Signal Analysis of Electrostatic Gas-Solid Two-Phase Flow Probe with Hilbert-Huang Transform

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Abstract *- Ring-shaped electrostatic gas-solid two-phase flow probe can provide mechanical parameters of the pneumatically transported powders, and has been used for measuring and controlling the pulverized coal flow distribution among conveyors leading to burners in coal-fired power stations. But the signal obtained from the probe demonstrates strongly non-linear characteristic. In this paper, efforts had been paid to investigate the signal by means of Hilbert-Huang transform, including the empirical mode decomposition (EMD) and Hilbert spectral analysis(HAS) on the signal of the probe. The EMD results unveiled that low-frequency oscillation existed and its amplitude was non-decayed. HAS interpreted the EMD results by time-frequency joint analysis and described the instantaneous behavior of gas-solid two-phase flow.*

Key words *- electrostatic; gas-solid two-phase flow; Hilbert-Huang transform*

I. INTRODUCTION

In coal-fired power station, normally coal is pulverized and pneumatically conveyed to burners. A common and well-documented phenomenon in pneumatic transport is that the movement of convoyed solids in a pneumatic pipeline generates electrostatic charge. Many different varieties of non-intrusive measurement method based on the phenomenon of electrostatic induction had been specially developed to measure the electric charge carried on solid particles in pipes of pneumatic transport, as well as to indirectly evaluate, determine, or estimate the following mechanical parameters of the two-phase gas–solid flows: mass flow rate, concentration, volume loading, and velocity. Incidentally, only one variety of method exists, which had been extensively developed, modified, described mathematically, and applied to practical laboratory and industrial installations. It is the one in which a ring-shaped metal electrode (probe, sensor, etc.) is used on which electric charge is induced when exposed to the electric field of a single charged particle or a flux of charged particles as, e.g., in a pipe of pneumatic transport.[1]

The output voltage of the probe should be proportional to the net charge that flows within the sensing zone of the probe, and the effective value (RMS) should be proportional to the mean value of a particle charge that flows in a pipe when with well defined calibration system.[2]

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Normally, assume that the mean mass flow rate depends on the effective voltage value of the probe linearly. But with real gas-solid two-phase flow, the effective voltage value of the probe is a stochastic process [3], the relationships between flow parameters and the signal are nonlinear and rather complex [4]. Traditional analysis method, such as FFT, short-time FFT, Wagner-Ville distribution and wavelets, can't provide clear result of the signal features. Here Hilbert-Huang transform is adopted and applied to the effective voltage value of the probe. This effort aimed to provide a novel way to investigate the signal of gas-solid two-phase flow.

II. HILBERT-HUANG TRANSFORM

Huang et al. [5] introduced a general signal-analysis technique to efficiently extract the information in both time and frequency domains directly from the data, called Hilbert-Huang Transform (HHT). It is a two-step algorithm, combining empirical mode decomposition (EMD) and Hilbert spectral analysis, to accommodate the nonlinear and non-stationary processes. This method is not based on a priori selection of kernel functions, but instead it decomposes the signal into intrinsic oscillation modes (represented by intrinsic mode functions (IMF)) derived from the succession of extrema. It is adaptive, efficient and without any prior assumptions.

The EMD of a one-dimensional dataset z(k) given on a sequence of points {k} is obtained using the following procedure[6].

(i) Set $r_0(k)=z(k)$ and set i=1.

(ii) Identify all of the extrema (maxima and minima) in $r_{i-1}(k)$.

(iii) Compute a maximal envelope, $\max_{i-1}(k)$, by interpolating between the maxima found in step (ii). Similarly compute the minimal envelope, $\min_{i-1}(k)$.

(iv) Compute the mean value function $m_{i-1}(k)$ of the maximal and minimal envelopes

$$m_{i-1} = \frac{[\max_{i-1}(k) + \min_{i-1}(k)]}{2} \tag{1}$$

(v) The estimate of the IMF is computed from $c_i(k)=r_{i-1}(k)-m_{i-1}(k)$.

