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Development of empirical correlation to predict droplet size of oil-in-water flows using a multi-scale Poincaré plot

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ABSTRACT

Oil-water two-phase flow phenomena are frequently encountered in many industrial processes. Droplet size and its distribution are important characteristics of oil-in-water flows and have a significant effect on the interfacial heat and mass transfers. In this study, we conduct an experiment on vertical oil-water two-phase flows with high water volume fraction and low mixture velocity. The information of droplet sizes is collected using a double-ring conductance probe during this experiment. We propose a multi-scale mean distance (MS-MD) and a multi-scale short-term distribution entropy (MS-STDE) based on a multi-scale Poincaré plot to characterize the short-term fluctuations of the probe signals. An empirical correlation is constructed based on the MS-MD to accurately predict the mean droplet size of oil-in-water flows. Meanwhile, the MS-STDE enables to correlate the short-term variability of collected probe signals to the complexity of the droplet sizes, and serves as a useful indicator of the droplet size instability.

1. Introduction

Oil-water two-phase flows widely exist in the petroleum, chemical and many other industries. The droplet sizes in oil-water flows have significant influence on the interfacial heat and mass transfers. Therefore, the measurement of the droplet sizes in oil-water flows is of great significance for characterizing flow dynamics and modeling flow parameters, such as drift velocity and phase volume fraction [1–4].

Methods, such as photography [5–7], electrical probes [8–11], wire-mesh [12] and laser-based technique [13,14], have been developed in the measurement of the droplet sizes in multi-phase flows. In particular, Evgenidis and Karapantsios [15] found that the void fraction fluctuations detected by a ring-shape conductance probe is positively correlated with the bubble sizes in vertical gas-liquid two-phase flows. Thus, analysis of the fluctuations of the probe signals is probably a beneficial way to predict the oil droplet sizes in oil-water two-phase flows.

Nonlinear analysis based on the time series have made great progress in various complex systems, such as physiological EEG and ECG systems [16–18], traffic system [19] and financial market system [20–22]. In multi-phase flow system, Guo et al. [23] proposed a nonlinear weighed multi-scale wavelet analysis based on Gaussian filter to detect the interfaces of different phases. Wang et al. [24] investigated the non-homogenous distribution of the oil droplets in vertical oil-water two-phase flows by a fractal scaling exponent. Zhuang et al. [25] developed a multi-scale weighted complexity entropy causality plane to indicate five typical oil-water-gas flow patterns. Mukherjee et al. [26] applied a PDF analysis of optical probe signals to indentify the flow patterns of upward gas-liquid-liquid three-phase flows. Wang et al. [27] analyzed the time reverse asymmetry of gas-liquid flows by using a multi-scale symbolic time-reverse method. The previous studies mainly focus on the flow structure and its dynamical evolution. However, some limitations exist in the measurement of droplet sizes using nonlinear analysis.

Poincaré plot is a two-dimensional graphical representation of temporal correlations within the adjacent values of a time series. Given a time series of the form x_i, x_{i+1}, x_{i+2}, $\cdots$, a Poincaré plot in its simplest form first plots (x_i, x_{i+1}), then plots (x_{i+1}, x_{i+2}), then plots (x_{i+2}, x_{i+3}), and so on. As an effective way to qualify short-term and long-term properties of time series, Poincaré plot geometry has been widely used in the analysis of nonlinear systems. Tulppo et al. [28] fitted an ellipse to the shape of a Poincaré plot to analyze the relations among its width, its length and the variability of the studied system. Brennan et al. [29] demonstrated that the width and length of the Poincaré plot cloud corresponded to the level of short-term and long-term variability of the system, respectively. The most common measures of Poincaré plot geometry are SD1 (standard deviation of short-term variability), SD2 (standard deviation of long-term variability) and SD1/SD2 ratios [30–34]. Hoshi et al. [35] verified the correlation among SD1, SD2, SD1/SD2 ratios and other nonlinear variables such as sample entropy, Lyapunov exponent, Hurst exponent (HE), correlation dimension and

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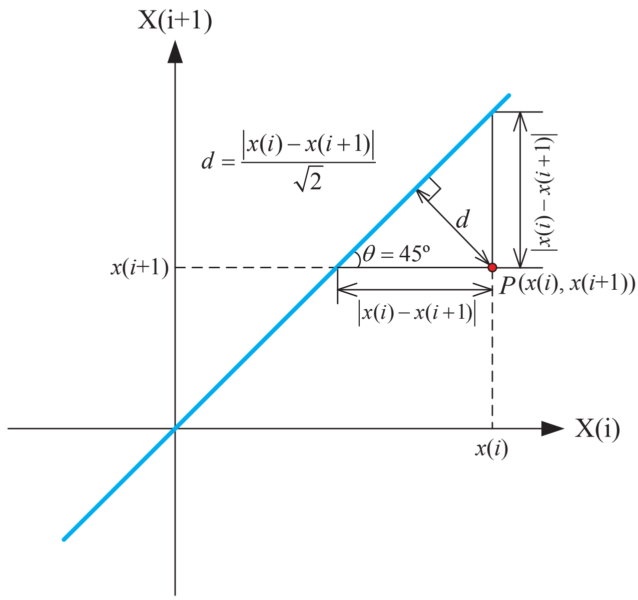

