A state-of-art review on chatter and geometric errors in thin-wall machining processes

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Abstract:

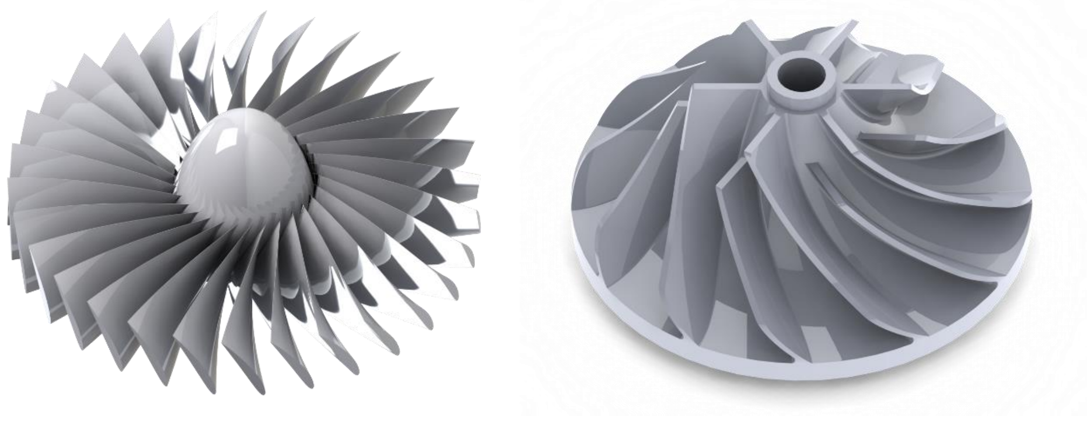
Thin-wall components are some critical parts that are extensively used in modern industries due to their high structural efficiency and low specific weight. However, precision machining of flexible thin-wall components has been a challenging task accompanied by many inevitable issues such as unexpected chatter vibration and large surface form errors. To solve these inherent problems and improve the machining quality, plenty of research has been carried out in the last decades. In this paper, a comprehensive review of previous studies on thin-wall machining process and issues has been conducted; The state-of-the-art technologies recently developed are introduced, and an in-depth discussion of both chatter vibration and thin-wall deformation have been presented in terms of the theories, mechanisms, the prediction, monitoring and elimination methods. Finally, development trends are summarised, and recommendations for future works are proposed based on the extensive review and the analysis of practical problems.

Keywords: Chatter • Dynamic instability • Thin-wall deflection • Prediction • Detection • Suppression • Compensation • Thin-wall machining

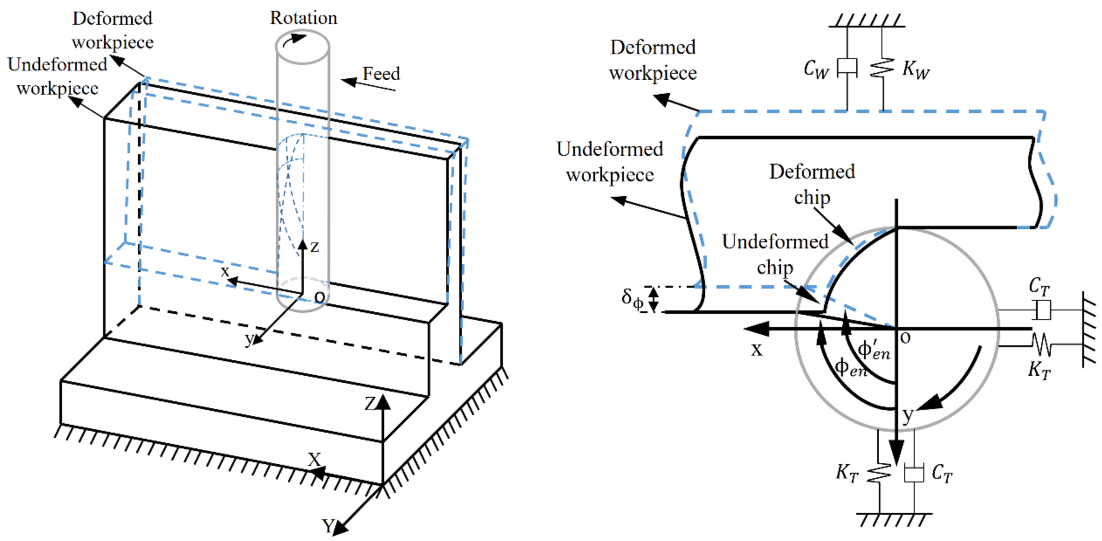
1. Introduction

Thin-wall components such as impellers, turbine blades and blade disks are widely used in the aerospace, automotive, defence and manufacturing industries. These components are featured with high structural efficiency, lightweight, and are often made from high-performance materials such as titanium alloys, nickel alloys and aluminium alloys. Despite their superior properties, thin-walled components are difficult to machine due to their free-form surfaces, low structural rigidity, weak damping and time-varying dynamic characteristics [1]. In order to reduce machining errors and increase machining efficiency, non-conventional machining approaches such as electrical discharge machining (EDM) and laser-assisted processes have been developed in the manufacturing of thin-wall parts [2-6]. However, the high residual stress left on the machined surface may deteriorate the surface integrity of the workpiece, and an extra finish machining process using various optimization methods has to be followed to remove the thermal defects [7, 8]. Furthermore, the surface quality issues would be magnified when machining difficult-to-cut materials such as titanium alloys because of their poor machinability caused by low thermal conductivity, high work hardening and high chemical activity [9-11]. In the finishing process of thin-wall parts, chatter vibration and part deformation are the most commonly-seen and troublesome defects, which result in dynamic interactions, poorly finished surface, high noise level, undesired residual stress and poor functional performance [12]. Therefore, a significant amount of studies focused on the prediction, monitoring and compensation of thin-wall machining has been proposed to improve the machining quality. Among these studies, the milling, turning [13-15] and boring [16, 17] operations are areas of particular focus, and this paper mainly concentrates on the research related to thin-wall milling processes.

There are several definitions to characterise thin-wall components, and typically "thin-wall" is defined by a large ratio of wall length to wall thickens [18]. The most common thin-wall components in the manufacturing industry are shown in Fig. 1(a). This kind of parts is mainly manufactured by removing a large proportion of material from their initial monolithic blocks to meet the requirements of lightweight design and eco-efficiency [19]. In most studies, these complex components are simplified to a cantilever plate to reduce the difficulties in modelling and analysing the thin-wall machining process, as shown in Fig. 1(b).



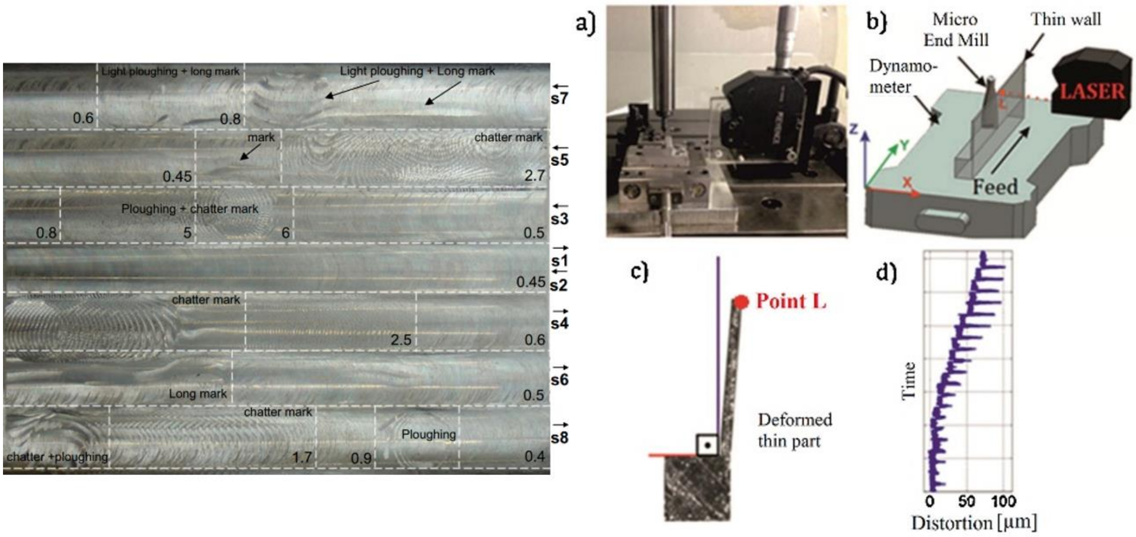
(a)



(b)

Fig.1 Common thin-wall components in industry and analytic models: (a) Impeller & Blade; (b) Cantilever plates.

In the process of machining thin-wall parts, particularly the intermittent machining like peripheral milling, the cutting process may become unstable when the tool-workpiece system is excited by the dynamic interactions, including the cutting loads and external impacts [20]. This instability issue can increase geometric error, deteriorate surface quality and lead to accelerated tool wear (Fig. 2(a)). In extreme circumstances, chatter could even cause sudden breakage of the cutting tool and damaged workpiece surface [21, 22]. Thus, chatter instability has become one of the major limitations to achieving high machining quality and productivity in the metal cutting process. Compared with normal parts, chatter is more likely to appear in the thin-wall machining process owing to the low rigidity of thin-wall parts, high material removal rate (MRR), time-varying tool-workpiece engagement conditions and dynamic characteristics [23]. Part deformation is another issue that cannot be ignored in the machining of flexible thin-wall components. Both the cutting tool and thin-wall part may deflect due to the varying cutting loads and the gradually reduced workpiece stiffness during the machining process [24]. The flexural deflection is almost inevitable in the finishing process due to the inherent low stiffness of thin-wall parts (Fig. 2(b)). Furthermore, multiple factors such as the cutting parameters, fixture design and operation sequences can also influence the magnitudes of thin-wall deformation [25].



(a) (b)

Fig. 2 (a) Chatter marks on the machined surface when the cutting is unstable [26]; (b) Dimensional error caused by deformation in thin-wall milling process [27].

As chatter and thin-wall deformation have significant impacts on surface quality and productivity, these disturbing issues have been studied extensively over the past decades. A wide range of experimental studies have been carried out to improve the performance of thin-wall machining, and plenty of theoretical models and compensation methods have been developed to predict and eliminate the excessive chatter and deformation errors. Meanwhile, various active/passive controlling strategies have been applied in practical machining processes.

In [28-30], the prediction and control methods of chatter vibration in different machining processes were comprehensively reviewed. However, there is still not a comprehensive review to critically summarize the published works about thin-wall machining. For this reason, more literature regarding the chatter vibration and part deformation issues in thin-wall machining processes is presented; meanwhile the state of the art technologies in improving thin-wall machining quality is introduced. The proposed analytic, mathematical, physical and statistical models are discussed in the following sections. Then, the interaction among each part is illustrated, some existing research gaps and scopes for future work are provided based on the review.

2. Chatter instability and relevant solutions

Chatter is one of the major barriers to high productivity and quality in the metal manufacturing process. To avoid this instability issue, plenty of research has been carried out based on the analysis of chatter generation, and various strategies were proposed to achieve a chatter-free machining process.

2.1 Mechanism analysis of chatter vibration

The phenomenon of chatter in the milling process was firstly identified by Taylor in 1907 [31]. After that, the mechanism of chatter had been investigated extensively, and several fundamental mechanism models of chatter vibration have been proposed [32-34].

Generally, chatter vibration can be categorised into primary chatter and secondary chatter based on their physical mechanisms. The primary chatter can be further identified as frictional chatter, mode coupling chatter, and thermo-mechanical chatter. Frictional chatter occurs due to the rubbing effect on the tool-workpiece contact areas [35]; Mode-coupling chatter is caused by the dynamic coupling of simultaneous vibrations sources that exist in different directions [33]; Thermo-mechanical chatter is caused by the unstable thermodynamical properties in the deformation zones [36]. Secondary chatter occurs due to the interaction between two consecutive tool revolutions and the phase difference between adjacent waviness on the cutting surface [37]. This phenomenon is also identified as regenerative chatter, which is the major cause of an unstable cutting process. Except for the regenerative chatter, forced vibration is another undesirable issue that mainly caused by time-periodic tool action and other external disturbances, which has a great impact on the dynamics of a stationary flexible workpiece and surface location errors of the machined part [38]. Compared with other vibration sources, regenerative chatter is particularly more common and uncontrollable in the milling process, therefore it is given more focus in this review.

The regeneration process is illustrated in Fig. 3. The milling system is simplified as an equivalent three-degree of freedom (DOF) system. The prior tooth trajectory of tooth (j-1) and workpiece profile is relatively smooth without waviness, but the cutting tool starts forming a wavy surface since tooth (j) due to the self-excited effect and external disturbances. The damped oscillation of the cutting tool and generated wavy surface would lead to varying phase shift and dynamic displacement between adjacent cutting trajectories, and consequently result in dynamic chip thickness and regenerative cutting forces. The growth of this regeneration process can further excite the vibration and become dominant when the frequency of oscillation is close to that of the dominant structural modes of the tool-workpiece system.

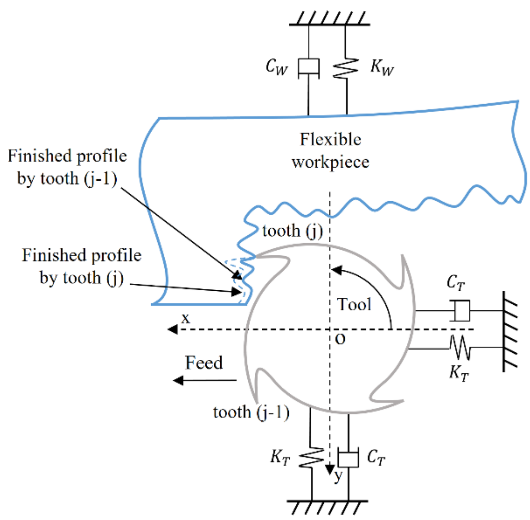


Fig. 3 Regeneration effect in a milling model with two DOF of tool.

