Axial stress measurement of concrete with nonlinear ultrasonic harmonic method

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Abstract

The working stress is an important indicator of the reliability of concrete structure. Nondestructive testing of the concrete working stress can directly evaluate the stress state of concrete structure, which plays an important role in the health diagnosis of concrete structure. When ultrasonic wave propagates in concrete, it is affected by the cracks and the harmonic component is generated. The concrete working stress has a direct influence on the number and development trend of the cracks, which provides a potential way to evaluate the working stress in the concrete by analysis the harmonic component. In this paper, a nondestructive testing method of concrete working stress based on nonlinear ultrasonic harmonic method is proposed. Specifically, the theoretical expression of the nonlinear coefficient of ultrasonic wave propagation in concrete is derived, and the relationship between the nonlinear coefficient and the concrete working stress is established. The sensitivity of the nonlinear coefficients is studied when the ultrasonic wave propagates perpendicular to the concrete stress direction. The relationship between the concrete working stress and the ultrasonic nonlinear coefficient is compared using four different strength grades of concrete. It is found that the nonlinear coefficient of ultrasonic wave increases with the concrete working stress, and the fitting relationship between the concrete working stress and the nonlinear coefficient is consistent with the theoretical formula. This study provides a possible way for the nondestructive detection of the concrete working stress.

Keywords: Concrete, working stress detection, nonlinear ultrasonic harmonic method, nonlinear coefficient, structural nondestructive testing

1. Introduction

1.1 Concrete stress and testing methods of concrete stress

Concrete is widely used in engineering construction because of its high strength, low cost and good durability. It is very important to evaluate the working stress of concrete structure for structural health diagnosis. Due to the existence of a large number of micro-cracks and voids in concrete as well as the multiphase and discrete composition of concrete, it is difficult to detect the working stress and identify the damage of concrete in engineering.

At present, the traditional testing methods of concrete working stress include local damage method and nondestructive testing method. Local damage method mainly refers to the stress release method, such as blind hole method, ring hole method and slotted method. The accuracy of these methods is not high, so it is difficult to make a more accurate assessment of the stress state of concrete structure. These methods can
cause local damage of concrete structure, and its measurement results are often affected by external environment. Non-destructive testing technology includes acoustic emission technology and ultrasonic testing technology. The traditional linear ultrasonic nondestructive testing technology mainly uses the principle of wave reflection and transmission to detect defects by measuring acoustic parameters such as sound velocity, attenuation, frequency spectrum, amplitude and so on. However, linear ultrasonic nondestructive testing technology has some limitations, it is not sensitive to stress damage in the early stage of materials.

1.2 Nonlinear nondestructive ultrasonic harmonic method

In the process of ultrasonic propagation, the interaction between ultrasonic wave and discontinuous medium shows nonlinear ultrasonic harmonic effect, which is the theoretical basis of nonlinear ultrasonic method. Because concrete structures work with cracks and the increase of stress is accompanied by the propagation of crack damage, which are closely related to each other. Related studies show that nonlinear ultrasonic characteristics are more sensitive to structural damage than conventional ultrasonic nondestructive testing. The nonlinear acoustic properties of metals have been studied experimentally in reference, the results show that the nonlinear acoustic parameters are more sensitive to the damage of materials than the linear acoustic parameters. Nonlinear Ultrasonic Harmonic Technology was first studied on fatigue damage of metal materials. In the 1960s, scholars took simple single crystal metal materials as the research object, studied the harmonic phenomena under ultrasonic excitation, such of these famous scholars are Breazeale and Thompson, who proposed in 1963 that the second harmonic amplitude is a function of the fundamental wave amplitude, and the second-order coefficient of stress-strain relationship in solids was also proposed and defined. Further studies have found that defects within metallic materials can cause the generation of high-order harmonics. Nazarov and Cantrell used metals as the research object and proposed a regular relationship between higher harmonics and the number of fatigue cycles. In the aspect of stress research, Lei Z W based on nonlinear ultrasonic theory proposed the use of the second harmonic coefficient to evaluate the stress of the adhesive layer of composite materials in 2009.

