TEMPERATURE EFFECTS ON NON-DESTRUCTIVE TEST IN REINFORCED CONCRETE USING ULTRASONIC GUIDED WAVES

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Ultrasonic guided wave (UGW) is a promising method of non-destructive test (NDT). Considering the temperature of serving environment of infrastructures are not constant, there is an urgent need to investigate the effect of temperature variations on UGW pitch-catch systems-an important tool in the field of structural health monitoring (SHM). First, the propagation properties of UGW in cylindrical waveguide are explored. Then an UGW test installation is designed to test the fabricated specimens, with a single steel rebar embedded in each center. The temperature range is from -40ºC to 60ºC, corresponds to normal Reinforced Concrete (RC) operations. An innovative algorithm was introduced to eliminate the dispersion effects. At last, the relationship curves between group velocity and temperature, as well as between amplitude and temperature are obtained. The results show that both the group velocity and amplitude of longitudinal modes is not very sensitive with temperature change.

Keywords: Non-destructive Test; Ultrasonic Guided Waves; Temperature; Dispersion; Reinforced concrete; Structure Health Monitoring

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ABSTRACT: Ultrasonic guided wave (UGW) is a promising method of non-destructive test (NDT). Considering the temperature of serving environment of infrastructures are not constant, there is an urgent need to investigate the effect of temperature variations on UGW pitch-catch systems-an important tool in the field of structural health monitoring (SHM). First, the propagation properties of UGW in cylindrical waveguide are explored. Then an UGW test installation is designed to test the fabricated specimens, with a single steel rebar embedded in each center. The temperature range is from -40ºC to 60ºC, corresponds to normal Reinforced Concrete (RC) operations. An innovative algorithm was introduced to eliminate the dispersion effects. At last, the relationship curves between group velocity and temperature, as well as between amplitude and temperature are obtained. The results show that both the group velocity and amplitude of longitudinal modes is not very sensitive with temperature change.

1 INSTRUCTIONS

UGW, as a newly developed tool, have many advantages comparing to traditional detective methods, Rose(2002). First, it can propagate a long distance (up to 20 meters) because of its little attenuation in steel rebar. This characteristic is especially suitable for detection of the long range bridges. Second, high sensitivity is another merit of the method. UGW have many different modes at a single frequency and these modes are sensitive to different defects. Third, UGW have broad coverage. The whole information of the rebar and concrete can be obtained using a pair of transducers. The reason is that the sound field spreads all over the waveguide instead of a single point or surface. Therefore, it is meaningful to investigate the application and influence factors of UGW.

Temperature change, especially in crush climate, may limit the sensitivity of UGW pitch-catch system. Earlier scholars have conducted amounts of research of temperature effects on plate-like structures. Blaise&Chang (2001) studied the characteristics of lamb waves at -90ºC and got the conclusion the wave amplitude reduced and an empirical model was developed. Lee et al. (2003) investigated the propagation properties of S0

mode in aluminum plates using pitch-catch system, and they observed a reduction in wave amplitude when the temperature rises in the range of 35 ºC to 70 ºC. Francesco&Salvatore (2008) proposed a model that considered all relevant temperature-dependent parameters of a pitch-catch system on of an isotropic plate, and the S_0 and A_0 response spectra in aluminum plates can be predicted with the model at the temperature range between -40 ºC to 60 ºC. George et al. (2006) proposed a method to overcome the temperature influence on the sensitivity of the pitch-catch system and a more reliable long-term system was obtained. Anthony et al. (2006) also explored the temperature effects on Lamb waves propagating in aluminum plate and presented an effective method to compensate this influence. However, few researchers studied the temperature effect on propagation properties of UGW in cylindrical waveguide. In this paper, we investigated the propagation properties of UGW in steel rebar (cylindrical waveguide) and explored the temperature effects on UGW propagation in RC. The in-service structures experience the temperature variation from -40 ºC (extremely cold climate in Winter) to 60 ºC (extremely hot climate in summer), thus, we examined the temperature effect in this range.