(vi) Each IMF is supposed to oscillate about a zero mean and in practice it is necessary to perform a 'sifting' process by iterating steps (ii)–(v) (setting $r_{i-1}=$

c_i before each iteration) until this is achieved. Successive IMFs will typically exhibit longer mean periodicities than their predecessors.

(vii) Once it is found that the c_i has a mean value that is sufficiently close to zero over all k (defined by a stopping criterion within some predefined tolerance ε), the residual $r_i(k)=r_{i-1}(k)- c_i(k)$ is computed.

(viii) If the residual $r_i(k)$ is a constant, a trend or has no more than three extrema, then stop; else increment i and return to step (ii).

Certainly, the following equation should be true,

$$z(k)=\sum_{i=1}^{n} c_i(k)+r_i(k) \tag{2}$$

Once IMF components are obtained, Hilbert transform can be applied to each component to get the amplitudes, and meanwhile the instantaneous frequency is calculated using equation (7).

$$H[c_i(t)]=\frac{1}{\pi}P\int_{-\infty}^{\infty}\frac{c_i(t')}{t-t'}dt' \tag{3}$$

where P indicates the Cauchy principal value. It is the convolution of $c_i(t)$ with 1/t; hence, the transform emphasizes the local properties of $c_i(t)$. $c_i(t)$ and $H[c_i(t)]$ form the complex conjugate pair by definition, so the analytical signal for the IMF can be gotten through equation (4) - (6):

$$z_i(t)=c_i(t)+jH[c_i(t)]=a(t)e^{j\varphi(t)} \tag{4}$$

$$a(t)=\sqrt{c_i^2(t)+H^2[c_i(t)]} \tag{5}$$

$$\phi(t)=\arctan\{H[c_i(t)]/c_i(t)\} \tag{6}$$

Where *a*(t) denotes the instantaneous amplitude or energy, and $\phi(t)$ is the instantaneous phase, its derivation is the instantaneous frequency

$$\omega(t)=d\phi/dt \tag{7}$$

At a given time t, the instantaneous frequency ω and the amplitude *a*(t) are calculated simultaneously so that these values are assigned to Hilbert spectrum, $H(\omega,t)$.

The marginal Hilbert spectrum is a measure of total energy contribution from each frequency over the entire data span in a probabilistic sense. It provides a quantitative way to describe the time-frequency-energy representation by integrating the Hilbert spectrum over the entire time span,

$$h(\omega)=\int_0^T H(\omega,t)dt \tag{8}$$

where T is the total data length.

Data was collected from the test rig of pneumatic conveyor at the University of Teesside. A diagram of the test rig is shown in Fig.1 and is based on the suction principle. The solids discharges into the test rig via the screw feeder and the solids mass flow rate into the rig is determined from the 'rate-of-loss' of weight. The air mass flow rate is obtained using an orifice plate located downstream of the cyclone i.e. in its exhaust.

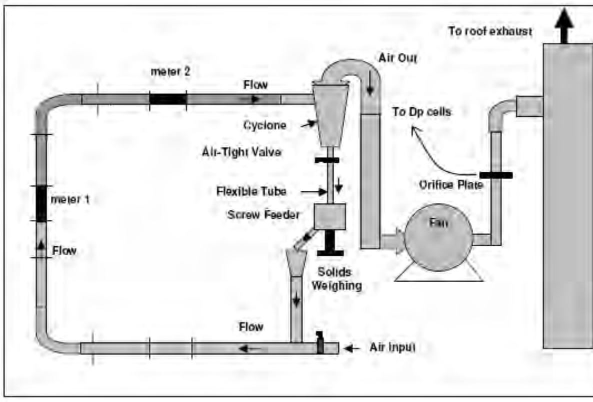

Fig.1. Pneumatic conveyor at the University of Teesside

Ⅲ. EXPERIMENT SETUP

The material used for the experiments was 'Fillite'. The average particle size was about 100μm. The maximum solids mass flow rate was over 50kg/hr.

