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Temperature Dependence of Ultrasonic Longitudinal Guided Wave Propagation in Long Range Steel Strands

LIU Zenghua*, ZHAO Jichen, WU Bin, and HE Cunfu

College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology,
Beijing 100124, China

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Abstract: Ultrasonic guided wave inspection is an effective non-destructive testing method which can be used for stress level evaluation in steel strands. Unfortunately the propagation velocity of ultrasonic guided waves changes due to temperature shift making the prestress measurement of steel strands inaccurate and even sometimes impossible. In the course of solving the problem, this paper reports on quantitative research on the temperature dependence of ultrasonic longitudinal guided wave propagation in long range steel strands. In order to achieve the generation and reception of a chosen longitudinal mode in a steel strand with a helical shaped surface, a new type of magnetostrictive transducer was developed, characterized by a group of thin clips and three identical permanent magnets. Excitation and reception of ultrasonic guided waves in a steel strand were performed experimentally. Experimental results shows that in the temperature range from –4 ℃ to 34 ℃, the propagation velocity of the $L(0,1)$ mode at 160 kHz linearly decreased with increasing temperature and its temperature dependent coefficient was -0.90 $(\mathrm{m} \cdot \mathrm{s}^{-1} \cdot (℃)^{-1})$ which is very close to the theoretical prediction. The effect of dimension deviation between the helical and center wires and the effect of the thermal expansion of the steel strand on ultrasonic longitudinal guided wave propagation were also analyzed. It was found that these effects could be ignored compared with the change in the material mechanical properties of the steel strands due to temperature shift. It was also observed that the longitudinal guided wave mode was somewhat more sensitive to temperature changes compared with conventional ultrasonic waves theoretically. Therefore, it is considered that the temperature effect on ultrasonic longitudinal guided wave propagation in order to improve the accuracy of stress measurement in prestressed steel strands. Quantitative research on the temperature dependence of ultrasonic guided wave propagation in steel strands provides an important basis for the compensation of temperature effects in stress measurement in steel strands by using ultrasonic guided wave inspection.

Key words: steel strand, ultrasonic guided waves, mode, temperature coefficient, magnetostrictive transducer

1 Introduction

Long range steel strands are widely used in a variety of civil structures and bridges as key load-carrying components. Examples of such use are prestressed tendons in high-rise concrete buildings and stay cables in cable-stayed and suspension bridges. With the growing number of applications of prestressed techniques in civil engineering, a significant amount of research attention has been paid to monitoring the condition of steel strands and some available methods have been applied to these spiral structures[1, 2]. Prestress loss caused by stress relaxation and other unforeseen circumstances can bring about load unbalance in steel strands and affect the safety of an entire prestressed structure. Prestress measurement of these steel strands during their service life is required to confirm the safety of the entire prestressed structure.

Ultrasonic guided waves can propagate long distances in waveguide structures with low attenuation, therefore they are suitable for the inspection of certain waveguides, such as pipes, rock bolts, rails and plates, and have been applied to these applications[3, 4]. On the basis of the acoustoelastic effect, the relation between the propagation velocity change of ultrasonic guided wave and the applied stress can be obtained. Using this relation, the level of applied stress in steel strands can be evaluated by measuring the propagation velocity of ultrasonic guided wave modes. KWUN, et al[5], researched the acoustoelastic effect of longitudinal guided waves in steel strands under tensile loading and found that a certain portion of the frequency components of guided waves will be absent in the frequency spectrum and their central frequency increases linearly with the logarithm of the applied tensile load. Later, the lowest longitudinal guided wave mode, $L(0,1)$, was also used to measure the applied stress level of seven-wire steel strands[6–8].

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* Corresponding author. E-mail: liuzenghua@bjut.edu.cn

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However, ultrasonic guided wave propagation is more seriously affected by the ambient temperature of the waveguides. WASHER[9] firstly examined the relation between the group velocity of ultrasonic longitudinal guided waves and applied stress in one of the wires of the steel strand under different temperature conditions. It was found that the relation between applied stress and the group velocity of longitudinal guided wave mode was relatively linear in the temperature range of from –9 ℃ to +51 ℃.

