Chirplet Transform in Ultrasonic Non-Destructive Testing and Structural Health Monitoring: A Review

M. S. Mohammed
Nuclear Engineering Department
King Abdulaziz University
Jeddah, Saudi Arabia
mshmohamad@kau.edu.sa

Kim Ki-Seong
Department of Mechanical Design Engineering
Chonnam National University
Yeosu, Republic of Korea
sngkim@chonnam.ac.kr

***Abstract*—Ultrasonic non-destructive testing signal can be decomposed into a set of chirplet signals, which makes the chirplet transform a fitting ultrasonic signal analysis and processing method. Moreover, compared to wavelet transform, short-time Fourier transform and Gabor transform, chirplet transform is a comprehensive signal approximation method, nevertheless, the former methods gained more popularity in the ultrasonic signal processing research. In this paper, the principles of the chirplet transform are explained with a simplified presentation and the studies that used the transform in ultrasonic non-destructive testing and in structural health monitoring are reviewed to expose the existing applications and motivate the research in the potential ones.**

Keywords-chirplet tranform; ultrasonic; guided wave; NDT; structural health monitoring

I. INTRODUCTION

Non-destructive testing (NDT) methods [1, 2] are used to examine the integrity of engineering materials and structures without altering them or affecting their serviceability. Ultrasonic testing [3, 4] is an important NDT method, in which a transducer sends an ultrasound pulse into the material under test, and the reflected or transmitted echo is received, processed and analyzed to provide useful information about the material's properties or about the presence of flaws and their sizes, locations, and severity. Besides conventional ultrasonic testing, ultrasonic guided wave inspection is established in the NDT applications. It uses lamb waves that are guided by the boundaries to propagate along the structure in order to evaluate its condition. The guided wave inspection in structural health monitoring (SHM) is carried out by an installed network of sensors, a processor, and an algorithm to instantaneously provide damage prognosis [5]. The usefulness of the received ultrasonic NDT echo signals can be challenged by the noise from several sources including the material's grain structure and by the limited resolution ability of the measurement system when the echo signals are overlapped due to the small space between the reflectors (interfaces or material flaws). In guided waves inspection, multimodal and dispersion constrain the analysis of the received signals. If the defect is located close to another reflector, it can be only detected if the reflected echo is resolved. The measurement system capabilities can be reinforced by using digital signal processing (DSP) to recover the useful and critical information masked by the poor quality of the signal. DSP methods such as Wiener deconvolution, spectral extrapolation, and minimum variance deconvolution have been used to enhance the time resolution of ultrasonic signals [6-9]. Artificial neural networks have been used for flaws' recognition and classification [10, 11]. Furthermore, many techniques have been proven effective in improving the signal-to-noise ratio (SNR) such as time averaging, matched filters, low-pass filters, high-pass filters, and band-pass filters, wavelet transform, and adaptive filters. Examples of noise reduction methods are reported in [12-15]. Guided waves signals in NDT and SHM applications are often processed using time-frequency analysis methods [16-18].

Corresponding author: Kim Ki-Seong

Chirplet transform is a signal approximation method that can provide inclusive solutions for flaw detection and characterization, nevertheless it is not as popular as other methods in the ultrasonic NDT and SHM signal processing research. The objective of this paper is to review the principles of chirplet transform, discuss the relevant research papers in ultrasonic NDT and SHM signal processing to expose existing applications, and motivate the research in potential ones.

II. CHIRPLET TRANSFORM

Chirplet transform was introduced in [19-21]. Its basis functions are derivable in time-frequency domain, while the derivation of the basis functions of the wavelet transform and short-time Fourier transform (STFT) are limited to the time domain, therefore the chirplet transform is a generalization of both former transforms. Furthermore, chirplet transform has more degrees of freedom than the wavelet transform, which allows the transform to identify up to eight signal parameters depending on the mother chirplet, and the application. Also, since the sinusoids are subsets of the chirplet, Gabor transform can be regarded as a special case of the chirplet transform. Chirplet analysis has been successfully applied to radar detection of moving objects in oceans, outperforming Doppler radar methods. Authors in [22] extended their work to address issues pertaining to the large number of parameters identified by their method and introduced an improved one that selects an adapted set of bases using the expectation maximization. The new method was named adaptive chirplet transform.

