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Experimental characterisation of the self-excited vibrations of spring-loaded valves

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HIGHLIGHTS

- Dynamic instability of a spring-loaded valve is investigated.
- The excitation mechanism is due to acoustic, structural, and hydrodynamic coupling.
- Limit cycle behaviour is observed for cases below the maximum valve lift.
- Increasing the valve spring stiffness is seen to cause more severe vibrations.
- Increasing the length of the piping is seen to destabilise the valve as well.
- The instability mechanism is analogous to that seen in compressor disk-type valves.

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ABSTRACT

Valves are omnipresent in industrial processes. As a result, they must perform reliably according to their specifications. Spring-loaded valves are particularly susceptible to vibrations, as they are inherently flexible, often operate at small openings, and therefore they are more likely to interact with the surrounding flow. The current study experimentally investigates the self-excitation mechanism of a model spring-loaded valve with an emphasis on the interaction between the system flow and sound fields, and the valve structure. Tests are performed for various values of valve stiffness and maximum allowable valve lift. In each case, the pressure drop across the valve is increased gradually until the valve becomes fully open. The valve was found to oscillate at the fully coupled resonance frequency resulting from the interaction of the valve vibration with the acoustic field of the piping system. The oscillation amplitude was found to be positively correlated to both the pipe length and spring stiffness value. Furthermore, initial spring compression was found to have only moderate effects on the range of static pressures that would cause instability.

1. Introduction

Valves are critical components to industrial processes. Whereas they are often designed to be replaceable and inexpensive, valve failures can cause costly shutdowns in addition to safety hazards in certain applications. Flow-induced vibration is an important concern for the operation of spring-loaded valves, as it can not only shorten the life of the valve but also affect its performance during operation due to oscillations of the flow area. As such, valve vibrations have been an ongoing subject of inquiry for over a half-century. Early researchers investigated stability problems in hydraulic control valves (Kasai, 1968).

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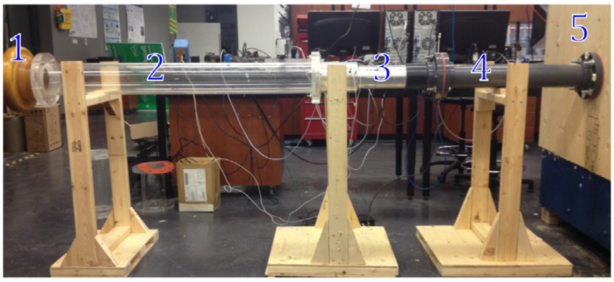

Fig. 1. Spring-loaded valve test facility. 1- Bellmouth entrance, 2- Upstream piping, 3- Valve test section, 4- Downstream piping, 5- Settling chamber.

Subsequent investigations mainly provided steady response modelling of valves subjected to flow (Killmann, 1972; Tsui et al., 1972) or performed a linear analysis of valve vibrations suitable for small amplitude oscillations (Kolkman, 1976). Certain studies considered nonlinearities in the structure of the valve, namely nonlinear gasket stiffness (Nayfeh and Bouguerra, 1990). Others provided physical descriptions of the interaction between the structure of the valve and the flow-field by simplifying the complex flow geometry. Such investigations presented by Weaver and Ziada (1980) as well as D'Netto and Weaver (1987) provide useful prediction capabilities for check and poppet valves. Additional experimental work done by Ziada et al. (1986) on multi-ring disk valves used in reciprocating compressors has exposed some important features of the excitation mechanism and showed that the vibration persists even under steady flow conditions. The vibration frequencies were different from the natural frequency of the valve, which would be due to the valve plate inertia and valve spring stiffness. The influence of the upstream and downstream piping was also observed, with oscillations observed to occur at frequencies close to the acoustic plane wave modes of the pipes. Finally, the work of Habing and Peters (2006) revealed that gas forces applied to spring-loaded valves in compressors behave in a quasi-steady fashion, while the same cannot be said for the discharge through the valve, especially when the valve virtually closes during vibration.

When acoustic effects are present, previous studies have shown the existence of an interaction mechanism between the structural properties of the valve, the acoustic properties of the piping system, and the fluid flow through the valve. One such study was completed by Baldwin and Simmons (1986), who provided a case study of dynamic instability of pressure relief valves in operation in various locations in steam power plants, and investigated their operational conditions to determine factors affecting instability. Other researchers (Ziada et al., 1987) conducted series of experiments for the purpose of selecting a suitable spring stiffness for a particular valve design in order to mitigate the severity of the self-excited oscillations and demonstrated coupling with the acoustic properties of the piping. Moussou et al. (2010) also considered the effect of reflected acoustic waves at the upstream pipe on the valve's dynamic instability for water flow through a particular safety relief valve. The instability frequencies were found to be a function of the valve geometry and its hydraulic properties. More recently, Allison and Brun (2016) conducted testing on a pilot operated relief valve and found similar acoustic coupling.

Some knowledge of the valve behaviour coupled with a downstream piping system may be gained from the study of musical wind instruments, where the conditions under which dynamic instability occurs need to be understood in order to produce pleasant sounds. The self-excited phenomenon can be considered similar to the spring-loaded valve case as the instrument player applies a pressure differential across the reed, which will oscillate at frequencies that are believed to depend on the boundary conditions of the tube. However, these studies tend to focus more on the sound resonant and sound radiation capabilities of the instrument rather than the oscillation characteristics of the reed. Wilson and Beavers (1974) experimentally investigated the effects of reed damping on the excited mode of the tube in a clarinet. Atig et al. (2004) provided a numerical analysis of the linear and nonlinear acoustic losses that cause a clarinet to saturate at certain frequencies but excessively attenuate the sound at others, defining its timbre and playing range.

While the above literature about spring loaded valves provides some valuable insight into valve vibration, a generalised description of the valve dynamics that accounts for the effects of the unsteady characteristics of the flow, the valve geometry, and fully defines the influence of the acoustic properties of the piping system remains elusive. To this effect, the current study aims to provide a foundation of experiments on a model spring-loaded valve that can be used to describe the self-excited instability behaviour of spring-loaded valves found in use in the industry, specifically as observed by Ziada et al. (1986, 1987). This will provide a reliable datum against which a simplified model of the unsteady hydrodynamics, the valve structural oscillations, and the acoustic pressure in the piping system could be validated in order to predict and design against flow induced vibration of spring-loaded valves.

2. Experimental methodology

The test facility used for this investigation is shown in Fig. 1. The design of the model valve involved several assumptions. A bell-mouth entrance is used for a smooth entrance of the air flow. The flow is then directed through a pipeline of variable length (140 mm in diameter) upstream of the valve test section. The test section contains a spring-loaded valve. Subsequently the flow is guided through additional piping (102 mm in diameter) of variable length to a settling chamber of a Roots blower