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Vibration sensor approaches for sand detection in oil–water–sand multiphase flow

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ABSTRACT

The real-time measurement of solid phase in oil–water–sand multiphase flow is significant in production process control and reliable operations, especially for reasonable sanding in oilfield. Aiming to improve the existing limitations in solid particle detection of a liquid–solid system, a vibration detection device for liquid–solid flow has been developed and its evaluation test is conducted indoor. This paper illustrates the application of a special wideband vibration sensor to monitor sand–water and sand–oil–water flows in pipeline. In this work, a primary measuring instrument was firstly proposed and designed to amplify vibration signal caused by sand impacting so that it can be much easier to receive for the sensor. Time–frequency analysis method and a characteristic sand frequency band digital filter were proposed to enhance the ability of sand detection in heavy liquid flow background noise. The experimental investigation considered sand–water flow and sand–oil–water flow, both with sand content more than 0.3 wt.‰ and size less than 325 mesh. The experimental findings showed that there is an obvious correlation between vibration power spectrum amplitude and sand concentration. Accordingly, the vibration technology would be helpful to enhance the solid detection for the multiphase system.
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1. Introduction

The transportation of sand solid in multiphase flow has widely influenced many areas of industry, such as oil and gas industries, the chemical industry and pollution control [1]. It has attracted considerable attention since a certain amount of sand in pipelines can cause serious erosive damage [2]. Multiphase flow involves the presence of more than one phase and the second phase can affect the fluid dynamics of the main flow. It is difficult to measure the multiphase flow parameters in this complex process [3]. As a result, it is valuable to obtain solid phase features in real-time effectively.

Particle detecting method in liquid phase has long been recognized as a challenge by engineers and researchers all around the world. Over the years, a number of sensor techniques have been developed and proposed to meet some of these difficult challenges. For example, C.L. Xu et al. [4] applied passive electro-static measurement system (installed with bulk and heavy ring-electrodes) to achieve the characteristics of particle velocity and size in gas–solid two-phase flow. N.R. Kesana et al. [5] obtained sand erosion results in multiphase slug and annular flow by invasive electrical resistance probes. However, this detection mechanism was not real-time, and flow streamline can be changed by the invasive installation into the pipeline. Despite of their availabilities, these particle detection approaches were relatively difficult to install and maintain. On the other hand, N.C. Hii et al. [6] monitored particle characteristics in gas–solid two phase flow by acoustic emission technology. Then M. El-Alej et al. [7,8] demonstrated that the acoustic emission technology was also capable of detecting the presence of sand particles in water–gas flow, and this method was mainly applied to the sand detection in air or water phase flow. I. A. Allahar [9] collected thirty sets of sand concentration signals in oil–water multiphase flow by using the acoustic sand detectors, and verified that this acoustic technology possessed superior sand detection ability. However, there were also some limitations for acoustic sand detectors. For example, when the mixed flow velocity was below 2 m/s, or the flow regime was slug and pulsating flow, the detected acoustic sand signals were error or uncertainty [10].

From the open literature, most of the experimental and theoretical works have focused on solid detection in air or single liquid phase flow, while sand detection in more complex multiphase flow has been rarely reported. Non-intrusion vibration sensor approaches for particle characteristics detecting in multiphase flow, particularly for particle concentration lower than 0.05% of multiphase volume have not been undertaken yet [11–13].

In principle, sand particles are transported with the flow, hitting the pipe wall at bends in the pipeline because of inertia and generating vibration wave. However, the small sand signals may not be successfully obtained by a particle detection sensor. Furthermore, the liquid flow

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background noise could also affect the measurement [14]. Consequently, how to obtain sand characteristic signal in relatively low concentrations without most of the flow background noise is a key issue to detect the solid phase in multiphase flow.

Aiming to improve the existing limitations in solid particle detection of a liquid–solid system, a novel & non-intrusion vibration sensor approach was explored for sand particle characteristic measurements in water–oil multiphase flow, and its evaluation test was conducted indoor in this work. As one key aspect, the fundamental principle of solid phase detection in multiphase flow mentioned in this article was to receive sand vibration signal through a non-intrusive immediate special wideband vibration sensor which was installed on the wall. The vibration sensor can obtain different sand concentrations and size information in multiphase flow which consisted of water and crude oil as dispersion medium. As another key aspect, according to the relationship between the vibration power and the velocity of particles in Eq. (2), a special auxiliary measurement instrument was designed to amplify signals generated by the low concentration of particles. Meanwhile, characteristic sand frequency band signal processing methods such as STFT analysis (Eq. 3), band-pass filter (Eq. 4), and Savitzky–Golay smooth analysis (Eq. 5) were used to minimize the interference of background noise. Firstly, the theory of vibration measurement technique and the real-time signal analysis method were described in Section 2. Secondly, the setup of the applied measurement systems and the design of impact parts which can amplify sand signal were explained in Section 3. The experimental simulation and measurement results were subsequently discussed in Section 4. Finally, the important conclusion was drawn in Section 5.

