Time-Frequency Analysis of Ultrasonic Echo for the Nondestructive Evaluation of Material Damage

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Abstract: In nondestructive material evaluation technique, ultrasonic echoes exhibit critical time and frequency information. A time-frequency distribution can provide an effective tool to obtain frequency dependent ultrasonic characteristics related to certain material properties. In the presented study, ultrasonic tests with high frequency contact transducers were carried out to thermally degraded steel. Measured echo signals were analyzed by wavelet transform. It is shown that, with the increase of thermal degradation, both the ultrasonic attenuation and its change with frequency gradually increased within a significant frequency band. But ultrasonic velocity was found relatively unchanged. The effectiveness of wavelet analysis to ultrasonic signal for the quantitative evaluation of material thermal damage is clarified.

Key Words: Time-Frequency Analysis, Wavelet Transform, Ultrasonic Echo, Attenuation, Velocity

1 Introduction

In industrial application, a large number of components in vital areas of infrastructure and large-scale plant, such as power plant, tubing pipeline, etc, are manufactured from steels. Many of these structures are designed on the basis that the consequences of in-service rupture due to thermal degradation are unacceptable. Thus, items of critical equipment must be the subject of periodic evaluations of fitness by means of a range of non-destructive testing (NDT) techniques.

In most situations, the ultrasonic pulse-echo technique provided an economic and effective NDT measure for meaningful assessment of material properties and microscopic damage since the penetrating power of the ultrasonic wave is able to detect subsurface damage and is sensitive to small changes in micro-structural properties [1][2].

The signal obtained in an actual ultrasonic measuring system is generally non-stationary and difficult to be analyzed due to frequency dependent scattering, attenuation and dispersion. Since the joint time-frequency analysis of a signal can provide its detailed time information at a concerned frequency and a detailed frequency distribution at any time indices, it should be an appropriate tool for ultrasonic signal processing. A lot of results about the application of time-frequency analysis to ultrasonic non-destructive tests have been reported in recent years [3][4]. These studies revealed that it is possible to obtain frequency dependent ultrasonic characteristics in time-frequency plane rather than only in time domain or frequency domain, and these characteristics can be applied to identify internal defects or to assess creep damage of crucial structure material.

In the presented study, ultrasonic nondestructive evaluation for material damage was carried out based on a measurement system developed. This paper describes this system, discusses the performances of some typical time-frequency methods used to analyze the obtained ultrasonic echoes and introduces the conducted ultrasonic testing on thermally degraded Cr-Mo steel specimens. We also present the obtained results and discussions concerning the effect of growth in specimen's internal grain size due to thermal degradation on certain frequency dependent ultrasonic behaviors by using wavelet transform.

2 Ultrasonic Measurement System

For ultrasonic tests, it is important to precisely measure the time and amplitude of echoes reflected from surface, internal defects and bottom of the tested specimen. Therefore, well established electronic equipment and advanced signal processing techniques are much necessary in this field.

The developed ultrasonic measurement system in this study is shown in Fig.1. A pulsar/receiver, which is capable of high frequency application up to 150MHz, was employed to generate, receive and pre-amplify ultrasonic pulses and echoes. Through a NBC connector, the received waves were acquired with a digital oscilloscope, with maximum sampling rate 2GHz in a single channel and 500MHz in quad channels. Thus, the system is capable of accurate measurement for time of flight (TOF) with resolution up to 0.5ns. Each of the scope's channels has an 8-bit A/D converter to digitize the acquired analogy signal. The digit oscilloscope was connected to a personal computer with GPIB bus, which makes it easier to store and analytically process ultrasonic wave data by a computer.

System software was developed using VC++ and MathCAD. It is able to control the oscilloscope's activity, transmit and store a large amount of data, perform time-frequency transform and analyses, etc.

Single transducer was used to conduct ultrasonic measurement in this system. It received all of the echoes reflected from the surface and bottom of the tested specimen. The system can operate with a wide range of transducers with different types of acoustic couple. In the presented study, direct contact between transducer and surface of specimen was conducted for velocity and attenuation analysis to thermally degraded steel.

