Physica A 449 (2016) 324–335

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Gas–liquid two-phase flow structure in the multi-scale weighted complexity entropy causality plane

Yi Tang, An Zhao, Ying-yu Ren, Fu-Xiang Dou, Ning-De Jin *

School of Electrical Engineering and Automation, Tianjin University, Tianjin 300072, China

HIGHLIGHTS

- We test both MS-WCECP and MS-CECP on typical nonlinear dynamic systems.
- MS-WCECP shows better anti-noise ability and signal distinguishing ability.
- We apply both algorithms to study gas–liquid two-phase flow system.
- MS-WCECP can more accurately indicate gas–liquid two-phase flow structures.

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 16 October 2015
Available online 12 January 2016

Keywords:
Nonlinear time series
Stability
Complexity
Multi-scale weighted complexity entropy causality plane
Gas–liquid two-phase flow

ABSTRACT

The multi-scale weighted complexity entropy causality plane (MS-WCECP) is proposed for characterizing the physical structure of complex system. Firstly we use the method to investigate typical nonlinear time series. Compared with the multi-scale complexity entropy causality plane (MS-CECP), the MS-WCECP can not only uncover the dynamic information loss of complex system with the increase of scale, but also can characterize the complexity of nonlinear dynamic system. In particular, the algorithm of MS-WCECP performs strong anti-noise ability. Then we calculate the MS-WCECP for the conductance fluctuating signals measured from vertical upward gas–liquid two-phase flow experiments in a small diameter pipe, the results demonstrate that the MS-WCECP is a useful approach for exploring the stability and complexity in gas–liquid two-phase flows.

1. Introduction

It is commonly known that measured signals from experiments provide us very useful information for uncovering the deterministic or stochastic characteristics of the system under study. Recently, various measures of complexity were developed [1–4], however, the task to distinguish between regular, chaotic system and stochastic process still remains unsolved. Particularly, previous approaches have limitations from the perspective of stability and robustness in the sense that real data are unavoidably contaminated by omnipresent dynamical noise [5–9]. Thus, they should be urgently improved to overcome this tough problem.

In recent years, based on the probabilistic description of physical system, a family of statistical complexity measures has been suggested [1–4]. The members of this family purport to ascertain the degree of periodicity and randomness of a system. Rosso et al. [10] firstly proposed the complexity entropy causality plane (CECP) combining permutation entropy with statistical complexity measure. Compared to permutation entropy, the CECP provides additional information regarding the peculiarities of a probability distribution. They used the CECP to describe the determinacy and randomness of a system

* Corresponding author.
E-mail address: ndjin@tju.edu.cn (N.-D. Jin).

http://dx.doi.org/10.1016/j.physa.2015.12.083

from the perspective of "information" and "disequilibrium". This method is very helpful to distinguish noise, chaotic system and stochastic process, and it has been applied to the analysis of sovereign bond markets [11], the stock market inefficiency analysis [12], commodity predictability analysis [13], the music classification [14], etc. In particular, it should be mentioned that the complexity of a system cannot be measured univocally. Therefore, multi-scale complexity entropy causality plane (MS-CECP) is attracting much attentions [15–17] due to its advantage in revealing the stability and complexity of physical structure for complex systems.

As a measure of system uncertainty and irregularity, entropy has attracted much attention because of its advantages in indicating the complexity of system structure. The approximate entropy [18] and sample entropy [19] have been proposed and commonly employed in medical and physiological signal analysis. Considering that single scale entropy lacks in stability and robustness, Costa et al. [20] proposed multi-scale sample entropy (MSE), aiming to reveal the complexity of nonlinear dynamic system from microcosmic and macroscopic perspectives. To avoid the noise effect, Bandt and Pompe [21] proposed a permutation entropy (PE). Then it has been widely applied to nonlinear dynamic systems, such as fractional Brownian motion and fractional Gaussian noise analysis [22], stock market prediction [23,24], physiological signal analysis [25–27], mechanical equipment condition assessment [28,29] and climate system [30]. In particular, weighted permutation entropy exhibits distinctive advantages in retaining the original information of time series and improving algorithm robustness, as well as signal classification ability [31–33].

Gas–liquid two-phase flow is considered as a nonlinear dynamic system featured by complex characteristics of chaos, dissipation, order and disorder. Nonlinear analysis methods have been widely used to uncover complex dynamic behaviors as well as the evolution mechanism of self-organization behind two-phase flow system [34]. Early studies mainly focused on extracting complexity exponents from experimental signals such as the Correlation dimension, Kolmogorov entropy, Lyapunov exponents [35,36]. However, these methods cannot clearly describe the characteristics of two-phase flow. Specifically, multi-scale entropy enriches the understanding of the evolution of two-phase flow patterns. Accordingly, seeking a novel measure to reveal the physical essence behind flow structure transition in two-phase flow is a universal concerned topic in multiphase flow study.

In order to more detailedly describe the dynamic characteristics of flow structure in gas–liquid two-phase flows, we construct the multi-scale weighted complexity entropy causality plane (MS-WCECP) with the weighted permutation entropy [32,33] and the statistical complexity measure [1–4]. The motivation of this study is to improve algorithm robustness of MS-CECP and accurately extract the dynamic information loss of two-phase flow structure. The proposed method enriches the knowledge of stability and complexity of two-phase flow structure and provides a useful tool to understand nonlinear dynamics in gas–liquid two-phase flows.

2. Multi-scale weighted complexity entropy causality plane

2.1. Statistical complexity measure

"Information" and "disequilibrium" describe the complexity of a system from different perspectives: "information" shows the amount of information needed for describing the behavior of the system under study; "disequilibrium" represents the distance between a given probability distribution and the equilibrium probability distribution. Since there exists numerous physical structures between periodic process and random process, it is difficult to thoroughly reflect the intrinsic patterns inside a system only through "information" or "disequilibrium". Statistical complexity measure describes the system possessing simple structures, but presenting complex dynamic behaviors from the aspect of "information" and "disequilibrium", it is intended to reveal hidden intrinsic patterns inside dynamic characteristics of the system under analysis.

For a given system that meets the probability distribution $P = \{p_j, j = 1, \ldots, N\}$, according to the Shannon information theory, the corresponding Shannon's entropy is given by: $S[P] = -\sum_{j=1}^{N} p_j \ln(p_j)$, denoting the uncertainty of a system. When the probability distribution P submits to the uniform distribution P_e i.e. $P = P_e$, $S[P]$ obtains its maximum value $S_{\max}$ and the given system is definitely random. So the entropic measure is given by:

$$H[P] = S[P]/S_{\max}. \tag{1}$$

According to the statistical complexity measure, the distance between the probability distribution P and the uniform distribution P_e is defined as $D[P, P_e]$ and the "disequilibrium" Q is defined as $Q[P] = Q_0\, D[P, P_e]$, where Q_0 is a normalized constant ($0 \le Q \le 1$). The definition of statistical complexity measure is given as follows:

$$C[P] = Q[P] \cdot H[P]. \tag{2}$$

The value of C is calculated with a given Q and H, aiming to reveal hidden intrinsic patterns inside dynamic characteristics of the system under study, which consists of LMC (Lopez-Ruiz, Mancini and Calbet) measure [1], SDL (Shiner, Davison and Landsberg) measure [2] and Jensen–Shannon complexity measure C_{JS}.

2.2. Weighted complexity entropy causality plane

Rosso et al. [10] proposed the complexity entropy causality plane (CECP) $C_{JS} - H_S$, C_{JS} writes:

$$C_{JS}[P] = Q_J[P, P_e] H_S[P], \tag{3}$$