A Study of Chatter in Robotic Machining and A Semi-Active Chatter Suppression Method Using Magnetorheological Elastomers (MREs)

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A Study of Chatter in Robotic Machining and A Semi-Active Chatter Suppression Method Using Magnetorheological Elastomers (MREs)

Lei Yuan

This thesis is presented as part of the requirements for the conferral of the degree:

Master of Engineering

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The University of Wollongong
School of Mechanical, Material, Mechatronic and Biomedical Engineering
Faculty of Engineering and Information Sciences

August, 2017
Declaration

I, Lei Yuan, submitted in fulfilment of the requirements for the award of Master of Philosophy, in the School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, Australia. I declare that this thesis is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Lei Yuan

August 2017
Abstract

Chatter is one of the major barriers for the robotic machining process. As the dominant vibration frequency of the chatter varies under different working conditions, Magnetorheological elastomers (MREs) whose stiffness is adjustable is an ideal device to be used for chatter control. This thesis presents a new chatter reduction scheme by attaching an MREs device on the spindle to absorb vibration at a specific frequency range. Firstly, a test was implemented to check the frequency-shift property of the designed MREs and then robotic milling of an aluminium block using ABB IRB6660 robot is tested at various conditions. Secondly, a semi-control system was established to operate the MRE absorber automatically. The experimental results showed a notable potential to reduce the chatter/vibration in the robotic milling application through semi-active vibration reduction using MREs device.

Keywords—Robotic Machining; Magnetorheological elastomers; Chatter; Mode Coupling
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## Tables of contents

Abstract ........................................................................................................................ I
Acknowledge .................................................................................................................. II
List of figures ................................................................................................................ VI
List of tables .................................................................................................................. X

### Chapter 1 Introduction ............................................................................................ 1
  1.1 Introduction and background................................................................................. 1
  1.2 My thesis aims and objectives ............................................................................ 6
    1.2.1 Aims............................................................................................................ 6
    1.2.2 Objectives ................................................................................................ 7
  1.3 Thesis outline....................................................................................................... 8

### Chapter 2 Literature review ..................................................................................... 10
  2.1 Chatter detection.................................................................................................. 10
    2.1.1 Sensor selection......................................................................................... 11
    2.1.2 Feature extraction .................................................................................... 15
  2.2 Chatter identification........................................................................................... 16
  2.3 Regenerative chatter ........................................................................................... 19
    2.3.1 The stability lobe diagram ....................................................................... 20
    2.3.2 Regenerative chatter reduction strategies ............................................... 22
  2.4 Mode Coupling chatter ....................................................................................... 36
    2.4.1 Passive strategies .................................................................................... 38
Chapter 3 Robot model and chatter analysis in robotic machining .............................. 59

3.1 Robot model ........................................................................................................ 59

3.2 Robot-tool model ................................................................................................. 61

3.3 Chatter analysis .................................................................................................... 63

3.4 Chapter summary .................................................................................................. 65

Chapter 4 The design of the multi-layered MRE absorber ........................................ 66

4.1 Introduction .......................................................................................................... 66

4.2 The Conceptual design of the laminated MRE absorber ........................................ 69

4.3 Parameters determination ....................................................................................... 70

4.4 Prototyping of an MRE-based absorber ................................................................. 74

4.5 Chapter summary .................................................................................................. 75

Chapter 5 Frequency-shift property of the MRE absorber ........................................... 76
List of figures

Chapter 1

Fig.1. 1 Robotic machining publications per year .......................................................... 2
Fig.1. 2 The negative effects of machining chatter ......................................................... 3
Fig.1. 3 Two main types of chatter ................................................................................. 4
Fig.1. 4 The frequency-shift property of MREs .............................................................. 6

Chapter 2

Fig.2. 1 The chatter detection process ........................................................................... 11
Fig.2. 2 The mechanism of regenerative chatter ............................................................ 20
Fig.2. 3 The feedback loop of regenerative chatter occurrence ..................................... 20
Fig.2. 4 The Stability Lobes Diagram ............................................................................. 22
Fig.2. 5 The SLD combining mode coupling effect ......................................................... 27
Fig.2. 6 The typical closed loop control system ............................................................. 29
Fig.2. 7 The proposed active damping system ............................................................... 34
Fig.2. 8 Diagram of the active damping setup ................................................................. 34
Fig.2. 9 Stability lobes diagram for uncontrolled and controlled cases ....................... 35
Fig.2. 10 The mechanism of mode coupling chatter ..................................................... 38
Fig.2. 11 The strategies of mode coupling chatter reduction ....................................... 39
Fig.2. 12 The principle of force control strategy ......................................................... 42
Fig.2. 13 The fabrication of both isotropic and anisotropic MR elastomers ............. 49
Fig.2. 14 SEM images of MREs: (a) anisotropic MREs; and (b) isotropic MREs. 49

Fig.2. 15 The operation mode of MRE devices ................................................................. 50

Fig.2. 16 The shear–compression mixed operation mode ................................................. 51

Fig.2. 17 Different configuration of MRE devices ............................................................ 52

Fig.2. 18 Adaptive vibration absorbers (AVAs) using MREs ........................................... 54

Fig.2. 19 An MREs based vibration isolator ................................................................. 55

Fig.2. 20 MREs suspension bushing ................................................................................. 56

Chapter 3

Fig.3. 1 The base coordinate system.................................................................................. 63

Fig.3. 2 The chatter frequency of (a) third group (b) second group and (c) first group .......................................................................................................................... 65

Chapter 4

Fig.4. 1 A typical single layered MRE absorber .............................................................. 68

Fig.4. 2 A multi-layer MRE absorber ............................................................................... 68

Fig.4. 3 The demonstration of the shake motion .............................................................. 69

Fig.4. 4 The design conception of MRE absorber ............................................................ 70

Fig.4. 5 The MRE and steel sheets .................................................................................... 73

Fig.4. 6 The Steel oscillator of the designed MRE absorber .......................................... 74

Fig.4. 7 The laminated MRE pillar .................................................................................... 75

Fig.4. 8 The proposed MRE absorber .............................................................................. 75

Fig.4. 9 The frequency-current relationship of proposed MRE absorber ............... 80
Chapter 5

Fig. 5.1 The setup for testing frequency-shift property of the MRE absorber .... 78

Fig. 5.2 The testing results (a) the magnitude and (b) the phase .................. 79

Fig. 5.3 The frequency-current relationship of proposed MRE absorber .......... 80

Chapter 6

Fig. 6.1 The structure of the system combining the robot, spindle and MRE device ........................................................................................................................................... 83

Fig. 6.2 The 3D model of the spindle .................................................................. 84

Fig. 6.3 The force signal during robotic milling .................................................. 86

Fig. 6.4 The chatter occurrence of case 1 ............................................................. 88

Fig. 6.5 The chatter occurrence of case 2 ............................................................. 89

Fig. 6.6 The chatter occurrence of case 3 ............................................................. 89

Fig. 6.7 The chatter occurrence of case 4 ............................................................. 90

Fig. 6.8 The chatter occurrence of case 5 ............................................................. 91

Fig. 6.9 The chatter occurrence of case 6 ............................................................. 91

Fig. 6.10 The chatter occurrence of case 7 ......................................................... 92

Fig. 6.11 The chatter occurrence of case 8 ......................................................... 92

Fig. 6.12 The chatter occurrence of case 9 .......................................................... 94

Fig. 6.13 The chatter occurrence of case 10 ....................................................... 94

Fig. 6.14 The chatter occurrence of case 11 ....................................................... 95

Fig. 6.15 The chatter occurrence of case 12 ....................................................... 95
Fig. 6.16 A summary of chatter occurrence of each group ........................................... 97

Fig. 6.17 The chatter severity comparison between group A, B and C .................... 98

Chapter 7

Fig. 7.1 The work flow of the semi-active control system ........................................ 101

Fig. 7.2 Flow chart of controller .............................................................................. 102

Fig. 7.3 The experiment setup for the semi-active control system ...................... 103

Fig. 7.4 The results of chatter occurrence .............................................................. 106
List of tables

Table 1 The summary of sensors ................................................................. 12
Table 2 The distinctions of regenerative and mode coupling chatter .................. 17
Table 3 Summary of current regenerative chatter reduction technologies .......... 23
Table 4 Forward kinematics of ABB IRB 6660 .............................................. 60
Table 5 The stiffness of each joint ............................................................... 62
Table 6 The original position ........................................................................ 64
Table 7 The frequency-current relationship .................................................. 80
Table 8 The experimental design of group A to C ......................................... 85
Table 9 The experimental results of group A to C ......................................... 87
Table 10 The experimental design of group D to F ....................................... 104
Table 11 The experimental results of group D to F ....................................... 104
Chapter 1 Introduction

1.1 Introduction and background

Modern industrial robots offer flexibility, efficiency, low cost and safety, that superseded many repetitive and hazardous manual operations [1, 2]. The total number of industrial robots in operation worldwide has been increasing to about 1.5 million units at the end of 2014 and it is expecting the world’s population of industrial robots would be more than 2 million [3]. Today, industrial robots have been widely employed in many industries for various applications, including welding, material handling, painting, assembly, machining, etc. [4]. Among them, robotic machining as a high value-added manufacturing process has attracted significant attention from both academics and industry. Fig.1.1 shows the number of publications with the keywords “robotic/robot machining”, searched in article titles, abstracts or keywords in Scopus, considering all documents published since 1990. Meanwhile, from industrial perspective, machining operations account for an estimated 15% of the value of all mechanical parts manufactured worldwide. In the USA alone, expenditures on machining are over $250 billion per year [5]. However, the inherent issues of industrial robots, such as poor accuracy, difficulty to program and low stiffness, limit the wide use of robots for machining applications [6-8], among which the insufficient rigidity is considered as the most significant drawback [9].
Vibration happens in all machining processes to a certain extent. When not properly controlled, it can result in poor surface quality, low productivity and abrasion or damage of the tools, as shown in Fig. 1.2 [10]. Moradi, et al. [11] categorised the vibration arose in machining process into two types: forced vibration and self-excited chatter. Forced vibration is caused by time-varying external excitations, for example, the vibration stems from the regular clash between the teeth of the milling tool and the workpiece. The forced vibration can be avoided or prevented relatively easily once the principle vibration source is identified. Quintana and Ciurana [12] pointed out that the instability in machining process is mainly due to chatter and it is more undesirable and less controllable compared with forced vibration.

Fig. 1.1 Robotic machining publications per year
Fig. 1.2 The negative effects of machining chatter [10]

Tlusty and Polacek [13] and Merritt [14] identified two most powerful sources of self-excited vibration (or chatter): regenerative chatter and mode coupling chatter as shown in Fig 1.3. The regenerative chatter occurs when the subsequent machining on the rough surface after the previous cutting path. During milling, the next tooth in cut collides with the wavy surface of the previous tooth and generates a new wavy surface. The chip thickness and the cutting force vary due to the phase difference between the wave left by
the previous tooth and the wave generated by the current one [12]. On the other hand, mode coupling chatter occurs when vibration in the thrust force direction generates vibration in the cutting force direction and vice versa. For CNC machining, the conventional wisdom focuses on the regenerative chatter of the machining tools such as boring bar and milling cutter, since the mode coupling chatter seldom happens due to the large stiffness of the CNC machine. However, in the robotic machining process, due to the low structure stiffness of the robot, it is observed that the entire robot structure can vibrate before regenerative chatter occurs [15]. The chatter on robotic machining is a more complicated issue and thereby improving robotic machining stability has been an interest of research in recent years.

Fig.1. 3 Two main types of chatter [13,14]
Many researchers have applied the mode coupling theory to explain and control the robotic machining chatter using either passive or active chatter compensation technologies. The passive strategy addresses the issue through changing the robot configuration, process behaviours, or system structure, including stiffness, damping, etc. The stiffness of industrial robots varies at different robot configurations and positions due to their serial articulated structure. By selecting the most optimal robot configuration and trajectory, less chatter was observed [16]. Other researchers focused on the suppression and absorption of the chatter energy by changing the system structure [17]. Recently, active chatter compensation, the particular force control based strategy has been a central topic in robotic machining study. In Cen, et al. [18], the authors developed an in-situ thin-film wireless force sensor to measure the machining forces in robotic milling operation. More commonly commercial available six degrees of freedom force sensor was used for machining force measurement [19]. However, active force control strategy mainly controls the chatter by limiting the cutting force instead of reducing the vibration.

