연속 웨이블릿 변환을 이용한 콘크리트의 One-Sided 응력파 측정기법 개선

Improvement for One-Sided Stress Wave Measurement Technique in Concrete using Continuous Wavelet Transform

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1. Introduction

Last year safety issues for airplanes were raised due to severe cracks and differential settlements in a newly constructed concrete pavement runway at Gimhae International Airport [1]. Pavements, even those age is young, suffer damage due to service loads, environmental effects, to name a few, and it is important that damage will be detected and characterized in a timely and reliable fashion to guarantee of those safety. The use of stress-wave based non-destructive testing methods, such as ultrasonic wave velocity techniques, enables inspection deep within the pavement and has the potential to offer information concerning the elastic moduli, strength gain, and the presence of damage[2]. However, the practical through-thickness nondestructive testing methods for concrete structures, especially those which offer access to only one side such as pavements, has been restricted because of the inaccessibility to the opposite side. Recently, researches concerning one-sided stress wave velocity measurements have been revisited with the measurement of Rayleigh wave (R-wave) in concrete in addition to longitudinal wave (L-wave) to overcome the limitation of through thickness L-wave velocity method [3,8,9]. Significant improvements have been reported for the accurate L-wave velocity measurement [3]. However, there have been few modifications on the R-wave velocity measurement in concrete. Rather, all previous researchers assumed that concrete behaves as a linear, elastic and isotropic solid ,and hence R-wave velocity does not change in transit between transmitter and receiver. However, laboratory and numerical experiments of the recent researches show multiple scattering of elastic waves from heterogeneities near the surface not only attenuates, but also delays coherent events [4]. Therefore, in order to effectively use surface waves for nondestructive testing or evaluation of concrete structures, techniques to determine R-wave velocity reflecting heterogeneity in concrete must be employed. This study aims at a modification of conventional one-sided stress wave velocity measurement technique that is developed originally by Popovics et al.[3]. A new R-wave velocity measurement technique using continuous wavelet transform (CWT) to reflect scattering effects is proposed, which is not in the case for the previous research. Laboratory experiments are performed on various specimens to validate the proposed technique and to demonstrate the differences and effectiveness of the proposed technique in comparison with the conventional techniques.

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2. Improved Rayleigh Wave Velocity Measurement Technique

2.1 Dispersion of Rayleigh Waves in Concrete due to Scattering from Heterogeneity

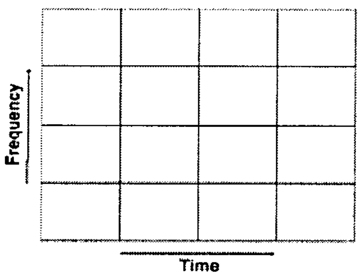
If the wave velocity depends on the wavelength, then the wave is said to exhibit dispersion. The principal feature of dispersion is that the shape of wave pulse (or disturbance) does not retain its initial shape as it propagates through the dispersive medium. In other words, when one measured dispersive wave signals using transducers, one can identify either the signal spreading or condensing in time domain. Such dispersion may be caused by (1) the presence of specimen boundaries (geometric dispersion); (2) the frequency dependence of material constants (material dispersion); (3) the scattering of waves by heterogeneities in a material (scattering dispersion), and (4) the dissipative dispersion of wave energy into heat in an irreversible process [5]. Surface waves are usually of the Rayleigh wave type (R-waves) and travel along the surface of the material. For an elastic, homogeneous and isotropic material, the propagation velocity of R-waves (V_R) is approximated by the velocity of shear waves (V_S) as [5],

$$V_R \cong \frac{0.862 + 1.14\nu}{1+\nu} V_S \qquad (1)$$

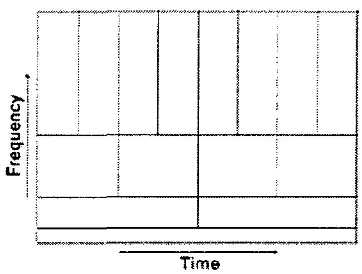
where ν is Poisson's ratio. It is obvious in Eq.(1) that R-wave velocity can be determined once the elastic constants of material are known, and thus it is non-dispersive in an elastic, homogeneous and isotropic material. It is natural to deduce that R-wave should be dispersive if the material of concern is neither of the assumptions. Generally, concrete is heterogeneous material with many scattering sources such as aggregates. Hence, the R-wave in this study assumed to be dispersive only due to scattering.

