CHAPTER 1

Introduction

1.1 Vibration in Machining Processes

1.1.1 Origin of the problem

In this thesis, the term *machining* refers to a process for removing pieces of raw material from a workpiece to make it become a desired final shape and size. Machining processes can be classified according to three well-known major categories:

- Cutting processes: These include three major methods of material removal, which are drilling, turning and milling.
- Grinding processes: These are abrasive processes, typically using a grinding wheel, to remove the raw material, which can achieve very smooth surface and accurate dimensions.
- Non-traditional machining processes: These include chemical, electric discharge machining (EDM), water jet cutting, laser cutting, etc.

This thesis focuses on cutting processes and, in particular, on milling. Although the techniques described are based primarily on milling operations they are also relevant to other cutting and grinding processes for which vibrational behaviour has many similar aspects.

In milling processes, a rotary cutter is used to remove the raw material. During the cutting operation, vibration arises in the machine-workpiece structure due to the cutting force that acts between the raw material being removed and the machine structure (cutting tool/spindle/frame). This leads to the surface of the workpiece having a wavy profile and results in poor quality and surface finish of the part. This problem has generated great interest from both industry and academic communities over several decades.

Machine operating conditions, such as spindle rotational speed, feed rate and depth-of-cut, directly impact on the cutting force and resulting vibration. The vibrational motion of the cutting tool relative to the workpiece becomes imprinted on the material surface. If the amplitude of the vibration is large then this situation will have several negative effects including cutting tool damage, excessive noise and poor surface finish. From the latter effect, the finished workpiece may have a size and shape that is unacceptable, leading to part rejection.

During cutting, the position of the surface of the workpiece at the current cutting location depends on the position of the tooth during the previous cut. In consequence, the forces that occur due to material removal are always influenced by the profile of the wavy surface due to the previous cut. This means there is “memory effect” which may be considered, from a dynamical systems viewpoint, as a time-delayed feedback effect [1], [2], [3]. This time-delayed feedback will involve a phase shift between the current and previous profile of the wavy surface. This can cause an amplification of vibration leading to self-excited (unstable) vibration during cutting. The surface waviness effect and phase relationship are shown in Figure 1.1.

Vibrational instability in machining processes is commonly referred to as “*chatter*” [1], [4], [5], [6]. Chatter involves self-excitation of flexible structure vibration within the machine and/or the workpiece. The occurrence of chatter places practical

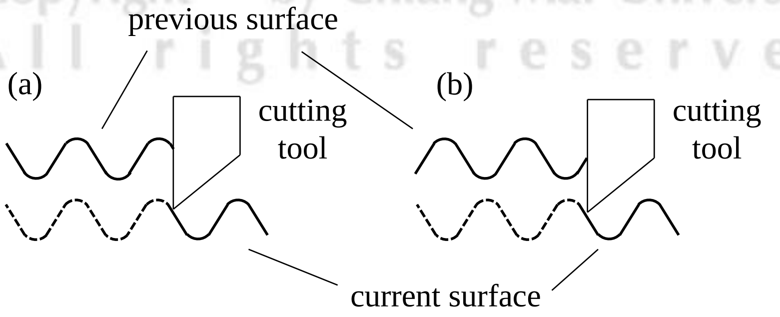

Figure 1.1 Exaggerated view of the current and previous wavy surface of the cut workpiece with examples of phase profile: (a) in-phase and (b) out-of-phase

limits on the achievable material removal rate [7], [8], [9], [10]. Therefore, potential methods to avoid chatter are of great interest and important topics for research. Generally, for basic machining operation in workshops, the operators will try to select the machine operating parameters to avoid chatter. For industries that use machining processes, the quantity and quality of machined product can be greatly increased by avoiding chatter. This has provided initial motivation for a great deal of research. Since the late 1950s, researchers have pioneered and built fundamental knowledge for this field. Tobias and Fishwick [4], Tlusty and Polacek [11] and Merrit [12] presented the first research results focused on the chatter phenomenon.

