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Vibration sensor approaches for the sand detection in gas–sand two phases flow

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ABSTRACT

The real-time measurement of solid phase in gas–sand flow is significant in the process of industrial production, especially for the economic benefit of natural gas production. Aiming to improve the existing limitations in solid particle detection of a gas conveying system, a vibration detection device for gas–solid flow has been developed and its evaluation test is conducted indoor. This paper illustrates the application of special wideband vibration sensor and sand mass flow computing method to monitor gas–sand flow in pipeline. In this work, a real-time computational formula for sand mass flow rate was firstly proposed. Both of the gas background noise reduction and the calibrated reference sand signals were considered in this formula. Besides, time–frequency analysis and characteristic sand frequency band digital filter methods were proposed to enhance the ability of sand detection in heavy gas flow background noise. The experimental investigation considered gas–sand flow both with sand content ranging from 0.0156 vol.‰ to 0.1 vol.‰ and sand size ranging from 45 μm to 180 μm. The results showed that there was a good correlation (less than ±8% uncertainties) between vibration energy and sand mass flow rate. Accordingly, the vibration technology provides a method for the detection of tiny particle size and dilute solid phase in solid–gas system, which lays the foundation for the quantitative particles detection in more complex multiphase flow.

1. Introduction

The transport of sand solid in a gas flow has widely influenced many areas of industry, such as oil and gas industries, coal-fired power plants, the chemical industry and pollution control [1–2]. The real-time monitoring of sand mass flow rate with different velocities and sizes are crucial in improving product quality and optimizing production efficiency [3]. Particularly, in natural gas production, the sand production rate is closely related to gas production capacity. In addition, the sand particles in pipeline could lead to safety hazards for production and transportation systems and eventually bring substantial economic risks [4]. As a result, it is valuable to obtain solid phase features effectively in real-time.

In the process of industrial production, a non-invasive and efficient method for monitoring the flow of sand particles in pipelines has been recognized as the challenge by researchers all over the world. Over the years, a number of sensor techniques have been developed and proposed to meet some of these difficult challenges. For example, Azzopardi B. J et al. [5] monitored the flow rate of solid-phase coal particle in pipeline by expensive twin plane electrical capacitance tomography (ECT) system, where particles were transported in a gas flow. Xu C.L. et al. [6] 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. Despite of their availabilities, these particle detection approaches were relatively expensive or difficult to install and maintain. Hii. N.C et al. [7] measured particle characteristics in gas–solid two-phase flow by acoustic emission technology. Guo M et al. [8] obtained the size distribution of particles in a gas–solid two-phase flow through acoustic sensing and advanced signal analysis. While, the sand mass flow rates monitored by both of them are above 1 g/s. On the other hand, vibration measurement has already been widely applied in gas–solid flow production and process control [9–11]. For example, Briongos J.V. et al. [12] researched on the theory of flow-induced vibration in fluidized beds and the vibration theory, which applied to the measured pressure fluctuations. Abbasia. M et al. [13] studied the bubble behavior by analysis of vibration signals in fluidized beds. Among these measuring of gas–solid two-phase flow, vibration method was mainly applied to gas–solid fluidized beds where the volume fraction of solid phase was above 0.01% of the pipe volume in general [14–16].

From the open literature, in a gas flow or pneumatic conveying system, most of the experimental and theoretical works have focused on solid detection with high volume fraction, while solid detection with

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low concentration (0.0156 vol.‰) and small particle size (45 μm) has been rarely reported. Non-intrusion vibration sensor approaches for the monitoring of trace amounts of particle mass flow rate in gas flow, particularly for the research of corresponding solid mass flow rate on line computational method have not been undertaken yet.

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 weak sand signals may not be successfully obtained by particles detection sensor. Furthermore, the gas flow background noise could also increase the measurement uncertainty [17]. Consequently, how to obtain sand characteristic signal in relatively low concentrations without most of the flow background noise is a key issue to solve for the detection of solid phase in multiphase flow.

Aiming to improve the existing limitations in dilute solid phase detection of a gas–solid system, a novel & non-intrusion vibration sensor approach was explored for sand particle characteristic measurements in gas flow, and its evaluation test was conducted indoor in this work. As one key aspect, the special wideband vibration sensor was used, and the sand characteristic frequency was obtained by short-time Fourier transform (STFT) and time domain analytical methods. Besides, band-pass filter was used to minimize the interference of background noise. As the other key aspect, a real-time sand mass flow rate computing method was proposed. The sand signal was superimposed on the gas flow background, which resulted in a real time gas flow output signal required for quantifying sand. Besides, the effect of particle sizes was also considered and a calibrated reference sand signal was used to adjust the monitored flow rate results.

