한국해양공학회지 제15권 제3호, pp 87~92, 2001 (ISSN 1225-0767)

Nondestructive Evaluation for Artificial Degraded Stainless 316 Steel by Time-Frequency Analysis Method

KI-WOO NAM AND YOUNG-UN KIM*

Division of Materials Science and Engineering, Pukyong National University, Busan 608-739, Korea
**Korea Institute of Maritime and Fisheries Technology, Busan 606-032, Korea*

KEY WORDS: Nondestrustive evaluation, Artificially degraded material, Sound velocity, Attenuation, Joint-time frequency analysis, Short time fourier transform and wigner-Ville distribution

ABSTRACT: *In this studys, joint time-frequency analysis techniques were applied to analyze ultrasonic signals in the degraded austenitic 316 stainless steels, to study the evolution of damage in these materials. It was demonstrated that the nonstationary characteristics of ultrasonic signals could be analyzed effectively by these methods. The WVD was more effective for analyzing the attenuation and frequency characteristics of the degraded materials through ultrasonic. It is indicated that the joint time-frequency analysis, WVD method, should also be useful in evaluating various damages and defects in structural members.*

1. INTRODUCTION

Acoustic Emission(AE) has demonstrated capabilities for monitoring structural integrity and for dynamically characterizing materials behavior. Many successes (Nam, 1999; Nam & kim, 1999; Nam *et al*, 1997) have been achieved by conventional acoustic methods with the use of event counts, AE energy, AE amplitude, and their changes with time.

Recent rapid progress in computer technology and measurement systems have had a strong positive impact in the development of signal detection and their real-time analysis for nondestructive evaluation (NDE) of defects in structural components using acoustic emission (AE) (Kim, 2000; Ziola, 1997) and ultrasonic signals (Abbate, 1997; Malik, 1996). In most of these applications, the signal processing is carried out through conventional Fourier analysis. It is difficult if not impossible to analyze signals of both time and frequency domain because the frequency components of the signal are a function of time variable. Therefore, joint time-frequency method, which can express both the time and the frequency on two-dimensional plane, is used to analyze both time and frequency domain for signals. These tools are generally referred to as time-frequency distribution or time-frequency analysis and have been found useful in numerous applications such as speech processing, sonar analysis, detection of electrocardiography (EEG) signals and X-ray diffraction. Joint time-frequency methods can be of linear or bilinear form. The Short Time Fourier Transform (STFT), Gabor Expansion, Wavelet transforms, etc are of the linear form. The bilinear forms are the Wigner-Ville Distribution (WVD) and Choi-Williams Distribution (CWD). The time-frequency analysis methods are being used increasingly in the signal analysis for NDE studies (Nam & Mal, 2001; Ahn, 2001; Nam & Moon, 2001). However, most of these studies involve theoretical analysis (Boashash, 1988; Jin, 1996; Lih, 1995) and experimental studies (Musha, 1991; Nam et al, 1999) have so far been limited.

In this study, the frequency characteristics of nonstationary ultrasonic signals from the degraded austenitic 316 stainless steel specimens were analyzed by means of the STFT and WVD methods. The relative effectiveness of the two methods in NDE applications is evaluated.

2. SHORT TIME FOURIER TRANSFORM

Because the classical Fourier transform analysis does not associate with any particular time instant, it does not explicitly reveal the time-varying nature of nonstationary signals. The most straightforward approach of characterizing a signal's frequency as a function of time is to divide the signal into several overlapping blocks and carrying out the Fourier transform of each individual block of data. This process has become known as the short time Fourier transform (STFT) and roughly reflects how the frequency content of a signal changes with time. The short time Fourier transform can be expressed by the following equation :

$$\mathrm{STFT}(t,\omega) = \int s(\tau)\, \gamma^{*}_{t,\omega}(\tau)\,d\tau = \int s(\tau)\, \gamma^{*}(-t)e^{-j\omega\tau}\,d\tau \qquad (1)$$

