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Scattering of Guided Wave Modes by a Thick Austenitic Stainless Steel Weld:

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Abstract

The study involves observation of scattering of guided Lamb wave modes from columnar grains of austenitic stainless steel weld. By edge mounting transducers of different frequencies, scattered wave modes are received from the double V weld in a 28 mm thick austenitic stainless steel plate. Time signals representing scattered wave modes are transformed into slowness-frequency domain for the known propagation distance of 398 mm, using reassigned short-time Fourier transform method. This results in reassigned spectrograms of the experimental dispersion curves. To identify the modes in the spectrograms, reassigned spectrograms are superimposed with theoretical dispersion curves, obtained using Disperse software. The modes are found to match well with the theoretical dispersion curves.To confirm the scattering phenomenon, reassigned spectrograms for incident modes are obtained from a plate of 28 mm thickness without welds using the through transmission method (edge mounting transducers). The results show that the incident modes for frequencies 1 MHz to 5 MHz comprise of many modes and are essentially non-dispersive. With the help of the high resolution reassigned spectrogram method, non-dispersive incident modes are found to be scattered selectively by the columnar grains into different individual modes.

1.Introduction

Guided waves are useful for damage detection due to a shorter testing times and long range propagation. Large plate-like structures and long tubular structures used in mechanical engineering, civil engineering, aerospace engineering and nuclear industries are examined using ultrasonic guided waves due to long testing times involved in conventional testing. Guided waves often come in numerous modes with different phase velocities and group velocities. The advantages of long range propagation and short testing times come with the price of unavoidable dispersion, mode conversions, multimodal behaviour, etc.The interpretation of guided wave signals is thus, complicated. Therefore, very often researchers resort to numerical modelling and signal processing techniques to achieve successful interpretation of signals. Along with the above complexities, guided waves can undergo scattering causing further difficulties in interpretation. When guided waves interact with a defect, they undergo mode conversion accompanied by scattering, in general. Scattering of guided waveswith defects can significantly alter the propagation properties of guided waves.

Scattering of bulk waves by defects and grains has been understood thoroughly with a good number of theoretical models. Similarly, scattering of guided waves by defects in engineering structures are understood to a large extent. Grahn [1] studied scattering of guided waves in plates with a circular partly through-thickness hole. Mckeon etal. [2] studied scattering of the lowest order symmetric Lamb modes from a circular inclusion, using a higher order plate theory. Norris [3] studied the theory of scattering of flexural wave from an elastic heterogeneity in a flat thin plate, using Mindlin plate wave theories. Lu et al. [4] studied the interaction of Lamb wave modes at different frequencies with a through thickness crack of different lengths in aluminium plates, using finite element method and experiments. It is seen that the most of the studies on scattering of guided waves are mainly focussed on the damage (open to the surface). In addition to the above, guided waves can undergo scattering at grain boundaries. It is seen in literature that the area of scattering at grain boundaries has not drawn much attention so far. To mention, Sundin et al. [5] have extended Lamb waves to estimate grain size in thin copper sheets using attenuation by scattering.

The present study deals with the observation of scattering of Lamb waves from austenitic stainless steel weld grains. To the best of the authors' knowledge, scattering from austenitic stainless weldements has not been reported so far. The study involves propagation of Lamb waves in a 28 mm thick austenitic stainless steel plate with a double V weld with 2.5 mm in the centre and 16.5 mm at the top and the bottom. The material chosen is a reactor grade material of prototype fast breeder reactor's main vessel plate.

In the experiment, guided waves were launched from an edge and made to propagate through the weld.The scattered modes were subsequently picked by the edge mounted transducer. First, the real challenge is to interpret numerous modes, whichare seen to present simultaneously due to the large frequency-thickness products. Secondly, the multimode guided waves undergo scattering at the columnar grain boundaries and generate further higher order modes. Third challenge lies in identifying the modes scattered. It will be shown in the paper that, the scattered multimodesare identifiedto a large accuracy,by generating dispersion curves of slowness versus frequency using time-frequency reassigned spectrograms and superposing them with the theoretical dispersion curves obtained using the Disperse software. The paper is organized as follows: time-frequency reassigned spectrogram theory forgenerating dispersion curves, experimentation, results and discussion and conclusion.

2. Theory:the reassigned spectrogram

Time-frequency representations (TFRs) are usually made for Lamb waves because of theirmutimodal nature. TFRs used to characterize Lamb waves, are based on short time Fourier transform (STFT)-spectrogram, Wigner-Ville distribution (WVD) or Wavelet transform (WT).The spectrogram has the advantage of bearing constant time-frequency resolution over all times but suffers from Heisenberg uncertainty principle, making it impossible to simultaneously have perfect resolution in both time and frequency. The time-frequency resolution of a spectrogram depends on the window size and type. The WVD involves interference terms in multi-component signals. Smoothing also affects resolution. The time and frequency resolutions of WT depend on the frequency. A TFR based on reassignment method improves time-frequency resolution by concentrating energy at a centre of gravity. Due to the improved time frequency resolution, only reassigned method has been considered for the present study. The method involves calculation of reassigned coordinate pair $(\tau,\acute{\omega})$ for each time-frequency pair (t,ω) in the original spectrogram obtained using STFT, where

