Chemical Engineering Science 61 (2006) 688–697
Chemical Engineering Science
www.elsevier.com/locate/ces

A novel local singularity distribution based method for flow regime identification: Gas–liquid stirred vessel with Rushton turbine

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Received 7 March 2005; received in revised form 1 August 2005; accepted 3 August 2005
Available online 13 September 2005

Abstract

A novel method employing a unique combination of wavelet based local singularity analysis and support vector machines (SVM) classification is described and illustrated by considering the case example of flow regime identification in gas–liquid stirred tank equipped with Rushton turbine. Pressure fluctuations time series data obtained at different operating conditions were first analyzed to obtain the distribution of local Hölder exponents' estimates. The relevant features from this distribution were then used as input data to the SVM classifier. Employing this method we could classify flow regimes with 98% accuracy. The results highlight the fact that the local scaling behavior of a given regime follows a distinct pattern. Further, the singularity features can be employed by intelligent machine learning based algorithms like SVM for successful online regime identification. The method can be readily applied to the other multiphase systems like bubble column, fluidized bed, etc.

Keywords: Support vector machines (SVM); Pattern classification; Flow regime identification; Nonlinear dynamics; Fractals; Multiphase reactors; Time series analysis

1. Introduction

Gas–liquid flows in stirred reactor depend on the operating conditions and the impeller design and can be classified into different regimes. These flow regimes in turn manifest different fluid dynamic characteristics (see Fig. 1) and demonstrate complex interaction of transport and mixing processes. Significant research efforts have been undertaken in the recent past for developing regime maps and the corresponding design correlations (see the excellent review of Nienow, 1998 and the references cited therein). However, the universal applicability of the regime maps and the correlations to design, scale-up and for setting up of operating protocols for industrial systems is not yet well established. Therefore, the need to develop a new robust experimental methodology based on a simple and non-intrusive measurement technique continues to exist.

Warmoeskerken and Smith (1985); Sutter et al. (1987) and Bombac et al. (1997) used intrusive techniques such as micro-impeller, hydrophones and resistivity probes respectively to extract the information of cavity structure present behind the impeller blades and develop flow regime map. These techniques are reliable for laboratory scale reactor but are difficult to use with industrial reactors. Paglianti et al. (2000) made an attempt to characterize the gas–liquid flows in stirred vessel by means of statistical methods such as non-linear time series analysis from the output signal of the non-intrusive probes. Paglianti et al. (2000) identified the flooding/loading transition by using time series analysis of the measured impedance. The proposed technique was limited only to identify flooding/loading transition, which is clearer and sharper than the other regime transitions.

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0009-2509/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ces.2005.08.002

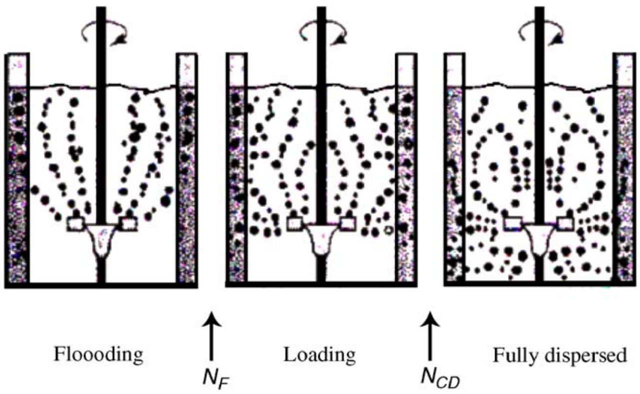

Fig. 1. Different flow regimes in stirred reactor equipped with Rushton turbine (Nienow et al., 1985).

