Time-Frequency Analysis of Long Range Ultrasonic Signals

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Abstract. Long range ultrasonic testing (LRUT) is a relatively new development within the non-destructive testing sector. Traditionally, conventional ultrasonic testing (UT) is performed at high frequencies, in the MHz range, and is capable of detecting small flaws within a range of millimetres; whereas long range ultrasonic inspection is carried out at lower frequencies, typically between 20 and 100kHz, and is capable of highlighting structural detail and discontinuities tens of metres from a test position. Conventional ultrasonic testing relies on the transmission of bulk waves, the velocities of which are independent of frequency and can usually be predicted easily if the elastic properties of the material under test are known. The dynamics of guided waves, however, are dependent upon frequency making the analysis of received data from a specimen complex. This paper will serve as an introduction to time-frequency representation and may allow a clearer understanding of the non-stationary raw signals produced by this inspection process. Currently, LRUT data are assessed in the time or distance domain using the amplitude vs. time ‘A-Scan’, therefore structural features and potential flaws are highlighted on a time-of-flight basis. However, as the data obtained are dynamic in time and frequency (non-stationary), time-frequency distributions could provide a mode identification or de-noising process to deal with the problem of coherent noise.

1. Introduction
The main objective of this paper is to excite many vibrational modes observed within a tubular structure experimentally and compare the time-frequency results with analytical dispersion curves generated using the modelling software DISPERSE [1]. The class of structure examined here is carbon steel pipe; a common material used within industrial refineries and petrochemical plants worldwide to convey a variety of hazardous and non-hazardous materials. Assessing the condition of assets such as pipework and associated pipelines is therefore an essential task. The importance is highlighted further by the huge expense of a shutdown period due to a failure or loss of contents and the potential environmental impact of such a failure. LRUT is used to good effect commercially to screen for corrosion, erosion and other types of wall loss such as pitting. During normal inspections on a wave guide such as a pipe, an axi-symmetric ring of sound or vibrational mode is produced by a bracelet of dry coupled shear transducers wrapped around the circumference of the pipe. Each transducer can be viewed as a point source possessing an output and the ring of sound produced is the result of the superposition of each output. As the number of transducers in this array increases, the purer the axi-symmetric mode becomes. However, at the test frequency range for this technique there are many...
vibrational modes possible which separate shortly after transmission. Each mode has a unique frequency dependent group and phase velocity curve; these curves display the dispersion characteristics for a specific waveguide. This dispersion effect produces a temporal and therefore spatial resolution problem within the received data. The excitation signals used for LRUT are usually modulated tonebursts which are limited to a frequency range where the desired mode used is relatively non-dispersive. The modulation used generates a narrowband pulse in the frequency domain in attempt to minimise this effect. The two most common functions used for this amplitude modulation are the Hann window and the Gaussian window.

As full vibrational mode control using a finite number of transducers in the array is not possible the received data is multimodal. Moreover, as the excitation signal possesses a bandwidth within which a frequency dependent response is possible, the data becomes non-stationary i.e. it contains information in terms of time and frequency. By using only one transducer, it is possible to move away from the idea of controlling a true axi-symmetric ring and therefore excite many modes at once. This method can be used to experimentally validate a set of dispersion curves for any given structure. Traditionally, this has been achieved by using the time consuming two-dimensional Fourier transform. However by using a broadband input signal and displaying the result of a single scan in terms of time and frequency, the dispersive nature of the structure can be revealed.

