Applied Acoustics 132 (2018) 182–190

Contents lists available at ScienceDirect

Applied Acoustics

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

Aerodynamic noise prediction of a centrifugal fan considering the volute effect using IBEM

Chen Jian[a], He Yuan[b], Gui Li[b], Wang Canxing[b,*], Chen Liu[a], Li Yuanrui[b]

[a] School of Energy and Power Engineering, University of Shanghai for Science and Technology, 200093 Shanghai, China
[b] Institute of Fluid Engineering, Zhejiang University, 310027 Hangzhou, China

ARTICLE INFO

Keywords:
Centrifugal fan
Noise
Dipole source
LES
Indirect boundary element method
Volute

ABSTRACT

Customer demands for quieter centrifugal fans in the industry have brought their noise to the forefront. It is found that dipole sources on the surfaces of the rotating impeller and volute are the main acoustic noise sources. The volute effect is seen to have a significant influence on the radiation characters of the fan, although this is frequently ignored by previous studies. Hence, the indirect boundary element method (IBEM) is employed to study the noise of an industrial forward-curved centrifugal fan and to take the effect of volute reflection and scattering of the sound wave into consideration. A large eddy simulation (LES) is used to gain reliable pressure fluctuations on the surfaces of volute and rotating blades. Then the FW-H equation and Lowson equation are applied to calculate the dipole sources on the surfaces of the volute and the blades respectively. The predicted aerodynamic noise of the fan with and without the volute is compared to experiment. The results indicate that the pressure fluctuations on the volute surfaces, especially on the tongue surface, are the main dipole source. It is also found that the application of IBEM can improve the prediction accuracy greatly, especially for the blade passing frequency and its higher harmonics.

1. Introduction

The centrifugal fan is widely used both in industries and civil engineering as a ventilation, dust removing, and cooling device. A lot of attention has been paid to the fan noise problem due to the growing demand for reducing noise levels and rigorous noise regulations [1]. Hence, there is a rich history of research involved in the study of centrifugal fan noise.

Compared to the experimental method, computational aero-acoustic (CAA) is becoming more and more popular in engineering applications due to the rapid development of the computer science [2]. Generally, the acoustic calculation methods can be categorized into three types, exclusively numerical approaches, exclusively analytical approaches, and hybrid methods [3]. Exclusively numerical approaches solve full nonlinear Navier-Stokes equations to compute the hydrodynamic sources as well as to predict the propagation of acoustic fluctuations to the observer. Those exclusively numerical approaches usually require tremendous computer resources to capture small acoustic fluctuations in large computational domain [4].

The second way to study the acoustic problems is the exclusively analytical approaches, especially the acoustic analogy which separates the propagation of the acoustic disturbances from the sources of these disturbances. The first acoustic analogy is proposed by Lighthill [5] in 1954, which rearranged the Navier-Stokes equations into a linear wave equation including the non-isentropic and viscous effects in the source terms. Many Lighthill's analogy studies [6,7] ignored the viscous effect and isentropic behavior to simplify the stress tensor. There are also some of the extensions or reformations of Lighthill's analogy, such as Curle's analogy [8], Ffowcs-Williams and Hawking's analogy [9], Goldstein's analogy [10] and Howe's vortex sound formulation [11]. It is difficult to find analytical expressions without introduction of simplifying assumptions for the realistic applications, especially for the applications whose source includes turbulence [3].

Thus, hybrid methods combine the strengths of the numerical and analytical approaches [12] are the most popular way to handle the realistic engineering problems. In general, the computational domain is split into two zones, one zone is in the near-field describing the source of the aerodynamic noise, another zone is the acoustic far-field describing the propagation of sound. Therefore, this method has two steps. In the first step, the CFD technology [13,14] is usually used to gain the unsteady near-field flow of the centrifugal fan. Most of the previous researches adopted the Reynolds-averaged Navier–Stokes (RANS) equations to simulate the unsteady flow field of fans and gain the sound generation in the near-field [15–19]. However, the RANS

* Corresponding author.
E-mail address: mecwangcx@zju.edu.cn (C. Wang).

https://doi.org/10.1016/j.apacoust.2017.10.015
Received 22 July 2016; Received in revised form 9 October 2017; Accepted 10 October 2017

method has inherent limitations in predicting the unsteady nature of a flow field [20]. More recently, researchers have employed the LES [21–24] to get the relatively accurate pressure fluctuation because the LES can gained the large-scale separation much more accurately than RANS-based computation [25]. In the second step (far-field), the analogy theory is adopted to predict the aerodynamic noise based on the noise source extracted from the unsteady flow field [26,27]. Many research groups used the free-space Green's function to predict the aerodynamic noise in free space. This function neglects the reflection and scattering effect of solid boundaries on the sound propagation. For centrifugal fan problems in particular, the reflection and scattering effect of the volute and blades should not be neglected.

Therefore, the finite element method (FEM) and boundary element method (BEM) are introduced to consider this effect of the volute. The use of the finite element method for acoustics was initiated by Gladwell [28] and it has been applied in many engineering fields from the seventies [29,30]. It can easily deal with inhomogeneous domains. Generally, a large number of elements are needed to represent the oscillatory wave as the polynomial function can only represent a restricted spatial variation. According to a general rule of thumb, at least 10 elements per acoustic wavelength are required [31]. Hence, the application of the FEM for practical industry problems commonly involves large sizes of model and expensive computational efforts. Compared with the FEM, the size of matrices of BEM is substantially smaller than that of FEM due to the reduction in dimensionality of BEM. This reduction makes BEM a more practical numerical tool for the acoustic problem [32,33].