A 2-D representation of the vibratory dynamics in milling operations may be considered as shown in Figure 1.2 [5]. Material removal is performed by a rotating tool with several sharp teeth around the circumference. When the current cut ends and the tooth leaves the surface, the next tooth attacks the previous wavy surface and generates a new wavy surface. This occurs with a phase difference between the wave left by the previous tooth and the wave left by the current one [11], [12], [13]. As the cutting force depends on the chip thickness, i.e. the difference between the current cutting surface and the previous one, a variation in cutting force occurs that can greatly amplify cutting

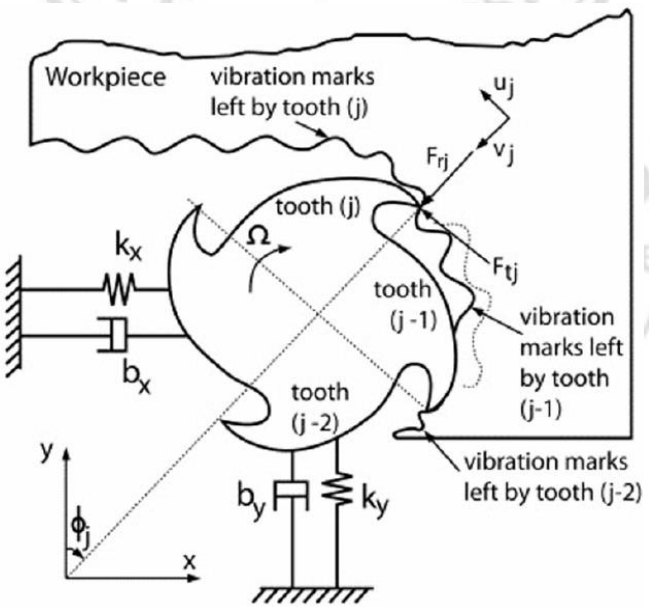

Figure 1.2 Dynamic model of milling with two degrees of freedom: the first regeneration of waviness in milling [5]

tool vibrations, potentially becoming dominant and building up to chatter [14]. Note that if the phase difference is zero, the dynamic (variation in) chip thickness is also zero and no extra variation in cutting forces occurs. If the phase difference is π then the dynamic chip thickness will have maximum amplitude, and therefore the oscillation in cutting forces will also be maximum. This situation is similar to the (1-D) case shown in Figure 1.1 except that vibration occurs laterally in two directions (x and y).

To deal with the phenomenon of chatter, various methods to specify and predict parametric boundaries for cutting stability have been developed. It is useful to determine where the border lies between stable and unstable cutting in terms of the material removal rate (MMR) and the spindle rotational speed. This boundary may be shown graphically by a so-called "*stability lobe diagram* (SLD)" [5]. The SLD is a powerful tool for determining the limits of machine operation and specifying the suitable/optimum operating parameters (typically in terms of axial depth-of-cut and spindle rotational speed).

1.1.2 Chatter control strategies

Strategies for control of chatter have been developed by many researchers focusing on various aspects, including detection, identification, avoidance and prevention by both active and passive means. These strategies can be divided into two