In order to compensate for the temperature effect on applied stress measurement in steel strands, it is essential to characterize the relation between the propagation velocity change of ultrasonic longitudinal guided waves and temperature shift. The purpose of the present study is to characterize the effects of temperature shift on ultrasonic longitudinal guided wave propagation in a long range traction-free steel strand. The temperature range was considered to be from –4 ℃ to 34 ℃ and the ultrasonic guided wave mode chosen was $L(0,1)$ at 160 kHz. In order to generate and receive this longitudinal guided wave mode, a new type of magnetostrictive transducer was developed. The experimental results offer future guidance for the temperature compensation of stress measurement in prestressed steel strands.

2 Ultrasonic Longitudinal Guided Waves in Steel Strands

There exist three types of ultrasonic guided waves: longitudinal modes, torsional modes, and flexural modes. These propagate along the axial direction of cylindrical structures. The former two are often used for the inspection of cylindrical structures because of their axisymmetric wave structures, while propagation of flexural modes is non-axisymmetric. In this paper, the temperature dependence of ultrasonic longitudinal guided wave modes characterized by non-zero radial and axial displacement components is researched.

When ultrasonic longitudinal guided waves are excited by transducers, they will propagate along each wire of steel strands separately. Each wire can be considered as an independent slender isotropic circular bar. In a single wire, longitudinal guided wave mode propagation is described by the following Pochhammer-Chree dispersion equation[10]:

$$\frac{2\alpha}{r}\left(\beta^2+k^2\right)J_1(\alpha r)J_1(\beta r)-\left(\beta^2-k^2\right)^2 J_0(\alpha r)J_1(\beta r)- \\ 4k^2\alpha\beta J_1(\alpha r)J_0(\beta r)=0, \qquad (1)$$

where r—Waveguide radius,

$\alpha^2=\frac{\omega^2}{c_l^2}-k^2$, $\beta^2=\frac{\omega^2}{c_t^2}-k^2$,

c_l, c_t—Bulk longitudinal and shear wave velocities in the material,

ω—Angular frequency, $\omega=2\pi f$,

k—Wave number,

J_0, J_1—Bessel functions of orders 0 and 1, respectively.

The phase velocity dispersion curves for longitudinal guided wave modes in the central and helical wires can be obtained by solving Eq. (1). The group velocity $c_g=\mathrm{d}\omega/\mathrm{d}k$ which is a function of the frequency and wave number can also be solved. Longitudinal mode dispersion curves in the helical and central wires of a seven-wire steel strand are shown in Fig. 1. Here, the strand's external diameter was nominally 17.80 mm while the diameters of the central and helical wires were 6.30 mm and 6.00 mm respectively. The pitch of the helical wire was 280 mm. The length L_h of one of helical wires of a steel strand of which length is L long can be expressed by[11]

$$L_h=L\frac{\sqrt{p^2+(2\pi R)^2}}{p}, \qquad (2)$$

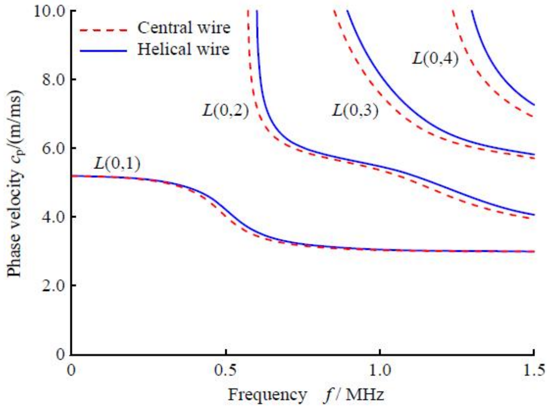
where p—Pitch of the helical wire,

R—Strand radius measured from the center of the steel strand to the center of the helical wire.

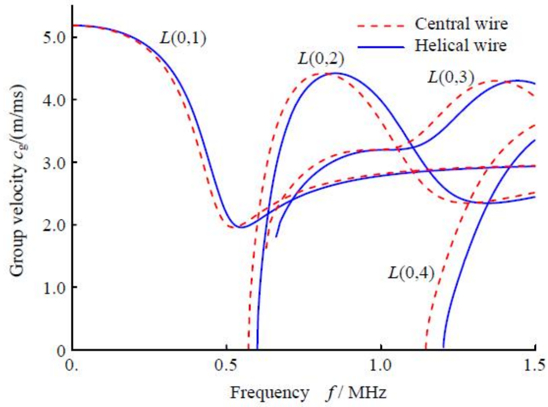
According to the configuration of our chosen steel strand, L_h can be calculated to be $1.009\ 5L$. The material properties used for the steel strands were as follows[12]: the longitudinal and shear wave velocities, 5 890 m/s and 3 230 m/s, respectively; the density, 7 843 kg/m^3. However, in Ref. [12], the base temperature condition of material property measurement was not given. It may be assumed that the temperature condition was about normal temperature, 22 ℃, corresponding to the material properties given above. At a certain temperature, some velocity deviations between experimental values and theoretical predications are inevitable. However, this will prove irrelevant as the base temperature will not affect the relation between the temperature change and group velocity of longitudinal guided wave modes later.