$$\tau = t - R\,\frac{\left(S_{th}(x,t,\omega).\,\overline{S_h(x,t,\omega)}\right)}{|S_h(x,t,\omega)|^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

$$\acute{\omega} = \omega - I\,\frac{\left(S_{dh}(x,t,\omega).\,\overline{S_h(x,t,\omega)}\right)}{|S_h(x,t,\omega)|^2} \quad \ldots\ldots\ldots\ldots\ldots \quad (2)$$

where$\overline{S_h(x,t,\omega)}$is the STFT of the analysed signal using a normalised window function h(t); and S_{th} (x,t,ω) and S_{dh} (x,t,ω) are the STFTs with t.h(t) and with the derivative of h(t) with t. This algorithm is readily available in Time-Frequency toolbox of Matlab. The reassigned spectrogram program was modified a little for the present study. Using the program, reassigned spectrograms for different scattered modes were obtained.

3. Experiment and analysis

Experiment was performed on an austenitic stainless steel plate of thickness 28 mm and length 519 mm. The weldment in the plate was located at 199 mm from one side. The frequencies of the transducers (M/s. Sonatest)used were 0.5 MHz, 1 MHz, 2.25 MHz, 3.5 MHz and 5 MHz and they were narrowband. A square wavepulser-receiver (M/s. Olympus) was used to excite the transducers and the RF signals were sent to NI ADC card for digitization. The pulser-receiver provided a trigger to the ADC card. The digitized signals were acquired in a laptop computer. The sampling rate for each test was set to be 10 times the transducers' resonant frequency. The A-scan signals were acquired with the averaging for 50 times to remove random noise and saved in ASCII format for post-processing.

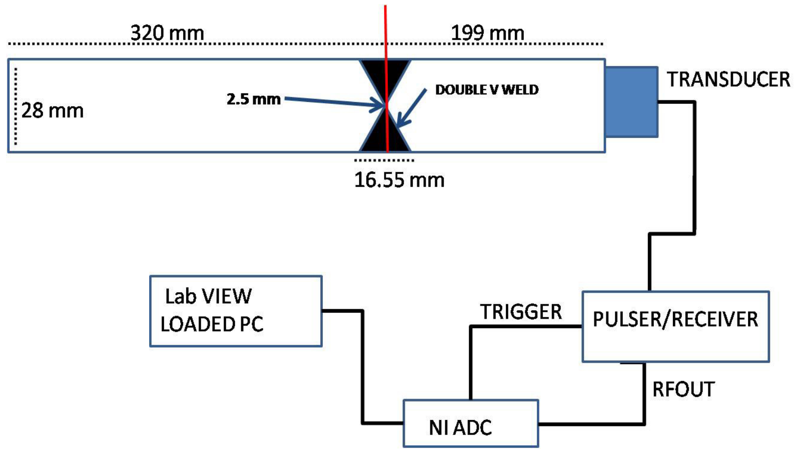


Figure 1. Schematic of the experimental set-up

Figure 1 shows the schematic of the experimental set up. In addition, a plateof 28 mm thickness and width 195 mm, without weld was also used. Using the same experimental set up and the transducers, data were acquired across the width, in both pulse echo and transmission techniques for the above frequencies, for reference.

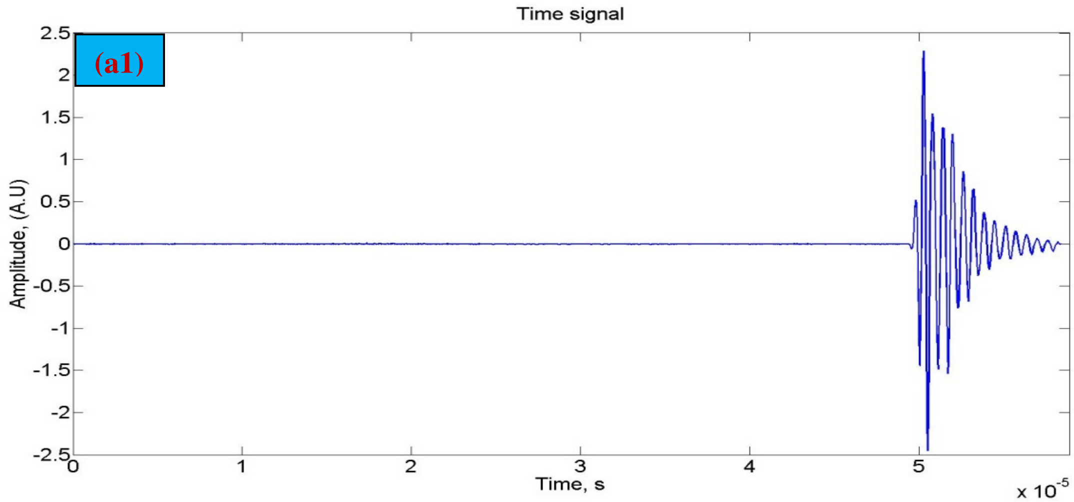
Generation of reassigned spectrogram: Application to detection of Lamb wave modes

