Interaction of Higher Order Modes Cluster (HOMC) guided waves with notch-like defects in plates

Cite as: AIP Conference Proceedings **1806**, 030015 (2017); https://doi.org/10.1063/1.4974583
Published Online: 16 February 2017

Sri Harsha Reddy K., Prabhu Rajagopal, Krishnan Balasubramaniam, et al.

Interaction of Higher Order Modes Cluster (HOMC) Guided Waves with Notch-like Defects in Plates

Sri Harsha Reddy K[1, a)], Prabhu Rajagopal[1], Krishnan Balasubramaniam[1], Samuel Hill[2], and Steve Dixon[2]

[1]*Centre for Non-Destructive Evaluation, Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai*
[2]*Ultrasonics Group, Department of Physics, University of Warwick, United Kingdom*

[a)]Corresponding author: k.sriharsha85@gmail.com

Abstract. Guided ultrasonic waves are widely used for long range inspection. Higher Order Modes Cluster (HOMC), discovered at the author's research group [1-3] consist of multiple higher order guided wave modes that travel together as a single wave-packet and without appreciable dispersion for distances in the range of meters. These waves not only propagate along the length of the structure but also cover the entire thickness, and in view of the higher frequencies, they can offer improved resolution over conventional low-frequency guided waves. This paper studies the sensitivity of axial plate HOMC to notch-like defects, evaluated by calculating wave reflection co-efficient. The studies are carried out using finite element models validated by experiments. Analysis is presented for better understanding of wave-defect interaction. Advantages and limitations for practical realization of the above approach are also discussed.

INTRODUCTION

In-process inspection of structures in industrial processes such as welding is essential for maintaining its overall integrity. Recently, ultrasonic guided waves based inspection has gained much attention, especially in the oil and gas industry, as they offer several advantages such as the ability to scan relatively large structures from a single transducer location and inspect both surface as well as internal defects due to their through-thickness modal nature. In addition to this, they can be selectively used for inspecting parts of layered or coated surfaces.

Conventionally, guided wave based methods are used in low frequency regime with an emphasis on selectively generating non-dispersive lower order modes in structures. However, the comparatively longer wavelength limits the spatial resolution of inspection. This can be improved with high operating frequencies compromising on the inspection range.

The recently discovered Higher Order Mode Cluster (HOMC) waves are attractive for this purpose, typically for an inspection range less than a meter. HOMC waves consist of multiple higher order guided waves that travel together as a cluster and without much dispersion for distances in the range of meters [1-3].

In this work, we demonstrate the interaction of HOMC waves with defects in the form of notches of different depths in mild steel plate. Finite Element (FE) simulations are used to gain insight into the wave-defect interaction. The reflection coefficient behavior study through simulations and experiments are then examined.

The outline of the paper is as follows. Initially, Lamb wave dispersion curves in mild steel plates are discussed, helping to predict the propagation characteristics of HOMCs as well as providing insights on how they can be generated. A description of the experimental set-up and procedure is then given, followed by the procedure for the simulation studies. Results for HOMC waves scattered by the notches are then presented and discussed in sight along with analytical validations, after which we conclude with directions for further work.

43rd Annual Review of Progress in Quantitative Nondestructive Evaluation, Volume 36
AIP Conf. Proc. 1806, 030015-1–030015-7; doi: 10.1063/1.4974583
Published by AIP Publishing. 978-0-7354-1474-7/$30.00

GENERATION OF HOMC

Recently, a group of higher order guided wave modes in plates were discovered that travel over medium range distances as a relatively non-dispersive cluster [1-3]. These Higher Order Modes Cluster (HOMC) waves are formed at a frequency thickness of between 15 MHz-mm and 40 MHz-mm, and are composite waves formed from the interference of several individual modes that travel with very similar speeds. In the high frequency-thickness region, the excitation angles for multiple modes are converging to a similar value, multiple modes are generated and the cluster of waves generated display properties different to the individual modes.

