The application of low frequency longitudinal guided wave mode for the inspection of multi-hole steel floral pipes

Z H Liu, X D Xie, B Wu, Y H Li and C F He

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

E-mail: liuzenghua@bjut.edu.cn

Abstract. Shed-pipe grouting technology, an effective advanced supporting method, is often used in the excavation of soft strata. Steel floral pipes are one of the key load-carrying components of shed-pipe grouting supporting structures. Guided waves are a very attractive methodology to inspect multi-hole steel floral pipes as they offer long range inspection capability, mode and frequency tuning, and cost effectiveness. In this contribution, preliminary experiments are described for the inspection of steel floral pipes using a low frequency longitudinal guided wave mode, \( L(0,2) \). The relation between the number of grouting holes and the peak-to-peak amplitude of the first end-reflected signal was obtained. The effect of the grouting holes in steel floral pipes on the propagation velocity of the \( L(0,2) \) mode at 30 kHz was analyzed. Experimental results indicate that the typical grouting holes in steel floral pipe have no significant effect on the propagation of this mode. As a result, low frequency longitudinal guided wave modes have potential for the non-destructive long range inspection of multi-hole steel floral pipes. Furthermore, the propagation velocity of the investigated \( L(0,2) \) mode at 30 kHz decreases linearly with the increase of the number of grouting holes in a steel floral pipe. It is also noticeable that the effect of the grouting holes cumulates along with the increase in the number of grouting holes and subsequent increase in reflection times of longitudinal guided waves in the steel floral pipe. The application potential of the low frequency longitudinal guided wave technique for the inspection of embedded steel floral pipes is discussed.

1. Introduction

With the acceleration of development in west China, civil construction activities for the transportation infrastructure such as rail and highway have increased significantly. Because of the mountainous terrain of this area, underground operations are extensively used in the civil construction. Shed-pipe grouting technology, an effective advanced supporting method, is often used in the excavation of soft strata. As a key load-carrying component, steel floral pipes provide support for shed-pipe grouting supporting structures by tying the separated strata to form a whole. In general, the length of these pipes varies from several meters to tens of meters. Therefore, it is important to provide a nondestructive testing method to evaluate the construction quality, including embedment quality and length measurement of steel floral pipes, and verify the safety of complete advanced supporting structures. Due to its advantages [1], which include long range inspection capability, mode and frequency tuning, and cost effectiveness, guided wave technique is suitable for the inspection of various structures including pipes, tubes [2-6]. As an emerging nondestructive testing method, the
technique allows for the inspection of structures with limited access from a single transducer position. Therefore, it is suitable for the inspection of steel floral pipes embedded in soft rock strata.

In order to measure the embedment length and evaluate support conditions of steel floral pipes, it is necessary to obtain end-reflected echoes. Low frequency guided wave modes with long wavelength and low sensitivity to grouting holes can be one option to achieve this aim. In this study, the experiments are conducted to investigate the propagation ability of a low frequency longitudinal guided wave mode in multi-hole steel floral pipes and the effect of grouting holes on the propagation velocity of this guided wave mode. The application possibility and potential of longitudinal guided wave technique for the inspection of steel floral pipes are also discussed.

2. Geometry of multi-hole steel floral pipes

Steel floral pipes acquire their name from the peach-like distribution of small grouting holes along their length. Figure 1 illustrates the configuration of a steel floral pipe and its grouting hole distribution. The grouting holes are distributed along four axial lines of the steel floral pipe. Here, $2l$ is the distance of adjacent holes on the same axial line, and $d$ is the diameter of grouting hole and between two neighbouring grouting holes on adjacent axial lines, the axial distance is $l$. Thus if the cylinder was unfurled the flat surface would look like a triangular lattice.

![Figure 1. Configuration of steel floral pipe and its grouting hole distribution](image)

In engineering construction, after a steel floral pipe has been inserted into the rock stratum, cement slurry, a mixture of cement and water, is pumped in under pressure from the end of steel floral pipe and forced out through the grouting holes. The cement slurry mixes with the surrounding soil and seeps into the rocks to strengthen the whole stratum. The surrounding stratum can achieve a higher strength after the cement solidification.

3. Longitudinal guided wave modes in steel pipe

Figure 2 shows the group velocity dispersion curves of longitudinal guided wave modes for a steel pipe generated using the Disperse software [7]. Here, the steel pipe external diameter is 89 mm and the wall thickness is 5 mm. The material properties used for the steel pipe are as follows: longitudinal and shear wave velocities: 5960 m/s and 3260 m/s; respectively; density 7932 kg/m$^3$.