2.2 Rayleigh Wave Velocity Measurement using Continuous Wavelet Transform

Laboratory and numerical experiments of the recent researches show multiple scattering of elastic waves from heterogeneities near the surface not only attenuates, but also delays coherent events [4]. One of main contributions of the phenomenon comes from the delayed P- and S-wave components including in R-wave group due to scattering, and those lead to further scattering of R-waves which exhibit dispersion. Therefore, in order to reflect scattering effects in R-wave velocity measurement, a signal processing technique which is very effective for dispersive signal analysis must be employed.



(a) STFT, WVD



(b) CWT

Figure 1. The tiling of STFT,WVD and CWT in time-frequency map

Continuous wavelet transform (CWT) has been used very successful in analyzing dispersive wave signals owing to its robustness of supporting size[6,7]. That is, the time-frequency tiling (or supporting range for each time-frequency window) of conventional time-frequency transform, such as short-time Fourier transform (STFT) and Wigner-Ville distribution (WVD), as shown in figure 1.(a), is fixed in time-frequency map. However, the tiling of CWT can be varying, as shown in figure 1.(b), and hence it is very effective as well as useful for analyzing dispersive signal rather than STFT and WVD [6]. In this study, CWT is used to determine time of flight of R-waves transit in two receivers in concrete due to its best-fit capability for analyzing dispersive signals.

Surface response generated by impact source is dominated by R-waves [5]. Then, it is possible to say that the time of flight of R-waves can be evaluated by obtaining the time difference in two maximums for the absolute value of the wavelet coefficients of each receiver's signal as,

$$\Delta t = \underset{t}{arg\,\max}\,\langle W_2(a,t)\rangle - \underset{t}{arg\,\max}\,\langle W_1(a,t)\rangle \tag{2}$$

where, Δt is time of flight and $W(a,t)$ is wavelet coefficients of the time domain signal $f(t)$. Wavelet transform is defined as follows [6],

$$W(a,t) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(\tau)g(\frac{\tau - t}{a})d\tau \quad a \neq 0 \tag{3}$$

where, $g(t)$ is a mother wavelet and a is a scale parameter. Once the time of flight between two receivers has been obtained, R-wave velocity is calculated using known distance(d) between two receivers as,

$$C_R = \frac{d}{\Delta t}. \tag{4}$$

This gives the same results in case of non-dispersive waves with the method that is the time difference of maximum peaks in the time domain signal of each receiver. Moreover, proposed method may give more reliable R-wave velocity in heterogeneous material, because the whole R-waves group, which shows dispersion, is considered in calculation of wavelet coefficient to reflect dispersion. In other words, a weighted averaging scheme is used for reflecting dispersion.

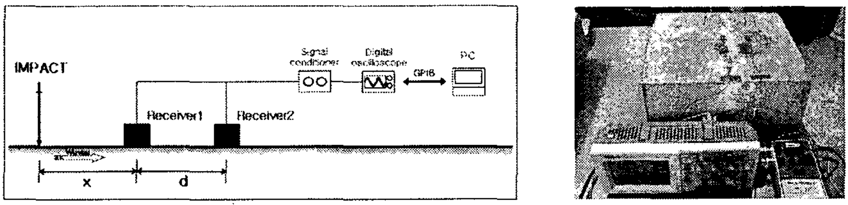


Figure 2 Experimental Setup

2.3 Experimental Setup

The hardware setup for the one-sided test consists of a controlled impact-based wave source, two receiving transducers, a digital oscilloscope connecting with signal conditioner, and a laptop computer. Configurations of setup are shown in figure 2. Since the proposed method is modification of Popovics *et al.*'s method, specific details of the setup can be found in reference [3].