In order to overcome the drawbacks of passive and active methods, an Adaptive Tuned Vibration Absorbers (ATVAs) device can be potentially utilised in robotic chatter reduction. ATVA is a device that has a time-varying natural frequency through altering its stiffness. Recently, a novel technology named Magnetorheological elastomers (MREs) was developed to be employed in vibration reduction research. MREs, as a smart material with controllable stiffness, are currently prevalent as the involvement of MREs endows the resonance frequency of an absorber to be tunable in real time, as shown in Fig.1.4 [20-22]. This semi-active property enables the absorber to adapt to vibration sources which are
frequency variant. With the employment of MREs, the absorber is able to control the vibration of the robot under different working conditions [22, 23]. Therefore, AVTA utilising MREs has been a notable topic which attracts considerable research interests due to the advantages of fast response, controllable frequency and broad working range. This paper presents an Adaptive Tuned Vibration Absorbers (ATVAs) using magnetorheological elastomer to be used for chatter control in robotic machining applications.

Fig.1. 4 The frequency-shift property of MREs [20-22]

1.2 My thesis aims and objectives

1.2.1 Aims

My research goal is to develop a chatter reduction system for robotic machining process using Magnetorheological Elastomers.
The goal would be achieved by fabricating an MREs device by studying the frequency-shift property of MRE materials. Then a semi-active control system would be employed to verify the effect of the absorber in robotic milling process. Finally, a complete closed-loop control is developed which includes an image acquisition system (accelerometers), a power amplifier, a DAQ board and controller with proposed algorithm. The feasibility of the entire system was proved based on the chatter occurrence of a milling process at various conditions.

### 1.2.2 Objectives

The objective of this thesis:

1) Conducting a literature review about chatter in robotic machining process which includes:
   - Chatter detection.
   - Mechanism of regenerative chatter and relevant chatter reduction strategies.
   - Mechanism of mode coupling chatter and relevant chatter reduction strategies.
   - MRE technology and MRE layer fabricating method.

2) The mode coupling chatter would be analysed by an ATI six-DOF Force/Torque sensor which was included between the robot wrist and spindle mount to collect real-time machining force data and the severity of the chatter between various experiments are compared based on PSD value of the force signal after Fast Fourier Transform (FFT).
3) The frequency-shift property of the MRE absorber would be tested by a group of the device including a shaker, vibration platform, accelerometers and relevant PC software.

4) The MRE layer would be fabricated by carbonyl iron particles (C3518, Sigma-Aldrich Pty. Ltd), silicon rubber (Selleys Pty. Ltd), and silicon oil (Sigma-Aldrich Pty. Ltd) within a certain ratio.

5) The feasibility of the system would be verified by several experiments under different cutting conditions such as the width of cut, depth of cut, travel speed, robot configurations, etc.

6) The complete system is integrated by the LabVIEW, the software will be developed to obtain chatter signals, determine the dominant frequency of mode coupling chatter and output signals to the power amplifier.

1.3 Thesis outline

Chapter 1 introduces the chatter issue during robotic machining process as well as a novel technology named MREs to absorb chatter energy. Then, the objectives of this study is presented. Followed by chapter 1, the rest of this thesis is divided into 6 sections.

Chapter 2 presents the literature about chatter issue during robotic machining process to identify the current gap in machining chatter study. Next, the literature about chatter
absorption technology called MREs was reviewed.

Chapter 3 firstly introduced a novel MRE structure called multi-layered MRE. Then, the structure of the proposed MRE absorber and the fabrication process was presented in details.

In chapter 4, the MRE absorber was tested using the vibration platform and swept sinusoidal signals. Based on the measurement, the frequency-shift performance of the proposed absorber was evaluated.

In chapter 5 tested the effectiveness of the proposed MRE device, the absorber was mounted to the machining robotic arm. Firstly, to evaluate the performance of the absorber, the chatter occurrence during the milling would be recorded with and without the absorber. Secondly, to test the performance of the absorber in different chatter frequencies, the test was conduct in more than one frequency, the severity of the mode coupling chatters would be compared in the end.

In chapter 6, upon the development of the proposed MRE absorber which was tested using passive control approach, the semi-active control system is developed and evaluated in terms of its vibration absorption effectiveness.
Chapter 7 concludes the primary results of this study and makes recommendations for the future work of chatter reduction during robotic machining process.

Chapter 2 Literature review

There are many literature addressing the issues around chatter during machining process including the vibration measurement, chatter mechanism and mitigation strategies. The regenerative chatter mechanism has been widely studied and reviewed in detail by [12, 24, 25]. Pan, et al. [26] claimed that the mode coupling chatter was the dominant chatter in the robotic milling process. Iglesias, et al. [6], Chen and Dong [27], [28] and Pandremenos, et al. [29] presented reviews of general vibration/chatter issue during robotic machining process. In this section, the chatter during robotic machining process and the chatter absorption technology called MREs was reviewed.

2.1 Chatter detection

The first step in machining chatter study is chatter detection and measurement. Various signal acquisition technologies are adopted to collect process data, such as velocity, acceleration, cutting force, acoustic emission for this purpose. Most of these signals need
to be transformed into features that illustrate the existence and severity of the chatter, including both time domain and frequency domain methods [30]. Fig.2.1 presents various sensors for chatter detection and relevant processing methods to identify the features of chatter. Moreover, some researchers also investigated chip thickness to analyse the stability of the machining process.

![Chatter Detection Diagram](image)

Fig.2. 1 The chatter detection process

### 2.1.1 Sensor selection

Sensor selection is considered as the most essential step for chatter detection [31]. In the current research field, the actual displacement of the vibration was derived by the indirect
data from sensors such as force sensor, accelerometer and acoustic emission as they are simpler to setup and more adaptable to various situations. The information of major indirect sensing methods for machining chatter detection in Table 1 and details are given bellow.

Table 1 The summary of sensors

<table>
<thead>
<tr>
<th>Sensor types</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force sensor</td>
<td>➢ High sensitivity and rapid response ➢ clearly distinguish chatter</td>
<td>➢ High cost</td>
<td>[17, 32-34]</td>
</tr>
<tr>
<td>Accelerometer</td>
<td>➢ Simple structure to detect chatter directly</td>
<td>➢ Low cost</td>
<td>[35-40]</td>
</tr>
<tr>
<td>Acoustic emission</td>
<td>➢ Good adaptability ➢ Adequate frequency bandwidth ➢ High accuracy</td>
<td>➢ Dependent on process parameters ➢ Environmental sensitivity</td>
<td>[41-44]</td>
</tr>
<tr>
<td>Sound sensor</td>
<td>➢ Adequate frequency bandwidth ➢ Good adaptability</td>
<td>➢ Environmental sensitivity</td>
<td>[45] [31, 46]</td>
</tr>
<tr>
<td>Device Power/current</td>
<td>➢ Working without interfering machining</td>
<td>➢ Insensitive to the change of cutting state</td>
<td>[47]</td>
</tr>
</tbody>
</table>

Force sensors, which are made of a group of strain gages, are widely used to measure the process force load, which indicates acceleration during vibration. Tlusty and Andrews [32]
conducted a series of experiments to compare the effectiveness of chatter detection using force sensor, vibration transducer and acoustic sensor in milling process. The force sensor exhibited a superior performance since it can be easily mounted between the machine and workpiece where the chatter arises, while the vibration transducer cannot be installed easily to generate sufficient vibration signals. In the experiment of Feng, et al. [33], the milling force signals in the direction perpendicular to the machined surface were gained by a dynamometer. Similarly, a tool-post dynamometer was utilised in the study of Dimla Sr and Lister [34], three static and dynamic components of the cutting forces and vibration data were investigated during a cutting process. The authors explained that force sensor was the best choice of machining chatter measurement.

Accelerometer is used to measure the acceleration of the machine tool, workpiece or machine itself to indicate the level of vibration. Chatter occurrence is demonstrated through the periodic variation of acceleration of target machining sectors, which is considered faster than measuring the position variation [37, 38]. Chiou and Liang [39] attached an accelerometer on the back of the shank to measure the chatter of turning tool. The accelerometer is considered as a relatively accurate sensor with fast response to machining chatter detection, its cost used to be quite high until recent year. Qin, et al. [40] presented a method to collect vibration signals of the end effector in robotic drilling using
two triaxial accelerometers. The effects of accelerometer location and orientation were analysed and demonstrated a successful result.

Acoustic Emission (AE) can be defined as the transient elastic energy spontaneously released in materials undergoing deformation or fracture. The energy contained in an AE signal and the rate at which it is dissipated are strongly dependent on the rate of deformation, the applied stress, and the volume of the participating material [41, 42]. A real-time machining chatter detection method using an acoustic signal as system feedback was presented by Tsai, et al. [43]. Chiou and Liang [44] presented a dynamic model of the root mean square cutting acoustic emission signal when chatter occurs during turning. The machining chatter was reduced by a hybrid method combining real-time acoustic emission signal and the proposed a dynamic model.

The machining noise emitting from chattering structure could be an indicator for chatter detection [48]. A microphone is used to collect valuable information to identify the chatter occurrence during the machining process [45, 46]. Delio, et al. [31] conducted a series of contrastive experiments and concluded that monitoring the vibration noise using a microphone was a reliable method for chatter detection due to its adequate frequency bandwidth. In order to detect a small distance error, laser displacement sensor is also employed in chatter detection. Dai, et al. [49] developed a vibration detection method for
robotic milling process using both a laser displacement sensor. Power and current measurements are also used to detect chatter occurrence during machining process [50, 51]. As the mechanical force was provided by electric drives and spindles, the chatter information can be obtained by the measurement of motor related parameters such as motor power or current and relationship between input current/power and output force [47]. The advantage of sensing power and current of the spindle is that the measurement apparatus does not interfere the machining process. This is especially beneficial for robotic machining due to the flexibility of industrial robots, which may be limited by extra devices.

2.1.2 Feature extraction

The raw sensor information usually needs to be processed in either time domain or frequency domain to extract useful features for further vibration analysis. The features of force signal are usually extracted in the time domain, Smith and Tlusty [52] developed peak-to-peak diagrams using milling force information in a time-domain to identify the stability boundaries. Vibration signals from accelerometer and sound signals are well presented in the frequency domain. To detect chatter occurrence in turning, Li, et al. [53] developed a method uses the coherence function between two crossed accelerations and analysed in frequency domain to demonstrate the chatter. In addition, techniques based on Fast Fourier Transform (FFT) are used to determine the chatter occurrence in the
frequency domain for measurement signal such as the Power Spectral Density (PSD) [31, 54, 55]. Zhu, et al. [56] argued that Wavelet Transform (WT) is more effective and offers more information due to its multi-resolution, sparsity and localisation properties through a comparative experiment.

### 2.2 Chatter identification

Both regenerative and mode coupling chatter were observed in practical robotic machining processes. Zhang, et al. [57] investigated the occurrence of both chatters using different cutting tools. During their experiments, the regenerative chatter was observed while using a long flexible tool, and mode coupling chatter was observed while using a short tool with larger stuffiness. The authors explained that the different results are due to the impact of tool structure which changes the stability boundary for both regenerative and mode coupling chatter. To be more specific, Tobias [58] stated that chatters may occur due to the insufficient dynamic stiffness of the machining system including machine itself, cutting tool, tool mount and workpiece. The regenerative chatter occurs locally at the cutting tool and/or workpiece when the local structure stiffness is not high enough to avoid regenerative feedback mechanism. On the other hand, mode coupling chatter occurs when the stiffness of the entire robot structure is not significantly higher than the process stiffness of the machining operation. In fact, both regenerative and mode coupling chatter
co-exist in all robotic machining process. Depending on which chatter mechanism is the bottleneck, usually only one type of chatter phenomena can be observed in a certain machining setup. Some important guidelines are summarised to provide a better understanding of chatter properties during robotic machining processes in Table 2 and followed by detailed descriptions:

Table 2 The distinctions of regenerative and mode coupling chatter

<table>
<thead>
<tr>
<th>Distinction</th>
<th>Regenerative chatter</th>
<th>Mode coupling chatter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Workpiece/cutting tools</td>
<td>Robot itself</td>
</tr>
<tr>
<td>Stiffness</td>
<td>Process stiffness &gt; machine stiffness</td>
<td>Robot stiffness &gt; process stiffness</td>
</tr>
<tr>
<td>Frequency range</td>
<td>Higher (hundred to thousand Hz)</td>
<td>Lower (around 10 to 20 Hz)</td>
</tr>
<tr>
<td>Machining force</td>
<td>Smaller force (a few Newton)</td>
<td>Larger force (hundreds of Newton)</td>
</tr>
</tbody>
</table>

- Regenerative chatter occurs in machining operations due to the closed-loop interaction between the machine tool-part structural displacements and the force process [59]. Thus, regenerative chatter occurs at the workpiece and/or cutting tools. While mode coupling chatter arises due to the insufficient stiffness and mode coupled structure of the robot itself, the chatter generally can be observed on the entire robot arm.
Compared to conventional machining system with a large structure stiffness which means the regenerative chatter is the main reason to cause vibration, when machining using an industrial robot, both chatter may occur depending on the distribution of the stiffness. Thus, identification of the robot stiffness and process stiffness is critical in chatter study. Currently, stiffness modelling is considered as a common method to predicted stiffness of industrial robot [60-64]. Moreover, Zhang, et al. [57] pointed out mode coupling chatter arises within a short stiffer cutting than a long elastic cutting tool.