Where, t is time, ω is frequency. Equation (1) is a regular inner product and reflects the similarity between the signal s(t) and the elementary function $\gamma(\tau-t)e^{-j\omega\tau}$. STFT spectrogram is the most simple and widely used time-dependent spectrum, which roughly depicts a signals energy distribution in the joint time-frequency domain. The corresponding STFT spectrogram can be expressed by the following equation :

$$FS(t, \omega) = | STFT(t, \omega) |^2 \quad (2)$$

In this approach, the size of the blocks determines the time accuracy: the smaller the block, the better the time resolution. However, frequency resolution is inversely proportional to the size of a block. Thus, while a small block yields good time resolution, it deteriorates the frequency resolution and vice versa (the window effect).

3. WIGNER-VILLE DISTRIBUTION

The Wigner-Ville distribution, originally developed by Eugene P. Wigner in 1932, has many properties that are useful for signal analysis, and has better resolution than the STFT. In WVD, the time-dependent auto-correlation function is chosen to be the Wigner-Ville Distribution, originally developed by Eugene P. Wigner in 1932, has many

$$R(t, \tau) = s(t + \tau/2)s^*(t - \tau/2) \quad (3)$$

which can also be expressed as eq. (4)~(6)

$$WVD_{auto(t,\omega)} = \int s(t + \tau/2)s^*(t - \tau/2)e^{-j\omega\tau}d\tau \quad (4)$$

Equation (4) is usually called the auto-WVD. The cross-WVD is similarly defined as

$$WVD_{cross(t,\omega)} = \int s(t + \tau/2)g^*(t - \tau/2)e^{-j\omega\tau}d\tau \quad (5)$$

In particular, for $s(t) = s1(t) + s2(t)$,

$$WVD_s(t,\omega) = WVD_{s1}(t,\omega) + WVD_{s2}(t,\omega) + 2ReWVD_{s1,s2}(t,\omega) \quad (6)$$

Clearly, the WVD of the sum of two signals is not the sum of their respective WVD_s, due to the presence of the cross-term $WVD_{s1,s2}(t,\omega)$ in the right hand side of equation (6). The cross-term interference is one of the drawbacks in applying WVD to certain types of signals.

4. SPECIMENS

For the ultrasonic inspection study, several specimens of AISI type 316 stainless steel (10mm diameter and 25mm long) were obtained from a bar stock. These materials are used in nuclear power plants pipes and reactors. The chemical compositions of the material are : C (0.06), Mn (1.8), Si (1.00), Cr (18.4), Ni (12.1) and Mo (2.2). The mechanical properties of the material are : yield strength 294MPa, tensile strength 578MPa and percentage of elongation 50. Figure 1 shows the geometry of a specimen.

5. EXPERIMENTAL PROCEDURE

The specimens were heat treated at the same temperature (1000℃) for different time duration (0.5h to 5h) in order to produce different microstructures (see Figure 4). Table 1 gives the details on the heat treatment given to the specimens.

Metallographic examination was carried out on samples cut from the heat-treated specimens. From the remaining portion, samples of 17mm thickness were obtained by machining. Surface grinding was carried out to obtain plane parallelism to an accuracy of better than 3m to eliminate the ultrasonic scattering and dispersion by surface roughness.

Ultrasonic signal measurements were carried out in real time using longitudinal probes. The probe was broadband with 5MHz central frequency (Panametrics, 0.5 inch). For bonding, ZG-F couplant of Krautkramer was used, and clamps were used to keep constant contact pressure and condition. Figure 2 shows a block diagram of the experimental setup for the ultrasonic inspection.

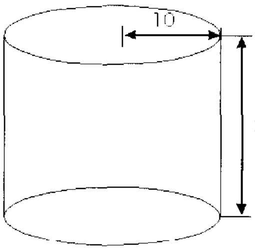


Fig. 1 Dimensions of a specimen (mm)

Table 1 Heat treatment given to austenite 316 stainless steel specimens.