All above are about the application of nonlinear ultrasonic harmonic method to damage assessment in metal field. In recent years, this method has been gradually applied to non-uniform materials such as rock, cement, concrete and so on. In the application of this method to concrete, it is used mostly for damage detection research. Maev proposed that the change of nonlinear coefficient can be used as the damage characterization of brittle materials. The studies of Stauffer and Chen Xiaojia show that the nonlinear ultrasonic method can be used to analyse the early damage of concrete.

1.3 Goals and objectives of this study

At present, there are few researches on the application of nonlinear harmonic method to the detection of concrete stress. The ultrasonic harmonic characteristics of rock and its variation with stress were studied in literature. The effects of emission frequency, aggregate ratio and drying degree on the sensitivity between nonlinear ultrasonic parameters and stress were also studied in literature. But the research results on
quantitatively characterizing the relationship between concrete acoustical and mechanical parameters have not yet been discovered.
In this paper, the nonlinear ultrasonic harmonic method is used to detect the stress of concrete members. The characteristics of ultrasonic signal and the characteristics of material mechanics and acoustical properties of ultrasonic wave propagating under the compression state of concrete are studied theoretically in this paper. The ultrasonic stress detection experiment of uniaxial compressive concrete was designed to quantitatively characterize the relationship between the acoustic and mechanical parameters of concrete and to further improve the experimental means of ultrasonic testing of concrete structure stress.

2. Theoretical study on testing method of concrete stress based on nonlinear ultrasonic harmonic

Based on the principle of stress identification, the correlation between mechanical and acoustic properties of concrete is studied, and the theoretical analysis of the parameters to be obtained is carried out. The wave theory is used to deduce the solution of nonlinear wave equation under harmonic excitation, and the nonlinear coefficient is extracted as the acoustic parameter to represent the stress state of concrete. This paper attempts to establish a quantitative relationship between nonlinear coefficient and stress so as to use nonlinear ultrasonic harmonic method to measure the stress of concrete members.

2.1 Derivation of nonlinear coefficient from nonlinear ultrasonic equations of discrete models

The classical nonlinear acoustic theory holds that ultrasonic wave, as an elastic stress wave, causes particles to vibrate in space following the stress-strain relationship of the medium. Under ultrasonic excitation, the absolute amplitude of particle reflects the microscopic strain process of material particle. Due to the existence of a large number of micro-cracks in the concrete, the interface of the crack is extruded in contact with each other under the ultrasonic excitation, and the internal discontinuity of the material is forced to vibrate. The crack interface exhibits strong motion nonlinearity under the ultrasonic excitation. Cracks alternate between "closed" or "open" states. The crack spacing changes with the ultrasonic stress wave stretching and compression. When the crack is closed, the ultrasonic wave is transmitted completely; when the crack is opened, the ultrasonic wave is partially reflected and diffracted; the ultrasonic wave is distorted in the reflection and transmission process, and the wave form is distorted. In frequency domain, high order harmonics appear and nonlinear response is produced. This kind of nonlinear ultrasonic signal carries a lot of internal information of concrete. The characteristics of mechanical properties and internal defects or damage caused by the change of microstructure of materials can be obtained. With the increase of the load, the damage evolution degree of the material increases, and the nonlinear response becomes more obvious under the collision mechanism, which explains the nonlinear harmonic effect from the crack contact collision mechanism. Therefore, the purpose of evaluating the stress state of materials can be achieved by analysing ultrasonic signals.

The wave equation of ultrasonic wave propagation in concrete medium is derived from the continuity equation of the medium and the equation of motion combined with the
perturbation theory. When the ultrasonic wave with large amplitude propagates in concrete medium, the nonlinearity caused by the interaction between ultrasonic wave and medium should be considered. Thus, the stress-strain will not simply satisfy the linear relationship.

Taking one-dimensional longitudinal wave as an example, the nonlinear stress-strain relationship of concrete media can be described as follows:

\[ \sigma = E \varepsilon \left( 1 + \frac{1}{2} \beta \varepsilon \right) \]  

(2-1)

\( \beta \) — Second order nonlinear coefficient.

