Proceedings of IPC2004
International Pipeline Conference
October 4-8, 2004, Calgary, Alberta, Canada

IPC2004-590

INSPECTION OF HOLLOW SUCKER ROD BY USING GUIDED WAVE

Li Longtao
College of Mechanical Engineering & Applied Electronics Technology, Beijing University of Technology, Beijing, 100022,
lilongtao@emails.bjut.edu.cn

He Cunfu
College of Mechanical Engineering & Applied Electronics Technology Beijing University of Technology, Beijing, hecunfu@bjut.edu.cn

Wu Bin
College of Mechanical Engineering & Applied Electronics Technology Beijing University of Technology, Beijing

Zheng Jingyu
College of Mechanical Engineering & Applied Electronics Technology Beijing University of Technology, Beijing

Li Ying
College of Mechanical Engineering & Applied Electronics Technology Beijing University of Technology, Beijing

ABSTRACT

Based on cylindrical guided wave technology, a new designed piezoelectric ring was presented here and it was put on the cross section of the hollow sucker rod's end to excite or receive guided waves in the hollow sucker rod. By selecting and exciting specific guided mode at a given frequency, two artificial cracks (20 mm×1 mm×0.5 mm and 20 mm × 1mm×1mm), which located on the hollow sucker rod, can be found in time domain. Tie-ins in the hollow sucker rod increase the complexity of analyzing the received signals. An alternative method presented here is that a fast guide mode was selected and excited at a specific frequency. Then, the echo from cracks will appear the front of the echo from tie-ins of the hollow sucker rod in the received signals. Some conclusions proved that the new designed piezoelectric ring was more effective than previous piezoelectric transducers and it is feasible to utilize cylindrical guided wave to achieve nondestructive inspection on hollow sucker rod.

Key words: guided wave, hollow sucker rod, inspection

INTRODUCTION

Recently, guided ultrasonic wave method plays an important role in non-destructive testing and evaluation (NDT&E) [1-4]. Hollow sucker rods are widely used in sucker pumping systems, which are installed in many oil wells. For the reason of safe production, there is always a demand to test whether there are any fatigue cracks on the hollow sucker rod. Conventional methods or not, such as ultrasonic, magnetic leakage, eddy current inspection, are point to point and very expensive. A troublesome is that the hollow sucker rod is smeary and there often is much remnant oil on it when it has been used. This can increase the difficulty of testing hollow sucker rod by above methods. Guided wave technique is an alternative method to solve this problem. Although much work has been published on the use of guided wave for pipe inspection [5-8], there still is a variation between pipe inspection and hollow sucker rod by guided wave. Generally speaking, a hollow sucker bar can simply be seen as a straight pipe. The key difference between them is that there are tie-ins in the hollow sucker rod's end. The tie-ins will contribute more complexity on anglicizing the received signal because there will be more mode conversion over there.

D.N. Alleyne [9] presented to excite guided wave in pipe by using dry-coupled piezoelectric transducers. Jian Li [10] used circular comb piezoelectric transducer and angle beam transducer array to excite cylindrical guided wave successfully. In their methods, the transducers are all mounted on the outer cylinder surface of pipe. Their idea is to excite axis-symmetric guided mode, whose energy contribution is even along the circumference of pipe. However, a problem is that the number of transducer mounted on the pipe is limited by the outer diameter. Although the space between transducers can be small, the excite energy is still not even. In this paper, a new designed piezoelectric transducer ring, which can be mounted on the cross section of the hollow sucker rod, is presented. The new designed piezoelectric transducer ring can excite axis-symmetric wave effectively. Then some artificial cracks on the hollow sucker rod were found by choosing specific frequency and guided mode.

GUIDED WAVE THEORETICAL BACKGROUND

Theoretical aspects of cylindrical guided wave propagation were initially researched by Gazis[11,12]. The dispersion equation of cylindrical guided wave takes form as follow:

