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Numerical Analysis of Centrifugal Compressor Noise

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Abstract

The objective of this research is to suggest the noise prediction method of the centrifugal compressor. It is focused on the Blade Passage Frequency (BPF) component which is regarded as the main part of the rotating impeller noise. Euler solver is used to simulate the flow-field of the centrifugal compressor and time-dependent pressure data are calculated to perform the near-field noise prediction by Ffowcs Williams–Hawkings (FW-H) formulation. Indirect Boundary Element Method (IBEM) is applied to consider the noise propagation effect. Pressure fluctuations of the inlet and the outlet in the centrifugal compressor impeller are presented and Sound Pressure Level (SPL) prediction results are compared with the experimental data.

1. Introduction

The experimental and analytical works have been conducted to understand the characteristics of the centrifugal compressor noise and to examine the influence of design parameters on the noise level [1-2]. From the results of them, it is observed that the BPF noise in relation to the impeller rotation plays an important role, which is found in the aeroacoustic study of the volute cut-off interacting with the impeller [3].

To compute this discrete noise, BEM solver coupled with Euler equations is developed. The indirect variational BEM in the frequency domain is used to predict the inner and the outer noise propagation of the centrifugal compressor. The primary variables including the difference in the pressure and the difference in the normal gradient of the pressure contain information from the interior and the exterior acoustic space. The indirect formulation can be combined with a variational approach in deriving the primary system of equations [4]. The advantage of such an approach is to reduce computer resources for assembly and solution because the boundary element system of equations is symmetric.

2. Numerical Methods

2.1 Flow Analysis

The three-dimensional compressible Euler equations with the impeller moving grid and the patched grid are solved to analyze the flow unsteadiness due to circumferential inlet and outlet pressure distortions of the centrifugal compressor impeller. In the generalized coordinate system, the governing equation is

$$\frac{1}{J}\frac{\partial \hat{Q}}{\partial t}+\frac{\partial \hat{E}}{\partial \xi}+\frac{\partial \hat{F}}{\partial \eta}+\frac{\partial \hat{G}}{\partial \zeta}=0 \tag{1}$$

The convective terms are discretized using Roe's flux difference splitting [5]. The primitive-variable extrapolation of the MUSCL approach is employed for higher-order spatial accuracy [6]. AF-ADI time marching method is adopted to calculate the unsteady flow-field of the rotating impeller [7].

2.2 Noise Prediction

FW-H equation of the point dipole assumption is used to define the noise source of the centrifugal compressor impeller [8].

$$p(\vec{x},t)=\frac{\cos\theta f}{4\pi}\left\{\frac{i\omega}{rc}+\frac{1}{r^2}\right\}e^{i\omega(t-r/c)} \tag{2}$$

In Eq. (2), $p(\vec{x},t)$ is the acoustic pressure, $\cos\theta$ is the directivity, f is the source strength, ω is the radiated frequency, r is the distance, and c is the speed of sound.

The boundary element method is based on expressing the acoustic pressure at a point within the acoustic medium as an integral over the boundary defining the acoustic domain, which is known as the Helmholtz integral equation [9].

$$Cp(\vec{r}_{dr})=\int_S\left[G(\vec{r},\vec{r}_{dr})\frac{\partial p(\vec{r})}{\partial n}-\frac{\partial G(\vec{r},\vec{r}_{dr})}{\partial n}p(\vec{r})\right]dS \tag{3}$$

where $\vec{r}$ is the point vector on the surface of the boundary element model, G denotes Green's function, $\vec{r}_{dr}$ is the vector specifying the location of the data recovery point, and C is the integration constant resulting from the integration of Dirac's function originating from the fundamental solution to the governing differential wave equation.

In order to derive the integral equation for the indirect formulation, the standard approach used in indirect boundary element formulations is applied [10]. The integral equations for the two acoustic spaces are added together. Within the integral the terms which include Green's function are factored out and the opposite direction of the unit normal between the two equations is taken into account in generating the new primary variables. The equations for the primary variables and the acoustic pressure at a data recovery point are

$$\delta p = p_1 - p_2\ ,\ \delta dp=\left(\frac{\partial p}{\partial n}\right)_1-\left(\frac{\partial p}{\partial n}\right)_2 \tag{4}$$

$$p(r_{dr})=\int_S\left[\delta p(\vec{r})\frac{\partial G(\vec{r},\vec{r}_{dr})}{\partial n}-G(\vec{r},\vec{r}_{dr})\delta dp(\vec{r})\right]dS \tag{5}$$

where δp is the difference in pressure between the two sides of the boundary and δdp is the difference in the normal gradient of the pressure.

