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Triple decomposition technique in air–water flows: Application to instationary flows on a stepped spillway

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ABSTRACT

Self-sustained instabilities and pseudo-periodic motion may be observed in hydraulic structures and industrial flows. Documented examples include the hydraulic jump, sloshing motion in a reservoir and surging waves in pooled stepped spillways. The instabilities may generate some very large turbulence levels and integral turbulent scales, combining the contributions of both slow fluctuations and fast turbulent fluctuations. Herein a triple decomposition of phase-detection probe signals was developed to identify the turbulent contributions of the slow and fast velocity components in highly aerated free-surface flows. The raw probe signals were split into slow and fast signal components and the air–water flow properties of each component were calculated. The method was applied to a new data set collected down a stepped spillway channel with two stepped configurations (flat and pooled). The latter configuration experienced some self-sustained pseudo-periodic instabilities. The data analysis results showed that the fast turbulent velocity fluctuations of the decomposed signal were close to the turbulence levels on the flat stepped spillway (i.e. in absence of instability). And the largest turbulent energy was contained in the slow fluctuating velocity component. The findings showed a new implementation of a triple decomposition technique to instationary air–water flows.

1. Introduction

In the past decades, many studies investigated experimentally air–water flows with natural free-surface aeration, including free-surface flows down spillway chutes (Rao and Kobus, 1971; Wood, 1991; Chanson, 2013). Most experimental works of air–water flows focused upon the time-averaged air–water flow properties providing basic flow information for the design of hydraulic structures (Wood, 1991; Chanson, 1997). Self-sustained instabilities and pseudo-periodic motion may be observed in air–water flows in hydraulic structures and industrial flows. Documented examples include the hydraulic jump (Bradley and Peterka, 1957; Mossa, 1999), sloshing motion in a reservoir (Armenio and La Rocca, 1996) and jump waves in pooled stepped spillways (Chanson, 2001; Thorwarth, 2008). Fig. 1 illustrates two prototype applications.

The appearance of instability processes depends on the flow conditions and configurations including boundary conditions. A number of researchers documented the unsteady nature of the air–water flows and associated surface waves (Killen, 1968; Toombes and Chanson, 2007). Mossa and Tolve (1998) and Leandro et al. (2012) studied the hydraulic jump fluctuations and their impact on void fraction distribution and free-surface profile. Toombes and Chanson (2007) showed the effect of surface waves on the void fraction and bubble count rates. On flat stepped spillways, some flow instabilities were observed for some intermediate flow rates (Elviro and Mateos, 1995; Chanson, 1996; Ohtsu and Yasuda, 1997). In pooled stepped chutes, some pseudo-periodic flow was documented on the Sorpe dam spillway during some uncontrolled spillway release (Chanson, 2001) and physically investigated by Thorwarth and Koengeter (2006) and Thorwarth (2008). The self-sustained unstable processes appeared at the spillway's upstream end and the jump waves propagated downstream (Fig. 1A).

Herein new experiments were conducted in a stepped chute with two stepped configurations: flat steps and pooled steps. Flow instabilities were observed in the latter setup and a new triple decomposition technique is introduced for the analysis of phase detection probe signals including the velocity fluctuation estimates, taking into account both the fast turbulent and slow fluctuating velocity components. After a short description of the physical setup, some basic observations are shown, before the triple decomposition technique is applied.

2. Signal processing of phase detection intrusive probes

2.1. Basic signal processing

In a free-surface flow, the void fraction ranges typically from 0% to 100%, as illustrated in Fig. 1A, and the mass and momentum

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Fig. 1. Surge instabilities in high-velocity open channel flows (A) free-surface instability down the Sorpe dam spillway, Germany in 2003 (Courtesy of Ruhrverband) – $\theta = 18°$, h 0 0.5–2 m (pooled steps), $Q = 6.9$ m^3/s, Re = 1×10^6 and (B) air–water-sediment surges down a channelised section of Rio Achumani, La Paz, Bolivia in 1993 (Courtesy of Francis Fruchard) – Flat step design.

