Study on the extension of acoustic flow metering devices to monitor transient phenomena

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Abstract

This paper presents an approach based on ultrasound sensing for the surveillance of pressure fluctuations in hydro installations, such as linearly valve closing of a pipeline or the cavitation phenomena "visible" via the pressure fluctuations. Changes in the water flow dynamics are characterized by the pressure variations in water. The purpose of our paper is to present the alternative brought by a non-invasive technique which has the advantage to emphasize the acoustic effect of the pressure variations. The experiment is performed in passive configuration so that the monitored environment is not affected by any additional emissions. A new signal processing technique is exploited in order to provide an accurate result to the characterization of this phenomenon.

1. Introduction

The surveillance of the pressure in water pipe networks is an important aspect in order to maintain the system running and to avoid damages, energy costs, customer complaints and additional maintenance costs [1]. A continuous pressure surveillance can assure safe drinking water, can detect surges which are known to create additional leaks, breaks and to drastically reduce infrastructure life [2]. The pressurized pipes present unsteady flows when sudden changes occur. However, one of the most dangerous phenomena which can happen in a pipeline system is the water hammer. This effect is generally caused by a valve which is suddenly closed. This closure forces the fluid to stop its motion and to change its direction. The highest risk of this phenomenon is that the resulting pressure may cause the pipe collapse.

As a result, the water hammer must be monitored and characterized in order to minimize the destructive effects that it may cause to the hydraulic system. In this sense, we propose to use a non-invasive technique with two ultrasonic transceivers that have the advantage of not requiring any extra manipulations upon the system or the pipeline. Ideally, they are placed as close as possible to the closing valve in order to accurately measure the overpressure. The acoustic sensors work in passive configuration so that their influence upon the surveyed phenomena is minimized. The recorded signals are explored to determine the TOF (time-of-flight) of the hydraulic shock. Additionally, the proposed method does not require only the acoustic effect of the water hammer, but also the noise and vibrations that come with it.

Furthermore, we choose to use the RPA (Recurrence Plot Analysis) method to determine the TOF. This method is based on the concept of state representation in the phase diagram. Then, the recurrences of these states, namely the states where the system returns, are highlighted on the recurrence or distance matrix. Considering our application and the fact that the acoustic effect of the water hammer is a transient signal, it appears as a sudden change on the phase space which is further translated into a vertical and horizontal white band on the recurrence or distance matrix [3]. In these matrix representations, the white bands imply that those points are totally distant from all other points in the phase space, hence the system is in a whole new different state.

Our objective is to determine the speed of the acoustic shock based on the TOF obtained using the proposed RPA method. Finally, the results are compared with the actual speed given by the geometry and the characteristics of the hydraulic system and with classical techniques usually used for the stated problem.

The paper is organized as follows: section 2 presents the classical approaches used in hydraulics to determine the pressure variation and the speed of the pressure wave. In section 3, it is described the RPA method and main characteristics. Section 4 outlines the experiment and the results obtained using both approaches: classical and signal processing. Finally, in section 5, the conclusions of our paper are presented, as well as our future work.

2. Water hammer effect

The water hammer of hydraulic systems is a periodic phenomenon that can occur in any piping system where valves are used to control the flow of liquids or stream. The effect of fully or partially closing a valve is a pressure surge or high-pressure shockwave that propagates through the system when a fluid in motion is forcefully changing direction or it is abruptly stopped. The forced stopping of the flowing fluid translates into changing their kinetic energy in pressure energy. The pressure in the valve section increases with Δp. This overpressure in a pipe, due to the water hammer effect, is directly related to the speed of the pressure wave [4-6]:

$$\Delta p = \rho \cdot c \cdot \mathbf{v}_0 \tag{1}$$

where ρ is the fluid density [kg/m^3], c is the speed of the pressure wave [m/s] and v_0 is the initial speed of the fluid [m/s]. Because of the fluid viscosity, part of the energy is dissipated attenuating in time the water hammer phenomenon [6]. The pressure wave speed, c, is also computed with the use of the characteristics of the fluid and of the pipe:

$$c = \frac{1}{\sqrt{\rho\left(\frac{1}{e_w} + \frac{D}{e \cdot E}\right)}} [\text{m/s}] \tag{2}$$

where e_w is the bulk coefficient of the fluid, D is the diameter of the pipe, e is the pipe wall thickness and E is the Young modulus of the pipe.

In the next section, we give details about the RPA method and how can we use this tool to determine the velocity of the pressure wave.

