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Study on Experiment of Acoustic Transmission in Pipe String

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Abstract

As a feasible option, surface signals can be transmitted downhole by taking downhole oil pipe as channel and sound waves as medium. In this paper, a longitudinal wave transmission experiment is conducted for oil pipes with limited length, and experimental environment and equipment are prepared. The experimental objects include 10 oil pipes of three sizes, and each pipe is arranged with a set of velocity sensor. The experiments of impact signals and continuous sine signals are performed, revealing the time-domain and frequency-domain properties of sound waves during transmission through different pipe nodes. Through detailed analysis of the experimental results, it is concluded that spectral distribution of longitudinal wave in pipes presents a comb filter structure with alternating passband and stopband, which is validated in respect of frequency domain and time domain. Moreover, distortion and attenuation of longitudinal wave signals may occur within passband frequencies.

Keywords: *sound wave; oil pipe; comb filter; frequency domain analysis*

1. Introduction

In the oil production engineering sector, it is optional that surface signals are transmitted downhole by using oil pipe as channel and sound wave as medium. Global scholars have investigated sound wave propagation in drill strings [1-4], but no systematic and profound researches have been conducted on downhole signal transmission in oil/water wells. In this paper, a set of experiment system is prepared on the surface, and longitudinal wave transmission properties in pipes are analyzed through the experiments, which include time domain analysis, frequency domain analysis and attenuation analysis, providing beneficial reference for the development of downhole communication techniques based on sound waves.

2. Establishment of Pipe Acoustic Transmission Mechanism Model and Simulation Analysis

1. Establishment of Pipe Acoustic Transmission Mechanism Model

The pipe string consists of multiple oil pipes and couplings. It denotes periodic structure features. The string is equivalent to an ideal pipe model (see Fig. 1), for which d_2 c_2 Q_2 a_2 and d_1 c_1 Q_1 a_1 are respectively length, acoustic velocity, density and cross section area of coupling and oil pipe.

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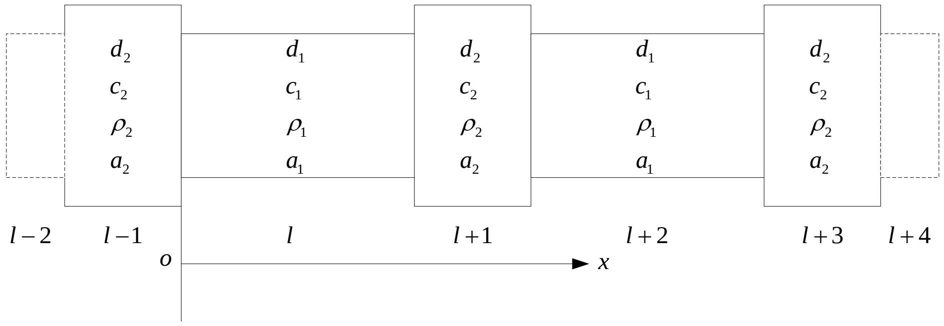


Figure 1. Schematic Diagram of the Periodic String

The related dispersive equation [5-6] is:

$$\cos kd = \cos\left(\frac{\omega d_1}{c_1}\right)\cos\left(\frac{\omega d_2}{c_2}\right) - \frac{1}{2}\left(\frac{z_1}{z_2} + \frac{z_2}{z_1}\right)\sin\left(\frac{\omega d_1}{c_1}\right)\sin\left(\frac{\omega d_2}{c_2}\right) \tag{1}$$

Phase velocity (c_p) is defined as:

$$c_p = \frac{\omega}{k} \tag{2}$$

Where, k is wave number, i.e. number of complete waves within a 2π unit length.

Group velocity is defined as:

$$c_g = \frac{d\omega}{dk} \tag{3}$$

2. Model Simulation Analysis

Referring to three oil pipe sizes commonly adopted in the fields (Table 1), and determining wave velocity as c=$5.05 \times 10^3 m/s$.

