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Chatter stability prediction in four-axis milling of aero-engine casings with bull-nose end mill

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Abstract An analytical model for chatter stability prediction in bull-nose end milling of aero-engine casings is presented in this paper. And the mechanics and dynamics variations due to the complex cutter and workpiece geometry are considered by analyzing the effects of the lead angle on the milling process. Firstly, the tool-workpiece engagement region is obtained by using a previously developed method and divided into several disk elements along the tool-axis direction. Secondly, a 3D dynamic model for stability limit calculation is developed and simplified into a 1D model in normal direction considering only the dominant mode of the workpiece. Then the cutting force coefficients, the start and exit angles corresponding to each disk element are determined. And the total stability lobe diagram is calculated using an iterative algorithm. Finally, several experimental tests are carried out to validate the feasibility and effectiveness of the proposed prediction approach.

1. Introduction

Thin-walled parts have been widely used in the aerospace industry, such as aero-engine casings, blades and impellers. They can significantly help to improve the working performance of aircraft. However, due to the complex structures and weak rigidity of their own, they also bring many machining difficulties and challenges. Chatter is one of the main machining problems, which leads to poor surface finish and low production efficiency.[1–16] In order to avoid chatter, the milling process must be conducted in a stable state. Thus, the machining stability prediction becomes very important in achieving good machining quality and high productivity. Many studies have been focused on this issue.

Tobias and Fishwick[1], as well as Tlusty and Polacek[2] developed the stability lobe theory in orthogonal cutting process, which makes it possible to predict the chatter phenomena of milling process. Altintas and Budak[3] presented an analytical method to generate stability lobe diagram directly in the frequency domain. They considered the average term in the Fourier series expansions as the approximation of time-varying directional coefficients and used an eigenvalue solution to solve the critical depth of cut. However, the single-frequency method cannot predict the additional stability region and the

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doubling bifurcations at small radial immersions.[4–7] To overcome this problem, Budak and Altintas[4,5] developed a multi-frequency solution of chatter stability, which includes the higher order terms of the Fourier series expansions. And Merdol and Altintas[6], Gradišeka et al.[7] extended the multi-frequency approach and the semi-discretization method to the milling cases of low radial immersion.

The dynamics of flat end milling are considered in the transversal directions of the cutter. However, for ball and bull-nose end milling, the dynamics must be considered in all the three directions.[8–16] Altintas[8] extended the two dimensional chatter stability theory to a three-dimensional chatter problem by adding the dynamics in the tool-axis direction. Based on this work, Seguy et al.[9], Campa et al.[10,11] and Adetoro et al.[12,13] calculated the stability lobe diagrams in bull-nose end milling of thin floors and thin walls by considering the nonlinearities of the axial immersion angle and the cutting force coefficients. For multi-axis milling, the effects of tool positions on the process geometry, mechanics and dynamics cannot be ignored. Shamoto and Akazawa[14], Budak and Ozturk[15,16] studied the influences of lead and tilt angles on the engagement region and predicted the chatter stability of five-axis ball end milling.

Aeroengine casings are typical thin-walled parts with ring-shaped and closed geometry structures and also present machining problems due to chatter. However, unlike the milling of thin plates, the dynamics in the milling of aero-engine casings is more complex owing to the symmetry of the structure and the support of the fixture.[17,18] The cutting deformation and vibration occur mainly in radial direction of the part and have a certain symmetry in circumferential direction of the part. The thinner the wall thickness is, the worse the cutting deformation and vibration become. And the dynamics of the process system such as the natural frequency and the stiffness will change significantly in the material removal process, even a small part of the undesired material is removed. Normally, the aero-engine casings are fixed by the axial pressing and radial supporting forms. And the dynamics of the part will be significantly different with different pressing forces or different supporting positions. All the above factors will make the milling process exhibit the nonlinear and strong time-varying characteristics, thus inducing drastic cutting chatter. Therefore, chatter prediction and suppression in the milling of aero-engine casings become more difficult.

In this paper, a calculation method of stability lobe diagrams in four-axis bull-nose end milling of aero-engine casings is presented. Firstly, the tool-workpiece engagement region is determined by considering the influences of lead angle. And based on the engagement region, the start and exit angles of each disk element, the directional coefficients can be obtained. Secondly, the chatter stability model is developed and simplified to 1D model by considering only the normal direction dynamics. And the total stability lobe diagram is obtained by using an iterative algorithm. Lastly, several milling tests verifies the feasibility and effectiveness of the chatter stability prediction method.

2. Chatter stability model

The chatter stability model used in this paper is the 3D model proposed by Altintas.[8] And the effects of lead angle on the engagement region, thus, on the directional coefficients are also discussed. The helix angle and the process damping are not taken into account in this chatter theory.

2.1. Calculation of tool-workpiece engagement region

In order to calculate the tool-workpiece engagement region, three coordinate systems are defined in four-axis milling process, as shown in Fig. 1. The first one is a fixed coordinate system, MCS, formed by the X, Y and Z axes of the machine tool. The second one is the process coordinate system, FCN, consisting of feed F, cross-feed C and surface normal N axes. x, y, z are the tool-axis coordinate in the TCS. The last one

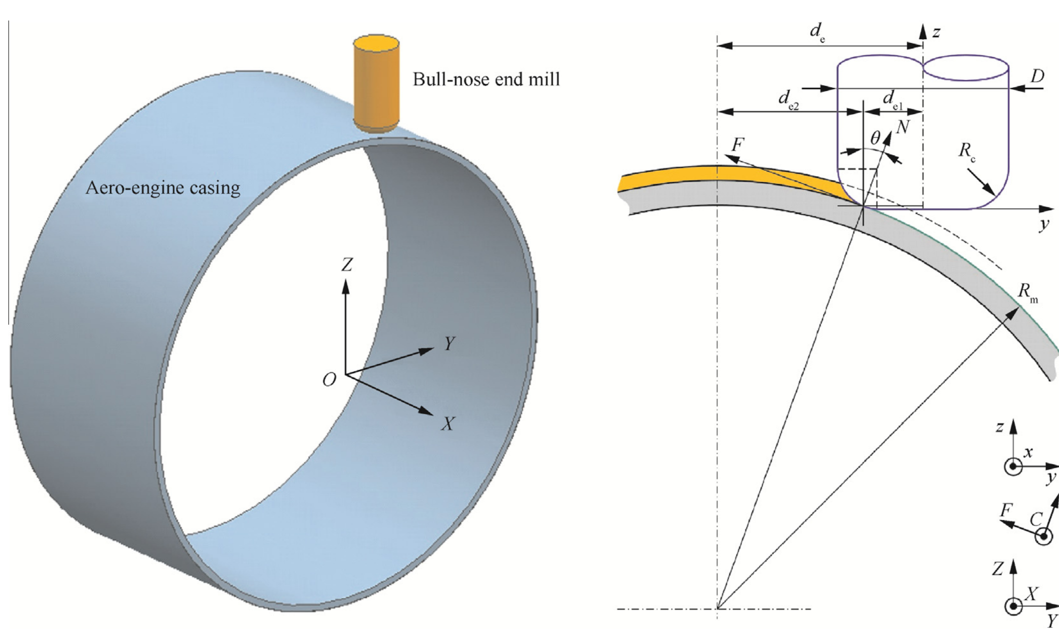

Fig. 1 Coordinate systems and lead angle.