3. Results and Discussion

The small-sized centrifugal compressor is used to demonstrate the noise prediction method. It has 12 impeller blades plus 12 splitters and is designed to operate in the counterclockwise rotation of 70,000 rpm. The fundamental BPF values of the inlet and the outlet are 14,000 Hz and 28,000 Hz respectively, which belong to the high frequency range. Figure 1 shows the geometry of the centrifugal compressor impeller and the pressure contour of Euler analysis. Pressure fluctuations of the inlet and the outlet in the centrifugal compressor impeller resulting from the blade rotation are observed.

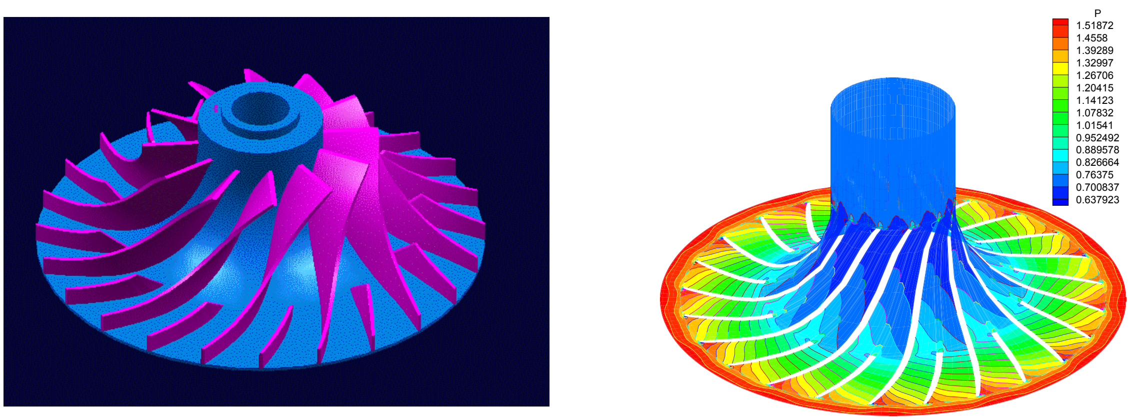

Figure 1: Centrifugal compressor impeller geometry and pressure contour computation

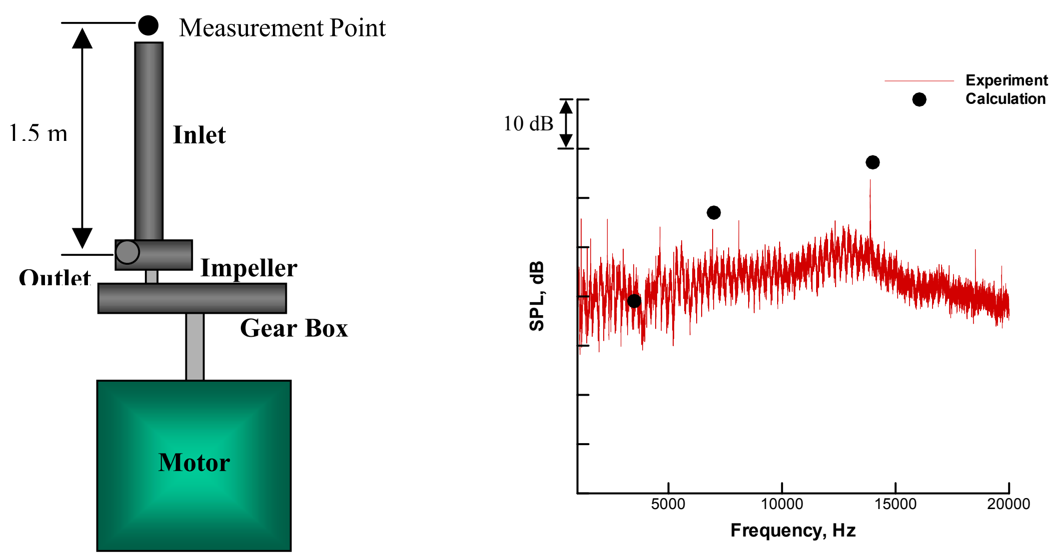

Figure 2: Noise measurement system and comparison of calculation and experiment

The noise spectrum is measured at a distance of 1.5 meters from the centrifugal compressor center. The chosen position is in front of the inlet duct end to minimize the influence of other noise components in the centrifugal compressor system. It is known that the fundamental BPF of 14,000 Hz is the dominant term and sub-harmonic components due to the non-linear effect are found. As can be seen in Figure 2, the numerical results about these discrete noises are predicted with sufficient accuracy.

4. Conclusion

In the present study, the numerical prediction method of the centrifugal compressor noise is introduced. Euler solver is used to express the impeller flow-field and we apply FW-H formulation to estimate the noise source. Indirect variational BEM is employed to take the noise propagation into account. To validate this technique, the calculation results are compared with the experimental data and agree well with them.

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