III. Application of Chirplet Transform to Conventional Ultrasonic Testing

The first application of the chirplet transform to ultrasonic NDT signals was the echo signal's parameter estimation [23, 24] which was an extension of an earlier work that used maximum likelihood estimation (MLE) principles to calculate amplitude, arrival time, center frequency, bandwidth, phase, and chirp rate [25, 26]. The selection of the chirplet transform assumed that ultrasonic echoes are composed of a superposition of chirplet echoes, so the close similarity between the analyzing chirplet and measured ultrasonic signals offers optimal representation. The chirplet transform has been used to represent the ultrasonic signal in the time-frequency domain decomposing it into a linear combination of Gaussian chirplets and then iteratively apply parameter estimation algorithm to each identified echo by applying a windowing strategy to segregate the individual echoes. The flowchart of the signal processing procedure and the equations for the echo parameter estimations based on the solutions of the chirplet transform are presented in [24]. The application of the transform via windowing is challenged by the design requirements of the window as the width should be small enough to limit the amount of noise during signal estimation but it should be wide enough to contain the required signal's information. Moreover, the performance can be deteriorated when closely-spaced reflectors are present. The method is comprehensive and advantageous because it calculates the parameters necessary to characterize the physical properties of the reflectors (flaws or materials' interface) and can be used for applications like target detection, data compression, deconvolution, object classification, velocity measurement, and ranging systems.

The performance of the method was compared to another signal processing method, the empirical mode decomposition (EMD) coupled with Hilbert transform [27]. The chirplet-based method performed better in the case of signals with interfering and overlapped chirplets. The performance demonstration of the above applications was carried out by inspecting a steel block with a flat-bottom-hole in a contact pulse-echo mode using a 5MHz probe. The same method was applied to analyze and estimate ultrasonic echoes in the testing of reverberant multilayered materials, which is an important and challenging application that examines the thin planner defects, disbonding, and lamination [28]. The estimated parameters were used to classify the ultrasonic echoes and calculate the physical properties of a layered structure such as layer thickness. The performance demonstration was carried out by inspecting a steel block with a flat-bottom-hole in an immersion testing setup using a 10MHz probe. The waveform acquired for the experimental verification of the method had high SNR and well-resolved echoes. The chirplet transform is suitable to play role in noise suppression and resolution enhancement in the inspection of composite and bonded materials.

IV. Application of Chirplet Transform to Ultrasonic Lamb Waves in NDT and SHM

The frequency content of the dispersive signal is time-varying, so using a time-frequency representation like the chirplet transform is suited for signal processing of the dispersive curves and defect's echoes identification. Authors in [29] introduced the chirplet transform to the signal processing of guided waves. They analyzed the theoretical time-frequency resolution of the transform in the dispersive waves. The application of the transform to the measured signals revealed that it is better than the STFT in the analysis of dispersive waves because the time-frequency tiling of the chirplet transform is adapted to the dispersion characteristics. Furthermore, an adaptive method was developed to simplify the analysis of the dispersion relationships of the measured signals. The research in [29] paved the way for the application of the transform to guided waves. Authors in [30] proved that a model-based chirplet transform method was effective in determining the energy distribution of the dispersive lamb waves. The Rayleigh-Lamb equations have been used to model the dispersion relationship and an adaptive method to calculate the frequency of the modes. The proposed method was used to address the inconsistency of the standard transform solution with the theoretical solution in the case of dispersive curves intersection.