Another feature to identify the chatter type is the different frequency ranges. Based on the equation of natural frequency (1),

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$

where $f$ is the natural frequency of the vibration, $k$ is the stiffness and $m$ is the mass the structure. Vibration from different elements of the machining system demonstrates different frequencies. As the entire robot structure is vibrating during the mode coupling chatter, its vibration frequency is relatively low, around 10 to 20 Hz [26, 65]. On the other hand, much less mass is involved in regenerative chatter as it happens locally around cutting tool or workpiece, resulting in higher chatter frequency, over hundreds or even thousands Hz.
Many researchers used force sensor to measure the process force signal and vibration. Compared to regenerative chatter which is normally induced by a small cutting force, mode coupling chatter can only occur under a relatively large cutting force (e.g. hundreds of Newton). Thus, from application point of view, the regenerative effect was considered as the dominant chatter during the finishing process such as grinding or polishing which are operated with a slight depth of cut and thereby a small cutting force was applied, while mode coupling chatter is more likely to occur during roughing process, such as milling and drilling, when a large amount of material is removed quickly.

2.3 Regenerative chatter

The regenerative chatter is considered to be the most significant cause of machining instability in machine tool [66]. In the analysis of regenerative effect, the occurrence of chatter includes an interference between the current machining segment and a wavy surface created from previous machining work [26]. During the machining operations, the chip thickness and the cutting force vary due to the phase difference between the wave left by the previous teeth (in turning it is the surface left after the previous revolution) and the wave generated by the current ones. As shown in Fig.2.2, if the surfaces of previous cut and current cut are in phase, the dynamic chip thickness will be constant. If the
surfaces are out of phase, the chip thickness variation would be maximum and thereby most likely to result in regenerative chatter [67]. From a control point of view, Fig.2.3 illustrates the feedback loop formed [68] during the regenerative process between the process dynamics and structural dynamics of the robotic machining system.

**Fig.2. 2 The mechanism of regenerative chatter [67]**

**Fig.2. 3 The feedback loop of regenerative chatter occurrence [68]**

### 2.3.1 The stability lobe diagram

Stability Lobe Diagram (SLD) is considered as the most effective tool for regenerative
chatter analysis [69] and Tobias [70]. SLD predicts the occurrence of regenerative chatter with regard to the cutting depth as a function of the spindle speed, as shown in Fig.2.4 [71-73]. SLD plots of the stable and unstable zones by identifying border between a stable cut (no regenerative chatter) and an unstable cut (with regenerative chatter), by employing the diagrams, it is possible to obtain a specific combination of machining parameters that results in maximum material removal rate without chatter [59, 74, 75].

To be more specific, Fig.2.4 illustrates that the objective of SLD is to demonstrate the maximum depth of cut without chatter varies with different spindle speed. A series of peaks (so called sweet points) are available and usually chosen for the best machining condition. In addition, at low cutting speeds the stability is greatly affected by process damping generated at the tool/workpiece interface, so linear process damping models have been developed to establish the lobes based on the characteristics of machining force, the cutter workpiece engagement and the dynamic properties of the machine-tool/milling-tool/workpiece system [76, 77]. In high and ultra-high speed machining, the maximum chatter free depth of cut becomes more spindle speed dependent, facts such as gyroscopic effect and centrifugal forces induce spindle speed dependent dynamics changes. In short, for accurate dynamics prediction, spindle speed dependent dynamics must be evaluated [78, 79].
2.3.2 Regenerative chatter reduction strategies

Both selections of stable machining parameters using the stability lobe and expansion the stable region of the diagram through modifying the system behaviour are common strategies for chatter mitigation as summarised in Table 3. Each strategy can be further categorised into two methods with distinct characteristics and applications as described in the Table, and more detailed explanations are given bellow.
Table 3 Summary of current regenerative chatter reduction technologies

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Mechanism</th>
<th>Method</th>
<th>Characteristic</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chatter avoidance</td>
<td>Selecting stable cutting parameters based on SLD.</td>
<td>Offline</td>
<td>➢ Generating SLD before machining &lt;br&gt;➢ Easy to select cutting parameters from SLD &lt;br&gt;➢ Complicated process generating SLD</td>
<td>Suitable for academic research</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Online</td>
<td>➢ Monitoring real-time chatter occurrence &lt;br&gt;➢ Simple process without SLD identification &lt;br&gt;➢ Flexible with various system setup &lt;br&gt;➢ Not suitable for finishing cause the damage is already imposed on the workpiece before adjusting &lt;br&gt;➢ Cost could be high using special sensor</td>
<td>Meeting the requirements of industry</td>
</tr>
<tr>
<td>Chatter suppression</td>
<td>Expanding the boundaries of the stable region</td>
<td>Passive</td>
<td>➢ Change the robot structure and/or the cutting tool elements. &lt;br&gt;➢ Simple and cost-effective &lt;br&gt;➢ Inflexible &lt;br&gt;➢ Limited performance</td>
<td>Effective for a certain fixed operation condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active</td>
<td>➢ Adaptive scheme for different cutting conditions &lt;br&gt;➢ Real-time control is possible &lt;br&gt;➢ Cost could be unacceptable</td>
<td>High-value and high demanding production such as aerospace</td>
</tr>
</tbody>
</table>

2.3.2.1 Offline approach by constructing SLD

Both offline and online methods can be used for the selection of chatter free machining
parameters. In offline approach, the identification of SLD is completed before the actual machining process.

A considerable amount of literature exists in SLD investigation and several approaches have been put forward to identify the stability boundary with a group of cutting parameters for various machining operations. Traditionally, researchers established SLD using analytical approaches due to the lack of sensing and data processing capabilities [80-83]. One of the analytical methods was the zero-order approximation (ZOA) presented by Altintaş and Budak [81]. This method is based on the transfer functions of the structure at the cutter-workpiece contact zone, static cutting force coefficients, radial immersion and the number of teeth on the cutting. It provides an analytical solution for generating SLD of a machining system with a varying cutting force and a large number of cutting teeth. Insperger and Stépán [84] developed another important analytical method called semi-discretization (SD) method, that determines the stability of a single point and computes directly the stability boundaries of linear delay differential equations with periodic coefficients and also with multiple or even with distributed delays [76]. In contrast to the analytical approach, which depends on the mathematical model of the regenerative chatter, the experimental method constructs and evaluates SLD without requiring specific knowledge of the machining process.
In the experiment of Quintana, et al. [71], the stability limit for a certain spindle speed is established through measuring the vibration during a gradual increase of the axial depth of cut using a microphone. Combining a series of such tests at different spindle speed, a complete SLD can be constructed without knowledge of the process model.

Similarly, Grossi, et al. [85] proposed a Spindle Speed Ramp-up (SSR) method to detect stable and unstable spindle speed at a specific depth of cut and then verify the stability using the Order Analysis technique. The complete SLD could be obtained with data from a series of tests carried out at different depth of cut. In addition, a combination of the analytical and experimental method is also developed taking the most advantage of both sides. In addition, analytical–experimental method combining advantages of both sides has been continuously developing in recent ten years. An analytical–experimental approach using an impact hammer instrumented with a piezoelectric force transducer was presented by [66]. In order to acquire transfer functions of the system, the structure was excited by an impact hammer firstly and then the vibrations were obtained with various sensors (i.e. acceleration, velocity and displacement sensors).

Hazel, et al. [86] pointed out that the conventional linear modelling method regarding SLD [87] is not suitable for the practical industrial robot. Therefore, the nonlinear vibro-impact was illustrated and included in the SLD generation process. Similarly, Ahmadi and Ismail [88] pointed out conventional SLD extraction method only based on
regenerative cutting force formulations while neglecting process damping. It was effective at high speeds but failed to predict stability at lower speeds. This phenomenon made it difficult to discern the boundary of stability in verification experiments of linear damping models. Their experiments confirmed that because of the nonlinearity of the process damping, the transition from fully stable to fully unstable cutting occurs gradually over a range of the width of cut.

Although “stability lobe diagram (SLD) remains as the most reliable method for machining chatter analysis Muhammad, et al. [89], the conventional methods of generating SLD is counterproductive due to the variation of dynamic behaviours at different robot configurations [15, 75, 90, 91]. New hybrid approaches to determine the stable zone of robotic machining tasks combining both traditional parameters (depth of cut and spindle speed) and parameters related to mode coupling were developed.

Li, et al. [90] explained that different cutting paths and feed motion would improve the surface quality of workpiece in the robotic metal cutting. To verify that, the influence of different cutter paths and workpiece clamping positions related to a Fanuc-1000i robot on the chatter stability of robotic milling were tested in their experiment. Then the corresponding chatter SLDs were plotted based on the modal parameters of both regenerative and mode coupled effects as shown in Fig.2.5 (a). Similarly, [28] verify that
the feed direction and position are the two noticeable factors that affect the stability of the process by establishing an SLD for ABB IRB 6660 industrial robot in the machining process at six different positions as shown in Fig. 2.5 (b). Wang, et al. [15] pointed out that compared to traditional SLD generation method, which considers spindle speed and depth of cut are the two critical factors, the two most significant factors that influence the stability of the process are the feed rate \( f \) and the depth of cut as shown in Fig. 2.5 (c). Therefore, the corresponding SLD methods considering mode coupled effect for robotic machining applications needs to be investigated.

Fig.2. 5 The SLD combining mode coupling effect [15, 28, 90]
2.3.2.2 Online approach for chatter avoidance

However, for industrial robots, due to its articulated serial structure, the structure dynamics varies at different configuration. It is difficult to generate a complete SLD for its entire workspace. An alternative method is to tune the machining parameter (spindle speed) online based on vibration measurement from sensors. Specifically, the spindle speed can be adjusted in real-time towards the sweet spots on the SLD, resulting in a possible maximum depth of cut and higher productivity without explicitly plotting SLD. Online chatter avoidance is generally carried out based on the control schemes and advanced sensing technologies, which were reviewed in the previous section.

Fig.2.6 illustrates a typical a closed loop chatter control for a milling system was presented by Muhammad, et al. [89]. The control system determines control action to eliminate regenerative chatter though the feedback from the sensors. Tsai, et al. [43] presented adaptive spindle speed tuning algorithm to avoid chatter in real time. An appropriate spindle speed compensation rate can be determined based on the real-time chatter level information which was obtained from sensor feedback. It was found that the proposed r spindle speed compensation was non-invasive, inexpensive, and convenient to facilitate. In addition, another type of online chatter avoidance approach is the chip thickness analysis. Based on the mechanism of regenerative chatter instability, some researchers claimed that monitoring chip thickness could provide information of chatter
However, it needs to mention that although the cutting condition can be adjusted to reach a stable condition from chatter, but they are unable to predict chatter onset in advance, the damage was already imposed on the workpiece (especially the chip thickness analysis approach), which makes online approach not suitable for the finishing cuts.

Fig.2. 6 The typical closed loop control system [89]

2.3.2.3 Passive strategies to suppress regenerative chatter

Besides avoiding regenerative chatter through selecting a group of machining parameters which makes machining in a stable zone, the second strategy to control chatter occurrence by changing the system behaviour to modify the stability boundary based on either
passive or active method. The passive method is based on the use of external devices that absorb chatter energy or technologies to break the regenerative effect.