In this paper, the lowest order longitudinal guided wave mode, $L(0,1)$ at 160 kHz, was chosen for defect detection in steel strands. As shown in Fig. 1, it can be seen that these two dispersion curves of helical and central wires in the steel strand almost overlap each other at the frequencies below 0.2 MHz. Furthermore, below the cutoff frequency, 571 kHz, of $L(0,2)$ mode in the center wire, only the $L(0,1)$ mode can be generated.

Group velocities of $L(0,1)$ at 160 kHz in the central and helical wires were 5 050.4 m/s and 5 064.3 m/s respectively and their relative error was not more than 0.3%, while the propagation distance of the ultrasonic guided waves in the helical wire was less than 1% of that in the center wire within a certain distance range of a steel strand. Therefore, it is unnecessary to identify and distinguish guided waves in helical and central wires respectively within the propagation distance of interest. However, considering that there are six helical wires compared to one center wire, it is understandable that the signals received from the helical wires will dominate the received signals in the steel strands. Therefore, in this paper, all the received signals will be analyzed based on ultrasonic longitudinal guided wave propagation in the helical wires of the steel strand.



(a) Phase velocity



(b) Group velocity

Fig.1. Longitudinal guided wave mode dispersion curves for the helical and central wires in a steel strand

3 Temperature Dependence of Ultrasonic Longitudinal Guided Wave Propagation

The material mechanical properties and dimensions of a steel strand will change due to their temperature dependence. A linear dependence of each property on temperature is assumed[13]

$$P(T)=P(T_0)+\frac{\partial P(T)}{\partial T}\Delta T\,, \tag{3}$$

where P —One of the material mechanical properties, such as Young's modulus E, Poisson's ratio ν,

T —General temperature,

T_0 —Reference temperature,

$\frac{\partial P(T)}{\partial T}$ — Temperature dependence coefficient, i.e., sensitivity of the material property to temperature.

By the following relation

$$\begin{cases} c_l=\sqrt{\dfrac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}, \\ c_t=\sqrt{\dfrac{E}{2\rho(1+\nu)}}, \end{cases} \tag{4}$$

one can obtain the temperature dependence of ultrasonic wave velocities, where ρ is the density.

Below about 500 ℃, the following values are considered for a steel strand for its structural steel properties: temperature dependence coefficients of Young's modulus $\frac{\partial E}{\partial T}$ and of Poisson's ratio $\frac{\partial \nu}{\partial T}$ are -0.08 GPa / ℃, 2.4×10^{-5} / ℃, respectively, obtained from the American Society for Metals[14] and the coefficient of linear thermal expansion α is 1.2×10^{-5} / ℃ as given by HO, et al[15].

On the basis of Eq. (4) and corresponding temperature dependence coefficients, the temperature dependence of the longitudinal and shear velocities are illustrated in the temperature range from –4 ℃ to 34 ℃ in Fig. 2. Here, the temperature dependence of the density is ignored. By data analysis, it can be seen that the temperature dependent coefficients of longitudinal and shear velocities are -0.94 ($\mathrm{m}\,\square\,\mathrm{s}^{-1}\,\square\,(℃)^{-1}$) and -0.64 ($\mathrm{m}\,\square\,\mathrm{s}^{-1}\,\square\,(℃)^{-1}$) using linear fitting.