2.2 Prediction of chatter instability

In order to achieve a chatter-free machining process, chatter prediction and determination of stable machining conditions are usually derived through the stability lobe diagram (SLD) approach or stability criterions like the Nyquist criterion [39, 40].

2.2.1 Dynamic behaviours of the tool-workpiece system

The milling system can be typically categorized as a rigid cutter-flexible workpiece model, flexible cutter-rigid workpiece model and flexible tool-workpiece model according to the stiffness and flexibility of the tool and workpiece [41], as illustrated in Fig. 4. Relevant dynamic models were proposed to describe the dynamic behaviour of the milling systems [42-44].

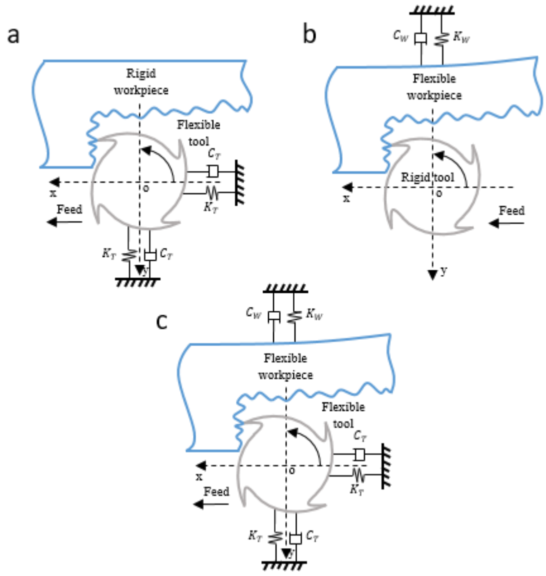


Fig 4. Simplified models for the tool-workpiece system.

Unlike the machining of workpiece with high stiffness, the stiffness of the workpiece is much lower than that of the cutting tool in thin-wall milling processes. Therefore, the frequency of chatter is mainly influenced by the dynamic properties and critical modes of the workpiece, and the tool-workpiece system can be simplified as a rigid cutter-flexible workpiece model. The workpiece can be modelled as a damped oscillator with a single DOF in the direction perpendicular to the cutting speed, as shown in Fig. 4(b). In some cases (e.g., peripheral milling), the dynamic behaviour of the workpiece and cutting tool could be similar, so the combined dynamic properties of the tool and workpiece should be considered when analysing the stability conditions. Then, the milling system can be simplified as a three DOFs system, in which the flexible thin-wall part have one DOF while the tool is considered to have two DOFS in the radial directions, as shown in Fig. 4(c).

Take the flexible tool-workpiece system as an example, the dynamic behaviour of this machining system can be described mathematically as:

$$\boldsymbol{M_S}\ddot{\boldsymbol{Q}}_{\boldsymbol{S}}(\boldsymbol{t}) + \boldsymbol{C_S}\dot{\boldsymbol{Q}}_{\boldsymbol{S}}(\boldsymbol{t}) + \boldsymbol{K_S}\boldsymbol{Q_S}(\boldsymbol{t}) = \boldsymbol{F_S}(\boldsymbol{t}) \quad (\boldsymbol{S} = \boldsymbol{T}, \boldsymbol{W}) \tag{1}$$

where $\boldsymbol{M_S}$, $\boldsymbol{C_S}$ and $\boldsymbol{K_S}$ are the mass, damping and stiffness matrices of the tool and thin-wall part, respectively. $\ddot{\boldsymbol{Q}}_{\boldsymbol{S}}$, $\dot{\boldsymbol{Q}}_{\boldsymbol{S}}$ and $\boldsymbol{Q_S}$ are displacement, velocity and acceleration vectors of each subsystem. $\boldsymbol{F_S}$ is the resultant cutting force vector acting on each subsystem, and $\boldsymbol{t}$ is the designates time. With the consideration of the regenerative effect and the periodic coefficient matrix, Eq. 1 can be solved as an eigenvalue problem after substituting the dynamic parameters and calibrated cutting forces. When forced vibration is included in the calculation, $\boldsymbol{Q_S}$ and $\boldsymbol{F_S}$ should be calculated as the superposition of both the dynamic displacements and force vectors due to chatter and forced vibration, respectively.

2.2.2 Modelling of cutting force in chatter prediction

An accurate and reliable cutting force model is the prerequisite for the prediction of both chatter and deformation errors. Plenty of studies has been carried out to analyse and calculate the cutting forces; generally, milling force models can be categorized into three categories: empirical model, mechanistic model and analytical model.

Empirical models [45, 46] are normally derived from the multi-element polynomial regression of cutting parameters such as spindle speed, feed rate, and depth of cut. Acceptable prediction accuracy can be achieved by this kind of model, but the real cutting mechanism is not considered in these models, and a large number of experiments are required to enhance their reliability. Mechanistic models have also been studied extensively [47-49]. The accuracy of those models depends on the experimental calibration of special cutting force coefficients and the established orthogonal cutting database. However, the calibrated cutting force coefficients are normally treated as constants and only available for certain tool-workpiece material pairs. To improve the accuracy and practicability of the cutting force model, analytical models [50, 51] were developed based on the real cutting mechanisms. In these models, the cutting edge of the helical milling tool is discretised into a finite number of slice elements along the axial direction. The elemental force components of each element are calculated based on the oblique cutting mechanism; the cutting force coefficients are evaluated as a function of the tool-workpiece material properties, tool geometry and cutting parameters. Then, the sum of cutting forces acting on the cutting edge is calculated by integrating the force components of each segment.

In stable milling processes, the force coefficients used in the cutting force models are usually considered as constants. However, the modelling of cutting forces in the thin-wall milling process is of high complexity because of consistent changing chip thickness and cutting forces caused by the occurrence of chatter and deformation of the workpiece. With the consideration of chatter, the cutting force models need to be modified according to the dynamic chip thickness and changing boundary conditions [52]. In previous studies [53-55], the instantaneous chip thickness was calculated as a combination of the static term and the dynamic part caused by the regenerative mechanism, which can be given by:

$$\boldsymbol{h_j(t)} = \boldsymbol{g_j}\left[\left(\boldsymbol{x(t)} - \boldsymbol{x(t-T)}\right)\mathbf{sin}\,\emptyset_{\boldsymbol{j}}\,\boldsymbol{(t)} + \left(\boldsymbol{y(t)} - \boldsymbol{y(t-T)}\right)\mathbf{cos}\,\emptyset_{\boldsymbol{j}}\,\boldsymbol{(t)}\right] \tag{2}$$

Where $\boldsymbol{x(t)}$ and $\boldsymbol{y(t)}$ are the vibration displacements in the feed and normal directions at current tooth j, $\boldsymbol{x(t-T)}$ and $\boldsymbol{y(t-T)}$ are the vibration displacements at previous tooth rotation period $(\boldsymbol{t-T})$, $\boldsymbol{T}$ denotes the time delay. $\boldsymbol{g_j}$ is the judgment function that determine whether the cutting tooth is engaged.

Taking the standard end mill (with N number of teeth) and down milling process as example, the cutting forces in the local tangential and radial directions can be calculated by substituting the instant chip thickness that obtained from Eq. (2) [56], which are given by:

$$F_{tj} = K_t a_p h_j(t), F_{rj} = K_r F_{tj} \tag{3}$$

Where K_t and K_r are the specific cutting coefficients that can be obtained from experiment results. a_p is the axial cutting depth.

Then the total cutting forces in the feed and normal directions are determined by projecting and integrating the cutting forces acted on each cutting edge:

$$F_x = \sum_{j=0}^{N-1} F_{xj}\,, F_y = \sum_{j=0}^{N-1} F_{yj} \tag{4}$$

Where,

$$F_{xj} = -F_{tj}\cos\emptyset_j(t) - F_{rj}\sin\emptyset_j(t) \tag{5}$$

$$F_{yj} = F_{tj}\sin\emptyset_j(t) - F_{rj}\cos\emptyset_j(t) \tag{6}$$

The dynamic cutting forces can be further converted into frequency domain in a matrix form through the Fourier transform as follow [57]:

$$\boldsymbol{F}(\omega) = \frac{1}{2}K_t a_p\left[\boldsymbol{A}(\omega)\left(1 - e^{-i\omega_c T}\right)\boldsymbol{\Phi}(i\omega)\boldsymbol{F}(\omega)\right] \tag{7}$$

Where $\boldsymbol{A}(\omega)$ is the directional matrix, $\boldsymbol{\Phi}(i\omega)$ is the frequency response function matrix and $e^{-i\omega_c T}$ is the delay term.

2.2.3 Prediction of the appearance of chatter

The early studies about chatter have shown that the boundaries between stable and unstable cutting regions can be visualised by a chart of axial depth of cut (DOC) and spindle speed, i.e., the stability lobe diagram (SLD) [57]. As presented in Fig. 5, the area above the curves represents the unstable cutting conditions that must be avoided. Based on SLD, an appropriate selection of chatter-free cutting parameters and maximum material removal rate (MRR) can be predicted prior to the machining process.

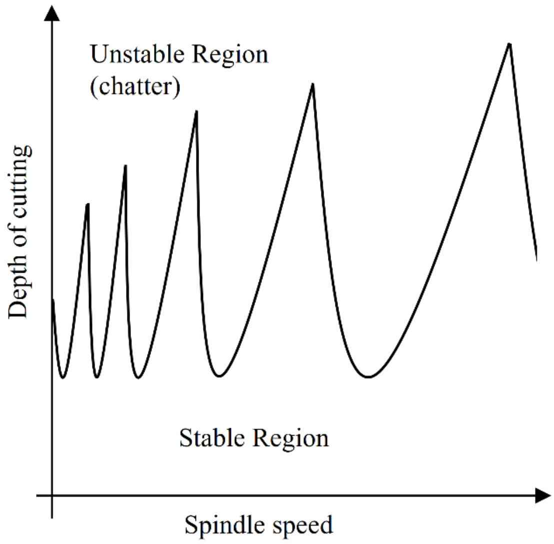


Fig. 5 Schematic illustration of chatter stability lobe (SLD).

The construction and accuracy of SLD greatly depend on the reliability of input data which include tool structure, specific force coefficients, tool/workpiece material properties, cutting parameters and dynamic properties of the machining system [56]. Once the dynamic chip thickness and specific force coefficients are identified, the SLD can be developed by identifying the frequency response functions (FRFs) of the machining system via experimental tests [58-61] and simulative methods [62-64]. The precise determination of the dynamic properties of the dominant modes is essential to carry out an accurate SLD analysis.

To measure the FRFs of the machining system, the hammer impact test is the most commonly-used experimental approach. The machining system is excited by an impact hammer instrumented with acceleration sensors, and the excitation responses related to the critical modes can be captured with the data acquisition and processing system [65]. Then, the measured vibration responses can be extracted and applied to analyse the dynamic characteristics of the machining system through associated analytical solutions. However, the standard impact test is not efficient or even impossible for complex thin-wall milling due to the varying natural frequency and mode shapes of the workpiece that relates to the dynamic material removal process. In some cases, the thin-wall part has to be divided into several zones considering the changing dynamics of the workpiece to solve this problem. The milling process is interrupted at each zone, and the FRFs are obtained at the corresponding cutting positions, resulting in a time-consuming process and incomprehensive prediction results.

As alternative methods, the structural dynamic modification method and finite element analysis (FEA) models were widely used to determine the varying FRFs of the machining system [66-71]. Seguy et al. [72] investigated the relationship between chatter and surface roughness evolution in thin-wall milling. The dynamic properties of the workpiece were obtained through an explicit 2D model and treated as constants due to the small material removal amount. Mane et al. [73] established a FE model to simulate the speed-dependent dynamic behaviour of the machining system in high-speed machining (HSM). The coupled dynamic properties of both the workpiece and the rotating spindle-tool set were taken into account to develop the 3D SLD, which presented the links between the depth of cut, spindle speed and the relative cutting position. Yang et al. [74] analysed the effect of material removal on dynamics of the in-process workpiece (IPW) with curved surfaces. The dynamics were determined by the FEM modal analysis based on a structural dynamic modification scheme with improved numerical efficiencies. Tuysuz and Altintas [75, 76] updated the FRFs of the thin-walled part through the reduced order dynamic substructuring method as well as the matrix perturbation method that showed about 20 times faster calculation speed than the full order FE model. Instead of repeated hammer impact tests, Ding et al. [44] divided the workpiece into several segments by FEA method and extracted the various modal features of tool-workpiece subsystems at each machining stage. Then the FRFs and stability conditions were calculated for different cutting stages through the frequency domain method. This study provided improved analysis results because both the flexibility of tool and workpiece were considered in the calculation.

Furthermore, Tian et al. [77] extracted the natural frequency and vibration mode of an engine blade through FE analysis. The results were then compared with the outcomes of the proposed matrix perturbation solution, and it has proven the efficiency of FE analysis as well as the proposed method in solving the eigenvalue. Yang et al. [78] utilized an efficient decomposition-condensation method and structural dynamic modification technique to update the material removal process of and predict the time-varying characteristics of the large-scale thin-wall component. The computational efficiency and memory consumption were efficiently enhanced as the rebuilding of the FE model and re-performing of modal analysis could be avoided. More recently, Wang et al. [79] calculated the time-variable dynamics of thin-wall blade structures in the milling process. The mass and stiffness matrices of the initial workpiece and change of the matrices due to material removal were obtained from the FEM model and third-order Taylor series, separately. And these results were taken as input for the proposed method to predict the dynamics of IPW with significantly enhanced computational efficiency.

