Magnitude and sign correlations in conductance fluctuations of horizontal oil water two-phase flow

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Abstract. In experiment we firstly define five typical horizontal oil-water flow patterns. Then we introduce an approach for analyzing signals by decomposing the original signals increment into magnitude and sign series and exploring their scaling properties. We characterize the nonlinear and linear properties of horizontal oil-water two-phase flow, which relate to magnitude and sign series respectively. We find that the joint distribution of different scaling exponents can effectively identify flow patterns, and the detrended fluctuation analysis (DFA) on magnitude and sign series can represent typical horizontal oil-water two-phase flow dynamics characteristics. The results indicate that the magnitude and sign decomposition method can be a helpful tool for characterizing complex dynamics of horizontal oil-water two-phase flow.

1. Introduction
Horizontal oil-water two-phase flow is a common phenomenon in oil well production and oil transportation. The behavior of oil-water two-phase flow under a wide range of flow conditions constitutes an outstanding interdisciplinary problem with significant applications to the industry. Understanding the dynamics of flow patterns is crucial for some important problems such as optimization of oil reservoir and management of oil well production. Due to the interplay among many complex factors such as fluid turbulence, phase interfacial interaction, and local relative movement between phases, horizontal oil-water two-phase flow exhibits highly irregular, random, and unsteady flow structure.

The early experimental investigations on horizontal oil-water two-phase flow patterns were mostly conducted in PMMA pipe of small diameter [1-2]. The flow pattern definition and classification are to a great extent subjective in the sense that flow pattern identification was mainly based on direct observations. In addition, no rules for flow pattern transitional boundary were proposed. Arirachakaran et al. [3] observed stratified flow, mixed flow, annular flow, intermittent flow and dispersed flow in a horizontal 25.1 mm-inner-diameter (ID) pipe. Trallero et al. [4] made a systemic experimental and model investigation for horizontal oil-water two-phase flow in a 50.8 mm-ID pipe and provided a new observation and definition for complex horizontal oil-water flow behavior, forming the widely acceptant flow pattern classification. Nädler and Mewes [5] made a detailed classification for horizontal oil-water two-phase flow in a 59mm-ID pipe and proposed two new flow patterns that were never described by the former researchers. Angeli and Hewitt [6-7] conducted horizontal oil-water two-phase flow experiments in non-corrosive steel pipe and acrylic pipe, and three
new stratified flow patterns were observed and defined. Now, it is generally acknowledged as the horizontal oil-water two-phase flow pattern definition proposed by Trallero et al. [4].

In the study of horizontal oil-water two-phase flow pattern identification, some progresses have been made in applying the nonlinear time analysis methods to the measured conductance fluctuation signals [8-9], however, there still exists the limitations in understanding their dynamical characteristics based on existing methods. Since the two-phase flow is a typical nonlinear system, characterizing horizontal oil-water two-phase flow from measured signals should be further explored and developed.

In recent years the detrended fluctuation analysis (DFA) method described by Peng et al. [10-11] has become a widely used technique for the detection of long-range correlation property in noisy, non-stationary time series. Ashkenazy et al. [12-13] proposed magnitude and sign decomposition analysis for analyzing heartbeat signals with long-range correlation. They concluded that the long-range correlations of magnitude series indicate nonlinear behavior and the sign time series mainly relate to linear properties of the original series. The time series analysis methods based on long-range correlation has been successfully applied to diverse fields such as DNA sequences [10-11], long-time weather records [14], geology [15], ethnology [16], physiological dynamics [17] and economics time series [18].

In this paper, we first measure the conductance probe fluctuating signals in a 20mm ID pipe, and the original signal can be decomposed into the magnitude and sign series. Then, the scaling exponents are respectively extracted by the detrended fluctuation analysis (DFA), and the nonlinear and liner properties of original time series are investigated. The results show that the combination of scaling exponents calculated from the magnitude and sign series cannot only identify the five water-dominant flow patterns, but also can fully characterize the fluid dynamics in the view of multi-scale.

2. Magnitude and sign decomposition method

Fluctuations in the dynamical output of physical and physiological systems can be characterized by their magnitude (absolute value) and their direction (sign). Here we perform detrended fluctuation analysis (DFA) [10] to find the correlations in the magnitude and sign sub-series.