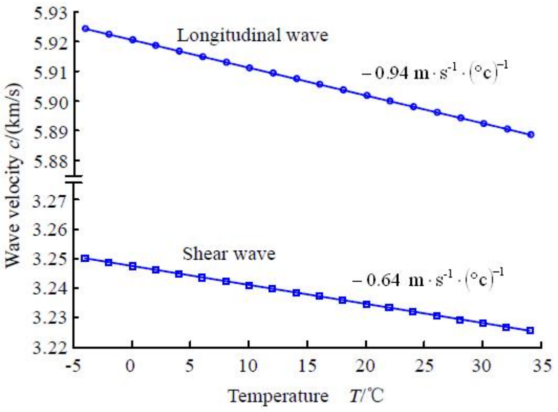


Fig. 2. Temperature dependence of longitudinal and shear wave velocities

Longitudinal and shear wave velocities at different temperatures are substituted into Eq. (1). The theoretical temperature dependence of $L(0,1)$ mode at 160 kHz is presented in Fig. 3. From this figure, it can be seen that both the phase and group velocities of this mode are relatively linear with temperature over the temperatures of interest. Furthermore, theoretical temperature dependent coefficients of phase and group velocities are linearly fitted to be -1.00 (m□s^{-1}□(℃)$^{-1}$) and -1.03 (m□s^{-1}□(℃)$^{-1}$), respectively. By comparing the temperature dependent coefficients of the propagation velocities of ultrasonic longitudinal and shear waves and the longitudinal guided wave mode $L(0,1)$ at 160 kHz, it can be concluded that propagation of this mode is a little more sensitive to temperature change than the former two waves theoretically.

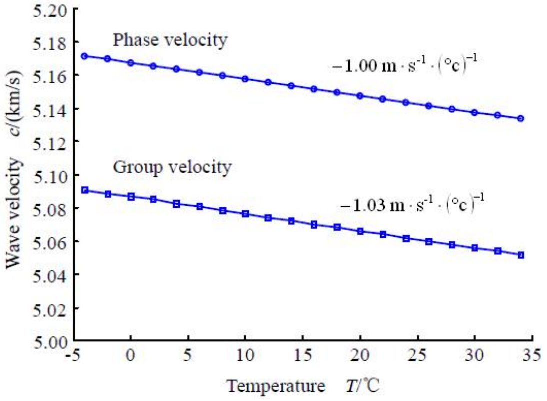


Fig. 3. Theoretical temperature dependence of $L(0,1)$ mode at 160 kHz in one of helical wires of the steel strand

4 Magnetostrictive Transducer

At present, there are two general types of ultrasonic transducers applied to ultrasonic longitudinal guided wave inspection of seven-wire steel strands: piezoelectric and magnetostrictive. Piezoelectric transducers must be directly in contact with the surface of the tested samples to transmit and receive ultrasonic waves in these structures. However, due to the complex helical surface of steel strands, piezoelectric transducers have to be installed at the end of a strand which is machined smooth for good elastic coupling. CHEN, et al[6], applied an acoustic emission transducer carefully mounted perpendicular to a steel strand's cross section to receive the signals of longitudinal guided wave modes. It is obvious that the application of piezoelectric transducers is unrealistic for the implementation of ultrasonic guided wave inspection of in-service steel strands especially when their end is hard or impossible to access. As an alternative, magnetostrictive transducers are more often used for ultrasonic guided wave inspection of steel strands because of their non-contact properties. To achieve effective generation and reception of ultrasonic longitudinal guided waves in long range steel strands, some work was performed on the development and application of magnetostrictive transducers. KWUN, et al[5], used magnetostrictive transducers to inspect seven-wire steel strands and found a relation between notch frequency and applied stress. WASHER[9] developed a type of magnetostrictive transducer with narrow frequency response centered at 320 kHz by confirming the period of the coils which equaled the wavelength of the chosen longitudinal guided wave mode. DI SCALEA, et al[7], performed stress measurement and defect detection in steel strands with the help of this type of transducer.

The working principle of the magnetostrictive transducer developed here was the same as that manufactured by WASHER[9]. The ultrasonic guided wave mode choice was achieved by confirming the section spacing of the spiral tube, which is the sensitive part of the transducer. In the magnetostrictive transducer that was developed, its sensitive part consisted of a three-section spiral tube and single-layer coil wound around the spiral with reverse normal winding along the axis direction of steel strand. Each section of the spiral tube was 16 mm long, which is approximately half the wavelength of the $L(0,1)$ mode at 160 kHz in one of helical wires of a seven-wire steel strand with a 17.80 mm nominal diameter. In order to enhance the generation and reception capabilities, impedance matching of the coil was implemented.

Two special treatments were applied to significantly improve the sensing ability of the developed magnetostrictive transducer. First, to reduce the effect of the magnetic resistance of the air gap in the whole magnetic circuit, a group of thin clips were specially designed as the joint between the saddle block and the steel strand. The configuration of the clip is shown in Fig. 4.