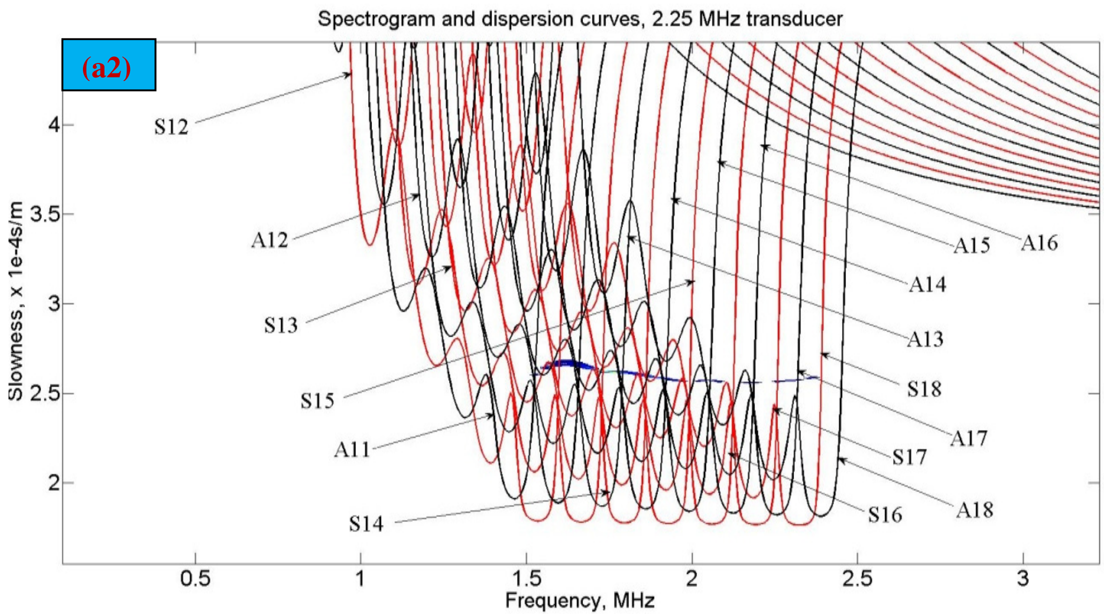
From the acquired data, a region of interest was chosen and reassigned spectrograms were obtained for the gated data, in Matlab for Hanningwindows ranging from N/2 to N/7 (N:length of the signal). Conventionally, reassigned methods transform time-domain signals into the time-frequency domain data, reducing the time-frequency spread of a spectrogram by relocating energy from its oldlocation (t,ω) to a new location (τ,ώ) [6]. In the context of Lamb wave signals, it is difficult to compare reassigned spectrograms made with different propagation distances because the arrival time is function of propagation distances, which cause time shifts. Hence, it is reasonable to normalize different times of arrival by propagation distances. The normalization will yield a physical quantity called slowness (s/m).The time-frequency to slowness -frequency transformation is a linear operation in time, while group velocity- frequency transformation is nonlinear. Transformation non-linearlities are avoided by slowness-frequency transformation. The reassigned spectrograms (slowness versus frequency) obtained by the transformation are nothing but dispersion curves for Lamb waves. Assessment of the accuracy of the dispersion curves obtained using reassignment methods requires benchmarking with analytical results, obtained by numerically solving Rayleigh-Lamb equations. Towards this, dispersion curves were generated using Disperse software, for a 28 mm thick stainless steel plate with properties such as Young's modulus as 200 GPa, density as 8000 kg/m^3 and the Poisson's ratio as 0.29. The data (slowness versus frequency) from Disperse were saved as a textfile in ASCII format. Finally, the dispersion data were superimposed on the reassigned spectrograms. All the reassigned spectrograms were made as coloured contours with proper thresholding.

