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Optimization of valve opening process for the suppression of impulse exhaust noise

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ABSTRACT

Impulse exhaust noise generated by the sudden impact of discharging flow of pneumatic systems has significant temporal characteristics including high sound pressure and rapid sound transient. The impulse noise exposures are more hazardous to hearing than the energy equivalent uniform noise exposures. This paper presents a novel approach to suppress the peak sound pressure as a major indicator of impulsiveness of the impulse exhaust noise by an optimization of the opening process of valve. Relationships between exhaust flow and impulse noise are described by thermodynamics and noise generating mechanism. Then an optimized approach by controlling the valve opening process is derived under a constraint of pre-setting exhaust time. A modified servo-direct-driven valve was designed and assembled in a typical pneumatic system for the verification experiments comparing with an original solenoid valve. Experimental results with groups of initial cylinder pressures and pre-setting exhaust times are shown to verify the effects of the proposed optimization. Some indicators of energy-equivalent and impulsiveness are introduced to discuss the effects of the noise suppressions. Relationship between noise reduction and exhaust time delay is also discussed.

1. Introduction

Pneumatic systems using high pressure compressed air as a power source widely exist in the industrial production. The air charging and discharging processes of pneumatic cylinder through valves are recurrent to generate aerodynamic noise, especially the venting of exhaust to the atmosphere directly [1–3]. Differing from steady state noise or continuous noise by the properties in the time domain, impulse exhaust noise similar to other impulse noises such as muzzle blast, commonly consists of single bursts with a duration of less than one second with peak levels 15 dB higher than background noise [4]. Impulse exhaust noise is intermittent, it contains rapid sound pressure transients and reaches extremely high sound pressures with a very rapid rise time.

There are two main assessments of risk of hearing loss in exposure to impulse noise, the peak level and the energy concept aimed at steady state continuous noise. Energy-equivalent method based on equal energy principle is applied to evaluate the impulse noise traditionally. However, there is the inadequacy in modelling the risk for hearing loss due to the underestimation of the purely energy-equivalent determination based to the present knowledge. Impulse noise exposures that contain high-level transients with short duration are more hazardous to hearing than energy equivalent uniform noise

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exposures [5]. When peak sound pressure levels (SPLs) exceed 135 dB, the risk of damage to the auditory system and other adverse health effects increases significantly. In China, the impulse noise number of occupational exposure in the workplace is limited less than 10,000 while the A-weighted peak SPL exceeds 120 dB(A) [6]. If the peak SPL increases 10 dB, the allowance of impulse exposure number should be reduced ten-fold [1]. Studies also introduced some impulsiveness indicators such as crest factor, kurtosis of impulse noise in order to correct the sound pressure level as a noise metric for risk assessment [7–10]. Therefore, it should pay close attention to reduce not only the equivalent SPL or SPLs in frequency but also the peak sound pressure or the impulsiveness of noise in time domain.

Several studies both on the mechanism and reduction methods of air exhaust noise were studied in recent years [11–15]. Impulse exhaust noise is generated by pulse jet in the pneumatic systems. Maa [11] indicated that the impulse noise as an important part of choked jet noise is generated by the shock waves due to the high pressure ratio. Potential energy of the compressed air in the cylinder converts to kinetic energy while air flow is accelerated through the valve [16]. Sound pressure of impulse exhaust noise is changed acutely because of the rapid flow change. According to Lighthill's general theory of aerodynamic noise, the flow noise through a valve is composed of acoustic monopoles caused by the variation of mass flow rate, dipoles representing the influence of solid boundaries upon the sound field and quadrupoles caused by turbulence [17,18]. The throttling effect of the valve is used to adjust the mass flow, and causes the flow acceleration generating large turbulent noise at the outlet. Besides, the fluid force on the valve shaft and solid body will also cause air fluctuation and sound [19]. Zhao and Shi et al. [13,14,20] pointed out that the acoustic source of impulse exhaust noise generated by impulse exhaust through valves is briefly acoustic monopoles and quadrupoles, and is mainly concentrated at the exhaust outlet.

Mufflers are commonly installed at the exhaust outlet to reduce the impulse exhaust noise. Muffling devices suppress the generation of noise or attenuate the noise already generated on the propagation path passively; but they are designed for specific equipment and may impede the exhaust, especially the dissipative mufflers [21–25]. Earmuffs and earplug protectors also help reduce exposure to both continuous noises as well as impulse noises. However, proper selection, fit and use of hearing protection, and other variables will impact hearing protector performance [26,27]. Instead, it is a more attractive method that improves the sound source characteristics directly to reduce the impulsiveness by changing the temporal properties of impulse exhaust noise.

Hence, this paper aims to attempt an approach that reduces the peak SPL for suppressing the impulse exhaust noise by the optimization of valve opening process. The common pneumatic poppet valve is introduced first to explain the exhaust passage. Then the sound source and flow characteristics of impulse exhaust are discussed. Based on the relationship between mechanical stream power and noise properties in time-domain, an optimized throat area curve of poppet valve under the constraint of the exhaust time during the valve opening process is obtained. Moreover, a 3-port valve directly driven by a servo motor was modified and installed in a typical pneumatic system to carry out the experiments. Indicators of the controlled impulse noise are discussed compared with the original valve finally.

The present paper is organized as follows. The typical pneumatic exhaust system with a common 3-port poppet valve and the mathematic model of flow properties are described first in Section 2. Section 3 presents the optimization method of valve opening process according to the relationship between the flow properties of exhaust and the acoustic properties of impulse noise. Section 4 describes the structure of experimental set-up including the modified servo-direct-driven valve. Section 5 presents the discussions of experiment results and, finally, Section 6 summarizes the main results of this paper.

2. Flow properties of impulse exhaust

2.1. Typical pneumatic system

Pneumatic systems such as pneumatic friction clutch and brake (PFC/B), clamping devices, and thrust control systems use pneumatic valves to control the cylinder pressure. Fig. 1 shows a typical application of a pneumatic system including an air reservoir or a single-acting cylinder, a 3-Port valve and an air source. The 3-Port valve is switched to change the port conductions for charging and discharging the compressed air. At the position shown in Fig. 1(a), port A connecting to cylinder and port R venting to atmosphere are connected allowing compressed air in the cylinder to be discharged; and at another position, compressed air from the air source is supplied to the cylinder. Besides that, exhaust valves are also used for discharging operation only. In most of the switching valves, the poppet is controlled by a pilot solenoid valve to achieve the switching actions. The exhaust passage schematic is shown in Fig. 1(b). When the spool valve moves up, compressed air in the cylinder will flow to port R through the throat between the spool valve and the valve body.

2.2. Model assumptions

Compressed air in the pneumatic cylinder exhausts to the atmosphere in a very short time after the valve opening. The air flows through the valve throat, of which the effective sectional area changes during the opening process. Exhaust passage of the valve can be considered as a convergent nozzle and a sudden expansion as shown in Fig. 2. In addition, some assumptions are given in details to facilitate the modeling of flow properties of impulse exhaust.