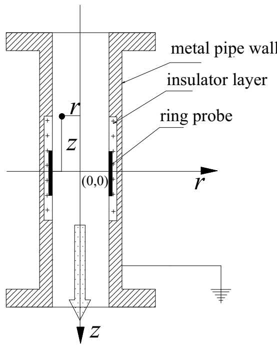

Fig. 2. Sectional View of ring-shaped electrostatic Sensor

The meter 2 is a Ring-shaped electrostatic gas-solid two-phase flow probe, which comprises of a short spool piece and a ring electrode (probe) with the surrounding insulator (Fig. 2). The ring electrode is mounted flush with the inner pipe wall offering non-intrusive measurement. Usually the metal pipe is earthed so that it acts as the electrostatic screen and also as the signal reference (signal ground) of the conditioning circuit input. Its output signal was sampled and RMS value was calculated and recorded in each second.

The experiment lasted 540 seconds, and the air speed was changed three times during the experiment. Fig. 3 shows the air velocity, signal RMS and solid mass. Left side y-axis scales air velocity and signal RMS, Right side y-axis scales solid mass (loss-of-weight).

FFT spectrum (Fig. 4) of the signal RMS value indicated some low frequency components existed but couldn't tell the details.

EMD results of the effective voltage value of the probe are given in Fig. 7. Based on the IMFs from EMD, Hilbert transfer is applied to all IMFs, and the result is showed in Fig. 5.

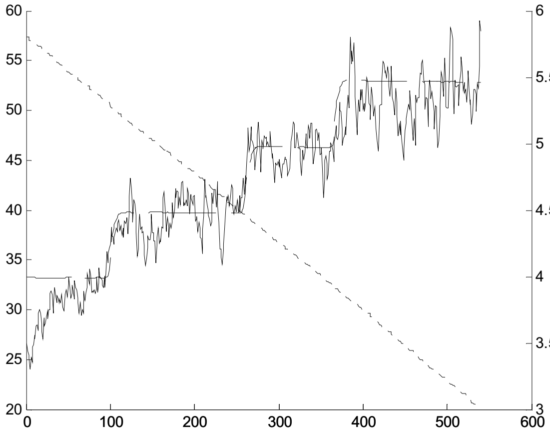

Fig.3. air velocity (--), signal RMS (-) and solid mass (…)

IV. RESULTS

Results from EMD and Hilbert-Huang spectrum clearly indicated that IMF5 and IMF6 contained low frequency oscillation and the oscillation was independent of the air speed and non-decayed. IMF6 reflected the three times changing of air speed. In IMF2, IMF3 and IMF4, short oscillations with large amplitude indicated the position of air speed changing. After the short oscillations, oscillations become stable with its amplitude proportional to airspeed.

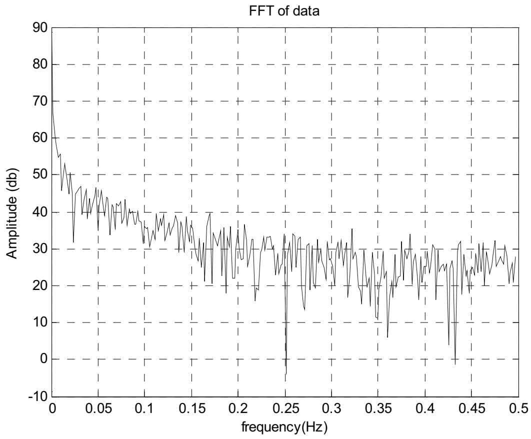

Fig .4. FFT spectrum of RMS value

In general, each flow of solid particles may be regarded as a mixture of an average flow and a superimposed, smaller, and irregular flow. The latter has been termed “flow noise”. With the EMD, the mode of solid particles flow can be represented by IMFs. Combining with Hilbert-Huang spectrum of IMFs, the flow can be investigated in time-frequency domain efficiently, not only an overall average value could be estimated from the probe output, but also the dynamic behavior could be described in time -frequency-energy. This could be a useful tool to analyses the roles of many facts which influence charging and discharging of the solid particle in flow, and to help understanding the principal of the probe in details.

