<Original Paper>

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Application of Nonlinear Ultrasonic Method for Monitoring of Stress State in Concrete

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Abstract As the lifespan of concrete structures increases, their load carrying capacity decreases owing to cyclic loads and long-term effects such as creep and shrinkage. For these reasons, there is a necessity for stress state monitoring of concrete members. Particularly, it is necessary to evaluate the concrete structures for behavioral changes by using a technique that can overcome the measuring limitations of usual ultrasonic nondestructive evaluation methods. This paper proposes the use of a nonlinear ultrasonic method, namely, nonlinear resonant ultrasonic spectroscopy (NRUS) for the measurement of nonlinearity parameters for stress monitoring. An experiment compared the use of NRUS method and a linear ultrasonic method, namely, ultrasonic pulse velocity (UPV) to study the effects of continuously increasing loads and cyclic loads on the nonlinearity parameter. Both NRUS and UPV methods found a similar direct relationship between load level and that parameter. The NRUS method showed a higher sensitivity to micro-structural changes of concrete than UPV method. Thus, the experiment confirms the possibility of using the nonlinear ultrasonic method for stress state monitoring of concrete members.

Keywords: Stress State Monitoring, Nonlinear Resonant Ultrasonic Spectroscopy (NRUS), Nonlinearity Parameter, Cyclic Load, Ultrasonic Pulse Velocity (UPV)

1. Introduction

Concrete consists of cement, coarse and fine aggregate, and water in a particular ratio, concrete has high compressive strength and good weather resistance [1]. However, as the lifespan of structures increases, either reinforced steel concrete or prestressed concrete structures suffer degradation due to long-term effects such as creep and shrinkage, lowering the concrete's design strength and usability [2-4]. Additionally, continual repetitive load causes the fatigue effect, which degrades the durability of structures. When a low frequency, high level of fatigue loading is applied, crack propagation can progress rapidly, such that the structures quickly reach the failure stage [5].

To prevent a sudden degradation of structure durability, it is necessary to apply a type of nondestructive evaluation with relatively high sensitivity. For the stress state monitoring of concrete structures under external loads, nondestructive evaluation technologies such as coring, penetration resistance, elastic wave measurement, etc., have been developed and are used in various fields [6]. Among these methods, ultrasonic wave measurement affects structures very little and involves a relatively simple method of monitoring the concrete damage [7,8].

For example, ultrasonic pulse velocity (UPV) is one of the linear ultrasonic methods based on the elastic stress-strain relationship. Several studies have been reported on UPV measurement used to estimate the stress level of concrete in consideration of the acoustoelastic effect and stress memory effect in cement-based materials under continuous or cyclic compressive loading. In detail, the acoustoelastic effect involves the

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dependency of measured factors such as ultrasonic velocity, this method uses a stress field, and does not involve linear elastic theory [9]. When using this method, a lower crack propagation rate in concrete under a load less than that of a maximum stress load that has been suffered before is called the stress memory effect [7]. To allow for a comparison of results, two effects are analyzed using the nonlinear method. However, there have also been reports on the linear ultrasonic method that have found the method to have limited sensitivity for evaluating micro-scale cracks of concrete [10].

On the other hand, previous research has reported that ultrasonic methods based on the nonlinear acoustic effect have had relatively high sensitivity and accuracy, sufficient to characterize cracks of on the micro-meter levels [11-14]. One of the nonlinear ultrasonic methods, the nonlinear resonance ultrasonic spectroscopy (NRUS) technique measures the resonant frequency shift, which is expressed as a function of the excitation level. Concrete is heterogeneous material, so it presents an inherent nonlinearity that causes a shift of the resonance frequency. Especially, nonlinearity rapidly increases when concrete has been damaged. There have been reports on several types of damage to concrete, such as fire damage or damage from the alkali-silica reaction, these types of damage greatly increase the nonlinearity [15,16].

On the other hand, there have been only few studies that have performed stress evaluation of concrete using nonlinear ultrasonic methods, except for one case study that performed higher harmonics measurement [17].