2 THEORETICAL STUDY

2.1 Concept of UGW

When mechanical vibrations are propagated in elastic media, elastic waves are generated. We call the waves, whose central frequency is higher than 20 kHz, ultrasonic waves. Ultrasonic waves are consisted with bulk waves and guided waves. The bulk waves propagate in the infinite media. It comprises longitudinal waves and transverse waves in isotropic media. While guided waves are similar with Rayleigh waves and Lamb waves, propagating in finite media. In addition, the propagation characters have to satisfy the boundary condition. At the boundary, reflections and refractions occur. The propagations of guided waves are in accordance with elastic theory in elastic media, while in non-elastic media, they follow the viscoelastic theory. Pipes, anchor molts, rails and steel rebar are typical waveguides.

2.2 Guided waves in steel rebar

The geometry profile of rebar is presented in Fig. 1. There are three different modes propagating in cylindrical waveguide, longitudinal modes L(0,m), torsion modes F(n,m) and flexural modes F(n,m). In this expression, and stand for circumferential order and modulus, respectively. The displacement is symmetrical corresponding to n=0, and the n=1,2,3,… mean asymmetrical displacements. Therefore, L(0,m), T(0,m) are symmetrical modes and F(n,m) are asymmetrical modes.

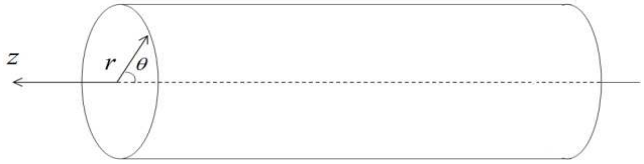

Figure.1 Geometry profile of steel rebar

The longitudinal modes that propagate in steel rebar have only two types of displacement, radical displacements and axial displacements. The boundary condition is $u_q = 0$, and u_z, u_r are independent with θ. Taking into account of the boundary

condition $s_{rr} = s_{rz} = 0$ (r=a), famous frequency equation can be achieved by solving the wave equation, Rose(2004).

$$\frac{2a}{a}\left(b^2 + k^2\right)J_1(a\,a)J1(b\,a) - \left(b^2 - k^2\right)J_0(a\,a)J_1(b\,a) - 4k^2 a\,b\,J_0(b\,a) = 0 \qquad (1)$$

where l is the length of guided waves, w is angular velocity, k is wave number, J is Bessel function and coefficients $a^2 = w^2 / c_L^2$, $b^2 = w^2 / c_T^2 - k^2$, c_L is velocity of longitudinal guided waves, c_T is velocity of transverse guided waves , c_P is phase velocity. This is an transcendental equation with independent variables w and k. This corresponds well with the fact that many modes are existed at a single frequency. This is the multiple modes property of UGW.

2.3 Temperature theory

The concrete can resist high compress force but low tensile force, while steel rebar have high performance in resisting both compress force and compress force. Steel rebar were fixed before the concrete were casted, in this way, the steel rebar and concrete become an integral solid object. One key point we cannot ignore is that the concrete and steel have similar temperature inflation coefficients. The coefficient of steel and concrete are $1.0 \sim 1.5 \times 10^{-5}$ and 1.2×10^{-5}, respectively. The relationship between volume and temperature is shown as follows:

$$L_T = L_0(1 + a\,\Delta T) \qquad (2)$$

$$V_T = V_0(1 + 3a\,\Delta T) \qquad (3)$$

Where L_T and V_T represent the length and volume at a certain temperature, L_0 and V_0 respectively represent the original length and volume, α is the linear inflation coefficient, while 3α is the volume inflation coefficient. Based on Formula (1) and (2), we can calculate the change and volume change that result from temperature change.

2.4 Calculation of dispersion curves

The curves that express the relationships between frequency, properties of waveguide and phase velocity and group velocity are called dispersion curves. The phase velocity is defined as the speed of the phase of wave propagation in the waveguide while group velocity corresponds to the speed of wave packet propagation. These are the two fundamental parameters that describe the characteristic of wave propagation. All waveguides, both symmetrical ones and asymmetrical ones, have special dispersion curves, Rose (2003).

HRB335 (Hot Rolled Ribbed Bars) are used in this experiment. According to GB1499.2-2007, nominal diameter is $16mm$, area of cross section is $201.1mm^2$, density is $r = 7858.5kg/m^3$, and Young's modulus, passion ratio are 206 GPa and 0.28, respectively. We can neglect the influence of ribs when the ratio of diameter to length is less than 0.4, Ervin et al. (2006).The ratio of diameter to length is 0.025. Thus, we can ignore the effect of steel ribs. Dispersion curves showed in Fig. 2 can be achieved by numerical calculation.