In general, the grouting holes can be considered as defects to be inspected using guided waves. Here, in order to evaluate the construction quality of the steel floral pipe and surrounding stratum, the interaction between the grouting holes and guided waves should be decreased to a minimum, resulting in low attenuation of the guided wave mode. Guided waves are generated at one of pipe end,
propagate along the whole pipe and are reflected from the other pipe end. The end-reflected signals will be received by the receivers. Measuring the amplitude and time-of-flight of the reflection signal, the safety of the whole advanced supporting structure can be evaluated. Low frequency longitudinal guided wave modes have long wavelength and are not sensitive to these grouting holes with low diffraction loss. Therefore, low frequency longitudinal guided wave modes have a certain potential to achieve this aim.

As shown in figure 2, the chosen excitation frequency of 30 kHz is close to the cutoff frequency, approximately 20 kHz, of the L(0,2) mode. At 30 kHz, the wavelength of the L(0,2) mode is about 189 mm and the mode shows relative low dispersion from the theoretical prediction. Figure 3 displays the radial and axial displacement of the L(0,2) mode at 30 kHz. The axial displacement is large compared to its radial displacement. Due to these propagation characteristics, the longitudinal guided wave mode can be excited efficiently using transducers generating an axial force in the pipe. Therefore, in this paper, the low frequency longitudinal guided wave mode, L(0,2) at 30 kHz, is chosen for the long range inspection of steel floral pipes.

![Group velocity dispersion curves of longitudinal guided wave modes for a steel pipe](image1)

**Figure 2.** Group velocity dispersion curves of longitudinal guided wave modes for a steel pipe

![Radial and axial displacement distributions of L(0,2) mode at 30 kHz](image2)

**Figure 3.** Radial and axial displacement distributions of L(0,2) mode at 30 kHz

### 4. Experimental investigation

#### 4.1. Experimental setup

The propagation ability of low frequency longitudinal guided wave modes was investigated experimentally. Furthermore, the effect of grouting holes on propagation velocity of low frequency longitudinal guided wave modes was analyzed.

Figure 4 shows the experimental setup for low frequency longitudinal guided wave mode inspection in steel floral pipes. It consists of a power amplifier Ultra 2020, computer, digital oscilloscope DPO 4054, function generator 33120A, the investigated 4.2 m long steel pipe sample and the developed PZT array. The dimensions of the steel pipe are as stated above, external diameter 89 mm and wall thickness 5 mm. For the efficient excitation and reception of low frequency longitudinal guided wave modes at low frequency, a new type of PZT array with longitudinal vibration mode was developed. For this type of PZT element, the working frequency decreases with its length. The length of each PZT element 75 mm and its width and thickness are 4 mm and 1 mm, respectively. 24 similar PZT elements were bonded equally around the circumference of one of the pipe ends as shown in figure 5. They were connected in parallel to form an array.

A 10-cycle sinusoidal tone burst modulated by a Hanning window is generated by the function generator and amplified using the power amplifier as the excitation signal. The PZT array is excited by
this amplified excitation signal through switcher. Longitudinal guided waves are generated and propagate along the pipe. When these signals are reflected from the grouting holes or the far end of the pipe, the same PZT array acts as a receiver for the reflected signals. The signals are averaged (512 averages) and recorded on the oscilloscope and transferred to the computer via an Ethernet connection.

4.2. Experimental results and analysis

For the investigated steel floral pipe the axial distance of adjacent grouting holes on the same axial line, $2l$, was 150 mm and the diameter of grouting holes was $d = 10$ mm. These dimensions are often used in engineering practice. For the experiments, the grouting holes were drilled one by one into the steel pipe, starting 1 m away from the PZT array. The holes are numbered sequentially by their distance from the transducer. The maximum number of the grouting holes is 60 and at last all of these grouting holes will be distributed in a 2.25 m long section in the steel pipe. The position of the drilled grouting holes is illustrated in figure 1. Longitudinal guided wave signals were recorded after the drilling of each grouting hole.

Figure 4. Experimental setup for low frequency longitudinal guided wave mode inspection in steel floral pipes

Figure 5. PZT array distributed equally around the circumference of pipe end
Figure 6. Longitudinal guided wave mode signals (center frequency 30 kHz) received in the steel pipe for different number of grouting holes.