In this research, a preliminary study was performed to investigate the stress-dependency of nonlinearity parameter on concrete. The NRUS technique was proposed in this study, this technique introduces a cross correlation to improve the measurement of the resonance frequency shift. For the experiments, two prism shaped concrete specimens were prepared. Under continuously increasing load and repetitive cyclic load, the nonlinearity parameters were calculated using the proposed NRUS technique.

With a comparison of the load level and the nonlinearity parameter, the dependency of the experimental results on the concrete stress state was verified. In addition, experiments were performed to measure the UPV of concrete samples under identical conditions, this was done to allow for a comparison of both experimental values, the nonlinearity parameter and UPV. Upon consideration of the results, the possibility of using the NRUS technique was confirmed for the monitoring of stress state under load conditions.

2. Experimental Details

2.1. Specimen Description

Two rectangular cubic-molded specimens were used in this study. The first sample (specimen 1) was subjected to a loaded continuously increasing load, and the second sample (specimen 2) was repetitively cyclically loaded, as described in the results section of the this paper. Mix proportion of the specimens are given in Table 1, where W is water, C is cement, S is the fine aggregate, G is the coarse aggregate with dimensions lower than 19 mm, and W/C is the water to cement ratio. Every sample was demolded after 24 hrs of curing at constant room temperature and 60% humidity and was then cured for 28 days in water. The compressive strength of the concrete samples was 50.0 MPa, this value was obtained

Table 1 Mix proportions and compressive strength of specimen

W/C (%)	Unit Weight (kg/m^3)				Strength (MPa)
	W	C	S	G	
0.5	180	360	837	970	50.0

for the five cylindrical samples. Cross-sectional dimensions were 100 mm × 100 mm and the height of the specimens was 300 mm.

2.2. Nonlinear Resonant Ultrasonic Spectroscopy (NRUS) and Experimental Setup

When a material presents a nonlinear stress-strain relationship, ultrasonic waves propagated through the material show different frequency characteristics, such as resonant frequency shift and higher harmonic peak generation of the incident frequency. This phenomenon is generally called the nonlinear acoustic effect [18]. If a material becomes more nonlinear, it will show stronger nonlinear characteristics. In one dimension, the nonlinear stress-strain relationship can be expressed as follows [19]:

$$\sigma = \int E(\varepsilon(t), \dot{\varepsilon}(t)) d\varepsilon \qquad (1)$$

where σ is the stress, ε is the strain, $\dot{\varepsilon}$ is the strain rate, and E is the elastic modulus, which is related to the strain and the strain rate. The elastic modulus E in Eq. (1) can be expanded as follows [19].

$$E(\varepsilon(t), \cdots) = E_0\{1 - \beta\varepsilon - \alpha\Delta\varepsilon + \cdots\} \qquad (2)$$

where E_0 is the linear elastic modulus, $\triangle\varepsilon$ is the strain amplitude proportional to the acceleration, and α is the nonlinearity parameter based on the hysteretic and discrete memory of material. In the case of the resonant wave shift behavior of concrete, the parameter α, which is involved with hysteresis and discrete memory mainly governs the nonlinear behavior [20,21].

$$\frac{f_0 - f}{f_0} \propto \alpha \cdot \Delta\varepsilon \qquad (3)$$

As the amplitude of the input signal increases, the resonant frequency decreases. A simplified relationship between frequency shift and wave amplitude can be written as Eq. (3). For more efficient measurement of the frequency shift, the shift is computed using a cross correlation of the power spectral density. This cross correlation, a statistical technique that compares the shifts of the peak values, can be used to calculate the numerical values of the frequency shift.