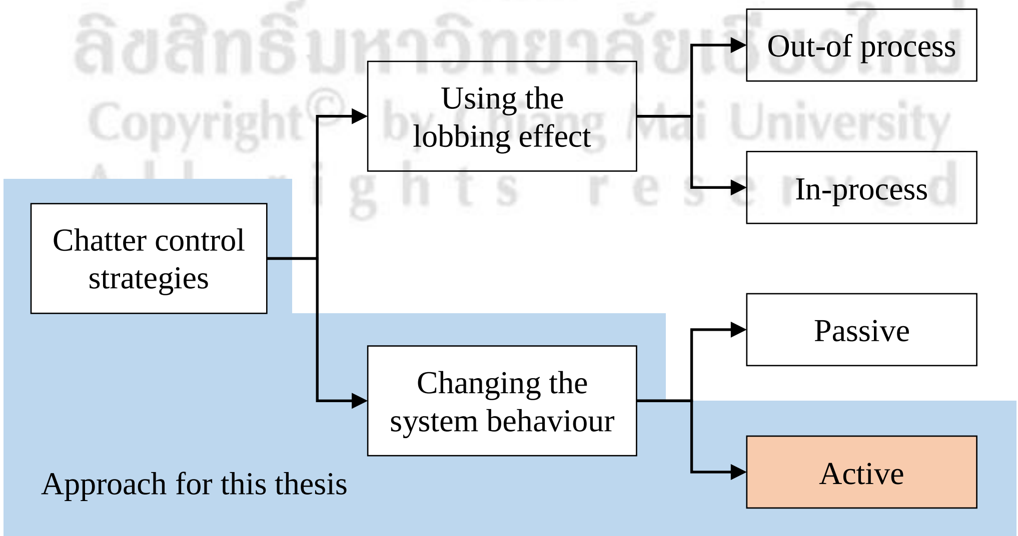

Figure 1.3 Chatter control strategies researching lines [3]

main groups according to Figure 1.3 [3]. For the first group, the focus is on how to operate within a stable zone of the SLD by selecting suitable cutting parameters. For the second group, methods are developed in order to avoid chatter by changing the system dynamics to improve the stability boundaries or by altering the cutting process in some way, such as by using non-standard cutting tool, e.g. variable pitch and helix angle of milling tool [15].

For the first group, it is possible to further classify according to two different approaches: out-of-process and in-process strategies. Out-of-process strategies focus on determining the correct SLDs by experimental identification or by using machining models. This may combine analytical and experimental methods. In-process strategies focus on the development of the measurement instruments by various sensor technologies and the implementation of process monitoring in order to identify or recognize chatter automatically.

For the second group, further classification can be made into passive and active control strategies. Passive strategies focus on the methodologies or techniques to modify the system dynamics by using passive elements in order to improve the stability boundary in cutting. These strategies are based on developing novel machine tool designs (e.g. Marui et al [16]) or using extra devices to change the cutting performance, (e.g. Kim et al [17]). Typically there is a requirement that the device will absorb vibrational energy to suppress chatter. Thus, the use of passive damping devices has often been considered [16] , [18]. Active strategies focus on using extra active devices (actuators) in order to change the system dynamics and thereby improve the suppression of chatter.

For this thesis, the focus falls within the second group as it deals with controller design methodologies that can used with active strategies for chatter control. Therefore, further discussion will focus on previous work within this group.

1.1.3 Active strategies for chatter control

For active strategies, recent developments have been supported by improvements in basic control technologies and hardware: computers, software programs, measurement sensors and actuators. These have greatly expanded the development frontier for active control of machining processes.

Since 2000s onwards, the number of published research paper concerning the active strategies to control chatter has rapidly increased [3]. Research on active control focuses on two aspects. The first aspect is the active hardware design, which may be an extra device or the new design of machine. Alternatively, some research studies have adopted hardware-in-the-loop testing to verify some aspect of the whole system design. The second aspect is the control algorithm and design approach which is suitable for the active hardware and will effectively control vibration in the cutting process.

For the hardware design, Dohner et al. [19] presented the active cutting control structure by using active damping. An electrostrictive actuator was used to actively control the motion of the spindle through a radial bearing in order to suppress the chatter by increasing the stability boundary in cutting (SLD). This research was probably the first successful demonstration of this approach in milling. E. Graham et al [20], J. Monnin et al. [21] and F. Kochtbène [22], adopted the milling machine design similar to Dohner [19] where the spindle bearings are directly actuated. Chiou et al. [23] used an approach which changed the structure dynamics and the model properties by using electrostatic and piezoelectric spindle bearing support. They also proposed an algorithm to control chatter in cutting. Huyanan and Sims [24] presented the active control of workpiece-induced chatter by using an active electromagnetic proof-mass actuator. Studies reported in [25], [26] and [27] involved a hardware-in-the-loop approach for testing chatter control strategies, where active damping was introduced using voice coils. The impact of damping levels on the onset of chatter and characteristics of vibration was also investigated through simulation and experiment.