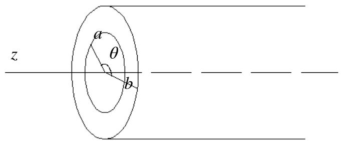


Figure 1. Pipe coordinate

$$D = \begin{vmatrix} c_{11} & c_{12} & \cdots\cdots & c_{16} \\ c_{21} & c_{22} & \cdots\cdots & c_{26} \\ \cdot\cdot & \cdot\cdot & \cdots\cdots & \cdot\cdot \\ c_{61} & c_{62} & \cdots\cdots & c_{66} \end{vmatrix} = 0 \qquad (1)$$

where c_{ij} is a function of *a* and *b*, inner and outer radius of the pipe (Figure 1) respectively, Lames constants λ and μ, density ρ ,frequency ω, and wave number k . Utilizing the governing wave equation, an assumed harmonic wave solution, solving appropriate traction free boundary conditions on the boundaries can lead to dispersion curves. Setting the determinant equal to zero yields roots, which are the phase velocity values extracted as a function of a frequency. Group velocity as opposed to phase velocity, measures the speed of energy transport of the waves in the pipe. Group velocity can be calculated from the phase velocity curves by the formula

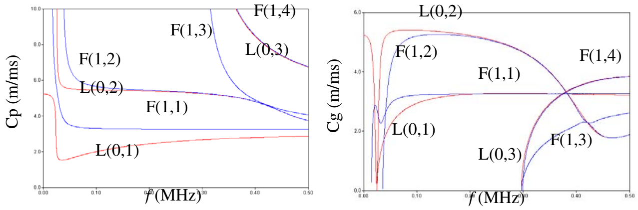
$$C_g = \frac{d\omega}{dk} = \frac{C_p^2}{C_p - \omega \dfrac{dC_p}{d\omega}} \qquad (2)$$

Because of the complexity of dispersion equation, no one can get its precise solution. Now, we can just obtain its numerical solution by computer programming. A numerical solution of the dispersion equation yields the phase and group velocity frequency is illustrated in figure 2, where a=31.34 mm and b=36.84 mm for a steel pipe.

Consider all guide modes propagating in the axial direction of pipe, there are three different type modes: longitudinal, torsional, and flexural modes. The longitudinal and torsional mode are axis-symmetric mode, the flexural mode are non-axis-symmetric mode.

TRANSDUCER DESIGN

According to M.J.S. Lowe [13], L (0, 2) guided mode at 70k Hz is suitable for testing the cracks on pipe. L (0, 2) mode is axis-symmetric and the major strain component is axial, so Alleyne [9] used some length-expander piezoelectric transducers to excite and receive L (0, 2) guided wave in a pipe. In the design of length-expander piezoelectric transducer, the electrode was polarized on the piezoelectric element's top and bottom surfaces, and the bottom electrode is extended over one end. When there are some voltage signals inputting on it, the piezoelectric element will expand along the length direction. However, according to table 1, the absolute value of piezoelectric constants d_{33} is larger than that of d_{31} for all piezoelectric materials. This means that if imposing a voltage on a piezoelectric element 3 direction, there will be more expanding amplitude in its 3 direction than 1 direction. Then there are less efficiency for length expanding by applying voltage on piezoelectric element's top and bottom surface.



(a) phase velocity dispersion curves (b) group velocity dispersion curves

Figure 2. dispersion curve of steel pipe. (inner radius is 31.34 mm, outer radius is 36.84 mm)

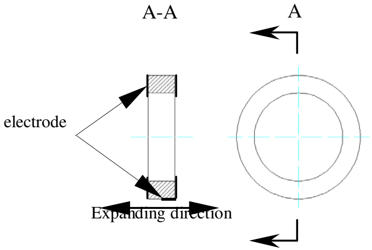


Figure 3. Sketch-map of transducer ring

Table 1 Piezoelectric constants of common materials

Piezoelectric constants	$BaTiO_3$	PZT-4	PZT-5	PZT-8	PMN
d_{31} (10^{-12} m/V)	-78	-100	-185	-90	-230
d_{33} (10^{-12} m/V)	190	200	415	200	700

To overcome above deficiency, a new designed piezoelectric transducer ring is presented here, see figure 3. The inner and outer radius of the piezoelectric transducer ring is equal to that of pipe. It is electroded on its top and bottom surface, but the bottom electrode is extended over the cylindrical surface partly so that the cable connected with the electrode can be educed when the bottom surface contacts with the cross section of pipe's end. In the piezoelectric transducer ring, the voltage applying direction is consistent with the main expanding direction. For example, here, PZT-5 were selected as the material of the transducer, its $|d_{33}|$ is about 2.24 times to $|d_{31}|$. So, the transducer ring in figure 3 will excite axis-symmetric guided wave in pipe efficiently. Because it is a complete ring, not a ring formed by attaching axis-symmetrically a series of elements around pipe, it can be more effective to suppress the non-axis-symmetric flexural mode. And because the transducer ring is put on the cross section of one end of pipe and its main expanding direction is axial, the torsional guided wave also can not be excited. In this paper, the transducer ring's dimension is inner radius 31.34 mm, outer radius 36.84 mm, thickness 3.7 mm and its material is PZT-5.