3. Recurrent Plot Analysis

The RPA method comes from the dynamical system theory. To define the distance or recurrence matrix, we start from the received signal, a time series that can be defined as follows: [3]:

$$\mathbf{x} = \{\mathrm{x}[1], \mathrm{x}[2], ..., \mathrm{x}[\mathrm{N}]\} \tag{3}$$

In the next step, the time series is translated in a m dimensional phase space, namely the phase diagram. In this new signal representation space, the values of the time series actually represent the coordinates of the phase diagram vectors as in:

$$\overrightarrow{v_{[\mathrm{i}]}} = \sum_{k=1}^{m} x[\mathrm{i} + (k-1)\,\mathrm{d}] \cdot \overrightarrow{e_k} \tag{4}$$

where $\overrightarrow{v_{[\mathrm{i}]}}$ are the phase diagram vectors, m is the embedding dimension of the phase diagram, d is the delay between the samples, $M = N - (\mathrm{m}-1)\,\mathrm{d}$ and $\overrightarrow{e_k}$ are the axis unit vectors.

Afterwards, the RPA method continues by creating the recurrence/distance matrices. The distance matrix is defined by the distances between the all the points from the phase diagram. The recurrence matrix is the thresholded form of the distance matrix. The following equations define the aforementioned matrices:

$$D_{i,j} = \mathcal{D}\left(\overrightarrow{v_{[i]}}, \overrightarrow{v_{[j]}}\right) \tag{5}$$

$$R_{i,j} = \Theta(\varepsilon - \mathcal{D}\left(\overrightarrow{v_{[i]}}, \overrightarrow{v_{[j]}}\right)) \tag{6}$$

where $D_{i,j}$ from eq. (5) is the element of the distance matrix computed with a certain distance (the Euclidean distance, norm L1, angular distance, etc.). In this study we used the Euclidean distance. In eq. (6), Θ is the Heaviside step function and ε is the chosen threshold (usually a constant). If the distance matrix is seen as a landform, where the altitudes are its values, the threshold ε represents a horizontal plane through the landform. Hereby, the recurrence matrix is obtained considering that the distances under the threshold represent recurrence points (obtaining the value 1 - usually drawn with black) and the values above the threshold are non-recurrent points (and equal to 0 - usually drawn with white).

The choice of the delay, d , is based on the mutual information function [3], which considers the entropy between the samples of the time series as low as possible, but not equal to zero. Also, the embedding dimension of the phase diagram, m , was obtained using the false nearest neighbors' function [3]. This function is based on the following concept: if m_0 is the actual dimension of the phase diagram, then, when the phase diagram is represented in an m - dimensional phase diagram ($m < m_0$), some points will appear as neighbors, but in the actual m_0 dimension, these points are distant; moreover, if the embedding dimension is too large, then the computation time significantly increases.

In order to detect a transient signal, the recurrence matrix is used considering the fact that sudden changes are represented in totally different regions of the phase diagram from all other states of the signal. Therefore, the effect is reflected on the recurrence matrix. This characteristic is present even if the signal-to-noise ratio is not that good, the recurrence matrix succeeding to point out the transient through a white horizontal/vertical band. The recurrence quantification analysis (RQA) based TDR (Time Distributed Recurrence) extracts this behavior [7]:

$$TDR(l) = \sum_{i=1}^{M} R_{i,l},\ i = \overline{1, M} \tag{7}$$

The transient detection curve is obtained using the complementary version of the RQA TDR:

$$TDR^{*}(l) = 1 - \frac{TDR(l)}{\max(TDR(l))} \tag{8}$$

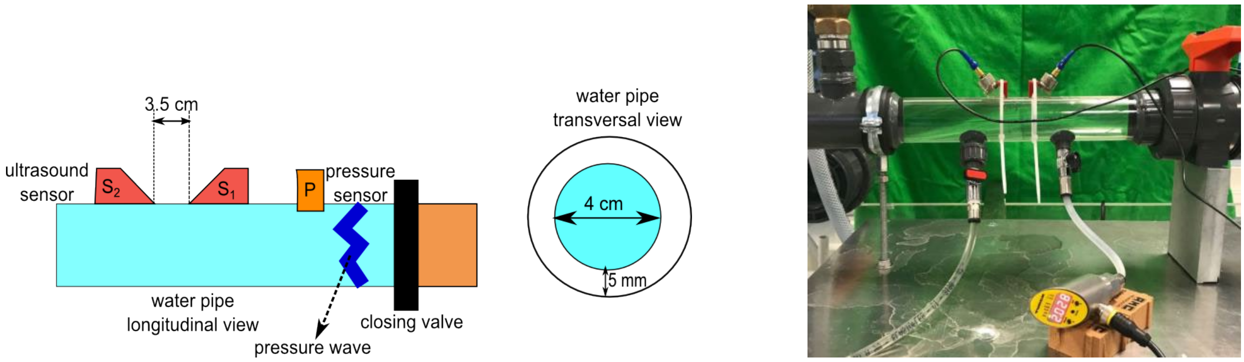
Considering that the transient signals are sudden changes in the time series, the points of the phase diagram corresponding to this behavior are not recurrent, therefore their values are zero. The complementary version of the RQA TDR highlights the white horizontal/vertical bands on the recurrence matrix.