Many researchers have proposed variant chirplet transform algorithms to address the complexity problem due to the number of dimensions of the standard transform. One method used to simplify the computation and interpretation is the matching pursuit [31], which was used to implement the chirplet transform for the application to SHM guided waves in isotropic plate structures using the pulse-echo testing method [32]. The trace resulting from the difference between the measured and a reference signal is processed using matching pursuit algorithm to calculate the time-frequency centers, chirp rate and energies of the signal. The matching pursuit is applied continuously until the energies of the signal atoms are 10% or lower of the first extracted atom. The frequency centers that do not belong to the excited bandwidth are discarded and the damage status of the structure is evaluated based on the calculated energies. The processing is carried on with mode correlation using the determined chirp rates, and the parameters of the identified modes are used to locate and characterize the defects. Authors regarded this version of the chirplet transform better than the conventional methods in resolving the multimodal reflections, robust in noisy signals, and computationally efficient. Future works promised by the authors were the application of the method to the guided wave inspection of the composite structures and revisiting the adopted assumption of point-scatterer, however no related research was found in the relevant literature.

Recently, chirplet matching pursuit has been presented to evaluate the damage in aerospace structures. The method utilizes a library of simulated damage signals generated by varying damage parameters of crack length, depth, and orientation [33]. The successful applications of the chirplet transform in the guided wave inspection motivated researchers to seek further solutions by employing this method. An adaptive algorithm based on chirplet transform has been introduced to evaluate its merits for dispersive mode analysis and calculate the mode displacement ratios and attenuation of lamb waves in [34]. The algorithm, which considered 5-dimensional parameters of the chirplet transform, uses basis functions designed to suit the dispersion relation of each mode.

A windowing technique was used to average the energy contents that belong to all points of the dispersive curves. The method offered advantages over the STFT in resolving the modes and extracting the required information. The limitations of sensitivity to noise, parameter uncertainties, and the need for accurate prior knowledge about the material properties and geometry demand research to improve the robustness of the method for this application. Another contribution to ultrasonic guided wave signal processing was brought by the authors in [35] who modified an algorithm that presented a spare representation of the signal using chirplets [36] to develop a chirplet mode decomposition technique for the separation of individual modes in a multimodal torsional signals measured in the magnetostrictive guided wave inspection of pipelines. To ease the implementation, authors replaced an MLE equation of those of [36] with a procedure that estimates the chirp rate and duration, uses the estimates to locate the chirp in time and frequency, re-estimates form a local measure, and uses the quasi-Newton procedure to find the closest local maximum of the likelihood function. This algorithm is a novel and reliable estimator for the parameters of multicomponent signals. The use of the procedure allows a precise calculation of the group velocity, amplitude, and modal energies, which are used to calculate the reflection coefficients, which are in turn used for defect sizing. The research results have been applied to the detection and characterization of pipe defects using torsional guided waves [37, 38]. An approach for resolution improvement and image fusion was developed in [39]. It comprises adaptive chirplet transform, Vold-Kalman filter, and a method for image fusion. The adaptive chirplet transform role in the method was to identify the signal components and estimate the instantaneous frequencies. The Vold-Kalman filter was used as a time-varying filter to use signal parameters, calculated by the adaptive chirplet transform to extract the time-domain waveforms reflected from the defects. Investigating alternative methods to the Vold-Kalman filter and comparing the performances can be a space for development in the use of adaptive chirplet transform in lamb wave applications.

V. CONCLUSIONS

The review revealed that the amount of research on ultrasonic NDT and SHM signal processing does not match the versatility and inclusiveness offered by the transform. The various variants of the chirplet transform are qualified to provide more and additional robust and effective solutions. Various implementations of the chirplet transform were successfully applied to ultrasonic signal processing, with most applications targeting the improvement of the dispersive curves' resolution in ultrasonic guided wave NDT and SHM applications. Published studies were reviewed to show the research progress since the transform was first applied to ultrasonic NDT and SHM, the areas of application, its advantages, and to briefly highlight the potential openings for further development, or to inspire new novel applications.

ACKNOWLEDGMENT

This study was supported by the Ministry of Knowledge Economy (MKE) through the Regional Innovation Centre program.