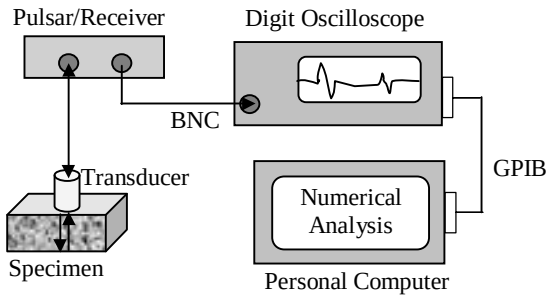

Fig.1 Schematic diagram of the system developed to undertake ultrasonic measurement

3 Performance Comparison of Time-Frequency Methods Used for Analyzing Ultrasonic Echo

The time-frequency analysis aims to deal with signal possessing non-stationary properties encountered in practice. It represents a signal in time-frequency plane with a two-dimensional time-frequency distribution function in order to obtain signal's time-varying spectra.

3.1 Basic Methods

A lot of time-frequency representation methods have been developed and improved [5]. Although the behavior of these methods is quite different and each has peculiar properties, Wigner-Ville Distribution (WVD), Short Time Fourier Transform (STFT) and Continuous Wavelet Transform (CWT) are three elementary methods.

For a given signal $f(t)$, its WVD is defined as the Fourier transform of its bilinear product at each time, that is:

$$WVD_f(t,\omega) = \int f^*(t-0.5\tau) f(t+0.5\tau) e^{-j\tau\omega} d\tau \quad (1)$$

where * represents complex conjugate.

The STFT of a signal $f(t)$ is defined as:

$$STFT_f(t,\omega) = \int f(\tau) w^*(\tau - t) e^{-j\tau\omega} d\tau \quad (2)$$

where w is a selected window function used for observing the signal's local spectrum by translating it along time.

The CWT of a signal $f(t)$ is defined as its convolution with a serial of scaled and translated wavelet base function $\psi(t)$, that is:

$$CWT_f(t,s) = \frac{1}{\sqrt{s}} \int_{-\infty}^{\infty} f(\tau) \psi^*(\frac{\tau - t}{s}) d\tau \quad (3)$$

where scale s>0. By varying the scale of wavelet, corresponding to Fourier frequency through carefully sampling to time and scale, and translating it along time, one can obtain a picture of the wavelet power spectrum at each time. The key of wavelet analysis is to choice a suitable wavelet function for actual applications. A commonly used wavelet function is Morlet wavelet, consisting of a plane wave modulated by a Gaussian function:

$$\psi(t) = \pi^{-0.25} e^{i\omega_0 t} e^{-0.5t^2} \quad (4)$$

where ω_0 is non-dimensional frequency, here taken to be 6 to satisfy the admissibility condition [6].

The time-frequency methods mentioned above can be easily implemented by fast algorithm, taking advantage of fast Fourier transform. This makes it possible to use them in various actual applications of signal processing.

3.2 Performance Comparison

An ultrasonic echo is received by a piezoelectric transducer, which transmits exciting pulse into a tested specimen and acoustically couples to it, when the pulse encounters an interface or internal non-homogeneity of the specimen in its propagating path.

As is shown in Fig.2, it is usually known that an ultrasonic echo is a broadband pulse modulated near the center frequency of the transducer used, and is

much similar to a Gaussian pulse in nature. Fig.3 plotted the contours of WVD, STFT and CWT for the actually obtained echoes given in Fig.2. It gives an intuitive performance comparison of these methods used for analyzing ultrasonic echoes.