Chatter energy extracts due to the dynamic interaction between the machine tool and the workpiece. Thus, if the accumulative energy can be absorbed, the feedback loop would be disrupted, which leads to a chatter free operation [94]. Miguelez, et al. [95] investigated the dynamic behaviour of boring bar and then developed a passive dynamic vibration absorber (DVA), which comprised an elastic spring and a viscous damper, for chatter suppression. In the research of Tarng, et al. [96], a piezoelectric inertia actuator is mounted on the cutting tool and acted as a tuned vibration absorber for the suppression of chatter in turning operations. It is shown that the tuned vibration absorber can modify the frequency response function of the cutting tool so as to improve cutting stability in turning operations.

Based on the principle of regenerative effect as shown in Fig.2.2, if the non-standard machining tool was designed and employed in machining applications, the regenerative effect would be disrupted. Currently, variable pitch and variable helix milling tools have been developed to avoid the onset of regenerative chatter. The concept of variable pitch tools was first carried out by Hahn [97], the phase was disturbed between the current and the passive chatter. Thus the constant delay of a conventional tool is modified to create
multiple discrete delays depending on the actual edge position and the number of flutes. Helical tools with non-constant or alternating helix angles introduce continuous changes in the local pitch angles along the tool axis. This special geometry causes continuous variation in the delay between flutes, which then perturbs the regenerative effect [98]. Based on the analysis of tooth engagement factor, Song, et al. [99] presented a structural geometry of variable pitch end mills with a high milling stability. In the study of Yusoff and Sims [100], in order to enhance the variable helix end millings tools to optimise the tool helix geometry with positive results compared to the traditional Sequential Quadratic Programming method in milling test.

In addition, Xiao, et al. [101] proposed a vibration cutting model to disrupt the regenerative effect, which contains a vibration cutting process without considering tool geometry. The setup consists of a rotary workpiece with a cutting speed and a vibrated tool employed by an ultrasonic electrostriction transducer. By vibrating the machining tool, vibration cutting achieved a higher cutting stability as compared with conventional cutting.

da Silva, et al. [102] developed passive shunt circuits to reduce chatter by embedding piezoelectric patches in the tool-holder connected to a passive shunt electrical circuit. The authors claimed that chatter instability can be reduced by increasing damping, so the
circuit was used to dissipate energy to provide extra damping to the system. In the research of Kim, et al. [103], a mechanical damper, which is composed of multi-fingered cylindrical inserts placed in a matching cylindrical hole in the centre of a standard end-milling cutter, was presented to increase system dimpling for chatter suppression during the high-speed milling process.

2.3.2.4 Active strategies to suppress regenerative chatter

In the active methods, the chatter is controlled through monitoring the system dynamic in a real-time, diagnosing the machining process and executing a better action to modify the system to an adequate situation.

Spindle speed variation (SSV) is a technology based on disturbance of the regenerative effect by creating varying tooth passing periods. Spindle speed variation can effectively be used in a wide spindle speed range since the frequency and the amplitude of the speed variation can easily be adjusted during the machining process [104]. Zaeh and Roesch [105] presented an SSV method to reduce regenerative chatter through determining a minimum spindle speed based on an analysis of the static and dynamic behaviour of a milling robot, the experimental results showed a better robotic milling process in the ultra-high speed zone.
Other researchers have been investigating active damping devices, which transfer chatter energy into the system to reduce the chatter occurred in a machine tool, to control regenerative effect. Based on an analysis of the physics behind regenerative chatter and the influence of structural damping, Ganguli, et al. [106] developed an active damping technique consisted an accelerometer sensor and a collocated inertial actuator as shown in Fig.2.7. The effectiveness of the proposed system was demonstrated through a mechatronic simulator during a turning process. The results showed that the system only needed an indistinct model of the system by the proposed velocity feedback approach and thereby it is practical for a broadband vibration suppression. Chen, et al. [107] proposed an active damping method of boring bars with an in-house designed magnetic actuator as shown in Fig.2.8. The actuator has been designed to have a linear force output relative to the input current and instrumented to control boring bar vibrations. The dynamic stiffness of the boring bar is increased considerably, leading to a significant increase in the chatter-free material removal rates.
Generally, various control algorithms were developed to operate robotic machining system. Thus, researchers have been investigating advanced control method to compensate regenerative chatter actively. Özer, et al. [108] presented a semi-active control technique to delay the onset of chatter when turning with a two-link robotic arm. The control strategy is based on varying the joint stiffness of the robotic arm using a
simple on–off type strategy synchronised with the spindle speed. It was found that Stability lobe diagrams have been enlarged significantly by comparing between controlled and uncontrolled cases as shown in Fig.2.9. Wu, et al. [109] also presented an active chatter control strategy to eliminate the external disturbance based on the inverse dynamics of robot machine whenever a disturbance signal is detected for an ITER vacuum vessel process including various machining tasks including threading, milling and boring. Březina, et al. [110] designed a PID controller to generate reactive force for the compensation of the regenerative.

![Stability lobes diagram for uncontrolled and controlled cases](image)

**Fig.2.** 9 Stability lobes diagram for uncontrolled and controlled cases [108]

To sum up, those various strategies based on either SLD or modification of system behaviour have been developing for a few decades, thus, there is already enough effort to solve the regenerative chatter issues during conventional machining applications. Based
on the mechanism of regenerative chatter, there is not much difference between conventional machining and robotic machining. Thus, more research effort should be spent investigating the mode coupling issue during robotic machining.

2.4 Mode Coupling chatter

Unlike regenerative chatter, which happens locally at either the machine tool or workpiece, when mode coupling chatter occurs, the entire robot structure will experience severe vibration. The term mode coupling means the vibration exists simultaneously in two or more directions coupling to each other with different characteristics as shown in Fig.2.10. The mode coupling chatter happens even when the successive passes of the tool do not overlap [57]. Its vibration amplitude has no fixed direction as the tool follows an elliptical path related to the workpiece. Although it is not common for modern CNC machine, mode coupling chatter can occur in robotic machining at a cutting force much smaller than the robot payload, due to the following two reasons: (1) the low stiffness (typically around as 0.1~1N/um level) of an articulated robot compared to a CNC machine (Commonly above 10N/um level), (2) the articulated serial structure makes the stiffness of robot at different directions possibly be very close to each other and varies at different robot configurations [26].
Gasparetto [111] studied the phenomenon from system theory point of view and provided a valuable 2D model for the analysis of mode coupling chatter, as shown in Eq (2).

\[
\begin{bmatrix}
M & 0 \\
0 & M
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_x \\
\ddot{u}_y
\end{bmatrix}
+ \begin{bmatrix}
K_x & 0 \\
0 & K_y
\end{bmatrix}
\begin{bmatrix}
\dot{u}_x \\
\dot{u}_y
\end{bmatrix}
= \begin{bmatrix}
-k \sin \gamma \cos \gamma & k \cos^2 \gamma & k \cos \gamma \sin \gamma \\
-k \sin^2 \gamma & k \cos \gamma \sin \gamma
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y
\end{bmatrix}
\tag{2}
\]

where \(M\) is the mass of the machining system, and \(K_x, K_y\) are the stiffness of the system along the two directions \(X_1, Y_1\).

The characteristic equation of the system was given as:

\[
\lambda^4 + \left(\frac{K_x + K_y}{M}\right) \lambda^2 + \frac{K_x K_y + (K_y - K_x)k \sin \gamma \cos \gamma}{M^2} = 0
\tag{3}
\]

the value of \(\lambda^2\) was obtained as:

\[
\lambda^2 = \frac{1}{2M} \left[-(K_x + K_y) \pm \sqrt{(K_x + K_y)^2 - 4K_x K_y \sin^2 \gamma} \right]
\tag{4}
\]

According to this equation, the mode coupling chatter only occurs when the process stiffness \(k\) is larger than the difference of two-principle stiffness of robot \(\Delta K\). It can be seen that the stability of the machine tool is not only dependent on the stiffness and damping of the system, but also influenced by the interaction of the various modes in the machining system.
2.4.1 Passive strategies

The mode coupling theory has been applied by many researchers for chatter mitigation in robotic machining process through either passive or active strategies as summarised in Fig.2.11. The passive strategy addresses the issue through changing the robot configuration to maximise the stiffness, optimise process behaviours and modify system structure to absorb chatter energy or disrupt mode coupling effect, while active strategy includes force control technology and real-time chatter absorption/disruption.
The stiffness of articulated industrial robots varies at different robot configurations due to their serial structure. The first type of passive chatter reduction takes advantage of this feature by selecting the most optimal robot configuration and trajectory. Research on stiffness modelling [112, 113] and parameter identification for stiffness model [114, 115] were important to fully understand the robot stiffness distribution in its workspace. Owen, et al. [116] developed a combined online/offline planning algorithm to optimise the robot trajectories such that the stiffness is maximised. Guo, et al. [117] established a robot posture optimisation model based on the Jacobian matrix to increase the robot stiffness. In addition, Andrisano, et al. [118] and Lopes and Pires [119] found that choosing a proper initial pose and workpiece location would lower the robot load and ease the joint torques.
Lopes and Pires [119] tested a new genetic algorithm to decide the location of the workpiece so that the lower load was added to their robotic model while carrying out the same task. Andrisano, et al. [118] reduced the external forces on the joints by designing an optimised initial pose for the robot. In this case, the robot performed the tasks with a lower joint force so that the less chatter was observed.

The second type of passive chatter mitigation strategy is to select the most suitable cutting parameters, since the machining process behaviours, such as cutting direction, machining tools, and cutting modes can dramatically change the magnitude and direction of the cutting force. In the research of Tunc and Stoddart [16], various alternative tool path patterns were evaluated and the optimum feed direction is selected to reduce chatter in a milling process using a Fanuc F200iB hexapod robot. Moreover, Pan, et al. [26] summarised a series of methods to reduce the impact of chatter on machining process:

a) A proper selection of cutting tool would reduce the chatter. The geometry of cutting teeth has a great impact on the cutting force. For example, the square insert is more recommended for robotic machining than the round insert as it directs less force in the normal direction to form a feedback loop for the mode coupling chatter.

b) Since the robot displays different mechanical properties, such as stiffness and damping, at different locations in the workspace, selecting a proper machining
location may have a more stable process.

c) The tool path and feed direction should be selected properly so that the machining force vector aligns with the stiffest direction of the robot structure.

d) Chatter is more observed in up-milling than in down milling.

Other researchers focused on the suppression and absorption of the chatter energy by changing the system structure. Conventionally, a vibration suppression device namely dynamic vibration absorbers (DVAs) are used in vibration control for a specific working condition [20]. The working principle of the DVA is that the vibration energy of the control subjects would be largely transferred to the oscillators when the DVAs are designed for a certain condition. For example, in the scheme of Kaldestad, et al. [120], a sandbag was attached to the spindle as a passive damper for robot milling process. The experimental result showed that it was an effective attempt to reduce vibration.

2.4.2 Active strategies

Recently, active chatter compensation, in particular, force control based strategy has been a central topic in robotic machining study. Traditionally, robotic machining tasks were performed under position control using a conservative travel speed and depth of cut so that the machining force does not exceed the limit. The efficiency of the machining process can be optimised by using controlled material removal rate (CMRR) through force control, as demonstrated in Fig.2.12. Cen, et al. [18] developed an in-situ thin-film
wireless force sensor to measure the machining forces in robotic milling operation. More commonly commercial available six degrees of freedom force sensor was used for machining force measurement [19]. Using force sensor data, Pan and Zhang [121] developed a chatter reduction solution through force control scheme. The controller regulated the machining force by adjusting the robot travel speed, avoiding a heavy cut that will result in chatter. Similarly, Liang and Bi [122] presented a programmable end effector using real-time force feedback to adjust operation behaviours such as spindle speed, feed rate, stacking sequence, and clamp force. In the research of Wang, et al. [123], the real-time thrust force is measured and three stages corresponding to the anatomical structures of the vertebra are identified based on the analysis of typical characteristic parameters of the force profiles. The cross-correlation to the standard profiles is adopted to judge the milling status. Moreover, Xie and Sun [124] claimed that force control is important to maintain a constant and stable process force for robotic grinding/polishing.