A collective review of time-frequency can be found in [2]. Here Debnath includes a paper by Boashash and Sucic which demonstrates some practical applications of time-frequency distributions (TFDs) and introduces the idea of instantaneous frequency and reviews some of the desired criteria for TFDs. Chapter 8 in [2] focuses on time-frequency / time-scale reassignment. Chassande-Mottin, Auger and Flandrin discuss the trade-offs between several TFDs including the main alternative to the Fourier based spectrogram, the Wigner-Ville distribution. Results displayed in this section highlight the main disadvantage when using the Wigner-Ville; localised interference caused by superposition of negative and positive values within the domain. It was concluded that the reassignment principle applied to a spectrogram produced the closest to ideal results. In [3] Flandrin discusses the reassignment principle further and explains how phase calculated by the short-time Fourier transform (STFT) can be ‘reassigned’ to closely follow an ideal instantaneous frequency. Note that all of the TFDs suffer from resolution problems related to Heisenberg’s notion that a specific frequency cannot be expressed exactly at a specific time. Prosser et al [4] carried out a set of acoustic emission experiments on a 6.35mm aluminium plate and displayed promising results. It was clear that the plate modes A0 and S0 were successfully generated and were dominant in the time-frequency domain. An analytical representation of S0 was overlaid onto the TFD, in this case a Pseudo-Wigner-Ville distribution (PWVD), showing good correlation. Documents [5] and [6] appear to contain the same results with [5] being a very concise report on a particular experiment and [6] providing an excellent review of TFDs including a scalogram using the continuous wavelet transform (CWT). The results show good contributions from the S0 and A0 plate modes using laser induced ultrasound in a 0.93mm thick aluminium plate. By using the reassigned spectrogram some of the higher order modes have been tracked successfully. However, where the modes intersect the solution becomes undefined. There are less vibrational modes present in a plate structure than in a hollow cylinder (e.g. steel pipe), so the problem under investigation in this paper is more complex. It is important to establish initially which modes can be excited effectively during this study.

2. Theoretical background
A transient signal such as those seen in LRUT can be displayed in the time domain as an A-Scan and also by using a Fourier transform, frequency content can be obtained. These display mechanisms are currently independent of each other in this field and do not therefore provide an adequate description of the multi-domain nature of this type of wave propagation. The first time-frequency distribution developed was the short-time Fourier transform (STFT). This method reduces a time domain signal into a series of windows of equal length. The Fourier transform for each window, also known as a Frequency bin, is returned yielding information about the signal in both time and frequency. Each
window is tiled to create an image, the energy density function of this process is known as the spectrogram. The STFT of a signal $s(t)$ is expressed as:

$$STFT(\omega,t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega \tau} s(\tau) h(t-\tau) d\tau$$  \hspace{1cm} (1.1)$$

Here $h(t)$ is a window function and $\tau$ represents the length of the signal. The spectrogram suffers from a lack of resolution at higher frequencies, this is due to the window length (frequency bin) being fixed across the length of the function. This limits the ability of the STFT to display rapidly varying information accurately throughout the entire signal.

An alternative outlook on the STFT came in the form of the Wigner-Ville distribution. This distribution uses the time domain signal $s(t)$ and its complex conjugate $s^*(t)$ as:

$$s(t + \frac{\tau}{2})s^*(t - \frac{\tau}{2})$$  \hspace{1cm} (1.2)$$

The TFD is then calculated by taking the Fourier transform of equation (1.2) with respect to the duration $\tau$:

$$WVD(\omega,t) = \int_{-\infty}^{\infty} s(t + \frac{\tau}{2})s^*(t - \frac{\tau}{2}) e^{-i\omega \tau} d\tau$$  \hspace{1cm} (1.3)$$

The WVD is capable of achieving better time and frequency resolution through good local time representation but suffers from additional interference terms which can produce a noisy TFD. This effect can be improved upon by applying a two dimensional filter. A bi-product of the filtering process is a blurred result which cancels out the original high resolution advantage of the WVD.

### 2.1. Dispersion

Figures 1 and 2 below show the first five fundamental modes for the pipe used in this experiment. All of these modes have frequency dependent velocities which in this case have been calculated analytically using the modeling software DISPERSE. It is clear from these plots that in order to control an axi-symmetric test using longitudinal excitation it is essential to use a narrow bandwidth as dispersion of the input signal as it propagates along the wave guide will impair the resolution of the time domain signal. In this investigation it is essential to apply the opposite notion. A broadband signal will in theory generate all modes displayed in figures 1 and 2 and the TFD can be manipulated to give accurate mode velocities for the test piece experimentally and with further refinement yield a set of experimentally validated dispersion curves. From knowing that many modes can exist at the same frequency and similar amplitudes (depending on excitation conditions), the LRUT technique can suffer from input mode impurity. Time domain scans (A-Scans) can become unpredictable when more than one mode is generated upon input.

![Figure 1. Group velocity curves for the test piece](image1.png)

![Figure 2. Phase velocity curves for the test piece](image2.png)
3. Experimental Measurements

To produce accurate arrival times and prevent any other scatter, it was important to maintain directionality during the experiment. This was achieved by setting up a through-transmission or ‘pitch-catch’ between the macro-fibre composite (MFC) transducer (Tx) seen in figure 3 and a Polytec PSV-400 1D scanning laser vibrometer (Rx). The MFC was dry-coupled to the outer surface of the pipe with a force normal to the pipe surface of approximately 100N. The total active area of the transducer was experienced a uniformly distributed coupling load. The major axis of the transducer was aligned with the major axis of the pipe; this ensured that the modes that propagated along the waveguide would be longitudinal. The transducer was also located at the very end of the pipe so that any backwards leakage of sound would not appear on the scans. The pulser/receiver used for the tests was a Teletest TT2. This unit has an external trigger which initiated synchronisation with the vibrometer during data collection.

