Time reversal of waves in pressurized pipes

Muhammad Waqar YP[1*], Moez Louati [1], Mohamed S. Ghidaoui[1]

1 Hong Kong University of Science and Technology, Hong Kong, SAR China

*Correspondence YP: mwaqar@connect.ust.hk

Abstract Time reversal (TR) of transient waves has been recently introduced as a powerful technique for defect detection in pipelines. However, there remains an unresolved paradox that although TR breaks down due to inevitable damping in real systems, TR based defect detection techniques are optimal in the sense of signal to noise ratio. This paper aims to address this paradox experimentally. The experiment is conducted in a simple pump-pipe-valve system and performed in two steps as described below. The results show that the time-reversed waves focus back on the source, effectively proving the time-reversibility of waves in pipes.

Keywords: Hydraulic transients, leak detection, time reversal, waterhammer, valve stroking.

Introduction

TR of waves is recently applied in pipeline hydraulics to develop defect detection schemes using transient waves (Waqar et al., 2019; Wang et al., 2019; Zouari et al., 2020). The accuracy and performance of these techniques are intriguing because the wave equation is strictly not time reversible in the presence of damping. For instance, the waterhammer wave equation with linear frictional damping is written as

$$\frac{\partial^2 H(x,t)}{\partial t^2} - a^2 \frac{\partial^2 H(x,t)}{\partial x^2} - R\frac{\partial H(x,t)}{\partial t} = 0 \qquad (1)$$

where H is the pressure head, t is the time, x is the position, a is the wave speed, and R is the linear damping coefficient. It is easy to verify that Eq. 1 (without last term) is time-reversible. However, with the damping term and changing t to $-t$ in Eq. 1 gives

$$\frac{\partial^2 H(x,-t)}{\partial t^2} - a^2 \frac{\partial^2 H(x,-t)}{\partial x^2} + R\frac{\partial H(x,-t)}{\partial t} = 0 \qquad (2)$$

Note that the damping term in the time reversed equation has a positive sign implying that TR does not hold.

This work aims to address this paradox experimentally. In particular, the objective is to investigate how well the time-reversed waves refocus back at the source and reproduce the transient trace that was injected through a source

Setup and Methodology

Property	Description
Length	142.08 m
Material	High density polyethylene
Diameter	79.2 mm
$H(x=0,t=0)$	19.95 m
$Q(x=0,t=0)$	0.4 l/s

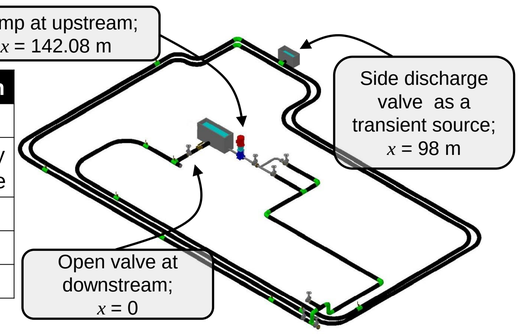

Figure 1: Schematic of the setup.

1) After establishing steady state flow, a valve at x = 98 m is rapidly and manually opened and closed in 0.1 s to induce a transient wave as a source;
2) The transient response of the system is recorded at (i) the downstream end, (ii) the upstream end, and (iii) near the transient source;
3) The recorded signals at upstream and downstream sides are flipped in time such that the first value becomes last and last value becomes first;
4) These time-reversed signals are used as boundary conditions in the transient model.

Results and Conclusions

- Figure 2a shows that the re-emitted waves refocus only at the correct source location and at the time of the source (i.e. t = 0.1 s). The localization error is about 0.97 m.
- Figure 2b shows pressure-time history at the refocused location which is similar to the measured transient trace near the source, implying that re-emitted waves followed their past steps accurately.
- It is concluded that various damping effects only affect the amplitude of the waves and do not alter the refocusing property of waves which is the key to localize defects.

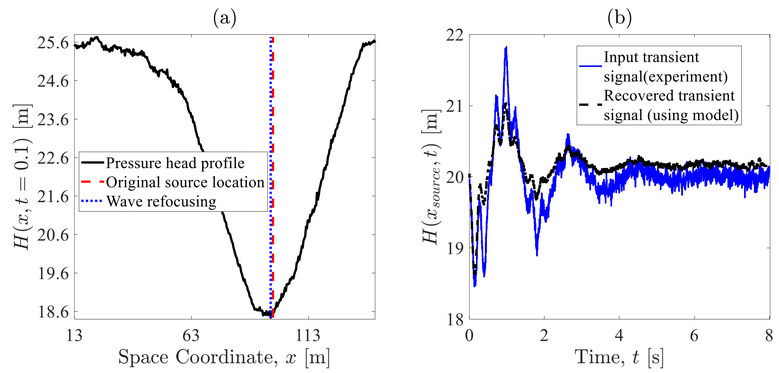

Figure 2: (a) wave refocusing at the source, and (b) transient pattern of the injected and refocused wave.

Bibliography

Waqar, M., Louati, M., & Ghidaoui, M. S. (2019). Leak Localization Using Time Reversal Technique. In the proceedings of the 38th IAHR World congress, held in Panama.

Wang, X., Lin, J., Keramat, A., Ghidaoui, M. S., Meniconi, S., & Brunone, B. (2019). Matched-field processing for leak localization in a viscoelastic pipe: An experimental study. *Mechanical Systems and Signal Processing*, *124*, 459-478.

Zouari, F., Louati, M., Meniconi, S., Blåsten, E., Ghidaoui, M. S., & Brunone, B. (2020). Experimental verification of the accuracy and robustness of Area Reconstruction Method for Pressurized Water Pipe System. *Journal of Hydraulic Engineering*, *146*(3), 04020004.