In the following paragraphs, we present the experimental setup used in our study.

4. Experimental setup and results

In order to test the feasibility of the signal processing method, an experimental platform has been designed, as it is depicted in Figure 1. This platform consists in a horizontal pipe supplied by a tank with a total volume of 200 liters. The air compressor creates the constant supply pressures needed for the experiments. A pressure sensor, P, is mounted upstream the closing valve at 45cm distance. The aforementioned pressure sensor is Gefran TK-N-1-Z-B16U-M-V and it has the measuring range between 0-16 bar absolute pressure with the output signal between 0-10V. The pipe has a circular exterior section of 4.5cm and a circular interior section of 4cm. The water is evacuated at the downstream end of the pipe through the 4cm orifice of the pipe. The two acoustic transducers are placed upstream the closing valve and the pressure sensors at 60cm and 63.5cm, respectively– Figure 1. The acoustic transducers have a wide bandwidth (40%) centered on 1MHz, but being able to receive signals found at lower frequencies in the spectrum. Both transducers are set in passive configuration (i.e., "listening" just like a sonar) and the received signals are sampled at rate of 10MHz for a period of 0.9 s.

We produce the water hammer effect by suddenly closing the valve. The pressure before closing of the valve is of 2.2 bar, while the maximum overpressure due to the water hammer phenomenon is 2.6 bar.



(a) (b)

Figure 1: The experimental configuration (a) and platform (b).

An introduction should explain the basic premise of the paper. A good introduction includes several paragraphs explaining the context for the research and why it is important, a short review of the current state of the art identifying unresolved issues or opportunities, a statement of what the research hopes to achieve, and a brief outline of the paper.

4.1 Our approach

The acoustic signals recorded by both sensors are presented in Figure 2. The acoustic transient signals appear during the pressure variation. Both acoustic transient signals have high energy. The RPA method is applied on the acoustic signals and computed the RQA TDR* for $m = 3$, $d = 18$ and $\varepsilon = 0.05$.

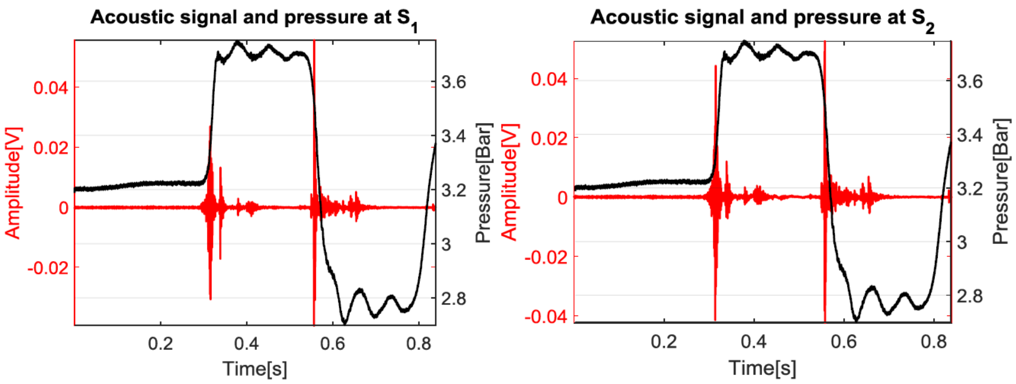


Figure 2: The recorded pressure fluctuations (black) and acoustic signals (red) at the two sensors

Figure 3 shows that the RQA TDR* measure succeeds to detect the acoustic transients regardless of mechanical vibrations and environmental noise recorded by the sensors. For the computation of the TOF, we consider the values for which the RQA TDR* was 90% from the maxima, namely TDR* = 0.9.