Table 1. Parameters of Three Oil Pipes

No. of oil pipe	1	2	3
OD (mm)	88.9	60.3	48.26
ID (mm)	77.9	51.8	41.9
Length of oil pipe (m)	9.76~9.98	9.75~9.97	9.83-10~10
Cross section area (m^2)	0.0062	0.0029	0.0018
OD of coupling (mm)	107.95	73.03	55.88
Length of coupling (mm)	100-114	114-127	159-178
Cross section area of coupling (m^2)	0.0092	0.0042	0.0025

Simulation results: seen from the dispersion equation, the frequencies on the right side of the equation with absolute values smaller than 1 will make up the passband; otherwise, they will make up the stopband. Figure 2 gives $\cos kd$ values in relation to variable frequencies. Figure 3 is the relationship curve of wave number vs. frequency. It shows dispersion phenomenon of periodic strings due to structural uniqueness and representation of discontinuous curves. As frequency increases, passband width increases, and stopband width decreases. Furthermore, ω / k is no longer a constant in this case. That means, longitudinal wave velocity for each frequency in the passbands is collectively correlated with frequency. Figure 4 is the relationship curve of group velocity vs. frequency in pipes. Spectrum characteristics in pipes are representative of a comb filter structure with alternating passband and stopband. Phase and energy transmission velocity of individual longitudinal waves are no longer constants, but functions of frequency since dispersion phenomenon occurs. With the increasing frequency, comb filter displays an overall band changes: passbands get narrower and stopbands become wider.

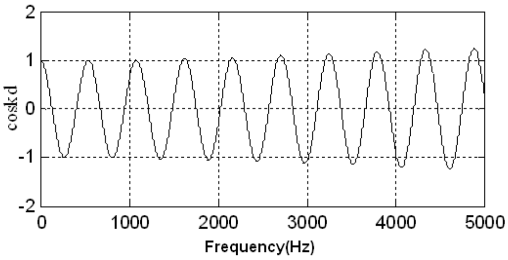


Figure 2. Curve of $f \sim \cos kd$ in Pipe

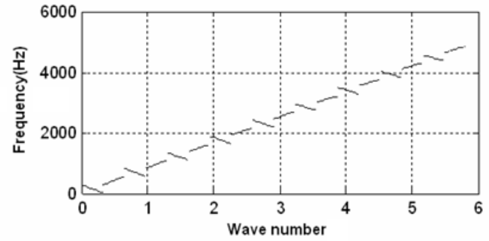


Figure 3. Curve of Wave Number k and Frequency

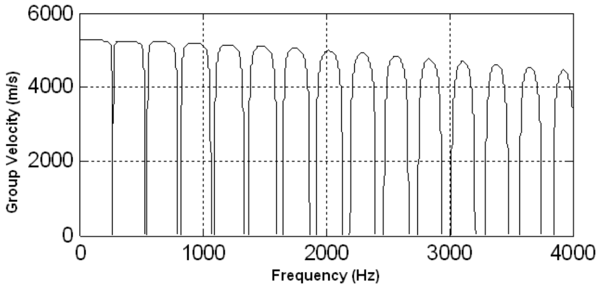


Figure 4. Group Velocity and Frequency Curve in Pipe

3. Establishment of Experiment System

The experiment system consists of three groups of 10 oil pipes. Place the oil pipes on the sleeper, and let them parallel to the surface. Take one end of the pipes as acoustic signals transmitting terminal, and install longitudinal wave data acquisition equipment on the pipes at the same time. Impact signals are given out from impact hammer, and continuous sine excitation signals are generated by HEV exciter; acoustic vibration signals in pipes are acquired by a wireless sensor network.

1.Acoustic Signal Sources

(1) Heavy-duty impact hammer

Heavy-duty impact hammer is mainly used for impact force experiment, so as to measure frequency response functions of the media. Figure 5 gives three models of heavy-duty impact hammer and associated hammer heads in black, red, green and orange. Each hammer comprises electric equipment (*e.g.*, acceleration sensor), which can connect with data acquiring equipment through joints. In addition, each hammer is configured with four hammer heads, which are adjustable with frequency responses of impact signals.

Figure 5. Three Models of Heavy-duty Impact Hammer

Figure 6. Exciter and Signal Transmitting Devices

2. Vibration Exciter

Vibration exciter is intended to exert exciting force within a certain frequency range onto the string. Exciter products available on the market include electrohydraulic, electric and electromagnetic vibration exciters. The working parameters of the vibration exciter elected in this experiment are listed in Table 2.

