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Signal analysis of an actively generated cavitation bubble in pressurized pipes for detection of wall stiffness drops

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ABSTRACT

Due to the increasing production of volatile new renewable energies as solar and wind, storage hydropower plants have to operate under harsh operation conditions in order to stabilize the electricity grid. As a result, highly transient water pressures occur in pressure tunnels and shafts more frequently. Non-intrusive monitoring techniques are therefore of special interest for these critical infrastructures. The propagation of a pressure wave generated actively by a cavitation bubble was experimentally investigated in a steel test pipe divided in several reaches. A local wall stiffness drop was simulated by replacing steel pipe reaches with less stiff materials as aluminum and PVC. Through the analysis of the pressure wave reflections due to the cavitation bubble explosion, recorded by two hydrophones placed at the extremities of the test pipe, the location of the weak reaches could be detected. An underwater spark generator was developed to produce cavitation bubbles in the pipe resulting in very steep shock waves. This allowed identifying very precisely the wave front and correspondingly the wave speed and the weak reach location. Compared to the wave analysis from water-hammer signals, the active cavitation bubble generation in the pipe is an innovative method that significantly increased the effectiveness of the detection of wall stiffness drops.

1. Introduction

The contribution of new renewable highly volatile energies is growing fast in the European electricity grid due to high subsidies. As a result storage hydropower as well as pumped-storage plants are subjected to more and more severe operation conditions resulting in highly dynamic pressures in steel-lined pressure tunnels and shafts. In order to avoid catastrophic fatigue failures of the steel liners, an effective monitoring of these critical infrastructures is crucial. Traditional safety assessment techniques are however very expensive since such inspections normally require the dewatering of the pressurized system, resulting in loss of energy production. Thus the development of a reliable, non-intrusive monitoring method is of great interest. The present paper proposes an innovative method based on the signal analysis of an actively generated cavitation bubble in a pressurized steel pipe, which allows the detection of reaches associated with a drop in wall

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stiffness.

A number of hydraulic assessment techniques for pipelines failure and leak detection have recently been developed in the fields of water-supply, gas and oil networks based on the analysis of transient pressure signals. Ferrante and Brunone (2003a) performed harmonic analysis on pressure transient signals, generated by valve closures. They derived the analytical expression of the pressure spectrum and showed that it could be related to the system characteristics. They also estimated the arrival time of reflected waves induced by leaks using the wavelet transform (Ferrante and Brunone, 2003b). Staszewski et al. (2003) developed a leak-severity estimation method based on the wavelet decomposition. Covas et al. (2005) applied the standing wave difference technique, normally used for cable fault location in electrical engineering, to locate leaks in pipe systems. This method is based on the frequency response analysis for multiple steady oscillatory-flow conditions, generated through small amplitude sinusoidal maneuvers of a valve. Beck et al. (2005) used the cross-correlation technique to locate features and leaks in simple pipeline networks, from a single pressure record. Misiunas et al. (2005) proposed a continuous monitoring technique based on the measurement of the travel time of the negative pressure wave induced by rapid breaks. Saldarriaga et al. (2006) developed a software tool to estimate the location of leaks in water distribution networks combining the inverse transient analysis with genetic algorithms. Following the same principle, Shamloo and Haghighi (2009) were able to numerically determine the leaks parameters including their number, location and size. Taghvaei et al. (2006) showed experimentally that the cepstrum analysis, performed on pressure-wave signals previously filtered using the orthogonal wavelet transform, can be employed to identify reflected waves due to leaks in simple pipeline systems. The proposed analysis was also used to estimate the severity of the leak. Stephens et al. (2008) applied the inverse transient method, combined with a genetic algorithm, to composite concrete-steel transmission pipelines to estimate the location of wall damages.

The general principle of all these methods is based on the analysis of the system response to pressure transients. When a pressure wave is generated at a point of the pipeline, it propagates through the entire system. Each time it goes through features such as changes in section, resistances or junctions of three or more pipes, the incident wave is partially reflected, partially transmitted and partially absorbed. The ratio between the reflected and transmitted energies depends on the importance of the change. Any new reflection boundary appearing in a network, is indicative of a new singularity. Moreover, the wave attenuation during propagation, which is mainly due to fluid friction, depends on the system characteristics.

Hachem and Schleiss (2012a) developed a new non-intrusive monitoring method to detect and locate local drops of wall stiffness in steel-lined pressure tunnels and shafts. This method is based on the analysis of water-hammer measurements, recorded by two pressure transducers placed at the ends of a steel test pipe, divided into several reaches. A local drop in the wall stiffness was modeled by replacing steel reaches with less stiff ones, made of aluminum or PVC. The water-hammer waves were generated through closure maneuvers of a valve located at the downstream end of the pipe. When the incident wave encounters the weak reach, which is characterized by a lower propagation speed, it is partially reflected and partially transmitted. The experiments showed that the location, and even the stiffness, of the weak reach can be estimated through the analysis of the reflected pressure signals. Nevertheless the analysis was proved to be effective only for significant stiffness reductions, around 98% (PVC reaches). When this value drops to approximately 63% (aluminum reaches), the location of the weak reach is no longer possible.

The work of Hachem and Schleiss (2012b) showed that the monitoring method could be significantly more effective when pressure waves characterized by a steep wavefront are analyzed. The objective of the present study is therefore to improve the sensitivity and precision of the monitoring method by replacing water-hammer with a more suitable pressure signal. An active pressure pulse was generated by underwater explosion of a cavitation bubble produced by a spark generator.

2. Theoretical background

2.1. Spark generated shock waves

Cavitation bubbles can be artificially generated by inducing the dielectric breakdown of water through high voltage electric pulses. The formation of plasma between the electrodes leads to very high temperature and pressure which are not in equilibrium with the surroundings. This produces an intense shock wave and the formation of an expanding cavity. As the shock wave front velocity is always larger than the particles velocity, it immediately detaches from the bubble. Both the cavity wall and the wave front velocities, initially supersonic, decrease with the expansion. Regarding the shock wave, the geometrical factor of spherical expansion and the energy dissipation both reduce the peak pressure and thereby the propagation speed. The slowing down of the bubble wall is mainly due to the transfer of plasma energy into potential energy through the expansion work done against the outer static pressure.

The bubble volume is soon filled with water vapor (and other gasses resulting from chemical reactions inside the plasma). When all the plasma energy is used up, the bubble reaches its maximum radius. At this point, the internal vapor pressure is much smaller than the outer water pressure and the bubble is compressed back to a small volume. This rapid collapse induces an overpressure, generating a second shock wave, similar to that induced by the initial breakdown. Due to the presence of non condensable gas, the bubble rebounds and expands again to a smaller maximum radius, as energy is lost, mostly in the collapse shock wave. Additional cycles may occur before the complete dissipation of the energy