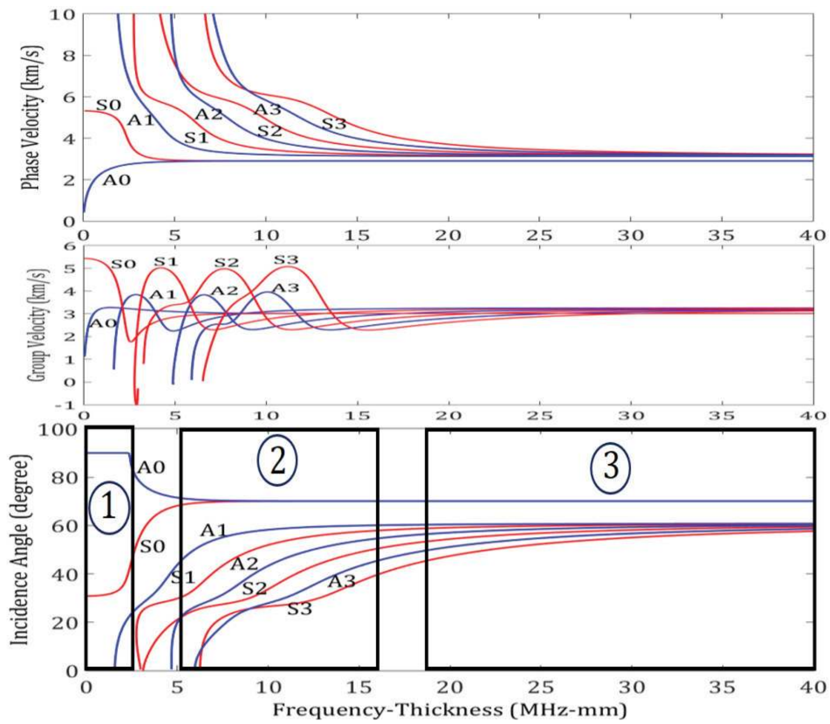


FIGURE 1. Variation of incidence angle with Frequency thickness for mild steel. Plotted using DISPERSE [4]; A - Dispersion region and B – non-dispersion region

Figure 1 shows the variation of incidence angle with the frequency-thickness product, for the Lamb modes that can be supported by a mild steel plate. The curves were plotted using DISPERSE [4] for obtaining characteristics of guided waves in simple waveguides. An optimal generation of HOMC waves occurs at about 52° and a wedge of this angle can be used for generating them using the angle-beam technique [1].

EXPERIMENTAL STUDIES

Experimental Setup

Experiments were performed on a mild steel plate of 10 mm thickness, 1 m length and 0.6 m width. HOMC waves were generated using a piezoelectric crystal mounted on a plexi-glass wedge with an angle of 52˚relative to the plate surface, and driven using a RITEC pulser receiver (RITEC Inc. USA, RPR-4000) at a frequency of 2 MHz. An ultrasonic couplant gel was used to effectively couple ultrasonic energy to the plate. A photograph of the experimental setup is shown in Fig. 2(a).

(a) (b)

FIGURE 2. Photograph of (a) experimental setup; (b) Plate showing the machined notches as a percentage of thickness.

Pulse echo configuration is used to capture the signals which are observed and recorded for subsequent analysis on a digital storage oscilloscope (Agilent Technologies DSX2012-A). Rectangular notches 5 different depths (5%, 10%, 20%, 30% and 50% of plate thickness) were machined on the plate through milling process. The notches are of 10 mm length and 2 mm width as shown in Fig. 2(b). The notches are located 10 cm away from one end of the plate. The distance is to ensure proper separation of the wave echoes from the notch and the plate end.

Experimental Procedure

The PZT Plexiglas-wedge transducer was excited using a 3 cycle tone-burst, with a center frequency of 2 MHz, generated by the RITEC pulser-receiver in a pulse-echo configuration. The transducer was placed on a perpendicular line bisecting each of the 5 notches, at a distance of 400 mm from the notch location, in different measurement runs. Waves scattered by the notches were received using a digital oscilloscope and were recorded for further analysis. Signals received were averaged using 128 ensembles for each reading to improve the signal to noise ratio. Also, the measurements were repeated five times for each notch depth case, in order to account for variability and ensure repeatable results. The performance of the HOMC modes waves is compared quantitatively through the reflection coefficient, which is the spectral ratio of displacement of the reflected signal to that of the incident signal in frequency domain. The incident signal is taken as the reflection from the plate edge; Separate readings were taken for this purpose with the wedge at a distance of 400 mm from the edge.

A frequency analysis of the signal recorded on the oscilloscope was done. The Fast Fourier Transform was applied to the signal to get the distribution of the signal across the frequency spectrum. The peak amplitude for each run, which occurred about the center-frequency excited, was noted and a mean value was calculated for the 5 readings taken for each notch depth case. This procedure was repeated for the incident signal. In order to understand the underlying wave mechanics, the reflection coefficient is plotted as a function of notch depth to wavelength.