3. Experimental Study

3.1 Test Specimen Preparation

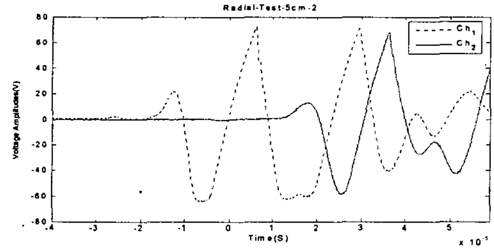
A series of experiments were conducted on engineering materials, such as steel block and concretes of varying composition, to examine dispersion behavior and to verify the proposed method. Detailed description of the specimen is tabulated in table 1. Steel is included for verification of the proposed method, since steel is relatively homogeneous elastic material, and hence its acoustical properties are relatively constant and measured easily. Concrete specimens were mixed and cured in laboratory. Sizes of the specimens are determined to avoid bottom and side reflections. The fresh concretes were cured 24 hours in room conditions after vibrating consolidation. Then the molds were stripped and the concretes were placed in a controlled humidity and temperature curing room for a period of 28 days.

Table 1. Specimen Description (c:cement, w:water, fa:fine aggregates, ca:coarse aggregates)

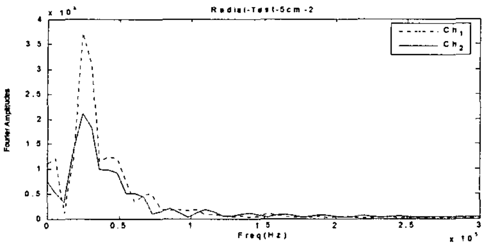
Materials	Dimensions (cm)			Compositions (c:w:fa:ca)	Ages (Days)	compressive Strength (kgf/cm^2)
	Width	Length	Height			
Steel	15	15	7	-	-	-
Concrete A	40	40	15	0.69:1:2.67:4.05	28-40	260
Concrete B	40	40	15	0.38:1:1.55:2.11	28-40	480

3.2 Experiments

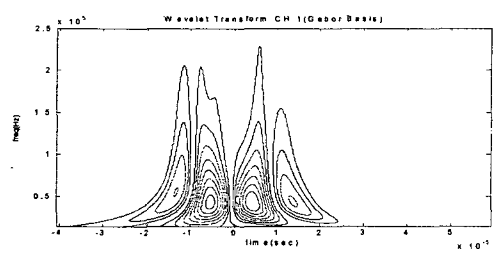
One-sided velocity measurements were taken for all the specimens. For each test, ten repeated one-sided measurements were carried out to remove incoherent background noise by stacking average. A wavelet basis using in this study is Gabor wavelet, since it is the most widely used basis for dispersive signal analysis[6,7]. Spacings(d) between receiver 1 (Ch.1) and receiver 2 (Ch.2) were changed and tested to identify the dispersion behavior of concrete and the stability of the proposed method compared with the conventional methods. Note that spacing for steel test was fixed since the size limited the interval test and steel is used only for verification of utility of the proposed method. Typical time domain signals obtained from one-sided measurements and their Fourier spectra and CWTs are shown in figure 3. The results both the conventional and the proposed methods can be found in tables 2 and 3, and figure 4.



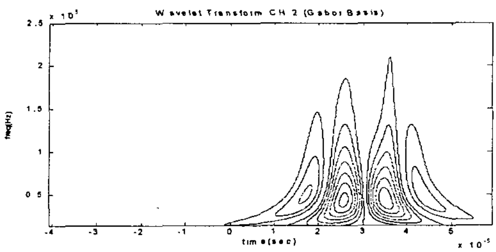
(a) Time Domain Raw Signal (Ch 1. and Ch. 2)



(b) Fourier Spectra (Ch 1. and Ch. 2)



(c) Wavelet Transform (Ch.1)



(d) Wavelet Transform (Ch.2)

Figure 3. Typical Signal Representations : (For concrete B with 7cm of receiver interval case)

Table 2. Measured Rayleigh Wave Velocities

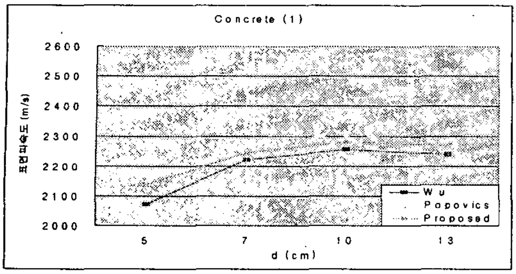
	Popovics' method (m/s)				Wu's Method (m/s)				Proposed Method (m/s)			
Spacings (d)	5cm	7cm	10cm	13cm	5cm	7cm	10cm	13cm	5cm	7cm	10cm	13cm
Steel	2925	-	-	-	2920	-	-	-	**2920**	-	-	-
Concrete A	2248	2285	2304	2286	2073	2221	2256	2240	**2137**	**2244**	**2281**	**2270**
Concrete B	2332	2536	2453	2390	2240	2362	2372	2350	**2298**	**2444**	**2425**	**2379**