The research about the use of active magnetic bearings (AMBs) to control the machine spindle vibration in milling processes includes the work of Chen and Knospe [28], Etienne Gourc et al. [29], Huang et al. [30], Fittro et al. [31], Pesch and Sawicki [32], van Dijk and van de Wouw [33], [34]. A new hardware design was presented for the chatter mitigation in milling process by using an active workpiece fixture in [35].

Controller design for active vibration control systems may be based on linear optimal and robust control methods. Early work by Mara et al. [36] presented a control approach using H_∞ control theorem with a state feedback control law to control the cutting vibration in boring process. An active dynamic absorber was used to generate the control force and the results were compared with the basic LQG design approach. For milling process with active control device, Dohner et al. [19] presented the discrete time output feedback control law with LQG control approach. Results showed that chatter affecting the face milling surface finish was avoided when the controller was applied. Robust control theory has been developed in order to deal with model error in the design of control algorithms. This is a powerful approach that may be based on optimal controller synthesis methods. These may involve a number of possible objective functions including those based on LQR [34] , [37], LQG [22], H_2 / H_∞ [32] and $\mu-$synthesis [34], [33], [38] formulations. Thus, there are many possibilities in terms of formulation of cost functions and system descriptions.

In the field machining vibration control, published papers concerning robust controller design include the work of Knospe and coauthors [28], [31], [38], N.J.M. van Dijk, N. van de Wouw et al. [33], [34], [39]. M. Maradi et al. [40] and X. Long et al. [41]. A summary of research publications on chatter control and the main approach/techniques used is given in Table 1.1. For standard robust control approaches, there have been a number of approaches used to account for time-delay effects arising from regenerative cutting forces. One method to treat time-delay terms in the model is as norm-bounded uncertainty in order that the stability of the approximated time-delay system is ensured under [20].

It is well-known that machining processes can involve time-delay feedback effects [42] due to the wavy surface influence from the previous cut affecting cutting forces during the current cut. For dynamical modelling these affects may be treated by Padé approximation theory [20], [28], [33]. Using Padé approximations is viable but the issue of increased model complexity and robustness to model errors must be addressed.

Controller synthesis by using the theory of linear matrix inequalities (LMIs) [43], has seen a lot of recent research interest, as this method has the flexibility to formulate design problems with multiple objectives of various types [44] [45] including systems with time delays [42]. However, the application of these methods for machining vibration prediction and control is still ongoing area of research. A recent study used

LMI methods together with Padé approximation for robust stability analysis/prediction in micromilling, but active control was not considered [20].

Controller design methods based on time-delay system models may offer improvements in performance for a given system and actuation scheme. With this approach, the control synthesis equations can be cast as set of linear matrix inequalities (LMIs) [43] derived from a suitably chosen Lyapunov-Krasovskii functional (LKF) [42], [46], [47], and these solved by numerical optimization. To-date, there has been only limited research on applying the LKF and LMI approaches to the problem of controller design for real machining processes.