2. Vibration measurement principles

In the process of fluid transmission, gravel-carrying multiphase flow produces a certain kinetic energy. When the sand with high speed is blocked by the surface of the pipeline, the vibration signal is generated by sands impacting on obstacle. Sand does work for obstacles and the impact of kinetic energy will be converted to the strength of the vibration. At the same time, a highly sensitive piezoelectric wafer inside a sensor will be deformed due to the effect of inertial force. On the surface of the conductive pole, the piezoelectric effect of piezoelectric crystal causes electric charge, and then results in vibration.

The production of sand impacting vibration can be decomposed into an additive process which consists of lots of balls and their impacts on an infinite great plate. According to Hertz's collision theory [15], the frequency of sand signals is generated by the collision between rigid balls and plate impact and the frequency reads:

$$f = u/2.94\left[\frac{5}{4}\mu_1^2\left(\frac{1-\mu_1^2}{M_1}+\frac{1-\mu_2^2}{M_2}\right)\rho_S\right]^{\frac{2}{5}} \quad (1)$$

the constant u indicates the relative vertical movement velocity of the balls with the plate; μ_1 and μ_2 are the Poisson ratio of the plate and the balls respectively; M_1 and M_2 are the elasticity modulus of the plate and the balls respectively. Vibration power T reads:

$$T = \int_0^a \frac{1}{2} h\rho_1 2\pi\omega^2 dR \quad (2)$$

the relationship of T, radius of volatility (a), distance from the origin (R), and transverse velocity (ω) is shown in Eq. (2), where ρ_1 and h are density and thickness of the pipeline respectively. Speed and radius of sand are the only variables by presenting experimental, and the vibration power increases with the increased particle mass concentration.

The vibration signals are further transformed to electrical signal and then delivered to computer system after amplification and smoothing. P.T. Liu and his team [16] have found the characteristic frequency band of sand in the following experimental facility, ranging from 10 to 15 kHz. There is a slightly different frequency band between continuous oil flow vibration signal and intermittent sand impacting vibration signal. In order to vary the sand and liquid flow signals, short-time Fourier transform (STFT) and frequency domain are selected to obtain the solid impacting information in a complex multiphase flow with heavy noise. The STFT provides a 2-D time–frequency domain for the variation of all frequencies contained in the vibration signal, and the magnitude of STFT on the vibration signal y(t), is defined as [17] mentioned:

$$TF(t, f) = \left|\int_{-\infty}^{+\infty} y(\tau)h*(\tau-t)e^{-i2\pi f\tau}d\tau\right| \quad (3)$$

where h (t) is a short-time analysis window centered at t = 0. The width of h (t) should be large enough to achieve a high frequency resolution on the time–frequency distribution, which can distinguish the adjacent frequencies from each other. The STFT reflects the energy distribution on the time–frequency plane.

A digital filter is selected as a filter type to monitor signal, that is, a difference equation consists of time domain signal input and output sequence. The transfer function of digital filter system reads:

$$H(z) = \sum\nolimits_0^M a_{1k}z^{-k}/(1+\sum\nolimits_{k=1}^N b_{1k}z^{-k}) \quad (4)$$

with N as filter order; M as the number of zero for the filter transfer function; and a_{1k} and b_{1k} as coefficients of weight function.

Vibration power spectra corresponding to oil–water flow versus oil–water–sand flow for different parameters is helpful to understand the results of sand detection [18]. Furthermore, Savitzky–Golay filter is selected to increase the signal-to-noise ratio without greatly distorting the signal. It is defined as follows:

$$y_j = \sum\nolimits_{i=-(m-1)/2}^{i=(m-1)/2} C_i y_{j+i} \quad \frac{m+1}{2} \le j \le n-\frac{m-1}{2} \quad (5)$$

the data consists of a set of n {x_j, y_j} points (j = 1,...,n), where x_j is an independent variable and y_j is an observed value. They are treated with a set of m convolution coefficients, C_i according to the expression.

3. Experimental setup and measurement techniques

3.1. Experimental realization

The system of solid detection in oil–water–sand multiphase flow mainly consists of impact parts, a data acquisition machine, signal processing software, a stirred tank, a pipeline and so on. Specifically, the system selects a screw pump with a maximum capacity of 12 m^3/h to enhance the circulation ability, as the screw pump possesses the advantages of smooth flow, transmission medium without forming eddy current, strong resistance to pollution, not sensitive to medium viscosity and so on [19–21]. A schematic diagram of test facility is shown in Fig. 1. The test facility was constructed of 304 stainless steel pipes of 25 mm in internal diameter and 10 m in total pipe length. A Perspex bend window with the same curvature as test section was inserted into the detachable impact parts for observation. The test section was positioned about 4 m downstream of the screw pump, and the flow was considered to be fully developed by the time it reached this section. The volume of every storage tank was 90 L to ensure a steady circulating system. The left tank was used for repeating the cyclic process, in particular, the left tank and pipeline form a loop in order to repeat the tank of oil–water–sand mixture egress and ingress. The right tank was used for single circulation, specifically, the right tank and left tank form a circuit in order to singly cycle the tank of oil–water–sand mixture. Oil–water flow and sand were firstly whipped into a mixture until smooth, and then whipped into the pipeline regardless of circulating mode. Vibration signals were collected by a vibration sensor installed on the wall. To ensure

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