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Effect of cutter geometric configuration on aerodynamic noise generation in face milling cutters

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ABSTRACT

Aerodynamic noise spectrum of rotary face milling cutters consists of a broad range of high frequencies and discrete tones. This paper aims to develop a method to calculate the aerodynamic noise generation and propagation by rotary face milling cutters. The effects of milling cutter geometry on the generation of aerodynamic noise are analyzed. Based on the computational fluid dynamics (CFD) method, the Ffowcs Williams–Hawkings (FW–H) equation is used to predict the sound pressure level (SPL) of aerodynamic noise in face milling cutters. The accurate calculation of time-varying flow variables along with the rotation of cutter is very important for the prediction of aerodynamic noise. In this case, the Navier–Stokes (N–S) equation is employed to evaluate the pressure and velocity fields around the milling cutters, first in a steady mode with the Multiple Reference Frames (MRF) model, and then in an unsteady mode with sliding mesh technique (SMT) by introducing the steady flow variables as its initial fields. It is found that both the overall aerodynamic noise due to the entire cutter and the aerodynamic noise only due to the cutter gullet regions are significantly affected by the number of cutter teeth/gullet regions. Moreover, six representative milling cutters with different tooth numbers and geometries of gullet regions are chosen to study the effects of gullet configuration on aerodynamic noise generation, and the characteristics of noise spectra generated by the cutters are analyzed. The aerodynamic noise generated only by the cutter gullet regions is found to be strongly dependent on the gullet design-volume and shape. The results also reveal that the gullet design advantage of Cutter C in reducing noise generation among the eight-tooth designs, and the gullet design advantage of Cutter A in reducing noise generation among the five and seven-tooth designs in this investigation.

1. Introduction

Face milling cutters are widely used in various manufacturing industries, such as aerospace, automobile, and mold making industries. As the environmental regulations on noise emission become stricter, the requirement of reducing the noise levels generated by high speed machine tools is becoming more pressing. In high speed milling, one of the major noise sources is the rotating cutters. The noise level generated by face milling cutters was reported to vary from 85 dB to 105 dB [1]. Even when the cutters are idling, the sound pressure level can be as high as 95 dB at 13,000 rpm [2]. Therefore, in designing milling cutters, the aerodynamic noise generated by the cutters should be taken into account along with other factors such as cutting performance and safety.

To date, the use of aero-acoustic principles to predict aerodynamic noise generation and propagation has gained enormous interests for fans, turbo machines, propellers, etc. The FW–H equation [3] was developed based on the acoustic analogy by Lighthill [4], and was often applied in the calculation of sound pressure due to the fluid flow in the vicinity of solid surfaces. Maaloum et al. [5] predicted the total noise radiated from a fan in far field according to the fluctuating forces on the blade surfaces by using FW–H equation. Farassat and Brentner [6] evaluated the aerodynamically generated sound from the main helicopter rotor based on the FW–H equation and proposed insightful discussions on the prediction of rotorcraft system noise. Mote and Zhu [7] developed a mathematical model to predict the aerodynamic noise in idling circular saws, the aerodynamic noise radiated from dipole sources at the rim of rotating circular saw was experimentally and theoretically studied. Jiang et al. [8] predicted the total broadband noise produced by the axial flow fans using the Fukano's model [9–11] with a computational fluid dynamics (CFD) code, and the errors between the experimental and predicted results were less than 5.5%. Boltezar et al. [12] studied the effect of irregular blade spacing of the radial fans on the total sound pressure level and the noise spectra by analyzing theoretically and confirming experimentally. It was found that alterations in blade spacing did not alter the total noise. However,

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the significant dispersion of the sound energy over several harmonics allowed for a reduction of the siren effect. Polacsek and Desbois [13] developed a kind of wake generator system to reduce fan interaction noise reduction based on experiments and computational aeroacoustics. The experimental results are assessed by a numerical approach using CFD. A Reynolds averaged Navier–Stokes solver is used to provide the unsteady flow variables on blades required for acoustics. The dipole source term of the FW–H equation is performed to model the interaction noise between the sound sources. Marathe [14] used the principles of solid mechanics and fluid dynamics to model the major sources of noise generation in face milling process which covers the cutting noise, aerodynamic noise, drive noise, and machine enclosure effects. The solid and hollow aluminum work-pieces with varying cavities were used to study the effect of work-piece geometry on the aerodynamic noise generation, and a reclosable steel enclosure was used to investigate the effect of the machine enclosure. Several parameters including work-piece geometry, cutting speed, and radiation efficiency were obtained by calibration experiments. However, the effect of cutter geometries was not captured in this model. Wu et al. [15] carried out experiments to study the effect of cutting speed, feed, cutter body geometry and cutting angle on the cutting noise. The machine tool dynamic characteristics was found to be an primary factors that affect the cutting noise, and the effect of cutting speed and the cutting angle is insignificant. The cutting force and cutting noise showed a closely correlation, and the main spectral peak frequency of the cutting noise was close to the first-order modal frequency of the work-piece system. Balachandran [16] found the vibration signals are usually dominated by the tooth passing frequency during the stable milling process. In contrast, during the instable chatter cutting, the vibration signals contain multiple frequencies which are usually dominated by both the tooth passing frequency and the chatter frequency. However, the effects of chatter frequency and tooth passing frequency on aerodynamic noise generation were not investigated. Sampath et al. [1] developed a cutting noise model to relate the cutter and work-piece vibrations to the sound field around the cutter in high speed milling process. The dynamic mechanistic face milling force simulation model was used to obtain the cutter and work-piece vibration data. The predicted total noise including the cutting noise and aeroacoustic noise compares well to the experimentally observed noise in face milling process. It is pointed that all the cutting speed, machine dynamics, and cutter geometry play important roles in determining total noise in face milling.