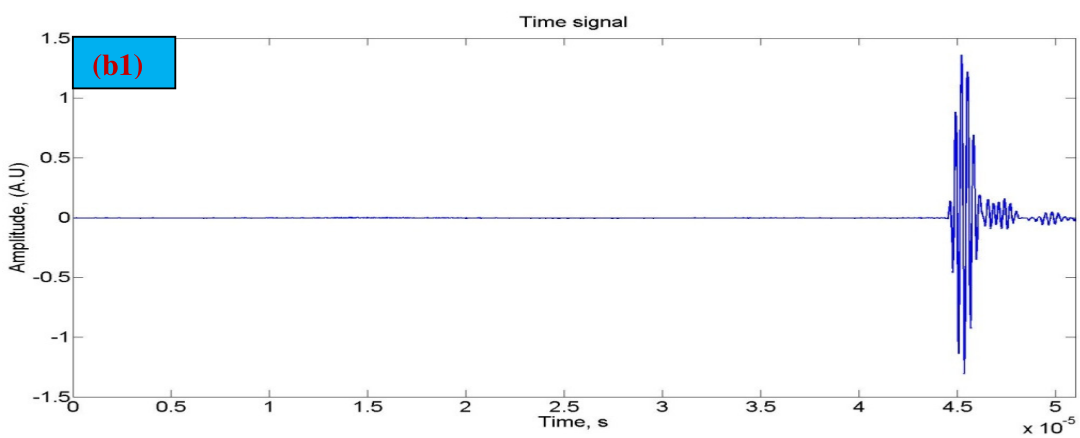
4. Results and Discussion

To ascertain the modes generated by scattering, incident modes should be known. The results for incident modes obtained from a reference plate without weld using through-transmission method for the propagation distance of 195 mm are shown in Fig. 2. Experiments were performed with frequencies 0.5 MHz, 1 MHz, 2.25 MHz, 3.5 MHz and 5 MHz. Typical results for 2.25 MHz and 5 MHz are shown in Figs 1 & 2. Figures 2(a1) & 2(b1) show time signals for frequencies 2.25 MHz and 5 MHz. The wave groups seen at 45 µs and 50 µs correspond to a propagation distance of 195 mm. It can be seen in Figs. 2(a2) & 2(b2), that the reassigned spectrograms for frequencies 2.25 MHz and 5 MHz show higher order modes but they are nearly non-dispersive and their slowness variation is ~ $0.1x10^{-4}$s/m. It appears that many higher modes propagate together as a cluster with a common group velocity of ~ 4000 m/s. The peculiarity of this behaviour could be attributed to phase matching of closely spaced modes. There are also regions in Fig. 2, which are not valid modes. They are referred to as extraneous modes [7], in literature. Further, the reassigned spectrograms for incident modes, obtained using pulse echo method in the reference plate, showed the similar behaviour of slowness. The incident modes, thus, served as reference for the scattering studies.

The results for scattered modes obtained in a welded plate using pulse-echo method for the propagation distance of 398 mm are shown in Fig. 3. Figures 3(a1) &2(b1) are the time domain signals for 2.25 MHz and 5 MHz. The scattered modes are marked in the figures; their amplitudes are weaker than that of the edge signals. The reassigned spectrograms for frequencies 2.25 MHz and 5 MHz show scattered higher order modes with their slowness variation to be ~ $1x10^{-4}$s/m to $1.5x10^{-4}$s/m. The group velocities of scattered modes are in the range of 3000 m/s to 5000 m/s. The frequencies 2.25 MHz, 3.5 MHz, 5 MHz showed higher distribution of modes than that for the frequencies 0.5 MHz and 1 MHz.Figures 2(a2) & 2(b2) show many higher modes propagating together as a cluster with a common group velocity of ~ 4000 m/s. This cluster of modes propagates and scatters at the columnar grain boundaries. Since, there are many grains in the weld, multiple scattering could occur. In addition, elastic in-homogeneity and impedance mismatch could add to the scattered modes. It can be seen that the modes participated in scattering are clearly brought by reassigned spectrograms, hence it will be easy to separate these modes from scattered modes from defects in the weld. The separation will enhance the signal to noise of the defect signals from welds.


Time signal
(a1)
Amplitude, (A.U)
Time, s
x 10^-5


Spectrogram and dispersion curves, 2.25 MHz transducer
(a2)
S12
A12
S13
S15
A11
S14
A15
A16
A14
A13
S18
A17
S17
S16
A18
Slowness, x 1e-4s/m
Frequency, MHz