Figure 6 shows the longitudinal guided wave mode signals (center frequency 30 kHz) received from the steel pipe for different numbers of grouting holes. As shown in figure 6(a), in the time range from 0-18 ms 11 end-reflected echoes of the L(0,2) mode can be seen when the pipe has no grouting holes. Therefore, the mode can propagate more than 90 meters in the pipe without significant loss of
energy. With the increase of the number of grouting holes in the steel pipe, additional, smaller reflected pulses in these signals can be observed between the end reflection echoes (figures 6(b-d)). When the number of grouting holes reaches 60, six end-reflected echoes can still be identified in figure 6(e). This shows that the \( L(0,2) \) mode at 30 kHz can propagate a distance of more than 50 m in the steel pipe with 60 grouting holes (diameter 10 mm). Figure 7 shows the relation between the number of grouting holes and the peak-to-peak amplitude of the first longitudinal guided wave mode signal received from the end reflection in the steel pipe. The effect of the number of grouting holes on the amplitude of the first end-reflected echo is almost imperceptible for the typical geometry investigated here. The wavelength of the mode is significantly larger than the hole diameter. It can be concluded that the grouting holes have relative limited effect on the propagation of low frequency longitudinal guided wave modes. In figure 7, some data fluctuations, partially due to inconsistent operation of experimental instruments, can be seen as the collection of data lasted a long time.

![Figure 7](image_url)

**Figure 7.** Relation between grouting hole number and peak-to-peak amplitude of the first end-reflected longitudinal guided wave mode.

However, with the increase in the number of grouting holes and subsequent increase in reflection times of longitudinal guided wave mode signals in the steel floral pipe, the effect of the grouting holes cumulates. When the grouting holes increase from 0 to 60, only the first six end-reflected echoes can be identified in the time traces. The other end-reflected echoes become gradually indistinguishable from the complex scattered signals at the grouting holes and cannot be identified from their waveform shape.

The effect of grouting holes on the propagation velocity of the low frequency longitudinal guided wave mode, \( L(0,2) \), at 30 kHz, was investigated. Figure 8 shows the zoomed waveforms of the first end-reflected echoes for different numbers of grouting holes from figure 6. It can be seen that the arrival time of the first end-reflected signals gradually increases with the increase of the number of grouting holes. This implies that the group velocity decreases when the number of grouting holes increases in the steel floral pipe.

Figure 9 illustrates the relation between the number of grouting holes and the group velocity of the \( L(0,2) \) mode with a center frequency of 30 kHz. From this figure, it is found that the group velocity of this mode decreases almost linearly with the number of grouting holes. Using a linear least square fit, the slope coefficient can be confirmed to be \(-0.43\) (m/s)/(per hole).
Figure 8. Zoom on the first end-reflected pulse from figure 6.

Figure 9. Relation between the number of grouting holes and group velocity of the L(0,2) mode at 30 kHz.
5. Conclusions and discussion
In this paper, the propagation ability of a low frequency longitudinal guided wave mode, the L(0,2) mode at 30 kHz, was investigated in multi-hole steel floral pipes. It was found that for the investigated, typical geometry the grouting holes have no significant effect on the amplitude of the first end-reflected echoes with a propagation distance of 8.4 m. However, with an increase of the number of grouting holes and propagation distance, the effect of the grouting holes accumulates and decreases the propagation ability of guided wave signals for long range inspection of steel floral pipes. The effect of the grouting holes on the group velocity of the L(0,2) mode at 30 kHz was analyzed. It was found using a linear least square fit that the group velocity of this mode decreases by 0.43 m/s per grouting hole.

According to the results, it has been shown that low frequency longitudinal guided wave modes have the potential for supporting quality evaluation of long steel floral pipes in civil engineering. It should be noticed that the L(0,2) mode at low frequency (30 kHz) is not the only suitable option for steel floral pipe inspection. As shown figure 2, the L(0,1) mode at a lower frequency range, below about 12 kHz, can also be used for steel floral pipe inspection as an alternative as it has long wavelength and similar, non-dispersive wave propagation characteristics. However, for the efficient excitation and reception of the L(0,1) mode at low frequency, the transducers would need to be developed further. For steel floral pipes embedded in soft strata, the attenuation of longitudinal guided wave signals due to the effect of the surrounding medium will have to be considered. Future work will include the investigation of the propagation ability and inspection potential of low frequency longitudinal guided wave modes in embedded steel floral pipes.

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References
[1] Rose J 2002 Mat. Eval. 60 53
[2] Lowe M, Alleyne D and Cawley P 1998 Ultrasonics 36 147
[3] Barshinger J and Rose J 2004 IEEE Trans. On Ultrason. Ferroelec. and Freq. Cont. 51 1547
[4] Liu Z, He C, Wu B, Wang X and Yang S 2006 Ultrasonics 44 e1135
[5] Liu Z, Wu B, He C, Wang X and Yang S 2007 Insight 49 41
[6] Demma A, Cawley P, Lowe M and Roosenbrand A 2003 J. Acoust. Soc. Am 114 611
[7] Pavlakovic B, Lowe M, Alleyne D and Cawley P 2000 Rev. Prog. Quant. NDE (Ames), Vol 16, ed Thompson D and Chimenti D (New York: Plenum) p 185