The DFA procedure involves the following steps. The time series is integrated after subtracting the global average and then divided into windows of equal size \( n \). In each window the data are fitted with a least-square polynomial curve. Since we use a polynomial fit of order \( l \), we denote the algorithm as DFA-\( l \). The integrated time series is detrended by subtracting the local polynomial trend in each window. The root mean square fluctuation \( F(n) \) of the integrated and detrended time series is calculated for different window sizes; when \( F(n) \sim n^\alpha \), the two-point scaling exponent is \( \alpha \). If \( \alpha = 0.5 \), there is no correlation and the signal is uncorrelated. An \( \alpha \) greater than 0 and less than 0.5 indicates anti-correlated. If \( 0.5 < \alpha \leq 1 \), the signal is long-range correlated. The larger the value of \( \alpha \), the stronger the correlations. For \( \alpha \geq 1 \), correlation exists but cease to be of a power-law form.

The correlation analysis of magnitude and sign sub-series consists of the following step:

- Given the original signal \( s(i) \) we generate the increment series, \( \Delta s(i) = s(i+1) - s(i) \);
- We decompose the increment series into a magnitude series \( |\Delta s(i)| \) and a sign series \( \text{sgn}[\Delta s(i)] \). The positive sign (+1) represents a positive increment, while the negative sign (-1) represents a negative increment. And if \( |\Delta s(i)| = 0 \), we choose \( [\Delta s(i)] = 0 \);
- To avoid artificial trends we subtract from the magnitude and sign series their average;
- We then integrate both magnitude and sign series, because of limitations in the accuracy of the DFA method for estimating the scaling exponents of anti-correlated signals (\( \alpha < 0.5 \));
- We perform a scaling analysis using second-order detrended fluctuation analysis (DFA-2) on the integrated magnitude and sign series;
To obtain the scaling exponents for the magnitude and sign series, we measure the slope of $F(n)/n$ on a log-log plot, where $F(n)$ the root-mean-square fluctuation function is obtained by DFA-2 and $n$ is the scale.

3. Experimental facility and data acquisition
Horizontal oil-water two-phase flow experiments were carried out in multiphase flow laboratory of Tianjin University, details about the flow facility refer to our previous published paper [19]. Figure 1 indicates the scheme of the sensor system installed in the 20 mm-ID pipe. The experimental mediums are tap water and No.15 industry white oil with a viscosity of 11.987 mPa·s (40 °C) and a surface tension of 0.035 N/m. Oil and water superficial velocities are both in the range of 0.1~3 m/s.

Figure 1. Scheme of the sensor system installed in the 20 mm-ID pipe.

Based on the horizontal oil-water flow pattern classification proposed by Trallero et al. [4], we classify the horizontal oil-water flow patterns into segregated flow and dispersed flow, in which the segregated flow includes stratified flow (ST) and stratified flow with mixing at interface (ST&MI), the dispersed flow includes dispersion of oil in water and water flow (D O/W&W), dispersion of water in oil and oil in water flow (D W/O& D O/W), dispersion of oil in water flow (D O/W) and dispersion of water in oil flow (D W/O). The schematic diagrams of six oil-water two-phase flow patterns are shown in figure 2. And the fluctuating signals of ring conductance probe for five typical flow patterns with water as the continuous phase are shown in figure 3 (except D W/O flow pattern because of non-conductivity).
4. Magnitude and sign scaling in flow pattern signals

To qualify the correlation in the magnitude and sign series of the five typical horizontal oil-water two-phase flow patterns, we apply the DFA-2 method to probe long-term nonlinear features of them. Our results show that the magnitude series of all flow patterns exhibits strong positive correlations characterized by \( \alpha_{\text{mag}} > 0.5 \) as shown in figure 4, suggesting nonlinear features in flow mechanism. As shown in figure 5, for low time scale all show very strong positive correlation behavior and they are similar; however for high time scale, the sign series shows the different anti-correlated behavior.

Figure 6 shows the distribution of flow patterns on the plane with magnitude scaling exponent \( \alpha_{\text{mag}} \) and sign scaling exponent for high time scale. It should be pointed that for D O/W flow pattern we use the magnitude scaling exponent for low time scales \( \alpha_{\text{mag}}^l \) instead of \( \alpha_{\text{mag}} \), in order to better explore the dynamics. As can be seen, the combination criterion is able to classify five different flow patterns.

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**Figure 3.** Signals of five typical flow patterns with water as the continuous liquid.

**Figure 4.** Magnitude scaling properties of five typical flow patterns.
4.1. Magnitude scaling analysis

As we can see in figure 6, the range regimes for $\alpha_{\text{mag}}$ of different flow patterns are different from each other. Previous studies have demonstrated that information about nonlinear properties of flow dynamics can be quantified by long-range power-law correlation in magnitude of the increments in fluctuation signals [12-13], so the different magnitude scaling exponents exhibit the different nonlinear dynamics of flow patterns.

