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Formulating a numerically low-cost method of a constrained layer damper for vibration suppression in thin-walled component milling and experimental validation

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A B S T R A C T

Due to its low stiffness and time-varying modal parameters, thin-walled workpiece milling is still a challenging problem. In order to reveal the influence of the relative position between the cutter and workpiece on the dynamic response of the flexible thin-walled component, and optimize the parameters of the constrained layer damper applied to suppress the machining vibration in thin-walled workpiece peripheral milling process, with assumption of chatter-free milling operation, a dynamic model of thin plate peripheral milling with constrained layer damper subjected to moving cutting force using Lagrange equation is proposed based on the first shear deformation theory. Considering the complexity and variability of the boundary conditions of workpiece in practical machining processes, a mixed Rayleigh-Ritz solution together with Courant's penalty method and differential quadrature method is presented to evaluate the damping performance and dynamic response. Courant's penalty method is used to handle the complex and changing boundary conditions, Rayleigh-Ritz method is employed to deal with the spatial partial derivatives, and differential quadrature method is applied to treat the temporal derivatives. The influence of the relative position between cutter and workpiece on dynamic response is investigated, and the response of milling position are calculated using presented technique and compared with the results measured through milling tests. The results show that an acceptable agreement between numerical and experimental results can be obtained and the present technique is efficient to estimate the dynamic response of thin plate milling. Additionally, the parametric study of constrained layer damper is performed through evaluating the root-mean-square of response, and the results can be used to optimize the parameters of the constrained layer damper for suppressing machining vibration and improving surface finish accuracy.

1. Introduction

Thin-walled components, such as turbine blades, multi-frame monolithic components, are widely applied in the aerospace industry, and the milling of these components is still a challenging problem due to the low stiffness and time-varying modal parameter [1]. From blank blocks to thin webs with complex geometries, the workpiece is machined using slender end mills, and the large amounts of material are removed during the machining process. The dynamic problems deduced by the effect of removing material and tool-workpiece engagement have greatly limited the productivity, because the trial and error based methods are generally employed to set cutting conditions [2].

The first and most important problem for thin-walled component milling is chatter vibration, which is a self-excited vibration and relates to the interaction between the end mill and workpiece. There are many methods proposed to predict the chatter stability, including the frequency domain methods [3] and time domain methods [4]. However, all these studies assumed that the dynamic characteristics of the system did not change during the whole machining processes.

A special phenomenon, occurring during the thin-walled workpiece milling process, is the time-varying dynamic characteristics or frequency response function (FRF). From the rest of the literature review, it can be seen that this dynamic characteristics is dependent on two key factors, material removal and relative position between the cutter and workpiece, and mainly studied by the finite element method (FEM). Neglecting the dynamic effect, based on FEM, Tsai and Liao [5] obtained the tool and workpiece's static deformation at any milling instant. Similarly, after conducting the quantitative analysis of the flexible workpiece's deformation by FEM, some control stratagems were proposed to compensate the machining error [6]. In addition, with the help of FEM, more

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factors, including the fixture layout, operation sequence and tool path [7], chips [8] and material removal [9], were considered in obtaining the dynamic characteristics of the machining system. Although it is easy to predict the dynamic characteristics of complex workpiece during machining by FEM, its computation efficiency is low, especially for high-speed milling. Kersting et al. [10] and Biermann et al. [11] integrated the finite element model, point-based model and oscillator-based approach into a system for simulating the NC milling process of thin-walled workpiece, which improved the computational efficiency compared with the conventional FE method. Apart from the FEM, with the interpolation of the transfer behavior of experimentally examined surface points, the position-dependent dynamic properties of the workpiece were obtained in study [12]. Although these FRFs along the tool path can be obtained from some simulations [10,11] or experiments [12], it is still unavoidable and time-consuming to conduct some impact tests or preprocess the simulated workpiece. Based on thin shell theory, Liu [13] used the Ritz method to calculate the mode shape of a simplified blade, which was a unified and computationally efficient method to predict the dynamic changes in milling process. However, the dynamic response was not obtained. Actually, based on Ritz method, it is more efficient to obtain the workpiece's position-dependent FRF since the process to remodel the machined workpiece is avoided.

In order to avoid the vibration and improve the surface finish accuracy of the thin-walled workpiece, many optimization approaches have been proposed, such as the optimization of cutting parameters, including the depth of cut, cutting velocity and feed velocity. However, for a complex workpiece, due to its difficulty in obtaining dynamic response, designing appropriate fixture is more suitable. For standard mechanical fixtures, many researchers focus on optimizing the fixture layout, number of fixture elements, and geometric parameter. Xiong et al. [14] presented a general method to determine the optimal clamping forces including their magnitudes and positions. Zeng et al. [15] designed an appropriate fixture layout scheme to suppress the machining vibration of the flexible workpiece. For enhancing the mass and stiffness, Kolluru et al. [2] designed a novel ancillary device to suppress the forced vibration in milling thin-walled circular components. A low melting temperature alloy is also used in the support structure to fulfill the required functions with simple structure [16]. However, all these solutions are mainly concentrated on damping vibrations arising from the components in machine tool system.