Specimen	Heat treatment	Cooling condition
S-1	0h	-
S-2	1000℃ / 0.5h	Air guenching
S-3	1000℃ / 1h	Air guenching
S-4	1000℃ / 2h	Air guenching
S-5	1000℃ / 3h	Air guenching
S-6	1000℃ / 5h	Air guenching

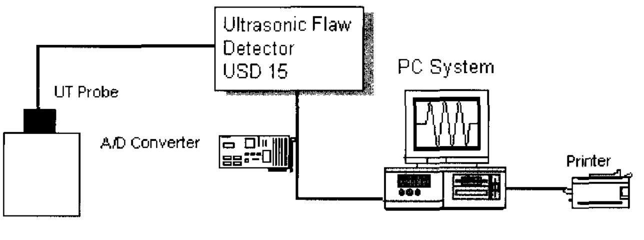
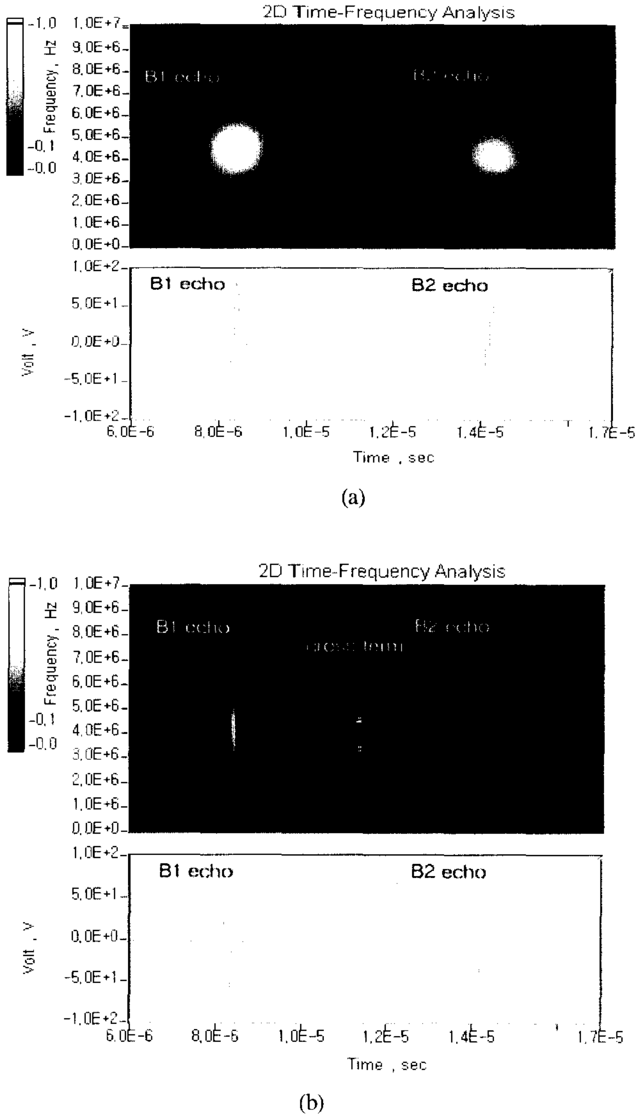


Fig. 2 Block diagram of the experimental setup

6. APPLICATIONS OF JOINT TIME-FREQUENCY ANALYSIS METHOD

In this study, Short Time Fourier Transform (STFT) and Wigner-Ville Distribution (WVD) were used to analyze ultrasonic signals. Figure 3 shows the STFT (Figure 3a) and WVD (Figure 3b) results for the same ultrasonic signal obtained from the degraded specimens. It can be seen that in spite of the presence of the cross-term interference, WVD results have a higher resolution and better clarity than the STFT results. Thus subsequent analysis of the ultrasonic signals were carried out with WVD.



