Applied Acoustics 145 (2019) 27–40

Contents lists available at ScienceDirect

Applied Acoustics

journal homepage: www.elsevier.com/locate/apacoust

Sound quality evaluation and prediction for the emitted noise of axial piston pumps

Junhui Zhang [a], Shiqi Xia [a], Shaogan Ye [a,b,*], Bing Xu [a], Shiqiang Zhu [b], Jiawei Xiang [c], Hesheng Tang [c]

[a] State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China
[b] Ocean College, Zhejiang University, Zhoushan 316021, China
[c] College of Mechanical and Electrical Engineering, Wenzhou University, Wenzhou 325000, China

ARTICLE INFO

Article history:
Received 20 August 2018
Received in revised form 15 September 2018
Accepted 19 September 2018

Keywords:
Axial piston pump
Sound quality
Semantic differential method
Neural network model

ABSTRACT

Sound quality has been an important attribute closely related to products' competitiveness. A neural network model is proposed to predict the sound quality of an axial piston pump based on the objective and subjective sound quality evaluations. Five psychoacoustic metrics of the objective evaluation and six adjective pairs of semantic evaluation method are utilized. The influences of the speed and outlet pressure on the objective and subjective evaluation results are compared. The correlations between the objective and subjective evaluation results are analyzed. The results show that the A-weighted sound pressure levels (AWSPLs) and loudness of the sound take on increasing with the increase of the speed and outlet pressure. There are strong correlations between the AWSPL and loudness and the perceptions of "unpleasant-pleasant" and "like-dislike", while the correlations between the fluctuation strength and the perception of "unpleasant-pleasant" and "like-dislike" are moderate, and the correlations between the roughness and sharpness and the perception of "unpleasant-pleasant" and "like-dislike" are weak. In addition, the results show that the sound quality model can predict the sound quality of axial piston pumps with good performance. This study lays the foundation for sound quality improvement of hydraulic displacement pumps.

1. Introduction

With the rapid increasing concern over global environmental protection, the demands for decreasing the environmental impact of fluid power systems and components are becoming more and more urgent. Low noise is often considered to be one of the most important customers' competitiveness for fluid power technology in the mobile, industrial, aerospace, and the other applications [1,2]. Axial piston pumps are the most widely employed power sources in these applications with the advantages of generating variable flow rate with high operating pressure [3,4]. However, the noise emitted from axial piston pumps is the prominent drawback [5], which is the main cause of annoyance to machine operators and customers in these fluid power systems.

The fluid-borne noise (FBN), structure-borne noise (SBN), and airborne noise (ABN) are the main noise emitted from the axial piston pump. The FBN is originated from the flow pulsation, which is mainly caused by the limited number of pumping elements and oil compressibility. The SBN is produced by the pulsating forces and moments acting on the internal parts of the pump. Both the FBN and SBN contribute to the generation of the ABN.

Based on the noise generation mechanism, many studies were carried out to improve the vibro-acoustic characteristics of the axial piston pump. A theoretical model was established to simulate the pressure and flow ripples in an axial piston pump [6]. The optimum parameters of the valve plate pre-compression and barrel kidneys were obtained to minimize the fluid-borne noise [7]. A novel timing mechanism was used to reduce the flow ripple at different operating conditions, and the sound pressure levels (SPLs) of the noise were reduced by up to 6 dB [8]. The cross-angle of the swash plate was found to be effective in reducing the noise, and the noise under the outlet pressure of 20 MPa and 25 MPa were respectively reduced by 3 dB(A) and 4.5 dB(A) [9]. Apart from reducing the noise excitation sources, structure modifications can also improve the vibro-acoustic characters of axial piston pumps. Ribs were added on the cover to optimize the main transmission path of radiated noise, and the result showed that the noise reduction of 1 dB(A) was achieved under the outlet pressure of 30 MPa

* Corresponding author at: State Key Laboratory of Fluid Power and Mechatronic Systems, Zhejiang University, Hangzhou 310027, China and Ocean College, Zhejiang University, Zhoushan 316021, China.

E-mail addresses: benzjh@zju.edu.cn (J. Zhang), xiashiqi@zju.edu.cn (S. Xia), shaoganye@zju.edu.cn (S. Ye), bxu@zju.edu.cn (B. Xu), sqzhu@zju.edu.cn (S. Zhu), jwxiang@wzu.edu.cn (J. Xiang).

https://doi.org/10.1016/j.apacoust.2018.09.015
0003-682X/

[10]. The housing was modified by the topology optimization and the result showed that the noise reduction of 2 dB(A) was achieved under the outlet pressure of 25 MPa [11]. In addition, research showed that free-layer damping materials [12], phononic crystals [13] and active control technologies [14–16] can be used to reduce the vibration and noise of axial piston pumps.

Most of the above-mentioned researches are focused on the reductions of the SPLs of axial piston pumps. However, the fluid power customers are having more awareness of the noise impacts on the health. The evaluation of the SPLs is insufficient because it cannot accurately reflect the human's auditory perception of sound quality to a great extent [17–19]. Therefore, it is of great importance to give a more detailed evaluation of the perceived sound quality of the noise emitted from axial piston pumps.