FINITE ELEMENT SIMULATIONS

In order to gain more insight into the propagation and scattering of the high-frequency guided waves, finite element simulation implemented in the commercial package ABAQUS 6.12 [5] was used. A 2D plane strain model was created for the studies, with the wedge and the plate modeled separately and connected using continuity conditions. The wedge was modeled as Plexiglas and the plate was modeled as mild steel. A 3 cycle Hanning windowed tone-burst signal centered at a frequency of 2 MHz was used as the force input to excite the system. A finite line source was used to model a one inch diameter probe for the HOMC waves, in order to mimic the experimental conditions. The material properties, as well as the other FE parameters, used in the simulations are listed in Table 1.

TABLE 1. Finite element parameters used in simulations

FE Parameter	Plate	Wedge
Material	Mild Steel	Acrylic/Plexiglas
Density	7850 kg/m^3	1180 kg/m^3
Young's Modulus	210 GPa	4.5 GPa
Poisson's ratio	0.28	0.37
Model Type	2D Plane Strain	2D Plane Strain
Element Size	λ/18	λ/18
Element Type	Linear Quadrilateral	Linear Triangular

A 10 mm by 600 mm mild steel plate is modeled as a test specimen using Absorbing Layers with Increasing Damping (ALID) [6] at both ends of the plate. The transducer wedge is placed at a distance of 400 mm from the notch. The excitation signal is generated from the wedge. Outputs requested are the displacements U_x and U_y of the monitoring points. The incident signal was obtained in the FE simulations the same way as in the experiments, by noting the wave reflected from the plate edge. The schematic representation of the model used for FE simulations is shown in Fig. 3.

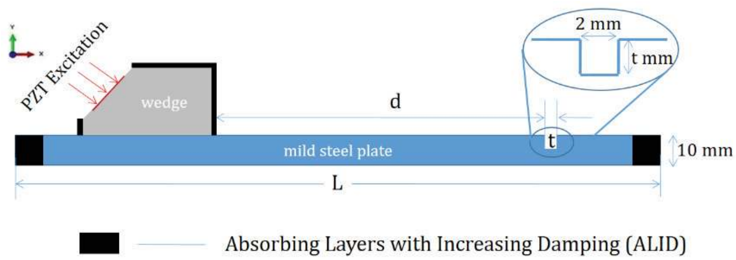


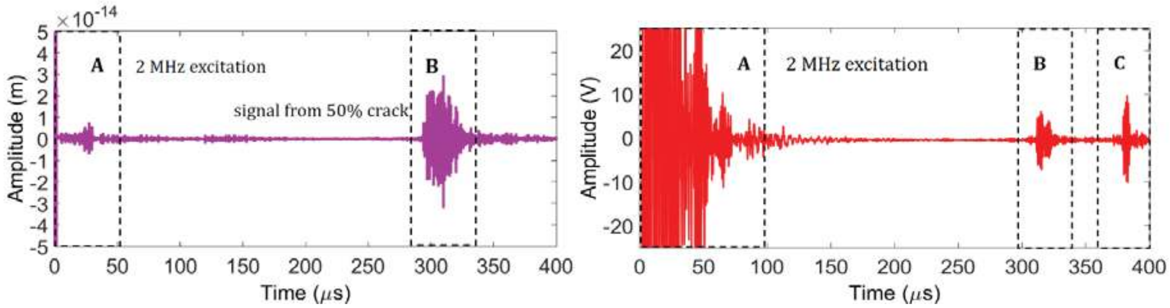
FIGURE 3. The schematic representation of the 2D model for FE simulations

The simulation is conducted for higher order mode cluster (HOMC) waves. The goal is to study the variation of reflection coefficient (RC) with variation in the notch depth. For this case the defect depths are varied from 5% to 50%, and the variation of RC for different notch depths will be calculated.

RESULTS

HOMC Scattering for Notches

For the FE simulations, the output was obtained by monitoring the displacement of a point on the transmitting surface of the wedge as pulse-echo method was performed. The output obtained in the 50% notch depth case is shown in Fig. 4(a). There are different regimes in the plot, including the incident wave and reflection from the defect. The reflection from the plate edge will not be present here as an ALID was used at both ends of the plates. The reflection from the defect occurs at about 300 μs. This is absent in the case of the plate with no defect.



(a) (b)

FIGURE 4. Time trace for 50% notch defect case obtained from (a) FE simulation, (b) Experiment; Regions marked 'A', 'B' and 'C' show the initial wave, the reflection from the notch defect and reflection from end of plate

For each notch depth, the signals recorded from the experiments were coherently averaged 128 times. Figure 4(b) shows the experimental time record signal obtained for the 50% case. The different regimes in the signal can be observed. For example, the initial part of the signal contains noise from multiple reflections inside the wedge. The echo from the notch can be observed from 300 μs to 320 μs. Finally, the reflection from the plate end can be observed from 360 μs to 380 μs. The modulus of the reflection coefficient, calculated at the center-frequency from experimental and FE results, is plotted with the notch depth, as shown in Fig. 5.