Table 2. Parameters of Vibration Exciter

Model	——
Max. exciting force (kgf)	50
Max. working frequency (Hz)	2000
Max. amplitude (mm)	±10
Force constant (kgf/A)	2.3
Max. peak electric current (A)	35
Nonlinear coefficient of exciting force in relative to electric current	< 0.1 %
Moving coil DC current (Ω)	0.50
Weight of movable component (kgW)	1.84
Natural frequency of movable component (Hz)	3.2
Matching power of amplifier needed (W)	500
Weight of vibration exciter (kg)	45
Dimensions of vibration exciter (mm)	$\phi = 230$ $h = 300$

Exciter and signal transmitting devices are shown in Figure 6.

2. Data Acquiring Equipment

In this experiment, wireless sensor network is used for longitudinal wave data acquisition. Acoustic data wireless transmission is made possible by integrating high precision acceleration sensors with wireless sensor network nodes. Figure 7 shows the layout of wireless sensor nodes.

In the experiment, Zigbee wireless network is used to send commands to all acceleration acquisition nodes and control data acquisition conditions (*e.g.*, start, stop, and transmitting data). Figure 8 shows the data acquisition process.

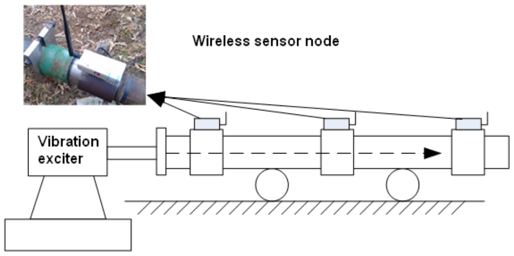


Figure 7. Schematic Diagram of Wireless Sensor Nodes

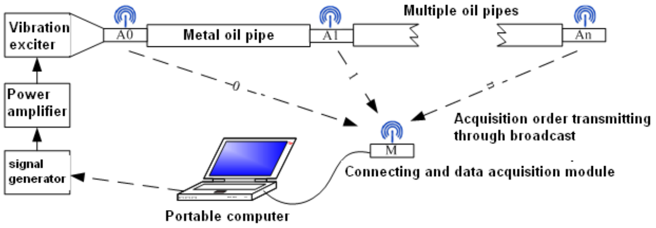


Figure 8. Process of Data Recording

4. Experiment Results Analysis

1. Time Domain Analysis of Impact Signals

Ten groups of longitudinal impact experiment are conducted for three groups of oil pipes respectively, and the hammer heads with different rigidity are taken in each group. In the experiment, time domain and frequency domain data are observed, which are basically consistent. Therefore, the data from one of the experiments is merely chosen as an example for further illustration. Taking No.1 oil pipe as example, the data acquired at 10 sensor nodes are offered in Figure 9, and the longitudinal axis expresses longitudinal wave amplitude values. Longitudinal wave data from No. 1, 4 and 10 sensor nodes are selected for detailed analysis (see Figure 10).

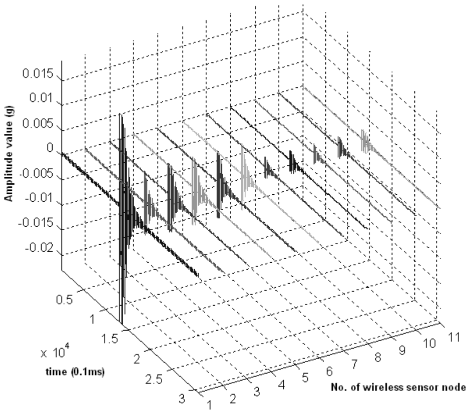


Figure 9. Data Graph from All Ten Nodes of the Wireless Sensor Network

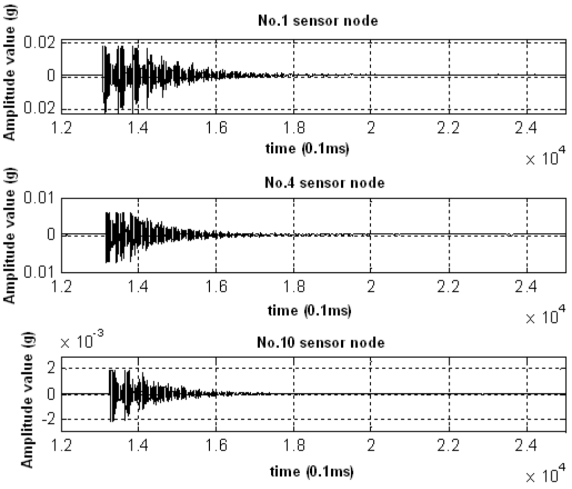


Figure 10. Data of the Longitudinal Wave from No.1, 4 and 10 Sensor Nodes

(1) Signal attenuation

Apparently, amplitude attenuation of longitudinal wave signals happens at No.1, 4 and 10 nodes after 0.25ms in Figure 10. It is mainly resulted from energy attenuation that is caused by reflection and refraction at the cross section points with sudden changes.