1.1.4 Research publication history of machining and time-delay system

Table 1.1 Published of researches and brief summarized

	Year	Cited by	Authors and et al	Ref. number	Modeling	Loop testing	Test rig	Real machine	AMB	PD/PI/PID	State feedback	Output feedback	LQR	LQG	Robust	mu - synthesis	H2/inf - synthesis	LMI/LKF
1	1995	11	M. A. Marra	[36]	☻												☻	
2	1995	817	Y. Altintas	[5]	☻													
3	1996	9	M. Hashimoto	[10]	☻			☻										
4	1997	22	F. Ismali	[48]	☻			☻										
5	2001	133	G. Stepan	[49]	☻			☻										
6	2002	53	A. Yilmaz	[50]	☻			☻										
7	2002	21	R. L. Fittro , C. C. R. Knospe	[38]					☻	☻					☻	☻	☻	
8	2003	12	R. L. Fittro , C. C. R. Knospe	[31]					☻							☻		
9	2003	81	E. Al-Regib	[51]				☻										
10	2003	367	K. Gu	[42]														
11	2004	72	J. L. Dohner	[19]	☻		☻	☻				☻		☻				
12	2004	343	Y. Altintas	[52]	☻													
13	2005	49	M. R. Movahhedy	[53]	☻													
14	2005	104	U. Bravo	[54]				☻										
15	2006	11	A. Ganguli	[26]		☻	☻											
16	2006	15	C. Mei	[55]	☻													
17	2007	18	S. Huyyanan, N. D. Sims	[56]	☻		☻	☻		☻								
18	2007	46	A. Ganguli	[27]		☻												
19	2007	55	A. Rashida	[57]	☻	☻		☻										
20	2007	47	M. Chen , C. R. Knospe, Member, IEEE	[28]					☻						☻	☻	☻	
21	2007	89	N. D. Sims	[58]	☻													
22	2008	75	N. D. Sims	[59]	☻													

23	2008	255	S. Xu	[45]														
24	2009	14	H. Moradi	[40]	☻			☻			☻				☻			
25	2009	2	N. J. M. van Dijk, N. van de Wouw	[39]	☻				☻						☻	☻		
26	2010	19	K. H. Hajikolaei	[60]	☻	☻												
27	2010	64	Y. Yang, J.Munoa, Y.Altintas	[61]	☻			☻										

Table 1.1 Published of researches and brief summarized (continued)

	Year	Cited by	Authors and et al	Ref. number	Modeling	Loop testing	Test rig	Real machine	AMB	PD/PI/PID	State feedback	Output feedback	LQR	LQG	Robust	mu - synthesis	H2/inf - synthesis	LMI/LKF
28	2010	158	E. Abele, Y. Altintas. Brecher	[62]														
29	2011	15	E. Gourc	[29]				☻										
30	2011	16	E. Turkes	[63]	☻			☻										
31	2011	16	Z. Yao	[64]			☻											
32	2011	226	G. Quintana	[3]														
33	2012	15	H. Cao	[65]	☻		☻	☻										
34	2012	28	L.T. Tunc , E.Budak	[66]	☻													
35	2012	29	N. J. M. van Dijk, N. van de Wouw	[33]	☻				☻			☻			☻	☻	☻	
36	2012	38	H. Cao	[67]	☻		☻	☻										
37	2012	8	H. Moradi	[68]			☻	☻										
38	2013	3	X. Long	[41]			☻								☻			
39	2013	18	X. Jin, Y. Altintas	[69]			☻	☻										
40	2013	6	H. Moradi	[70]	☻													
41	2014	2	N. J. M. van Dijk, N. van de Wouw	[34]	☻				☻			☻			☻			
42	2014	5	E. Graham	[20]			☻	☻							☻			☻
43	2014	21	J. Momin	[21] [71]			☻	☻			☻				☻			
44	2014	12	J-B. Niu	[72]	☻													
45	2014	17	G. Totis	[73]	☻		☻											
46	2014	45	Y. Altintas	[74]														
47	2014	1	A. Fischer	[75]	☻													
48	2014	224	H. Li	[46]	☻													☻
49	2015	1	A. Weremczuk	[76]	☻													
50	2015	3	Z. Zhang	[77]	☻													
51	2015	9	H-T. Zhang	[37]							☻		☻	☻	☻		☻	
52	2015	11	N. Grossi	[78]				☻										
53	2015	1	H. Cao	[79]				☻										
54	2015	1	Y. Ding	[80]	☻													
55	2016	0	J. Sun, J. Chen	[47]														
56	2016	0	L. Sallese	[35]	☻		☻	☻										
57	2016	2	J. Munoa	[81]														
58	2016	2	T. Huang	[30]	☻			☻		☻			☻					
59	2016	0	F. Kochtbène	[22]	☻		☻	☻							☻	☻	☻	

