Flow Measurement and Instrumentation 49 (2016) 31–39

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

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

Application of extreme learning machine to gas flow measurement with multipath acoustic transducers

Longhui Qin, Liang Hu*, Kai Mao, Wenyu Chen, Xin Fu

State Key Laboratory of Fluid Power & Mechatronic Systems, Zhejiang University, Hangzhou, China

ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form
18 February 2016
Accepted 20 March 2016
Available online 21 March 2016

Keywords:
Ultrasonic gas flowmeter
Extreme learning machine
Numerical verification
Installation effects
Artificial neural network
Support vector machine

ABSTRACT

To reduce the large integration errors brought by traditional methods in gas flow measurement under complex flow field, artificial neural network, support vector machine and other intelligent algorithms have been put into use. But these intelligent methods consume much time for training and need intensive user intervention for network design. This paper proposes to apply extreme learning machine to multipath ultrasonic flowmeters, which can analytically determine the output weights of networks instead of error backpropagation algorithm and iterative tuning of the parameters, and therefore provide high metering accuracy at extremely fast learning speed as well as require least human intervention. To test its effectiveness under different flow field and sensitivity to complex flow profiles, extreme learning machine is applied to determine the flow rate under two piping configurations, which can produce mild and severe flow disturbances. The determination errors are compared with a traditional integration method on the position of 5D and 10D as well as with the path orientation of 0° and 90°. Then 7 installation angles and 9 installation positions are respectively configured to study the performance and sensitivity of UFMs to installation effects. Finally, a comparison between extreme learning machine and other two intelligent algorithms is made in training and test time, the mean squared error and the maximal metering error under severe flow disturbance. It is found that extreme learning machine has rather high determination accuracy for flow rate at extremely fast learning speed and it is insensitive to the installation effects of ultrasonic gas flowmeter.

1. Introduction

In the field of gas flow measurement, the metering accuracy is often greatly influenced by spatial inhomogeneity of the flows under measurement. It can be effectively improved if multipath at a set of discrete chords are used to sample the flow velocity profile and achieve much richer information on the fluid characteristics in pipes [1–3]. Multipath ultrasonic flowmeters (UFMs) based on transit-time principle use pairs of acoustic transducers performing a number of measurements in several measuring planes of a pipe to achieve the accurate flow rate and have been widely applied in many diverse applications in industry [3].

The flow rate of typical multipath UFMs is traditionally determined by the summation of flow velocities along fixed paths multiplied by corresponding weight factors, for which the path positions and weight factors vary depending on the numerical integration method adopted. Among a variety of integration methods, Gaussian orthogonal quadrature possesses the highest approximation precision and based on it, many other integration techniques are developed for UFMs, including the most widely used Gaussian-–Jocabi [4] and OWICS (Optimal Weighted Integration for Circular Sections) [5]. Once the integration technique to be applied is determined, flowmeter must be manufactured according to corresponding path positions and flow rate should be calculated referring to the tabulated weight factors. These numerical methods have been proved to have good integration accuracy for steady, ideal and fully developed flows [7–12]. However, the traditional methods are all derived from a constant assumption that the flow velocity distribution under measurement is symmetric and homogeneous without any flow disturbance and could be formulated mathematically. It would result in huge errors when the flow field becomes complicated under non-ideal piping configurations [13–15]. In addition, many other deviations during real manufacture and installation process will bring in flow disturbances. For example, UFM is installed in a biased angle [1,16,17], protrusion or recess is produced due to unsatisfactory transducers installation [18], or inaccurate path positions are manufactured [19,20].

In order to improve the metering accuracy of UFMs under complex flow field, some intelligent algorithms were introduced to

* Corresponding author.
E-mail address: cmeehuli@zju.edu.cn (L. Hu).

http://dx.doi.org/10.1016/j.flowmeasinst.2016.03.003
0955-5986/

reduce the errors resulted from disturbed flow profiles. Luntta [21] proposed to apply artificial neural network (ANN) to compute the weights for different paths of UFMs, which modified the weight factors of traditional Gaussian quadrature in different path orientations and proved ANN could be used to UFM. Whereas only slight improvement of the metering accuracy was achieved since the single layer linear neural network adopted had not taken full advantage of the feature extraction and strong regression ability of ANN. An intelligent UFM based on flow calibration facility was exploited in [22] to utilize a flow field recognizer to differentiate the flow patterns via a learning algorithm and then provided accurate meter readings, which obtained a success rate of 95% for flow profiles recognition. It was in fact the same as ANN in principle but the detailed algorithm and results of determining flow rate were not given. An ANN method based on error back-propagation (BP) algorithm with a single hidden layer was designed for a 4-path UFM and errors within $\pm 0.3\%$ are achieved under complex flow field downstream two elbows out-of-plane [23]. Then [24] applied support vector machine (SVM) which is based on VC dimension and structural risk minimization to reduce the errors existing in traditional weighted integration methods for UFMs, which showed high accuracy within $\pm 0.5\%$ for flow rate determination under strongly distorted flow profiles. The above researches have proved that intelligent algorithms such as ANN and SVM are capable to obtain satisfying metering accuracy when applied to UFMs.