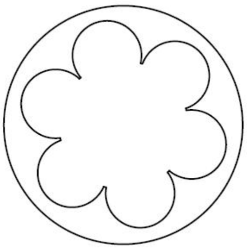


Fig. 4. Configuration of thin clip

The inner shape of this thin clip is coincided with the transverse cross section of the seven-wire steel strand and the outer shape was circular. Each clip was slightly less than 0.5 mm thick and could be sleeved onto the steel strand from its end. The total thickness of the 12 pieces of thin clips together was equal to the width of the saddle block approximately. Secondly, three identical permanent magnets were uniformly installed outside the thin clips to provide a homogeneous bias magnetic field inside the spiral tube and steel strand. The permanent magnet distribution of the magnetostrictive transducer on the surface of the steel strand is illustrated in Fig. 5.

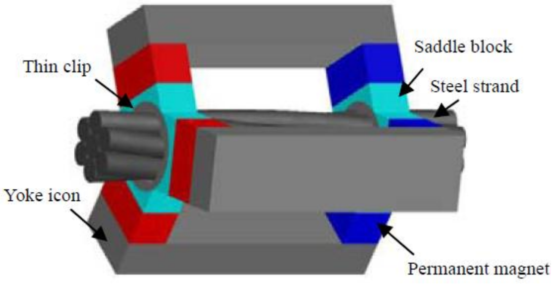


Fig. 5. Permanent magnet distribution of the magnetostrictive

transducer on the surface of steel strand

The special arrangement of the bias magnetic distribution effectively improved the generation of the axisymmetric longitudinal guided wave mode and suppressed unwanted flexural guided wave modes in each wire of the steel strand.

5 Experimental Research

5.1 Experimental setup

As shown in Fig. 6, the experimental setup for longitudinal guided wave mode inspection in steel strands consisted of a computer, digital oscilloscope DPO4054, function generator 33120A, power amplifier Ultra 2020, a steel strand sample and the developed magnetostrictive transducers.

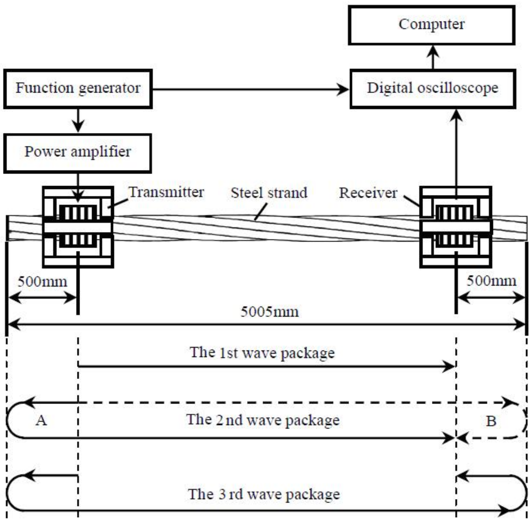
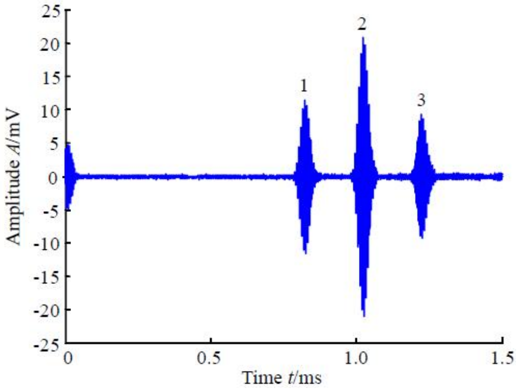


Fig. 6. Schematic diagram of experimental setup and propagation path of received ultrasonic longitudinal guided wave signals in the steel strand