To analysis the obtained process parameters and associated delay differential equations, plenty of works have been devoted to the development of efficient algorithms from either time or frequency domain methods. In [80], Tlusty and Ismail investigated the features of non-linearity during the turning and milling process in time domain. In the work of [81, 82], the milling force under dynamic cutting conditions was predicted, and the structural dynamics of flexible plate type structure and end mill was analysed through the discrete time domain simulation. Later on, Smith and Tlusty [83] performed a time-domain simulation of the milling process and used the peak-to-peak graphs to evaluate the cutting force and variation information. Insperger and Stepan [84-86] firstly presented a semi-discretization method (SDM) method for stability analysis of linear delayed systems. This method improved the prediction accuracy of small radial immersions conditions and has been extensively applied to time delay problems in the milling process. A subsequent study in [87] further proved the convergence efficiency of first-order approximation of the delayed term in the semi-discretization process. Later, Ding et al. [88] proposed the full-discretization method (FDM) based on the direct integration scheme. In this method, the time-periodic and time delay items are discretised into discrete time interval, then the system response can be calculated through the direct integration scheme and the stability is analysed via the Floquet theory. It was demonstrated that FDM could provide improved both computational efficiency and prediction accuracy. Based on these works, the improved SDMs and FDMs with higher convergence rates and accuracy were developed for stability prediction [89-95].

Except for these indispensable methods, some other numerical and analytical time domain based methods [96-99] were proposed to calculate the delayed differential equations and construct the stability chart. Taking the time-domain finite element method [100-103] as example, the cutting time intervals were divided into a finite number of temporal elements and the delay equations were transformed into the form of a linear discrete map. Then the stability boundary of the system was determined by the eigenvalues of the map. Insperger et al. [104] and Mann et al. [105] have shown that this method is more efficient than the SDM when the time in the cut is small and the result was experimentally validated.

As for frequency-domain-based methods, Altintas and Budak [56] firstly proposed a zero-order approximation (ZOA) method to estimate the dynamic cutting force coefficients and stability based on the zero-order Fourier series. This method has become one of the most representative methods for milling stability solution and applied in many machining operations [106]. However, the ZOE is mainly applicable to large radial immersion condition, and it was demonstrated that the results of ZOA might be inaccurate when period doubling instability and mode interactions occurred [107, 108] in interrupting machining. Furthermore, the multi-frequency (MF) method [109] was used to evaluate the stability limits in low-immersion milling. As more Fourier expansion terms and higher harmonics of the directional factors were considered in this method, the accuracy had been increased even though with lower calculation efficiency. This method was further analysed and extended to improve the convergence at different cutting conditions [110-112]. For instance, Altintas et al. [113] compared the efficiency and accuracy of different frequency domain methods and semi-discretization method in predicting the milling stability borders. Zatarain et al. [114, 115] analysed the stability limits in milling by considering the influence of helix angle and using the MF solution. The results showed that the helical shape could help to suppress the double period chatter. Munoa et al. [116] employed the MF solution to develop the SLDs by considering the interactions between different dominant models.

In addition to the development of algorithms to improve the calculation and convergence speed, some researchers made the efforts on the construction of SLD with higher accuracy as stability analysis of thin-wall milling process became more complicated due to the changing tool-workpiece engagements, continuous material removal process, and the varying dynamic characteristics of the workpiece. In some cases, the chatter-free cutting parameters for thin-wall machining were selected from the two-dimensional SLDs that related to the axial DOC and spindle speed [53, 117]. However, the dynamic characteristics of IPW and FRFs at the tool tip depends on tool position and changes with the material removal process. As a result, conventional 2D SLDs may result in incomprehensive and inaccurate prediction results and need to be extended to 3D SLDs corresponding to different tool positions [118]. Some chatter prediction algorithms and analytical models with improved performance were proposed to achieve accurate construction of SLDs with full consideration of the changing dynamic behaviours and the overall FRFs of the machining system [119-123].

Bravo et al. [119], for instance, developed the 3D SLD by considering the spindle speed, cutting depth and workpiece geometric state at each machining step, and predicted chatter by considering the changing dynamic characteristics of both the tool/workpiece subsystems. Jin et al. [63], Qu et al. [120], and Feng et al. [64] performed similar works which include the effect of workpiece geometry or cutting position along the tool-path. Campa et al. [26] developed both 3D and 2D SLD for the prediction of stable thin floors machining, which was similar to the above-mentioned studies. However, the effect of DOC was ignored because this parameter was fixed during the machining, and the 3D diagram was simplified to a 2D diagram that only involved the spindle speed and tool position. Yang et al. [74] investigated the varying dynamics of the thin-wall workpiece with curved surfaces. The tool position related IPW dynamics and varying engagement conditions were considered to plot the 3D SLDs in terms of axial depth of cut, spindle speed and tool position. Zhang et al. [121, 122] developed a numerical model and plotted the 3D SLD to investigate dynamic characteristics of thin-wall part at different processing positions. The effect of part deflection was considered simultaneously in this model. More recently, Dang et al. [123] predicted the 3D SLDs by considering the tool position and material removal-dependent FRFs of the IPW. The efficiency of computation was improved by reducing the dimensions of the mass/stiffness matrices and the number of in-analysis modes. Yan et al. [110] considered the dynamic properties of both cutter and workpiece, and an improved MF solution was applied to predict the stability limits.

Apart from the tool position and material removal process, the impact of process damping on SLDs was also analysed in many studies [124]. Because lower cutting speed is preferred for the machining of thin-wall parts made from nickel and titanium alloys, while the process damping plays a critical role in examining the damping force and enhancing the machining stability at such cutting conditions. Budak and Tunc [125, 126] proposed an identification and modelling method to accurately determine the process damping coefficient and also the chatter-free cutting parameters. Based on this model, they further investigated the influence of cutting parameters and tool geometry on process damping and stability [127]. It was demonstrated that lower cutting speed, cylindrical flank geometry, higher hone radius could lead to increased process damping and stability. Later on, the process damped stability behaviour of the multi-mode milling system was predicted using the first order analytical frequency domain solution and time domain model [128]. In the study of [129], the material removal process, multiple modes and process damping were considered when modelling the stability of IPW. Then the structure dynamic modification method and FE method were used to predict the dynamics of IPW, and the modified third-order full discretization method was applied to establish the 3D SLD.

From the studies on the construction of accurate SLDs, it can be concluded that more process characteristics have to be taken into account for the stability analysis of the thin-wall milling process. The accuracy of these SLDs can be significantly improved with the consideration of sufficient factors in the milling process, whereas the complexity of the models is also increased.

2.3 Suppression/elimination of chatter vibration

In practical machinings, such as multi-axis machining of thin-wall parts with complex contour, the establishment of the SLD needs a comprehensive analysis of the machining dynamics, which is time-consuming and error-prone. For such operations, suppression and elimination methods with different types of instruments were developed to achieve a chatter-free machining process. Generally, the strategies for chatter suppression and elimination can be classified into two categories: active strategies and passive strategies. These strategies are developed based on either the installation of extra devices or optimization of cutting parameters, which can provide the correlated external energy, dissipate the internal energy, interpret the regenerative effect and consequently eliminate the growth of chatter vibration.

2.3.1 Active chatter control strategies

It was found that, when chatter occurs, drastic fluctuations in vibration amplitudes could be found because the real-time critical frequency changed from the original tooth-passing frequency to the frequency around the natural frequency of the machining system [130]. Active chatter control is a strategy based on the continuous on-line monitoring of the dynamic state, the diagnoses of sudden signals and instant responses on the process to ensure the active detection and elimination of chatter vibration. The on-line data acquisition, feature extraction/identification modules, processing methods, diagnosis modules and execution actuators are the key components for the active control systems.

On-line data acquisition is achieved by monitoring processing signals such as cutting forces, acceleration, sound, velocity and displacement. Various types of sensors such as dynamometer, acoustic sensor and accelerometers are applied with associated filters to acquire the above signals [131-133]. The measurement of force signals is the most commonly-used method in detecting chatter vibration because the force signals directly reflect the dynamic status during the milling process and can meet multiple analysis requirements. Acoustic signals of the machining process can be measured using microphone or acoustic emission sensors, which provide useful feature information associated with abnormal cutting conditions [134]. Also, chatter can be detected from the drive motor current commands supplied by the CNC machine while no external sensor is required [135]. The occurrence of chatter vibration detected by spindle motor current and microphone measurements is shown in Fig. 6.

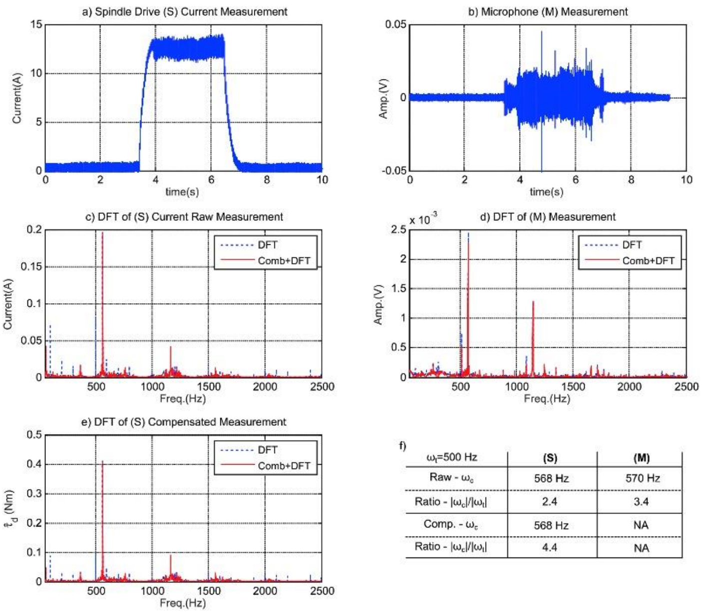


Fig. 6 Chatter decided by motor current and microphone [135].

The acquired signals consist of periodic components caused by the intermittent cutting action, the chatter components caused by self-excitation and the perturbation components stand for the external noise. In order to identify the occurrence of chatter, the acquired raw signals are analysed by different feature extraction methods and compared with the predefined thresholds or indicator [37, 136]. Generally, the chatter feature extraction methods can be divided into three main categories: time-domain analysis, frequency-domain analysis and time-frequency analysis.

The time-domain methods are used to identify chatter by extracting the sensitive features and analysing the abnormal peak amplitudes of acquired signals [137, 138]. The obtained time-domain signals can also be transformed into the frequency-domain via Fourier Transform methods. Then, the frequency-domain methods were adopted to detect the chatter as chatter can cause a significant frequency shift [113, 139]. However, the locations of suddenly-changed signals cannot be identified using standard Fourier Transform. Therefore, the time-frequency methods, such as Fast Lifting Wavelet Transform, are applied for feature extraction because these signal processing methods can simultaneously locate the time and specific frequency component of sudden frequency changes [140-142].

Various methods for extracting features from measured signals are reported in the literature. For example, Kolluru et al. [143] investigated the coupled dynamic response of tool and thin-wall workpiece. Vibration signals were analysed in the frequency domain (Fast Fourier Transform (FFT)) and time-frequency domain (Short-time Fourier Transform (STFT) and 3D FFTs) to study the acceleration signals, the evaluation and evolution of frequency components through FFT are presented in Fig. 7. Feng et al. [132] analysed the milling force signals by FFT and wavelet transform for the detection of chatter occurrence. Meanwhile, the surface topography was evaluated as evidence to prove the onset of chatter. Grossi et al. [144] presented a novel Spindle Speed Ramp-up (SSR) test to detect chatter, and an experimental stability map was developed. The captured signals were analysed using the Order Analysis (OA) technique to detect chatter frequencies. This research was further improved to identify the speed-varying FRFs and extract the chatter limits [145]. By processing the raw signals with the above-mentioned methods, the extracted features are then analysed to diagnose the occurrence of chatter. Normally, chatter is verified via the comparisons between the predefined chatter threshold value obtained from the prediction models and identified signals in the cutting process [146-148].

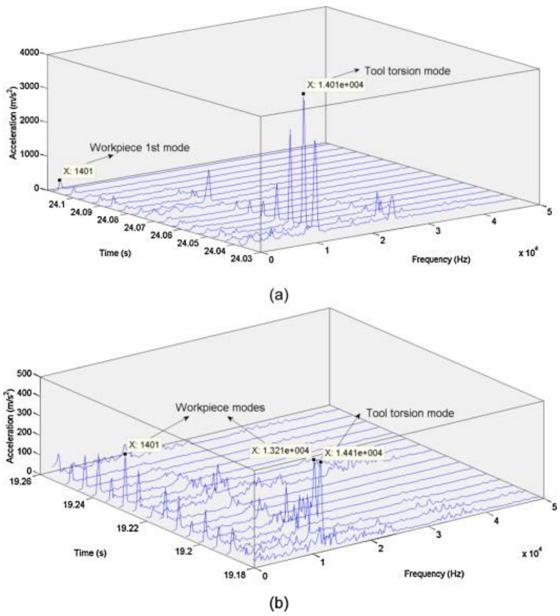


Fig. 7 Frequency analysis using FFT method [143].