The equation of motion of particles propagating through concrete material in x direction is

\[ \rho \frac{\partial^2 u}{\partial t^2} = \frac{\partial \sigma}{\partial x} \]  

(2-2)

Positive strain is expressed as

\[ \varepsilon = \frac{\partial u}{\partial x} \]  

(2-3)

Concrete is such kind of material between discrete medium and continuous medium. Starting from the discrete model, assuming a column of compressible longitudinal waves propagating along the x axis into the concrete medium and combining with the equation of (2-1), the nonlinear wave equation of ultrasonic longitudinal waves in the discrete model can be obtained.

\[ \rho \frac{\partial^2 u}{\partial t^2} = E \left( \frac{\partial^2 u}{\partial x^2} + \beta \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2} \right) \]  

(2-4)

The relationship between the elastic constant E and the longitudinal wave velocity c is

\[ c^2 = \frac{E}{\rho} \]  

(2-5)

Thus, the formula (2-3) can also be expressed as

\[ \frac{\partial^2 u}{\partial t^2} = c^2 \left( \frac{\partial^2 u}{\partial x^2} + \beta \frac{\partial u}{\partial x} \frac{\partial^2 u}{\partial x^2} \right) \]  

(2-6)

Assuming that the initial condition of formula (2-4) is

\[ u(0,t) = A_0 \sin \omega t \]  

(2-7)

By using the stepwise approximate perturbation method, the solution of the upper formula (approximate to the second order) can be obtained as follow:

\[ u(x,t) = A_0 \sin(\omega t - kx) + \frac{1}{8} (A_0^2 k^2 \beta x) \cos 2(\omega t - kx) \]  

(2-8)

It is theoretically explained that the frequency of ultrasonic wave propagating in concrete material is redistributed and the second harmonic wave with frequency of 2 \( \omega \) is produced in addition to the fundamental frequency \( \omega \).

The amplitude of the fundamental wave is

\[ A_1 = A_0 \]  

(2-9)

The amplitude of the second harmonic wave is

\[ A_2 = \frac{1}{8} A_0^2 k^2 \beta x \]  

(2-10)
Therefore, the nonlinear coefficient is obtained as follows:

$$\beta = \frac{8}{k^2 x A_k^2}$$

(2-11)

Where $k = \omega / c$ is the wave number and $x$ is the ultrasonic sound path. This is a classical nonlinear ultrasonic feature of concrete materials, manifested as the growth of the second harmonic, the amplitude of which is related to the intensity, frequency, wave speed, and distance travelled by the waves.

3. Experimental study on testing method of concrete stress based on nonlinear ultrasonic harmonic

In this chapter, the ultrasonic stress detection system is built based on the principle of nonlinear ultrasonic stress detection. Based on the conditions of ultrasonic propagation in concrete materials, the experimental research on the nonlinear ultrasonic testing stress is carried out, including uniaxial compression load test and ultrasonic stress detection test. The acoustic-mechanical test system of uniaxial compression concrete is established. Considering the influence of concrete strength grade on nonlinear parameters, concrete uniaxial compression tests with four different strength grades are designed. The ultrasonic testing test of loaded concrete was carried out with different frequency transmitting and receiving probes to evaluate the applicability of the method.

3.1 Specimen production and maintenance

The concrete strength grades selected in this test are C25, C30, C35 and C40 respectively. The size of the specimens is 100mm×100mm×100mm, and 3 specimens are made for each strength. The coarse aggregate of concrete is 5-20 mm limestone crushed stone, fine aggregate is 5-10 mm limestone crushed stone, cement is ordinary Portland cement.

