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Transient wave-blockage interaction and extended blockage detection in elastic water pipelines

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ABSTRACT

Extended partial blockages are common in pressurized water pipelines and can result in the wastage of energy, the reduction in system carrying capacity and the increased potential for contamination. This paper investigates the transient wave-blockage interaction and its application to extended blockage detection in pipelines, where blockage-induced changes to the system resonant frequencies are observed. The frequency shifting is first inspected and explained in this study through wave perturbation analysis, providing a theoretical confirmation for the result that unlike discrete blockages, extended blockages cause resonant frequency shifts in the system. Furthermore, an analytical expression is derived for the relationship between the blockage properties and the resonant frequency shifts and is used to detect the blockages in this study. The obtained results are validated through both numerical applications and laboratory experiments, where the accuracy and efficiency of the developed method for extended blockage detection are tested.

1. Introduction

Pressurized conduits transporting fluids such as freshwater, seawater, storm-water, wastewater, oil, and blood often experience partial blockages during their lifetime. The blockages begin in the form of a small increase in the wall roughness that grows with time from physical or chemical processes and can eventually block a sizeable portion of the pipe cross sectional area (Stephens, 2008). These blockages result in the wastage of energy, a reduction in the pipe carrying capacity and the increased potential for contamination. In addition, the severely throttled flows from blockages cause flow redistribution in the pipe network and can result in the overpressure of pipes and the development of leaks. It is therefore of paramount importance to detect blockages so that they are dealt with in a timely manner.

Transient-based method, where a transient signal is injected into the conduit and the response measured at specified locations, is a promising approach for detecting defects in pipes and has been used in the detection of discrete blockages, leaks, and assessment of pipe wall condition (Liggett and Chen, 1994; Brunone, 1999; Brunone and Ferrante, 2001; Vítkovský et al., 2000; Wang et al., 2002, 2005; Ferrante and Brunone 2003; Covas et al., 2004; Mohapatra et al., 2006; Sattar et al., 2008; Lee et al., 2004, 2006, 2008; Stephens, 2008; Duan et al., 2011a, 2011b, 2012, 2013; Mohapatra and Chaudhry, 2011;

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Nomenclature

a	wavespeed
A	pipe cross-sectional area
C^*	shear decay coefficient in unsteady friction model
C_n	amplitude of boundary wave
C_p	amplitude of incident pressure wave
D	pipe diameter
f	friction factor
g	gravitational acceleration
i	imaginary unit for complex number
I	amplitude of incident wave
k	wave number
L	pipe length
m	integer number
P	pressure head
Q	discharge
R	amplitude of reflection wave
R_f	friction damping factor
R_e	Reynolds number
t	time
x	longitudinal distance
Y	characteristic impedance of pipeline
γ	relative error of prediction
δ	operator of variation
ε_a	change of wavespeed
ε_A	change of pipe cross-sectional area
ε_L	longitudinal blockage range
ε_Y	change of characteristic impedance
ε_λ	change of wave propagation coefficient
θ	wave number
λ	wave propagation coefficient
ν	kinematic viscosity
ξ	coefficient relating to the blockage size
ρ	density of fluid
ω_{rf}	resonant frequency of pipe transients
ω_{th}	theoretical frequency of a pipe system
$\Delta\omega_{rf}$	shift size of resonant peak frequency

Subscripts and superscripts

b	quantity of blockage pipe case
S, U	quantity of steady and unsteady state
0	quantity of uniform pipe case
1, 2, 3	section indexes of blockage pipeline.

Meniconi et al., 2009, 2011, 2013). The tenet of this approach is that a measured pressure wave signal in a conduit is modified by, and thus contains information on, the conduit properties.

Stephens et al. (2005), Brunone et al. (2008) and Duan et al. (2012) proposed that blockages in pipes are divided into two categories—discrete and extended blockages—according to its relative length to the total pipeline length. In the context of discrete blockages, Contractor (1965) shows that a discrete partial blockage causes a partial reflection of a waterhammer wave where the amplitude of the reflected wave provides information on the severity of the constriction and the arrival time of the reflected wave provides the location of the blockage. The findings in Contractor (1965) have been confirmed and used for blockage detection by Wang et al. (2005) and Meniconi et al. (2009, 2011, 2012). Wang et al. (2005) showed that a discrete blockage in a pipe system introduces a frequency dependent damping to the transient signal and developed a technique for locating and sizing discrete blockages based on this damping. Mohapatra et al. (2006), Sattar et al. (2008) and Lee et al. (2008, 2013) found the effect of the blockage in time translates to a pattern being imposed onto the amplitudes of the resonant responses from the system and this pattern can be used to detect and locate the discrete blockages in the frequency domain.

Field tests by Stephens et al. (2005) and laboratory experiments by Meniconi et al. (2012) showed that extended blockages have significantly different impacts on the system responses compared to discrete blockages and discrete blockage detection techniques are not applicable for extended blockages. Stephens et al. (2005) shows that severe wall deterioration is often associated with a reduction in the pipe flow area as well as wavespeed, with nearly 40% reduction in both parameters observed in the field. Similarly, extended changes in pipe wall thickness and material was found to produce changes in the wavespeed in the laboratory studies of Hachem and Schleiss (2011, 2012a, 2012b) and Tuck et al. (2012). Duan et al. (2012) and Tuck et al. (2012) show that extended blockage changes the amplitude as well as the position of resonant responses from the system. An analytical expression for the blockage-induced changes in the system resonant frequencies was derived in Duan et al. (2012) and was used for detecting extended blockages in pipelines. To determine the properties of the blockage, an optimization process coupled with a Genetic Algorithm (GA) was used to fit the observed resonant frequencies with the theoretical expression. This approach was verified using numerical as well as experimental results in Duan et al. (2012, 2013) and Meniconi et al. (2013). It was found from these studies that the solution process is time consuming and its efficiency decreases significantly with the number of blockages in the system. A simplified form to the original analytical equations was developed in Duan et al. (2013) and the computational efficiency was increased by sacrificing the accuracy of the solution.

This paper further investigates the effect of extended blockages on the system frequency response and proposes an improvement to the frequency domain method for detecting extended blockage in pipes. The frequency shifts due to wave-blockage interaction is inspected using wave perturbation analysis and the expression for the resonant frequencies shifts proposed in Duan et al. (2012) is simplified using a first order approximation and the result is validated numerically and experimentally.