Time signal
(b1)
Amplitude, (A.U)
Time, s
x 10^-5

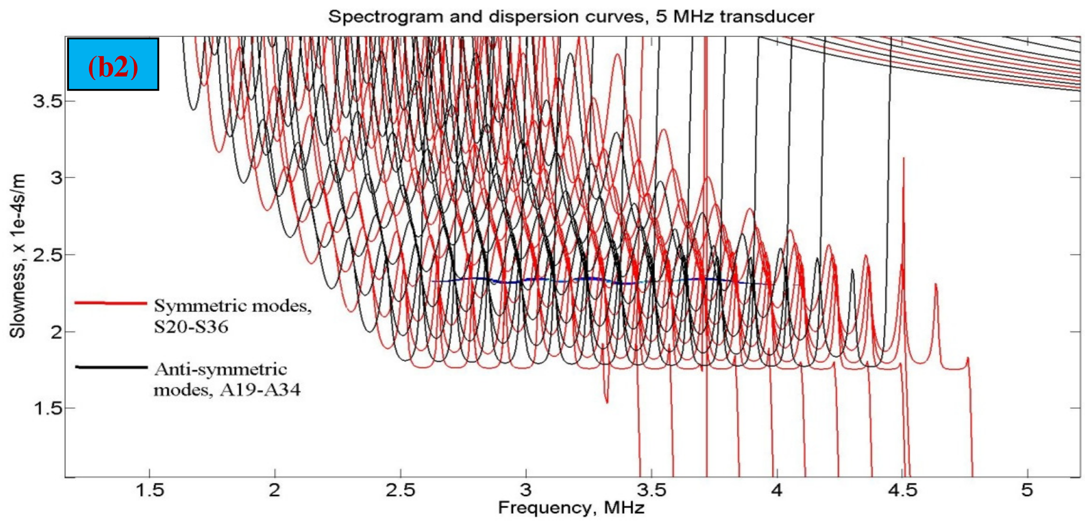
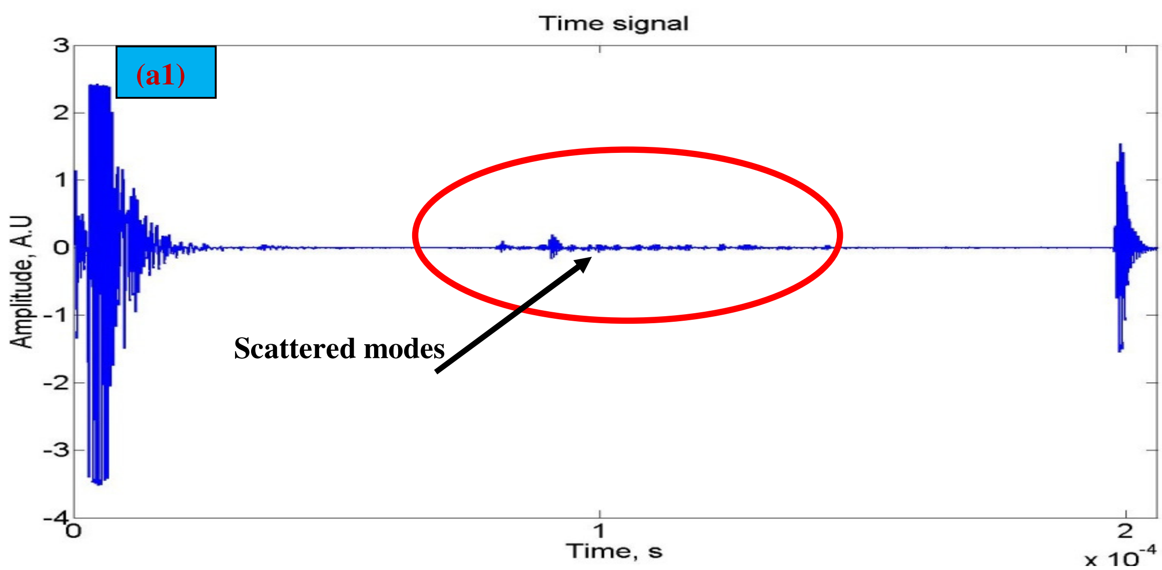