2. Vibration measurement principles

In the process of solid–gas two phases flow transmission, particle-gas conveying flow produces a certain kinetic energy. In the bend, when the flow direction changes, sand's inertia causes it to deviate from the streamlines of the carrying flow, resulting in particle impingement on the walls of the pipe. Sand does work for obstacles and the energy is converted to vibration energy traveling within the pipe wall. At the same time, the vibration is picked up by the highly sensitive piezoelectric wafer inside the sensor and converted into electric charge signal.

The kinetic energy (KE) [18] of a particle of mass m that is moving with velocity v is given by:

$$\mathrm{KE} = \frac{1}{2} \cdot m \cdot v^2 \tag{1}$$

From the Eq. (1), it is clear that the generated total vibration energy depends on particle velocity (v), particle weight (m) (size) and the number of particles per second colliding with the pipe wall.

The electric charge signals are further delivered to signal processing work system after amplification and denoising. In order to vary the slightly different frequency band between weak sand and strong gas flow impacting, the sand characteristic frequency band in sand–gas flow signals is processed by short-time Fourier transform (STFT) and time domain analytical methods. 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 [19] mentioned:

$$\mathrm{TF}(t, f) = \left| \int_{-\infty}^{+\infty} y(\tau) h * (\tau - t) e^{-i2\pi f\tau} d\tau \right| \tag{2}$$

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.

Digital filter is chosen as filter type for obtain optimal sand signals, that is, a difference equation [20] consists of time domain signal input and output sequence. The transfer function of digital filter system reads:

$$H(z) = \sum_0^M a_{1k} z^{-k} \Big/ \left(1 + \sum_{k=1}^N b_{1k} z^{-k}\right) \tag{3}$$

where N is the filter order; M is the number of zero for the filter transfer function; a_{1k} and b_{1k} are coefficient of weight function.

During the process of sand detection in gas–solid flow, the sand mass flow rate is used to reveal the result of solid flow monitoring and evaluation. The vibration kinetic energy of gas–sand two phase flow is accumulated within per second. The charge signal amplitude of sensor proportional to vibration kinetic energy is converted, according to the feature of output charge signals which are proportional to input force [21]. Therefore, corresponding gas–sand flow mass rate trend is obtained, and this parameter is described by vibration energy (VE) in Eq. (5). In order to reduce the interference of gas flow back ground noise G(v) (Eq. (6)), the system should subtract the gas flow background noise from the overall vibration signals within sand characteristic frequency band. For quantitative and accurate sand measurement, this delta vibration energy is converted to sand mass flow rate by division with a calibrated reference sand signal. The calibrated reference sand signal is calculated based on gravitational force in funnel (Experiment-1), and the particle size and the sand impact velocity are also considered. The reference sand noise vibration energy S(v,p) (Eq. (7)) is calculated under the sand mass rate of 1 g/s. The dimension calibration factor for Eq. (4) is 1 and it is simplified in this paper. Finally, the final real-time sand mass flow rate (g/s) computational formula is obtained:

$$\text{Sand mass flow rate} = \frac{\mathrm{VE} - G(v)}{1000\, v / \left[p \cdot S(v, p) \,|_{1\ g/s} \right]} \tag{4}$$

VE is the overall vibration energy($(mv)^2$), G(v)is the vibration energy of gas background noise, p is the sand size (m), v is the current flow velocity (m/s), and S(v,p) $|_{1\ g/s}$ is the sand noise vibration energy ($(mv)^2$) for 1 g/s sand rate injecting. All the above specific definition of parameters is shown below:

$$\text{Vibration energy (VE)} = \frac{1}{T} \int_0^T V^2(t)\, dt \tag{5}$$

where V (t) is the time dependent voltage signals (millivolt/mv) from the sensor, and T is the duration of the sampling period (second). Eq. (5) describes the vibration energy ($(mv)^2$) of sand–gas flow by vibration sensor approaches.

In addition to the major factor of flow velocity, gas background noise is also influenced by parameters such as pressure, temperature, pipeline material/dimension/configuration and mounting. Targeting good accuracy, it is essential to calibrate the background noise on site for each measurement. The polynomial is used to reveal the relationship between vibration energy and current gas background noise as approximate function. In this polynomial, the increasing order of polynomial will increase the computational error and affect instabilities of computations, so that three-order is specially considered [22].

$$\text{Gas background noise } G(v) = C \cdot v^3 + D \cdot v^2 + E \cdot v + F \tag{6}$$

where C, D, E, F are the background noise polynomial coefficients, and v is the current conveying gas flow velocity (m/s). This function represents gas noise vibration energy ($(mv)^2$), which is defined for a sensor installation by measuring background noise at a range of current gas