The mixture ratio of concrete with four different strength grades is as follow:

<table>
<thead>
<tr>
<th>Table 3-1 Design table of mix ratio of concrete components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Order number</td>
</tr>
<tr>
<td>---------------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

In the preparation process, concrete mixers are used to mix the components of concrete evenly, and then the mixed concrete slurry is injected into the 100mm×100mm×100mm plastic mold in turn, then the specimen is numbered and marked. The specimens are put on the vibration table to be compacted and then placed statically for 24 hours. After the concrete specimens are formed and removed, they are immediately put into saturated Ca(OH)$_2$ solution for 28 days.
3.2 Test system construction

The system layout and signal flow of nonlinear ultrasonic harmonic method are shown in Fig. 3-1. This detection system consists of two subsystems: mechanical system and acoustic system as shown in figure 3-2 and figure 3-3. The mechanical system includes DNS300 electronic universal testing machine and mechanical data analysis system. The acoustic system includes ultrasonic signal generator, signal amplifier, ultrasonic signal transmitting probe, ultrasonic signal receiving probe and ultrasonic oscilloscope.

![Fig. 3-1 schematic diagram of nonlinear ultrasonic harmonic stress measurement system](image1)

![Fig. 3-2 Layout of Ultrasonic testing system under No-load](image2)

![Fig. 3-3 Layout of ultrasonic testing system under loading](image3)

In the ultrasonic testing system, the single contact contralateral method is used to make the acoustic test of concrete specimens. The frequency of the transmitter probe is 50 kHz and the frequency of the receiving probe is 100 kHz. Because the surface of the concrete specimen is not absolutely smooth, there is an air interlayer in the contact surface between the concrete specimen and the probe. The ultrasonic signal will be reflected in the air, which will make a negative effect on the received signal, the coupling agent should be used to eliminate the air gap. Due to the consideration of coupling property, chemical stability and cleanness, medical vaseline is used in this test as the coupling agent.
3.3 Uniaxial compression load test and ultrasonic testing test

Most of the concrete in normal service is at low stress level, and the working stress is generally not higher than 50% of the ultimate strength of concrete. Based on the special sensitivity of nonlinear parametric harmonic method to early stress identification of concrete, this loading test focuses on the acoustic characteristics of the stress stage before the ultimate strength of concrete.

Uniaxial compression load test and ultrasonic stress test were carried out. The loading was graded according to 1/15 to 1/10 of the failure load. Taking C30 concrete specimen as an example, the ultrasonic response signal of concrete specimen under no load was saved before loading. When loading, the load value per stage is 20 kN, the loading rate is 3 kN/min, and the load between each stage remains stable. After the waveform on the oscilloscope is stabilized, the response signal on the ultrasonic oscilloscope is saved. The Olympus ultrasonic pulser and oscilloscope used in this experiment are shown in Fig. 3-6 and 3-7. In this experiment, the sampling frequency is 5M Hz and the sampling amount is 10 k. In order to suppress the nonlinear signal of ultrasonic transmitter, the level of input signal is controlled between 10 mV~80 mV. When the ultrasonic wave propagates in the specimen, the ultrasonic energy decreases continuously with the increase of the internal stress of the concrete specimen. In order to reflect the change of the sound energy, the gain value is set to be 59 dB.

4. Results and discussions

4.1 Processing of nonlinear Acoustic signals

In this experiment, the corresponding ultrasonic response signal data can be obtained for each concrete specimen under each stage loading. Based on MATLAB software, the time domain and frequency domain analysis of ultrasonic signal data obtained from the experiment are carried out. Fast Fourier transform (FFT) is used to transform the time domain signal of ultrasonic pulse into frequency domain signal. Based on the analysis of ultrasonic signal in time domain and frequency domain, the characteristic amplitude at the characteristic frequency of fundamental wave and second harmonic is extracted. The average value of the acoustic parameters tested by each group of three specimens is calculated as the acoustic parameters of this group. The nonlinear ultrasonic parameters of concrete under uniaxial compressive loading are calculated by the formula of nonlinear coefficient, and the variation law of nonlinear coefficient of ultrasonic wave with stress under uniaxial compression is studied.
4.2 Data processing results

Each stress value corresponds to three nonlinear ultrasonic parameters, including the amplitude of the fundamental wave, the amplitude of the second harmonic, and the nonlinear coefficient. The nonlinear coefficient can be calculated by substituting the first two parameters into the simplified formula. In this way, the stress-nonlinear parameter diagrams of concrete of each strength grade can be obtained. The following three figures are given as an example of C30 concrete. In order to save space, only the final stress-nonlinear coefficient diagram is given under other strength grades.