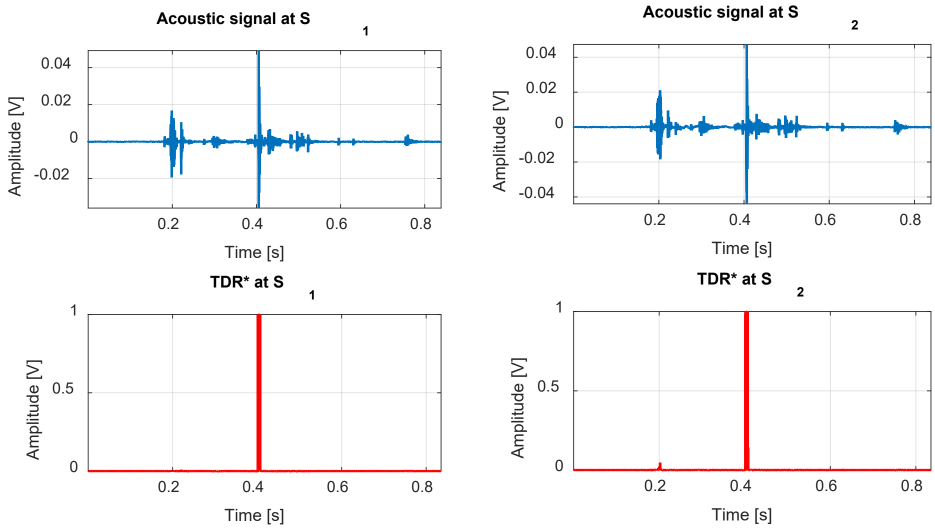


Figure 3: The curve detection of the acoustic signal arrived at the sensors using RQA TDR* measure: (a) acoustic signal arrived at sensor S1; (b) acoustic signal arrived at sensor S2

With the TDR* measure we obtained the TOF of $60\mu s$. With the distance between the sensors of $3.5\ cm$, the speed of the pressure wave c_{RPA} is 583 m/s. Also, considering the time of arrival of 90% of the maximum value of the acoustic transients' maxima (classical signal processing approach - SP), we get TOF of $58\mu s$, namely c_{SP} is 603 m/s. The difference between the classical approach and the RPA method is given by the diffusion of the acoustic wave generated by the water hammer.

4.2 The Joukowski approach

Using the eq. (2), the theoretical value of pressure wave speed in the Plexiglas pipe is computed considering the parameters of the water and the pipe as given by Table 1.

Parameter	Value
ρ	1000 kg/m^3
e_w	2.1GPa
e	5 mm
E	3.2GPa

Table 1 The characteristics of the pipe and fluid

With these values, the theoretical pressure wave speed obtained is $c_{th} = 580\ m/s$.

4.3 Results

The results from Table 2 show that RPA approach gives satisfying results very close to the theoretical value. The precision depends on the choice of the threshold for the TDR* measure.

Method	Speed of the pressure wave
c_{th}	580 m/s
c_{RPA}	583 m/s
c_{SP}	603 m/s

Table 2 The speed of the pressure wave in different approaches

The theoretical value for the industrial hydraulic systems presents the difficulty to determine a correct elasticity modulus of the materials that may be degraded and changed since their design, which will directly influence a correct evaluation of the pressure wave speed and so, of the maximum pressure. Moreover, for certain systems, the geometrical characteristics may not always be available.

The signal processing approach (SP) does not imply complex computational procedures using only an imposed level of the acoustic transients, but has a lower performance compared to the theoretical value. The error may be due to the fact that the acoustic signals are diffused, so the TOF may be altered. We emphasized that the correlation, a state-of-the-art method used in the computation of the TOF for acoustic signals, did not give any realistic result in this case.

5. Conclusions

The studied effect, namely, the water hammer, proved to have a high risk of provoking damages to the water pipe system if sudden changes that affect the flow are performed without control in the hydraulic systems. The proposed method is non-invasive and has no influence upon the measured data and the surveyed phenomenon. This approach has the advantages of precisely detecting and characterizing the water hammer effect. Moreover, being a non-invasive method means that the ultrasonic sensors are easily placed on the monitored system without needing a direct contact with the fluid.

As we demonstrated in the paper, the RPA tool has a high potential to determine an accurate value of the velocity of the fluid with little prior knowledge about the monitored pipe system. The algorithm is compared with the Joukowsky equation. The latter, has the disadvantage of needing all the characteristics of the hydraulic system, which are not easily obtained in some cases.

Further work foresees an acoustic transceiver calibration for different configurations and the use of the acoustic transceivers in active configuration for the flow rate computation.

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