

Chatter and deformation in machining thin-walled flexible components

Ge Wu^{1,a}, Wencheng Pan², Xu Wang¹, John Mo¹ and Songlin Ding¹

¹School of Engineering, RMIT University, Victoria, 3082, Australia

²Centre for Precision Technologies, School of Computing and Engineering, University of Huddersfield, United Kingdom

*Corresponding author: ^a s3636981@student.rmit.edu.au

Abstract. Flexible components are widely used in the automotive and aerospace industries. However, the low rigidity of workpiece and large quantities of material removal in machining process leads to the instability of the process such as chatter and deformation. Chatter is a detrimental phenomenon resulting from dynamic interaction between machining tool and workpiece. It can cause poor surface quality and reduced productivity, and thus become one of the main limitations to achieve high productivity and good surface quality. Meanwhile, the varying cutting forces during machining can excite cutter and part structures and lead to significant deflections. For these reasons, machining of flexible components has been a research emphasis of both industrial and academic researchers for many years. Plenty of studies have been carried out to solve these problems, and most proposed studies focused on how to predict, identify, prevent and suppress chatter and deformation. This paper reviews the progress of relevant research and classifies the existing strategies developed to ensure stable machining of flexible components. The most appropriate technique for each specific problem is selected and discussed considering various aspects of machining.

1. Introduction

Thin-walled flexible components are widely used in the aerospace, automotive and energy industries in application such as blades, impellers and engine casings [1,2]. They are usually made from a raw block of material by removing up to 95% of the material from the initial block. However, flexible workpieces are prone to vibrate in cutting processes due to its low structure stiffness and damping. During the machining processes, particularly the intermittent cutting like milling, when excited by the external force or impact, the cutting process becomes unstable and flexural deflection may occurs in the static situation or large vibration may happen in the dynamic process which will deteriorate the surface quality and lead to form errors of the workpiece. It becomes more severe in machining difficult-to-cut materials such as titanium alloys due to generation of high cutting force. In some extreme circumstances, vibrations could even damage the cutter and workpiece.

In order to improve machining quality and productivity, the occurrence of vibration and chatter was investigated in this paper, and various strategies for predicting, identifying, controlling, suppressing and compensating were introduced.

2. Negative effects during machining of flexible workpieces

During the machining process, problems such as instability, dimensional errors and even sudden breakage of the tools could occur. The instability of the process is a self-excited vibration, known as chatter. Chatter phenomena may appear in the roughing process with high material remove rate (MRR) as well as in the finishing of flexible workpieces. During the machining process, the workpiece also



experiences deflection, because periodically varying machining forces applied by the cutter can excite the workpiece both statically and dynamically [3]. Static errors produce dimensional errors and dynamic errors leading to poor finished surface.

2.1 Dynamic stability chatter

Generally, chatter is clarified into two categories: primary and secondary chatter. Primary chatter can be caused by cutting friction between cutter and workpiece, by thermo-mechanical effects on chip formation or by mode coupling. Secondary chatter can be caused by the regeneration of waviness on the engagement area, as shown in Fig. 1 [3]. By the effect of some external disturbance, the cutter starts a damped oscillation relative to the workpiece and the surface roughness is undulated. This regenerative effect can greatly amplify vibration and is one major cause of instability during machining process.

2.2 Deformation and surface form errors

The dimensional accuracy of the finished surface profile is one of the most critical considerations. However, the machining of thin-walled flexible components is further complicated by the periodically varying cutting forces and vibrations, which statically and dynamically excite the cutter and workpiece, leading to significant deformations [4]. Consequently, the deflections and relevant vibrations can result in surface location errors and poor surface roughness.

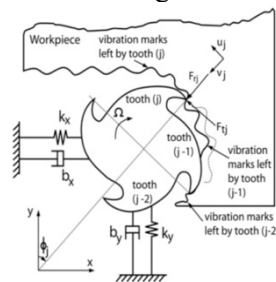


Figure 1 Regeneration of waviness with two DoF

3. Strategies and methods

To solve the stability issues of thin-walled components, plenty of research has been conducted based on the analysis of regenerative chatter and various methods are proposed to achieve chatter-free machining process.

3.1 Stability lobe diagram (SLD)

A stability lobe diagram (SLD) is an offline method developed for the stability prediction of chatter-free machining conditions with respect to spindle speed and axis depth of cut. As such, stable machining can be applied by selection of reasonable process parameters via a SLD prior to machining [5].

