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Procedia CIRP 31 (2015) 521 – 526

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15th CIRP Conference on Modelling of Machining Operations

Modeling and cutting path optimization of shallow shell considering its varying dynamics during machining

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Abstract

During the milling process of shell structures, such as blades and engine casing, the change of thickness varies the dynamics of the workpiece considerably, which may induce unstable cutting conditions and thus influences the quality of the machined surface. In this paper, common shell structures are firstly simplified as doubly curved shallow shells to notably minimize the computation amounts, and then an analytical model was presented to predict the dynamic changes in the material removal process. The Ritz method and the thin shallow shell theory are combined to solve the dynamic characteristics of the shallow shell structures.

Furthermore, based on the simulation results of the above analytical model and the stability lobes theory, the workpiece is divided into several subregions according to the variation of dynamics stiffness. In each subregion, the dynamic characteristics are assumed to be constant to simplify the analysis. Afterwards, trial cuts are performed respectively in each subregion to select the best cutting parameters. The optimized tool paths are generated according to the trial cuts which will guarantee a stable cutting operation during the entire machining process with high efficiency and good surface quality. Finally, experiments are performed to verify the proposed method.

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations

Keywords: Material removal; Stability; Tool path; Optimization

1. Introduction

Thin-walled structures are widely reported in the literature. In the milling process of such structures, deformation and vibration often occur due to the low- rigidity of the workpiece, which leads to poor machining accuracy. To ensure the surface quality of machined parts, both the changes of the static and dynamic characteristics of the thin-walled structure should be considered in the whole milling process.

As for the changes of dynamic characteristics in the milling process of the thin-walled workpiece, since the removal of material implies that the modal parameters are continuously changing. Atlar et al. [1], Seguy et al. [2] and Thevenot et al. [3] calculated the dynamics evolution of the thin-walled workpiece through Finite Element Method (FEM), and then the stable cutting conditions were calculated for the thin walls and the thin floor. Budak et al. [4] used a prediction method for the workpiece dynamics based on a structural modification technique, the FRF of the workpiece is obtained using FEA only once, and it is continuously modified by considering the removed volume during the cycle. However, these methods are relatively universal and are mainly based on FEM software, which reduces its computational efficiency and application.

Meshreki et al. [5] developed an analytical model to capture the dynamic response of thin-walled pockets while considering the continuous change of thickness during milling operations. It could accurately capture the dynamic effect of the thickness change with prediction errors of less than 6%. However, it doesn't apply to shell structures to some extent. Since unlike plate, there are both the membrane stress and the bending stress, even though the shell is under small deflection, which make the analysis more complicated.

Among all categories of thin-walled structures, shallow shells are a special but an important kind, which can be defined as a three-dimensional object with a relatively small thickness compared to the other sizes of the mean surface. For flat plate, cylindrical shell (e.g. engine casing), spherical shell,

Peer-review under responsibility of the International Scientific Committee of the “15th Conference on Modelling of Machining Operations
doi:10.1016/j.procir.2015.03.059

and some twisted shells (e.g. turbomachinery blades), they can all be described or approximated by a unified representation as a doubly curved shell. To avoid vibration in the milling process of shallow shell structures, determination of natural frequencies and modal shapes is an essential step. Many methods and theories have been developed previously to predict the free vibrational characteristics of doubly curved shallow shells with arbitrary boundary conditions. Leissa et al. [6] used shell theories to analyze the vibration of the rotating blade. Qatu[7-9], Qatu and Asadi [10] presented massive comprehensive study of shallow shell vibrations of different kinds of boundary conditions. However, little analytical work has been done to take into account the dynamic changes due to the material removal process during milling of such kind of shells. This paper aims to utilize the doubly curved shallow shell theories into a wider practical use in the flank milling process. An analytical model to predict the frequencies and modal shapes of cantilevered shallow shell considering the continuous change of thickness during milling is presented.