Besides the above-mentioned methods, chatter detection is also studied based on the development of artificial neural networks. Various network-based schemes such as self-organizing map (SOM) neural network, recursive neural network (RNN) and convolutional neural network (CNN) were used to monitor the occurrence of chatter by means of signal feature processing and deep learning [149-153]. These proposed intelligent control systems are efficient for monitoring and recognising chatters, but the robustness, accuracy and response rate of the neural network largely depend on continuing self-learning, training, and testing process.

On-line detection of instant chatter is a promising solution to interfere in the process and avoid the occurrence of chatter. However, the accuracy of chatter identification by different on-line approaches largely depends on the algorithms and the setup of data acquisition systems. In the machining of thin-wall components with complicated geometries, the proper installation of sensors is difficult, and the sensors mounted in incorrect places could hinder the feed of cutting tools. An alternative way for on-line detection is to analyse the machined surface by off-line surface characterization methods [154]. Normally, the characterization of the surface topography can be captured and analysed by using power spectral density (PSD) and relevant signal processing methods [64, 132, 155], which provide a clear assessment of chatter marks on the machined surface. In PSD analysis, higher magnitudes of PSD plots at a smaller spatial frequency or higher spatial wavelength indicates high amplitudes of the wavy surface profile due to dynamic cutting [156]. In this method, the precise capture of the machined surface and the critical power spectral density is required to identify the occurrence of chatter. The observed surface topography can be viewed as evidence for determining the pattern of chatter, as shown in Fig. 8.

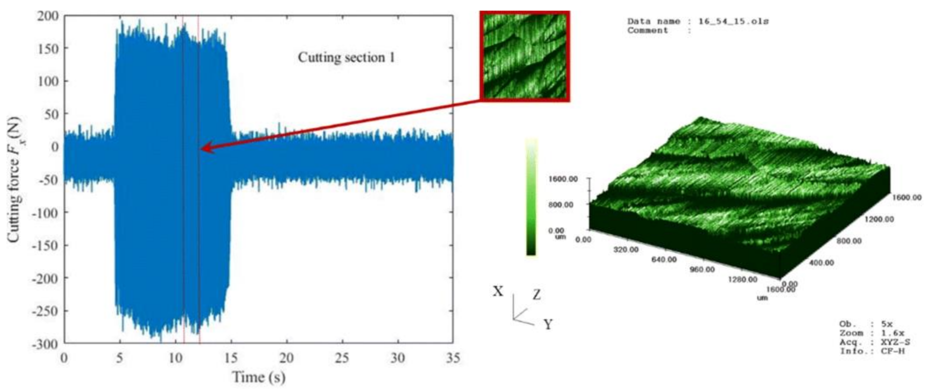


Fig. 8 Milling force signals and surface topography at certain cutting section [64].

Once the onset of chatter is detected (either by the on-line monitoring or off-line recognition methods), active control strategies could be used to execute corresponding decisions to compensate for the current vibration status. The most-common actuators in active systems are hydraulic, piezoelectric and electromagnetic actuators [157-161]. Desired compensations can be made via these active actuators by generating forces or displacements on the cutting tool and workpiece, and then, the regenerative effects can be reduced by the correlated external intervention. Additionally, the machine's own drive can be controlled by dedicated algorithms to suppress the occurrence of chatter instead of using external actuators [162, 163]. The illustration of the spindle control loop is illustrated in the following figure.

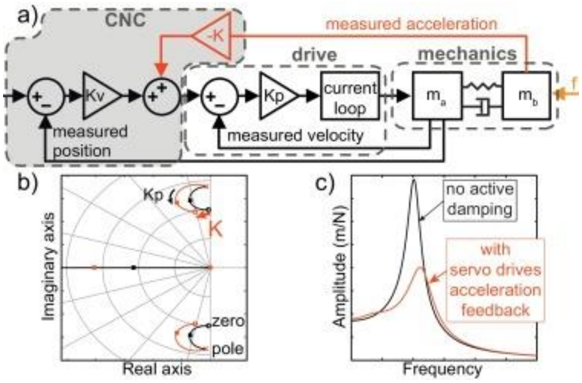
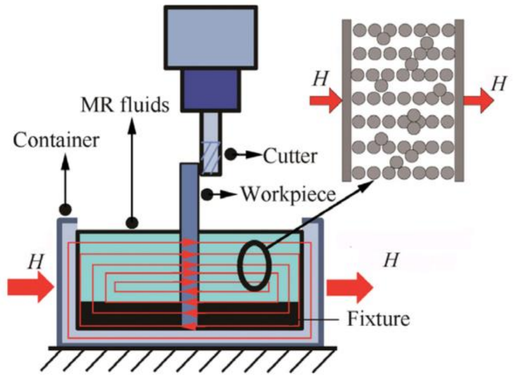
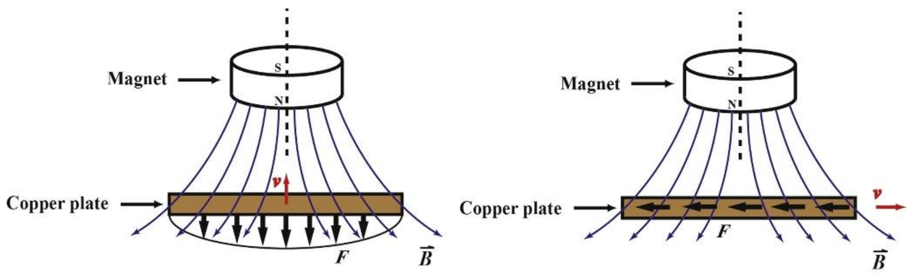


Fig. 9 Control block diagram of the active control loop for a simple case [163].

In order to actively change system behaviour and eliminate the instability, another strategy is to use the active damping approach, such as the application of magnetorheological (MR) and electrorheological (ER) fluids. For instance, Diaz et al. [164] and Ma et al. [165] proposed MR fluid-based flexible fixtures for machining complex thin-wall parts, and the external damping constraint of MR fluids was considered when built the dynamic equations of the workpiece-fixture system. The rheological property of the MR fluid was controlled by the application of an external magnetic field, which provided extra damping property for the machining system. Jiang et al. [166] also investigated the controlling of MR flexible fixture in the machining of thin-wall parts. The shear stress performance of MR fluid and workpiece properties were investigated to obtain the best clamping performance. The effectiveness of the eddy current damping approach was verified in several studies [167, 168]. It was demonstrated that the eddy current damping effect was generated due to the electromagnetic induction when the workpiece was vibrating within the magnetic field, resulting in an additional damping effect on the motion of the workpiece.



(a)



(b)

Fig. 10 (a) Flexible fixture based on MR fluids [165]; (b) Magnet's flux in workpiece [168].

Apart from the aforementioned methods, chatter can be disrupted by means of spindle speed variation (SSV) [42, 169-171]. In SSV machining, the spindle speed is dynamically modulated to disrupt the regenerative effect. The stability limits of the machining system could be greatly enhanced by the proper selection of variable frequency and the range of spindle speeds. SSV machining can be easily achieved in turning and milling because the frequency and amplitude of the speed variation can be automatically adjusted in the CNC machine [172, 173]. However, there are still some limitations to SSV for thin-wall milling and industrial applications. Firstly, the SSV technique is not eco-friendly because a large portion of energy is consumed in modulating spindle variation. Furthermore, it is hard to achieve a quick response of the spindle speed variation to instantly disrupt chatter due to the extremely high moment of the spindle system, so it is considered to be sufficient only in the low spindle speed range [174]. Additionally, the adjustments of spindle speed in HSM could lead to extra instability of the tool-spindle system.

Except for these commonly-used methods, the optimization of tool orientation, machining procedure was also investigated in previous studies for chatter suppression [175-177]. Alan et al. [178] applied the structural modification method to obtain the FRFs at different machining stages and optimized the cutting strategy to increase the chatter-free MRR. Similarly, Luo et al. [179] presented an optimization procedure for removing workpiece materials in thin-wall milling. The proposed step removal method started from the last machining step, and the uncut material of the most flexible part was firstly considered to obtain a stable cutting process. Then, the removed material stock was sequentially added for each machining step until the initial geometry was obtained. Budak et al. [180] used single-frequency and multi-frequency solutions to solve the chatter problem and improve the productivity in 5-axis milling operations. Sun and Altintas [181] proposed an automatic optimization approach for chatter-free tool orientation of 5-axis ball end mill. The tool orientation was optimized at each cutting location by checking the feasible rotational positions within the searching scope and evaluating the stability of each position based on the Nyquist criterion. Ozkirimli et al. [182] proposed a numerical frequency domain solution and combined this method with the ZOA frequency method to predict the stability limits of multi-axis milling with complex tool geometries. More recently, Tunc and Zatarain [183] investigated the effects of stock thickness, stock shape and tool axis to improve the stability of thin-wall parts during 5-axis finish milling. Variable stock thickness selection and stock shape distribution were simulated through the FEM method and verified by experiments; meanwhile, the tool axis was optimised to reduce the vibration and machining time. Further, Liu et al. [184] investigated the effects of tool helix angle and tilt angle on milling vibrations and surface topography when milling sidewall surfaces. Ji et al. [185] considered the spindle-system-tool-workpiece interactions and speed effect when establishing the dynamical model of the spindle system and obtain the SLDs of five-axis flank milling. Moreover, the simultaneous milling process of thin-wall components [186, 187] was studied in several research. The results showed that the stability limits and productivity could be significantly improved in thin-wall machining with properly selected cutting parameters.

2.3.2 Passive dampers, fixture and tool design

Although active control strategies can provide a fast and precise control response, the actuators are expensive and dedicated control algorithms are required. Furthermore, it is difficult to integrate the actuators and sensors into the machine system in some real industrial scenarios, especially for the machining of complex thin-wall parts. In addition to active control strategies, effective passive suppression strategies, including special tool structures, cost-effective fixtures and various additional devices such as passive dampers and absorbers are also widely adopted in both industrial manufacture and laboratory research. The application of these devices can efficiently improve the damping capacity of the machining system and expand the stable zones by changing the system behaviour. Moreover, no external energy is required for the dissipation of oscillation energy while the regenerative process can be disrupted [188]. Fig. 11 illustrates the schematic diagram of some commonly used passive damping systems.

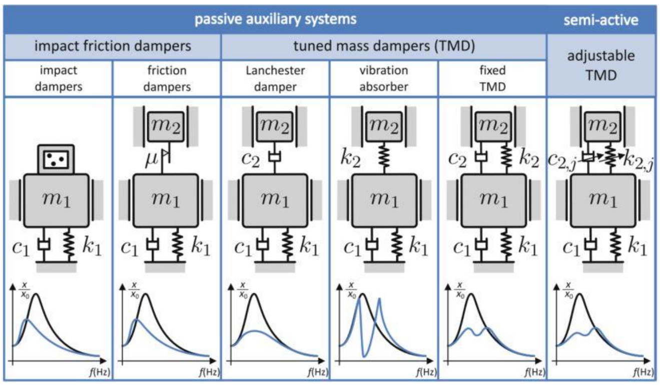
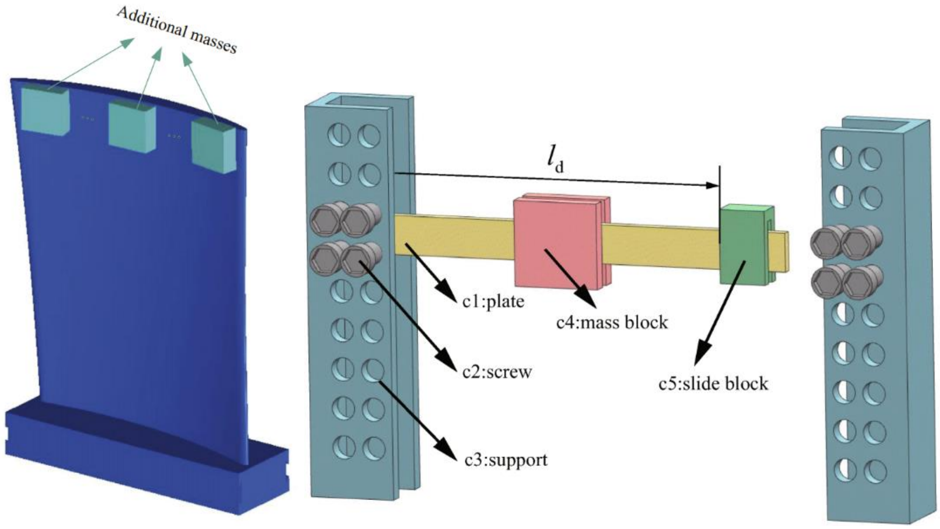


Fig. 11 Passive dampers developed for chatter control [23].

Among the proposed passive strategies, tuned mass dampers (TMDs) is the most practically used applications due to their simplicity, reliability and adaptability. TMDs improve the structural stability by adding extra inertial mass to the initial machining system, so the damping of the coupled system can be increased by accurately tuning the natural frequency of the TMDs within a certain frequency range of the critical modes of the machining system [189]. Wan et al. [190] improved the chatter stability by attaching optimal additional masses to the upper side of the workpiece (Fig. 12(a)). The structural dynamic modification scheme was developed to obtain the varying dynamics of the IPW with the combined effects of additional masses and the material removal process. Yuan et al. [191] developed a passive damper with tuneable stiffness to suppress the vibration occurring in the thin-wall milling process (Fig. 12(b)). Modal analysis of the damper was completed by using the FE method and optimal parameters of the passive damper were calculated by considering the influence of the continuous material removal process.