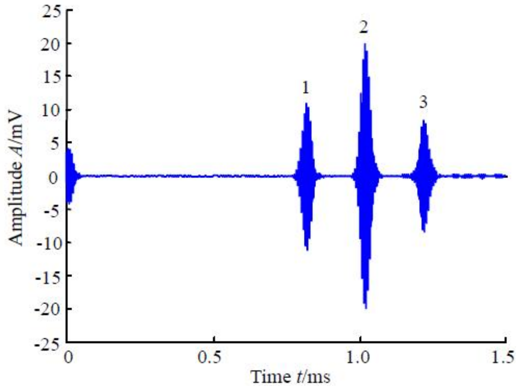
On the basis of a pitch catch arrangement, a pair of magnetostrictive transducers, acting as the transmitter and receiver respectively, were used for the generation and reception of ultrasonic longitudinal guided waves in steel strands. A 10-cycle sinusoidal tone burst modulated by a Hanning window was used as the excitation signal. It was triggered by the function generator and then amplified by the power amplifier for use as the excitation of the transmitter. Consequently, ultrasonic guided waves were generated and propagated along the axial direction of each individual wire of the steel strand. After a certain propagation time, ultrasonic longitudinal guided wave signals were received by the receiver and inputted into the oscilloscope and stored in the computer. According to the received signals and their time histories, the propagation velocity change of the ultrasonic longitudinal guided waves at different temperatures could be detected. The material parameters of the chosen steel strand sample and the dimension of its cross-section were the same as in the previous sections. In order to accumulate the temperature effect on ultrasonic longitudinal guided wave propagation, the steel strand sample used was 5 005 mm long.

5.2 Experimental Results and Analysis

On the basis of the magnetostrictive transducer arrangement in the steel strand sample shown in Fig. 6, ultrasonic guided wave signals at different temperature were obtained. The steel strand was placed under different natural temperature conditions in Beijing.



(a) Original signal



(b) Denoised signal

Fig. 7. Received ultrasonic longitudinal guided wave signal in the steel strand at 34 °c

The experiments were implemented at twelve temperature conditions which are –4 ℃, –2 ℃, 0 ℃, 2 ℃, 6 ℃, 10 ℃, 14 ℃, 18 ℃, 22 ℃, 26 ℃, 30 ℃ and 34 ℃. Furthermore, during the entire measurement procedure, the transducers were kept in their fixed installation position for high repeatability. The excitation frequency was kept constant at 160 kHz. At this frequency, only the lowest order longitudinal guided wave mode, $L(0,1)$, could be generated. The original received signal at 34 ℃ in 0–1.5 ms is shown in Fig. 7(a). In order to improve the identification of the ultrasonic guided wave signal, the discrete wavelet transform was used for the denoising processing and the Daubechies wavelet of order 40 was used as the mother wavelet due to its narrowband character resembling[16]. By discrete wavelet transform processing, the denoised signal of Fig. 7(a) was obtained and is shown in Fig. 7(b). Compared with that of the original signal, the signal to noise ratio (SNR) of the denoised signal in Fig. 7(b) is shows obvious improvement. As shown in Fig. 7(b), there exist three wave packages. The propagation paths of these wave packages in the steel strand are illustrated in Fig. 6. The first wave package was a direct wave of $L(0,1)$ mode which propagated directly from the transmitter to the receiver. The second wave package was the superposition of the two reflection echoes A and B which first propagated in both directions of the steel strand and were reflected by the two ends of the steel strand respectively, reaching the receiver at the same time interval after being generated by the transmitter. One of the superposed parts, reflection echo A, in the second wave package propagated continuously along the steel strand. It was reflected at the near end from the receiver and received again by the receiver. According to the above analysis, the propagation distances for these three wave packages, 1, 2 and 3, was confirmed to be 4 005 mm, 5 005 mm and 6 005 mm in the steel strand without consideration of the dimension effect of magnetostrictive transducers. Furthermore, the difference in propagation distance between the first and third wave packages in Fig. 7 was exactly 2 000 mm in the center wire and 2 019 mm in the helical wire of the steel strand, as calculated by using Eq. (2).

In order to get an improved view of the temperature dependence of the received signals, Fig. 8 shows only the waveforms of the direct wave of the $L(0,1)$ mode of the received longitudinal guided wave signals for different temperature conditions. From a more detailed view of these waveforms, the monotonic propagation time prolongation of the direct wave can easily be observed when the temperature increases from –4 ℃ to 34 ℃. Fig. 9 gives the peak arrival time for each cycle of the wave fronts of the direct wave of the $L(0,1)$ mode shown in Fig. 8. The number of cycles increases from top to bottom for the curves plotted in Fig. 9.

As seen in Fig. 9, the change in the peak arrival time for each cycle of these wave fronts is almost linearly related to the temperature shift. Furthermore, the same rising slope tendency can be observed for the peak arrival times for all the cycles.

In order to reduce the effect of the transducer dimension on the precision of the confirmation of the propagation distance as much as possible, the calculation of the propagation velocity of the $L(0,1)$ mode was performed by measuring the propagation time interval of the first and third wave packages of the received guided wave signals under different temperature conditions, as shown at 34 ℃ in Fig. 5. The propagation distance difference between the first and third wave packages was 2 019 mm in the helical wires according to the above analysis.

