Information Sciences 275 (2014) 360–369

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Propagation properties of acoustic waves inside periodic pipelines

Deli Jia [a], Caihao Cui [a,*], Siqi Wang [b]

[a] School of Automation Harbin University of Science and Technology, Harbin 150080, China
[b] No.3 Oil Production Factory of Daqing Oilfield Co., Ltd., Daqing 163152, China

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form 1 January 2014
Accepted 12 January 2014
Available online 21 January 2014

Keywords:
Acoustic wave
Periodic pipeline
Finite difference method
Transfer matrix method
Spectrum distribution analysis
Fault diagnosis

ABSTRACT

This paper presents a new method to model and to simulate the propagation properties of the acoustic wave in periodic pipelines. First, an ideal model of pipeline and its dispersion equations of acoustic waves are constructed and described in detail in order to implement this method. Subsequently, the classical finite difference method is applied to determine the boundary conditions of the pipelines. In addition, the transfer matrix method is used to simulate the propagation process of the acoustic waves inside the pipelines. Finally, by conducting length-limited periodic drill string experiments, it is shown that this model and algorithm can be used to obtain the acoustic-wave spectrum distribution and impulse response characteristics inside periodic pipelines under operational conditions. This method provides a theoretical basis for the fault diagnosis of acoustic-wave transmission systems for oil industry applications.

1. Introduction

Periodic pipelines are widely employed in modern oil industry applications such as mining and transportation. Periodic pipelines have recently been used as communication channels to transfer data, which has contributed to the rapid development of oil exploration and borehole control technology.

In 2004, the EvoLogics and Baker Hughes used the drill strings as acoustic data transmission channels. The maximum depth reached and transfer rate were 620 m and 720 bps, respectively. In the same year, the company Halliburton (USA) developed an acoustic telemetry system (ATS), which used acoustic waves to continuously transmit data through underground oil pipes every 2 min for 20 days. In 2007, XACT Downhole Acoustic Telemetry Inc. and Extreme Engineering Ltd. improved on this technique by constructing an ATS with a system transmission rated up to 20 bps at a test depth of 2500 m.

In the case of wireless communication utilizing periodic pipelines, the quality of acoustic-wave communication inside periodic pipelines depends on the propagation properties of acoustic waves [10,15]. Thus, it is essential that the properties of the pipe's acoustic-wave transformation are precisely identified, particularly the spectrum distribution of the acoustic wave and characteristics of the impulse response [12,14]. Because acoustic waves are severely attenuated through the pipes, acoustic-wave transmission systems may break down when the physical conditions inside the pipes change.

In the absence of accurate models to predict acoustic-wave propagation in pipelines, previous applications have been entirely experiment-based. Further, in the case of a breakdown in the system, a large amount of time and effort is required to

* Corresponding author. Tel.: +86 0451 86390664.
E-mail addresses: jiadeli@hrbust.edu.cn (D. Jia), chrishardyhust@163.com (C. Cui), wangsiqi@gmail.com (S. Wang).

http://dx.doi.org/10.1016/j.ins.2014.01.018

ensure its subsequent functioning. In this light, it is essential to model and simulate the propagation properties of acoustic waves in periodic pipelines to aid in reducing downtime.

Herein, we derive the dispersion equations for an ideal periodic pipeline model and describe these equations. We apply the classical finite difference and transfer matrix methods and simulate and verify the acoustic wave spectrum distribution and impulse response characteristics inside periodic pipelines. This paper provides a theoretical basis for fault diagnosis of the acoustic-wave transmission systems used in the oil industry.

The remainder of this paper is organized as follows: Section 2 describes an ideal model of a pipeline, frequency equations, and transient analysis of acoustic waves, which are subsequently used in the experiment section. Section 3 describes the proposed method for the drill string experiments. Section 4 details our proposed method with a scheme for fault diagnosis of a wave transmission system. Section 5 concludes this paper with remarks on further studies.

2. Modeling and simulation

2.1. Model of the periodic pipelines

The purpose of studying and modeling pipeline transmissions is to obtain the amplitude attenuation and spectrum distribution produced by the pipe and to determine the relationship between parameters such as material, length, cross-sectional area, and density of the periodic pipeline as acoustic waves travel through the pipeline system [19].

When acoustic waves are transmitted inside the pipelines, each element of the pipeline must satisfy the differential equations of motion, the dynamic equilibrium conditions and stress–strain requirements described by classical Newtonian mechanics [11,23]. According to the state of motion and force on each element inside the pipeline, the wave equation can be determined by using the relationship between Newton's second law of motion and the constitutive relations of the pipelines [5]. To simplify the model, the following boundary conditions are assumed:

1. The responses of all the materials to any type of input are assumed to be approximately linear;
2. The connections of pipelines are firm and concentric;
3. Flexural wave and torsional waves are ignored;
4. Gravity and buoyancy are not considered.

Fig. 1 shows a one-dimensional infinite pipeline structure. The direction along the pipe is denoted by the variable X. The time interval and initial cross-sectional area are denoted by t and A, respectively. The Young's modulus and unit weight are denoted as E and γ, respectively, and these parameters are not affected by acoustic disturbances and time. The displacement, $u(x,t)$, is given by

$$u = u(x,t). \tag{1}$$

Supposing that the wave is elastic, the one-dimensional formula of the stress–strain is

$$\sigma_x = E\frac{\partial u}{\partial x}. \tag{2}$$

At the displacement element at the position x, shown in Fig. 1, the stress is σ_x. The stress becomes $\sigma_x + (\partial\sigma_x/\partial x)\Delta x$ at a distance Δx from the original position. Thus, the inertial force is $-\Delta x A(\gamma/g)(\partial u/\partial x)$. According to Newton's second low, the equation of motion for this case can be written as:

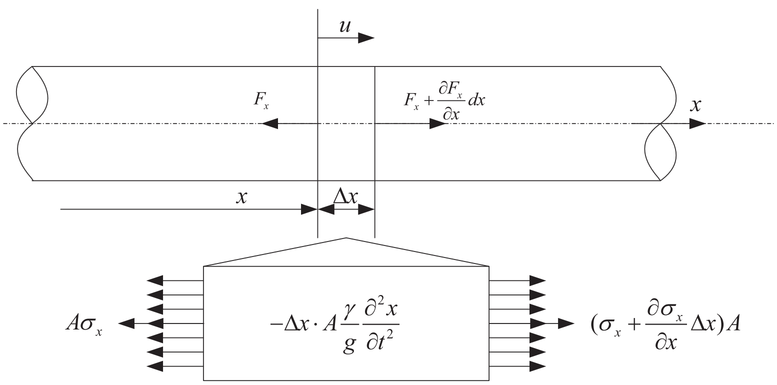

Fig. 1. One-dimensional infinite pipeline structure.