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A numerical optimization on the vibroacoustics of a centrifugal fan volute

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ABSTRACT

A numerical optimization is presented to reduce the vibration and noise of a centrifugal fan volute. Minimal vibration was considered as the aim of the optimization, and the calculation of sound field induced by the vibration of the volute was only based on the final results of the optimization. After the three-dimensional unsteady flow simulation of a centrifugal fan, the parametric finite element model of the volute was created using the pressure fluctuations at blade passing frequency on the volute as external excitation forces. To validate the finite element model of the volute, natural frequencies and amplitudes of the normal velocities of the volute at blade passing frequency were measured. A good agreement was found between the numerical and the experimental results. Then, random method and first-order optimization method were applied in the optimization process. The numerical optimization of the volute was carried out using the local thickness of the volute as design variables and the quadratic sum of the nodal velocities as an objective function. Numerical optimization results show that the volute vibration is reduced by the optimization method. Finally, vibroacoustics of the volute before and after the optimization were calculated by direct boundary element method. The results show that the radiated power of the vibroacoustics of the volute is reduced significantly as well as the vibration of the volute after the optimization.This numerical optimization process provides a useful reference for vibroacoustic reduction of centrifugal compressors and centrifugal fans whose fluids should be kept strictly in a system without leakage.

1. Introduction

Centrifugal fans, compressors and pumps are widely applied in industrial and civilian use. Their noise problems in these applications, which are classified into flow-induced noise (aeroacoustics) and vibration-induced noise (vibroacoustics), have been studied extensively. The noise spectrum of a centrifugal fan is characterized by broadband noise with prevailing discrete frequency tones. The prevailing discrete frequency tones, which are related to the rotational frequency (RF), are referred to as tonal noise. And the blade passing frequency (BPF) component is usually most noticeable among them.

Centrifugal fans usually have internal flow open to the ambient. The internal flow-induced noise radiates directly from the inlet and outlet openings. Generally, the vibration-induced noise is so small compared with the flow-induced one that it can be omitted. Thus, the flow-induced noise becomes the main part of the centrifugal fan's noise. So, most studies on

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fan noise focus on aeroacoustics, particularly on dipole sources. Neise [1] summarized that the primary source of fan noise was forces (dipole source) which were generated by the interactions between turbulent flow and objects such as blades, the vane and the volute. Feshe and Neise [2] showed that the low frequency broadband noise of a centrifugal fan was induced by the flow separation located on the shroud and the blade suction sides of the impeller. Tonal noise sources of a centrifugal fan were studied in Refs. [3,4], which indicated that the volute tongue region was the main source of tonal noise. Jeon and Duck [5] studied the volute influence on noise propagation of a centrifugal fan by putting a wedge near the centrifugal impeller and applying a newly developed Kirchhoff–Helmholtz boundary element method (BEM). Recently, with the development of computer science, numerical studies on sound radiation of turbomachinery have become possible through computational aeroacoustic techniques. Ballesteros-Tajadura et al. [6], Khelladi et al. [7], and Liu et al. [8]studied fan noise radiation through the following procedure: Unsteady flow fields were obtained first by the computational fluid dynamics (CFD) technology, then the aeroacoustic sources were extracted, and finally sound radiation to free field was calculated by FW-H equation ignoring the presence of the volute.

Most of the current studies on fan noise have dealt with aeroacoustic problems. However, the noise is induced not only by internal turbulent flow but also by flow-induced structure vibration. In many fluid machinery, the fluid should be strictly kept in systems (*e.g.* petrochemical compressors) without any leakage. The rotor–stator interaction produces aerodynamic and acoustic pressure fluctuations. Generally, the amplitude of aerodynamic pressure fluctuation is much higher than that of the acoustic one, so the structural vibration contributed by acoustic pressure fluctuation can be neglected. Meanwhile, vibroacoustics radiated from the structure should be considered undoubtedly. Koopmann et al. [9] measured velocities on the casing surface of a fan and used BEM to compute the radiated sound power. Jiang et al. [10] quantitatively simulated the vibration and the noise of a pump's structure induced by internal flow.

Study on the vibroacoustics of big fluid machinery, *e.g.* centrifugal compressors, is restricted by our numerical and experimental conditions. As a preliminary study, a volute's vibroacoustics induced by the internal flow of a centrifugal fan at BPF was simulated and optimized in this paper. A weakly coupling strategy from the unsteady flow field to the vibration, then to the noise radiation was realized. Unsteady Reynolds-averaged Navier–Stokes equations were applied to simulate the three-dimensional unsteady flow of the centrifugal fan. The pressure fluctuations on the volute were obtained and transferred to node forces. Then, Fast Fourier Transform was applied to these time series of node forces to extract blade passing frequency components. And a harmonic analysis of the volute loaded by the BPF component was carried out. To validate the finite element model of the volute, natural frequencies and the amplitudes of normal velocity of the volute vibration at BPF were measured and compared with the simulated ones. Random method and first-order optimization method were used to optimize the volute, in which the local thickness of the volute was taken as design variables and quadratic sum of the nodal velocities was used as objective function. Finally, direct boundary element method (DBEM) was used to simulate the volute vibroacoustics to validate that the optimized volute based on the reduction of vibration can also reduce the vibroacoustics.

2. Experimental setup

In this study, we utilized an industrial centrifugal fan (T9-19 no. 4A) with 12 forward-curved blades as the experimental machine. The fan was driven by a 3.0 kW AC motor rotating at 2900 rev/min with a blade passing frequency of $2900 \times 12/60 = 580$ Hz. Table 1 shows the main dimensions of the impeller of the tested fan. Fig. 1 shows the sketch of the volute in millimeters. A test facility for the aerodynamic and acoustic characterization of the fan was designed and built following China Standards GB-12362-85 (*i.e.* test methods of aerodynamic performance for fans) and GB-2888-91 (*i.e.* methods of noise measurement for fans, blowers, compressors and roots blowers). Fig. 2 shows the sketch of the test facility with its main elements.

The experiments were carried out in a hemi-anechoic chamber of the National Engineering Center of Fluid Machinery and Compressor in China. As shown in Fig. 2, the dynamic pressure and volume flow rate of the fan's inlet were based on the static pressure measured by a YJB-150 compensate-type micromanometer. A flow regulation unit in the front of the

Table 1
Impeller dimensions.

Geometric structures	Dimensions
Vaneless diffuser outlet diameter, D_3 (mm)	460
Impeller blade outlet diameter, D_2 (mm)	400
Impeller blade inlet diameter, D_1 (mm)	164
Impeller inlet diameter, D_0 (mm)	155
Impeller outlet width, b_2 (mm)	36
Impeller inlet width, b_1 (mm)	70
Blade thickness, h (mm)	2.5
Blade number, B	12
Blade inlet angle, β_{1A} (deg.)	38
Blade outlet angle, β_{2A} (deg.)	126
Cutoff clearance (mm)	10