Comparing with FFT spectrum, marginal Hilbert spectrum could more clearly show the possibility that the frequency components exist in the probe output.

An interest phenomenon can be seen from the Hilbert-Huang spectrum. Each time the air speed was increased (nearby 100,250,400 seconds), frequencies in IMF 2, IMF and IMF4 dropped down during transition and climbed up after transition. In normal sense, the frequency should be increased during the transition to reflect the disturbance of the flow. But Hilbert-Huang spectrum gives a contrary answer.

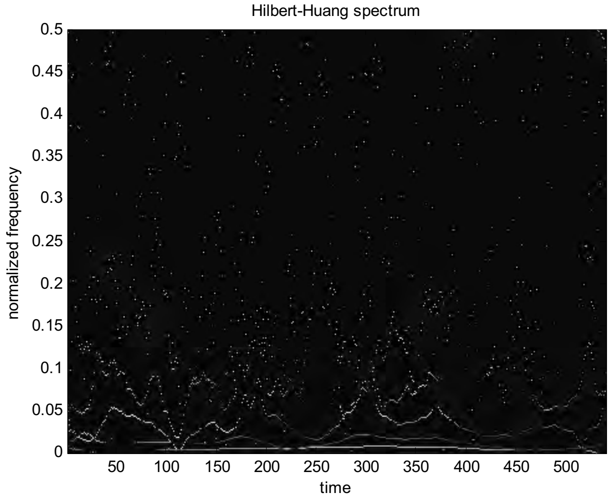

Fig.5. Hilbert-huang spectrum of IMFs

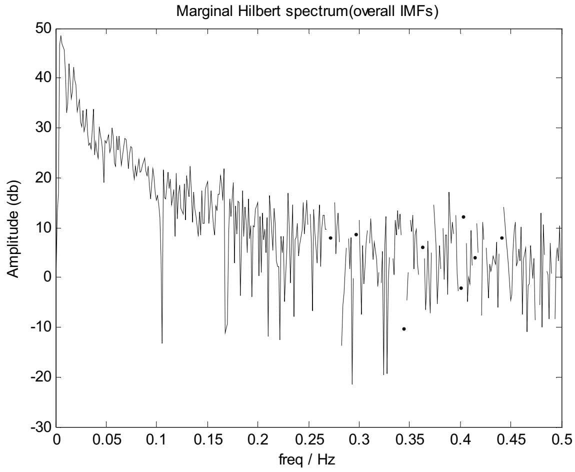

Fig.6. Marginal Hilbert spectrum of IMFs

V. CONCLUSION

In this paper, Hilbert-Huang transform including EMD, Hilbert-Huang spectrum and marginal Hilbert spectrum, had been applied to the RMS value of the output of Ring-shaped electrostatic gas-solid two-phase flow probe. By Hilbert-Huang transform, signal structure and the instantaneous behavior of gas-solid two-phase flow probe can be investigated in detail in time-frequency domain. The result showed Hilbert-Huang transform could be a useful tool for researching the charging and discharging process of gas-solid two-phase flow. More future work should be done based on this method so the features of the stochastic process of the probe signal can be described more precisely.