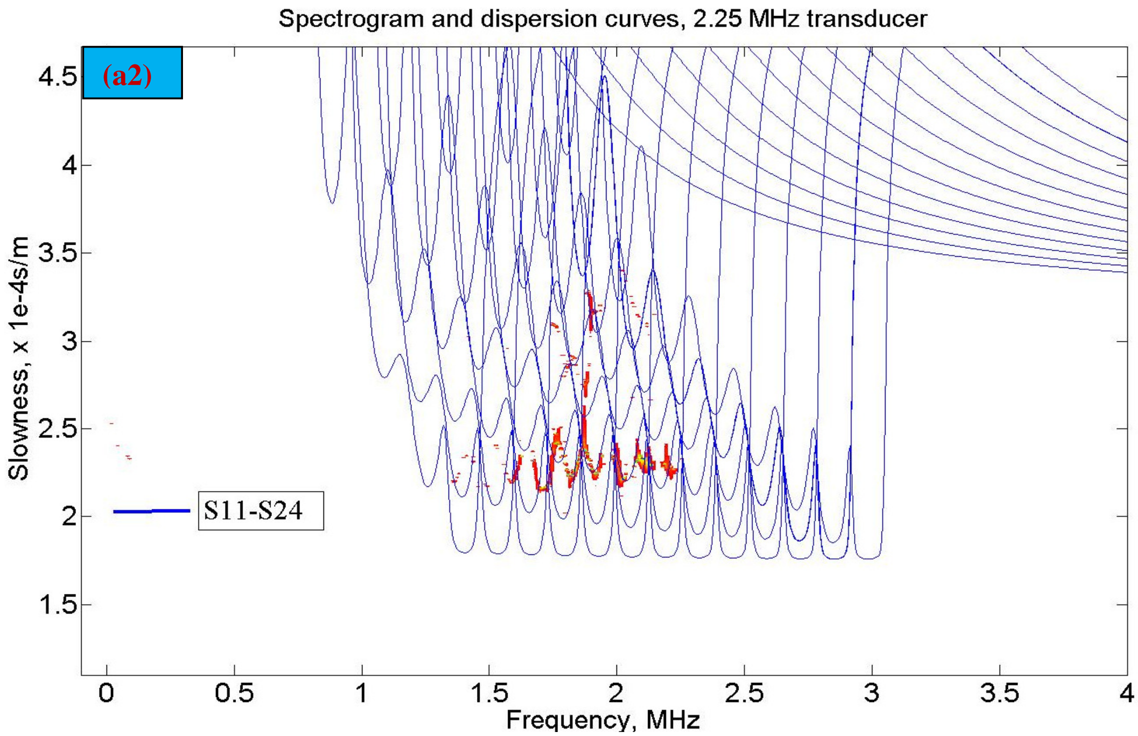
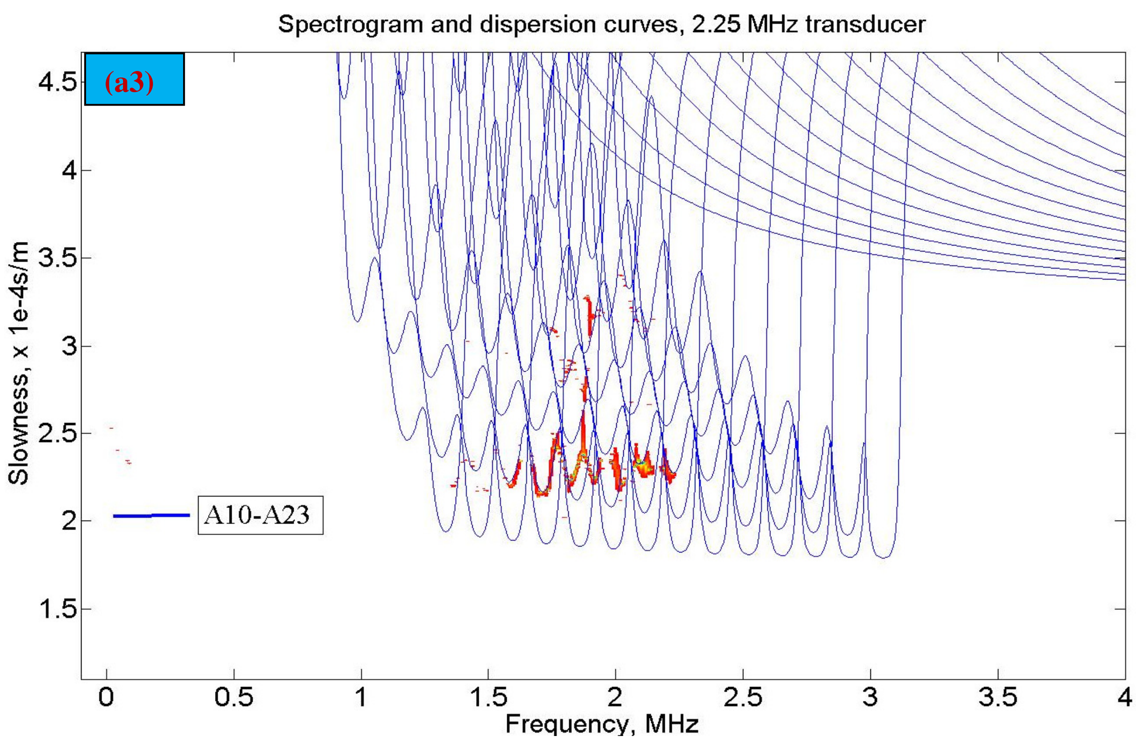
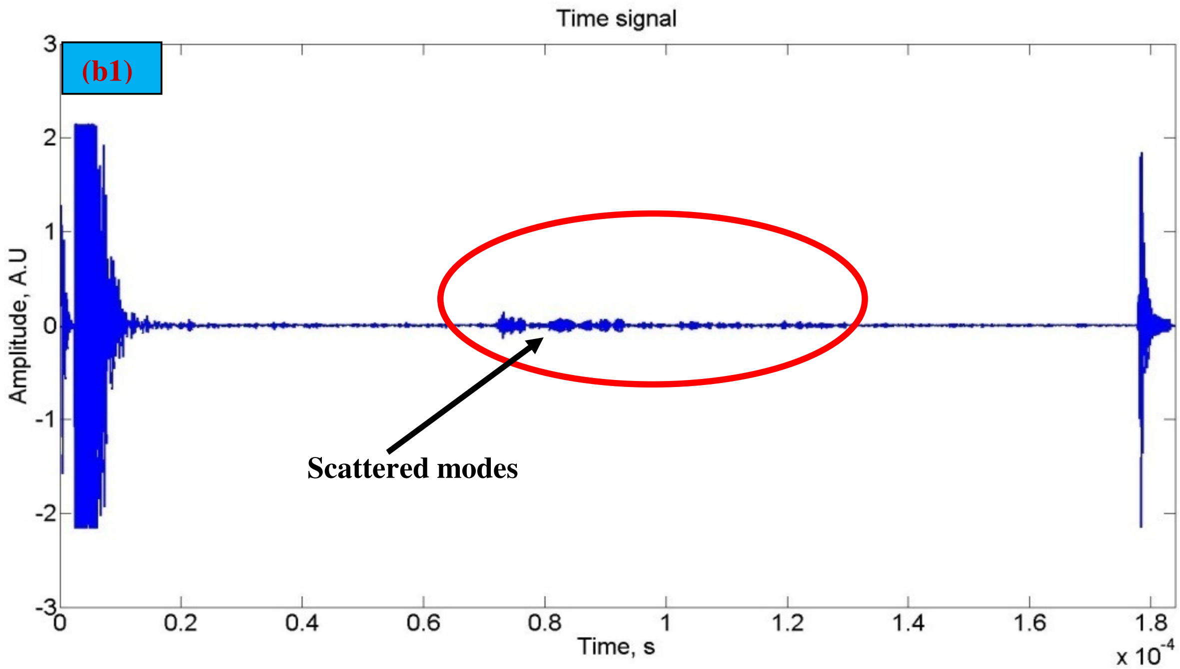