(a)

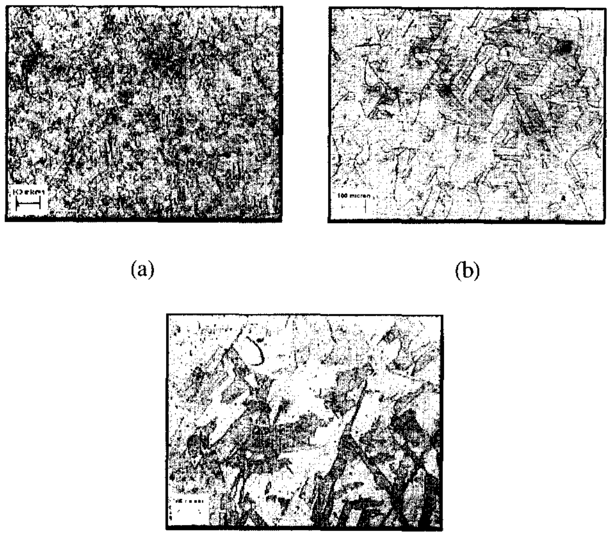
(b)

Fig. 3 Analytical results for the same ultrasonic signal obtained from degraded specimens.
(a) Short Time Fourier Transform (b) Wigner-Ville Distribution

7. FREQUENCY CHARACTERISTIC OF ULTRASONIC SIGNALS

In general, ultrasonic wave speeds change as the material degrades due to ultrasonic scattering and dispersion by the grains, extraction and void. Representative photomicrographs of the specimens subjected to heat treatments of 0h, 1h and 5h are shown in Figure 4. It can be seen that the grain size became larger with increasing degradation time.

Figure 5 shows the measured ultrasonic longitudinal wave speed of the same specimens whose microstructures are given in Figure 4. The velocity was measured by time frequency analysis as well as



(a) (b)

(c)

Fig. 4 Micrographs of degraded specimens through heat treatment. (a) 0 hour, (b) 1 hour, (c) 5 hour

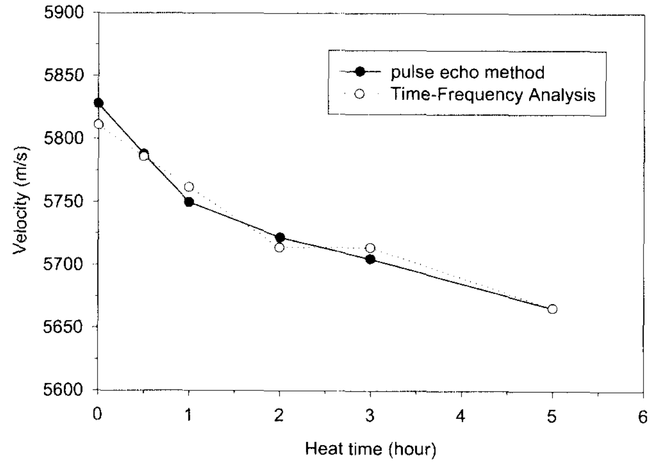


Fig. 5 Relationships between heat treatment time and ultrasonic velocity

by pulse echo method. This figure shows that the wave speeds measured by the two methods are comparable and the wave speed decreases with increasing degradation time. It can be concluded that the ultrasonic wave speed is a strong function of texture in austenitic stainless steel.

Ultrasonic attenuation measurements are also influenced by the degradation time and a small number of large grains may change the attenuation coefficient significantly. Figure 6 shows the attenuation coefficient, α, measured from the frequency-time analysis and the pulse echo method. In the time frequency analysis, the attenuation coefficient is obtained from the center energy ratio of frequency of B1(first echo) and B2(second echo)(Fig.7) and the amplitude ratio of back face echo (B2/B1) is obtained from the pulse echo method. In Figure 6 the attenuation coefficient obtained from STFT and WVD have comparable values; the back echo results are somewhat smaller. However, the trend in the curves is the same; attenuation increases with degradation time.

In the attenuation measurements, the CRT screen of the ultrasonic equipment was maintained at a constant, 80% of the height of B1, to analyze the frequency change of B1 in the degraded specimens[Grayali et al., 1985]. Figure 7 shows the result of frequency change using WVD. Specimen frequency could be known which frequency of high range decrease and center frequency become low according to heat treatment time. As indicated earlier, WVD has good resolution in frequency, but it has the drawback due to the presence of the cross term between B1 and B2.