(2) Amplitude values of received signals

Also, Figure 10 shows that longitudinal waves of No.1, 4 and 10 nodes have the same waveform and phase. However, the amplitude value is the maximum at No.1 node, moderate at No.4 node and the minimum at No.10 node. The peak value is 0.023g at No.1 node and merely 0.004g at No.10 node. In other words, peak amplitude is attenuated to be 17.4% of original signal amplitude after longitudinal wave signals transmit through an about 100m-long pipe.

(3) Peak time

Through correlation, it is found that the peak time of No.1 node (1310.0ms) and No.10 node (1328.0ms) has a difference of about 18.0ms. In the real measurements, No.1 oil pipe has a total length of 95.450m or so, and the calculated acoustic velocity is $c_L = L / \Delta t = 5300.3 m / s$, which is agreeable with the range of steel wave velocity (5200~5300m/s) mentioned in the references.

2. Frequency Domain Analysis of Impact Signals (0-1KHz)

A spectrum analysis is performed for the signals from No.1 and 10 nodes in Fig. 10, and Fig. 11 shows the related spectrum graph. For received signals, only the spectral structure within a frequency range of 0-2.5KHz is investigated. The signals out of the frequency domain are negligible due to severe attenuation. Fig. 12 gives the partial enlarged graph, in which three narrow stopbands are clearly seen, similar to the calculated stopbands.

The following conclusions are worked out based on the spectrum analysis:

(1) In Figure 12, spectral distribution of longitudinal waves in pipes presents a comb filter structure evidently. Besides, passbands are wide, stopbands are narrow, and passbands and stopbands occur alternately.

(2) Figure 12 shows about 10 peaks in each passband clearly, which attribute to, theoretically, limited length of joints and oil pipes. Therefore, when the longitudinal waves reach the boundary or joints on the one end of the pipes during transmission, the waves will reflect and stack back and forth between them. As a result, some phenomena (*e.g.*, standing wave, resonance or phase cancellation) will occur to the waves of different frequencies.

(3) Owing to some factors (*e.g.*, measurement errors of geometric parameters and oil pipe connection), real passbands have an about 50Hz deviation towards high frequency, and passbands and stopbands are relatively agreeable in the width.

(4) The theoretical analysis reveals that very steep jumps often emerge at the passband edges, but this phenomenon is not seen in the experiments, because Fourier transform points are limited and partial energy is mixed and stacked in the stopbands. Seen from the group velocity dispersion curve, the group velocity around the passbands declines to zero, since partial energy fails to reach the receiving terminal in the sampling process.

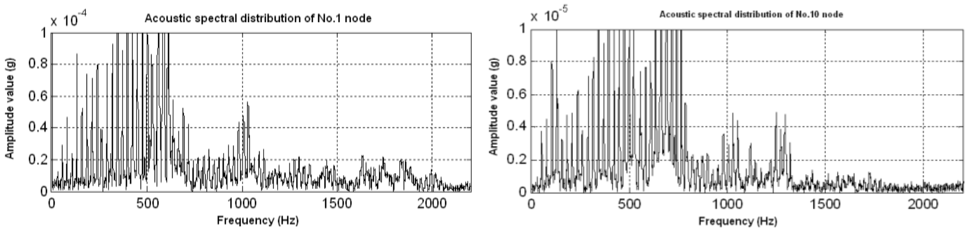


Figure 11. Partial Enlarged Spectral Distribution: No.1 and No.10 Nodes (0~2KHz)

