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Research papers

Artificial Neural Networks and pattern recognition for air-water flow velocity estimation using a single-tip optical fibre probe

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ABSTRACT

Interest in air-water flows has increased considerably for the last decades, being a common research field for different engineering applications ranging from nuclear engineering to large hydraulic structures or water quality treatments. Investigation of complex air-water flow behavior requires sophisticated instrumentation devices, with additional challenges when compared to single phase instrumentation. In this paper, a single-tip optical fibre probe has been used to record high-frequency samples (over 1 MHz). The main advantage of this instrumentation is that it allows direct computation of a velocity for each detected bubble or droplet, thus providing a detailed velocity time series. Fluid phase detection functions (i.e. the signal transition between two fluid phases) have been related to the interfacial velocities by means of Artificial Neural Networks (ANN). Information from previous measurements of a classical dual-tip conductivity probe (yielding time-averaged velocity data only) and theoretical velocity profiles have been used to train and test ANN. Special attention has been given to the input selection and the ANN dimensions, which allowed obtaining a robust methodology in order to non-linearly post-process the optical fibre signals and thus to estimate interfacial velocities. ANN have been found to be capable to recognize characteristic shapes in the fluid phase function and to provide a similar level of accuracy as classical dual-tip techniques. Finally, performance of the trained ANN has been evaluated by means of different accuracy parameters.

1. Introduction

Air-water flows can be often found in large hydraulic structures, where self-aeration occurs as a complex and turbulent air-water compatibility phenomenon (Valero and Bung, 2016). When air entrainment occurs, flow bulking, friction reduction and turbulence modulation can be observed (Chanson, 2013), drastically changing the main flow properties and thereby complicating the flow behavior prediction. In spillway flows, recent research efforts have focused both on the aerated region (Boes and Hager, 2003; Bung, 2011; Chanson and Toombes, 2002; Felder and Chanson, 2009; Wilhelms and Gulliver, 2005; Zhang and Chanson, 2016a) and the non-aerated region (Amador et al., 2006; Castro-Orgaz, 2010; Meireles et al., 2012; Valero and Bung, 2016; Zhang and Chanson, 2016b). However, some key challenges remain unresolved (Chanson, 2013; Matos and Meireles, 2014). Similarly, air-water flow properties within hydraulic jumps have also attracted researchers' interest (Chanson and Brattberg, 2002; Murzyn et al., 2005; Wang and Chanson, 2015; Wang and Murzyn, 2016; Wang et al., 2014).

Although some new non-intrusive techniques are available (Bung, 2013; Bung and Valero, 2015, 2016a–c; Leandro et al., 2014), intrusive techniques are still the most widely used option (Boes and Hager, 2003; Chanson and Brattberg, 2002; Chanson and Toombes, 2002; Felder and Chanson, 2015; Wang and Chanson, 2015; Wang and Murzyn, 2016; Wang et al., 2014; Zhang and Chanson, 2016a). When the air fraction (C) exceeds 1–3%, accuracy of common instrumentation for single phase flow measurements is typically affected and conductivity or optical fibre probes become the best option (Felder and Chanson, 2015). Further discussion on single phase instrumentation applicability to slightly aerated flows can be found in Frizell (2000) and Matos et al. (2002). However, when using intrusive measurement techniques, some drawbacks and limitations can arise. Few attempts have been done to improve accuracy of such devices, testing different settings and signal post-processing techniques (Bung, 2012; Felder and Chanson, 2015). Given the considerable impact of scale effects (Chanson, 2009, 2013; Felder and Chanson, 2009; Murzyn and Chanson, 2008) and the increasing interest in the determination of air-water turbulence features (Bung and Valero, 2016c; Felder and Chanson, 2009; Wang and Murzyn, 2016), more demanding measurements in prototype and large

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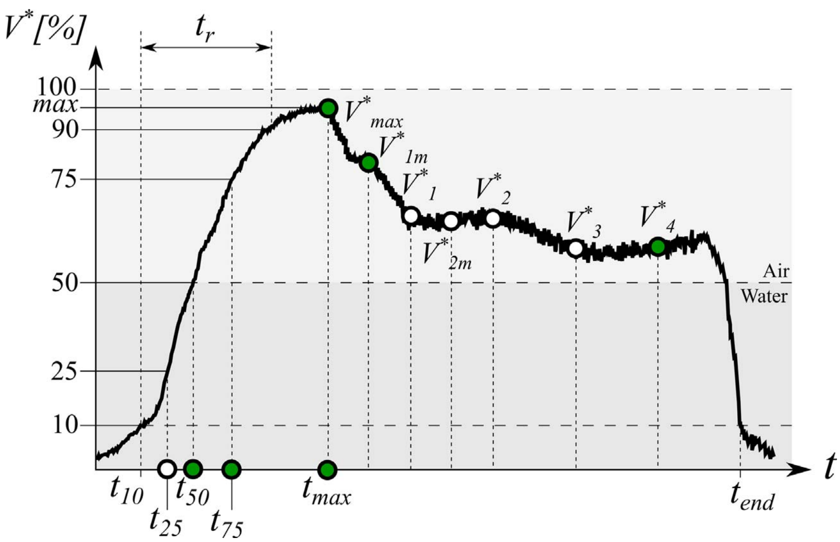

Fig. 1. Exemplary phase detection function for a bubble-tip impact event (note that t_r can be directly extracted from the signal). Main parameters describing the phase detection function have been marked out (green for the finally selected inputs of the Artificial Neural Network). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

scale laboratory models may require from more exigent use of experimental techniques.