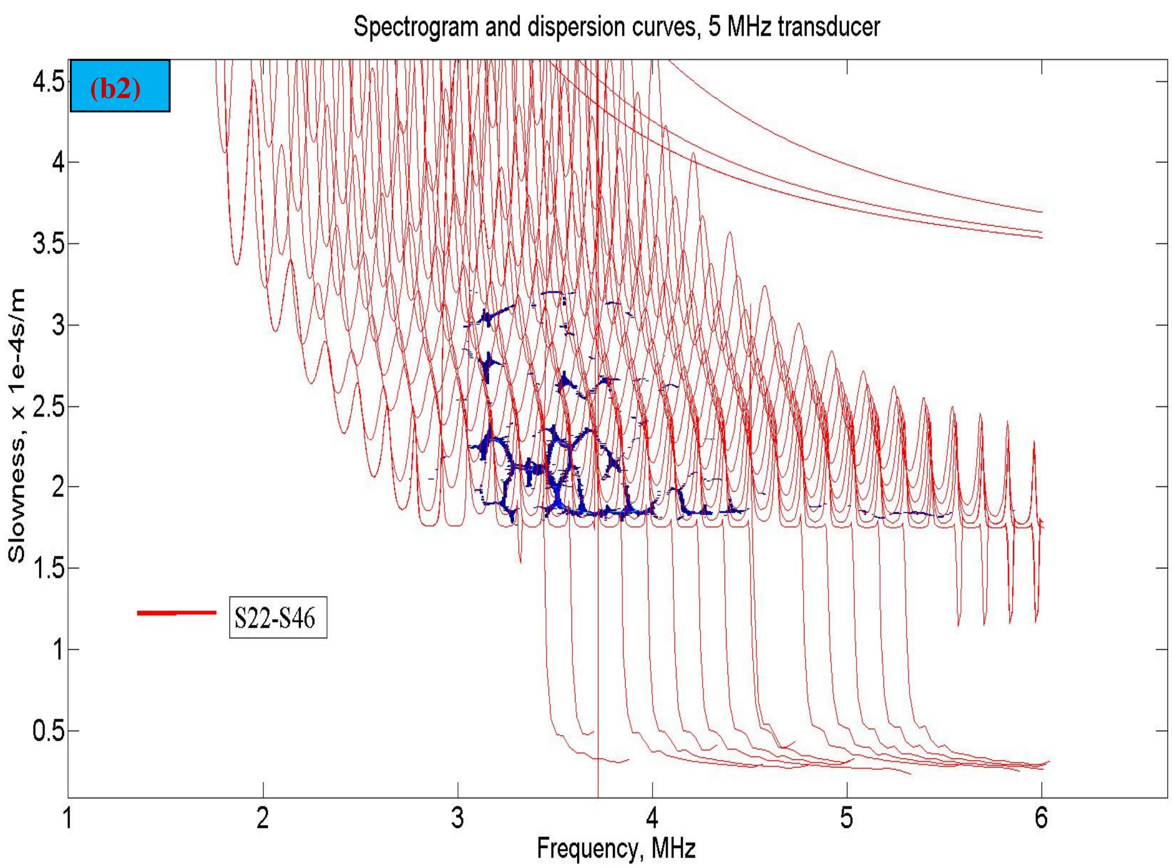
Figure 2. Incident modes in the reference plate, superimposed with analytical dispersion curves from disperse software (a1) time signal for 2.25 MHz transducer, (a2) reassigned spectrogram for 2.25 MHz transducer, (b1) time signal for 5 MHz transducer and (b2) reassigned spectrogram for 5 MHz transducer