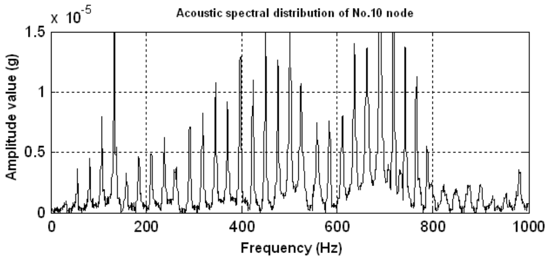


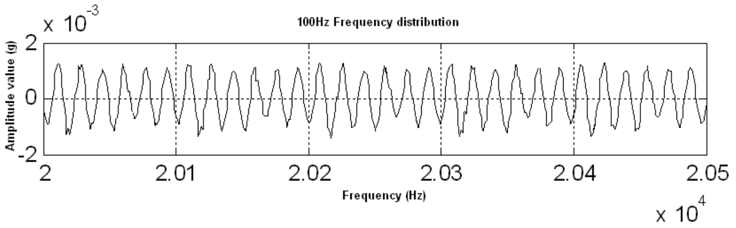
Figure 12. Partial Enlarged Spectral Distribution: No.10 Node (0~1KHz)

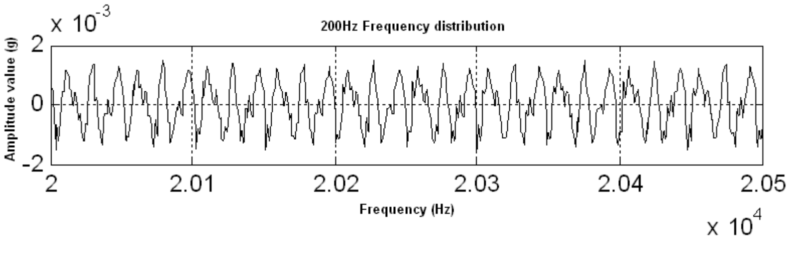
According to the analysis results of time domain and frequency domain distribution data at No.10 node of No.2 and 3 oil pipes, the oil pipes have a smaller diameter, a smaller cross section area and more evident gravity influence. Severe wave amplitude attenuation of No.3 oil pipe demonstrtes that it is unsuitable to take thin pipes as acoustic transmission channel.

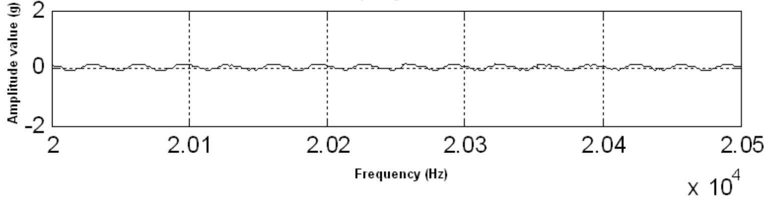
3. Analysis of Sine Excitation Signals

An excitation experiment of continuous sine signals is to further verify the influences of longitudinal wave transmission in pipes on passbands and stopbands. According to experiment results of impact signals, five typical frequencies (100Hz~500Hz) are selected for string analysis. Continuous signals properties can be seen through correlation of signal amplitude and spectral distribution. Among the selected frequencies, 100Hz, 200Hz and 500Hz are in the passbands; 300Hz and 400Hz belong to the stopbands, and it is expected that the wave transmission effects are poor.

Figure 13 shows acoustic waveforms acquired at No.10 sensor node at five excitation frequencies in the experiment successively. Apparently, analogous sine wave forms are observed at 100Hz, 200Hz and 500Hz, but at 300Hz and 400Hz, it is hard to identify intuitively because of severe signal attenuation.