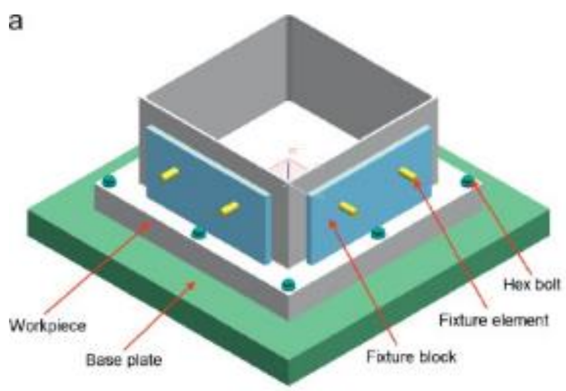
(a) (b)

Fig. 12 (a) Attached additional masses on workpiece [190]; (b) Structure of the passive damper [191].

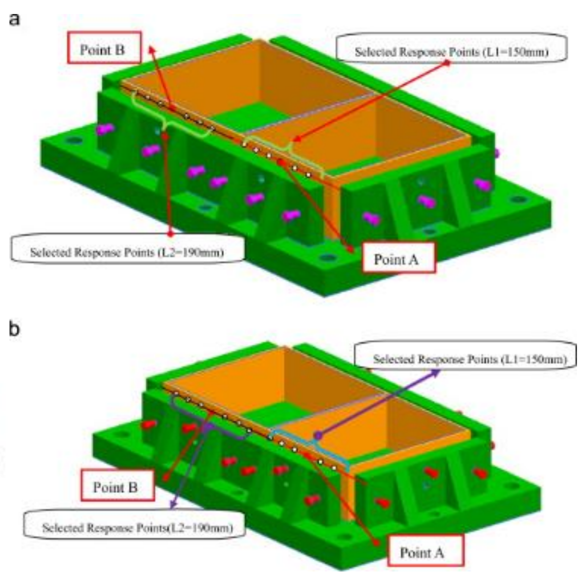
With the consideration of the inherently dynamic nature of thin-wall components, TMDs should be installed at some critical locations where the dominant modes have considerable amplitudes of vibration. However, the implements may limit the movement of the cutting tool in multi-axis machining, and abundant space is required for the installation. Meanwhile, the efficiency of TMDs may be significantly limited in thin-wall machining because it is difficult to achieve accurate tuning and expected performance due to the changing dynamic properties of the IPW. In addition, TMDs are generally designed for a fixed machining system, and their versatility is still a problem. Therefore, the development and accuracy of the tuning procedure, as well as the control algorithm, is still a challenge for the application of self-adaptive TMDs in the thin-wall machining process.

To address these problems, novel passive damping approaches without physical additions were proposed to reduce the chatter instability in thin-wall machining. For instance, Zhang et al. [141] improved machining stability by submerging the milling system in viscous fluid. The damping of the milling system was increased obviously due to the added mass of the viscous fluid and the extra energy loss; the milling force was also reduced significantly due to the lubrication effect of silicone oil. Later on, Liu et al. [192] investigated the supporting effect of air jet assistance on the processing precision and quality of the machined surface of the thin-wall part. The results showed that the perpendicular impact force on the impingement surface generated by the air jet improved the cutting stability, surface quality, and the part deformation was reduced at the same time.

The development of reliable fixtures and their layouts is another cost-effective way to strengthen the thin-wall component with controlled vibration. Fixtures are designed to rigidly support the workpiece during the machining process and ensure an accurate location of the workpiece relative to the cutting tool and machine datum. Studies focused on the fixturing for thin-wall machining were carried out regarding the design and optimization of fixtures and fixture layout, clamping sequence and associated surface-form errors [193, 194]. Zeng et al. [195] developed a novel fixture-design method (Fig. 13(a)) to reduce the vibration of the flexible workpiece. A dynamic model of the workpiece-fixture-cutter system was built, and the location, the cutting forces and the number of the fixture were optimized. Wan et al. [196] evaluated the dynamic response of multi-framed thin-wall workpiece with different layouts of fixture constraints (Fig. 13(b)). It was found that the support locations of fixture influenced the frequency, shapes and also amplitudes of the vibration signals. Therefore, the fixture layout needed to be optimised to make sure that the frequency of the workpiece-fixture system was out of the range of the cutting frequency, which consequently suppressed the occurrence of the chatter. Wan et al. [197] improved the stability in the machining of long strip-like thin-wall by applying tensile prestress to the workpiece. The authors investigated the relationship between the prestress, the critical axial cut depth and the natural frequency of the workpiece. The designed prestressing support provided the thin-wall workpiece with desired prestress and also the stiff clamping function.



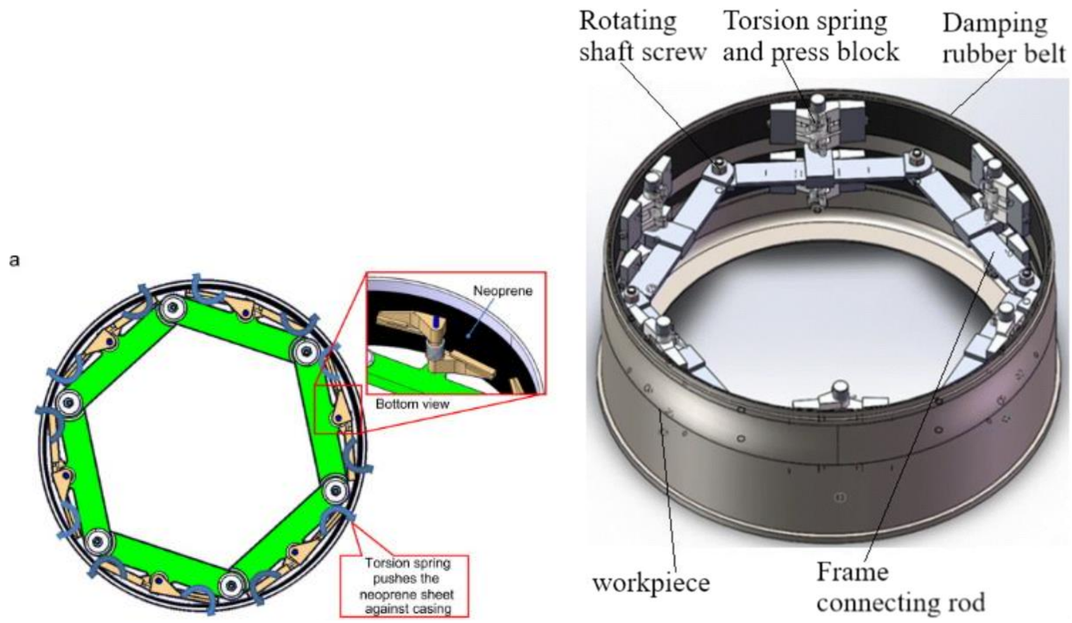
(a)



(b)

Fig. 13 Designs of fixtures for thin-wall machining [195, 196].

Considering the complexity of thin-wall machining, some researchers also made attempts on the designing of innovative fixtures, such as the hydraulically actuated fixtures [198] for thin wall castings. Kolluru et al. [199] proposed a pre-tensioned articulated device to improve the stability of the circular thin-wall components and control the machining vibrations (Fig. 14(a)). This device increased the system damping compared with the viscoelastic based surface damper, which significantly reduced the machining vibration. Similarly, Wang et al. [200] designed a flexible fixture that consisted of rubber belt, torsion spring, pressing block, rotating shaft screw, and frame connecting rod (Fig. 14(b)). A hybrid dynamic model and FE model of this method were developed to evaluate the effect of the flexible fixtures on vibration suppression of thin-walled castings.



(a) (b)

Fig. 14 Novel fixture designs for machining of flexible workpiece [199, 200].

Similar to the TMDs, fixtures are commonly clamped at areas with lower stiffness, which aims to reduce the amplitudes of chatter. The reasonable design of fixtures and fixture layout can significantly enhance the dynamic machinability and surface quality of the in-process workpiece. However, the application of conventional mechanical fixtures could lead to dimensional errors due to the excessive clamping forces and the induced local contact deformation. Also, the placement of fixtures could hinder the access of the cutting tool in multiple operations. Therefore, the clamping locations and sequence should be verified prior to machining through different prediction methods.

The design of non-standard tool structures includes the variable helix angle tool, variable pitch angle tool (as shown in Fig. 15) is an alternative method for disrupting regenerative effect and improving machining stability. The geometric irregularities of these types of tools can continuously change the phase difference among cutting edges. It has been demonstrated that variable helical tools could create continuous variation in the local pitch angles along the tool axis [201, 202], and the variable pitch tools created multiple discrete delays among cutting edges in each revolve of the cutting tool [203, 204].

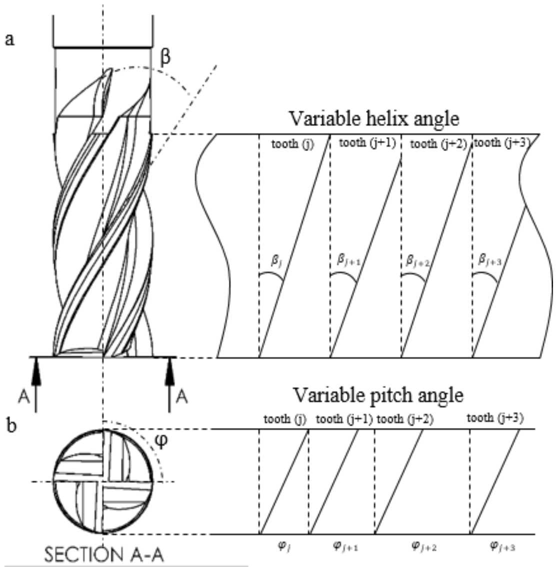
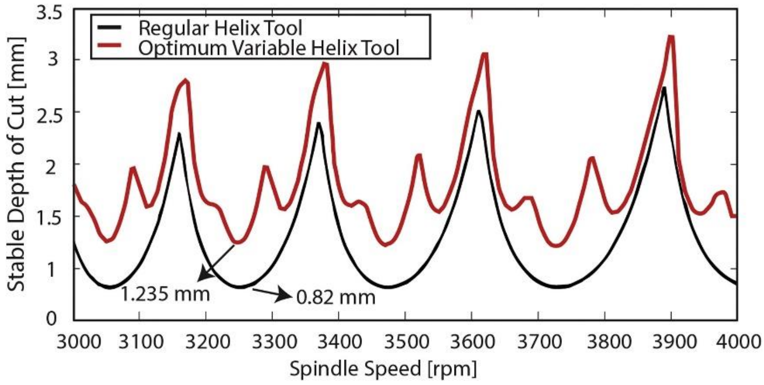


Fig. 15 Variable Pitch tool: (a) variable helix angle end tool and (b) variable pitch angle end tool.

Altıntas¸ et al. [205] proposed an analytical model to predict the SLD and select the optimal pitch angles for variable pitch cutter. Based on that work and the zero-order frequency domain method, Budak [206, 207] further presented an analytical method for the design of a tool with nonconstant pitch variation, and this method was verified through actual applications in terms of stability, productivity and surface finish. Later on, Zatarain and Dombovari [208] predicted the stability of machining with irregular pitch tools in medium and high order lobes regions by using the implicit subspace iteration method. With this method, accurate prediction of SLDs and selection of pitch angle can be achieved with less calculation time. In the study of Comak et al. [209], the optimal design of variable geometry tools for thin-wall milling was explored. The dynamics and stability of variable pitch and helix tools were modelled and solved with the semi-discretization and ZOA methods. The optimal selection of pitch and helix angle variations was experimentally verified. Niu et al. [210] proposed a mechanistic model for variable pitch and variable helix milling tools. The cutting coefficients and run-out parameters were identified through a combined nonlinear optimization algorithm to further analyse the dynamic stability and the multi regenerative effects. The effects of variable helix and pitch angles on the stability limits of SLDs are shown in Fig. 16.



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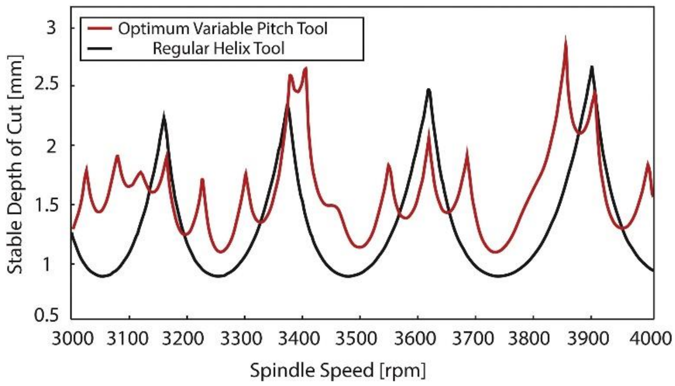

(b)

Fig. 16 (a) Effect of variable helix tool; (b) Effect of variable pitch tool [209].

The serrated tool is another type of tool with special flute geometries. Serrated tools can create non-uniform time delays along each cutting edge due to the difference of the serration wave flutes [211-214]. However, serrated tools can produce periodic cutting marks on the finished surface, so they cannot be used for finishing operations.

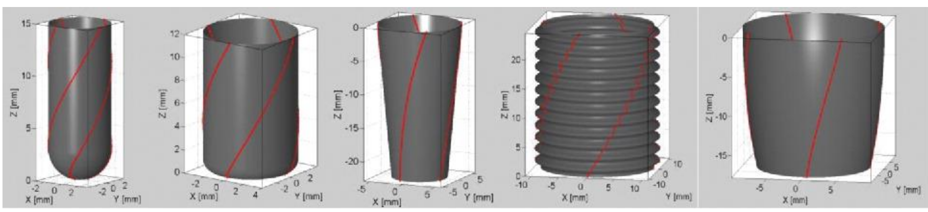

Fig. 17 Traditional (ball, bull, and tapered) and innovative tools (Strassman type and barrel type) [214].