Practically, the achievement of an accurate SLD for the machining of flexible workpieces greatly depends on the accuracy of workpiece dynamics which is time-varying and represented by frequency response function (FRF) or natural frequencies and corresponding mode shapes. However, this might be difficult or even impossible for cases of flexible workpiece, as the FRF varies along the tool path and in time due to continuous material removal and the displacement of the workpiece varies dynamically along the tool axis (Fig.2) [6]. Thus, modelling and analysing the varying dynamics of the workpiece are the main tasks before predicting the system stability. The use of reasonable analytical methods or FEM is particularly important to solve these problems.

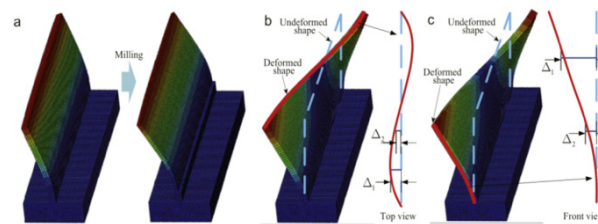


Figure 2. Varying workpiece dynamics [6].

The stability of a cutting tool is a function of the FRF at the tool tip, which varies with the cutter position and changes within the cutter's work volume, the stability lobes are always changing, and this leads to the third dimension of SLD, corresponding to the tool position. In earlier studies, approaches to obtain stability lobe diagram avoiding chatter vibrations are generally based on some specific positions, resulting in an incomprehensive and inaccurate chatter prediction.

To improve the accuracy of chatter prediction, various factors have been added into the models and made it increasingly complicated. For instance, in high speed machining flexible workpiece, where gyroscopic moments and centrifugal forces on both bearings and spindle shaft have a significant influence on the stability borders and induce spindle speed-dependent dynamics changes. To achieve a more accurate dynamics prediction, spindle speed-dependent dynamics must be evaluated. Moreover, an approach to defining the 3D SLD milling of thin-wall components is proposed by considering both the influences of cutter helix angle and the dynamic behaviour of workpiece. A systematic cutting force model is established that is capable of combining the helix angle effect and run-out effect of cutter [7].

Deflection and chatter of tool or workpiece are common in the milling process for thin-walled components. But earlier research only focused on varying workpiece dynamics related to the first and second aspects shown in Fig. 2 and the variation of the system dynamics along the tool axis is always neglected. However, it was found that the time variation of the coupling deflection of the tool-workpiece system must be taken into account because the deflection and dynamic characteristics of the workpiece are time-variant, and the milling stability is influenced not only by the modal parameter but also by deflection which can induce the variation of the immersion angle. Therefore, variations of workpiece dynamics along the tool axis together with the variations of workpiece dynamics caused by the material removal and tool position have to be investigated simultaneously.

Mathematically, the regenerative effect is generally described by the time delayed differential equation (DDE) with time dependent coefficients [3]. The stability analysis in milling processes of flexible components becomes more complicated due to discontinuous machining and various process phenomena. Hence, to obtain reasonably accurate predictions for machining processes, different models have been developed to obtain stability lobe and predict chatter by means of SLD.

Altintas and Budak [8] developed a new analytical method of single frequency solution or zero order approximation (ZOA). This approach provides a fast estimation of the stability and can be fed directly with FRF. ZOA is precise enough for most processes, but for highly interrupted cutting processes, the presence of an additional unstable regions respect to the double period chatter and mode interactions can lead to inaccuracies. To solve these problems, multi-frequency domain method (MFM) was also presented. Except the frequency domain methods for stability analysis, a temporal finite element analysis (TFEA) method was presented by considering the time-dependent nature in each discrete-time interval. Later, a semi-discretization method (SDM) was proposed, which has higher computation efficiency. More recently, a full-discretization method (FDM) which has a higher converse rate without losing precision is presented and improved, while the method of matrix perturbation is proposed to solve the natural modal of the modified flexible structure. As an alternative to modelling approaches, other methods based on experimental, probabilistic or artificial intelligence approaches have been proposed to calculate real SLD.

