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Can low frequency accelerometry replace pressure measurements for monitoring gas-solid fluidized beds?

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A B S T R A C T

This paper is addressed to introduce a methodology based on low frequency accelerometry that can be used for gas-solid fluidized bed monitoring, and for dynamic diagnosis purposes. The proposed methodology consists on extracting the low frequency information encoded within an accelerometry signal, by means of the Hilbert transform method. The time and the frequency domain analysis show how this low frequency information is directly related to the conventional pressure fluctuation measurements, providing useful information on bulk and bubble dynamics. The cross-correlation and the coherence function analysis between the pressure and the envelope process of the measured accelerometer signals "E", exhibit values approaching unity for frequencies ranging between 2 and 4 Hz. This reveals that pressure signals and accelerometry envelope are related processes. The results from the Coherent Output Power, COP, and the Incoherent Output Power, IOP, analysis confirms that both pressure and envelope time series exhibit the same global and local features open the possibility of using low frequency accelerometers instead of conventional pressure transducers for monitoring and for dynamic diagnosis purposes.

1. Introduction

The monitoring of gas-solid fluidized beds (FB) has been an important issue since they were first used in industry. As the dynamical behaviour characterizing those systems is complex, it is necessary to monitor different bed properties continuously. As an example of that dynamical complexity, it has been shown that, depending on the operational condition, FB can exhibit dynamical chaotic features (Daw et al., 1990; Schouten and van den Bleek, 1992), which can be used, for instance, to predict malfunctioning (van Ommen et al., 2000, 2004).

During the past, a large research effort has been directed towards developing measurement techniques aimed to get knowledge on the dynamic phenomena that take place within the bed (Werther, 1999; Yates and Simons, 1994); some examples are the capacity and the inductance measurements (Brereton and Grace, 1993; Louge and Opie, 1990), techniques based on optic fiber probes (Amos et al., 1996; Zhang et al., 1998), and laser based measurements (Briongos and Guardiola, 2003; Solimene et al., 2007). However, among those techniques, the pressure fluctuations measurements remain as the most used technique (Johnsson et al., 2000; Sasic et al., 2007). The success of the pressure monitoring is explained by its low-cost and the direct relation that exists between the property measured and the bed dynamics. Moreover, from pressure measurements sampled at relatively low frequency it is possible to extract useful information about the bulk, bubble and wave dynamics (van der Schaaf et al., 2002). Therefore, both the quality and the quantity of the low frequency information contained in the pressure signal make this technique the most used to monitor the bed dynamics. Nevertheless, it has several great disadvantages that compromise its applicability to industrial installations: on one hand, the measurement of pressure fluctuation is a local technique, thus it has been reported that the dynamic measured can be affected by different factors such as the pressure probe itself or by the probe length (van Ommen et al., 1999), moreover, some other additional measurement problems might appear such as solid probe blockage. On the other hand, invasive features should be considered, since it is necessary to perforate the vessel in order to introduce the pressure probes inside the bed, limiting applications under severe, corrosive and high pressure/temperature conditions, and pressure probes can represent an obstacle for the free development of bubbles and solid motion.

According to that, the need for non-invasive measurement methods is clear, which in principle will offer several advantages with respect to the invasive methods. Thus, because they are located outside the vessel, they neither suffer the harsh operating conditions inside the bed nor do they interfere with the bed

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dynamics. Nevertheless, the application of these methods in industrial fluidized beds is still an unresolved matter; some factors such as the large size of industrial facilities becomes a big challenge for reported non-invasive measurement techniques such as tomography, ECT.

During the last decade, the need for non-invasive techniques led to the development of acoustic monitoring methods, which are based on microphone/hydrophone and accelerometer measurements (Boyd and Varley, 2001). Those acoustic techniques are later applied as active or as passive methods (Cents et al., 2004; Herrera et al., 2002; Boyd and Varley, 2002). With regard to the passive acoustic emission in which the signal collected is created by the fluidizing process itself, acoustics measurements have been reported by either placing the sensor inside (Zukowski, 2001) or outside the vessel (Briongos et al., 2006b; Cody et al., 1996; Finney et al., 1998). In spite of the initial advantages of the external acoustic measurements (non-invasive and low implementation cost), they present some problems. Thus, the measured signal is very complex, and it can be strongly influenced by factors such as the background noise, secondary mechanical vibrations and the vessel response. Moreover, working at ultrasonic measurement ranges is frequently used to avoid noise. Nevertheless, this would lead to high computational costs due to the great number of data in each sample. For this reason, most of the published papers have used data analysis based on averaged properties, which have been mainly attributed to particle dynamics (Cody et al., 1996; Tsujimoto et al., 2000).