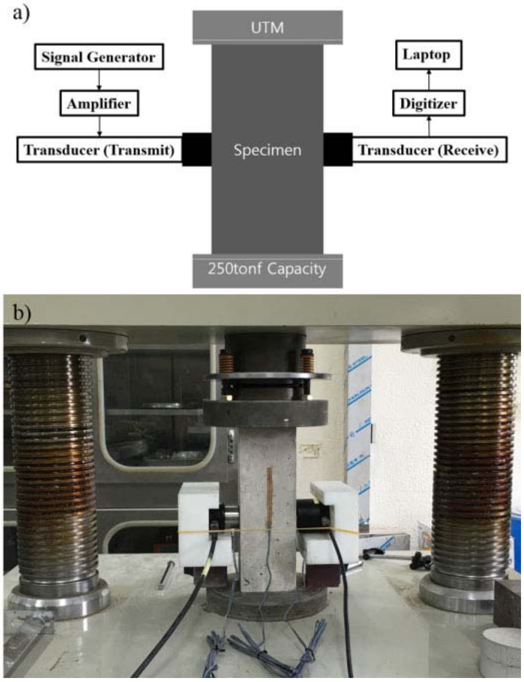


Fig. 1 Experimental description of proposed NRUS technique: (a) schematic experiment setup and (b) specimen loaded in 250 tonf UTM machine

A simplified illustration of the experimental setup is provided in Fig. 1 (a). The specimen is fixed at the center line of the UTM (250 tonf capacity). The transmitted wave frequency is calculated using the 2 MS/s sampling rate and a 100 ms pulse width. Using the signal generator (National Instruments Crop. PXI 5421), a 50 kHz continual pulse wave is generated. After that, the signal is amplified 20 times using a signal amplifier (NF Corporation, BA4825) and transmitted and received through ultrasonic transducers (ultrasonic transducer, Olympus NDT, Inc. Panametrics X1019, V1011) attached to both sides of the specimen. For various strain amplitudes, the voltage of a transmitted wave is normally varied from 60 V to 240 V.

At each load level, measurement is repeated three times and the averaged nonlinearity parameter is used in the analysis. In addition, during the measurement, compressive load is constantly controlled by the UTM and all experimental processes are controlled by a laptop.

Fig. 2 shows the representative results measured in step 1. In the FFT process, the raw signal of an ultrasonic wave in the time domain is transformed to the power spectral density in the frequency domain. In order to improve the frequency resolution, zeros of 599 times the number of recorded samples were added. As can be seen in Fig. 2 (b), the resonant frequency is around 17 kHz for all measurements [21].

Therefore, it was possible to determine the heretic nonlinearity parameter by measuring the frequency difference using Eq. (3). After cross-correlation, measured values of the resonance frequency shift are plotted along the transmitted voltages. The ‘T’ in Fig. 2(c) stands for ‘Trial’. Thus, as represented by Eq. (3), the nonlinearity parameter α can be calculated using the slope of the plotted data with the axis of the two variables. Tendency and sensitivity are analyzed according to the nonlinearity parameters for each step of the design load.

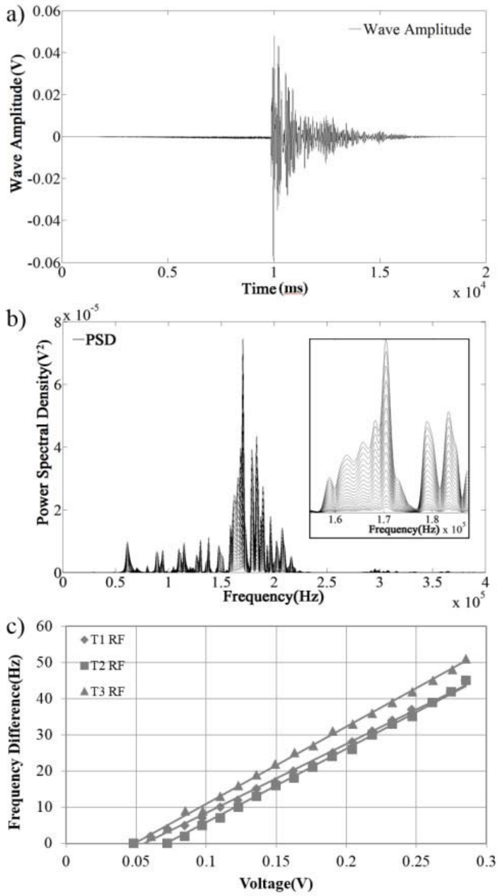


Fig. 2 Signals measured in step 1: (a) time domain raw signal (b) frequency domain signal (c) relative frequencies plotted with transmitted voltages