Figure 8 shows the change in the center frequency of the ultrasonic signals of Figure 7 as functions of the degradation time. This figure shows that the center frequency decrease almost exponentially as the degradation time increases. Ultrasonic signals are strongly affected by the material microstructure including grain size, extraction of grain boundary and surface roughness. An ultrasonic pulse generally has a limited bandwidth and it contains frequency components involved in the band. Each frequency component in an echo waveform can be affected by changes in the microstructure. In the degraded material the high frequency components of the signal rapidly attenuate and this results in a lower center frequency of the pulse.

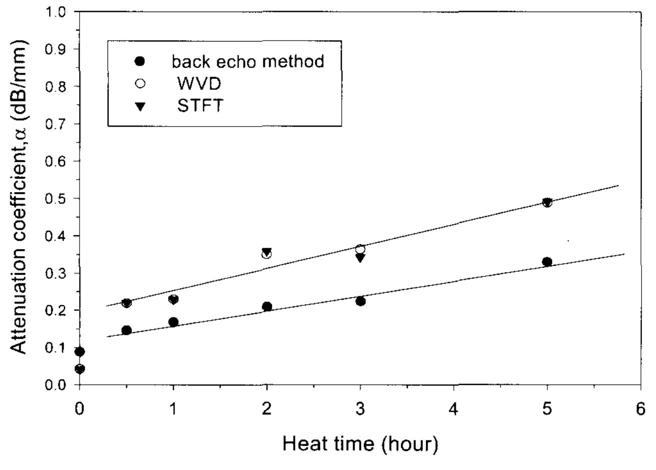
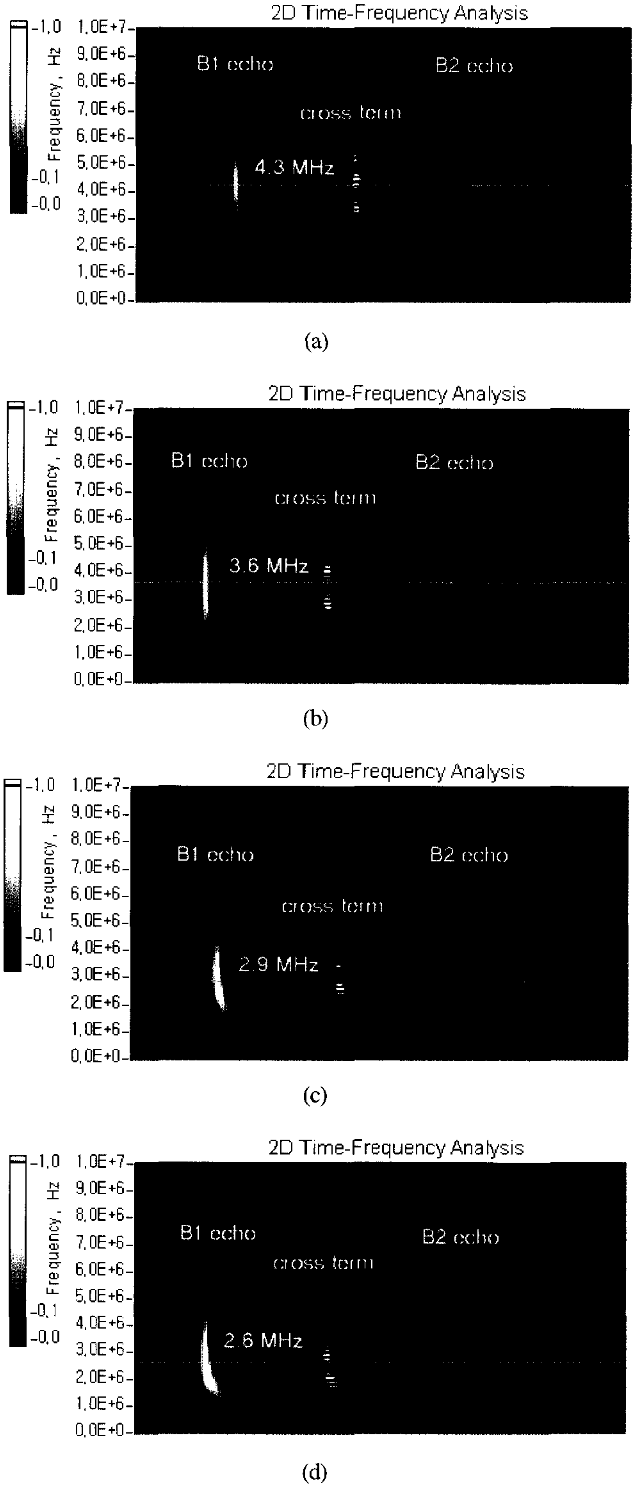