fluxes are encompassed within the flow region with void fractions less than 95% (Cain, 1978; Wood, 1985). A number of physical data demonstrated that the high-velocity gas–liquid flows behave as a quasi-homogenous mixture and the two phases travel with a nearly identical velocity, the slip velocity being negligible (Rao and Kobus, 1971; Cain and Wood, 1981; Wood, 1991; Chanson, 1997). In such aerated flows, a robust metrology is the phase-detection needle probe (Fig. 2A). Although the first needle probe designs were based upon resistivity probes, both optical fibre and resistivity probe systems are commonly used (Cartellier, 1992; Chanson, 2002). The needle probe is designed to pierce bubbles and droplets. Fig. 2B illustrates a typical signal output and corresponding instantaneous void fraction. The flow conditions are listed in the figure caption. In Fig. 2B, each steep drop of the signal corresponds to an air bubble pierced by the probe tip.

In free-surface flows, the basic signal processing of the raw voltage signals is based upon a single threshold technique and some statistical analyses of the raw signal. The threshold is typically between 40% and 50% of the air–water range (Toombes, 2002; Chanson and Felder, 2010). The basic outputs are the void fraction, the bubble count rate and air/water chord size distributions.

A cross-correlation analysis between the two probe tip signals yields the maximum cross-correlation $(R_{xy})_{\max}$ for a time lag T corresponding to the average interfacial travel time between the probe sensors (Herringe and Davis, 1976; Chanson, 1997). The time-averaged interfacial velocity V is calculated as $V = \Delta x/T$ where Δx is the distance between probe sensors. The integration of the auto- and cross-correlation functions from the maximum correlation $(R_{xy})_{\max}$ to the first zero-crossing yields the correlation integral time scales T_{xx} and T_{xy} (Fig. 2C):

$$T_{xx} = \int_{\tau=0}^{\tau=\tau(R_{xx}=0)} R_{xx}(\tau) \times d\tau \tag{1}$$

$$T_{xy} = \int_{\tau=\tau(R_{xy}=(R_{xy})_{\max})}^{\tau=\tau(R_{xy}=0)} R_{xy}(\tau) \times d\tau \tag{2}$$

where T_{xx} is the auto-correlation integral time scale characterising the longitudinal air–water flow structure and the cross-correlation integral time scale T_{xy} characterises the vortices advecting the air–water flow structure (Chanson and Carosi, 2007). The broadening of the cross-correlation function compared to the auto-correlation function yields the turbulence intensity (Kipphan, 1977; Chanson and Toombes, 2002). The dimensionless expression of the turbulence velocity fluctuations may be expressed as (Appendix A):

$$Tu = \frac{\sqrt{2}}{\sqrt{\pi} \times T} \times \sqrt{\left(\frac{T_{xy}}{(R_{xy})_{\max}}\right)^2 - T_{xx}^2} \tag{3}$$

where T_{xy} and T_{xx} are the correlation time scales (Eqs. (1), (2)) (Fig. 2C). Within some approximations (Appendix A), a simplified result is (Chanson and Toombes, 2002):

$$Tu = 0.851 \times \sqrt{\frac{\tau_{0.5}^2 - T_{0.5}^2}{T}} \tag{4}$$

where $\tau_{0.5}$ is the time scale for which $R_{xy}(T + \tau_{0.5}) = 0.5 \times R_{xy}(T)$, and $T_{0.5}$ is the characteristic time for which $R_{xx}(T_{0.5}) = 0.5$.

2.2. Signal decomposition technique

When a monophase flow motion is characterised by slow fluctuations, a turbulence characterisation may be based upon a triple decomposition of the instantaneous velocity signal (e.g. Hussain and Reynolds, 1972; Lyn and Rodi, 1994; Fox et al., 2005; Brown and Chanson, 2013). The instantaneous velocity signal $u(t)$ is decomposed into three components:

$$u(t) = U + u'(t) + u''(t) \tag{5}$$