All the points corresponding to ST flow patterns locate in zone A with lowest value (0.697~0.767). In this flow pattern, both phases are continuous phase, and oil-water interface is clear and smooth. Because of stable movement and small interface fluctuation during the flowing process, this flow
pattern has lowest $\alpha_{\text{mag}}$ and weakest nonlinear composition. The points corresponding to ST&MI flow all locate in Zone B, and $\alpha_{\text{mag}}$ of this flow (0.787–0.845) is greater than that of the ST flow. The ST&MI flow has a wavy interface with dispersed oil and water droplets randomly distributed close to it. With wavy characteristics of the interface, the positive correlation of the ST&MI flow is absolutely stronger than that of the ST flow, suggesting correspondingly stronger nonlinear features.

For D O/W&W flow, the corresponding points locate in the zone C with $\alpha_{\text{mag}}$ (0.894–0.925). With further increase of mixture flow rate, more liquid droplets appear on the oil-water interface. And the random movement of the oil droplets dispersed in the continuous water phase makes the positive correlation of this flow pattern enhanced. In D W/O & D O/W flow mainly in Zone D with $\alpha_{\text{mag}}$ (0.864–0.996), the wavy characteristics of the interface between the upper water-in-oil flow and bottom oil-in-water flow indicates the stronger positive correlation. The same zone of $\alpha_{\text{mag}}$ between D W/O & D O/W flow and D O/W&W flow shows that the magnitude correlation of single layer dispersion flow is similar with that of two layers dispersion flow. The magnitude series of D O/W flow shows much stronger positive correlation for low time scale ($\alpha_{\text{mag}}^1=1.601–1.783$) than any other flow patterns, which shows D O/W flow has strong positive correlation but without power-law property; however the correlation of this flow pattern for moderate to high time scale $\alpha_{\text{mag}}^2$ turns into less than 1, reflecting the intrinsic movement of D O/W flow could be also nonlinear motion with power-law correlation [10].

4.2. Sign scaling analysis

Previous studies have shown that the time series composed of the sign of the increments in the original signal contain information about the underlying dynamics which is complementary and independent from the original and the magnitude series [12].

The strongest anti-correlated behavior of ST flow for high scale with the least value $\alpha_{\text{sign}}^2$ (0.145–0.178) reflects that large and small values of the time series are most likely to alternate. Since the existence of slippage and interaction between oil and water phase, the conductance signals are wavy instead of completely smooth. Note that the fluctuation amplitude is very little but its frequency is high, which agrees with the anti-correlation of sign series. Compared with ST flow, the value $\alpha_{\text{sign}}^2$ of ST&MI flow is greater with wide range (0.193–0.398) showing the weaker anti-correlation and the various kinds of motion forms.

The value $\alpha_{\text{sign}}^2$ of D O/W&W flow with narrow range (0.187–0.207) is almost less than that of D W/O & D O/W flow (0.194–0.365), which shows the stronger anti-correlation. The main reason for wide range of D W/O & D O/W flow is its dominant flow feature, which is the combination of the motions of oil and water droplets around the interface and the fluctuation of the wavy interface between oil and water phase. And there exists difference between them, however, two points of D W/O & D O/W flow still locate in the zone of D O/W&W flow. By observation of the experimental flow pattern map, one of these two points locates the boundary from ST&MI flow to D W/O & D O/W flow, and the other locates the boundary from D O/W&W flow to D W/O & D O/W flow. The values $\alpha_{\text{sign}}^2$ of D O/W flow are distributed in a wide range (0.153–0.326) due to the dispersed distribution of oil droplets in full pipe, so the nonlinear and linear characteristics of this flow pattern exhibit more complicated behaviors.

5. Conclusions

Magnitude and sign decomposition method cannot only characterize signal property related to multi-scale phenomena, but also can analyze long-range correlation property of original time series from magnitude and sign increment series. Especially, positive power-law correlations in the magnitude
series indicate the presence of long-term nonlinear features in the original signal; in contrast, the sign series relates to the linear properties of the original signal. Thus this method can be suitable and clear to probe dynamics of original time series.

Our result shows the magnitude and sign decomposition method can fully reveal the nonlinear dynamics of five flow patterns with water as the continuous phase for different scales. The magnitude increment series of ring conductance sensors reflect different positive correlation property of all flow patterns; the sign increment series shows but different anti-correlation property of flow patterns for high time scale. So we can sensitively identify the horizontal oil-water two-phase flow patterns in terms of the joint distribution of magnitude and sign scaling exponents. In this regard, the multi-scale and nonlinear analysis-based approach can be an effective tool for understanding the dynamic characteristics of horizontal oil-water two-phase flow.

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