REFERENCES

[1] P. J. Shull, Nondestructive Evaluation: Theory, Techniques and Applications, Marcel Dekker, 2001

[2] C. Hellier, Handbook of Nondestructive Evaluation, McGraw-Hill, 2003

[3] American Society for Nondestructive Testing, Nondestructive Testing Handbook Volume 7: Ultrasonic Testing, Columbus, 2007

[4] L. W. Schmerr. Jr, J. S. Song, Ultrasonic Nondestructive Evaluation Systems: Models and Measurements, Springer, 2007

[5] Z. Su, L. Ye, Identification of Damage Using Lamb Waves, Vol. 48, Springer London, 2009

[6] S. K. Sin, C. H. Chen, "A comparison of deconvolution techniques for the ultrasonic nondestructive evaluation of materials", IEEE Transactions on Image Processing, Vol. 1, No. 1, pp. 3-10, 1992

[7] F. Honarvar, H. Sheikhzadeh, M. Moles, A. N. Sinclair, "Improving the time-resolution and signal-to-noise ratio of ultrasonic NDE signals", Ultrasonics, Vol. 41, No. 9, pp. 755-763, 2004

[8] H. Jin, K. Yang, S. Wu, H. Wu, J. Chen, "Sparse deconvolution method for ultrasound images based on automatic estimation of reference signals", Ultrasonics, Vol. 67, pp. 1–8, 2016

[9] S. J. Mirahmadi, F. Honarvar, "Application of signal processing techniques to ultrasonic testing of plates by S0 Lamb wave mode", NDT & E International, Vol. 44, No. 1, pp. 131-137, 2011

[10] E. P. de Moura, M. H. S. Siqueira, R. R. da Silva, J. M. A. Rebello, L. P. Caloba, "Welding defect pattern recognition in TOFD signals Part 1. Linear classifiers", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 47, No. 12, pp. 777-782, 2005

[11] S. L. S.Lalithakumari, B. S. B.Sheelarani, B. V. B.Venkatraman, "Artificial Neural Network based Defect Detection of Welds in TOFD Technique", International Journal of Computer Applications, Vol. 41, No. 20, pp. 17-20, 2012

[12] G. K. Sharma, S. Bhagi, S. Thirunavukkarasu, B. P. Rao, "Wavelet transform-based approach for processing ultrasonic B-scan images", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 59, No. 2, pp. 93-99, 2017

[13] M. S. Mohammed, K. Ki-Seong, "Signal conditioning for the recursive least-squares filter in ultrasonic testing of materials", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 59, No. 11, pp. 591-595, 2017

[14] M. S. Mohammed, K. Ki-Seong, "Shift-invariant wavelet packet for signal de-noising in ultrasonic testing", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 54, No. 7, pp. 366-370, 2012

[15] M. S. Mohammed, K. Ki-Seong, "Improving an adaptive filtering system for ultrasonic testing", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 56, No. 5, pp. 240-245, 2014

[16] W. H. Prosser, M. D. Seale, B. T. Smith, "Time-frequency analysis of the dispersion of Lamb modes The Journal of the Acoustical Society of America, Vol. 105, No. 5, pp. 2669-2676, 1999

[17] M. Niethammer, L. J. Jacobs, J. Qu, J. Jarzynski, "Time-frequency representations of Lamb waves", The Journal of the Acoustical Society of America, Vol. 109, No. 5, pp. 1841-1847, 2001

[18] L. De Marchi, A. Marzani, S. Caporale, N. Speciale, "Ultrasonic guided-waves characterization with warped frequency transforms", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 56, No. 10, pp. 2232-2240, 2009

[19] S. Mann, S. Haykin, "The Chirplet Transform : A Generalization of Gabor' s Logon Transform", Vision Interface, Vol. 91, pp. 205-212, 1991

[20] S. Mann, S. Haykin, "Chirplets' and 'warblets': novel time–frequency methods", Electronics Letters, Vol. 28, No. 2, pp. 114-116, 1992

[21] S. Mann, S. Haykin, "The chirplet transform: physical considerations", IEEE Transactions on Signal Processing, Vol. 43, No. 11, pp. 2745-2761, 1995