Apart from these fixtures, other passive and active damping methods are also used to improve the machining stability. In active damping methods, piezoelectric actuators and electrorheological fluid are widely used in boring and turning [17,18]. However, due to its complexity, the active damping control is not easy to implement in real industrial environment. Passive damping method is more widely used since it is easier to design and place, e.g., the tuned mass damper (TMD) or called tuned viscoelastic dampers (TVD). The TMD (or TVD) consists of a mass, a spring and a damper, which dissipates the energy by the damper inertia force. Yang et al. [19] designed and optimized the multiple tuned mass dampers to increase the chatter resistance of the machine tool structures. The negative real part of FRF of the machine was selected as the optimal object. Rashid et al. [20] validated the reliability of the multi-TVDs to damp the vibration of a steel block under milling. Similarly, Kolluru et al. [21,22] also applied multi-TVDs to a thin-walled ring-type casing and studied its coupled interaction. It was found that the damping performance varies with depths of cut and the couple interaction changes from the tool's torsional mode to bending mode. Based on the spindle speed rather than the flexible workpiece's FRF, Bolsunovsky [23] proposed a new method to tune the mass damper that can operate successfully for workpiece with any frequency response function. However, a proper spindle speed should be firstly determined. Taking the material removal process into consideration, Yang et al. [24] designed a new passive damper with tunable stiffness that can be adaptive to the varying machining process. In this device, the frequency tuning is achieved by orienting the mass block inside the circular damper. Combined with

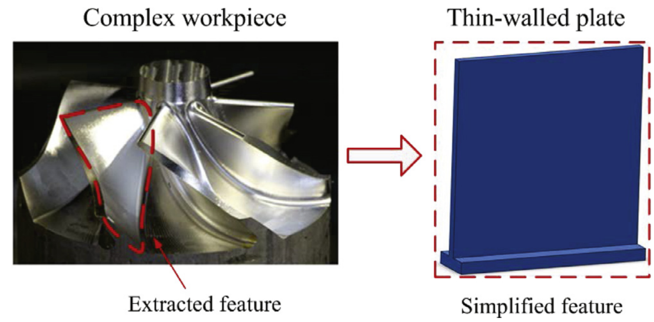

Fig. 1. Simplification of complex thin-walled workpiece.

eddy current damping, a two-DOF magnetic tuned mass damper was designed to damp a thin-walled part with multiple modes [25]. Dissipating energy by friction, the granular particle damper was also used to mitigate the chatter during milling process [26].

In this paper, the constrained layer damper (CLD) is used to suppress the machining vibration. It is implemented by attaching a viscoelastic layer covered with a stiff constraining layer to the structural member. This treatment dissipates energy through shear deformation of the viscoelastic layer. Actually, the CLD has been widely used to suppress structure vibrations. Kiehl et al. [27] applied the CLD to eliminate the squeal noise in trams. In order to suppress the cutter's vibration, the CLD boring bar [28,29] and CLD milling arbor [30] were also designed to improve their damping performance. However, the CLD has not been used to suppress the machining vibration of the thin-walled workpiece. Since the damping performance of particle damper is dependent on many factors and cannot be accurately quantitatively obtained [26], one advantage of the CLD is its dynamic characteristics can be mathematically expressed and its parameters can also be theoretically optimized. In addition, the TMD is always tuned to damp a specific mode, which means the structure should have a single resonance or a group of resonances with similar strain energies. However, for thin-walled workpiece machining, there are always several modes dominating the vibration. Therefore, the CLD is more suitable for damping thin-walled structure machining, which is only dependent on the surface strains.

The motivation of this paper is to optimize the parameters of the constrained layer damper applied to suppress the machining vibration of thin-walled workpiece and reveal the influence of relative position between cutter and workpiece on the dynamic response of the flexible thin-walled component. Therefore, with the assumption of a chatter-free milling process (e.g., small depth of cut), the influence of material removal on dynamic characteristics can be neglected, and only the effect of time-varying modal parameter due to relative position change between tool and workpiece is considered. This paper presents a dynamic model for a thin-walled plate peripheral milling with a full constrained layer damper (CLD) under moving cutting force. The paper is organized as follows. In Section 2, a dynamic model of the thin-walled plate milling is presented, including cutting force model, geometry and constitute relation of thin-walled plate, energy formulas, the set of governing equations of motion and dynamic response, and then the validations of the presented model and results analysis are demonstrated in Section 3. Parametric study of the constrained layer damper plate is carried out in Section 4. Section 5 concludes the paper.

2. Dynamic model

In aerospace industry, the complex structure of thin-walled workpiece always makes it difficult to conduct theoretic analysis and to predict the deformation during machining. As shown in Fig. 1, a reliable method is to simplify the extracted features as a thin-walled plate with different boundary conditions. Due to the low stiffness of the workpiece (about 10^5 N/m) and the higher one of the cutter (around 10^7 N/m), it