Various authors have also identified regimes of operation by analyzing the extracted nonlinear dynamical, fractal and statistical features from pressure fluctuation measurements (Bai et al., 1996, 1997; Johnsson et al., 2000; Letzel et al., 1997; Lin et al., 2001; Wu et al., 2001; Xie et al., 2003, 2004). These studies were mainly restricted to fluidized bed and bubble column. Recently, Khopkar et al. (2005) characterized the gas–liquid flows in stirred reactor employing wall pressure and torque fluctuations and used non-linear time series analysis to set up robust criteria for the identification of the prevailing flow regimes. They differentiated the flow regimes based on the cavity structure present behind the impeller blades and also estimated the key time scale of the fluid dynamics. In the present study, we have proposed a novel methodology for characterization of time series based on the combination of wavelet based local singularity distribution analysis and support vector machines (SVM), a newly developed pattern classification method. The method developed is subsequently applied for characterization of flow regimes in stirred tank vessel with Rushton turbine. While wavelet techniques have been extensively used in several engineering applications including chemical engineering (Chen et al., 2004; Ellis et al., 2003; Kulkarni et al., 2001; Kulkarni et al., 2001; Park et al., 2001; Roy et al., 1999; Zhao and Yang, 2003), the use of local singularity distribution analysis is relatively new and finds recent applications in biomedical engineering, stock market, etc., for analyzing and charactering time series. (Scafetta et al., 2003; Struzik and Siebes, 2002; West et al., 2004). SVM, a novel tool for classification, is firmly based on rigorous statistical learning theory (Burges, 1998; Vapnik, 1995, 1998). SVM also has found wide spread use including applications in process engineering (Agarwal et al., 2003; Chiang et al., 2004; Kulkarni et al., 2004).

In the present work, wall pressure fluctuations were measured in a gas–liquid stirred reactor equipped with Rushton turbine. The time series of the pressure fluctuations were first subjected to singularity analysis based on wavelet transform modulus maxima (WTMM) method. The relevant features extracted from this analysis were employed as input data by SVM for identifying the operating regimes. The remaining part of the paper is organized as follows: Section 2 provides a detailed description of the proposed method for time series characterization, Section 3 provides a brief description of the experimental set up of stirred vessel and in Section 4 we discuss the results of flow regime identification in a stirred vessel. The salient conclusions are highlighted in Section 5.

2. Time series characterization using singularity distribution and SVM

The methodology proposed for characterization of time series is a novel combination of singularity analysis and SVM classification. The time series under consideration is first subjected to WTMM method and the most informative features from the singularity distribution are extracted. These features are then used as input to SVM for intelligent discrimination of the time series. SVM being a supervised learning method, data is divided into training and test sets. The model is built using the features extracted from the training set of time series. The trained model can then be readily employed for online characterization and identification of unseen test data. The algorithmic steps involved in the proposed methodology are shown Fig. 2, while the details of method are explained in the subsequent sections.

2.1. Characterization of singularities

Many experimental or empirical time series have fractal features i.e., for some instances, the series $f(x)$ displays

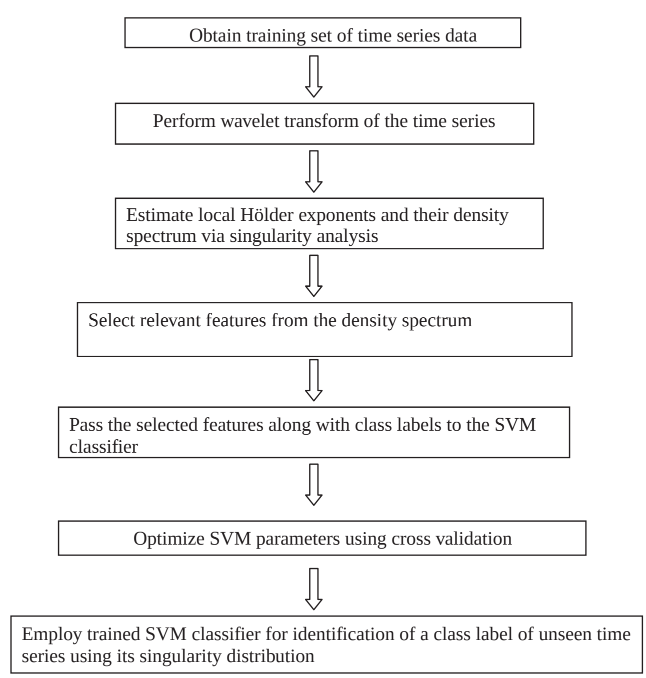

Fig. 2. Proposed methodology for time series characterization.