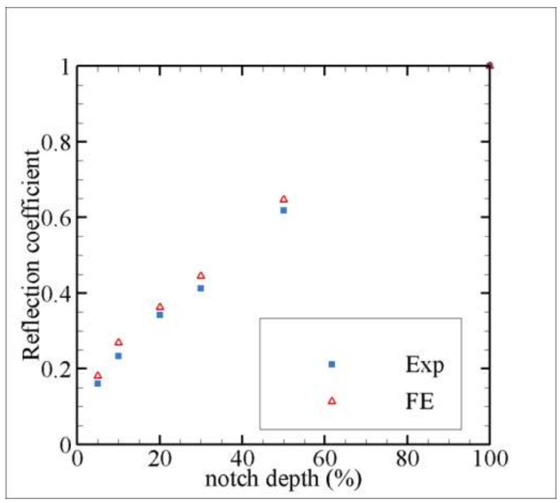


FIGURE 5. A plot of reflection coefficient against percentage of notch depth

In general, we observe, as expected, that the RC increases as the notch depth increases. The low sensitivity for lower notch depths, was seen in the experimental results which represents in **Fig. 5**. The variation in the results of FE and experiments is likely due to the fact that in the simulations, we used a plane wave approximation whereas in the experiments, beam divergence exists. As the notch depth increases, higher percentage of the incident wave is reflected back, and both results agree better. We were unable to perform fully 3D FE simulations, as the computational requirements were prohibitive: the smallest 3D model required, need about 300 million degrees of freedom.

DISCUSSION

In this section, we make use of analytical methods to understand more physical insight into the trend presented in the results section. From Fig. 5, it was observed that the reflection ratio increases monotonically with crack depth**.** Here, an analysis of reflection behavior based on the Kirchhoff approximation valid at high frequencies is useful by making use of representation integrals and notations as reported previously in [7-9].

The reflection ratio is given by Eqn. (1)

$$R(b, l, \omega)= \frac{u_k^{sc}(\vec{r},\omega)}{u_i^{inc}(\vec{s},\omega)} \tag{1}$$

Where $u_i^{inc}(\vec{s}, \omega)$ is the incident displacement field and $u_k^{sc}(\vec{r}, \omega)$ is the scattered displacement field.

Using the high-frequency Kirchhoff approximation [7], we have $u_i(\vec{s}, \omega) = u_i(\vec{s} \in S^+, \omega) = 2u_i^{inc}(\vec{s}, \omega)$. With the assumption that the incident wave field as well as the stress fields in the absence of any defects are uniform across the crack face. Since HOMC is a combination of several higher order modes, the equation reduces to the following and can be written as

$$R(b, l, \omega) = \frac{2l}{\mathrm{P}u_0(\omega)} \int_0^b u_i^{inc}(y, \omega) \sum_{p=0}^{n} Wp(\sigma_{ij}^{p})(y, \omega) dy \tag{2}$$

Where, $u_0(\omega)$ is the (known) incident displacement spectrum is obtained at a convenient position, l is the crack length, b is the notch depth, ω is given frequency, P is the Poynting vector, dy refer to the infinitesimal dimension in the thickness direction, σ_{ij} is the in-plane stress component, u_i is the in-plane displacement component, W_p is weight of the mode and n is the number of modes in the cluster.

Modal Decomposition

As previously mentioned, HOMC is a combination of several higher order modes in the cluster. For understanding the contribution of each mode in the cluster, modal decomposition is performed to find out the weights of each mode present in the cluster. In order to perform this, displacement profile of each individual mode across the thickness is obtained using DISPERSE [4] software package. In addition, by monitoring the points across the thickness while performing the finite element simulations, a displacement profile was plotted. Here, a Genetic Algorithm technique was used in MATLAB for predicting the weights of each mode in the cluster using both FE and analytical profiles (the summation of displacement profiles for all modes). The predicted modal weights of the incident HOMC wave before interacting with the defect was obtained by using the GA, and is shown in the **Table 2**.

TABLE 2. Weights for each mode from model decomposition before interacting with the defects

Weights Predicted							
A0	**S0**	**A1**	**S1**	**A2**	**S2**	**A3**	**S3**
0.61	0.62	1.39	0.18	0.16	0.28	0.16	0.06

These weights are superimposed with each of the analytically obtained displacement profiles for each mode to form the displacement profile of the HOMC as a whole. This composite displacement profile is in good agreement with the displacement profile plotted using FE simulations. The combined resultant displacement profile plot for both FE and Analytical methods is shown in the **Fig. 6**, which implies that predicted weights using GA are accurate.

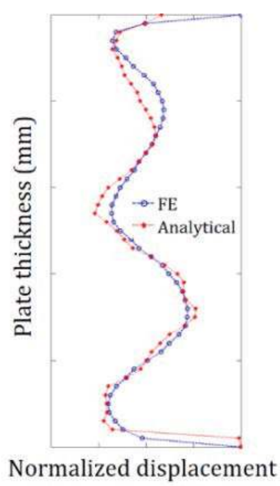


FIGURE 6. A plot of displacement profile across thickness

These mode values depend on parameters such as material, wedge angle and frequency-thickness product. This shows for the composition of the higher order modes cluster to be tailored to the desired requirement. If surface sensitivity is required, the HOMC can be composed of a higher proportion of modes with large amounts of surface displacement. Conversely, the HOMC can be made to be insensitive to surface conditions by utilizing modes with most of the energy concentrated in the center of the plate. Indeed, in some circumstances, it has been shown that it is possible to only generate a high frequency A1 mode, which as minimal displacement on the surface of the plate [10]. It should also be noted that, for a given case, the weights predicted using GA will change upon defect interaction since the scattered field vary with defect depth. This phenomenon can be explained using Eqn. (2). The weights of the modes predicted for each defect case is shown below in the Table 3.

TABLE 3. Weights for each mode from model decomposition after interacting with the defects, for a mild-steel plate of 10 mm thickness at 2 MHz

	Predicted Weights							
% defect	**A0**	**S0**	**A1**	**S1**	**A2**	**S2**	**A3**	**S3**
5	0.38	0.05	0.86	0.06	0.32	0.54	0.25	0.09
10	0.83	0.50	0.75	0.35	0.31	0.39	0.04	0.09
20	0.60	0.88	0.66	0.37	0.31	0.20	0.03	0.35
30	0.09	0.49	0.00	0.05	0.34	0.07	0.27	0.45
50	0.91	0.51	0.75	0.48	0.01	0.21	0.03	0.03

CONCLUSIONS AND FUTURE WORK

This paper demonstrated the feasibility of using higher frequency guided mode clusters (HOMC) for remote inspection of notch defects which can develop during manufacturing processes. Experiments also demonstrated the ability to estimate the notch depth by measuring the reflection coefficient which increases monotonically with increase in notch depth. Our experimental measurements are in good agreement with the numerical and analytical results. The inverse model used, gives promising information regarding the contribution of the individual modes present in the cluster. Further investigations are underway to develop an online inspection technique to monitor pipe welding processes.

REFERENCES

1. L. Satyarnarayan, J. Chandrasekaran, and B. W. Maxfield, NDT & E International, **41**, 32–43 (2008).
2. J. Chandrasekaran, I. Anto, K. Balasubramaniam, and K. S. Venkataraman, Insight Non-Destruct. Test. Condition Monitoring, **51**(6), 606–611 (2009).
3. D. Ratnam, K. Balasubramaniam, and B. W. Maxfield, IEEE Transactions, Ultrasonics, Ferroelectrics, and Frequency Control, **59**, 727–737 (2012).
4. B. Pavlakovic, M. Lowe, P. Cawley, D. Alleyne, "Disperse: A general purpose program for creating dispersion curves," in *Review of Progress in Quantitative Nondestructive Evaluation*, eds. D.O. Thompson and D.E. Chimenti, (Plenum: New York), **16,** 185-192 (1997).
5. ABAQUS 6.12 user's manual, 2012, http://abaqusdoc.ucalgary.ca/v6.12/
6. Rajagopal P, Drozdz M, Skelton M, Lowe M J S, and Craster R, NDT & E International **51**, 30–40 (2012).
7. Rajagopal P. Towards higher resolution guided wave inspection: scattering studies. PhD thesis. Imperial College London: Mechanical Engineering Department; 2007 available online at: https://workspace.imperial.ac.uk/nde/Public/Prabhu_Rajagopal_Thesis.pdf
8. Rajagopal, P. and M.J.S. Lowe, Journal of the Acoustical Society of America, **122**(3), 1527-1538 (2007).
9. Prabhakaran Manogharan, Xudong Yu, Zheng Fan, Prabhu Rajagopal, NDT & E International, **75**, 39-47 (2015).
10. Pauyan Khalili and Peter Cawley, IEEE Transactions, Ultrasonics, Ferroelectrics, and Frequency Control, **63**, 303-312 (2016).