3.2. *In & out-of-process strategies for chatter identification*

The out-of-process strategies consist of methods that aim to identify the location of the stability boundary of the machining process to select stable cutting parameter combinations without modifying the characteristics of the machining system. To detect the onset of chatter, one of methods is based on the average power spectral density (APSD) of the machined surface topography. The power spectral density is expected to capture chatter marks and provide a quantitative assessment tool for identifying chatter. Previous studies also proved the feasibility of spectral analysis of machined surface for detecting instability. Through spectral analysis, the characterization of the unevenness of the machined surface topography can provide clear indication of the chatter [5].

In cases that it is difficult to make prediction and selected the reasonable machining parameters in advance, in-process strategies for online chatter detection have been developed by monitoring signals such as cutting forces, vibration, sound, displacement, etc. These methods based on different types of sensors or instruments to obtain process information and do not need SLD identification. Vibration sensors such as dynamometer, accelerometers, acoustic emission, microphone and electrical power sensors can be employed for chatter detection. The acquired signals are then analysed by different signal processing methods in order to distinguish whether chatter will occur.

Generally, there are three types of signal processing methods: time domain analysis, frequency domain analysis and the time-frequency domain analysis. During machining process, when chatter occurs, a significant increase of the amplitude of acquired time domain signal can be detected. Time domain signals can also be transformed into frequency domain by Fourier transform which is suitable for the stationary signal process, especially when the magnitudes of feature frequency components of signals are distinct. However, when machining flexible workpieces, the non-stationary signal will occur and the locations of suddenly changed signals cannot be picked up using Fourier transform. Wavelet transform can be employed as an alternative for detection of locations and frequency bandwidths of suddenly changed signals although it cannot get the specific frequency component of signals.

3.3 *Chatter suppression*

Since flexible workpiece cannot provide enough stiffness during the machining process, supporting fixtures are commonly employed in actual machining situations to rigidly and accurately clamp the workpiece. In order to suppress the chatter, fixtures are normally placed at the points with large amplitudes of vibration. Reasonable design of fixture layout can efficiently improve the machining accuracy and obviously suppress chatter during machining.

For flexible workpiece, fixture solutions can be either standard mechanical fixtures or dedicated non-conventional fixtures such as magnetorheological (MR) fluid and piezo-electric dampers. Researchers of traditional mechanical fixture for flexible workpiece focused mainly on the optimization the position of locators, clamps sequence and associated fixture errors. In terms of non-conventional fixtures, a semi-active control flexible fixture based on MR fluids has been proposed for the complex flexible workpiece machining, which takes the dynamic damping properties into consideration [9].

3.4 *Active & passive chatter elimination*

The objective of passive control is to improve the damping of the critical modes by passive solutions while no external power supply is needed for vibration energy dissipation. Passive control strategies are normally effective, low cost and easy to carry out. Therefore, it has been widely used in the industry. Tuned mass dampers and tuned viscoelastic dampers are the most commonly used passive systems. A combination of several vibration absorbers can also be applied. However, the complexity when implementing them in real industrial conditions should be taken into account since they cannot be mounted on complex structure with irregular geometries such as vanes. Thus, the applications of passive dampers for suppressing machining vibration in many industry sectors are limited.

Generally, active avoidance methods are based on the application of extra actuators as well as an

integrated control loop, which can dissipate the vibration energy, inject energy or disrupt the regenerative effect during machining. These devices can produce forces or displacements by controlled actuators that are able to provide enough compensation to cover the major range of machine tool structure modes so that chatter can be prevented and reduced.

For passive control, physical addition onto the workpiece can lead to the dynamics changes and sometimes limits the engagement of cutter, especially in the application of multi-axis machining. To address this problem, some novel methods have been proposed to mitigate the chatter of flexible workpiece, for instance, by submerging the milling system in viscous fluid. The milling stability limits could be enhanced substantially since the damping of the milling system increases obviously with the employment of the silicone oil.

More recently, the non-contact eddy current damping has also been utilized [10]. The damping ratio of the workpiece can be improved by eddy current and without physical contact, and the damping force is able to resist the vibration at the machining point. However, this method only allows the design with less volume and mass.

Machining stability can be obviously improved by employing the right combination of tools structure on the basis of using reasonable tool materials. The application of non-standard cutting tools such as variable helix angle tool and variable pitch angle tool can efficiently decrease cutting vibration by disrupting the regenerative effect. For instance, barrel type or curved end mills can have significant impacts on the avoidance of chatter. These innovative tools are specially intended for machining complex shapes and freeform geometries.