[22] S. Mann, "Adaptive "chirplet" transform: an adaptivegeneralization of the wavelet transform", Optical Engineering, Vol. 31, No. 6, pp. 1243-1256, 1992

[23] Y. Lu, R. Demirli, "Chirplet transform for ultrasonic signal analysis and NDE applications", IEEE Ultrasonics Symposium, Rotterdam, The Netherlands, March 6, 2006

[24] Y. Lu, R. Demirli, G. Cardoso, J. Saniie, "A successive parameter estimation algorithm for chirplet signal decomposition", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 53, No. 11, pp. 2121-2131, 2006

[25] R. Demirli, J. Saniie, "Model-based estimation of ultrasonic echoes. Part I: Analysis and algorithms", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 48, No. 3, pp. 787-802, 2001

[26] R. Demirli, J. Saniie, "Model-based estimation of ultrasonic echoes. Part II: Nondestructive evaluation applications", IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 48, No. 3, pp. 803-811, 2001

[27] Y. Lu, E. Oruklu, J. Saniie, "Chirplet Signal and Empirical Mode Decompositions of Ultrasonic Signals for Echo Detection and Estimation", Journal of Signal and Information Processing, Vol. 4, No. May, pp. 149-157, 2013

[28] Y. Lu, R. Demirli, E. Oruklu, J. Saniie, "Estimation and classification of ultrasonic echoes backscattered from reverberant multilayered materials", International Congress on Ultrasonics, Vienna, Austria, April 9-13, 2007

[29] J. C. Hong, K. H. Sun, Y. Y. Kim, "Dispersion-based short-time Fourier transform applied to dispersive wave analysis", The Journal of the Acoustical Society of America, Vol. 117, No. 5, pp. 2949-2960, 2005

[30] H. Kuttig, M. Niethammer, S. Hurlebaus, L. J. Jacobs, "Model-based analysis of dispersion curves using chirplets", The Journal of the Acoustical Society of America, Vol. 119, No. 4, pp. 2122-2130, 2006

[31] S. G. Mallat, Z. Zhang, "Matching pursuits with time-frequency dictionaries", IEEE Transactions on Signal Processing, Vol. 41, No. 12, pp. 3397-3415, 1993

[32] A. Raghavan, C. E. S. Cesnik, "Guided-wave signal processing using chirplet matching pursuits and mode correlation for structural health monitoring", Smart Materials and Structures, Vol. 16, No. 2, pp. 355-366, 2007

[33] H. Zhang, C. E. S. Cesnik, "Damage characterization based on nonlinear guided wave simulation and chirplet matching pursuit algorithm", Health Monitoring of Structural and Biological Systems XII, Denver, USA, March 4-8, 2018

[34] F. Kerber, H. Sprenger, M. Niethammer, K. Luangvilai, L. J. Jacobs, "Attenuation Analysis of Lamb Waves Using the Chirplet Transform", EURASIP Journal on Advances in Signal Processing, Vol. 2010, No. 1, 2010

[35] C. Y. Kim, K. J. Park, "Mode separation and characterization of torsional guided wave signals reflected from defects using chirplet transform", NDT & E International, Vol. 74, pp. 15-23, 2015

[36] J. C. O'Neill, P. Flandrin, W. C. Karl, "Sparse representations with chirplets via maximum likelihood estimation", IEEE Transactions on Signal Processing, Vol. 48, pp. 42-53, 2000

[37] C. Y. Kim, K. J. Park, "Characterization of Pipe Defects in Torsional Guided Waves Using Chirplet Transform", Transactions of the Korean Society for Noise and Vibration Engineering, Vol. 24, No. 8, pp. 636–642, 2014

[38] Y. W. Kim, K.J. Park, "Application of chirplet transform for detecting axial cracks in pipes using torsional guided modes", Insight-Non-Destructive Testing and Condition Monitoring, Vol. 59, No. 3, pp. 138-143, 2017

[39] L. Zeng, M. Zhao, J. Lin, W. Wu, "Waveform separation and image fusion for Lamb waves inspection resolution improvement", NDT & E International, Vol. 79, pp. 17-29, 2016