CHAPTER 1

Introduction

1.1 Motivation

Good quality and low cost of a product are always required by all customers. Those two factors of a product are mainly determined by the production machines. Good quality of a product is assured by high precision of the machine tools. Low price of a product can be achieved by increased productivity through high manufacturing speed together with minimized auxiliary process times and process stability. Therefore, high precision and speed are two demands for modern machine tools to provide products that satisfy customers [76].

Byrne presented curves in [8], as shown in Figure 1.1, tracing the development in manufacturing capability in terms of achievable machining accuracy during the last 60 years. Ultra-precision machine tools under computer control can position the tool relative to the workpiece to a resolution and positioning accuracy in the order of 1nm. For "precision machining", the accuracy could now achieve $10nm$ with the help of accurate machine elements. In "normal machining", e.g. CNC turning and milling machines, accuracies of 10 to 100 μm can be achieved. Besides knowing those concrete values of accuracies that machine tools can achieve, the tendencies to higher accuracies of machine tools also catch the eyes.

Precision manufacturing relies, to a significant extent, on the quality and accuracy of a machine tool. One important factor which affects the accuracy of a machined component is the error caused by the vibration of the machine tool. The commonly approved solution is to use rigid components to improve the accuracy of the machine system.

High Speed Machining (HSM) is also a mainstream trend. Origin of interest in HSM was the work done by Salomon in 1931 [20]. His definition of HSM is based on chip removal temperature reduction with high cutting speed (5-10 times higher than in conventional machining) in a machining process. Though later researchers have unfortunately not been able

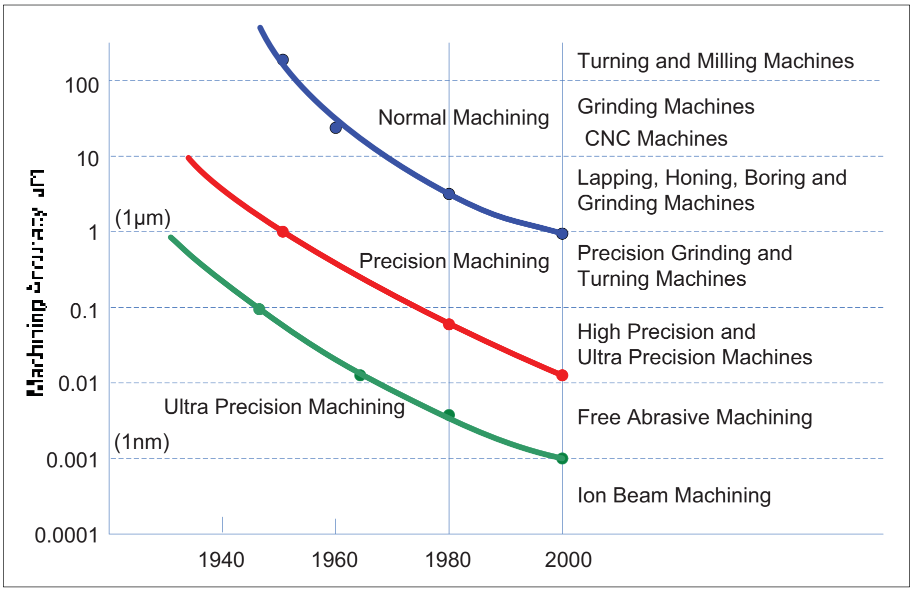

Figure 1.1: Development of achievable "Machining" accuracy over the last sixty years [8]

to verify this theory to its full extent, they also confirm that there is a relative decrease of the temperature at the cutting edge that starts at certain cutting speeds for different materials [20]. Table 1.1 [1] gives an example of some cutting speeds [3] for general knowledge of normal and high speed in cutting process. The cutting speed is dependent on the character of the workpiece material. For instance, for cutting gray cast iron, figures greater than 6m/s might be high-speed machining, whereas for softer aluminum alloys, 50 m/s is high-speed.

To perform HSM applications it is necessary to use light, but rigid machine tool to achieve high speed and minimize problematic vibrations. Light and rigid machine tool assures high acceleration, high eigenfrequency of the system, therefor high speed. Rigid machine tool assures no low eigenfrequency in the axis, therefore high accuracy.

Therefore, both precision and high speed machining require rigid machine system. However primarily due to space, weight, and power constraints, this is not always possible. Elasticity is unavoidable in some mechanical systems such as: high speed pick and place robots, coordinate measurement machines, hard drive testing machines, gantry cranes and so on. In machine tools, due to the power trains elements such as belts, spindles, gears and so on, the rigidity of the machine tool is also limited. All those kinds of mechanisms suffer from vibration related problems undergoing point-to-point, trajectory following, and other common motion tasks. The effective use of such systems can only be achieved when such vibrations can be properly handled.

Thus the demands of high quality and low cost of product motivate researchers to find a

[1]WC:Tungsten Carbide; PCD: polycrystalline diamond; CBN:cubic boron nitride; sia.: sialon; cer.: ceramic; +:more than

Work material	Solid tool - end mill, drill WC, coated WC, PCD, ceramic		Indexable tool - shell and face mill WC, ceramic, sialon, CBN, PCD	
	Typical velocity (m/s)	High Speed (m/s)	Typical velocity (m/s)	High Speed (m/s)
aluminum	5+ (WC,PCD)	50+ (WC,PCD)	10+	60+ (WC,PCD)
cast iron				
soft	2.5	6	6	20(sia.,cer.)
ductile	1.75	4	4	15(cer.)
steel				
free machining steel	1.75	6	6	10
alloy	1.25	4	3.5	6
stainless	1.75	2.5	2.5	4.5
hardness RC65	0.4	2	0.5(WC) 1.5(CBN,cer.)	0.75(WC) 3(CBN,cer.)
titanium	0.625	1	0.75	1.5
superalloy(Iconel)	0.75	1.25	1.3(WC) 3.5(sia.)	6(sia.,cer.)