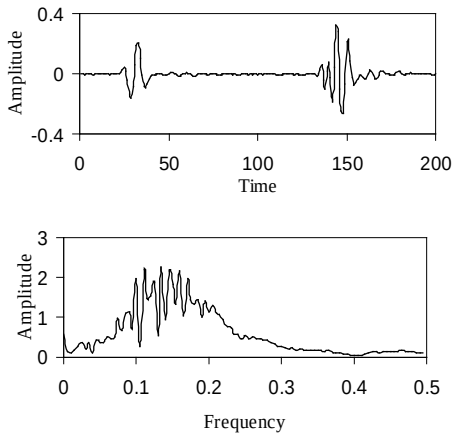

Fig.2 Waveform of two tested ultrasonic echoes and their amplitude spectrum

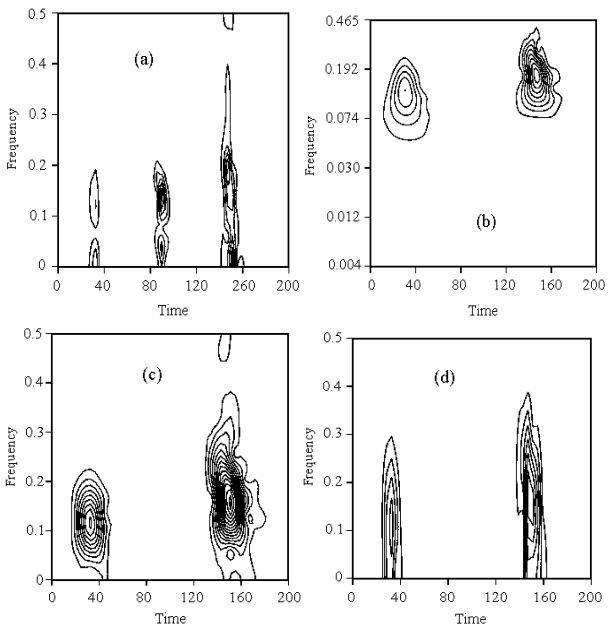

Fig.3 Time-frequency distribution of two tested echoes: (a) WVD; (b) CWT based on Morlet wavelet; (c) STFT with 31-Hamming window; (d) STFT with 9-Hamming window

Theoretically, a high time and frequency resolution can be achieved by WVD. However, in the case of multi-component signals, it can also introduce unwanted cross-term interference due to the bilinear product in the definition of WVD.

The STFT is free of cross-term interference, but its behavior greatly depends on the window function used. Although most of the commonly used window functions can be applied to it, it is difficult to make a tradeoff between time resolution and frequency resolution by STFT due to the length-fixed window.

The scale-varying structure of CWT makes it possible to have a finer frequency resolution for low frequency components than high frequency components, and a finer time resolution for high frequency contents than low frequency contents. This is quite useful for most of the actual applications.

From theory and performance comparison, it is clear that the wavelet transform based on Morlet function is suitable for analyzing ultrasonic echo since it can achieve excellent time and frequency concentration and can track frequency trend at a local time better than other methods. The presented results in the following part of this paper are based on this kind of wavelet transform.

4 Ultrasonic Testing for Thermally Degraded Steel

Ultrasonic non-destructive evaluation for material thermal degradation was carried out based on the measurement system developed in this study.

4.1 Specimen and Transducer

Tested specimens for present work were made of 2-1/4Cr-1Mo steel, mainly used for power boiler heating tubes and high pressure piping, processed by heat treatment followed by air-cooling. As shown in Table 1, the grain size, measured according to JIS G551, increased with the increase of heated temperature and held time.

Table 1: Heat treated 2-1/4Cr-1Mo specimens

Specimen	Temperature (˚C)	Time (hours)	Average Grain Diameter (μm)
S1	As received		13
S2	950	1	38
S3	1050	20	119
S4	1100	100	188

Each specimen was machined to a unified plate, 80mm long, 12mm wide and 6mm thick, with smooth and parallel faces to ensure precise measurement.

Ultrasonic tests were conducted using two commercial high frequency contact transducers with central frequency of 30MHz and 50MHz, respectively.

For a given specimen, statistic results presented were based on multiple tests at different locations on its surface. Furthermore, one hundred times summed averaging was taken at each location so as to reduce random noise.

4.2 Obtained Waveforms and Their CWT

Fig.4 gives the obtained signals from four specimens by using the 30MHz transducer. Similar waves were obtained using the 50MHz transducer.