However, the training process of ANN is time-consuming and meanwhile easily trapped in local minimum due to the slow gradient-based learning algorithms and iterative tuning for the parameters and networks [25,26]. As for SVM, the computational costs and storage requirements will increase largely with respect to the number of training examples and optimization method is necessary to achieve good clarification or regression performance [25]. In addition, the network design for traditional ANN and SVM is sensitive to plenty of structural and learning parameters, which are critical to their generalization performance. The determination of these parameters, including learning epochs, learning rate, stopping criteria and so on for BP, and selection of models, kernel function and its parameters, and regularization parameters for SVM depends greatly on designers' empirical experience, experimental comparison or space search in a wide range [24–28]. All these drawbacks make the implementation of ANN, SVM and their variants extremely slow and difficult, which heavily prevents the development of intelligent UFMs.

In 2004, a new learning scheme of single hidden-layer feedforward neural networks (SLFNs) called extreme learning machine (ELM) is proposed in [29], which randomly chooses the input weights and analytically determines the output weights of SLFNs. Without iterative tuning the weights and biases repeatedly, ELM can be used in in feature learning, clustering, classification, and regression at extreme learning speed that is up to hundreds of times faster than BP [30,31], and ELM has been proved having better generalization ability than SVM [31,32] and applied successfully in many applications [30–34]. In addition, except for the number of neurons in the hidden layer, there are no other parameters needed to be determined when ELM is applied, as a result of which its design requires the least user intervention and is easy to implement [30,31,35,36]. Therefore, this paper proposes to apply ELM to a 6-path UFM to determine the flow rate under complicated flow fields.

On one hand, numerical simulation based on computational fluid dynamics (CFD) is helpful to avoid the impacts caused by additional errors in experiments, such as precision and stability of acoustic transducers, electronic circuit, manufacture of meter body and so on, which would cover a much larger range of errors than the improvement effect of the proposed method for UFMs. On the other hand, numerical simulation has been proved to have good agreement with experiments for UFMs [37,38] and widely adopted in many similar researches [12,13,23,24]. This paper will adopt numerical simulation to verify the proposed method aimed at focusing on minimizing the errors caused by integration methods. The purpose of this paper is to take advantage of the strong generalized performance and extreme learning speed of ELM, to provide a simple and fast calculation method for flow rate determination of UFMs, which possesses high metering accuracy and is easy to be realized. To verify ELM's application to UFMs, two piping configurations are numerically modeled, which are suggested by International Organization of Legal Metrology (OIML) to test the performance of UFMs under mild and severe flow disturbances [39]. ELM and a traditional integration method are respectively applied to a 6-path UFM on 5D and 10D downstream elbows as well as with the path orientation of 0° and 90° aimed to compare their accuracy and performance under the above two piping configurations from 1 m/s to 30 m/s. Furthermore, the sensitivity to installation effects of UFMs with ELM applied is studied and analyzed via variation of the determination errors for flow rate with respect to the path orientations as well as installation positions. Finally comparison between ELM and other two intelligent algorithms, ANN and SVM, is made in training and test time, the mean squared error and the maximal metering error under severe flow disturbance.

2. Theory of multipath ultrasonic flowmeter and ELM

2.1. Flow rate calculation for multipath ultrasonic flowmeter

The schematic diagram of a transmit time 6-path UFM is given in Fig. 1, where 6 parallel paths are arranged in the plane P_m according to OWICS method. The angle α between P_m and the cross section P_1 of the pipe is 45°. A_i and B_i are a pair of acoustic transducers positioned at path i. The line velocity v_{pathi} is obtained based on the transit time t_{up} and t_{down} that ultrasound pulses propagates upstream and downstream as shown in Eqs. (1) and (2) [1,17]

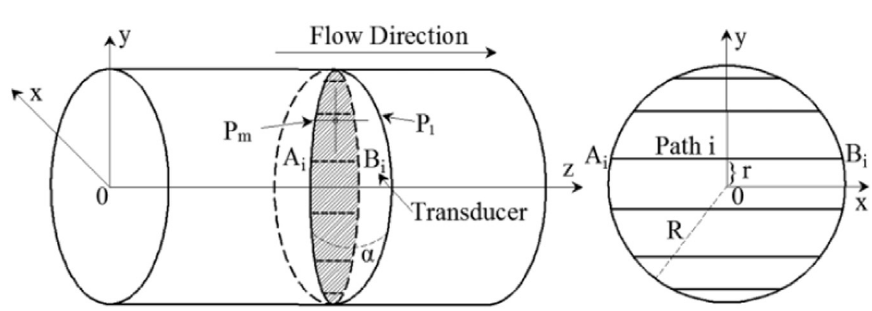

Fig. 1. The schematic diagram of a 6-path UFM.