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Modelling time-domain vibratory deflection response of thin-walled cantilever workpieces during flank milling

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ABSTRACT

While machining thin-walled workpieces, the chatter and corresponding damage to the machined surface can be avoided if that is predicted well in advance. Currently, investigations of machining vibrations mainly rely on experiments, which are costly and difficult to perform and FEM simulation methods that are many times computationally cumbersome. This work presents a mathematical model to obtain time domain forced vibration deflection response of a thin rectangular cantilever plate for any time and space varying external loads. The model is adapted for a milling process to obtain machining vibration response of a thin impeller blade by simplifying its geometry as a thin rectangular cantilever plate. The developed model was verified by checking the natural frequencies and mode shapes obtained by the model with the Finite Element simulation results for a thin cantilever plate. Peripheral milling experiments were performed to machine a thin rectangular cantilever plate of Ti-6Al-4V alloy on a vertical 3-axis CNC milling machine. Milling forces and workpiece acceleration were acquired during machining. Workpiece material properties and moving machining forces obtained by Linear Edge Force Model are input to the model. The model was validated by comparing vibratory deflection of thin cantilever plate obtained by the model and by the acquired experimental data. In general, the developed model can be used to obtain time-domain forced vibration response of thin rectangular cantilever plate workpieces.

1. Introduction

In machining of thin impeller blade like components, chatter is encountered at certain parametric conditions. To tackle the machining chatter problem, it is important to know the vibration characteristics of workpiece during machining. Both, experimental and modelling approaches are used to study and supress the machining vibrations. A brief review of these works is presented below.

Majed et al. [1] developed an analytical approach to predict displacement of thin walled workpieces during end milling. They linked feedback of the displacement amplitude with the cutting forces to address the influence of dynamic displacement of the workpiece because of chip load. Their numerical model has capability to predict thin wall displacement. Schmitz et al. [2] presented analytical approaches of using Rayleigh method and reacceptance coupling method to predict dynamics of fixed-free beams of varying geometries during thin rib machining. They validated the method by comparing natural frequency and stiffness values of different beam profiles with the experimental values. Chen et al. [3] developed a machining deformation prediction model using FEM which included the deformation of previous cutting and nominal cutting depth of current cutting. They validated the model with experimental results and also proposed an approach of active error compensation in multi-layer milling.

Yang et al. [4] proposed a dynamic model to predict SLD for peripheral milling of thin walled workpieces having curved surfaces. The model included dynamics of tool and workpiece, their engagement and tool feed direction. They used modal analysis on the FEM model to characterise the effect of material removal on workpiece dynamics. Zeng et al. [5] presented an approach to design a fixture for suppressing machining vibrations of flexible workpieces. They considered cutting force as a disturbance input and fixture element as a control input for the dynamic model of workpiece-fixture-cutter system. They validated the effectiveness of the proposed approach using an impact hammer and machining experiments. Junjin et al. [6] proposed MR fluid-based flexible fixture to investigate chatter suppression during machining. They simplified the assembly of complex thin-walled workpiece, fixture and damping constraint as a rectangular cantilever beam. Their proposed model showed good agreement with the experiments. Huang

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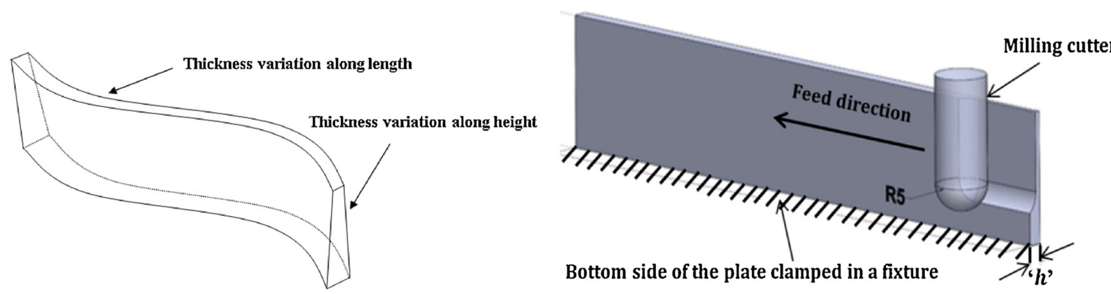

(a) Geometry of a single impeller blade

(b) Simplified design of a thin impeller blade with milling cutter

Fig. 1. (a) and (b) Geometry of a single impeller blade and its simplified design used in this work.

et al. [7] came up with a tool orientation optimisation method for reducing vibrations during ball-end milling of thin-walled impeller blades. In their method, the direction of cutting force was kept in the plane of higher workpiece stiffness to achieve lesser workpiece vibrations. They concluded that the proposed optimized tool orientation method can reduce the machining vibrations.