Fig.2. 12 The principle of force control strategy
2.5 Discussion of chatter issue during robotic machining

As reviewed earlier, with a poor setup, the mode coupling chatter can occur way below the payload of the robot, which dramatically limits the productivity. Compare to regenerative chatter, there is still lack of theoretical understanding and practical strategy to tackle the issue. Most of the current studies focus on passive strategies, which include maximising structure stiffness, optimising process behaviour and chatter absorption. Force control technology was also developed to actively avoid mode coupling chatter in through controlled material removal rate. However, force control strategy mainly controls the chatter by limiting the cutting force though a lower cutting speed instead of reducing the vibration, the maximum productivity is still limited by the chatter effect. Therefore, it is necessary to develop an ATVAs to absorb chatter energy based on its character of real-time and a large range of adjustment.

Recently, Magnetorheological elastomers (MREs) based ATVAs are considered as a new candidate of smart devices. The basic operating principle of MRE device is the field-dependent material property. In the presence of a magnetic field, the modulus and the damping of the MRE material would be changed immediately with the change of the magnetic field [125]. This provides a potential feature a novel semi-active or active
vibration absorber. The MRE based ATVA would be of benefit in the chatter control application where the mode coupling effect is dominant during robotic machining with a great ability to absorb massive energy in a real-time control. Therefore, it is necessary to propose a literature review of MRE material to gather the advanced knowledge in the vibration control field.

### 2.6 Introduction of MRE technology

#### 2.6.1 The MRE material

Magnetorheological elastomers are solid, rubber-like materials whose mechanical properties (stiffness) can be controlled by applied magnetic fields to provide tuned or adjustable mounts and suspension devices [126]. Magnetorheological (MR) effect can be observed in the presence of a magnetic field and magnetic sensitive particles, this is also called field-dependent material mechanical property. After removing the magnetic field, MRE materials remain its initial mechanical property [127, 128]. In addition, some advantages are summarized by researchers:

- MREs are considered as a stable material because the particles are fixed in the rubber, no extra container is required to keep the material in certain place.
- There is a very short response time of MREs, normally only several milli-seconds after the magnetic fields vary. Due to the fixed position of particles in the matrix, no extra time is needed to arrange particles again while a new magnetic field is applied. All these characteristics have made MRE material an ideal technology for various vibration control applications in different engineering disciplines [129].

Since the MR effect was discovered by Rabinow [130] in the 1940s, considerable research efforts have been devoted to the magneto-mechanical phenomena. Shiga, et al. [131] firstly studied dynamic viscoelasticity of immiscible polymers blends, which are composed of semiconducting polymer particles and silicone elastomer, under the influence of a magnetic field. Then, Jolly, et al. [127] investigated the material properties of the magnetorheological elastomer. In their test, a silicon rubber based magnetorheological elastomer and a quasistatic dipolar model were employed to identify the modulus change inside of the MREs. Li, et al. [129] and Li, et al. [23] provided a comprehensive review and discussion of current research on the MRE device fabrication, performance characterization, modelling, challenges, potential and applications. Theoretically, MRE materials can be made by mixing various composite materials which are a mixture of micron-sized magnetic particles in a non-magnetic matrix [132]. Commonly, most of MRE materials consist the iron or carbonyl iron particles, the rubber or silicone rubber and additives (typically silicon oil) within a certain ratio.
2.6.2 The property of MREs

Generally, the property of MRE layers depends on the material selection and the ratio of raw material including micro-scale ferromagnetic particles, a non-magnetic solid or gel-like matrix. Hence, in this section, the properties of MRE layer based on raw material selections and the raw material ratio of the composite rubber are briefly investigated.

Firstly, based on the tasks on the MRE devices, it is required to choose ferromagnetic particles with the high magnetic field permeability and magnetic saturation properties, which means a higher MR effects would be utilized [126]. In the current studies, although a few kinds of metal materials, such as cobalt, nickel and alloys of iron, have been successfully applied in MR fluids (MRF). Iron remains the best candidate to fabricate the MREs due to the difference between the MRE and MRF. Iron particles and carbonyl iron particles, provide a low remanent magnetism which makes the particles stay at the original position instead of sticking together, exhibit a very short response time after the magnetic field is changed or removed. Li, et al. [133] investigated the MR effect of the carbonyl iron particles in MREs. It was found that the carbonyl iron provided a large range (5% to 500%) MR effect. In addition, the size of the ferromagnetic particle has impact on the MR effect, the MR effect generally improves with the larger size of the particles. For instance, an MREs sample with the 40 µm range particles has a great amelioration (20 times more) on MR effect compared to those with mean particle sizes
of about 5 μm [134].

Secondly, the elastomer matrix selection has a significant impact on the property of the MRE layer. Many materials have been utilized to be the elastomer matrix such as natural rubber and polyurethane. Generally, the polyurethane exhibits a better MR effect (up to 150%) while just 20% MR effect can be offered from natural rubber. Nevertheless, silicon rubber and its analogues still remain the predominant elastomer matrix in MREs fabrication due to their outstanding advantages: the natural rubber provided a better property for MRE devices and the silicon rubber exhibits a relative high MR effect while it is easy to be manufactured from liquid precursors [135].

Thirdly, in order to optimize the MRE modulus which is considered as a critical property of the MRE material, the weight percentage of the raw materials is always changed. Generally, in order to increase the MR effect, the weight percentage of ferromagnetic particles needs to be increased. For instance, in the research of Gong, et al. [136], 20 weight percentage of an MRE sample with carbonyl iron exhibits a 3% MR effect while a 51% MR effect was measured from an MRE with 70 weight percentage of carbonyl iron particles. In addition, it has to mention that excepting for considering MR effect, the mechanical property, which is always changed with a different weight ratio of raw materials, is another consideration in practical use.
2.6.3 The fabrication of MRE layer

Isotropic MREs and anisotropic or aligned MREs are considered as the two main types of MRE materials, which differ by distinct ways of curing [137, 138]. Fig.2.13 illustrated a general process of fabricating the isotropic MREs and anisotropic MREs, firstly, three ingredients (iron particles, silicon rubber and silicon oil) are mixed homogenously. Note that the air bubbles inside of the blends need to be eliminated through a vacuum chamber or heat treatment. Secondly, different curing processes were employed between isotropic MREs and anisotropic MREs, the isotropic MREs are cured without the external magnetic field, so it is also called unstructured magnetic elastomers, while the anisotropic MREs need to be used within the presence of the magnetic field. During the second process, the magnetic particles would be able to align in the direction of magnetic field to form a chain-like or column structure in the matrix. Thus, after curing, these particles will be locked in the matrix as shown in Fig.2.14. As a result, the mechanical property of those two types of MREs would be different in the external magnetic field.
Besides manufacturing the MRE layer, the whole MRE device needs to be designed regarding operation modes and magnetic circuit distribution. In this section, the basic design of MRE devices is discussed.

2.6.4 Basic design of MRE devices

Fig. 2. 13 The fabrication of both isotropic and anisotropic MR elastomers [137]

Fig. 2. 14 SEM images of MREs: (a) anisotropic MREs; and (b) isotropic MREs [138]
design concept is reviewed those two aspects.

2.6.4.1 Operation modes

The operation modes selection including shear mode, squeeze mode and field-active mode is a critical step to develop MREs. Among them, although field-active mode has been used for MRE device, shear mode and squeeze mode based operation pattern are massively used in both academics and industries. To determine the specific operation mode, the configuration combining of aligned chain directions and field directions needs to be identified for the proposed anisotropic and/or isotropic MRE device, as shown in Fig.2.15.

Popp, et al. [139] investigated MREs performances under both shear and squeeze modes. Experimental studies demonstrated that the resonance frequency under shear mode was much smaller than that in the squeeze mode because of the different modes the MREs were subjected to. Zhou [140] conducted a series of experiments to test he damped free vibration of an MRE system. It was found that the shear storage modulus is a linear function with respect to the magnetic field. In addition, compared to squeeze mode, a
wide frequency range can be proposed with the MRE vibration absorber which works in a shear mode [141].

Besides choosing a shear mode or squeeze mode, a combination mode called shear–compression mixed mode or shear-squeeze mode was proposed in recent years. In the scenario of Yang, et al. [142], a novel MRE mixed mode isolator in shear–compression mixed mode was proposed as shown in Fig2.16. The test results demonstrated that with the applied current, natural frequency of the proposed MRE isolator could be controlled more effectively than those of shear or compression mode.

![Fig.2.16 The shear–compression mixed operation mode [142]](image)

**2.6.4.2 Magnetic circuit modes**
Normally, electromagnetic coils or solenoids are employed to provide a controllable magnetic field for the MREs based device. The magnetic field would be changed with the change of the applied current. An optimal magnetic circuit scheme brings the device with the best MR effect for the MRE material. Theoretically, in order to fully use of magnetic field to achieve the best performance, the magnetic field flux and the motion of the MRE device should be designed vertically to each other. In the current studies, the C-shape magnetic circuit design is regarded as the best magnetic circuit scheme for MRE devices due to minimum energy losses through the enclosed magnetic flux field path. Fig.2.17 illustrates three layouts for a magnetic circuit design of MRE devices [23].

![Diagram of magnetic circuit designs](image)

**Fig.2.17 Different configuration of MRE devices [23]**

Conventionally, most of the MR fluid devices use the first magnetic circuit layout which the smart material is arranged outside of the electromagnetic coil and the axial of the coil is parallel to material motion direction. However, it is not applicable for MRE device due
to a large portion is required to be energized. Compared to the first configuration, the smart material is closed attached to the top and bottom of the solenoid in the second configuration. Currently, many of MRE device including vibration absorbers and vibration isolators featuring this structure [143] [144]. The drawbacks of this layout are the extra conditions are required to emerge the layer of MREs. As shown in Fig.2.17, in the third configuration, the MRE layer is placed inside of the solenoid. Compared to other two layouts, the great advantages of it is a complete active area and uniform magnetic field. The magnetic field can be fully used to energize the MRE materials.

2.6.5 The applications of MREs

Currently, MREs has been supplied to many engineering applications based on their special field-dependent properties. Among all the applications, MREs are regarded as the best candidate for tasks of vibration absorption and isolation, which can be found in plenty of engineering fields, such as mechanical, civil and automobile. To be more specific, MREs hold promise in enabling controllable stiffness devices, adaptive tuned vibration absorbers and isolators.

MREs were employed in dynamic vibration absorber as the smart spring system in [145]. Fig.2.18 demonstrates the structure of their adaptive vibration absorbers (AVAs) using MREs, the AVA consists three essential components including the mass (base mass and
absorber mass), the coils and the MRE elements. Due to the MREs, it can operate in a large frequency instead of a specific range. Furthermore, in the research of Deng and Gong [146], the MRE absorber was proposed and worked in a shear mode. The experimental results indicated that the resonance frequency of the absorber can be adjusted in a large range by varying electrical currents, the relative frequency change is as high as 145%.

Fig.2. 18 Adaptive vibration absorbers (AVAs) using MREs [145]

MRE technology is also used to develop appliance for vibration isolation. For instance, novel devices need to be developed to isolate noise and vibration to cater the demand for low cost, quiet operation and increased operator comfort in modern vehicles. Stelzer, et al. [147] designed an MREs based vibration isolator to mount on the vibrating component
in the vehicles as shown in Fig.2.19. The proposed isolator was mounted on the compressor, which generates and transmits vibration to the automobile, to suppress high frequency vibration. Moreover, the isolator also restraints vibration from the compressor due to the vehicle road inputs effectively.

The MREs were used as variable stiffness devices in vehicle industry for a few decades. For instance, Stewart, et al. [148] designed an apparatus for reducing brake shudder in motor vehicles using MREs which employed as a part of suspension bushing as shown in Fig.2.20. The system can determine the ideal suspension bushing stiffness based on the brake actuation signal. Then, the matched electrical current is selected to adjust the magnetic field according to the proposed algorithm.

Fig.2. 19 An MREs based vibration isolator [147]
Chapter summary

Chapter 2 outline the important information that this thesis fits in to. The chatter occurrence during robotic machining process with the regard to both regenerative and mode coupling chatter, then the chatter suppression strategies was reviewed. Currently, as reviewed and discussed before, the regenerative chatter reduction has been investigating for a few decades and thereby the systematic solution for regenerative chatter has been well established while there is limited research effort to deal with coupling chatter. In addition, be different from conventional machining process such as CNC machining which the regenerative is regarded as the dominant chatter. On the other hand, the mode coupling chatter is more likely to happen in robotic machining process
due to the inherent weakness (low stiffness and mode coupled structure). Therefore, more research should be spent on the chatter reduction method for mode coupling chatter,

Many studies referenced in this chapter conclude that passive strategy is the main direction to avoid chatter occurrence and there is still lack of active chatter reduction solution for mode coupling chatter during robotic machining process besides force control scheme which just tries to avoid chatter. Thus, an active chatter suppression strategy would be developed, to be more specific, an ATVA device should be developed to absorb the chatter energy.