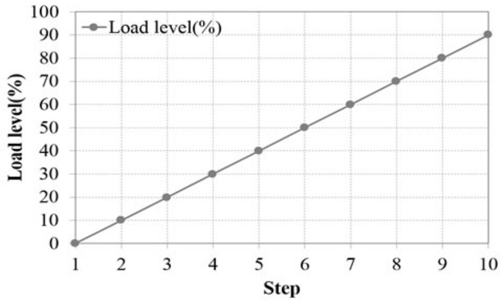


Fig. 3 Specimen 1: continuously increasing load

2.3. Experimental Results:

Load cycle for specimen 1 is designed as shown in Fig. 3. The load difference between each step was set at 5 MPa, which was 10% of the compressive strength. The total number of steps was 10. At first, the nonlinearity parameter was measured under no load, it was then measured under increasing compressive load.

The relationship between the averaged nonlinearity parameter and the step number is plotted in Fig. 4. Results show that nonlinearity parameters of NRUS are dependent on external load level. The value for undamaged concrete (step 1) was measured and found to be over four times larger than the lowest value of this parameter, this value decreased as the load increased until 60% of the compressive strength

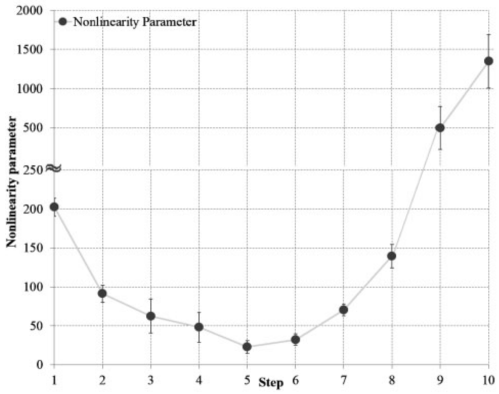
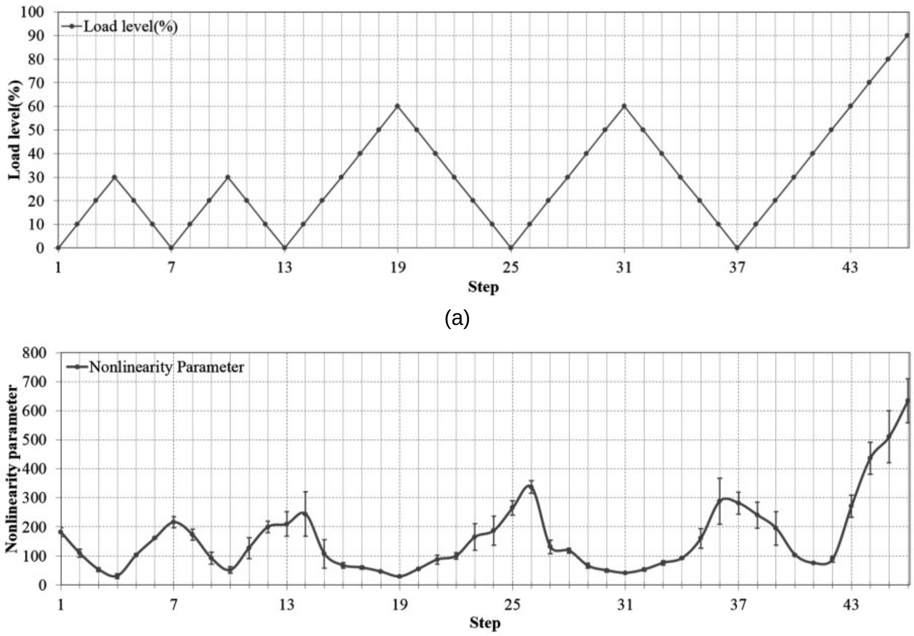


Fig. 4 Experimental result: NRUS on specimen 1

level. It can be seemed that the closing of inherent contact-type micro cracks causes the nonlinearity of the concrete to decrease [22].