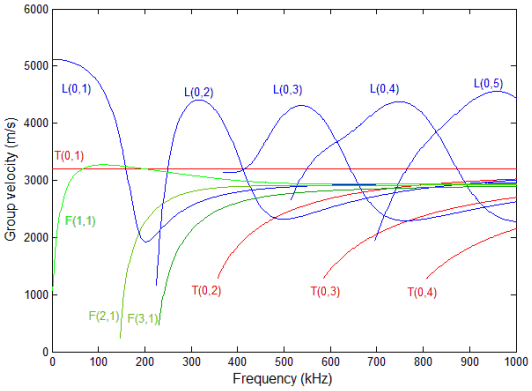

Figure.2 Dispersion curves of 16-mm steel rebar UGW setup

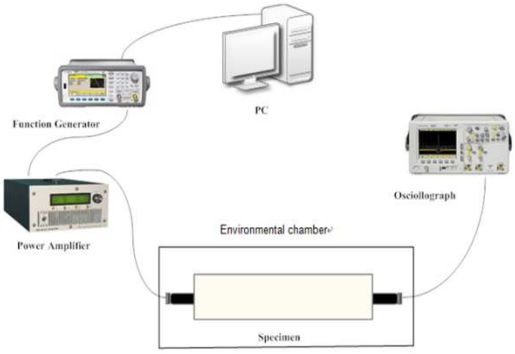

Figure.3 Schematic diagram of

3 EXPERIMENT DESCRIPTION

3.1 Specimens preparation

A set of specimens (100´ 100´ 150*mm*) were casted with a steel rebar embedded in the center of the cross section. The diameter of steel rebar is 16mm and the length of the steel bar is 550mm. The bonding length of intact one is 150mm and the free length is 200mm. The ratio of sand to concrete to water is shown in Table 1. These specimens were maintained in standard maintaining room for 28 days before conducting the test.

Table 1. Design strength and materials ratio of specimens No.1~4

Specimen No.	Strength(MPa)	Concrete(kg)	Sand(kg)	Water(kg)	Gravel(kg)
1	20	0.4665	1.1025	0.3075	1.7235
2	30	0.627	0.9195	0.3075	1.746
3	40	0.8085	0.8445	0.3075	1.7145
4	50	0.945	0.8115	0.3075	1.767

3.2 Experiment Setup

The experiment setup was designed as shown in Fig. 3. The system was consisted with RC specimens, which were laid in the environmental chamber with temperature control, circular piezoelectric transducers (16×0.5mm), arbitrary function generator, power amplifier and oscilloscope. Both ends of steel rebar were fabricated to smooth by lathe to eliminate the excitation of undesired modes. Then the circular PZTs were glued on both ends of rebar via epoxy resin. Before performing the experiment, we investigate the physical properties of materials. Both the capacitance of PZT and the bonding strength of epoxy resin differ less than 3% as temperature evaluates from -40 ºC to 60 ºC.

3.3 Optimization of input signal

Based on theory of dispersion, single audio signal is the most ideal input signal to conduct experiments to get rid of the influence of dispersion, whereas exact single audio signal is hard to produce in practice. Therefore, we modulated the sinusoidal signals by

Hanning window to excite the longitudinal modes. In order to avoid the overlap of different modes and get relatively narrow frequency band signal (this case was clearly expressed in Fig. 5), ten-cycle modulated sinusoidal signal were employed. Because higher frequency will bring us many undesired modes, which will the data were difficult to analyze, lower frequency signals are more desirable. According to Fig. 2, the lowest cut-off frequency is 147.5 kHz. However, the central frequency of piezoelectric ceramics is 130 kHz. Considering all the above factors, 90 kHz signal was employed in this experiment, and we set the peak value of amplified signal as 200 volts. Both two channels of the oscilloscope were employed to collect the data. One channel monitored the signal amplified from the amplifier, as shown in Fig. 6, and the other one collected the waveform at the receiving ends of the specimens, as shown in Fig. 7.

