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Cavitation influence on hydroacoustic resonance in pipe

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ABSTRACT

In pipe systems, pressure and flow fluctuations below cutoff frequency propagate as plane waves along pipes. Depending on the pipe length and propagation velocity, resonance leading to high amplitude pressure fluctuation may occur. At low pressure, cavitation is an important source of fluctuation. Beside its active role in the mechanism of noise generation, the cavitation reflects partially the incoming plane waves. This may modify the values of the eigenfrequencies of the system consisting of the pipe, the contained fluid and the vapor cavity. The influence of cavitation is experimentally investigated in a hydroacoustic resonator: a straight pipe connecting two tanks. At three quarters of the pipe length, a bluff body is placed cross flow to generate periodic vortex wake cavitation in a limited section of the pipe. The analysis of the wall pressure measurements along the hydroacoustic resonator results is performed with the help of a one-dimensional transient model of the pipe including the compliance of the cavities created in the wake of the bluff body. The results of the numerical simulations enable the determination of both the eigenvalues within the resulting system of equations and the mode shape of the pressure fluctuations corresponding to the experimental results.

1. Introduction

Cavitation plays an essential role in the generation and the propagation of acoustic waves in the hydraulic systems. It is of major concern for numerous industrial applications such as hydropower (Arpe et al., 2009), pumps (Berten et al., 2007), ship propellers (Watanabe and Brennen, 2003) and rocket propulsion (Bouziad, 2005; Bouziad et al., 2003). The generation and propagation of noise in pipes has been studied for a long period of time and is still topical (Eid and Ziada, 2011; Hachem and Schleiss, 2011). The review article of Reethof (1978) concerning noise induced by turbulence gives a good overview of the physical mechanism and the technical concerns. However, few studies involve the problematic nature of cavitation and mainly focus on noise generation, see Testud et al. (2007) and Hassis (1999); in their study of cavitation noise induced by single-hole and multi-hole orifices in pipes, Testud et al. (2007) observed eigenmodes in a domain bounded by the cavitating orifice and a valve containing air pockets. The air pockets and the vapor cavities were suspected to reflect the acoustic waves. As a result, the fluctuations were confined between those two reflective boundaries and eigenmodes have been observed in this restricted domain of the hydraulic circuit. In his experimental research, Hassis (1999) investigated the noise induced by a cavitating valve. His analysis included the effect of the vapor cavity on the pressure waves. He applied an analytical model to correlate the measured resonant frequencies upstream and downstream the valve with the help of the propagation velocity in the cavitating section of the pipe and its length.

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Nomenclature

A	pipe cross section (m^2)	K	vapor cavity compliance (m s^2)
a_0	plane wave velocity (m/s)	K_w	liquid compressibility (Pa)
B	pipe width (m)	L_{TOT}	pipe length (m)
C	flow velocity (m/s)	P_{yx}	cross power spectral density (c_p^2/Hz)
c_p	pressure coefficient	P_{xx}	power spectral density (c_p^2/Hz)
D	bluff body diameter (m)	p	pressure (Pa)
D_h	hydraulic diameter (m)	p_v	water vaporization pressure (Pa)
f	frequency (Hz)	Re	Reynolds number
f_{cutoff}	pipe cutoff frequency (Hz)	St	Strouhal number
f_D	drag frequency (Hz)	T	frequency response function
f_L	lift frequency (Hz)	V_c	vapor cavity volume (m^3)
f_n	pipe natural frequency (Hz)	λ	wave length (m)
f_s	source frequency (Hz)	ρ_0	water density (kg/m^3)
		σ	cavitation index
		σ_i	incipient cavitation index value

In the present paper, the influence of hydrodynamic cavitation on pipe hydroacoustic resonance is investigated experimentally and numerically. The analysis is restricted to pressure fluctuation below cutoff frequency, f_{cutoff}= 19 000 Hz in the present experiment; accordingly plane wave propagation is assumed. The flow in a straight PVC pipe connecting two tanks at constant pressure has been investigated. At three quarters of the pipe length, a bluff body is placed cross flow to induce flow separation. The resulting flow instability, known as bluff body induced vortex shedding, generates acoustic pressure waves. For a sufficiently compact body, $D \ll \lambda$, the flow instability is equivalent to a dipole source of sound. In the framework of acoustic plane waves propagation in a pipe, this type of source is also known as momentum source and its amplitude and frequency are related to the drag force applied on the bluff body (Blake, 1986). Depending on the flow velocity, the frequency of the source may match one of the eigenfrequencies of the system and eventually lead to hydroacoustic resonance. The system refers to the hydroacoustic resonator including fluid compressibility and the effect of the pipe wall deformation. For a pure liquid, the propagation velocity of acoustic plane waves in a pipe is determined by the fluid compressibility and the wall stiffness (Ghidaoui et al., 2005; Nicolet, 2007; Tijsseling, 1996). Kortweg's equation (1) provides a good approximation of the propagation velocity of acoustic plane waves in an elastic pipe:

$$\frac{1}{a_0^2} = \rho_0 \left(\frac{1}{K_w} + \frac{\Delta A}{A \Delta p} \right), \tag{1}$$

where the first term on the right accounts for the fluid compressibility while the second term accounts for the elastic deformation of the pipe.

At low pressure, cavitation is observed in the wake of the bluff body. In such condition, the amplitude of the acoustic fluctuation is strongly amplified in the entire pipe as the cavitation is an efficient source of sound. The corresponding source, interpreted as a mass source, is due to the variation of the vapor cavity volume (Blake, 1986). A strong coupling exists between the acoustic pressure fluctuation and the mass source in the cavitating region. This coupling results in the modification of the eigenfrequencies of the system. The hydrodynamic cavitation may therefore have two effects on the hydroacoustic resonance of the pipe. First, the cavitation can be an additional source of noise. Second, the eigenfrequencies of the system are modified by the cavitation. In the present study, it is found that the first effect could be neglected and we focus on the study of the second effect which consists mainly of a strong decrease of the pressure wave propagation velocity in the cavitating region of the pipe. The cavitating section being short with respect to the pipe length, a one-dimensional mathematical model of the time dependent pipe flow using a lumped cavitation compliance can be successfully applied to describe the influence of cavitation on the eigenmodes of the system, see for instance Brennen and Acosta (1976) and Watanabe and Brennen (2003), who have applied such model to the cases of cavitating impeller in circuit and propeller resonance in a water tunnel.

The cavity compliance, K, defined as Eq. (2) is the partial derivative of the vapor volume, V_c, with respect to the pressure in the cavitating region (Brennen and Acosta, 1976; Rubin, 1966) and therefore accounts for the relation between the pressure in the source region and the mass source due to the vapor cavity:

$$K = -\rho_0 \frac{\partial V_c}{\partial p}. \tag{2}$$

The paper is organized as follows. In Section 2, the hydroacoustic resonator and its instrumentation are introduced and the presentation of the investigated flow conditions is given as well. Then, in Section 3 the main results are presented, which contain the mass and the momentum source frequency, the influence of the cavitation index on the eigenfrequency of the system and the evaluation of the resonance frequency. In Section 4, the mathematical model is developed and