Many studies on the sound quality were developed in the engineering applications, which can be evaluated by the objective psychoacoustic parameters or subjective jury test. Psychoacoustic indexes, such as loudness, sharpness, roughness and fluctuation strength are often used as quantitative values in the objective evaluation of the sound quality. There has been an increasing demand to improve the sound quality of the vehicle noise, which comprises about 40% of the environmental noise in a city [20,21]. A roughness model of the vehicle interior noise was developed [22]. A sound quality index of the booming and rumbling noise was proposed using the artificial neural network [23]. The noise of the diesel engine is the main cause of the vehicle interior noise to passengers. The sound quality of a diesel engine was improved by an approach based simulation optimization [24,25], and the sound quality parameters can be respectively reduced by 33.36 sone (loudness), 0.13 acum (sharpness) and 0.08 asper (roughness) by optimizing the block of diesel engine [26]. A feedback controller was employed to reduce the loudness of the engine induced cavity noise [27]. Loudness and sharpness were used as the output of the sound quality prediction model of the vehicle noise, where the wavelet and neural network were utilized [28]. An equal-loudness compensation method was proposed to improve the sound quality [29]. In addition, the noise emitted from the household appliances, such as refrigerators, can affect our living environment. The loudness and roughness [30] and a synthesized indicator of sound quality [31] were found to be effective in predicting the noise and comfort of refrigerators.

Jury test is an essential approach to evaluate the sound quality with the human subjective point of view, where such methods as the rating scale method [23,32–34], paired comparison method [35–39] or semantic differential method [40,41] can be employed. The sound quality of the booming and rumbling noise emitted from a passenger car was evaluated using the artificial neural network [23]. The time and frequency masking were utilized to evaluate the knocking noise emitted from diesel engines [32]. A discomfort model was proposed based on the acoustical parameters of the micro commercial vehicles [33]. A sportiness model was proposed, where the effect of loudness was excluded [34]. The sound quality of different aircraft sounds was evaluated through a model-based method [35]. The sound quality of the diesel engine was improved using the multi-channel active noise controller [36]. An integrated satisfaction index (ISI) of the subjective evaluation of the diesel engine was proposed and it was found that the ISI of the diesel engine was closely related to the loudness and sharpness [37]. An optimization model of the low-frequency acoustics of the vehicle interior noise was validated [38]. The sound quality prediction models based on three different algorithms, the lasso, elastic-net and stepwise, were compared with the jury test [39]. The noise emitted from the electromagnetic system of the electric vehicle makes it difficult to appeal to customers. The semantic differential method was utilized to evaluate the sound quality of the electric vehicle [41]. In addition, a neural network model was proposed to predict the sound quality [40].

However, little work has been done to evaluate the sound quality of axial piston pumps [42]. The purpose of the present study is to conduct an investigation on the sound quality evaluation and prediction of an axial piston pump with the objective and subjective approaches. This paper is organized as follows: Section 2 describes the test rig and the procedure of the noise test. Section 3 introduces the notions of the psychoacoustics metrics and analyzes the influences of speed and outlet pressure on the objective evaluation results. Section 4 presents the semantic differential method, test stimuli and procedures of the subjective evaluation. In Section 5, the influences of the speed and outlet pressure on the semantic differential evaluation are compared, the relationships between the objective and subjective evaluation results are analyzed and revealed, and a model is developed based on the neural network to predict the sound quality. Section 6 presents the conclusions.

2. Noise test of the axial piston pump

2.1. Descriptions of the test pump and test rig

The test pump for the sound quality evaluation is a swash plate type pump with nine pumping elements. The related parameters of the test pump are as follows. The maximum displacement is 40 cm^3/r, the rated speed is 1500 r/min, the maximum outlet pressure is 35 MPa, and the outline dimension is around 333 mm × 200 mm × 230 mm.

Fig. 1 shows the arrangement of the test rig. The dimension of the test room was 6 m × 5 m × 4 m, where sound-absorbing materials were installed on the wall to reduce the sound reflection. The test rig was located in the center of the test room. Fig. 2 shows the schematic diagram of the test rig, and Table 1 lists the detailed descriptions. The power source of the test axial piston pump was an electric motor, whose speed was regulated by a frequency converter. A drum-gear coupling was employed to transfer torque from the electric motor to the test pump. A cover with sound-absorbing materials was installed on the test rig to insulate the noise of the electric motor and shaft coupling. A tachometer was used to measure the speed. The inlet pressure and the temperature of the oil were measured by a low-pressure sensor and a temperature sensor, respectively. A relief valve was utilized to regulate the outlet pressure. The outlet pressure was measured by a high-pressure sensor mounted on the outlet line. The output flow rate of the test pump was measured by a flow meter.

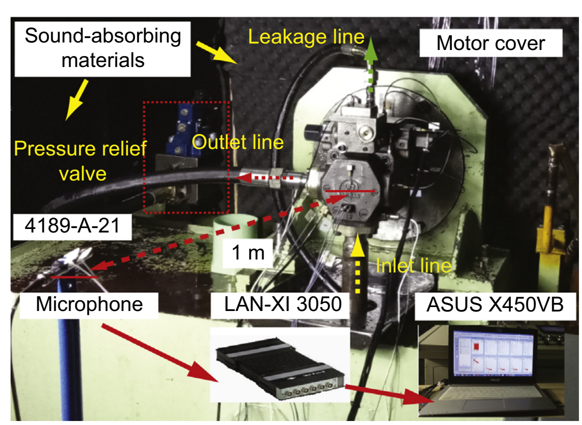

Fig. 1. Arrangement of the test rig.