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Flow visualization study of flow-induced acoustic resonance in closed side branches

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ABSTRACT

The phenomenon of flow-induced acoustic resonance is encountered when an acoustic mode of a side branch is coupled with the flow instability oscillations, which may generate undesirable vibrations of components in pipe systems. In particular, flow-induced acoustic resonance has caused some problems in nuclear power plants. In this study, the characteristics of the flow-induced acoustic resonance in square closed side branches are investigated experimentally. Three different aspect ratios of L/b = 5, 6 and 7, where L is the branch height and b is the branch width, are investigated with Mach number up to 0.22. The flow structures in different acoustic and hydrodynamic modes are visualized using a high speed camera, and the frequencies counted by visual measurement agree well with the frequencies measured by dynamic pressure sensors. The effects of side branch height on the amplitude and frequency characteristics of the acoustic resonance are demonstrated. The results indicate that the maximum normalized pulsation amplitudes in different resonance modes decreases in branch height, acoustic mode and hydrodynamic mode. The branch height has little influence on the Strouhal number at onset of resonance, which is about 0.55 for the first hydrodynamic mode and 0.95 for the second hydrodynamic mode in this work. The maximum normalized fluctuating pressure at the first acoustic mode occurs at a Strouhal number close to 0.43. The hysteresis phenomenon in the evolution of the fluctuating pressure as a function of the velocity is analyzed.

1. Introduction

The flow-induced acoustic resonance phenomenon is excited when an acoustic mode of a side branch is coupled with the flow instability oscillations, which may generate undesirable vibrations of components in pipe systems. In particular, in nuclear industry, many Nuclear Power Plants (NPPs) have conducted extended power uprate in recent years, which increases the flow velocity of the main steam lines. Experiments, performed in actual plants (DeBoo et al., 2006; Ziada, 2010) and scale models (Takahashi et al., 2010, 2016), and numerical analysis (Morita et al., 2011; Takahashi et al., 2008) have demonstrated that higher flow velocities in the main steam lines may increase the fluctuating pressure acted on the steam dryer in NPPs. Meanwhile, the flow-induced acoustic resonance in closed side branches, formed by safety relief valve (SRV) stub pipes, was considered to be the main cause (Takahashi et al., 2016).

Many investigations of the flow-induced acoustic resonance in closed side branches and the attenuation methods in the background of NPPs have been reported in the literature (Okuyama et al., 2009, 2012; Takahashi et al., 2008, 2016; Tamura et al., 2012). In particular, a design chart which can predict the critical flow velocities in the main pipe at onset of resonance is developed by Ziada and Shine (1999). They found that both the velocity distribution at the mouth of the branch and the diameter ratio of the side branch to the main pipe (d/D) have strong influence on critical St. Graf and Ziada (Graf and Ziada, 2010) developed a semi-empirical method, considering the integrated effect of shear-layer excitation by a pressure difference across the shear layer, to predict the fluctuating pressure amplitudes under conditions of different flow and geometric parameters. The phase and amplitude of the measured source term used in the semi-empirical method were experimentally derived for a wide range of sound pressure level (SPL) and Strouhal number.

However, investigations focusing on flow visualization and movement of vortex are quite limited. In this work, the flow-induced acoustic resonance in square closed side branches is investigated experimentally to clarify the resonance mechanism. Three

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Nomenclature

a	width of square main pipe (m)	n	order of the acoustic mode
b	width of square branch (m)	P	root mean square amplitude of acoustic pressure (Pa)
c	velocity of sound (m/s)	P^*	dimensionless pressure pulsation ($2P/\rho V^2$)
f	frequency (Hz)	SPL	sound pressure level (dB), P0 = 20 μPa
L	height of branch (m)	St	Strouhal number
L_c	characteristic length (m)	T	temperature (°C)
L_d	length of developing section	V	velocity (m/s)
L_e	end correction (m)	ρ	density (kg/m^3)
m	order of the hydrodynamic mode		
Ma	Mach number		

different aspect ratios of L/b = 5, 6 and 7, where L is the branch height and b is the branch width, are investigated with Mach number up to 0.22. The flow structures in different acoustic and hydrodynamic modes are visualized using a high speed camera. The effects of side branch height on the amplitude and frequency characteristics of the acoustic resonance are declared. The hysteresis phenomenon in the evolution of the fluctuating pressure as a function of the velocity is analyzed.