![Figure 3. An example of the MFC transducer used in this investigation](image)

In order to generate scans possessing a good signal to noise ratio (SNR), the collection averages on the vibrometer was set to 512. Random environmental noise is generally subdued by applying averages. The vibrometer was focused at a distance of 2.895m away and in line with the MFC delivering the input signal. A digital bandpass filter was also set up in the Polytec collection software in order to improve SNR further. The lower cut off frequency was set to 2kHz and the upper cut off frequency was set to 275kHz. This input is broadband with respect to normal LRUT range (20kHz to 100kHz), but it was viewed that any additional data outside of normal range could provide some additional information.

Once the data was collected a set of Matlab I/O routines were implemented and all files were set to a format which could be used as input to a C source code based time-frequency toolbox. The sampling frequency of the received data was set to 1MHz. With the collection length being nearly 3m and the sampling frequency being high, the data sets processed by Matlab were large. This caused problems during processing and the issue will need to be solved in order to make the process more efficient.
4. Results

The processed results displayed were obtained from laboratory trials on a 6m long 6 inch schedule 40 carbon steel pipe (Outside diameter = 168.28mm, wall thickness = 7.112mm).

In Figure 4 a broadband, relatively flat (ignoring the Fresnel ripples) is observed before the signal enters the transducer. However, upon transmission, the transfer function of the MFC appears to distort the received spectrum seen in Figure 5. The region between 50kHz and 150kHz is subdued in such a way that it becomes a trough in the data. It also appears that the data above 150kHz lies close to the noise floor where in fact the transmission spectrum in Figure 4 shows good energy levels up to 250kHz. It is possible that the transducer is acting as a hardware filter and therefore providing unwanted amplitude modulation. Generally, the frequency response of a vibrometer of such specification is not usually thought to cause large distortion as it is flat. The twin spectrum peaks seen in Figure 5 carry forward into the TFD as darker regions (displayed in Figure 7). In an ideal case the spectrum would be flat and there would not be any dominant regions displayed in the TFD.

Figure 6 shows the received A-Scan at the vibrometer. The scan seems surprisingly clean which suggests that either the MFC was not capable of generating all of the fundamental modes given the set up or that the vibrometer was not sensitive to some of the modes at the focal point. A wider scan of the received area will confirm this. The beginning of the A-Scan was padded with zeros as inter-channel leakage was observed and could affect the result of the TFD. There is modal information in front of the main reflection which upon comparing the TFD and the A-Scan appears to be either L(0,2) or F(1,3) (the ‘F’ is used to denote ‘flexural’). Figure 7 shows the spectrogram of the data with the analytical arrival times for each fundamental mode superimposed for the purpose of identification. The data is not in sync with the analytical curves as there is a group delay associated with the processing and input signal parameters. However, again it is clear that L(0,1) and F(1,2) are dominant and that there is a weak presence of L(0,2) and F(1,3) arriving in front of the main reflection. The five fundamental modes shown in the dispersion curves and superimposed in Figure 6 are not the only solutions in existence. The equally spaced ridges trailing behind the main reflection possessing similar intensity are likely to be higher order modes of the same family as L(0,1) and F(1,2).
5. Conclusions
In conclusion, this initial study has successfully generated and displayed experimental dispersion relationships for some of the fundamental vibrational modes that exist within a 6inch schedule 40 steel pipe. It is clear that the experimental set up needs refining to promote some of the weaker modes present in the current data. Transducer selection is also a key factor in displaying uniform results across the desired bandwidth. The nature of contact transducers adds another dimension of complexity contained in coupling conditions, material surface condition and associated resonances.

Although the STFT was capable of displaying the multi-modal nature of these signals, refining the results to gain a more accurate image is needed. This may be achieved by exploring the attributes of other TFDs and perhaps include the CWT for decomposition. The modal analysis of pipes is more complex than plates as a large family of flexural modes exist. With this in mind, it is important to find a very resolute time-frequency technique to display or decompose this information accurately.

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