Now we consider the effect of the propagation distance prolongation and contraction due to the temperature shift on the measurement of propagation velocity. The length change with temperature for a slender cylinder steel wire is linear with temperature and can be expressed as

$$\Delta l = l_T - l_{T_0} = \alpha (T - T_0) l_{T_0} , \tag{5}$$

where l_{T_0} and l_T are the reference and final lengths for the temperature change from T_0 to T, respectively.

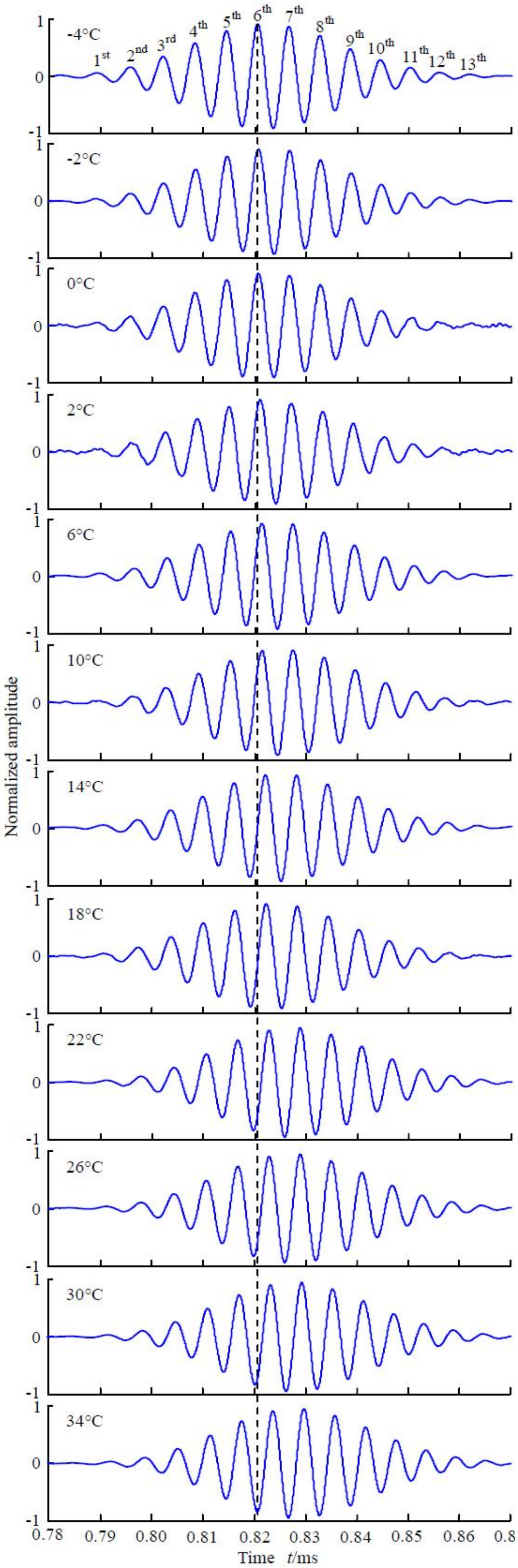


Fig. 8. Time-of-flight variation of received direct wave signals under different temperature conditions

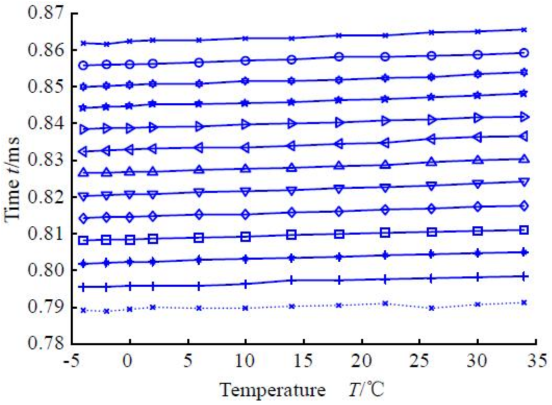


Fig. 9. Peak arrival time of 13 cycles of a direct wave of the $L(0,1)$ mode under different temperature conditions

For example, when the temperature rises to 34 ℃ from the reference temperature 22 ℃, the prolongation of propagation distance difference between first and third wave packages was calculated to be only 0.3 mm. Therefore, the relative derivation due to propagation distance change can be considerably ignored.