Fig. 6 Influence of degradation time on ultrasonic wave attenuation



(a)

(b)

(c)

(d)

Fig. 7 Degradation evaluation of the ultrasonic signals by WVD. (a) 0 hour, (b) 1 hour, (c) 3 hour, (d) 5 hour

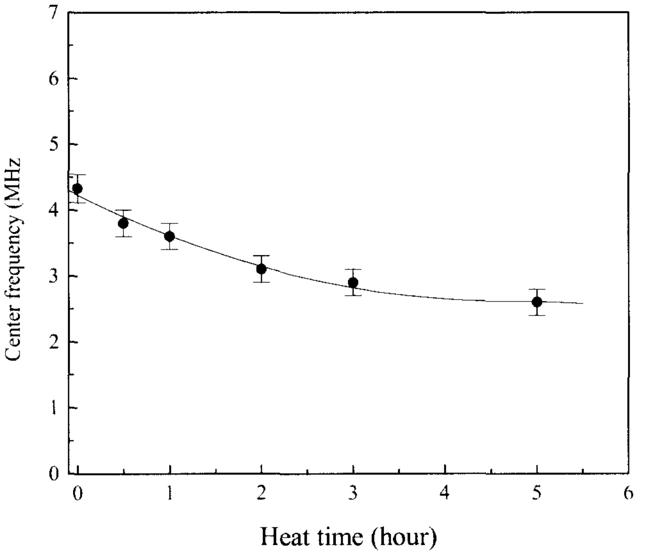


Fig. 8. Center frequency of ultrasonic waves in degraded specimens

Figure 9 shows the change in the measured frequency components from 2MHz to 7MHz in the signal B1 for the degraded specimens. Figure 9(a) was obtained for the base metal; its center frequency was 4.3MHz. Therefore, the amplitude of each frequency component is very high at 4MHz and 5MHz. Figure 9(b) was obtained from the 1hr degraded specimen and the center frequency was 3.6MHz. Figures 9(c) and (d) show results obtained in 3hr and 4hr degraded specimens, respectively. These figures contain high amplitude components at 2MHz and 3MHz but the amplitudes are low above 5MHz. This is due to the increase in the attenuation of the high frequency components by coarse grain and extraction of grain boundary etc, in the degraded specimens.

Figure 10 shows the relation of velocity, attenuation cofficient and center frequency. The value of attenuation cofficient indicates an almost linear increase as heat time increases. But the velocity and center frequency indicate an exponential decay as heat time increases.

8. CONCLUSIONS

This study analyzed the frequency characteristics of acoustic emission from ultrasonic signals in the artificially degraded austenitic 316 stainless steel. The feasibility of applying the STFT and WVD time-frequency analysis methods to ultrasonic of the degraded material was investigated. The results obtained from the present study can be summarized as follows:

(1) The time-frequency analysis methods can be used to analyze non-stationary ultrasonic signals more effectively than conventional techniques.