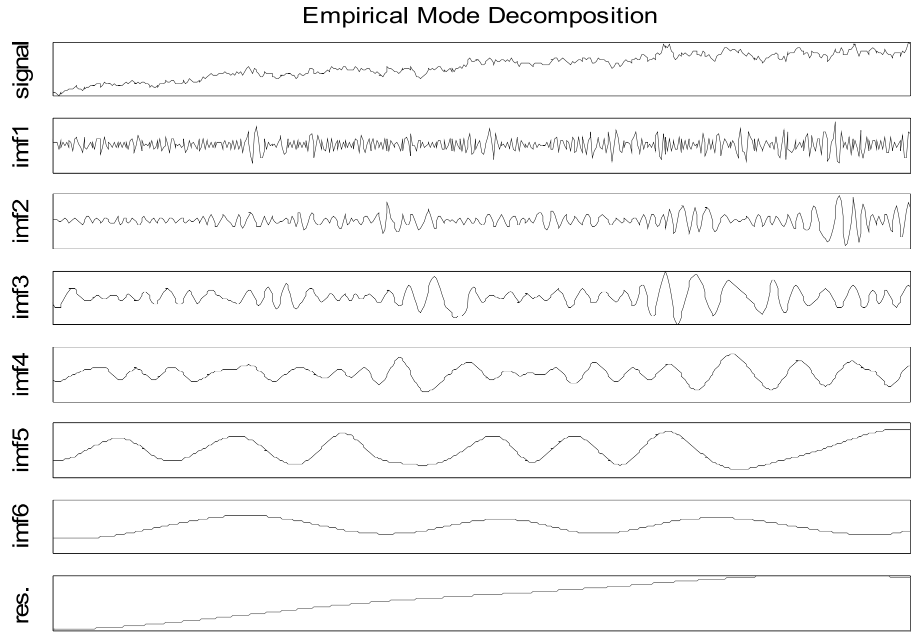

Fig. 7. IMF components of the probe signal

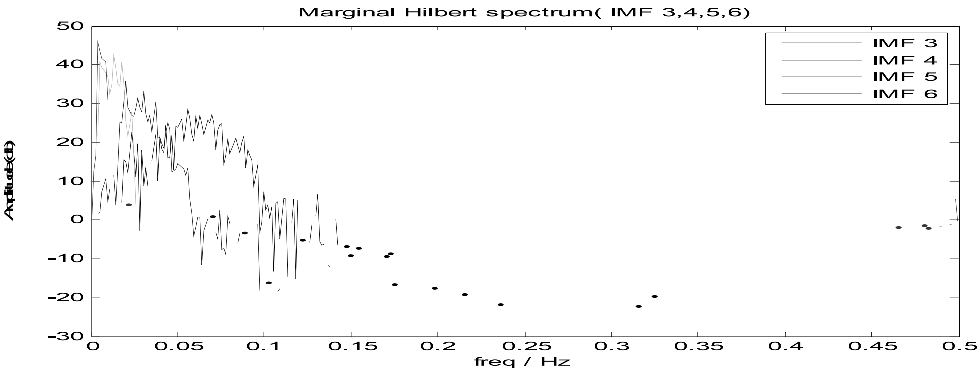

Fig.8. Marginal Hilbert spectrum of IMF 3,4,5,6

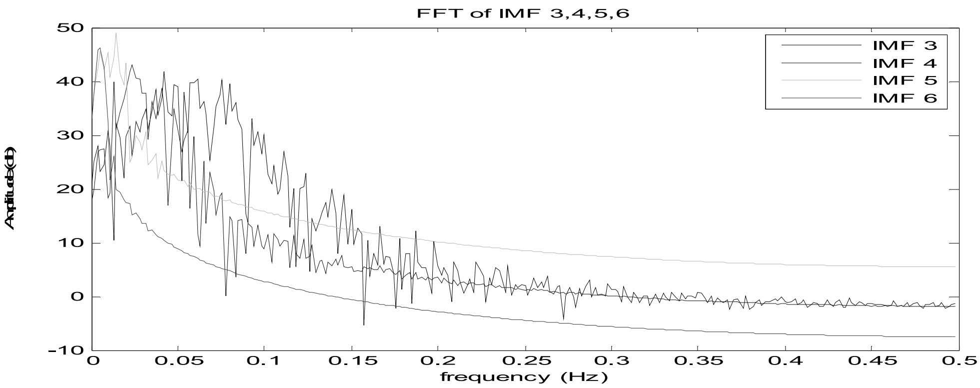

Fig.9. FFT of IMF 3,4,5,6

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