60	2017	0	D. Hajdu	[82]	☻													
61	2017	0	F. Chen	[83]	☻		☻	☻										

1.2 Objective

The aim for the work described in this thesis was to develop and compare controller design methodologies for active control of regenerative vibration in machining processes in order to improve/increase operating regions for stable cutting. The main focus is on the use of modern robust controller design methodologies and new techniques for controller design based on combined models of machine structure flexibility and cutting force generation mechanisms.

1.3 Scope

This research covers the development of robust controller designs for active control of vibration and stability in machining processes. The controller design approach is based on using Lyapunov-Krasovskii functionals (LKFs) and robust stability criteria formulated in the terms of LMI constraints. The results are compared to existing controller design methods based on modern optimal control methods. The test rig used in this study is a mock-up of a milling machine spindle with flexible rotor/cutting tool. Modelling of the system requires complex models of structural dynamics and these are also developed and verified. This test system is used as a basis for verifying and comparing different controller designs.

1.4 Thesis Outline

The remaining contents of this thesis are organized as follows:

Chapter 2 reviews the necessary background knowledge on machining processes to understand the principles of the cutting dynamics and how to determine the cutting stability boundary. The general system model of the machining structure including effects from cutting dynamics leads to a time-delay feedback structure and this model may be used to predict stability boundaries. The conventional method to construct stability boundaries in the form of a stability lobe diagram (SLD) will be presented. Also, in this chapter, example numerical results will be presented for cutting stability boundaries based on SLD approach and Padé approximation of the time-delay.

In Chapter 3, the important fundamental theory in the field of robust control will be described. This will cover basic theory on linear matrix inequalities (LMIs) and the application of Lyapunov-Krasovkii functionals (LKF) to stability analysis of time-delay systems. Some useful concepts from robust control theory and the specification of the types of system error will be presented. Then, the steps to formulate the LKF robust control problem for synthesizing controllers from LMI equations are described. Two types of control laws for the time-delay system - state feedback and output feedback controllers - are considered.

Chapter 4 explains the design concepts for the test system to perform cutting emulations via hardware-in-the-loop testing. This will be used to confirm the ability of the designed controllers to improve/increase the cutting stability boundary. The main components of the test system are detailed, including structural part properties, functionality of parts, actuator design and operation for cutting vibration control and cutting force generation. The test system sensor configurations (displacement sensors and strain gauge sensors), instrumentation, data acquisition and control hardware, will also be described. Finally, experimental results for the test system under localized PD feedback control are reported, including frequency response measurements, SLDs and results from cutting emulation.

Mathematical modelling of the test system is described in Chapter 5. A finite element model (FEM) of the test system is first developed which is suitable for initial evaluations and is later used for state feedback controller design. After the test system was constructed, system identification methods were applied in order to obtain more accurate models which are suitable for output feedback controller synthesis. Some model-based prediction of stability boundaries under PD control are then shown, which highlight limitations of this type of control approach. Finally, the frequency responses of the FE model and the system ID models are compared with the real frequency response measurements from the test system.

In Chapter 6, the optimized controller designs from Chapter 3 are applied to the test system. The controller designs based on LKF are compared with those obtained using standard robust methods (based on quadratic Lyapunov functions for non-time-delay system model). The controllers considered here are of two main types which are state feedback control law and output feedback control law.

Results from experimental implementation and testing with the synthesized controllers are presented in Chapter 7. These results cover the experimentally determined SLDs, comparisons of cutting stability boundaries for each controller and results from cutting emulation to confirm the operating performance of the controllers. Finally, the summary of this work with discussion and possibilities for future work are presented in Chapter 8.