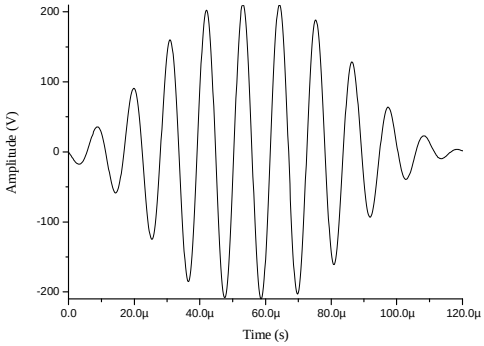

Figure.4 Input signals in time-domain cycles of signals

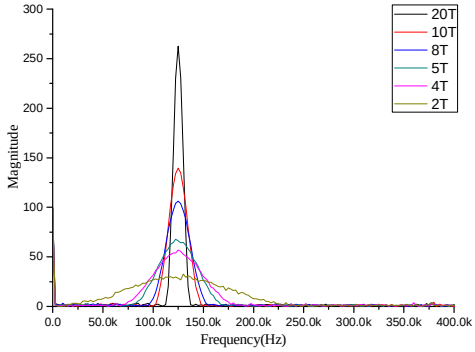

Figure 5. Band width of different

4 EXPERIMENTAL RESULTS AND DATA PROCESSING

4.1 Signal denoising

Environmental and equipment are the two main sources of noise in the collected signals. And these noise are mainly lower frequency, comparing to ultrasonic waves in the experiment. Therefore, FFT was used in the beginning of signal process. The band pass module was employed, and the lower frequency threshold and higher threshold were set as 60 kHz and 120 kHz, respectively. The results showed that the ratio of signal to noise(S/N) could be well ameliorated. Fig. 7 shows the waveform of specimen No.4 when the temperature is -30 ºC.

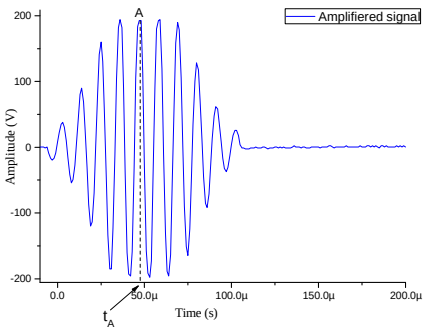

Figure.6 Amplified input signals waveform

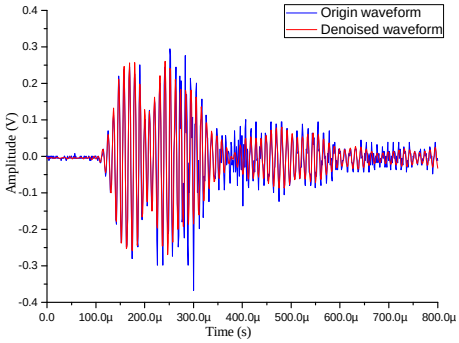

Figure 7. Example waveform and denoised

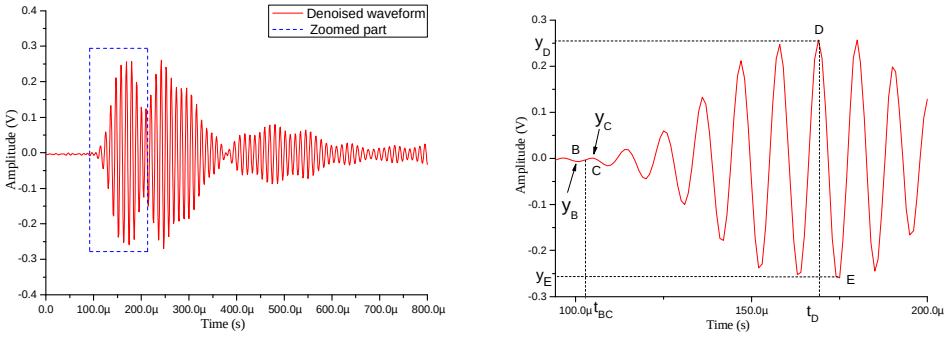

Figure 8. Amplified part of example waveform

4.2 Elimination of dispersion

Dispersion means the velocities (both group velocity and phase velocity) alter as the frequency changes. And the property of UGW can be clearly seen in Fig.6~8. The first wave in the received signal represents the fastest mode, that is L(0,1), however, the cycles have increased significantly because of dispersion. There are more than fifteen cycles in the first wave, as shown in Fig.8. It is hard to calculate the time of travel(TOF) via the time that correspond to the peaks of excited and received waveforms. Take the waveform shown in Fig.8 as an example, the common method to calculate TOF is that,