2. Experimental apparatus and test sections

A schematic diagram of the pressurized-air test facility used in this work is illustrated in Fig. 1. The facility was equipped with a screw air compressor, a pressurized-air tank, a filter, two regulating valves, two absorption silencers, a needle valve, a smog chamber, and a turbine flowmeter. The absorption silencers were installed at the inlet and outlet of the test section to decrease the noise coming from the valves and air compressor. The static pressure in the system was regulated by the pressure regulating valve. The flow rate was combined controlled by the flow regulating valve and the compressor. The smog pipe was used to inject the flow-tracing particles.

The test sections were made of 10 mm acrylic glass and the cross sections of the side branch and the main pipe were both square as shown in Fig. 2(a). Table 1 shows the dimensions of the test sections in detail. The inner width of the main pipe and side branch were both 50 mm. Three different aspect ratios of L/b = 5, 6 and 7, where L is the branch height and b is the branch width, were investigated. The edges of the branches were sharp right angles as shown in Fig. 2(b). Fig. 2(c) presents the visualization system, in which a high speed camera is used to measure the two-dimensional flow fields in the mouths of the square branches. The high speed camera captures the positions of the flow-tracing particles injected by the smog pipe. The tracer particles were mixture of water and glycerin, the density of which was adjusted to be the same as air to eliminate the influence of mixed-in tracer on flow characteristic. The concentration of the tracer particles was optimized according to the flow state.

The static pressures and temperatures of the pressurized-air were measured by pressure transmitters and thermal couples respectively. The static pressure in the main pipe was atmosphere in the present work. The turbine flowmeter was used to measure the local volume flow rate, which was converted to mass flow rate based on the state parameters of the local pressurized-air measured by the local thermal couple and pressure transmitter. The mass flow rate was converted to volume flow rate again in the test section based on the local state parameters of pressurized-air. A silicon piezoresistive high frequency dynamic pressure sensor was installed in the closed end of the side branch and two other dynamic pressure sensors were installed at both ends of the test section in the main pipe to measure the pressure fluctuations. A four channel spectrum analyzer was used to analysis the pressure signals. The flow velocity in the main pipe was ranged from 10 to 75 m/s in the present work.

The uncertainties of parameters used in the experimental analysis are listed in Table 2. Repeatability tests were performed to assure the consistency and repeatability of the experimental results. The sampling rate of the data acquisition is 5 kHz and each signal is averaged 10 times which correspond to 10 s in real time.

3. Results and discussion

3.1. Amplitude and frequency characteristic

Fluctuating pressures at the closed end of a side branch, having height of 250 mm, are shown in Fig. 3 for three different main pipe velocities, 31.5, 38.4 and 41.5 m/s. It is observed that the fluctuating pressures are in the form of sine wave at velocities of 38.4 and 41.5 m/s, which means acoustic resonance occurs under these two conditions. The frequencies of the fluctuating pressures are almost the same, which indicates the two pressure fluctuations are at the same acoustic mode. The amplitude of the fluctuating pressure at velocity of 41.5 m/s is significantly large than that at velocity of

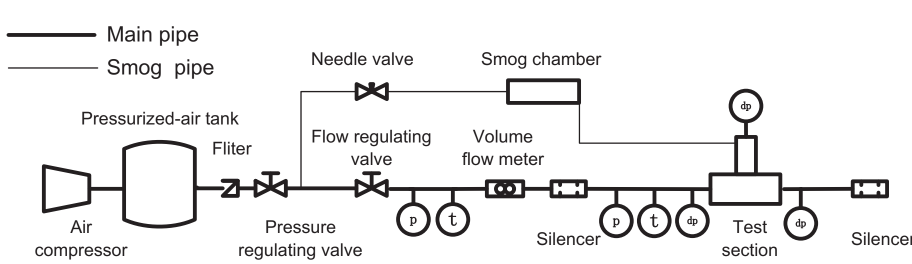

Fig. 1. Scheme of the experimental system of acoustic resonance.