Fig. 1. Calculation of the distance from a point to the identity line of Poincaré plot.

detrended fluctuation analysis (DFA). Interestingly, as a further development of the geometry study, the point distribution characteristics on the Poincaré plot have attracted attention. Przemyslaw et al. [36,37] paid attention to how points on Poincaré plot distributed above and below the identity line and proposed asymmetry features of short-term blood pressure variability. Cohen et al. [38] derived a second-order Poincaré plot and a central tendency measure (CTM) to quantify the variability of time series, which effectively separated the congestive heart failure patients from normal individuals. Based on the measures of Cohen et al. [38], Huo et al. [39] analyzed the way in which points on the Poincaré plot departed from the original point, and developed a quadrantal multi-scale distribution entropy to describe the dispersion features of the points. Based on the generalization of the conventional two-dimensional Poincaré plot, Henriques et al. [40,41] introduced a visualization method to investigate the multi-scale characteristics, self-similarity and complexity loss of nonlinear systems. Ruan et al. [42] concentrated on the angular dispersion and distance dispersion of the points on the Poincaré plot and put forward the vector angular index and vector length index, and then four measures characterizing the dispersions of points on the Poincaré plot were extracted for atrial fibrillation detection.

In general, analysis of the feature how the points distribute on the Poincaré plot reveals more details of nonlinear system. In order to comprehensively reflect the short-term characteristics of the time series, we propose a multi-scale mean distance (MS-MD) and a multi-scale short-term distribution entropy (MS-STDE) to characterize the short-term variability properties in different parallel regions of the Poincaré plot. An experiment on vertical oil-water two-phase flows is conducted. The proposed MS-MD is employed to predict the oil droplet sizes of oil-in-water flows. In addition, we correlate the short-term variability of collected probe signals to the complexity of the droplet sizes.

2. Materials and methods

2.1. Poincaré plot and short-term variability analysis

On the Poincaré plot of time series, each value of the series is regarded as a function of the preceding value. If the time series is denoted as $\{x_i\}(i = 1, 2, \cdots n)$, the current value of the series x_i is represented on x-axis, and the value of the next time x_{i+1} is represented on y-axis. In this way, each point (x_i, x_{i+1}) on the Poincaré plot corresponds to two successive values of the time series.

If the point (x_i, x_{i+1}) is on the identity line of the Poincaré plot, that is, x_i is equal to x_{i+1}, which means the state of the system has not changed in per unit time. Besides, point (x_i, x_{i+1}) either above or below the identity line corresponds to unequal neighboring values, which means the state of the system has varied from x_i to x_{i+1} in per unit time. Fig. 1 shows the calculation of the distance d from a point to the identity line of the Poincaré plot. As can be seen, the distance d to the identity line is proportional to $|x_{i+1}-x_i|$. The shorter the distance is, the lower the absolute difference of the two successive values will be, indicating that the variability of the system is smaller in per unit time, and vice versa. Thus, on the Poincaré plot, the distance from the point to the identity line is a measure of the short-term variability level of the system. The longer the distance is, the higher level the short-term variability will be, and vice versa. Since the points on the identity line do not reflect any short-term variability, only the points above or below the identity line are taken into consideration in the following discussions.

In addition, it should be noted that the level of short-term variability does not always keep constant but fluctuates from time to time. In Fig. 2(a), two data segments enclosed in rectangular frames are identical and fluctuate slightly. If we plot the points of the two segments within the coordinates of (X(i), X(i + 1)), as shown in Fig. 2(b), the points distribute near the identity line which indicates that the level of the short-term variability is low. In Fig. 2(c), the data segments enclosed in the rectangular frames fluctuate widely, and accordingly the corresponding points on the Poincaré plot distribute far from the identity line (see Fig. 2(d)), which implies that the level of the short-term variability is high.

In order to characterize the short-term variability, we propose a new distribution entropy, i.e., short-term distribution entropy (STDE), to reveal the complexity of the short-term variability. As shown in Fig. 3 2N lines which all parallel with the identity line are created. The distance of the kth line to the identity line is set as

$$d_k = kd \quad (1 \leqslant k \leqslant N) \tag{1}$$

where d is equal to $d_{\max}/N$, and $d_{\max}$ is the maximum distance of the points to the identity line. Thus, the 2N lines divide the whole Poincaré plot into N subregions based on the distance of the pointes to the identity line. In this way, the continuous change of the short-term variability level is quantified into N kinds of levels of short-term variability.

The number of the points in each subregion is counted to calculate their ratios to all points in the studied region, which are denoted as $p_1, p_2, \cdots p_N$. Thus, the short-term distribution entropy (STDE) of the Poincaré plot is defined as

$$\mathrm{STDE} = -\sum_{i=1}^{N} p_i \log_2 p_i \tag{2}$$