It is shown in the literature that the machining stability can be significantly improved by correct optimization of tools structures, and different innovative tools are particularly promising for machining thin-wall components without carrying out complex analytical models [215]. Therefore, the research and development of these types of milling tools will have a remarkable impact on the machining of thin-walled parts in the future.

3. Cutting loads induced deformation and relevant solutions

In a chatter-free cutting process, cutting loads induce deflections of the slender type tool and thin-wall workpiece are considered as the major dimensional errors [216]. The dimensional accuracy of the machined surface could directly affect the functional performance of the thin-wall part. Therefore, various strategies, including error prediction and compensation methods, were studied and applied in thin-wall machining processes to analyse the mechanism of flexible deformation and to eliminate dimensional errors. Relevant analytic models, prediction, compensation and elimination methods are introduced in the following sections.

3.1 Mechanism of thin-wall deformation

In the thin-wall milling process, the transient cutting load applied to the thin-wall component can lead to a displacement (δ) of the contact point, depending on the stiffness (k) of the tool-workpiece engagement area.

$$F = k * \delta \qquad (\mathbf{8})$$

For thin-wall part under cutting, the actual cutting point could deviate from the nominal point and deflect to a new location due to the existence of workpiece deflections (Fig. 18).

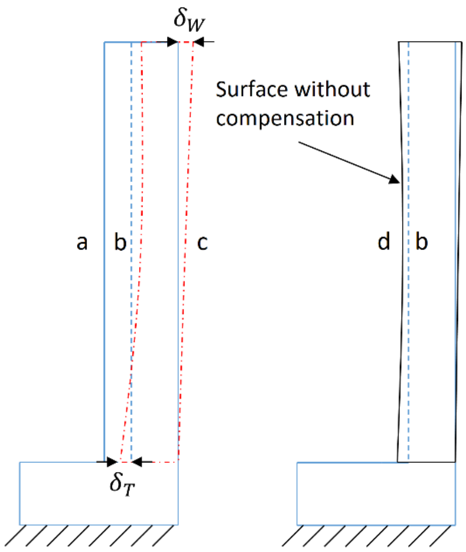

Fig. 18 Illustration of forced-induced deformation in thin-wall milling.

By simplifying the model, the thin-wall part is generally assumed to be a cantilever plate, and the deflections in the feed and axial tool directions can be ignored. In Fig.18, Line a indicates the initial workpiece surface, Line b presents the planed profiles of the finished workpiece, while the red Curve c indicates the actual surface due to the tool/workpiece deflection. Considering the spring-back of the flexible cutting system after unloading, the machined surface is showed as the black Curve d. In a flexible tool-workpiece system, the surface form error can be derived by:

$$\delta_e = \delta_T + \delta_W \quad (\mathbf{9})$$

Where δ_e is the total static deformation error, δ_T and δ_W are the deflection errors of tool and workpiece, respectively.

Generally, the magnitudes of static deformation depend on the cutting strategies, tool geometry, and properties of the tool/workpiece material that directly linked to the in-process cutting loads and varying stiffness of the workpiece in the material removal process. Due to the deviation error, the radial depth of cutting and immersion angles are deviated from their planned values for any engaged cutting points during the machining, and the actual material removal volume is also deviated from its theoretical value. Therefore, the prediction of dimensional errors in the thin-wall milling process is of high complexity, so in most cases, only the cutting force is considered as the dominant factor to simplify the machining conditions, while the effects of thermal load and residual stress are ignored. However, the residual stress caused by the thermal-mechanical loads and uneven material removal process can also lead to considerable deformation errors of the finished workpiece [217]. The distribution of residual stress is influenced by cutting parameters and cooling strategies, and it was demonstrated that proper control of the stress distribution alleviated the part deflection up to 45% [218]. Furthermore, several researchers investigated the influence of thermal load in thin-wall machining [219-221]. In metal cutting processes, a significant amount of energy is converted into cutting heat due to the friction effect and plastic deformation in the deformation zones, and a proportion of the cutting heat is transferred into the workpiece [222]. The thermal load has a significant impact on thin-wall deformation as it can change the properties of workpiece material and the amplitudes of thermal expansion, especially in dry machining processes and the machining of difficult-to-cut materials. Also, the time-varying tool/workpiece engagement and continuous material removal further complicate the localized temperature field and stress distribution [223]. Consequently, the thin-wall part could present unexpectable surface deviations without the compensation of thermal effects.

3.2 Error prediction for thin-wall milling process

To obtain acceptable dimensional tolerance without carrying out costly cutting trials, analytical prediction models were developed to investigate the process response. In the following sections, the development of flexible cutting force models and deformation analysis models for the prediction of the thin-wall milling process are presented.

3.2.1 Cutting force models and iterative algorithms

Conventional cutting force models cannot be applied directly in the prediction of thin-wall milling process and need to be modified based on the real cutting conditions. In the machining of flexible thin-wall workpiece, cutting force dynamically changes due to the tool/workpiece deflections and variable tool/workpiece engagements. To be specific, the cutting force is calculated with the instantaneous uncut chip thickness, which is a function of the tool immersion angles determined by the part deflection; in reverse, the part deflection is influenced by the cutting loads [224]. To ensure the accuracy of the prediction models, conventional rigid cutting force models need to be modified with the consideration of the flexible characters of the thin-wall part as well as the coupling interaction between the cutting loads and induced deformation [225, 226].

A significant amount of work [227-230] on flexible cutting force models and relevant iterative algorithms were carried out to provide a more accurate description of the dynamic tool/workpiece engagement and to find the equilibrium state of the cutting forces and part deflection. Ratchev et al. [224, 231] presented a theoretical flexible force model to predict the force-induced errors in thin-wall machining. This cutting force model was developed using an iterative algorithm, and the calculated results were fed as inputs for the FE part deflection model to simulate the deformation and dynamic behaviour of the thin-wall part. Wang et al. [232] investigated the static errors in flexible milling regarding mesh strategy, discretization of cutting forces, tool-workpiece coupling and rigidity variation of the workpiece. The calculating efficiency of the cutting force model and the FE model was significantly improved by the used iteration scheme and material removal model. Wan et al. [233, 234] proposed a new iteration scheme for the calibration of the instantaneous uncut chip thickness and cutting forces in flexible peripheral milling. The effects of cutter/workpiece deflections and engagement variation were taken into account, and the iteration procedure was proceeded to correct the cutting conditions and dimensional surface errors. Kang et al. [235] further improved the simulation efficiency of the iterative algorithm by using the flexible iterative algorithm (FIAL) and double iterative algorithm (DIAL). The accuracy on the prediction of actual cutting depth, surface form errors and maximum surface form error was improved. This work was followed by research [236] which presented the coupling effect of regenerative dynamic displacement in thin-wall milling operations. The radial cutting depths and varying engagement boundaries at different feed positions were corrected based on an improved iterative process, and the SLD was established by considering the in-process dynamics and force-induced deformation effect simultaneously. Li et al. [237] analysed the deformation of micro thin-wall structures based on the iterative finite element method. Cutting forces were calculated by considering the deformation-related radial cutting depth and the tool edge radius.

It could be found that flexible force models start with the calculation of initial cutting forces without considering the tool/workpiece deflections, and the initial conditions from the rigid model are applied to the cutting units in the deformation model to estimate the static deflections at the initial cutting location. Then, the obtained deflections and engagement variation are used to modify the radial cutting depth, immersion angles and cutting forces. Taking the down-milling process as example, the actual radial DOC a_e' and entry angle $\emptyset_{en}'$ are given by:

$$a_e' = a_e - \delta_e \tag{10}$$

$$\emptyset_{en}' = \pi - \cos^{-1}(1 - \frac{2a_e'}{R}) \tag{11}$$

Where $\mathrm{a_e}$ is the planned radial DOC. The immersion angle $\emptyset'_{en}$ is then given as input to calculate the z axis boundaries and iterative cutting force as presented in [226, 238]. In a standard cutting force model for the end mill tool, the tool is normally discretised into a finite number of slice elements, then the differential cutting forces on each infinitesimal segment are integrated along its z axis boundaries:

$$F_c(i,j) = \int_{z_{i-1}}^{z_i} F_c\left(\emptyset_j(Z)\right) dz \; (c = x, y, z) \quad (\mathbf{12})$$

Where z_i and z_{i-1} are the upper and lower limits of element i on tooth j. In down-milling process, the lower limit keeps constant while the upper limit is varying as a function of the changing entry angle:

$$z_i = \frac{1}{k_\beta}\left[\emptyset - \frac{2\pi(i-1)}{N_f} - \emptyset_{en}\right] \quad (\mathbf{13})$$

Where $\emptyset$ is the initial angular position and k_β is the lag angle at current segment (i,j).

In the next iteration step, the revised cutting forces are used to correct the cutting conditions (e.g., deflection, thermal load) in the subsequent deformation analysis. The iterative procedure and coupling analysis are continuously performed until the local deformation and cutting load converge to a stable state, which means the following condition is achieved:

$$|\mathrm{a}_e^{\mathrm{N}} - \mathrm{a}_e^{\mathrm{N-1}}| \leq \varepsilon \quad (\mathbf{14})$$

Where $\mathrm{a}_e^{\mathrm{N}}$ and $\mathrm{a}_e^{\mathrm{N-1}}$ are the actual radial DOCs of N-th and (N-1)-th iteration steps at a certain cutting position, ε is the predefined tolerance that used to control the precision.

After that, the cutting tool rotates with a fixed angular interval and the iterative procedure is performed for this new cutting position. The iterative process is repeated along the tool path until the results of all the cutting positions are obtained. A typical iteration process is shown in Fig. 19.

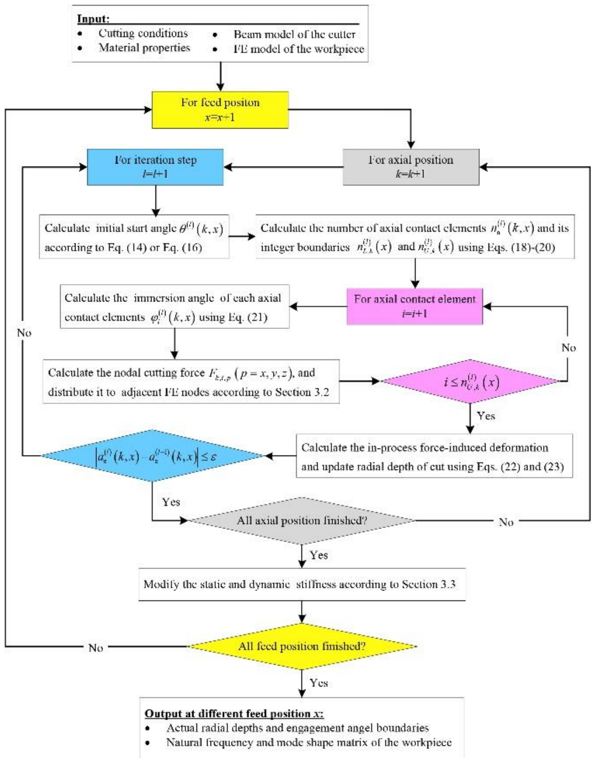

Fig. 19 Flowchart for a flexible force model and associated iteration process [236].

In summary, the basis for the prediction of thin-wall milling is to develop a reasonable and efficient flexible cutting force model that can reflect the actual cutting conditions. The literature has proven the importance of iterative algorithm for the prediction of thin-wall milling process, and it is the major difference between the rigid and flexible models [235].

3.2.2 Finite element models

Over the past decades, numerical analysis models have been widely developed to investigate the non-linear problems in metal cutting processes. The combination of the FEA method and experimental methods makes the modelling of machining process under comprehensive cutting conditions more efficient. Particularly, some special CAD/CAM software packages and FEA models are well established to analyse the thermal-mechanical coupling problems and cutting loads induced errors in thin-wall machining, and experimental-based investments for machining prediction can be reduced. These packages and models can efficiently simulate the material flow, heat transfer, thermo-mechanical coupling, and non-linear dynamic behaviours of the tool-workpiece system.

In the studies of metal cutting process, plenty of two-dimensional (2D) FEA models with a good approximation were developed for the simulation of practical machining and optimization of process planning [239, 240]. However, 2D modelling is mainly established for the orthogonal cutting process, and it is not suitable for simplifying the thin-wall milling operation using a 2D model due to the complex thermal-mechanical coupling and engagement conditions of tool/workpiece. Consequently, three-dimensional (3D) finite element models were established to present a more realistic simulation for thin-wall milling operations.

For 3D modelling of thin-wall milling, two approaches were mainly used in the previous studies to analyse the deformation behaviour of the thin-wall part. The first type of 3D models only contains the main body of the workpiece. The cutting loads are calculated previously and then applied on the workpiece to simulate the elastic-plastic deformation induced during the machining process [241-244]. Rai and Xirouchakis [245, 246], for example, developed a comprehensive FEM based model to predict the transient temperature/stresses distribution and part deflection in the thin-wall milling process. The machining conditions such as the calculated thermo-mechanical cutting loads, initial residual stresses, material removal, fixture layout, operation sequence, tool path and cutting parameters were taken as inputs. However, the cutting force models used in these studies were traditional rigid models that did not consider the coupling effects of cutting force and part deflections.