EXPERIMENTAL SETUP AND RESULTS

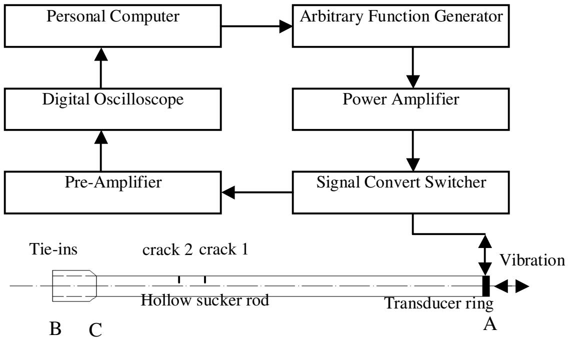
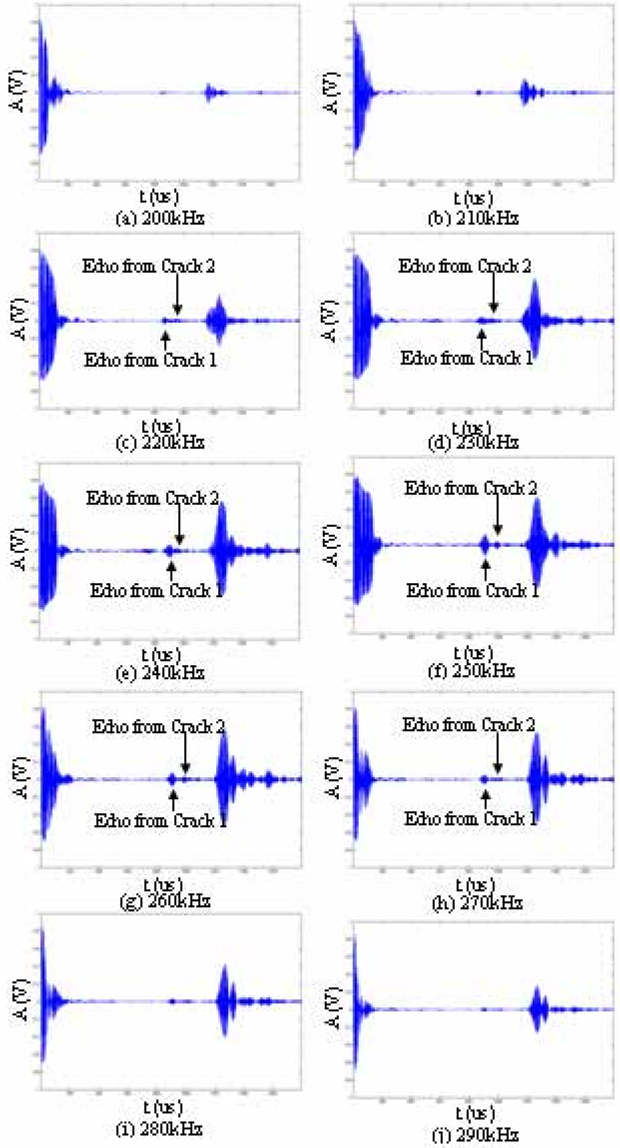


Figure 4. Schematic diagram of instrumentation

The setup and instrumentation used is shown in figure 4. An arbitrary function generator (HP 33120A) delivered the excitation signal to a power amplifier (Ultra 2020) whose output was sent to the transducer ring, which mentioned above. Because the transducer ring acted as transmitter and receiver and the excitation signal voltage was far higher than receive signal voltage, there must be a signal convert switcher between the power amplifier and transducer to modulate transmit signal and receive signal. The received signal from the transducer ring was amplified and transferred to a digital oscilloscope (TDS 3032B) for digital capture, and then it was transferred to a PC for processing and display. In any case, the signal output by the arbitrary generator was a 10-cycle tone burst modulated by a Hanning window. The voltage output by the power amplifier was about 200 V peak-peak value and the receiver amplifier gain was typically set to 20 dB. In figure 4, it can be seen a steel pipe that from A to C, the inner radius is 31.34 mm and the outer radius is 36.84 mm. From B to C, it is a tie-in, which has screw thread; its outer radius is about 42 mm. The distance from A to B is 3080 mm and that from B to C is 134 mm. Crack 1 and crack 2 are artificial slots, which their dimensions (length× width× depth) are 20 mm×1 mm×0.5 mm and 20 mm × 1mm×1mm separately. Crack 1 was removed from A point 2192 mm and crack 2 was removed from A point 2442 mm.