Biermann et al. [8] developed a simulation system for modelling regenerative workpiece vibrations during the five-axis milling of free-form surfaces. To correlate workpiece dynamics with chip geometry, they coupled time-based simulation for the material removal process with a FE-based workpiece model. It suggests chatter-free process parameters during five-axis milling of free-form surfaces. Kolluru et al. [9] investigated a workpiece-tool coupled dynamic response model for workpiece geometries such as thin-walled straight cantilever and a thin-walled ring-type casing. They analysed the acceleration signals acquired during machining in the frequency (FFT) and time-frequency (STFT and 3D FFTs) domains. Their analysis of the open geometry structure showed the presence of combined response of tool and workpiece under various depths of cut. On the other hand, closed geometry structure exhibited a complete dominance of tool mode at the higher depths of cut. Wang [10] concluded that Nonlinear Tuned Mass Damper shows more than 30% improvement in the critical limiting cutting depth over Linear Tuned Mass Damper. Long et al. [11] proposed an active vibration control system consisting of a specifically designed active stage for controlling relative vibrations between the tool and workpiece. Using numerical simulations and milling experiments, they concluded that the proposed controller decreases relative vibrations between the workpiece and tool. Shamoto et al. [12] presented a new method to machine flexible plates with high accuracy by performing simultaneous double-sided milling. They rotated two milling cutters at different speeds to cancel the regenerative effects on both sides of the workpiece. They experimentally confirmed that machined plate flatness and machining efficiency are improved about three times over the one-sided milling process by using the proposed method.

In summary, several mathematical, experimental and FE simulation methods have been developed to analyse and supress machining vibrations of thin-walled workpieces. Many experimental efforts in the literature including active controllers, fixture design and tool orientation optimization have shown some improvements in reducing the machining vibrations. Researchers have mainly focused on developing dynamic models of workpiece-tool machining system and correlated them with machining stability using analytical and finite element methods. Few have proposed dynamic models for machining of thin beams as analogy to study thin-walled workpiece machining. However, a mathematical model, which can give a complete time domain vibration response of thin-walled plate workpieces during machining, has not been developed thus far. Modelling exact time domain vibration response of complex shaped thin-walled components like impeller blades is difficult. Hence, the first step towards achieving this would be to model the vibration response of simplified geometry of such components. Therefore, the goal of this work is to develop a mathematical model to obtain time domain vibratory response of a thin cantilever plate; a simplified geometry of thin impeller blade and validate the model by performing specific experiments. Such model would facilitate the closer approximation to the knowledge of workpiece vibrations occurring during machining thin-walled components like impeller blades without performing the machining experiments.

2. Theme of work

Machining thin walled structures like impeller blades is complicated and chatter is frequently encountered. In such cases, machining parameters that provide minimum workpiece deflection and chatter are the main concerns. A mathematical model in this context would provide a prior knowledge of workpiece deflection while machining thin-walled structures. Fig. 1-(a) & b) shows geometry of a single thin impeller blade and its simplified design used in this work, respectively. More specifically, the aim here is to develop a mathematical model which can give vibration response of a complex shaped impeller blade during its milling. As seen in Fig.1-(a), a typical impeller blade has a curvature along its length. Its thickness varies along the length as well as height. After opening the curved face of the blade, it will become a cantilever plate with varying thickness. In this work, the variation in thickness of the blade is neglected. Hence, the impeller blade is considered as a thin rectangular cantilever plate with constant thickness, as seen in Fig. 1-(b). With different combinations of plate thicknesses, dynamic characteristics of a complex shaped thin walled workpieces can be interpreted. This will help to obtain more generic solution for vibrations of thin impeller blades.

Fig. 2 shows a block diagram of various steps followed to model vibration response of a complex impeller blade during its milling using thin plate theory. The developed vibration model is further applied to machining process. In our simplified case, bottom edge of the thin rectangular workpiece is clamped in a fixture. The peripheral milling is performed along the opposite edge as shown in Fig. 1-(b). The plate will have clamped-free-free-free boundary conditions. As the milling cutter moves along the feed, milling force becomes moving load acting along the feed direction. Thus, it is a case of workpiece undergoing forced vibrations due to an external moving load. Therefore, the goal of this work is to model time domain forced vibration response of a thin rectangular cantilever plate under the moving loads.

3. Model formulation

3.1. Approach to modelling

Basis function expansion method is used to model the forced vibration response of a thin rectangular plate. In this method, mode