In steel case, the conventional method and the proposed method give almost same velocity and very low coefficient of variation (COV). This shows that steel is a non-dispersive medium for R-wave as predicted and verifies utility of the proposed method even in non-dispersive case.

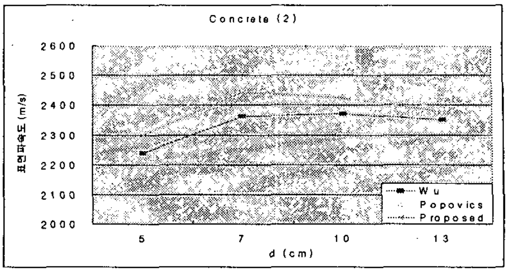
For concretes, it is observed that the difference exists not only between the conventional Popovics' and Wu's methods, but between the conventional and the proposed method. This exhibits the dispersion of R-wave in Concrete. Popovics' method regards an arrival of largest component as R-wave arrival. On the other hand, Wu's method regards an arrival of first surface components as R-wave arrival. If R-wave in concrete is non-dispersive, then it must be same both Popovics' and Wu's methods. However, the largest arithmetic difference is about 200 m/s between the methods as well as COVs of the methods are larger than that of the proposed method, and it resulted in dispersion. And this also suggests that the point-wise measurement may be main source of error in practical nondestructive testing and evaluation. Because there is no standardized method for R-wave velocity measurement[3], its measurement strongly depends on the tester's choice of arrival point. Therefore, to reduce such a source of error, the whole R-waves group, not a point-wise, must be considered. This is an innate scheme of the proposed method because wavelet transform implies weighted average. It can be induced from the result that the proposed method reflects dispersion effects. Because R-wave velocities of the proposed method are placed in the near-middle of the conventional methods, moreover, the COV are significantly less than those. Additionally, from COV results, the proposed method may give better consistency than that of the conventional methods. COV values of the conventional methods are 1.5 times to 1.8 times larger. It is suggested that the location of second receiver is larger than 5cm far from first receiver to minimize the magnitude of the error in the measurement of the receiver spacing. Because significant discrepancies are observed in 5cm results. This is already pointed out by previous research[3]. Finally, when comparing the 7cm, 10cm, and 13cm data, it is evident that deviations between Popovics' and Wu's methods get decrease when spacing is increased. This phenomenon is most likely results of attenuation of P-and S-waves components. Since P- and S-waves attenuation are more rapid that R-wave[5], the scattering effects due to those components have to be reduced also by attenuation. This affects the dispersion of R-waves, and hence reduces the deviation.

Table 3. Mean Value of Measured Rayleigh Wave Velocities and Coefficient of Variations(C.O.V.)

Materials	Popovics' method		Wu's Method		Proposed Method	
	Mean Velocity (m/s)	C.O.V (%)	Mean Velocity (m/s)	C.O.V (%)	Mean Velocity (m/s)	C.O.V (%)
Steel	2925	0.18	2920	0.14	2920	0.09
Concrete A	2289	2.88	2241	3.39	2261	1.88
Concrete B	2450	2.57	2371	2.58	2401	1.63



(a) Concrete A



(b) Concrete B

Figure 4. Graphical Representations of Surface Wave Velocities in Concrete (Line Fitting)

4. Conclusions

In this study, a new Rayleigh wave velocity measurement technique using CWT is proposed to improve one-sided stress wave velocity measurement technique. From the experimental study, the proposed method successively reflects scattering effects for R-wave velocity measurement in concrete, which did not consider in previous researches. The method can be independent from tester differences, which previously strongly depends on the tester's choice of R-wave arrival time. Thus, the proposed method may be very useful and effective when it apply to the practical measurement for nondestructive testing.

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