To the best of the authors' knowledge, there are few works in literature that use advanced techniques over external passive acoustic signals for getting low frequency information (Briongos et al., 2006b; Finney et al., 1998). Besides, those previous works deal with the unwanted slugging regime. Consequently, the challenge of finding a low-cost, non-invasive methodology that can replace the conventional pressure measurements is still open.

This paper is addressed to introduce a methodology based on low frequency accelerometry that fulfils the challenge. The proposed methodology consists on extracting the low frequency information encoded within an accelerometry signal, by analyzing the envelope process of the measured accelerometer signal. This low frequency information is shown to be directly related with the conventional pressure fluctuation measurements and consequently, it provides useful information on bulk and bubble dynamics that can be used for monitoring and dynamic diagnosis purposes.

2. Accelerometry fundamentals

The mechanical vibration can be seen as an oscillation motion about a reference position. Moreover, it is well known that the oscillatory motion can originate waves and *viceversa*. In that way, the vibration measurement has information on the physical phenomena behind the oscillating motion. Thus, in order to understand how the information is encoded, let us consider as first approximation the simpler case, where a physical phenomena originates a wave that leads to a periodic oscillating motion, in that case the movement can be described by the harmonic motion as sinusoids. Moreover, the wave theory also establishes that different waves can couple to generate a phenomenon known as beats where the information of forming waves is encoded.

In order to characterize the mechanical vibration, it is necessary to measure such an oscillatory motion where both the amplitude and frequency information are encoded. In principle, it should not matter whether the displacement, velocity or acceleration parameters are measured when studying mechanical vibration, since all three quantities are related by integration or differentiation. However, the physical nature of vibrations sources and the characteristics of the transducers used for measuring, make one parameter preferred over the others. Thus, it is well known that displacement measurements are suitable when a wide-band signal is expected and the low-frequency component has to be studied, whereas acceleration, which gives most weight to high-frequency components is applied for high frequency studies (Gatti and Ferrari, 1999). However, the accelerometers are most commonly used in practice because of their versatility, small dimensions, wide frequency and dynamic operational ranges, availability and low price. Up to now, the limiting parameter for applying accelerometry to study low frequency phenomena has been the unfavourable signal-to-noise ratio that characterizes the low frequencies components of the conventional measured accelerometer signals, which used to have poor low-frequency response characteristics.

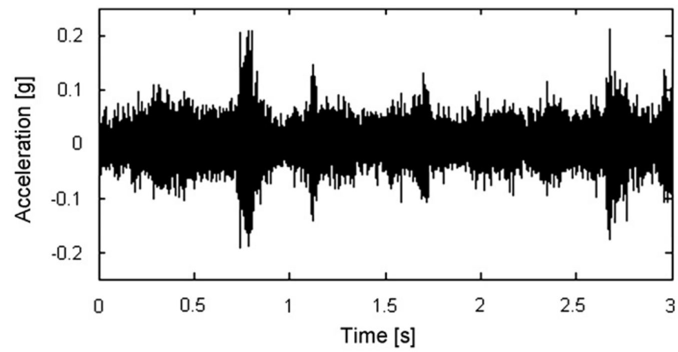

Fig. 1. Experimental accelerometry signal in a FB.

In contrast to conventional accelerometers, in this work, the mechanical vibrations of a FB, are measured with accelerometers with high sensitivity ($\sim$995 mV/g), which allow to study the low frequency information encoded within the measured signal. An example of the measured accelerometry signal is shown in Fig. 1, where the beat phenomena characterizing narrow band signals can be observed.

As stated above, it is well known that, in order to extract the low frequency information of the phenomena behind the measured signal, it is not suitable to use the direct accelerometry signal (Harris and Piersol, 2002). According to that, for extracting the low frequency information, it is a common practice to integrate the power of the signal with a moving root mean square, rms (Norton, 1989). That operation returns the envelope process associated to the signal. Consequently, similar information can be obtained with other techniques such as the Hilbert transform method or the use of nonlinear energy operators (Huang et al., 2009).

Since most of the dynamical phenomena characterizing FB dynamics such as bubble, and bulk dynamics take place at relatively low frequency (generally below 20 Hz), this paper focuses on the low frequency information stored within the acceleration signals by using the Hilbert transform method to extract the low frequency information. Furthermore, the time and frequency domain analysis are applied to compare the similarity between the pressure and the envelope acceleration, "E", signals recovered through the Hilbert transform methodology,

3. Analysis methods

3.1. Frequency domain

The frequency domain analysis has been widely applied to characterize fluidization regimes (Satija and Fan, 1985; Zijerveld