(2) Damage evaluation of the artificially degraded SUS 316 could be estimated from the attenuation coefficient and velocity of

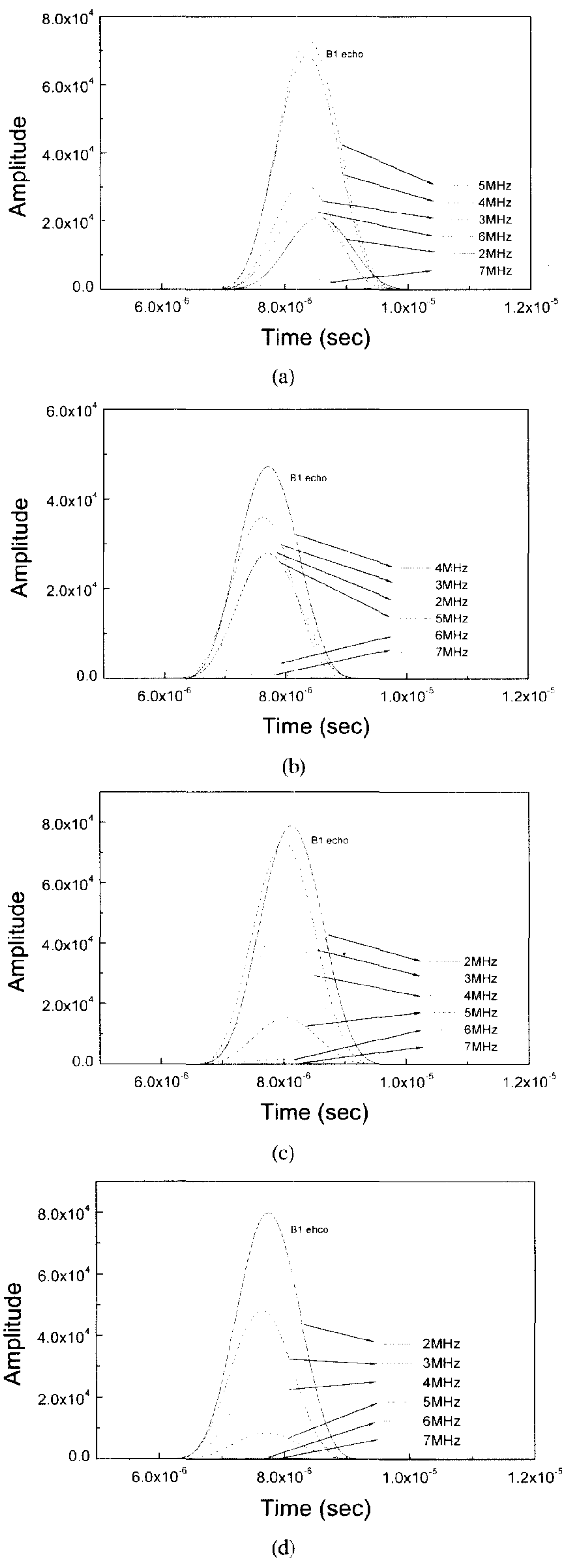


Fig. 9 Frequency components of back echo by degradation time. (a) 0 hour, (b) 1 hour, (c) 3 hour, (d) 5 hour

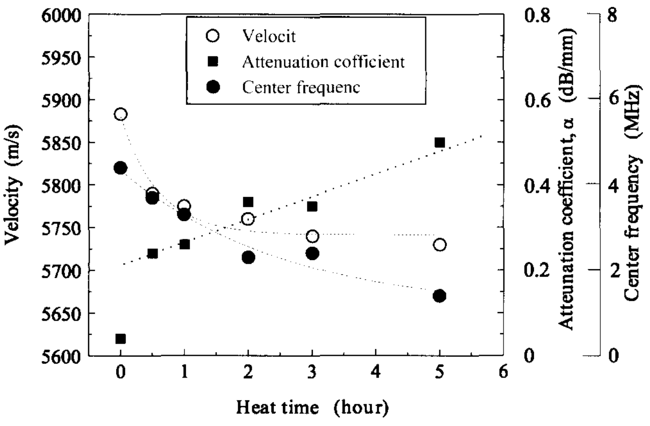


Fig. 10 Relation of velocity, attenuation coefficient and center frequency.

ultrasonic waves by time-frequency analysis method.

(3) Degradation could be evaluated with measurement of center frequency change and attenuation change of each frequency component using WVD.

(4) The value of attenuation coefficient indicates an almost linear increase but the velocity and center frequency indicate an exponential decay as heat time increases.