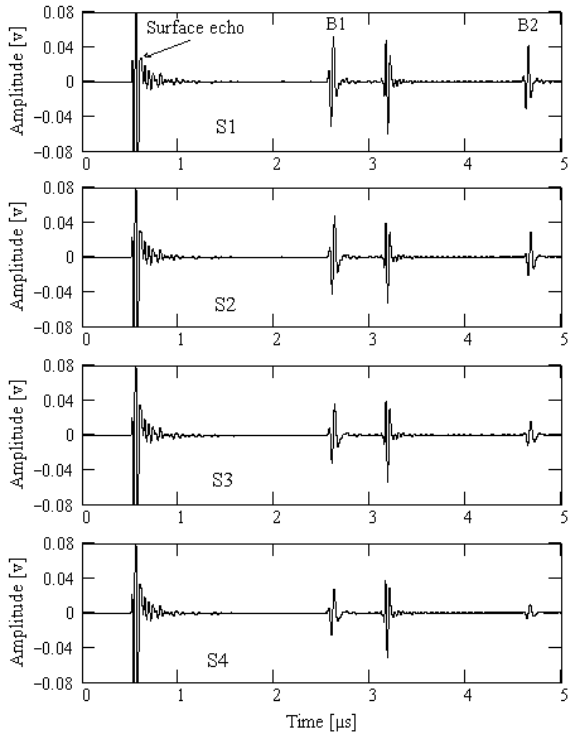

Fig.4 Ultrasonic echoes measured from tested Cr-Mo steel specimens (30MHz transducer)

It was observed that the surface echo, reflected from a specimen's surface when an ultrasonic pulse reached it, appeared immediately behind the delay line echo of a transducer. The first bottom echo B1, reflected from the specimen's bottom when part of the pulse reached it, appeared near 2.6μs. The second bottom echo B2, reflected when part of waves in B1 entered into the specimen again and reached its bottom, was found near 4.6μs.

The CWT based on the Morlet function was applied to analyze these received signals. The CWT of above waves is plotted in Fig.5. The differences between echoes are clearly depicted in time-frequency plane. Thus, it is possible to calculate frequency dependent ultrasonic parameters according to the value and location of the peak around each echo.

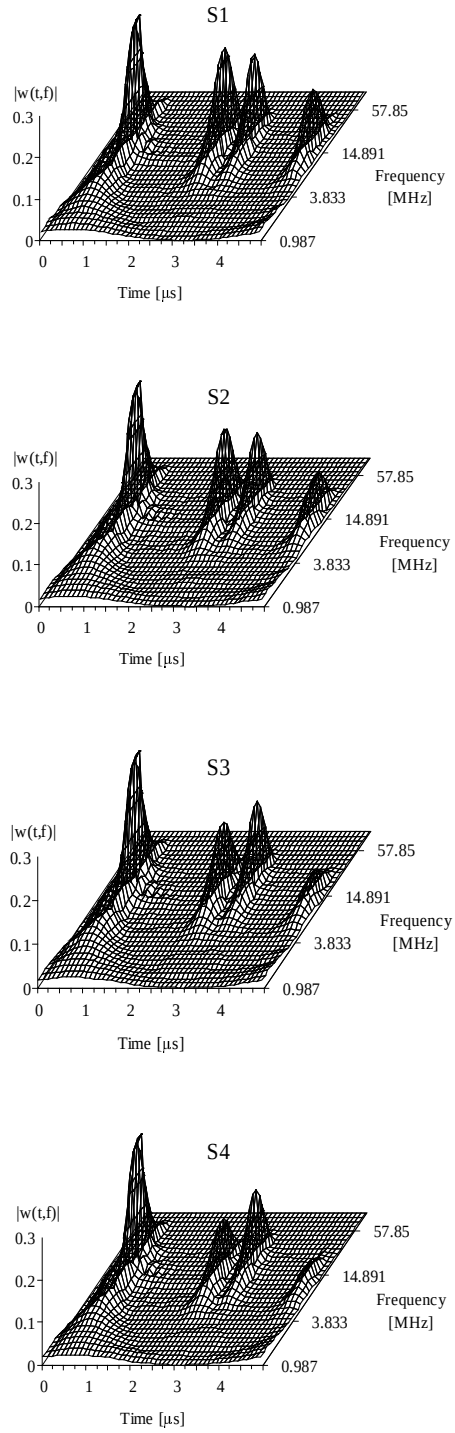

Fig.5 CWT of echoes measured from tested Cr-Mo steel specimens (30MHz transducer)

5 Results and Discussions

In ultrasonic nondestructive technique, some of the selected ultrasonic parameters, such as velocity and attenuation, were measured and related to certain

material properties for the purpose of detection and evaluation of material's internal damage.