In order to accurately analyse thin-wall deflection and support the iterative procedure used in flexible cutting force models, different methods were developed in the literature. Li et al. [247] predicted the surface form errors of both the flexible workpiece and the slender end-mill in five-axis milling of thin-wall structures, based on an iterative approach and sub-structuring method. In this work, the cutter-workpiece engagements, instantaneous uncut chip thickness and the machining deflections were iteratively calculated for all cutting positions. Liu et al. [248] employed the finite element model updating method and the flexible model to evaluate the local equilibrium and analyse the machined surface errors in large-scale face milling. Further in [249], Ge et al. analysed the dynamic interaction of the machining system, and an error prediction model was established based on the stiffness matrix reduction method. The proposed iterative prediction method was verified by the FE models and then applied to the error compensation system.

Generally, the flexible thin-wall part is modelled as a low rigidity cantilever plate, and certain material properties and boundary conditions are allocated to this structural model. The calculated dynamic cutting forces are cooperatively applied as inputs of the thin-wall models to obtain the deformation values at each iterative step through the FEA solver. The iteration process is performed for every tool position along the tool path to include the effects of tool/workpiece deflections and material removal process. In order to describe the material removal process, a group of elements that equivalent to the tool swept volume is deactivated at each feed position. Fig. 20 presents the schematic of cutting loads and workpiece deformation.

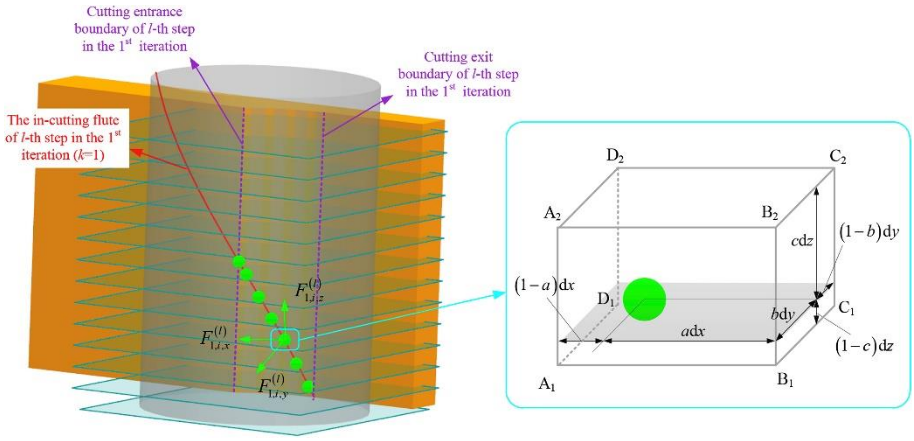

Fig. 20 Discretization of the cutting edge and the application of cutting forces [236].

Studies focused on the development of 3D FE models (Fig. 21) were also conducted based on the actual cutting mechanisms [250-252]. In these studies, various material constitutive models are used to model the workpiece material properties, and Johnson-Cook (J-C) constitutive model is the most widely-used model which describes the effects of strain hardening, strain rate hardening, and thermal softening on material behaviour under high strain, strain rate and temperature conditions. The split-Hopkinson pressure bar (SHPB) tests are carried out to characterize the behaviour of the material under different strain rates and initial temperatures [253-255]. Meanwhile, different chip separation criterions such as the J-C shear failure criterion are applied to realize the material failure and chip separation from the workpiece. The frictional behaviour of the tool-chip interface is normally described by the modified Coulomb friction model [256], which divides the tool-chip contact area into the sticking area and sliding area. The states of the contact surfaces are identified by comparing the maximum shear stress across the interface with the normal stress acting between the contacting surfaces. Additionally, the heat sources generated by the rubbing effect and plastic deformation in cutting zones also need to be defined. Besides, the convective cooling conditions should be applied to the outer surface of the tool and workpiece to simulate the application of coolants. The key point of the 3D simulation is how to efficiently calibrate the parameters that are involved in the FEA model, such as contact and boundary conditions.

Based on the simulation method, time-consuming experiments of thin-wall machining can be avoided. Moreover, cutting parameter optimization and NC program generation for thin-wall parts can be well supported.

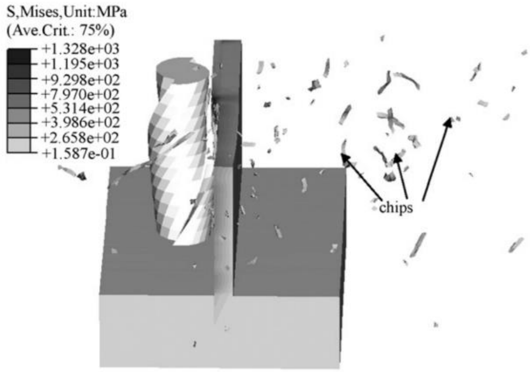

Fig. 21 3D thin-wall milling process via FE simulation [253].

3.3 Error elimination and compensation for thin-wall milling process

Many machining strategies were established for error elimination and compensation in thin-wall milling process. To avoid defective components and compensate for deformation errors that directly affect the performance of the finished workpiece, one solution is the on-line measurement and compensation based on the captured surface form errors. Touch probes and displacement sensors are employed for monitoring and measuring thin-wall deformation [257, 258], as shown in Fig. 22.

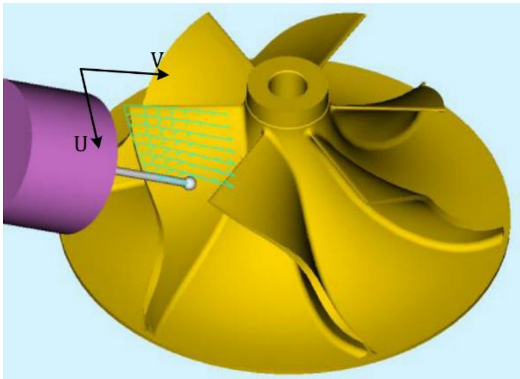

Fig. 22 Touch probe used for on-line measurement [258].

A number of studies made efforts on the on-line measurement in flexible thin-wall machining. For example, Huang et al. [258] presented an integrated compensation method for 5-axis flank milling of flexible thin-wall part, based on the on-machine measurement (OMM) inspection system. The touch-trigger probe was used to capture the machined surface, and the obtained geometry was compared with the cutter's envelope surface to calculate machining error caused by part and tool deflection. Guiassa [259] tried to eliminate tool offset error by the on-machine probing method and obtained probing data. Calibration and compensation were implemented by comparing the deviation vector of the probing data with the design profile. A similar approach was reported by Wang et al. [260], they used the machine-integrated touch probe to measure the machined workpiece, and the cutting parameters were adjusted according to the calculated compensation value.

There are also some other methods presented in the literature for on-line monitoring. Wang et al. [261] proposed an information-localization strategy for the machining of large thin-wall parts. A binocular vision sensor was used to measure the initial structure information of the workpiece, and the touch probe was used to verify the deviation error for further compensation procedure. Wang et al. [142] realized dynamic monitoring of the machining deformation and time-varying characteristics of the thin-wall part by analysing the force signals processed from the least square fitting method and lifting wavelet transform.

Based on the on-line measurement, the real-time compensation process can be realized by sensors and controlled actuators, which can analyse the data and then adjust the machining system with certain compensation values. Various strategies are available in the literature for the real-time compensation of flexible surface form errors [262, 263]. Among them, Diez et al. [264] proposed an in-process strategy for compensating workpiece deformation by correcting the relative position of the tool-workpiece during machining. The deviation value was determined from the comparison of actually measured cutting forces and estimated resultant forces in rigid machining. Then, this value was used to generate the motion command signal to control the piezoelectric actuator and to compensate for the relative position of the tool and workpiece. To solve the time-delay problem in online compensation methods, Wang et al. [265] applied an improved forecasting compensatory control (FCC) system combined with a deformation prediction model considering both the deterministic and stochastic deformation errors. The real cutting deformation was monitored using the online measurement system that consists of a laser displacement sensor and a laser controller. Then, the compensation was conducted in real-time by calculating the control signals for the programmable logic controller (PLC), the numerical controller (NC), and the servo driver. Zhang et al. [266] proposed a real-time ultrasonic thickness measurement and compensation method in mirror milling, based on the modified Smith predictor (MSP) and disturbance observer (DOB). The thickness measurement delay and the accuracy of thickness compensation were improved to a great extent through the application of MSP-DOB. In the study of Wang et al. [267], the laser displacement sensor and controller integrated within the supporting manipulator was used to detect the normal deformation of a large thin-wall workpiece. The measured deformation errors were used as the input to the compensation sub-program, and then the generated codes were executed by the servo driver of the CNC machine.

Real-time thin-wall error compensation strategies have shown their ability to improve machine accuracy and production efficiency with quick response, which is desirable in the industry environment. However, the measurement requires high sensitivity and performance of sensors and controllers to detect slight deflections of tool and workpiece, which increases the machining costs.

Another solution to determine machining conditions and eliminate machining errors is the off-line method. The cutting-loads induced surface form errors are predicted and then the predicted errors are used to optimize the tool path, cutting parameters and sequence before machining. Among different compensation methods, the process planning strategy is widely used in practical milling operations. Generally, the optimized cutting strategies which ensure the minimum part deformation can be obtained through experimental statistics models, prediction models and neural network (NN) based models. Experimental models were developed based on the ANOVA method by analysing the effects of the cutting parameters and machining strategies on surface quality [45]. Apart from experiment-based research, the dimensional surface errors can also be predicted in advance by using the CAD/CAM packages and FEA method. Finally, off-line modification such as the mirror compensation method can be carried out by reprogramming the NC code or optimizing milling strategies to correct the nominal cutter path and obtain the required machining accuracy [268, 269].

The mirror compensation method is the most widely used off-line compensation strategy in previous studies [270-273]. In the compensation procedure, the local surface profile error is firstly predicted by the prediction model at a given cutting position. Then, the tool position is optimised to the reverse direction with the value of predicted machining error. The compensation of each cutting position should be calculated iteratively by considering the changes of radial cutting depth and properties of the in-process workpiece. Finally, the modification of tool position at each feed step is repeated along the feeding direction. The illustration of mirror compensation is shown in Fig. 23.

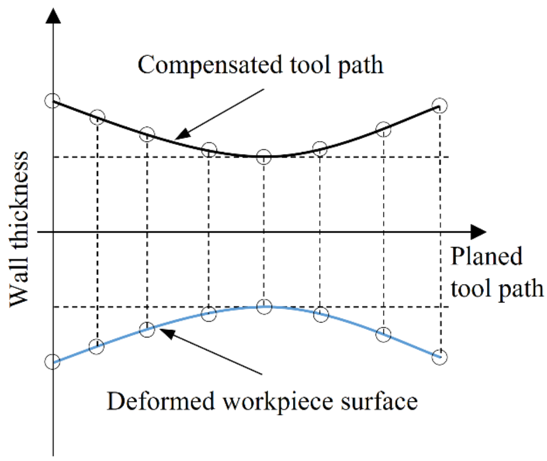

Fig. 23 Mirror compensation method.

Except for the mirror compensation method, other tool path planning and cutting sequence optimization approaches are also reported in the literature. Wang et al. [274] presented a method to control the geometric errors in the milling of thin-wall parts. The change of rigidity of the workpiece was considered, and the material removal sequence was modified through the reversed design planning. The optimization algorithm started from the finished workpiece geometry; then, a block of material was added to the position with higher stiffness at each step; finally, the process was reversed to obtain the optimised material removal sequence. Du et al. [275] performed the compensation procedure based on the fast APDL method, in which the force-induced deformation errors were compensated by revising the cutting trajectory and engagement angles based on APDL, then the optimized tool path was obtained through the polynomial interpolation methods. In order to reduce geometry errors in five-axis machining of curved thin-wall parts, Ma et al. [276] analysed the instantaneous cutting-amount and position-depended rigidity of the parts and then reprogrammed the feed speed to achieve a constant ratio between the cutting force and workpiece rigidity, so that the deformation at certain cutting-positions could be harmonized. Altintas et al. [277] compensated the deformation errors in ball-end milling of a blade by iterative estimation and modification of cutter-workpiece engagements and tool path coordinates. A deviation tolerance was set and the cutter-workpiece engagement was calculated until the surface error converged. Li et al. [278] characterized the surface deviation errors by comparing the sample points on the design surface with those on the machined surface and minimized the machining errors by modifying the tool path. The optimized tool path was achieved by adjusting the guiding curves and following the minimum zone criterion.

Although error prediction and compensation for flexible components have been well developed, there are still challenges in modelling structural deformation efficiently and accurately when various cutting conditions are considered. Some compensation strategies are often associated with complex algorisms, and the prediction is uncertain due to multiple error sources such as thermal-mechanical coupling. Meanwhile, the uncertainties could be increased when different cutting tools or coolant strategies are applied.

4. Discussion

In the machining of flexible thin-wall components, the low rigidity and continuously changing stiffness of the workpiece lead to both dynamic instability of the cutting process and static deformation of the workpiece, which has inherently restricted the production quality and efficiency. Thus, high-performance thin-wall milling is still one of the most challenging operations in the industry.

In order to improve the machinability of thin-wall components, one of the primary research directions is the dynamic stability related issues. Extensive research focused on this subject has been performed and these studies attempt to achieve a chatter-free cutting process with maximizing MRR. In chatter-free process planning, the dynamic responses of the machining system are firstly identified, utilizing either experiments or simulation methods. Then, the chatter stability analysis is carried out to confirm the stable regions and proper selection of the cutting parameters. In the thin-wall milling process, dynamic behaviours of the flexible system are time-varying due to the continuous material removal process and changing tool positions. Therefore, the accuracy of SLDs largely dependents on the determination of in-process properties of the machining system. Various experimental and analytical studies have been conducted for the prediction of dynamic characteristics, but there are still limitations in these existing methods. For instance, the versatility of current experimental methods is insufficient, while the FE models are sometimes oversimplified. In practice, it is not an easy task to obtain the FRFs during the machining process, and the stability analysis is relatively complex. Therefore, the application of active and passive chatter control strategies could be more efficient than the analytical methods, especially for industrial applications.