Since the early study of Neal and Bankoff (1963), phase detection probes have become a common measuring technique in multiphase flow disciplines. The working principle of optical fibre probes is based upon the change of light refraction at air-water interfaces. Usually, these probes comprise two conical tips (dual-tip probes), being both tips intended to record two signals based on the same bubbly events. Similarly to conductivity probes (Chanson and Toombes, 2002), the most probable lag time (T) can be obtained by cross-correlating both signals and consequently a mean interfacial velocity (v) can be computed, given that the distance between both tips (Δx) in flow direction is accurately known:

$$v = \Delta x / T \tag{1}$$

Nonetheless, a second type of optical fibre is available based on a single-tip configuration. In such case, no cross-correlation can be performed since only a single signal is recorded. High sample rates help to record a more detailed signal (i.e.: phase detection function, see Fig. 1) and voltage gradients may be characterized with higher accuracy. Hence, single bubble/droplet velocities (v_i) can be approximated by:

$$v_i \approx L / t_r \tag{2}$$

where t_r is the so-called rising time, which represents the time that it takes to the voltage signal to pass from a lower threshold to an upper threshold (e.g. from 10% for the water level to 90% for the air level) and L is a characteristic length scale that the bubble/droplet travels through the probe, often referred to as latency length (Cartellier, 1998; Cartellier and Barrau, 1998a,b).

Given a large number of velocities (v_i) obtained from the same number of bubble/droplet impacts, the mean velocity can be computed as an ensemble average:

$$v = \frac{1}{N} \sum_{i=1}^{N} v_i \tag{3}$$

with N the total number of samples (in this case the number of detected bubbles/droplets). A more robust approach to outliers would be considering the median value instead of the average, being the median the value which separates the ensemble in two equal parts (the 50% lower values from the upper 50%).

To avoid a certain level of sensitivity to uncontrollable parameters (e.g. the angle of impact on the bubble interface), the probe geometry can differ from the commonly used dual-tip optical fibres. Thus, some more complex geometries, e.g. a cone + cylinder + cone geometry of the tip, could be used (Cartellier and Barrau, 1998b). Cartellier (1998) reports a relative error of around 10% both for air fraction estimation under laboratory conditions. Further discussion on the probe-bubble interaction and the effect upon the air fraction measurement accuracy can be found in the study of Vejražka et al. (2010). Errors are globally comparable for the single-tip and the dual-tip optical fibre techniques, but sensitivity to the flow regime can differ. For finely dispersed flows, single-tip optical probes are better suited while double-tip probe performance is better whenever large gas inclusions are present (Cartellier, 1998). Therefore, application of single-tip probes in highly turbulent aerated spillway flows becomes challenging. Also, their actual response is sensitive to small geometrical defects occurring at their tips as indicated by Cartellier and Barrau (1998a,b). Use of more complex data processing techniques than the rather simple rising time/velocity correlation provided by Eq. (2) can yield improved performance of the instrumentation.

In this study, raw signals have been recorded with a single-tip optical fibre in a highly aerated flow on a moderately sloped stepped spillway; similar to the setup described in Bung and Valero (2015) and Bung (2011). These new signals have been processed evaluating the accuracy of the simple – yet physically based – approach of Eq. (2). At a second stage, they have been used to train and test an Artificial Neural Network (ANN). One of the main strengths of ANN is to allow detection of both simple and complex patterns in the input, which could remain indistinguishable to the researchers' naked eye (it must be noted that different bubble/droplet impact events can generate different phase functions signatures). Different ANN configurations have been tested by means of the PyBrain open-source package (Schaul et al., 2010) and Python 2.7.

2. Experimental setup

All measurements have been conducted in a moderately sloped stepped spillway (1V:2H, chute slope $\phi = 26.6°$, step height s = 6 cm) located at the Hydraulics Laboratory of FH Aachen, for three different flow rates q = 0.07, 0.09 and 0.11 m^2/s. The total drop height is 1.74 m with a flume width of 0.50 m. Water is pumped from a lower basin into an open head tank from where it is conveyed into the stepped chute via an approaching channel of 1 m length. In order to complete a wide range of interfacial velocities, measurements have been conducted at downstream edges of step 13, 14, 18, 19 and 21 (see Fig. 2). Velocity in x-direction has been obtained perpendicularly to the pseudo-bottom with 2 mm spacing in the z-coordinate, resulting in 646 measurements. It must be noted that the air-water flow was found to be in the uniform flow region at step 21 for the highest discharge (see Figs. 2 and 3) according to Bung (2011).