(5) Based on NDE analysis of ultrasonic signals by time-frequency analysis method, it should also be possible to evaluate, in real-time, various damages and defects in structural members.

REFERENCES

Abbate. A., Schroeder. S. C., Koay, J. and Das. P. (1997). "Signal Detection and Noise Suppression using a Wavelet Transform Signal Processor : Application to Ultrasonic Flaw Detection", IEEE Transaction on Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 44, No. 1, pp 14~26.

Ahn, S. H. and Nam, K. W. (2001). "Characteristics of Signals Emanating from Fatigue Crack Propagation and Penetration of a Surface Crack in a 6061 Aluminum Plate", Journal of Ocean Engineering and Technology, (in press).

Boashash, B. (1988). "Note on the Use of the Wigner Distribution for Time-Frequency Signal Analysis", IEEE Trans. Acoustics, Speech, Signal Processing, Vol. 36, No. 9, pp 1518~1521.

Grayali. n. and Shyne. J. C. (1985). "Effect of Microstructure and prior austenite grain size on acoustic velocity and attenuation in steel", Review of Progress in NDE, Vol. 4B, Plenum Press, New York, pp 927~936.

Jin, X. M. Malik, M. A. and Saniie, J. (1996). "Singular Value Decomposition of Wigner Distribution for Time-Frequency Representation of Ultrsonic Echoes", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 15, pp 765~772.

Kim, H. S., Kang, C. Y. and Nam, K. W. (2000). "Fatigue Characteristics of High Strength Fire Resistance Steel for Frame Structure and Time-frequency Analysis of its Acoustic Emission Signals," J. Kor. Inst. Met. & Mater.,Vol. 38, No. 11, pp 1478~1482.

Lih. S. S., Mal, A. and Bar-Cohen, Y. (1995). "Ultrasonic Evaluation of Thermal Degradation in Adhesive Bonds", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 14, pp 1489~1496.

Malik, M. A., Jin. X, M. and Saniie, J. (1996). "Joint Time-Frequency Processing of Ultrasonic Signals", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 15, pp 2089~2096.

Musha, T. and Kawamura, J. (1991). "Wiger Distribution Function and its Application for the Ultrsonic Nondestructive Evaluation", JSNT, Vol. 40, pp 587~591.

Nam, K. W. (1999). "Acoustic Emission from Surface Fatigue Cracks in SS41 Steel", Fatigue Fract. Engng. Mater. Struct., Vol. 22, pp 1103~1109.

Nam, K. W. and Kim, S. J. (1999). "Life Prediction by Retardation Behavior of Fatigue Crack and its Nondestructive Evaluation", Journal of Ocean Engineering and Technology Vol. 13, No. 3, pp 36~48.

Nam, K. W., Kim, S. J., Lee, K. C., Oh, J. H., Oh, S. K. and Lee, J. S. (1997). "Acoustic Emission during Fatigue Crack Penetration Behavior of Surface Cracked Plate", Journal of Ocean Engineering and Technology, Vol. 11, No. 3, pp 29~38.

Nam, K. W., Lee, K. C. and Oh, J. H. (1999). "Application of Joint Time Frequency Analysis Methods of Nondestructive Evaluation," ASME International Mechanical Engineering Congress & Exposition, November 14 - 19, NDE-17, 67~74.

Nam, K. W., and Mal, A. (2001). "Characteristics of Elastic Waves Generated by Crack Initiation in Aluminum Alloys under Fatigue Loading", Journal of Materials Research, Vol. 16, No. 6, pp 1745-1751.

Nam, K. W. and Moon, C. K. (2001). "Classification of Acoustic Emission Signals from fatigue crack propagation in 2024 and 5052 Aluminum Alloys", Journal of Ocean Engineering and Technology, (in press).

Ziola, S. and Searle, I. (1997). "Automated Source Identification using Modal Acoustic Emission", Review of Progress in Quantitative Nondestructive Evaluation, Vol. 16, pp 413~419.

2001년 6월 9일 원고 접수
2001년 7월 25일 수정본 채택