Moreover, to avoid vibration in the machining process of thin-walled shallow shell, a tool path optimization method based on trial cuts is proposed in this paper. It is more reliable than the methods totally based on simulations or offline stability analysis. The implementation of this method could improve the machining efficiency and ensure the part quality in practical engineering use.

2. Theoretical model development

To develop a relatively unified and computationally efficient model for predicting the dynamic changes in the milling process of thin-walled shell structures, it is essential to take as many as possible typical shell structural components and milling strategies into consideration.

2.1. Mathematical model for common shell structures

Shell structures are often witnessed in the aerospace industry, the geometrical features of common aerospace structural components could be characterized into some simple shells such as spherical shell, hyperbolic paraboloidal shell, circular cylinder shell and other complex shells, such as blades and engine casing, as shown in Fig. 1.

As we can see, shell structures mentioned in Fig. 1 have radii in one or two directions, and some have a twist in a certain direction. To well represent the shell geometries in Fig. 1, the doubly curve shallow shell was introduced, which could preserve the correct geometry of the shell structures better than the plate and decrease the complexity required to model many kinds of common shell structures.

Considering a doubly curved shallow (small rise compared to the smallest radius of curvature) shell, the fundamental equation of the middle surface of the shell in an orthogonal absolute coordinate system (ACS) can be expressed as

$$z = \frac{x^2}{2R_x} + \frac{xy}{R_{xy}} + \frac{y^2}{2R_y}, \tag{1}$$

where R_x and R_y are curvature radii in their corresponding directions, and R_{xy} represents the twist of the surface. To simplify the analysis, they are taken to be constant. When projected along the z-axis, the projection of the origin point of the ACS is in the middle of the projection of the shell.

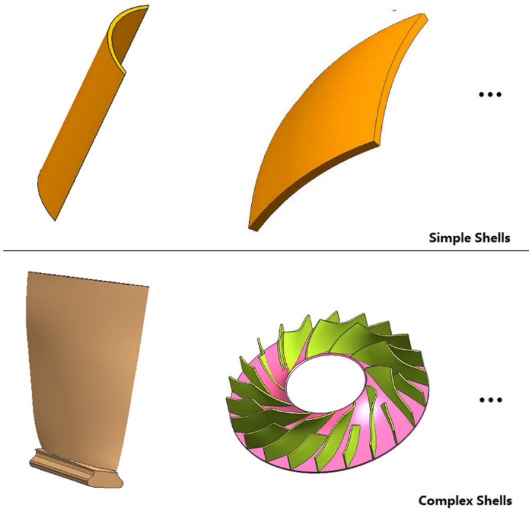

Fig. 1. Common shell structures in industry.

2.2. Modeling the varying thickness of different cut patterns

Various forms of cutting patterns could be evolved in the milling process of shell structures, which result in different variation patterns of thickness. In general, cut patterns could be classified into three main strategies, namely offset strategies, single direction raster strategies and raster strategies, which are described and illustrated in Ref. [11]. Besides, in the milling process of the shell structure, there exist possibilities that the cut layers are multiple, which makes the representation of thickness more complicated.

When projected upon the xy-plane, the target shallow shell forms a closed region, and the x-axis and y-axis are re-defined in a different orthogonal world coordinate system (WCS) as shown in Fig. 2. To make the analysis simple, in this paper, the proposed model is limited to the cantilever shallow shell and the projected cantilever boundary curve is approximated to a linear boundary when projected on the xy-plane (it is not always an ideal line in practice). Next, the projected region is divided into nine subregions by four piecewise smooth curves. From left to right, boundary curves and divide curves are represented by $u_1(x)$, $u_2(x)$, $u_3(x)$, $u_4(x)$ in turn. From bottom to top, divide curves and boundary curves are represented by $v_1(x)$, $v_2(x)$, $v_3(x)$ in turn. The nine subregions are marked with S_1, S_2…S_9, and the thickness of each sub-region is h_1, h_2... h_9. The boundary curves are determined by the boundaries of the workpiece and the divide curve are determined by the intermediate shapes of the workpiece during machining.