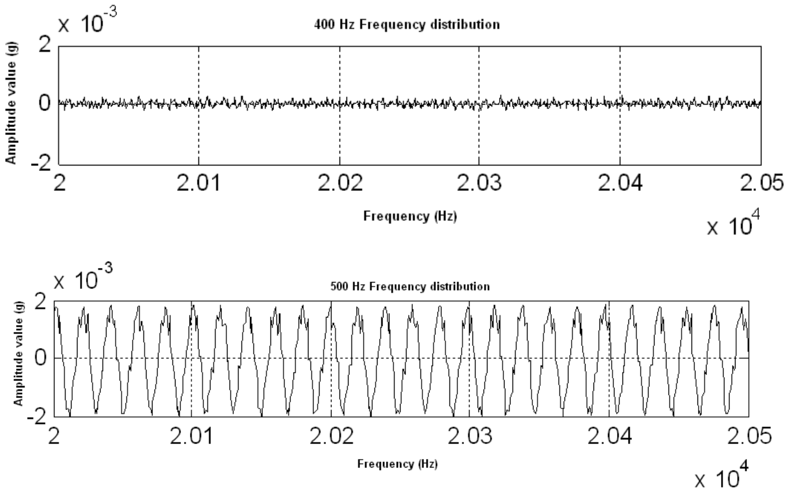
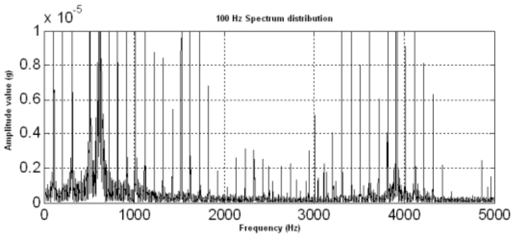
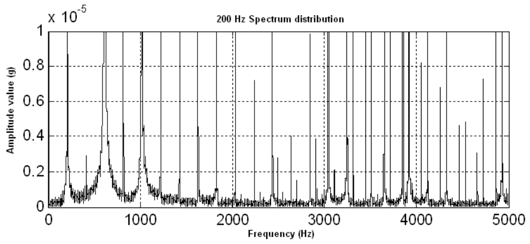


Figure 13. Sine Continuous Longitudinal Wave Transmission in time Domain (100~500Hz)

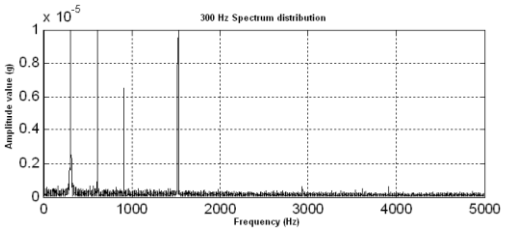
After observing received waveforms in the experiment, spectrum transform is conducted, and passbands and stopbands are identified explicitly, as shown in Figure 14. At the excitation frequency of 100Hz, 200Hz and 500Hz, waveform amplitude attenuation is small, but at 300Hz and 400Hz, signal amplitude attenuation is severe, and main carrier frequency of sound waves are hard to distinguish.



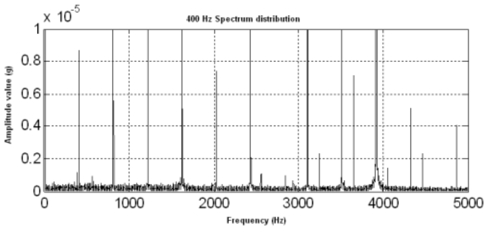
100Hz



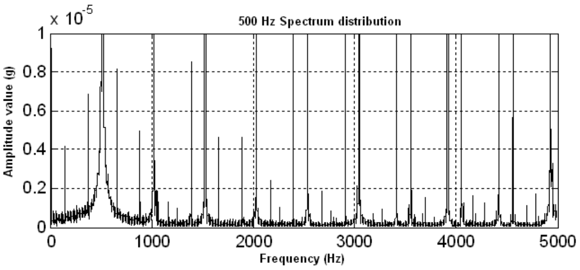
200Hz



300Hz



400Hz



500Hz

Figure 14. Continuous Sine Excitation Spectrum Distribution: 100Hz~500Hz

It indicates that acoustic transmission has high requirements for frequency in the periodic string structure. Frequency distribution curve patterns of sound waves in pipes should be clarified in the design of communication carriers. Proper passbands are selected by integrating with exciter functions. Selection of adequate wave frequencies favors extending acoustic transmission distance in the pipes, and plays a key role in realizing acoustic communication techniques.

Based on validation of a continuous sine wave excitation experiment, wide band signals centering on passbands should be selected for carrier frequency in pipes.

4. Conclusion

In this paper, longitudinal wave transmission experiments are conducted for oil pipes with limited length. Experiment environment and equipment are introduced in detail. Ten oil pipes of three different sizes are taken in the impact experiment and continuous sine signals experiment. Wireless sensor network technique is used in the data acquisition. Time domain and frequency domain properties at each node under the excitation of impact and sine signals are attained. The experiment results are analyzed in detail, providing basis for downhole tubing communication based on sound wave.

Acknowledgement

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