Many researchers have used the BEM to compute the noise of a centrifugal fan. Jeon et al. [26] simplify the structure of a centrifugal fan to one impeller and volute tongue without the volute casing. The Kirchhoff–Helmholtz BEM is used to simulate the noise reflection and scattering by the tongue and impeller. Langthjem and Olhoff [34] adopted the conventional BEM to analyze the sound radiation and scattering of a two-dimensional centrifugal pump. Polacsek et al. [16] used the BEM to simulate the interaction noise of a fan. All BEMs mentioned above are direct BEM which can only handle an interior or exterior acoustic problem with a closed boundary surface or thin-body separately. That is the reason why a lot of previous research was conducted without the consideration of the effect of volute reflection and scattering to the sound wave. Hence, some researchers proposed the imaginary surface [35] to construct a closed surface or a thin-body BEM [36] and take the scattering effect of the volute into consideration. Harwood and Dupere [31] used Dirichlet-to-Neumann (DtN) mapping operator to evaluate geometrically complex regions. Mao and Qi [37] employed the thin BEM to compute the rotating blade noise of a centrifugal fan scattered by volute. However, errors related to BEM were found. Those errors included the computing the influence coefficients, evaluation of the internal points near the boundary and the discretization. And the inclusion of the DtN added a new source of error into the BEM [3].

Different from the direct BEM, the IBEM can not only handle the combined interior/exterior problems but also deal with acoustic problems with an open boundary surface. Zhang et al. [38] employed the IBEM to compute the transfer considering the presence of openings and radiation from both sides of the piston type sources. The IBEM was also implemented to study the vibro-acoustics of an exhaust manifold acoustic radiation [39]. Another major advantage of the IBEM is that it can model the acoustic domains on both sides of a thin structure [40]. The computational domain of a centrifugal fan is a domain with opening and thin surfaces. Therefore, IBEM seems a very promising method to predict the aerodynamic noise of a centrifugal fan.

In this paper, we adopted the LES turbulence model to gain the unsteady flow field of an industrial centrifugal fan with forward swept blades. Moreover, the FW-H equation and Lowson equation are employed to calculate the far-field noise by solving the free space Green's function, and the IBEM is employed to study the noise radiation considering the effect of the volute.

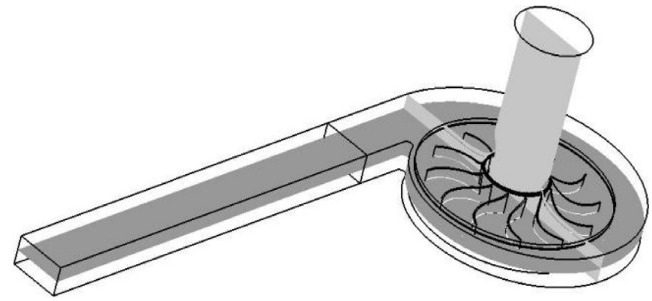

Fig. 1. A 3D model of the fan.

2. Description of the fan and numerical noise prediction model

2.1. Description of the centrifugal fan

The industrial centrifugal fan studied in this paper consists of an impeller, a vaneless diffuser and a volute. In order to get a reliable flow field, the internal leakage between the impeller front shroud and volute is taken into account. Fig. 1 and Table 1 present the 3D model and detailed dimensions of this fan. The computational domain is separated into four parts, the inlet domain, the impeller domain, the volute domain and the outlet domain. Designed rotating speed is 2900 rpm and the design volumetric flow is 0.35 m^3/s for this fan. According to the number of blades and rotating speed, the blade passing frequency (BPF) of the fan is 580 Hz.

2.2. Noise prediction procedure

The inflow which generates the aerodynamic noise of the centrifugal fan is very complex. The noise source can be divided to monopole, dipole and quadrupole. The dipole caused by the pressure fluctuations on the blades and volute surface is the main source in a low Mach number fan [32]. The noise prediction procedure in this paper is shown in Fig. 2. This prediction procedure has two steps, the simulation of the flow field and the calculation of the noise and the detailed procedure will be discussed in the following paragraphs.

2.2.1. Simulation strategies of flow field

3D modeling, mesh generation, steady simulation and unsteady simulation are included in this part. 3D modeling was constructed with the parameters presented in Table 1. The model meshing is dominantly influenced by the turbulence model. A steady simulation was conducted firstly to reduce the computational cost and it offers a relatively reasonable initial flow field for the unsteady simulation. The RNG k-ε model is applied in this steady simulation to consider the effects of curvature, swirl and rotation [37]. A standard logarithmic wall function

Table 1
Dimensions of the fan.

Vaneless diffuser outlet diameter	460 mm
Impeller blade outlet diameter	400 mm
Impeller blade inlet diameter	164 mm
Impeller inlet diameter	155 mm
Impeller outlet width	36 mm
Impeller inlet width	70 mm
Blade thickness	2.5 mm
Blade number	12
Blade inlet angle	38°
Blade outlet angle	126°
Volute width	64 mm
Distance between impeller and tongue	40 mm
Gap between impeller front shroud and volute	2.7 mm