Magnetorheological elastomers have been tested as a novel solution in absorbing vibration energy in many applications, thus, they are an ideal candidate for mode coupling chatter reduction during robotic machining. In addition, a control system would be developed to target specific frequencies in real-time through varying the mechanical properties (stiffness) of the MRE absorber. The properties, fabrication, design concept and general applications of MREs from current literature have been reviewed and analysed.

To be summarised, the target of this research is first to develop a MREs based AVVA to control or eliminate the mode coupling chatter during robotic machining process.
Secondly, a series of experiments should be scheduled to verify the effectiveness of MRE absorber in the robotic machining process.
Chapter 3 Robot model and chatter analysis in robotic machining

As reviewed in Chapter 2, the characteristic of MRE based ATVA determines chatter (or vibration) in a certain frequency range can be absorbed. Thus, before designing MRE absorber, it is necessary to investigate the frequency of machining chatter based on the robot model.

3.1 Robot model

In this study, ABB IRB 6660 robot was used in the machining test. Compared to conventional CNC machine, the obvious structure feature of the industrial robot is the multiple degrees of freedom (DOF). Traditionally, Denavit-Hartenberg (DH) model [149] is employed to demonstrate the robotic kinematics and dynamics by identifying the forward kinematics. Based on the DH modeling method and the data from the manual of ABB IRB 6660 robot, DH parameters were calculated as in Table 4. The $\theta$, $d$, $a$ and $\alpha$ are joint angle, joint distance, link length and link twist angle, respectively. The values of symbol, $d_1=814.5$mm, $d_4=893$mm, $d_5=200$mm, $d_6=210$mm, $a_1=300$mm, $a_2=700$mm, $a_3=280$mm and $a_5=240$mm.
Table 4 Forward kinematics of ABB IRB 6660

<table>
<thead>
<tr>
<th>Joint</th>
<th>$\theta$</th>
<th>$d$</th>
<th>$a$</th>
<th>$\alpha$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$q_1$</td>
<td>$d_1$</td>
<td>$a_1$</td>
<td>$-90^\circ$</td>
</tr>
<tr>
<td>2</td>
<td>$q_2$-$90^\circ$</td>
<td>0</td>
<td>$a_2$</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>$q_3$</td>
<td>0</td>
<td>$a_3$</td>
<td>$-90^\circ$</td>
</tr>
<tr>
<td>4</td>
<td>$q_4$</td>
<td>$d_4$</td>
<td>0</td>
<td>$90^\circ$</td>
</tr>
<tr>
<td>5</td>
<td>$q_5$</td>
<td>0</td>
<td>0</td>
<td>$-90^\circ$</td>
</tr>
<tr>
<td>6</td>
<td>$q_6$+$180^\circ$</td>
<td>$d_5$+$d_z$</td>
<td>$a_x$</td>
<td>0</td>
</tr>
</tbody>
</table>

Regarding DH-convention the forward kinematics can be derived by the equation (6):

$$A_i(q_i) = T_{r_z}(\theta_i)T_{t}(a_i,0,d_i)T_{r_z}(\alpha_i)$$

(6)

Thus, the homogeneous transformation from base to end effector coordinate system was obtained as:

$$^0T_E(q) = ^0T_1(q_1) ... ^5T_6(q_6)$$

(7)

$$= A_1(q_1) ... A_6(q_6)$$

Employing the $x_E=f(q)$ in forward kinematics to calculate the analytical Jacobian as:

$$J(q) = \frac{\partial f(q)}{\partial q} = \begin{bmatrix}
\frac{\partial f_1}{\partial q_1} & ... & \frac{\partial f_1}{\partial q_n} \\
\vdots & \ddots & \vdots \\
\frac{\partial f_m}{\partial q_1} & ... & \frac{\partial f_m}{\partial q_n}
\end{bmatrix}$$

(8)

$$m = \dim(x_E),$$

(9)
\[ n = \dim(q), \]
\[ \Delta x_E = J(q)\Delta q \]

The Jacobian matrix will be employed to demonstrate the displacement approximation structure, which is due to the machining force, of the robot-tool.

### 3.2 Robot-tool model

The general robot-tool structure equation in task space in time domain is

\[ \begin{bmatrix} M \end{bmatrix}\ddot{x} + \begin{bmatrix} C \end{bmatrix}\dot{x} + \begin{bmatrix} K \end{bmatrix}x = \{F\}, \]

where \([M]\), \([C]\) and \([K]\) are six by six mass, damping and stiffness matrix, respectively. \(\{F\}\) is the vector of external forces which has special contribution to chatter phenomena in robotic machining. The vector \(\{x\}\) represents the system’s degrees of freedom, that are 3 translational and 3 rotational in case of the robot’s end effector. Since Pan, et al. [26] and Gasparetto [111] explained that damping matrix could be ignored due to its solely stability increasing effect in mode coupling analysis, only mass and stiffness matrix to be identified through establishing the robotic structure.

The stiffness matrix could be represented in joint space as:

\[ \tau = K_q\Delta q \]

where \(\tau\) is the torque load on each joint and \(K_q\) is a diagonal six by six matrix with the joint stiffness values on its diagonal. Mousavi, et al. [28] established a model for ABB
IRB 6660 model to deduce the joint stiffness values in Table 5 which will be utilized in this study.

Table 5 The stiffness of each joint

<table>
<thead>
<tr>
<th>Axis</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$10^6$</td>
<td>$2 \times 10^6$</td>
<td>$2 \times 10^6$</td>
<td>$4 \times 10^5$</td>
<td>$4 \times 10^5$</td>
<td>$4 \times 10^5$</td>
</tr>
</tbody>
</table>

In joint space the stiffness of each joint is independent to each other. Thus, the stiffness matrix can be transformed to Cartesian Space $K$ (the value of $K$ depends on current configuration of the robot) by the Jacobian matrix,

$$K = [J(q)^T K_q^{-1} J(q)]^{-1}$$  \hspace{1cm} (14)

The mass matrix in joint space can be obtained through the dynamic model and the Hessian of the robot’s kinetic energy $T$. Switching mass matrix from joint space to work space coordinates is similar to stiffness matrix transformation as

$$M = [J(q)^T M_q^{-1} J(q)]^{-1}$$  \hspace{1cm} (15)

To calculate the kinetic energy $T$, a 3D model of the robot was established by ABB to obtain physical data which was used to construct dynamic model of robot by Lagrange method. Then, combining Newton’s second law for discrete dynamic system and variational mass. The equation (16) was deduced and then the mass inertia matrix (17) was given

$$T = 0.5(\dot{q}^T M^g \dot{q})$$  \hspace{1cm} (16)
\[ M_q = \frac{\partial^2 T}{\partial q^2} \]  

(17)

### 3.3 Chatter analysis

Pan, et al. [26] investigated that the frequency of mode coupling chatter is the same as the base frequency of the machine. Thus, to analysis chatter frequency, the first step is to deduce the base frequency. Base frequency of a mechanical structure are calculated without contemplating an external force, just using the homogeneous solution that is represented by the system’s eigenvalues. Hence, the characteristic equation

\[
\det([K] - [M]\lambda^2) = 0
\]

(18)
yields in task space and joint space 6 base frequencies that obviously depend on the robot’s configuration as both stiffness and mass matrices depend on it. Thus, the mathematical model assists to analysed vibrational mode of the IRB6660 from ABB of various positions.

![The base coordinate system](image)

**Fig.3. 1 The base coordinate system**
Although the low frequent modes are the xyz modes that need to be considered in the machining operations. In the practice, major chatter was observed along XY plane which was parallel to the machining table as shown in Fig. 3.1. Thus, the modelling of the first 3 modes and their base frequencies were calculated. Modelling each frequency by changing the robot’s position in x- and y- direction up to 450mm in 30mm steps according to the designate original position which joint angles were listed in Table 6. Then, all the results were plotted in Fig. 3.2 (a) the third mode, Fig.x (b) the second mode and Fig.x (c) the first mode. It shows that nearly all chatter frequencies were located in the frequency range of 7 to 20 Hz. In addition, although these values are not exactly the same as the joint space calculation since modes influence each other. They were proven that the frequency of mode coupling chatter is always around 10 to 20 Hz in [26]. Thus, the MRE in this study would be designed to operate in the frequency range of 7 to 20 Hz.

Table 6 The original position

<table>
<thead>
<tr>
<th>Axis</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (rad)</td>
<td>-0.1091</td>
<td>-0.6317</td>
<td>0.5590</td>
<td>-1.6607</td>
<td>1.4591</td>
<td>2.1310</td>
</tr>
</tbody>
</table>
3.4 Chapter summary

In this chapter, robot model and robot-tool model were established to assist the chatter frequency analysis. Relative equations were deduced to calculate the major chatter occurrence during robotic machining process and thereby the operating frequency range of MRE absorber was given accordingly.

Fig.3. 2 The chatter frequency of (a) third mode (b) second mode and (c) first mode
Chapter 4 The design of the multi-layered MRE absorber

This chapter firstly introduced a novel MRE structure called multi-layered MREs. Then, the structure of the proposed MRE absorber and the fabrication process was presented in details.

4.1 Introduction

Recent developments of adaptive tuned vibration absorbers (ATVAs) featuring MREs have been attracted much attention due to the advantages of MRE materials including short response time, controllable stiffness and low environment dependence. Generally, the working principle of MRE absorber is that the chatter energy of the controlled objects would be largely transferred to the oscillators of the absorber (as kinetic energy of oscillators) under certain working conditions that the MRE absorber is designed for. Thus, it is required the MRE layer to provide a maximum stroke for the oscillator. Traditionally, the single layer MRE structure has been employing to manufacture the ATVA for a few decades as shown in Fig.4.1, the stroke range is a more prominent limitation of it. As a result, only the vibration energy with narrow amplitude range can be transferred to the oscillator.
Another target of MREs design is to be constructed featuring a broad controllable frequency range. Nevertheless, it is still hard to operate in a low frequency range with a single layer MRE device. Currently, in order to construct an ATVA which is working in low frequency, the mass of the oscillator is usually determined to be a large value and an MRE layer with a low rigidity is required. However, the MREs with a low rigidity structure does not have enough strength to support the oscillator with a large mass. Based on the current literature, the application of ATVA using a single layer of MRE sheet is limited to absorb vibration energy in a medium to high frequency range. Commonly, the chatter occurring in robotic machining is around 10Hz and the large mass oscillator is required due to the large mass of the upper robotic arm (usually few hundred kilogram). Additionally, the mode coupling chatter usually has a large amplitude. Thus, the current single layer MRE is not suitable to be used ATVA, this is the motivation of this research.

Currently, as shown in Fig.4.2, a concept of a novel multi-layer MRE structure was carried out by Sun, et al. [20], compared to traditional single layer MRE, the steel sheets are bonded onto the single MRE layers to form the multi-layer MREs. There are three advancements of the laminated MRE structure. Firstly, the vertical support ability for a large mass of oscillator can be significantly improved. Secondly, the large mass oscillator promotes the capability of the ATVA to operate in low frequency range. Moreover, a relative larger stroke of the oscillator makes the ATVA absorb more vibration energy with
large amplitude. In this section, a design process of a multi-layer MREs based ATVA for robotic machining was presented.

Fig. 4. 1 A typical single layered MRE absorber

Fig. 4. 2 A multi-layer MRE absorber
The Conceptual design of the laminated MRE absorber

The working principle of MRE absorber is that the chatter energy of the controlled objects would be largely transferred to the oscillators of the absorber (as kinetic energy of oscillator) under certain working conditions that the MRE absorber is designed for. Currently, the advanced ATVA consists of four main parts: the dynamic mass, and controllable spring element (MRE layers), magnetic conductor and excitation coils [22]. Among them, the efficient component of MRE device is its oscillator or so called dynamic mass. In addition, the operation mode was selected as shear mode considering the target mode coupling chatter mainly occurs in horizontal plane. To ensure the ATVA works by the shear mode, the smart spring elements (MRE layers) stick on the oscillator and the mounting plate in vertical order as shown in Fig.4.3.