However, the nonlinearity parameter increases after a compressive load level of 60%, because micro cracks propagate and grow into macro-cracks after a certain load level [23]. At this load level, the effect of crack formation is larger than the effect of the closing of inherent cracks. Therefore, the phenomena of the closing of micro cracks cannot explain the increase of the nonlinearity parameter at higher load levels. When the load level almost reached the level of the compressive strength, the nonlinearity parameter was found to rapidly increase due to the severe damage of the concrete.

In the case of specimen 2, to verify the influence of the cyclic loading, cyclic compressive load was also applied using the UTM, the results were, as shown in Fig. 5(a). In detail, there were five stages of cyclic loading. In the first and second stages, the concrete sample was loaded up to 30% of the compressive strength. Noticeable points are step 1, 4, 7, 10 and 13, which are equivalent to the condition of no load or to the condition of 30% of the compressive strength. Next, in the third and fourth stages, load is applied at a level of up to 60% of the compressive strength. Important points are 6 steps apart: for example, steps 19, 25, 31, and 37. The last stage is designed to continuously increase until the ultimate stress level is reached. Other conditions are the same as those used for the monitoring of specimen 1.



(a)

(b)

Fig. 5 Load design and results from specimen 2: (a) repetitive cyclic load (b) experimental result: NRUS

The experimental results for specimen 2 are shown in Fig. 5(b). As can be seen in the figure, the dependency of the parameters on the external load is clear. In step 1, the parameter value is about four times larger than the minimum value, which is similar to the case of specimen 1. According to the external load, the parameter values changes in an inversely proportional manner. Over the 70% stress level, at step 44, the value increased, as was the tendency for specimen 1. It can be estimated that the concrete started to become damaged in this range.

Using the acoustoelastic theory, the characteristic ultrasonic values can be measured, these values change with the applied stress state. This phenomenon has been reported by previous researchers [8,9]. Similar to the situation in acoustoelastic theory, the change of the nonlinearity parameter is dependent on the stress state of the concrete. As explained in the results, both specimen 1 and specimen 2 show changes of the parameters depending on the stress fields of the materials.

In addition, in the results obtained for specimen 2, the stress memory effect is observed. As is the case in the range of compressive strength under 60%, the parameter varies from 31 to 635. In comparison, the values of the nonlinearity parameters in step 7 and step 13, which are non-loaded states after 30% loading, are about 2.3% different (Stages 1 and 2 in Fig. 5(b)). Further, the values of the parameters in steps 25 and 37 are about 5.4% different (Stage 3 and 4 in Fig. 5(b)). In summary, the relative change between stages 1 and 2 is 2.3%. And, again, the change is 5.4% between stages 3 and 4. In contrast, the gap between stages 2 and 3 is 16.1%, which is 3-7 times larger than the gap that occurs for similar load level stages. It can be seemed that this is due to the stress memory effect, a phenomenon in which fewer cracks are generated in concrete at load levels lower than those experienced before.