Sampath et al. [2] conducted experiments on two different cutters to understand the aerodynamic noise generation in face milling cutters. The dipole sources were observed to be the most important in determining the noise generation. The aerodynamic noise spectrum consists of discrete noise and broadband noise which contributes significantly to the total noise. A noise prediction model based on Farassat's formulation was developed. However, the effect of the quadrupole and partial monopole sources was largely neglected, and the predicted noise was nearly 4 dB lower than the observed noise. In addition, it was found that the discrete noise occurs at the rotational frequency and its harmonics, but no peak occurring at the cutter's natural frequency implies that the cutter was not excited into resonance. Ji and Liu [17] developed a modeling approach to investigate the aerodynamic noise generation and propagation in idling face milling cutter. The approach includes an aerodynamic model for evaluating the flow variables Navier–Stokes equation and an aeroacoustic model for predicting the aerodynamic noise using FW–H equation including the dipole and monopole source terms. The predicted noise spectra showed a good agreement with the experimental results. The noise directivity was found in the vertical plane, and the irregular tool spacing can spread the maximum sound power at the rotational frequency to higher frequencies. The insert rake faces and the cutter gullet regions were found to be the primary contributors to the aerodynamic noise through comparing noise spectra due to the different regions on the cutter surface.

To the best of our knowledge, little research has been performed regarding the effect of cutter geometric configurations and parameters such as the number of cutter teeth/gullet regions, and the gullet design-shape and volume on the aerodynamic noise in face milling cutters. In this paper, in order to accurately capture the complex physical features of face milling cutters, the flow field analysis is performed by solving the N–S equations using a finite volume method. The remainder of the paper is organized as follows. In the next section, the numerical simulation method of flow fields around face milling cutters is briefly introduced. In the following section, the FW–H equation is provided and experiments are carried out to validate the predicted aerodynamic noise. After that, the effect of the number of cutter teeth/gullet regions on the overall aerodynamic noise and the aerodynamic noise generated only by the cutter gullet regions are investigated. More importantly, a detailed discussion on the effect of the cutter gullet configuration on the aerodynamic noise generation is presented. Finally, conclusions are drawn in the last section. Fig. 1 illustrates the general framework of this research, OASPL is the abbreviation of overall sound pressure level representing the aerodynamic noise generated by the entire cutter and SPLg represents the sound pressure level generated only the cutter gullet regions.

2. Numerical simulations of flow variables around face milling cutters

2.1. Calculation method

Due to the complex geometry of face milling cutters, Fluent software package is utilized to perform the flow field analysis, which solves the 3D and incompressible N–S equations using Large Eddy Simulation method. The pressure–velocity coupling equations are solved with SIMPLE algorithm. The pressure interpolation scheme and the momentum equations are solved using the standard algorithm and bounded central differencing discretization respectively, similar to the methods adopted by Ji and Liu [2,17]. To accurately calculate the unsteady velocity and pressure fields as the milling cutter rotates, the steady flow fields are firstly calculated using Multiple Reference Frames (MRF) model, and then the unsteady flow fields are solved with the sliding mesh technique (SMT) by introducing the steady flow variables as its initial fields. The governing equations of momentum and mass in rotating coordinate system can be written in the following equation [18]:

$$\frac{\partial \mathbf{Q}}{\partial t}+\frac{\partial \mathbf{F}}{\partial x}+\frac{\partial \mathbf{G}}{\partial y}+\frac{\partial \mathbf{H}}{\partial z}=\frac{1}{Re}\left(\frac{\partial \mathbf{F}_v}{\partial x}+\frac{\partial \mathbf{G}_v}{\partial y}+\frac{\partial \mathbf{H}_v}{\partial z}\right) \tag{1}$$

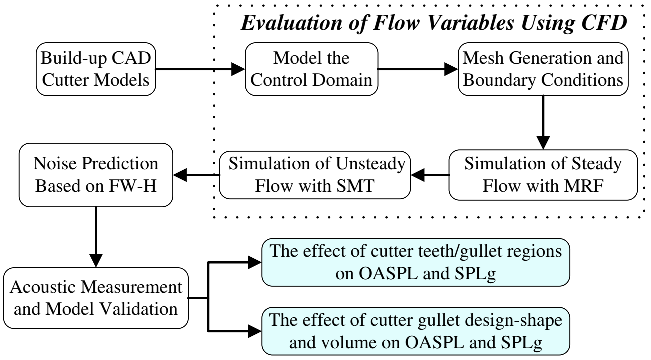

Fig. 1. Block diagram of numerical simulation of flow and acoustic fields.