![Graphs showing relationships between stress and nonlinear parameters for C25, C30, C35, and C40 concrete](image)

**Fig. 4-1** relationship between nonlinear parameters and stress of C30 concrete

**Fig. 4-2** relationship between nonlinear coefficient and stress of concrete of various strength grades
4.3 Results analysis

The acoustic parameters of the above four concrete specimens under ultrasonic excitation are shown in Table 4-1.

<table>
<thead>
<tr>
<th>Four different strength grades of concrete</th>
<th>amplitude of fundamental wave under no load</th>
<th>Initial nonlinear coefficient</th>
<th>Stress value of parameter sudden increase(N/mm²)</th>
<th>Stress ratio in sudden increase of parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>C25</td>
<td>0.0065</td>
<td>45</td>
<td>13</td>
<td>0.52</td>
</tr>
<tr>
<td>C30</td>
<td>0.0062</td>
<td>38</td>
<td>15</td>
<td>0.50</td>
</tr>
<tr>
<td>C35</td>
<td>0.009</td>
<td>20</td>
<td>19</td>
<td>0.54</td>
</tr>
<tr>
<td>C40</td>
<td>0.014</td>
<td>17</td>
<td>24</td>
<td>0.60</td>
</tr>
</tbody>
</table>

When ultrasonic wave propagates in concrete, the reflection and transmission signals of interface are accompanied by obvious nonlinear behaviour. The law of nonlinear effect of concrete specimen under no-load and loading is analysed as follows:

When the concrete is under no load, there is still a weak nonlinearity, which is reflected in the initial nonlinear coefficient. This part of the initial nonlinearity is related to the classical nonlinearity of concrete material, which is the contribution of the inherent crystal dislocation, anharmonicity, initial pores and microcracks. With the increase of concrete strength grade, the first wave amplitude and second harmonic amplitude increase, and the initial nonlinear coefficient decreases.

With the increase of load, the amplitude of the first wave and the second harmonic wave decrease, the nonlinear coefficient increases, and the whole trend of rise and fall is obvious. From the above results, it can be seen that the first wave amplitude, the second harmonic amplitude and the nonlinear coefficient are discrete with the increase of stress. The general trend can be divided into three stages: steady rising stage, sharp rising stage and descending stage.

Steady rising stage: when the stress is less than 50 ~ 60% of the failure stress, the microcracks in the material develop stably, and the nonlinear coefficient shows a steady upward trend with the increase of the stress.

Sharp rising stage: When the stress increases to 60%~70% of the ultimate stress, multiple cracks appear in the specimen, and the nonlinear coefficient begins to rise sharply. The acoustic impedance of air is much larger than the acoustic impedance of concrete, the ultrasonic wave will scatter and reflect at the interface of materials with different impedance, and it needs more diffraction to reach the receiving probe. With the opening and closing of cracks driven by ultrasonic longitudinal waves, high-order harmonics are also generated. As the stress increases, the first wave amplitude and second harmonic amplitude decrease. The nonlinear coefficient reflects the degree of signal distortion and harmonic effect in the process of ultrasonic propagation in the medium. With the increase of stress, the nonlinear response of ultrasonic wave in the propagation process is more obvious. It is reflected in the increase of nonlinear coefficient.

Descending stage: when the stress is more than 70% of the ultimate stress, the specimen is close to be destroyed, the crack is broken through, the structural integrity is fundamentally changed, the mechanical properties are seriously degraded, the acoustic impedance suddenly increases and the propagation weakens, and the ultrasonic wave mostly reflects and attenuates rapidly. The response signal is near to zero and the nonlinear coefficient decreases rapidly.
5. Conclusions

When the ultrasonic longitudinal wave propagates in concrete, the waveform will be distorted and high order harmonic will be produced. The nonlinear coefficient changes obviously with the increase of stress, so the nonlinear coefficient can be used to characterize the stress of concrete.

The initial nonlinear parameters of concrete with different strength grades are different. With the increase of concrete strength grade, the first wave amplitude and second harmonic amplitude increase, and the initial nonlinear coefficient decreases.

References