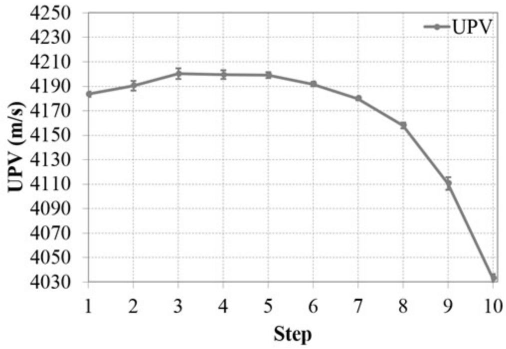


Fig. 6 Experimental result: UPV on specimen 1

3. Sensitivity Comparison with UPV

In order to verify the sensitivity of the proposed NRUS technique, UPV was measured under identical condition as those used for specimen 1. Using a signal generator (National Instruments Corp. PXI 5421), an ultrasonic pulse wave was amplified to 400V and continuously transmitted through a 50 kHz ultrasonic transducer (Olympus NDT, Inc. Panemetrics X1019). The signal was received by the coupled transducer and pulse receiver. Using a trigger and an analysis of the arrival peaks, the propagation time of the ultrasonic pulse wave was measured. Therefore, the UPV can be calculated according to the wave propagation time and the width of the specimen [24]. Fig. 6 shows the measured wave velocities.

As a result of NRUS, it can be seemed the acoustoelastic effect clearly appeared. Meanwhile, about the stress memory effect, the velocity difference between stage 2 and 3 is about 25%, while the differences are 8.3% and 6.0% between stages 1 and 2 and between stages 3 and 4, respectively.

For comparison, the sensitivity parameter that is used in the nonlinear ultrasonic method is defined as below:

$$S(f,x) = (f(x) - f(1)) / f(1) \tag{4}$$

where f is the measured value obtained in this

Table 2 Sensitivity comparison between NRUS and UPV

Specimen	Stress level(%)	Sensitivity (%)	
		NRUS	UPV
1 Increasing	10	-54.97	0.16
	20	-69.16	0.40
	30	-76.24	0.38
	40	-88.74	0.37
	50	-84.11	0.20
	60	-65.24	-0.09
	70	-31.06	-0.61
	80	144.25	-1.75
	90	566.38	-3.60

study (nonlinearity parameters and UPV) and x is the number of experiments [25]. The calculated sensitivities for the stress levels from 10% to 90% are summarized in Table 2. To allow for representative results, values in the 30%, 60%, and 90% levels are compared. Under the 60% load level, the sensitivity of the UPV values at 30% and 60% is too small to allow a distinction of the measured values and the errors. In contrast, the values of NRUS are different by over 65%. In addition, the gap between 30% and 60% shows values of about 5-10% and 0.1-0.3% for NRUS and UPV, respectively. This shows the relative sensitivity of the nonlinear ultrasonic method. At the ultimate strength level, the parameter increased to over 550%, while the ultrasonic velocity varied by about 3.6%. In conclusion, the sensitivity of the NRUS technique is higher than that of the UPV technique. Therefore, it can be confirmed that the proposed NRUS technique sensitively represents the stress state of concrete.

4. Conclusion

In this study, a nonlinear ultrasonic method is proposed to monitor the stress state of concrete material under various load conditions. For the effective measurement of resonant frequency shifts, an improved NRUS technique was proposed and adopted. Using the proposed NRUS technique, the nonlinearity parameter was measured for two specimens, at each load step with continuously increasing or repetitively cyclic compression. After that, to investigate the dependency of the parameter on the external load level, the parameter values were plotted for each load level. For specimen 1, as the load increases, the hysteretic behavior of the concrete, which is induced from various conditions, decreases until reaching 60% of the compressive strength level, the parameter rapidly increases in the ultimate stress range. Further, for specimen 2, changes of the parameters are also reported to correspond to the applied load level. Through a comparison of nonlinearity parameter values, the dependency of the nonlinearity parameter can be explained as resulting from the change of the hysteretic parameter and the stress memory effect. In addition, UPV measurement showed similar results, which could also be explained by the two effects. Through the sensitivity calculation, the NRUS technique is found to be more sensitive than the UPV technique.

Therefore, it can be concluded that the proposed NRUS technique can be applied to monitor the stress state of concrete members, such as prestressed concrete beams, it should also be possible to improve this technique to make it adaptable for in-situ use. Through further study about the technique, the NRUS-stress relation proposed in this study will be investigated.

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