Table 1.1: Example of some cutting speeds [3]

way to get rid of vibration for machine tools, or at least reduce them to an insignificant degree, especially those have inherent structure flexibility, so that the aims of high accuracy and high speed can be achieved.

1.2 Problem Description and Aims

The problem of reducing vibrations is a complex one that can be approached in many ways. Kozak [30] presents a simple manner to categorize those approaches by looking at a flexible dynamic system under control as shown in Figure 1.2, which can be found in every control text book.

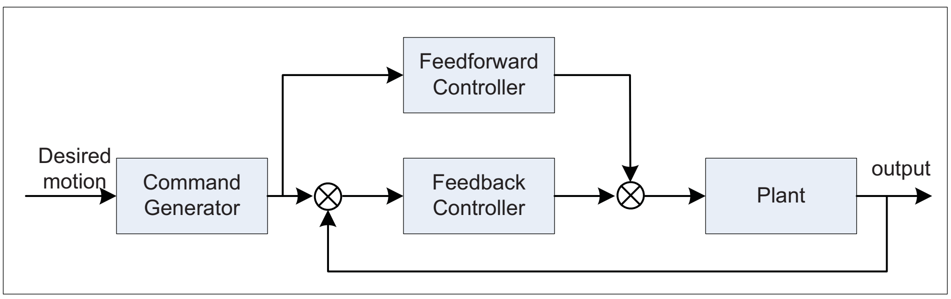

Figure 1.2: Block diagram of a typical closed loop control

There are four primary blocks in the above system. Researchers have made different efforts to reduce system vibration through those four blocks. They are the

1. Plant,
2. Command Generator,
3. Feedback Controller,
4. and the Feedforward Controller.

The Plant Block

The plant is normally the first concern for a researcher to think about when vibration reduction task is presented. The elastic structure of the plant is a source of vibrations. Therefore, making the plant system more rigid and/or adding damper to the plant are two main approaches.

The increasing of the rigidity sometimes comes with the increase of the inertia or mass of the components of the plant. This results in a reduced payload, worse dynamic behavior and increased cost. There are usually many trade-offs that must be considered in order to produce a physically and economically viable mechanism. Moreover, the elasticity that comes from power trains in the mechanical plant restricts the level of rigidity that can be reached.

Adding damper to the plant is usually done by adding damping material to a mechanism. However, modifying a pre-existing plant can be costly and difficult, and making modifications to reduce vibration can potentially change the performance of other aspects of the mechanism, e.g. the stiffness.

In this work, the plant is not targeted for eliminating vibrations, because the aimed solution is to reduce the vibration for any plant. But the knowledge of parameters of the plant is as important as getting rid of vibrations itself. Therefore, parameter identification is the first step. Two main domains of identification exist: frequency domain and time domain identification [1, 19, 36, 42]. The time domain identification is the classical approach to system identification. In the frequency domain identification, the frequency response of the system is used to estimate the plant parameters. However, the existing methods of parameters identification are either too complicated or not suitable for high order systems. As the characteristic parameters of the plant have to be known for the final solution, the first aim of this work is parameter identification for machine tool system of any order.

Aim 1: Identifying parameters of the plant for any order of the system.

The Command Generator Block

System vibrations come in mainly two forms. First form of vibrations are transient and die out after a period of time. The second form of vibrations are steady state vibrations, which are constant in magnitude and frequency, and do not die out. This second form of vibrations are generally caused by some periodic excitation. In general, vibrations can come in any combination of these two types. Vibrations can be caused by many different sources. Command generator is one of the sources. Typical example of command that brings the transient vibration is a step input.

A lot of efforts are dedicated to create or modify commands that cause the system response to satisfy desired transient/steady state performance characteristics [46, 47, 56, 57]. There is at least one distinct advantage of using the command generation approach over the other approaches: systems that suffer from troublesome dynamic behavior, such as vibrations, can be retrofitted to take advantage of command generation schemes at low cost and with generally no modifications needing to be made to the mechanical system and controller.

Limiting jerk, the derivative of acceleration, is now commonly applied to command generator of motion control [32, 33, 37, 55]. It can effectively reduce transient vibrations though not completely. The resulted s-curve of velocity profile, however, has no effect in getting rid of resonance vibration.

Some researchers turn to inverse dynamics [48]. When the system model is inverted, an input can be found by specifying the output. Unfortunately, the selected output trajectory does not always lead to an input, and it can be difficult to find the optimal trajectory. All kinds of time optimal trajectory, though also jerk limited, try to get a time optimal aim, but in the end the vibrations make the plant system a longer time to settle down, not to mention the bad accuracy. This is because the trajectory may contain the eigenfrequency of the plant system, thus inducing the resonance vibration. This initiates the idea of designing the trajectory that is jerk-limited, has no eigenfrequency of the mechanism, and is semi time optimal. This is the second aim that this work will achieve.