Active chatter control methods are developed to monitor and improve the process stability through signal detection, analysis and corresponding chatter elimination measures. It was demonstrated that machining stability could be significantly improved by the on-line chatter recognition and active control solutions due to their excellent features such as real-time response, high precision and stability in various conditions. Meanwhile, these methods do not need the identification of dominant models and dynamic properties of the machining system. However, the real-time detection approach is required for instantaneous identification of the dynamic characteristics of the machining system. As a result, one of the drawbacks of active control methods is that costly devices and dedicated algorism are required for real-time detection and compensation, which makes some of the approaches difficult to be implemented in industrial environments. Moreover, the external sensors need to be placed close enough to the workpiece in order to diminish the information dissipation and capture reliable signals. This could possibly impede the movement of the cutting tool. Therefore, integrated and intelligent data acquisition, processing and executive modules are desired to be embedded into the machine system. Another drawback of the on-line detection method is that response actions are normally taken until vibration signals are recognised, so defects of the part are already caused, which is not acceptable in the finish machining of the thin-wall part. Therefore, a critical objective of this method is in-time chatter detection and diagnosis, which can define the onset of chatter at the primary stage. In this way, the active control system could adapt timely responses before the chatter is completely developed. On this point, it is necessary to develop efficient signal recognition algorithms to detect useful signals as earlier as possible. Also, the development of efficient sensors with quick response, high precision and lower production costs will significantly improve the performance of on-line detection in actual industry operations.

To improve machining stability with feasible and efficient approaches, plenty of reliable passive suppression solutions for thin-wall machining were proposed by means of stiffness enhancement and operation optimization. The application of TMDs is proven to be efficient and robust for addressing vibration issues without external energy. Nevertheless, the TMDs require accurate tuning for optimal performance, which is difficult for thin-wall machining because of the varying in-process properties of the tool-workpiece system. Meanwhile, the versatility of the passive damping devices and the space restrictions still limit the application of these passive methods in many industry cases. In relative terms, the design and optimization of tool structure is another direct and effective method for chatter suppression. The importance of a proper design of pitch and helix angles for increasing the stability limits have been proven.

Furthermore, cutting tools with innovative features can be used for the machining of complex and freeform geometries with maximized MRR.

The existing chatter prediction and elimination methods can be summarized as follows:

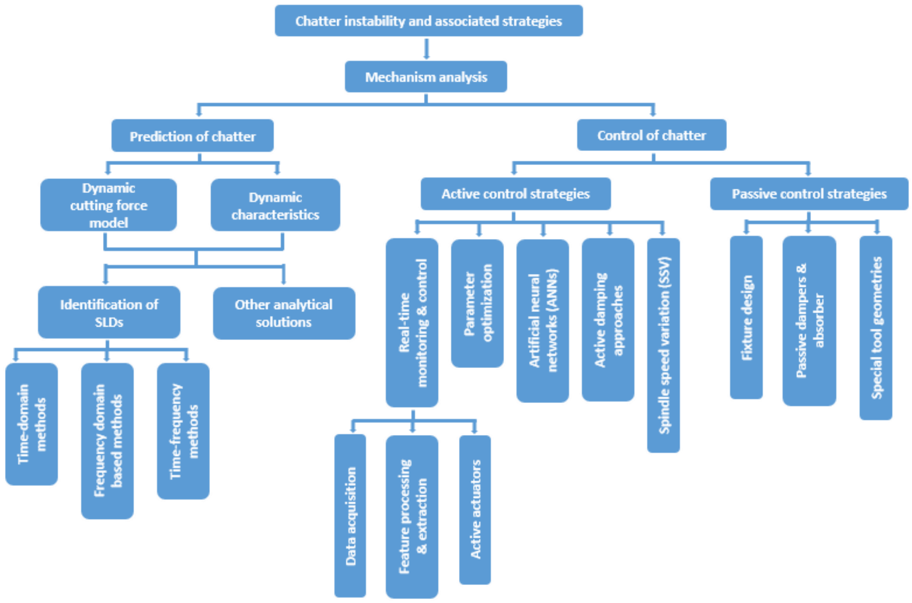

Fig. 24 Chatter and associated solutions

Meanwhile, a significant amount of attempts have been made to predict and analyse thin-wall deformation through both analytical and numerical methods. Cutting conditions such as cutting forces, temperature field and residual stresses distribution that may affect machining-induced deformation have been extensively investigated. To enable the consideration of these parameters in the simulation of machining processes, flexible cutting force models combined with feasible FE models are widely developed. However, the force-induced part deformation is mainly considered in most studies, and few studies have taken into account the effects of thermo-mechanical coupling in the development of analytical models. Moreover, the deflections of both the cutting tool and the workpiece are rarely considered when the rigidity of the cutting tool is lower. Additionally, the engagement conditions change dynamically due to both chatter and part deflection during the thin-wall milling process. This could, in reverse, influence the machining stability and deformation values. Thus, the part deflection has a complex interaction with machining stability, and these two issues should be considered simultaneously to establish a more realistic model. However, few studies have been conducted with the consideration of the combined effects. Besides, most studies were carried out in 3-axis operations, and the thin-wall component is simplified to cantilever plat. However, in practice, multi-axis machining is widely used in the manufacturing of thin-wall parts such as impellers, turbine blades and blisks. There are few papers aiming to improve the efficiency of multi-axis milling of thin-wall components with complicated features.

The previous studies have highlighted the importance of accurate FE models for high-accurate simulation of thin-wall machining. Nevertheless, 3D multi-physics simulation of the thin-wall machining process is still a challenge. The complex interaction between thermal-mechanical field and highly non-linear feature makes it difficult to define the precise boundary conditions and present a reasonably cutting process. Currently, only a few works are reported on the 3D modelling of thin-wall machining. Meanwhile, these studies considered limiting factors, and the boundary conditions and machining process usually are oversimplified, leading to lower prediction accuracy. So, there is still a lack of a comprehensive FE model for the prediction of thin-wall machining, and some critical factors, which include the accurate description of the overall process conditions such as contact condition, fixture layout, and the application of coolant, should be taken into account.

Fig. 25 shows the proposed methods used for thin-wall deformation analysis.

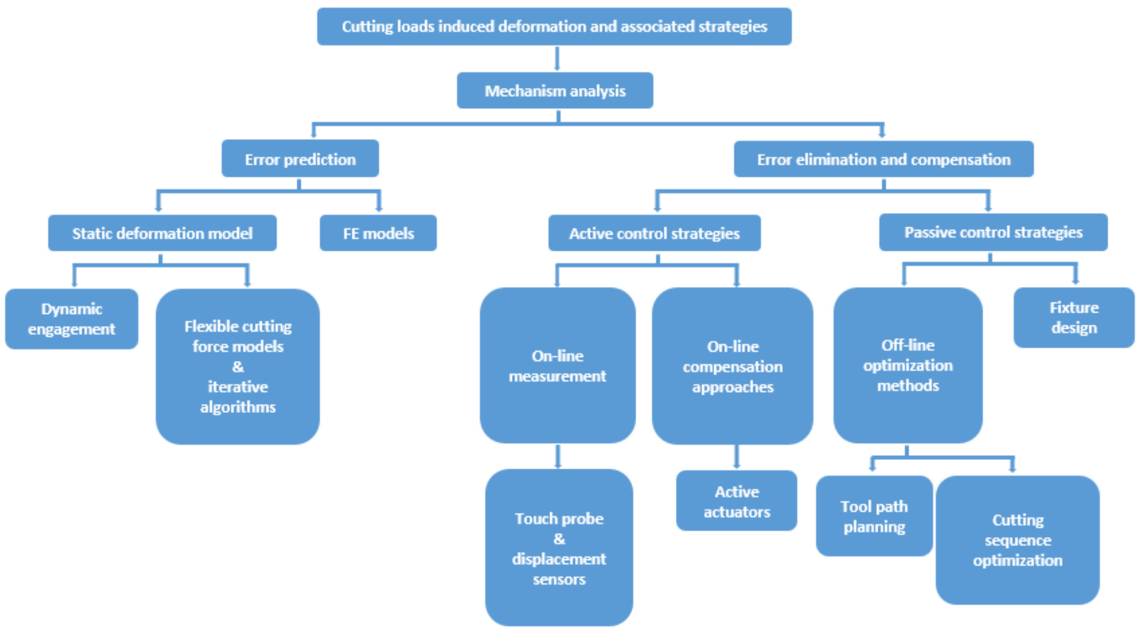

Fig. 25 Cutting-induced thin-wall deformation and associated solutions

So far, various strategies were proposed to solve the dynamic and static issues in thin-wall machining, the workflow and interaction between each section are illustrated within the following chart. This operation sequence can be applied to improve the machining performance in thin-wall machining.

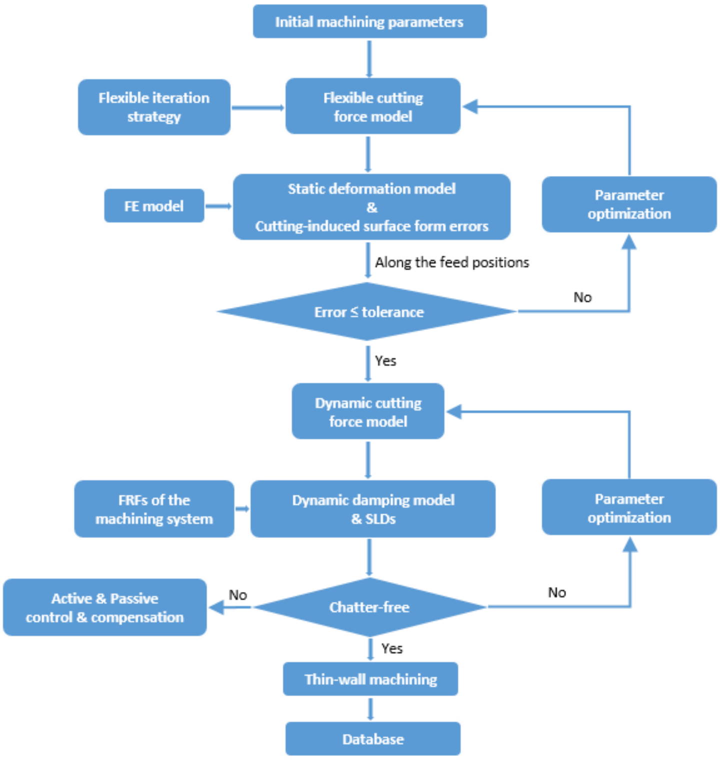

Fig. 26 Processing flow of thin-wall components

5. Conclusions and future works

Chatter instability and part deformation have adverse effects on the machining of flexible thin-wall components, and they are the major constraints on achieving high productivity and machining quality. Therefore, the development of high-efficiency prediction and compensation methods is critical for the stability and deformation analysis of thin-wall parts. A large amount of research work has been carried out to analyse the complex thin-wall milling operation through experimental, analytical and numerical methods over the years. This paper comprehensively reviews the relevant studies on the prediction, detection and elimination methods for both chatter and surface form errors. Various methods were proposed with regard to chatter and surface form errors, and the key is to make a comprehensive analysis and condition judgment of the specific problem that arises in the practical cutting process, and to choose the most appropriate prediction and control methods for each machining case so that better system stability and higher machinability can be achieved.

There are also some research directions for future improvements regarding the processing technologies and conditions. For instance, there are limited studies focused on the effects of coolant strategies in thin-wall machining. To improve machining ability, new cooling media such as nanoparticles [279-281], high-performance cooling strategies such as minimum quantity lubrication (MQL) and cryogenic minimum quantity lubrication (CMQL) machining could be applied in the thin-wall milling process. Researches have shown that both MQL and CMQL machining can provide enhanced performance in terms of tool life and surface quality compared with conventional cooling strategies [282-284]. Therefore, it is suggested to establish both the analytical model and FEA model for estimating the cutting loads, machining stability and part deformation as functions of cutting parameters and coolant conditions. Moreover, additive manufacturing (AM) has demonstrated its outstanding formability for processing complex thin-wall structural parts in recent years. Currently, microstructure configuration and mechanical properties of the additive manufactured thin-wall parts have been studied in many studies [285-287]. However, considering the complex anisotropic characteristics and significant variability of this kind of parts, the residual stresses distribution, potential chatter and deformation mechanisms during the machining still need to be explored.

Based on the critical review, existing issues and limitations of the current research are discussed, and the scopes for future work are proposed. Future works can be concluded as follow:

(1) Improve the simplicity and versatility of current experimental methods for actual industry environments.
(2) Develop integrated and intelligent data acquisition, processing and executive modules for actual industry environments.
(3) Develop efficient signal recognition algorithms and reliable sensors with quick response, high precision and lower production costs for actual industry environments.
(4) Design and optimization of cutting tools with innovative features.
(5) Develop comprehensive prediction models that consider the structure deflections of cutting tool/workpiece and the chatter instability simultaneously.
(6) Develop comprehensive FE models for simulation of thin-wall machining by considering the overall process conditions.
(7) Improve the efficiency of multi-axis machining of thin-wall components with complicated features.
(8) Improve the machining ability of thin-wall components through high-performance machining strategies such as cryogenic minimum quantity lubrication (CMQL) machining and Additive Manufacturing.

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