Generally, ultrasonic measurement involved in comparing the time of flight and the change of amplitude between a surface echo and a bottom echo. However, in the situation of contact measurement, the surface echo was difficult to be distinguished from the delay line echo of a transducer. Therefore, the difference between the first bottom echo B1 and the second one B2 was usually compared since they directly related to time of sound flight and loss of sound energy caused when ultrasonic wave traveled through a specimen twice.

5.1 Results from Waveforms

Table 2 gives the measured data concerning velocity and attenuation for four kinds of tested specimens, by comparing B1 and B2 from the obtained waveforms.

Table 2: Velocity and attenuation measured from obtained waveforms

		S1	S2	S3	S4
Velocity (m/s)	30MHz	5952	5920	5930	5938
	50MHz	5947	5915	5923	5932
Attenuation (dB/mm)	30MHz	0.09	0.18	0.30	0.38
	50MHz	0.09	0.17	0.28	0.35

From the measured results, obvious decay in echo's amplitude was found, but the velocity was found relatively unchanged. However, our purpose is to find the behavior of these changes at different frequency and to determine the relationships between the range of these changes and the internal grain size. Next paragraph gives more detailed results obtained by means of time-frequency analysis.

5.2 Results from Time-Frequency Analysis

Because an ultrasonic echo is generally band-limited, it is important to determine a significant frequency band previously, so as to obtain meaningful results. Below this band, accurate time of the echo was obscured due to wavelet transform. Above this band, the transducer was unable to effectively receive those high frequency components from the reflected wave.

5.2.1 Group velocity

Velocity is one of the basic ultrasonic properties. Its change is related to the alteration of elastic modulus and the density of a material as the sound wave traveled through it.

The group velocity means the velocity at each frequency. In a time-frequency plane, it was calculated as the time of flight between the local peak around B1 and that of around B2 at each frequency, divided by transmitted distance (twice of the specimen thickness). Fig.6 gives the results of group velocity obtained.

It was observed from these results that the relatively low levels of change in ultrasonic velocity appear to be due to small differences in the phase present rather than the direct consequence of any increasing in grain size caused by thermal degradation in Cr-Mo steel.

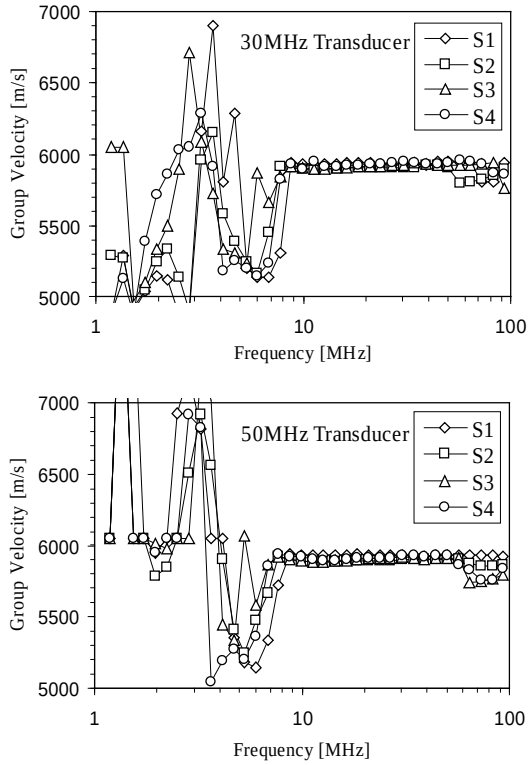

Fig.6 Group velocity

5.2.2 Attenuation ratio

Attenuation is principally caused by the heat condition and scattering as the sound wave traveled through material.