Fig. 10 gives the experimental results of temperature dependence for the $L(0,1)$ mode at 160 kHz in the steel strand. It was obtained from the propagation distance difference divided by the peak arrival time difference between the 6th cycle of first and third wave packages under different temperature conditions. As shown in Fig. 10, it is clear that the propagation velocity change of $L(0,1)$ at 160 kHz is extremely linear with the temperature shift and its rate of change is about -0.90 $(\mathrm{m}\cdot\mathrm{s}^{-1}\cdot(℃)^{-1})$ using the linear fitting approach. The experimental temperature dependence coefficient of group velocity is very close to theoretical prediction, -1.03 $(\mathrm{m}\cdot\mathrm{s}^{-1}\cdot(℃)^{-1})$.

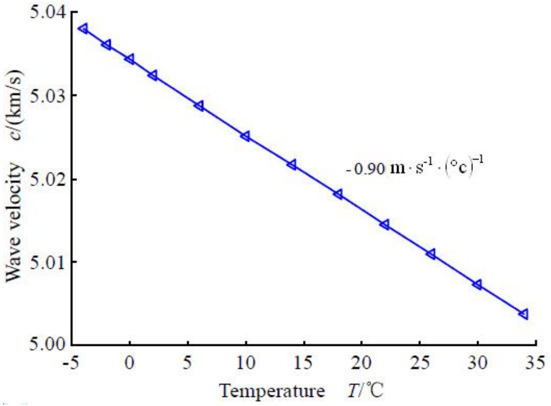


Fig. 10. Temperature dependence of the $L(0,1)$ mode at 160 kHz in the steel strand

6 Conclusions

(1) A new type magnetostrictive transducer was developed to generate and receive ultrasonic longitudinal guided waves in steel strands. This type of transducer is characterized by a group of thin clips for reducing the effect of the magnetic resistance of the air gap by using three identical permanent magnets which provide a homogeneous bias magnetic field inside the spiral tube and steel strand.

(2) In experiments, ultrasonic longitudinal guided wave signals were obtained for different temperature conditions and denoised by discrete wavelet transform processing. It was observed from these received signals that the propagation velocity change of $L(0,1)$ at 160 kHz was extremely linear with temperature shift and its rate of change was about $-0.90\,(\mathrm{m}\cdot\mathrm{s}^{-1}\cdot(℃)^{-1})$. The experimental temperature dependence coefficient of group velocity was close to the theoretical prediction.

(3) The effect of dimension deviation between the helical and center wires and the thermal expansion of the steel strand on ultrasonic guided wave propagation was also analyzed. It was found that this effect can be ignored compared with the effect of the change of material mechanical properties such as Young’s modulus and Poisson’s ratio due to temperature shift.

(4) By comparing the temperature effect on the propagation of conventional ultrasonic waves and the longitudinal guided wave mode $L(0,1)$ at 160 kHz, it can be concluded that the longitudinal guided wave mode was slightly more sensitive to temperature changes theoretically. Therefore, it is necessary to consider the temperature effect on ultrasonic longitudinal guided wave propagation in steel strands to improve the accuracy of stress measurement in prestressed steel strands.

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Biographical notes

LIU Zenghua, born in 1973, is currently an associate professor in *College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, China.* He received his PhD degree from *Beijing University of Technology*, *China,* in 2006. His research interests include modern measurement and control technology, ultrasonic nondestructive testing, structural health monitoring, and advance sensor technology.
Tel: +86-10-67391720; E-mail: liuzenghua@bjut.edu.cn

ZHAO Jichen, born in 1984, is currently a PhD candidate in *College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, China.* His research interests include ultrasonic nondestructive testing and structural health monitoring.
E-mail: zhaojichen@emails.bjut.edu.cn

WU Bin, born in 1962, is currently a professor and a PhD candidate supervisor in *College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, China.* His main research interests include wave mechanics, advance nondestructive testing method and modern measurement and control technique.
Tel: +86-10-67392067; E-mail: wb@bjut.edu.cn

HE Cunfu, born in 1958, is currently a professor and a PhD candidate supervisor in *College of Mechanical Engineering and Applied Electronics Technology, Beijing University of Technology, China.* His main research interests include modern measurement and control technology, ultrasonic nondestructive testing and structural health monitoring, and advance sensor technology.
Tel: +86-10-67391938; E-mail: hecunfu@bjut.edu.cn