The transducer ring was coupled on the cross section of hollow sucker rod's end (as shown in figure 4), not on its surface. The responses of hollow sucker rod when the excitation was provided by the transducer ring are shown in figure 5. Table 2 summarized the experimental results for from 200 kHz to 290 kHz operating frequency.

Figure 5's results show that the transducer ring can excite and receive axis-symmetric guided wave and suppress the appearance of non-axis-symmetric guided wave in hollow sucker rod successfully. According to group dispersion curve, L (0, 2) mode is the faster guided mode in the range of 200 kHz - 290 kHz, so if there are any crack echo in the received signal, they should appear in the front of echo from B end (See figure 4). Figure 8 (c)-(h) proved this idea. For a steel pipe, the end echo of L (0, 2) should a single wave-packet. However, in figure 5, the echo from B end has much a little wave-packets, this was that because it happened mode conversions, which caused by the screw thread of tie-in on B end. But this can not influence analyzing the received signal because the crack echo is ahead. In figure 5(f), 250 kHz is an optimum testing frequency and the two cracks' echo can be distinguished clearly at that frequency. The amplitude of crack echo and end echo of L (0, 2) are diminished as below 240 kHz (as shown in figure 5 (a), (b), (c), (d) and (e)) or above 260 kHz frequency(as shown in figure 5 (g), (h), (i), and (j)). One reason was that the attenuation of



(a) 200kHz (b) 210kHz (c) 220kHz (d) 230kHz (e) 240kHz (f) 250kHz (g) 260kHz (h) 270kHz (i) 280kHz (j) 290kHz

Figure 5. L(0,2) guided wave echoes in a steel hollow sucker rod

Table 2 Operating frequency and group velocity of L (0, 2) mode

Frequency (MHz)	200	210	220	230	240	250	260	270	280	290
Group velocity(m/ms)	5.23	5.20	5.16	5.12	5.07	5.02	4.96	4.90	4.83	4.75

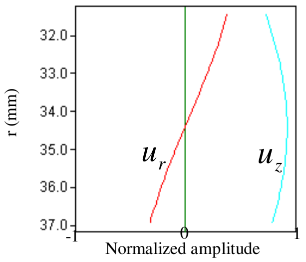


Figure 6. Wave structure of L(0,2) at 250 kHz

wave-packet's energy rises as frequency increasing. Another reason was that the applied frequency range was far from the frequency response range of the transducer ring used in the experiment. According to wave structure of L (0, 2) at 250 kHz (See figure 6), the axial displacement are larger and milder than the radial displacement. This means it can be equally sensitive to internal or external cracks at any circumferential location in the hollow sucker rod. So, L (0, 2) guided mode at 250 kHz is a good choice to test cracks on the hollow sucker rod.

It should be stressed that there is a main bang near the starting time in the received signal. This was caused by the signal convert switcher, not receive useful signal. For common sense, higher frequency's wave will be more sensitive to cracks. However, its energy attenuation will also rise. Then, a suitable frequency should choice, and the frequency should also be in the range of frequency response of transducer.

CONCLUSION

A new designed transducer ring was presented here for exciting and receiving axis-symmetric guided wave successfully. The non-axis-symmetric guided wave can be suppressed in pipe thoroughly, because the transducer ring can be coupled on the cross section of one end of pipe completely. Guided wave technique was introduced to hollow sucker rod crack testing perfectly.

Applying faster guided mode can avoid the influence of tie-in of hollow sucker rod in the analysis of signal. This is feasible if the cracks are not in the tie-in, which has screw thread. Further development of utilizing guided wave for hollow sucker rod will concentrate on cracks near or in the tie-in.

ACKNOWLEDGMENTS

This research was supported by the Beijing Natural Science Foundation under contract number: 3011001 and supported by National Natural Science Foundation of China under contract number: 10372009 and 10272007.

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