The attenuation ratio at each frequency obtained in a time-frequency plane was the ratio of the local maximum value near B1 to that of B2 at that frequency, divided by transmitted distance.

From the results shown in Fig.7, ultrasonic attenuation was observed gradually increased with thermal degradation increased within a significant frequency band of 10MHz to 30MHz. Not an obvious difference related to the central frequencies of the transducers was found.

Fig.8 gives the dependence of the attenuation on grain size, in which error bars indicated the range of

the attenuation's change with frequency within this frequency band. It was found that the grain size greatly affected the ultrasonic attenuation and the change of attenuation in terms of frequency.

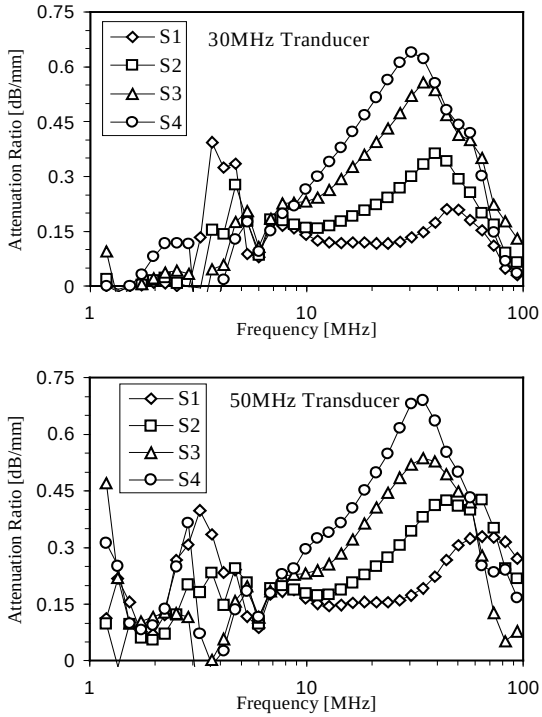

Fig.7 Attenuation ratio

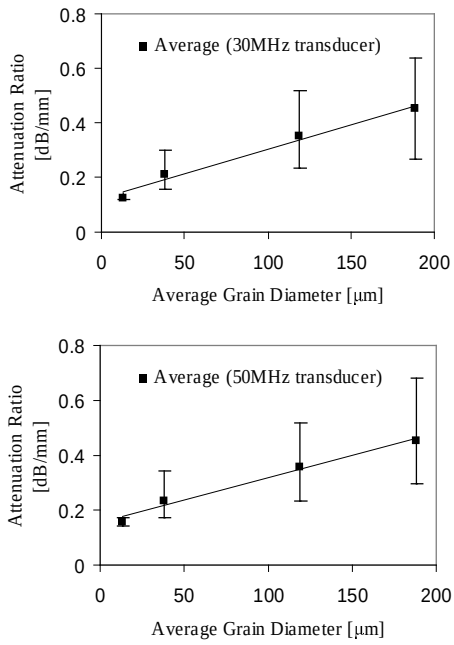

Fig.8 Attenuation ratio vs. grain size within 10MHz~30MHz significant frequency band

Meaningful evaluation of data produced by ultrasonic testing is strongly dependent on equipment, specimen accuracy, etc. Above observations are in accordance with general expectations and previous published results regardless of any frequency dependence [1]. The effectiveness of time-frequency analyses, especially CWT, to ultrasonic echoes for the evaluation of material damage is therefore clarified.

6 Conclusion

This study concerned the application of time-frequency analyses in the field of ultrasonic nondestructive material evaluation. It is concluded that the wavelet transform provided an effective tool to obtain frequency dependent ultrasonic characteristics, such as group velocity and attenuation ratio related to certain material properties. Present results indicated that, with the increase of thermal degradation of Cr-Mo steel, both the attenuation and its change with frequency gradually increased within a significant frequency band, though velocity was observed relatively unchanged. These results obtained in a time-frequency plane are certainly useful for quantitative evaluation of material damage.

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