3.5 Error prediction & compensation

To control the deformation and surface quality in the machining of flexible components strategies are either error prediction or error compensation. Error compensation involves smoothing processing and tool path modification, which were normally applied in finish machining.

In cases of no chatter, the static deflection errors of cutter and workpiece are the main source of dimensional errors in machining of flexible components. In the case of static deformations during the machining of flexible components, research mainly focused on quantifying the errors by means of direct measurement or numerical simulation.

Another method to solve the static deformations problem is the in-process measurement and compensation. The application of a piezo-actuator for real-time deformations compensation during peripheral milling has been explored. The in-process compensation strategy can determine the value of deformation based on the comparison of actual measurement and the estimated values. To predict the dimensional form errors caused by deflections of both flexible workpiece and slender cutter, a new method was recently presented for 5-axis flank milling of flexible components [11]. The influences of cutting forces on both the cutting tool and the workpiece were considered, and the effect of deflections on the immersion was calculated. The effect of cutter runout was also considered. The deflections of the cutter-workpiece engagement were analysed to predict the surface errors on the finished workpiece at the final stage.

The application of CAD/CAM packages for defining optimal cutting strategies and tool paths has been well established in the last decade. These packages can model material removal, thermo-mechanical coupling, dynamic behaviour, and better surface profile can be obtained. NC program directly affects the machining efficiency and accuracy. However, due to various errors in the process of NC programming, accuracy of the finished surface may not meet the design requirements. In order to eliminate machining errors and improve the quality of the machined workpiece, a novel methodology of error compensation for flexible workpiece has been presented based on the inverse reconstruction model [12,13]. In this method, the workpiece is represented by discrete point cloud (DPC) for error prediction. The deflection of discrete points caused by geometric errors, cutting force-induced errors, and some other errors are taken into account so that the DPC positions can be obtained. Then the new DPC is established using inverse reconstruction model and the smoothing problem of DPC is solved simultaneously using a fairing algorithm. Thus, the modified workpiece model and tool

path can be applied for processing.

4. Conclusions

Chatter and deflection are detrimental phenomenon occurred in machining process especially in machining flexible thin-walled workpiece, which are major limitations to achieve high productivity and satisfactory surface quality. Therefore, the prediction of machining stability for chatter avoidance and compensation for deformation are critical in high performance machining. Significant research has been carried out on the chatter and deformation problems and enormous progress including both analytic and experimental methods have been made over the years.

References

- [1] R.A.R. Izamshah, J.P.T. Mo, S. Ding, Key Engineering Materials, **458**, pp. 283-288 (2011)
- [2] S. Ding, D.C.H. Yang, Z. Han, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, **219**, pp.255-263(2005)
- [3] G. Quintana and J. Ciurana, International Journal of Machine Tools and Manufacture, **51**, pp. 363-376 (2011)
- [4] Z. Li, O. Tuysuz, L. Zhu and Y. Altintas, International Journal of Machine Tools and Manufacture, **128**, pp. 21-32 (2018)
- [5] K. Singh, R. Singh and V. Kartik, Procedia Manufacturing, **1**, pp. 593-606 (2015)
- [6] Yang, Y., Zhang, W., Ma, Y., & Wan, M., International Journal of Machine Tools And Manufacture, **109**, pp. 36-48 (2016).
- [7] X. Jin, Y. Sun, Q. Guo and D. Guo, The International Journal of Advanced Manufacturing Technology, **82**, pp. 2123-2136 (2015)
- [8] Altıntaş, Y., & Budak, E., CIRP Annals, **44**, pp. 357-362 (1995)
- [9] J. Ma, D. Zhang, B. Wu, M. Luo and Y. Liu, The International Journal of Advanced Manufacturing Technology, **88**, pp. 1231-1242 (2016)
- [10] M. Butt, Y. Yang, X. Pei and Q. Liu, Precision Engineering, **51**, pp. 682-690 (2018)
- [11] 11.Z. Li, O. Tuysuz, L. Zhu and Y. Altintas, International Journal of Machine Tools and Manufacture, **128**, pp. 21-32 (2018)
- [12] S. Ding, R.A.R. Izamshah, J. Mo, Y. Zhu, Key Engineering Materials, **458**, pp. 289-294 (2011)
- [13] X. Zuo, C. Zhang, H. Li, X. Wu and X. Zhou, The International Journal of Advanced Manufacturing Technology, **95**, pp. 2369-2377 (2017)