being a clean representation compared with the analytical solution of the dispersion curve. It was also noticeable that each calculated IMF was specialised in certain frequency ranges. In this regard, it led to the failure of the frequency ranges that contained multiple modes. Consequently, Ding *et al.,* [32] combined the HHT with WT to distinguish the overlapping broadband simulated LW signals. Better results were obtained, and this indicates that this hybrid method can enhance the performance of the conventional HHT and WT analysis for the highly overlapped signals. The wave packets were decomposed into IMFs and the local maximum of the wavelet coefficients of the elemental signals is used to describe the dispersive curve.

2.3 Matching Pursuit Decomposition (MPD)

Besides normal TFRs, another algorithm that was used for the LW modes discrimination is the Matching Pursuit Decomposition (MPD). MPD is an iterative algorithm that decomposes LW responses into linear combinations of atoms that belong to a redundant dictionary. The dictionary of the MPD consists of a collection of time-frequency atoms which are dilated (timescale), translated (time-shifted) and modulated (frequency-shifted) versions of a single basic atom. Gaussian signals are regularly chosen as the basic dictionary atom since they are the most concentrated signals in time and frequency which are effective for nearly non-dispersive waves. This dictionary is obviously not suitable for a dispersive LW. This drawback has driven more researchers to find a new solution called the adaptive dictionary to represent the characteristics of a measured signal [33]. Robustness to noise, accuracy of time-frequency resolution, efficiency of high computational and ease of post-processing are the benefits of this analysis [34].

2.4 Other Techniques

Another strategy applied to extract the multiple modes is warped frequency transforms (WFT) as proposed by Marchi *et al.,* [35]. The tiling parameter used is the key point for this proposed method. Its tiling was composed of atoms with a nonlinear modulation in frequency and designed to match the spectro-temporal structure of the different LW modes. Such tiling is obtained by selecting an appropriate warping map that reshapes the frequency axis. The map design is based on the prediction of dispersion curves for the considered waveguide. The proposed WFT is fast, invertible, and covariant to the group delay shifts of LW.

Some researchers proposed a mode separation technique based on an oblique polarisation filter [36]. The effectiveness of this filter depends on the individual mode of the polarisation parameter, that is the ratios of in- and out-of-plane displacements and phase-shift between fundamental symmetric and anti-symmetric modes. 3-D elasticity theory was also proposed to decouple the wave modes for symmetric laminates. Boundary conditions were imposed on both mid-plane and top surface to separate the symmetric and anti-symmetric modes. All the applied signal processing techniques were summarised in Table 1. The table listed the advantages and the limitations of each of the techniques.

Table 1
The summarised information about the signal processing techniques for the broadband excitations

Analysis	Advantages	Limitations
2D FFT	Frequency and velocity are directly linked	The need for exact, spatially sampled data restricts the practicality of 2D FFT [8] It is suitable for signals with stationary frequency content.
STFT	Capable of isolating the individual reflections, identifying their time–frequency centres and classifying their modes using the time–frequency ridges [12]	1. STFT may not give good resolution at high frequencies because of the use of a fixed window function [13]. 2.Incapable of resolving overlapping multimodal reflections [14].
Reassigned spectrogram	Better time-frequency concentrations [8]	Unwanted distortion of the reassigned spectrogram due to lack of definition occurs at the intersection of modes [15]
Wavelet	1.Easily separate information and noise without needing a complex windowing step 2.Width of the time frequency window vary with the scaling parameter [17].	Difficulties to distinguish modes at the higher frequency especially at the intersection of the dispersion curve [19].
Squeezed wavelet transform	Reconstruction of the original signals or its component [24].	No better performance for the broadband signals [24].
Chirplet transform	Chirplet provides additional control over the shape, location, and orientation of the time-frequency atoms	Destroying the ridge pattern due to the neighbouring interference [26]
WVD	It can exactly localize sinusoids, Dirac impulses and linear chirp [29].	Always has additional interference terms for other type of signals [29].
PWVD	1.Perfectly resolve a multicomponent signal [30]. 2. Sharpen the time-frequency distribution image [29]	1. Higher background noise level because smoothing just reduced not eliminate the noise [31] 2. Limited time resolution raises the problem in determining the peak time which affects the accuracy of the prediction of the time of arrival and group velocity. 3. Many peaks appeared for a particular frequency which is corresponded to the arrival of the different modes [29].
HHT	Works well for the frequency ranges where there are only a few modes exist [29].	Fail to separate the multimode signals which is occupying the same frequency band and intersecting each other in time and frequency [29].
HHT is combined with WT	Effectively separate the frequency components that contains multiple modes [32].	No explanation has been found.
MPD with adaptive dictionary	Accurate time-frequency resolution, robustness to noise, high computational efficiency and ease of post-processing [33].	No explanation has been found.
WFT	Fast, invertible, and covariant to the group delay shifts of Lamb waves [35].	No explanation has been found.

3. Conclusions

LW technique has demonstrated considerable promise as a SHM tool. They are commonly employed for structural health monitoring because they provide an affordable evaluation, are able to travel relatively long distances, and are extremely vulnerable to interior defects. However, dispersive and multimodal behaviours lead to the signal complexity, which may have an impact on the accuracy of the signal interpretation. As a result, researchers have proposed various of signal processing techniques to improve the signal interpretations by extracting the individual modes. The conventional and newly developed hybrid method was utilised for the mode separation. Each of the proposed method showed their own strength and weaknesses based on their application. It is a continually evolving process for the Lamb wave based SHM system for better performance. The capability of the developed algorithm to separate the Lamb wave modes is the indicator of the success of the applied approach.

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