Fig.4. 3 The demonstration of the shake motion
In addition, the magnetic conductor is the critical part of the MRE absorber, because the magnetic circuit is formed by it. As shown in Fig.4.4, for shear operation mode, the MRE layer is placed on the bottom of the solenoid coil and the direction magnetic field is perpendicular to the shear force direction. To install the excitation coil, four steel columns was designed inside of the oscillator which would be covered by four non-magnetic supporters made from 2 mm thick plastic. For a coil, an 800 turns of 0.5 mm diameter copper wire were twined tightly around solenoids. To assess the principle design of the magnetic circuit, representation in Fig.4.4 illustrates the schematic for the initial design of the vibration absorbers with four MRE sheets, as well as the magnetic closed loop circuit.

### 4.3 Parameters determination

To transfer chatter energy to MRE absorber, the natural frequency of the absorber needs
to be designed to match the excitation frequency through the adjustment of the MRE’s stiffness based on the mechanism of resonance [150]. Thus, in this section, the dimensions of the MRE layer, as well as other components of the absorber, would be determined to match the target low external excitation frequency based on theoretical calculation. Secondly, the frequency bandwidth of the absorber would be obtained based on the change of magnetic field controlled by the current of the excitation coils.

The natural frequency of MRE absorber is $f$:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$  \hspace{1cm} (19)

where $k$ is the stiffness and $m$ is the mass of the absorber. Combining the mathematic relation developed in Deng and Gong [151], the initial natural frequency of the MRE absorber, $f_0$, can be expressed as below:

$$f_0 = \frac{1}{2\pi} \sqrt{\frac{G_0 A}{nmh}}$$  \hspace{1cm} (20)

where the $G_0$ is zero-field modulus, the $A$ is the contact area between MRE layer and the oscillator, $n$ is the number of the layers, the $m$ is the mass of the steel oscillator and the $h$ is the thickness of the MRE layer.

The entire natural frequency range $f$ of the ATVA can be calculated as:

$$f = f_0 + \Delta f$$  \hspace{1cm} (21)

where $\Delta f$ is the magneto-induced frequency. According to Sun, et al. [20], the generally frequency $f$ can be calculated as:
\[ f = \begin{cases} 
\frac{1}{2\pi} \sqrt{\frac{G_0 + 36\phi \mu_0 \mu_1 \beta^2 \tilde{H}^2 \left( \frac{a}{d} \right)^3 \zeta}{nmh} A} & \text{If the iron particles do not saturate} \\
\frac{1}{2\pi} \sqrt{\frac{G_0 + 4\phi \mu_0 \mu_1 M_s^2 \left( \frac{a}{d} \right)^3}{nmh} A} & \text{If the iron particles saturate}
\end{cases} \] 

(21)

where \( \phi \) is the volume fraction, \( \beta = (\mu_p - \mu_1)(\mu_p + 2\mu_1) \), \( \mu_0 \) is the vacuum permeability, \( \mu_1 \) and \( \mu_p \) are the relative permeability of silicon rubber and the particles, respectively. \( a \) is the average radius of iron particle. \( d \) is the original particle distance. \( M_s \) is the saturation intensity of the particles.

In chapter 2, the frequency range of MRE absorber was determined as 7 to 20Hz. In order to control such vibration, the natural frequency of the MRE absorber needs to be designed accordingly. Therefore, combining the Eqs. (18), (19), (20) and (21) above, a prototyping process was developed as following to decide the parameters of the MRE absorber.

The first step is to decide the mass of the upper oscillator. It has to mention that more vibration energy from the target object could be transferred to the oscillator if its mass is large enough. However, the overweight oscillator would result in limited workload for the robot. If the mass of the steel oscillator is too small, its vibration absorption capability will be compromised. Therefore, a proper mass (20kg) was designed considering both
sides. The laminated steel-MRE structure consists of 3 layers of steel lamina and 3 layers of MRE lamina. Both the thickness the steel and MRE lamina are 1mm as shown in Fig.4.5. The geometry of the MRE and steel were designed as shown in Fig.4.6 and thus the A was determined as 0.01 m² in total of four sheets. For other parameters, their values depend on the different ratio of the weight ratio of carbonyl iron particles, silicon rubber and silicon oil, the formulation 7:1.5:1.5 was selected as the weight ratio to fabricate the MRE layers.

Fig.4. 5 The MRE and steel sheets
4.4 Prototyping of an MRE-based absorber

In this study, 12 slices MRE sheets were manufactured with the weight ratio of carbonyl iron particles (C3518, Sigma- Aldrich Pty. Ltd), silicon rubber (Selleys Pty. Ltd), and silicon oil (Sigma-Aldrich Pty. Ltd) was 7:1.5:1.5, those ingredients were weighed and mixed in a beaker. The container was placed in a vacuum pump to separate the air bubbles from the mixture. Then the mixture was filled in a mold and placed in a room at a stable ordinary temperature for seven days. Three MRE sheets were stuck on the three steel sheets layer by layer as shown in Fig.4.7. The four multi-layered MRE pillars were bonded on the bottom of steel column after installing the excitation coils as shown in Fig.4.8. The last step was to place the oscillator as well as laminated MRE pillar on the mounting plate.
In this chapter, the laminated MRE pillar, as well as the entire MRE absorber, was designed and fabricated based on the frequency range of mode coupling chatter during robotic machining process.
Chapter 5 Frequency-shift property of the MRE absorber

The identification of the frequency-shift property is essential and fundamental to analysis an MRE absorber, it demonstrates the valid frequency bandwidth and the natural frequency change of the MRE absorber. In this chapter, the MRE absorber was tested using the vibration platform and swept sinusoidal signals. Based on the measurement, the frequency-shift performance of the proposed absorber was evaluated.

5.1 Transmissibility of the MRE absorber

As a single degree-of-freedom (SDOF) system, thus, the transmissibility can be identified. According to Zhang and Li [141], the transmissibility of the MRE absorber can be represented by magnitude and phase from the equation:

\[
T = \sqrt{\frac{1 + (2\varepsilon \lambda)^2}{(1 - \lambda^2)^2 + (2\varepsilon \lambda)^2}}
\]

\[
\varphi = \tan^{-1} \frac{-2\varepsilon \lambda^3}{1 - \lambda^2 + (2\varepsilon \lambda)^2}
\]
\[ \varepsilon = \frac{\zeta}{2m\omega'} \quad (24) \]
\[ \omega' = \sqrt{\frac{k}{m}} \quad (25) \]
\[ \lambda = \frac{\omega}{\omega'}, \quad (26) \]

where \( \zeta \) is the damping ratio, \( \omega \) is the external vibration frequency and the lateral stiffness of the MRE layer is \( k \). The transmissibility \( T \) reaches its peak value when resonance phenomenon appears. In addition, the phase difference between the oscillator and the mounting plate is \( -\frac{\pi}{2} \), in this case, the natural frequency of the multi-layer absorber is the corresponding excitation frequency.

### 5.2 Experimental setup

Experimental tests were implemented to evaluate and characterize the frequency-shift performance of the designed MRE absorber in this section. Fig. 5.1 shows the vibration testing device utilized to evaluate the performance of the absorber, including shaker, vibration platform, accelerometers and relevant PC software. An aluminium sheet was mounted on the two linear bearings, which were supported by the vibration platform. The mounting plate of the MRE absorber was directly fixed on the aluminium sheet to transfer the vibration. The shaker was excited by a harmonic signal generated by computer and amplified by a power amplifier. A DC power supply was used to provide current to the
MRE absorber solenoid such that the amplitude and direction of the current could be controlled thus to change the strength and direction of the electromagnetic field. The lateral acceleration of the mounting plate and the MRE absorber were measured by two accelerometers which were installed on the surface of the two elements. These accelerations were then transferred to the computer via the Data Acquisition (DAQ) board, while the signal collection, recording, and processing systems were developed using the LabVIEW program. With this system, the transmissibility of the MRE absorber was recorded and displayed directly on the computer.

![Image of test setup](image_url)

**Fig.5.** The setup for testing frequency-shift property of the MRE absorber

### 5.3 Test results

In the test, the sweeping signal was set with a frequency range from 5 to 25 Hz to excite the shaker to drive the horizontal vibration platform. The measured signals from accelerometers were sent to a dynamic signal analyser. The frequency-shift performance of the MRE absorber is tested under the electric current from 0 to 2.0 A with a step of 0.2A.
Fig. 5.2 The testing results (a) the magnitude and (b) the phase.

Fig. 5.2 shows the transmissibility of the absorber (the peak of the transmissibility line is the resonance frequency point). Based on that, Table 7 lists the natural frequency with the respect to the currents. Then, the resonance frequency of the absorber was plotted.
and demonstrated in Fig. 5.3. The result illustrates that the magnetic system is able to control the resonance frequency of the absorber (from 6.8 to 20 Hz under the current varying from 0 to 2.0 A). Moreover, the lowest natural frequency can be identified as low as 6.8 Hz, this proven that the laminated structure of the MRE absorber has characteristic of low natural frequency. The relative frequency of the device is nearly 200% in Table 7, which demonstrates a great frequency bandwidth of the absorber.

Table 7 The frequency-current relationship

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>0</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
<th>1.2</th>
<th>1.4</th>
<th>1.6</th>
<th>1.8</th>
<th>2.0</th>
<th>Relative change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural frequency (Hz)</td>
<td>6.8</td>
<td>6.9</td>
<td>7</td>
<td>7.2</td>
<td>8.2</td>
<td>9.8</td>
<td>11.5</td>
<td>14.8</td>
<td>17.5</td>
<td>19</td>
<td>20</td>
<td>194%</td>
</tr>
</tbody>
</table>

Fig. 5. 3 The frequency-current relationship of proposed MRE absorber
5.4 Chapter summary

In this chapter, the frequency-shift property of proposed MRE absorber was tested. The obtained transmissibility demonstrates a good frequency range of laminated structure of the MRE absorber under the electric current from 0 to 2.0A which matched the target frequency range (7~20Hz). In addition, the relative frequency change was nearly 200% and the lowest natural frequency is 6.8 Hz which showed advantages (low natural frequency and board frequency range) of the laminated structure of the MRE absorber.
Chapter 6 Verification of the MRE absorber

To test the effectiveness of the proposed MRE device, the absorber was mounted to the machining robotic arm. There are two specific targets: firstly, to evaluate the performance of the absorber, the chatter occurrence during the milling would be recorded with and without the absorber. Secondly, to test the performance of the absorber in different chatter frequencies, the test was conducted in more than one frequency, the severity of the mode coupling chatters would be compared and thereby the conclusion can be given.

6.1 Experimental setup

Experimental verification of the effectiveness of the MRE absorber was conducted in the robotic milling with an aluminium workpiece. The MRE absorber system was attached to the spindle that is held by an ABB IRB 6660 machining robot. Fig. 6.1 illustrates the entire structure of the system combining the robot, spindle and MRE device. In addition, an ATI six-DOF Force/Torque sensor was included between the robot wrist and spindle mount to collect real-time machining force data for vibration analysis. An adjustable DC power supply was employed to provide power for MRE absorber.
Fig. 6. The structure of the system combining the robot, spindle and MRE device
It should be noted that since the goal of the experiment is to validate the effectiveness of the MRE absorber in a milling process rather than to test the adaptive control of the MRE absorber under a large amount of various cutting conditions, cutting parameters were set as a constant value through the tests. Fig.6.2 demonstrates the 3D model of the milling system with MRE absorber and the cutting direction. Three groups of tests were designed using various cutting conditions including cutting speed, the depth of cut, cutting direction and the current of the MRE absorber, as listed in Table 8. To compare the performance of MRE absorber, four cases were designed in each group to compare the magnitude of mode coupling chatter at the original cutting condition without mounting the MRE absorber and other three tests milling with MRE under the current of 0 A, proper value (1.3 A or 1.55A) and maximum value (2.0 A).

![3D model of the milling system](image)

**Fig.6.2** The 3D model of the spindle.
The test results including cutting force, chatter frequency and power spectral density (PSD) were also recorded in the same table for analysis. Additionally, in order to ensure the consistency of the results, the wavy surface left from the previous cut was cleaned before the next test. In order to analyse the mode coupling chatter, the measured force single (Fig.6.3) was processed in both time and frequency domain using MATLAB. The
severity of the chatter between various experiments is compared based on PSD value of the force signal after Fast Fourier Transform (FFT).