Spectrogram and dispersion curves, 2.25 MHz transducer
(a2)
S11-S24
Slowness, x 1e-4s/m
Frequency, MHz
4.5
4
3.5
3
2.5
2
1.5
0
0.5
1
1.5
2
2.5
3
3.5
4


Spectrogram and dispersion curves, 2.25 MHz transducer
(a3)
A10-A23
Slowness, x 1e-4s/m
Frequency, MHz
4.5
4
3.5
3
2.5
2
1.5
0
0.5
1
1.5
2
2.5
3
3.5
4


Time signal
(b1)
Amplitude, A.U
Scattered modes
Time, s
x 10^-4
3
2
1
0
-1
-2
-3
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8


Spectrogram and dispersion curves, 5 MHz transducer
(b2)
Slowness, x 1e-4s/m
S22-S46
Frequency, MHz
4.5
4
3.5
3
2.5
2
1.5
1
0.5
1
2
3
4
5
6

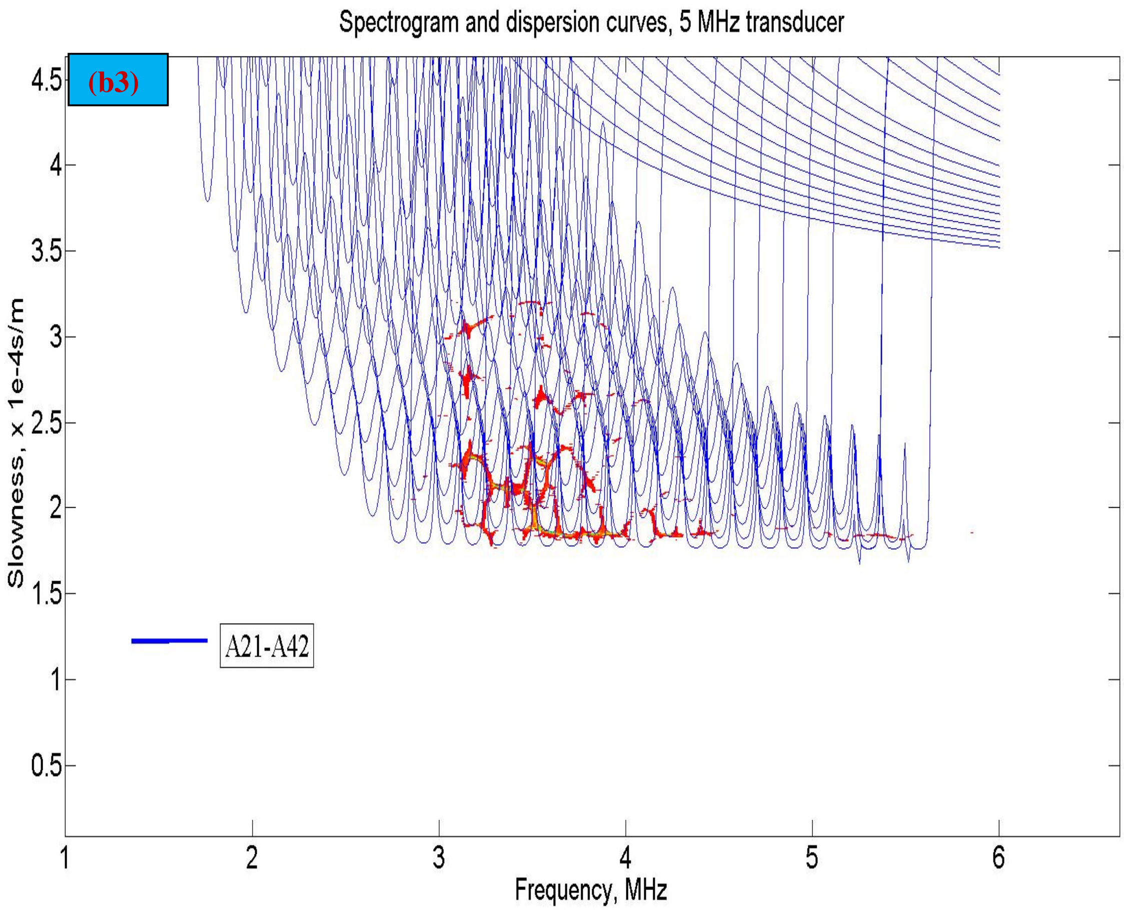


Figure3.Time signals and reassigned spectrograms, for scattered modes from columnar grains, superimposed with analytical dispersion curves from disperse software (a1) time signal for 2.25 MHz transducer, (a2) 2.25 MHz transducer: symmetric modes, (a3) 2.25 MHz transducer: anti-symmetric modes, (b1) time signal for 5 MHz transducer, (b2) 5 MHz transducer: symmetric modes and (b3) 5 MHz transducer: anti-symmetric modes.

5.Conclusions

The above study demonstrated scattering of Lamb waves by columnar grains of austenitic stainless steel weldments using the dispersion curves obtained using the reassigned method. It has been observed that the incident modes for frequencies 1 MHz to 5 MHz comprise of many modes and are essentially non-dispersive. These modes are selectively scattered by the columnar grains into individual modes. Due to the use of the high resolution reassigned spectrogram method, each individual scattered mode has been found out precisely. The study is preliminary, in the sense of demonstrating the scattering, however, it has a good potential of characterizing weld microstructures and also to select suitable modes which are least affected by the grains of the weld to enhance signal to noise ratio of defect signals from austenitic stainless steel welds. Besides, finite element simulation and theoretical analyses incorporating the elastic in-homogeneity need to be performed for the proper understanding of the phenomenon and this forms the future work.

References

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