$t_0 = t_D - t_A = 169.15 - 47.30 = 121.85ms$, then group velocity

$n_{go} = l / t = 0.55m / 121.85 \times 10^{-6} = 4513.75m / s$, while the theoretical value of L(0,1) at 90 kHz is $n = 4810m / s$, $err_0 = |4513.75 - 4810| / 4810 = 0.0678$. In order to get more precise result, a new method was introduced. We named the time of the beginning of first wave as t_{BC}, $t_{BC}=(t_B+t_C)$, while B and C are the first two points nearest with D and satisfy the following formula,

$$|y_C - y_B| \le |y_D - y_E| \times 0.005 \quad (4)$$

TOF was calculated again basing on formula 3, optimal TOF,

$$t_{opt} = [(t_D - t_A) + t_{BC}] / 2 = [(169.15 - 47.30) + 102.75] / 2 = 112.30ms$$

$$n_{gopt} = l / t_{opt} = 0.55 / 112.30 \times 10^{-6} = 4897.6m / s$$

$$err_{opt} = |4897.60 - 4810| / 4810 = 0.0182 < err_o$$

4.3 Correlation curves

Using this improved algorithm, the relationship curves between group velocity and temperature, amplitude and temperature, can be got and they are shown in Fig. 9 and Fig. 10. Fig. 9 shows that the different strength concrete have similar group velocities, both the difference between lowest velocity and theoretical value, highest velocity and theoretical value are less than 4%. Thus, we can get the conclusion group velocities are relatively stable as the temperature alters from -40 ºC to 60 ºC. From Fig.10, although the peak-to-peak value fluctuates to some extent, we can find the rule that, as the strength increases, the peak-to-peak value decreases. We ascribe this phenomenon to the

theory that higher strength concrete has better bonding strength between steel rebar and concrete, leading to higher energy leakage to the surrounding medium.

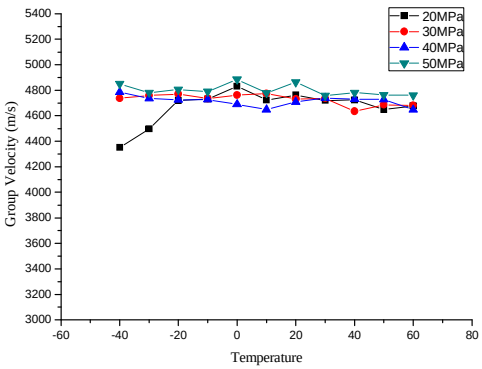

Figure.9 Relationship curves between group velocity and temperature

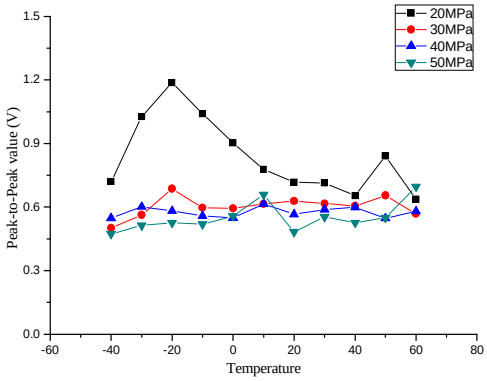

Figure.10 Relationship curves between Peak-to-peak value and temperature

5 CONCLUSIONS

This study validates the feasibility of UGW in non-destructive detection of civil engineering and proves the robust characteristic of this technique. Longitudinal ultrasonic guided wave is an effective tool for non-destructive test. Dispersion curves of steel rebar (cylindrical waveguide) were achieved through numerical calculation, facilitating the analysis of dispersive characteristic of UGW. Based on the study of dispersive characteristics of UGW, proper signal length and modes are vital factors that affect the performance of the detection system. Group velocity is not very sensitive to temperature variation, and it is not affected by concrete strength. The energy of guided waves that propagate in the steel rebar is affected by concrete strength. The peak-to-peak values significantly reduce as the strength increases.

The results in this paper is based on the specific layout and the length of concrete specimens, without considering the influence of sensor arrangement, rebar diameter, rebar properties, temperature, humidity and stress on propagation of UGW. And these factors need further study in future.

6 ACKNOWLEDGEMENTS

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