![Graph](image)

**Fig.6. 3 The force signal during robotic milling**

### 6.2 Test Results

The first case in group A as shown in Table 9, was the original robotic milling setup without the MRE absorber. As the FFT results of machining force shown in Fig.6.4 the frequency of the mode coupling chatter was 12.28 Hz, the PSD was 21.1 dB. Fig.6.5 shows the same figure for case 2, which has MRE absorber attached to the spindle with current set to 0A. The PSD of the mode coupling chatter was reduced to 12.7 at 12.84 Hz. Considering the natural frequency of the MRE absorber without electric current is 6.9 Hz, it was proven that the proposed MRE absorber reduced the chatter vibration to a certain...
degree, even the natural frequency of it and the frequency of mode coupling chatter do not match each other strictly.

Table 9 The experimental results of group A to C

<table>
<thead>
<tr>
<th>Index</th>
<th>MREs information</th>
<th>Experimental results</th>
</tr>
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<tr>
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<td>Current of MREs (A)</td>
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<tr>
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<td></td>
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</tr>
<tr>
<td></td>
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<tr>
<td></td>
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<tr>
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<tr>
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<td>6</td>
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<tr>
<td></td>
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<tr>
<td></td>
<td>8</td>
<td>2.0</td>
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<tr>
<td>C</td>
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<tr>
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<td>10</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Fig.6.6 illustrates the chatter occurrence in case 3, according to the cutting parameters in Table 8 and the frequency-current relationship from Fig.4.3, the natural frequency of the absorber changed to 12.5Hz. it can be seen that the mode coupling chatter was reduced
to 2.141 dB at 11.97 Hz. Considering the original PSD of the mode coupling chatter was 21.1 dB, nearly 90% of the chatter energy was absorbed by the proposed device.

Case 4 was designed to test the MRE absorber under the current of 2.0 A during the same milling process. According to the frequency-current relationship from Fig. 6.7, the natural frequency of MRE absorber was increased to over 20 Hz, which does not match the frequency of mode coupling chatter. The result illustrates the mode coupling chatter increase again back to 4.409 dB on PSD, which was considered as a more unstable process compared to case 3. All the tests of group A validate that the MRE absorber works efficiently when its natural frequency matches the natural frequency of the vibrating source.

Fig. 6.4 The chatter occurrence of case 1
Fig. 6. 5 The chatter occurrence of case 2

Fig. 6. 6 The chatter occurrence of case 3
To test the effect of the MRE absorber under different cutting parameters, the depth of the milling and the cutting speed were changed to 3 mm and 20mm/s, respectively in group B. Similar to group A, the result in Table.9 and Fig.6.8 and Fig.6.9 demonstrate the chatter was reduced with MRE absorber under the proper current (1.3A) and the chatter occurred again under the currents (2.0A and 0A) which make the natural frequency do not match the frequency of mode coupling chatter as shown in Fig.6.10 and Fig.6.11. Based on the results of group B, there is still more than 80% of the chatter energy was reduced. the trend of chatter occurrence under different MREs current value is consistent to group A and group B with different cutting parameters.
Fig. 6.8 The chatter occurrence of case 5

Fig. 6.9 The chatter occurrence of case 6
Fig. 6. 10 The chatter occurrence of case 7

Fig. 6. 11 The chatter occurrence of case 8
Then, the cutting conditions was changed largely in group C. Similar as group A and B, the first case in group C was designed to identify the original chatter frequency and magnitude of PSD. Therefore, in group C, the chatter arose at the frequency of 17 to 18Hz under the cutting condition as shown in Table 8 and Table 9. In case 9 (Fig.6.12) and case 10 (Fig.6.13), the PSD of the mode coupling chatter without and with MRE absorber were 37.33 dB and 23.41 dB respectively. So according to the frequency-current relationship in Fig.5.3, the current was changed to 1.55A and thereby the natural frequency was adjusted to 17 Hz in case 11 as shown in Fig.6.14. Then, the entire milling process became stable which means the MRE absorber, under the proper current, worked effectively to absorb the chatter energy in the proposed frequency range. In addition, Fig.6.15 demonstrates that the PSD of chatter increased slightly when the current changed to 2.0. Due to the small strength difference of the magnetic field under the current between 1.55A and 2.0A, the stiffness of the MRE absorber remains nearly the same. Thus, most of the chatter energy was absorbed by the device.
Fig. 6. 12 The chatter occurrence of case 9

Fig. 6. 13 The chatter occurrence of case 10
Fig. 6. 14 The chatter occurrence of case 11

Fig. 6. 15 The chatter occurrence of case 12
6.3 Analysis and discussion

Table 9 listed the PSD value from three groups of test. It can be seen that the MRE absorber reduced the chatter effectively with proper setting of current value. To be more specific, Fig.6.16 summarized the results of those three groups, it illustrates that most of the chatter energy (80% to nearly 100%) was absorbed by the proposed MRE absorber under the proper current. On the other hand, if the natural frequency of the MRE absorber and the chatter frequency differ, the efficiency of MRE absorber decreases which means the MRE absorber works the best when the natural frequency of it matches the chatter frequency.

In addition, it should be pointed out that the effectiveness of MRE absorber was tested under different machining conditions in three groups. According to the results of group A, group B and group C in Fig 6.17, it can be seen that the MRE worked effectively under different cutting parameters.

Moreover, it is important to highlight that the chatter occurred at two different frequencies (around 12Hz in group A and B and around 18Hz in group C). It implies that the effect of proposed device to absorb chatter in designate frequency range which can be used in the machining process under various milling conditions.
Fig. 6. A summary of chatter occurrence of each group
In this chapter, a series of experiments were conducted to test the effectiveness of the proposed MRE device using ABB IRB 6660 robot. Based on the experimental results and analysis in this chapter, it can be summarized as: firstly, the MRE absorber reduced the chatter effectively with proper setting of current value which was selected from the frequency-current relationship from Fig.5.3, if the natural frequency of the MRE absorber and the chatter frequency differ, the effects of MRE absorber decreases. Secondly, the MRE absorber worked effectively to reduce the mode coupling chatter with different chatter frequencies which makes it possible to operate with a large range of machining.

Fig.6. The chatter severity comparison between group A, B and C

### 6.4 Chapter summary
tasks.
Chapter 7 The semi-active control system

Upon the successful development of the proposed MRE absorber which was tested using passive control approach, the semi-active control system is developed and evaluated in terms of its effectiveness.

7.1 Introduction

As aforementioned, the main working principle of the proposed MRE absorber is to match the excitation frequency (the frequency of mode coupling chatter) with the resonance frequency of the MRE absorber through adjusting its stiffness. Therefore, in the developed semi-active system, the real-time frequency signals of the mode coupling chatter is recorded using sensors for the frequency adjustment.

Fig. 7.1 demonstrates the concept of the chatter absorption system using semi-active control scheme. An accelerometer sensor was attached to the robotic arm to measure the chatter information. Then, the measured signals in time domain were delivered to the controller and processed to the frequency-domain by the short time Fourier transform (STFT) method, consequently the dominant frequency $f_{\text{max}}$ was obtained. Next, the control signal would be calculated according to obtained frequency-current relationship.
of the MRE absorber and current-signal relationship of the power amplifier. Finally, the controlled current was input to the MRE absorber to enforce the stiffness adjustment.

Fig. 7.1 The work flow of the semi-active control system

7.2 Experimental setup

Based on the working principle above, Fig. 7.2 demonstrates the work flow of the LabVIEW based controller, STFT is used to convert the vibration information in a time-domain into a frequency-domain format to determine the dominant frequency $f_{\text{max}}$. Then, according to the current-signal relationship of the power amplifier and frequency-current relationship which was generated in the frequency-shift property test, the control signal was output to the power amplifier to adjust the stiffness of the MRE absorber through varying current in real time. Fig. 7.3 shows the setup of the experiment. The rest setup of this test is same as the test in chapter 5 and three groups of tests were designed using various cutting conditions including cutting speed, the depth of cut, cutting direction and the current of the MRE absorber, as listed in Table 10. Group D was designed to compare
the effectiveness of MRE absorber with and without semi-active control. Similar as group D, group E was carried out to verify the results under different cutting conditions. Then, the cutting parameters were changed dramatically to excite the mode coupling chatter with different frequencies in group F to test the effectiveness of the absorber in a large frequency range under semi-active control.

Fig. 7. 2 Flow chart of controller
Fig. 7. The experiment setup for the semi-active control system
Table 10 The experimental design of group D to F

<table>
<thead>
<tr>
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<th>Cutting parameters</th>
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<tr>
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<tr>
<td>D</td>
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<tr>
<td></td>
<td>14</td>
</tr>
<tr>
<td>E</td>
<td>15</td>
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</tr>
<tr>
<td>F</td>
<td>17</td>
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<tr>
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7.3 Results and analysis

Table 11 The experimental results of group D to F

<table>
<thead>
<tr>
<th>Index</th>
<th>Cutting parameters</th>
</tr>
</thead>
<tbody>
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</table>
In group D, as listed in Table 11, the MRE absorber was attached to the spindle, the FFT results of machining force, the frequency of the mode coupling chatter was 12.33 Hz, the PSD was 6.996 dB. Fig.7.4 shows the same figure for case 14, which has the same milling condition, the PSD of the mode coupling chatter was reduced to 2.076 dB at 12.5 Hz with the MRE absorber under semi-active control. Compared to case 13, more than 70% of the chatter energy was absorbed by the MRE absorber in case 14. To test the absorber in a milling process with a larger chatter energy and different milling setups. In group E, the semi-active control system was tested with the different cutting parameters as shown in Table 10. Fig.7.4 shows a good result that more 80% of the chatter severity was suppressed. In addition, the last group was proposed to test the performance of the system at different chatter frequency. A great improvement can be observed from Fig.7.4, nearly all mode coupling chatter was reduced by the MRE absorber and the entire cutting process was extremely smooth. From the results of group D, E and F, it can be concluded that the proposed MRE absorber with semi-active control system reduced the mode coupling chatter arose under different cutting condition effectively. The advantage of this system is not only the remarkable chatter suppression, but also the operation simplicity once the whole system is setup. the system can detect the chatter occurrence and adjust the stiffness of the MRE absorber with desired natural frequency to match the various chatter frequencies automatically, no human intervention is required during the robotic machining process.
Fig. 7. The results of chatter occurrence
7.4 Chapter summary

In this chapter, a semi-active chatter reduction system using MREs was proposed and tested. The whole control system is automated without any human intervention. From the experimental results, the chatter energy was largely absorbed by the semi-active control system indicating the high efficiency of the proposed method and system. In addition, the real-time control system can deal with complex machining application, in which the frequency of the chatter may vary significantly during the cutting process.
Chapter 8 Conclusion and future work

8.1 Conclusion

This study has developed a semi-active chatter reduction method for robotic machining using the MRE technology. A MREs based chatter absorber was designed and tested through a robotic machining process. The experimental results showed that the proposed MRE absorber effectively reduce the chatter with the proper setting of input current. The general contributions of this thesis include: 1) Machining chatter during robotic machining process was reviewed and the mode coupling chatter reduction approach was proposed; 2) A novel MRE structure called multi-layered MREs was introduced to absorb low frequency mode coupling chatter during a robotic machining process; 3) An intelligent control system was established to trace the frequency of the mode coupling chatter and adjust the input current of MRE in a real time; 4) The experimental results showed a great improvement of the severity of mode coupling chatter indicating that the proposed MRE structure is an effective chatter absorber in robotic machining processes.

8.2 Future works

The present research has made progress in successfully applying a semi-active chatter
reduction method for robotic machining using MREs. However, further study about chatter occurrence during robotic machining process and optimization of the MRE absorber are desired in the future work. The recommendations were summarized below according to the present study.

1) Criterion to evaluate the performance of the proposed MRE absorber is required to be established. In this experiment, only the chatter severity which is based on FFT was used as an evidence to evaluate the performance of the proposed absorber. In future, other aspect, such as the quality of the milled surface, will be investigated to evaluate the effectiveness of the chatter absorption.

2) A chatter map for the entire robot work envelope is desired. The operation frequency range of proposed MRE absorber is analysed from the mechanism of mode coupling chatter and current literature. However, there is still a lack of information of the chatter occurrence for the entire robot work envelope to confirm the operation frequency range. Thus, a chatter map based on the stiffness of the industrial robot, and the cutting setup including depth and width of cut, spindle travel speed, spindle rotating frequency, etc. is helpful to improve the performance of the MRE absorber.
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Appendix A
Publications

- Paper published:


- Paper under review: