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Technical note

Vibro-acoustics of a pipeline centrifugal compressor Part II. Control with the micro-perforated panel

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ABSTRACT

Structural vibration and noise radiation of a single-stage centrifugal compressor excited by the internal unsteady flow is investigated experimentally in the first part of our work [Zhou et al. Appl Acoust 2018;131:112–28]. Experimental results for acceleration of vibration and sound pressure under different rotational speeds indicate that the straight discharge pipe connecting the volute is forced to vibrate the most intensively at the blade passing frequency (BPF) and acts as the major contributor to the compressor noise emission. In this paper, a pipe micro-perforated panel (PMPP) is optimally designed with the genetic algorithm to suppress vibration and noise radiation of the straight discharge pipe section. A maximum sound pressure level (SPL) reduction of 20 dB for the BPF component and 8 dB for the overall noise are observed under the tested working conditions, while the influence of the PMPP on the aerodynamic performance of the compressor is negligible. The PMPP may be a promising method for controlling the tonal component of vibro-noises radiated from the centrifugal compressor.

1. Introduction

As one kind of general machinery, the centrifugal compressor is used for gas production, turbocharging the engines of automobiles or large ships, pressurizing gas in booster stations, etc. With the increased mass flow and pressure ratio, its radiated sound power grows as well and even violates the noise emission regulations set by the local government. Manufacturers have been forced to pay more attention to its noise level in the design stage.

Over the past decades, researchers have been focused on the aerodynamic noise of the centrifugal compressor. Either the experimental measurement (see Raitor and Neise [1]) or the numerical simulation with the aid of the computational fluid dynamics (CFD) and the boundary element method (BEM) (see Sun and Lee [2–4]) has been utilized to investigate the annoying air-borne noise radiated from a typical centrifugal compressor. In applications of the automotive turbocharger [5–7] and the vacuum cleaner suction unit [8–11], it also attracted much attention. Efforts for suppressing the air-borne noise generated by the centrifugal compressor have been devoted to the appropriate design of the diffuser. Liu [12–16] designed an acoustic liner in the vaned diffuser region using Helmholtz resonator arrays to achieve a maximum of 13 dB sound pressure level (SPL) reduction while maintaining the aerodynamic performance. Ohta et al. [17–20] developed a tapered vaned diffuser which turned out to be effective in noise reduction and compressor performance improvement. It could offer meaningful guidelines for the diffuser vane design.

All the preceding researches discuss the centrifugal compressor noise just from the aerodynamic view since its inlet or outlet connects with the atmosphere directly. However, for compressors operating in many engineering applications, such as natural gas transmission and petrochemical industry, it may be difficult for the aerodynamic noise to radiate into the environment straightforward due to the connected pipes at the inlet and outlet of the compressor. In such cases, volute, suction and discharge pipes are excited to vibrate simultaneously by the internal unsteady flow and then radiate noises into the atmosphere. The so-called structure-borne noise arises and behaves in quite a different way from the aerodynamic one and may dominate the overall noise level in case that the sealing unit is well designed. Thus, vibro-acoustic characteristics of the centrifugal compressor connecting with suction and discharge pipes will be of technical importance to its noise control. Motriuk and Harvey [21] pointed out that the inlet guide vanes and diffuser should be responsible for the high-frequency pipe wall vibration and significant attenuation was provided by removal of the diffuser vanes. Price and Smith [22] reported that the high-frequency piping vibration was excited by the vortex shedding and amplified by high-order cross-wall acoustical modes for centrifugal compressors. Some techniques to impair the vibration energy or prevent the high-order acoustical modes were also provided and tested, such as flow-splitters,

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Nomenclature

c_0	speed of sound in air [m/s]
c_{2r}	radial component of the flow speed at the impeller outlet [m/s]
d	aperture diameter of the micro-perforated panel [mm]
D_g	gap depth of the micro-perforated panel [mm]
$f_{BPF,2}$	blade passing frequency of the impeller [Hz]
f_{em}	characteristic frequency of the motor [Hz]
$f_{n,2}$	characteristic frequency of the shaft on the compressor side [Hz]
j	the imaginary unit
k	micro-perforated constant
m	specific acoustical mass of the micro-perforated panel [s]
n	rotational speed of the impeller [r/min]
r	specific acoustical resistance of the micro-perforated panel
t	thickness of the micro-perforated panel [mm]
u_2	the linear speed at the impeller outlet [m/s]
w	weighting function
z	specific impedance of the micro-perforated panel
z_{bla}	number of impeller blades of the centrifugal compressor
α	sound absorption coefficient of the micro-perforated panel
$\bar{\alpha}$	average sound absorption coefficient
η	viscosity coefficient of air [kg/(s m)]
ρ_0	density of air [kg/m^3]
σ	perforation of the micro-perforated panel
φ_{2r}	flow coefficient of the centrifugal compressor
ω	angular frequency [rad/s]

Subscripts

	1 for the first panel of the double-layer micro-perforated panel and 2 for the second

Abbreviations

BEM	boundary element method
BPF	blade passing frequency
CFD	computational fluid dynamics
PMPP	pipe micro-perforated panel
FEM	finite element method
FR	frequency ratio
FFT	fast Fourier transform
GA	genetic algorithm
HEP	high efficiency point
MPP	micro-perforated panel
OWWCFSSI	one-way weakly-coupled fluid- structure-sound interaction
PSD	power spectral density
SPL	sound pressure level

tube bundles and the reactive silencer. Numerical simulation also served as an effective tool to investigate the characteristics and generation mechanisms of the flow-induced structure vibration and noise of the centrifugal compressor. However, it would be a challenging job since it actually referred to three relevant and troublesome steps: unsteady three-dimensional internal flow field simulation using CFD, structure vibration analysis excited by the internal pressure fluctuation using the finite element method (FEM), sound radiation from the vibrating structure using BEM or FEM. Jang et al. [23] computed the flow-induced vibration of a multi-stage centrifugal pump by the unsteady time-domain one-way fluid-structure interaction, which served as the input of the BEM procedure to get the structure-borne sound field [24,25]. A one-way weakly-coupled fluid-structure-sound interaction (OWWCFSSI) method was implemented by Lu and Cai [26–28] to determine the vibration of a centrifugal fan and its emitted noises. Both influence of the structure vibration on the internal flow field and the surface acoustic pressure on the structure vibration were reasonably neglected in their simulations, i.e. the one-way interaction. Zhou et al. [29] developed a numerical model to explore the flow-induced vibration and noise of a centrifugal compressor, and investigated the influence of thickness of the outlet pipe wall on the overall acoustic power output.

In the first part of our work [30], the structural vibration and noise of a pipeline centrifugal compressor was experimentally investigated and the discharge pipe was proved to be the primary noise source. This paper will be focused on noise reduction strategy for the compressor. As

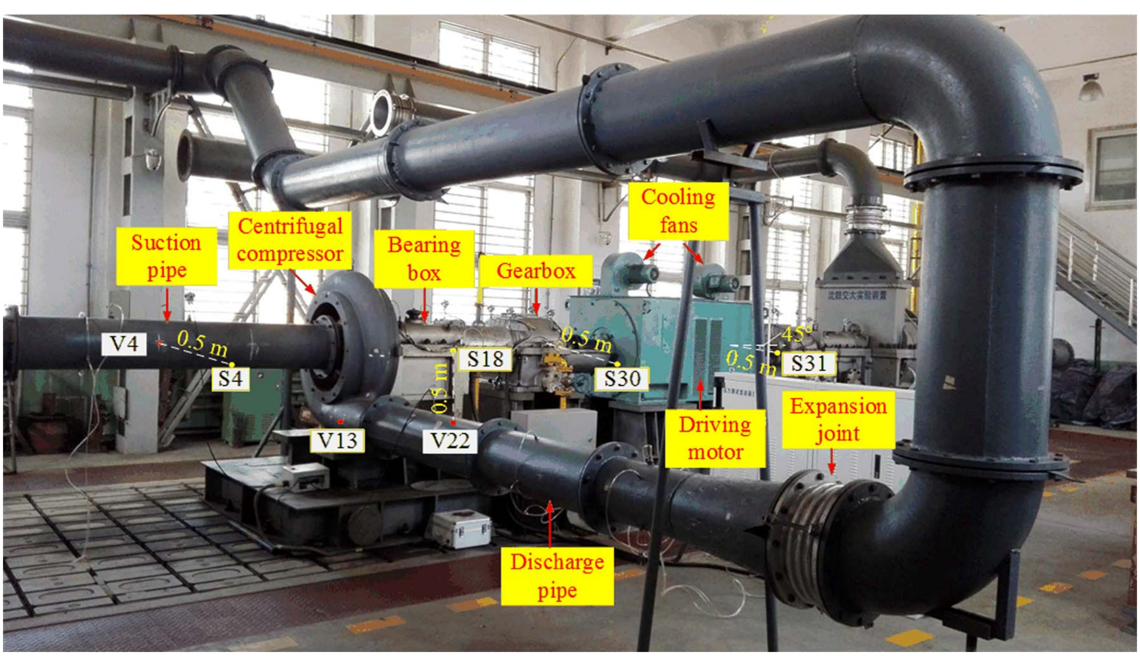

Fig. 1. Test rig.