Design and Development of TDOF System with PD Controller for Turning Operation

Shanmugasundaram B[1,*] and Suresh Prabhu P[2]

[1]Research Scholar, Mechanical Engineering, Karpagam University
Coimbatore, India

[2]Director - Research, Karpagam University
Coimbatore, India

*Corresponding author's email: bshan_india [AT] rediffmail.com

---

ABSTRACT--- ***Active vibration control technique is very important for increasing life of various components and structures; this results in lower fatigue, better accuracy, and low maintenance. In the turning operation, chatter or vibration is a frequent problem, which affects the result of the machining and in particular the surface finish. Tool life is also influenced by vibration. The objective is to design and develop a two degree of freedom (TDOF) system with Proportional-Derivative (PD) controller for turning operation to reduce regenerative chatter with the aim of improving productivity, quality of surface finish, tool life and reducing environmental noise caused by chatter. A system consisting of a workpiece subsystem (workpiece with end supports represented by mass, stiffness, damping coefficient) and a cutting tool subsystem (tool with its supports represented by mass, stiffness and the damping coefficient). A Mechatronic system has been proposed and developed for reducing tool vibration in lathe tool during machining. It consists of electrical and mechanical components; the PD controller is designed to control the chatter that occurs between the tool and the workpiece. A Piezo actuator and sensor was embedded into the tool holder. The PD controller is used to send a feedback to the actuator. The PD controller is to be designed so that it suppresses the settling time and dampens the tool. The effective cutting stiffness and effective cutting damping are modeled as a spring and damper during machining. The original response of the system is modeled using transfer function method. Their output responses were obtained using Mat lab software.***

Keywords--- Self-Excited Vibration, Chatter, Control System, Transfer Function

---

1. INTRODUCTION

Developments in machine tools during the past few decades have raised a growing number of vibration problems. In all cutting operations like turning, boring, milling, etc., vibrations are induced due to the deformation of the workpiece. This implies several disadvantages. Many different solutions to minimize the problem have been developed but the fundamental problem is still there.

The system investigates the stability of manufacturing with slender tools and improvement of stability by optimal tool parameters using Genetic Algorithm. The objective is to suppress the chatter vibration and bring better stability during cutting process by designing a damped tool holder for existing machine tools. It is noted that the higher negative magnitude of stability boundary corresponds to best stability margin [1]. The system investigates an active vibration control of a beam using virtual instrumentation software. A single degree of freedom spring, mass damper system is actively controlled using piezoelectric elements. The optimal control is arrived at all frequencies using virtual instrumentation software. The intelligent optimal control with varying parameters is found to be more effective than a control with a fixed parameter control system [2]. The model provides a systematic approach for identifying optimum surface roughness performance in end-milling operations. The purpose of their research was to demonstrate a systematic procedure of using Taguchi parameter design in process control of individual milling machines and also to demonstrate a use of the Taguchi parameter design in order to identify the optimum surface roughness performance with a particular combination of cutting parameters in an end-milling operation [3].

Signal parameters characterizing Acoustic Emission (AE) detected during metal cutting have been theoretically correlated in a simple manner, to the work material properties, cutting conditions, and tool geometry [4]. The vibration of a tool-workpiece system in a straight turning process is induced by random disturbances and their effect on a product surface. It is noticed that for large enough level of noise, the tool and a workpiece start to vibrate due to random forcing [8] [9] [10]. The system utilized vibration signals to set up a multiple regression model that was capable of predicting the in process surface roughness of a machined workpiece using a turning operation [11].

2. SELF-EXCITED VIBRATION

Self-excited vibration occurs when a steady input of energy is in some way modulated into vibration. As seen in Figure. 1, the amplitude of this type of vibration increases with time. In metal cutting, chatter is a self-excited vibration that occurs between a tool and a workpiece. Chatter can be detrimental to the surface finish, as well as the tool life. The basic cause of chatter is the dynamic interaction of the cutting process and the machine tool structure.

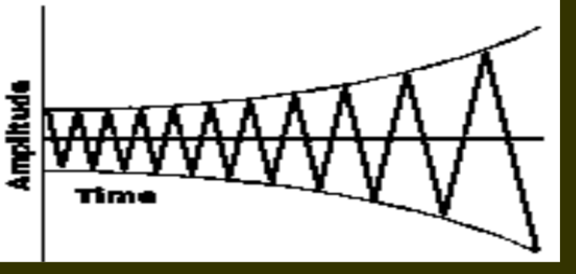

Figure 1: Self-Excited Vibration

3. CONTROL SYSTEM

The dynamics of the control object is the largest source of difficulty in implementing control. So, most of the techniques devised to design controllers deal with dynamics and controller tuning. Tuning refers to the process of setting parameter values so as to achieve satisfactory performance. In the digital control world, a controller is a section of software that implements an algorithm that takes the measurement of the control object's output as its input and produces as its output the actuation signal. Effects of each of controllers K_P and K_D on a closed loop system are summarized in the Table 1.

Table 1: Effects of Controller

CL Response	Rise Time	Overshoot	Settling Time
K_P	Decrease	Increase	Small Change
K_D	Small Change	Decrease	Decrease

4. DYNAMIC CUTTING PROCESS

Active vibration control technique is very important for increasing life of various components and structures; this results in lower fatigue, better accuracy, and low maintenance. A Piezo actuator and sensor was embedded into the tool holder. The PD controller is used to send a feedback to the actuator. The PD controller is to be designed so that it suppresses the settling time and dampens the tool. The active method of controlling tool setup is shown in Figure. 2.

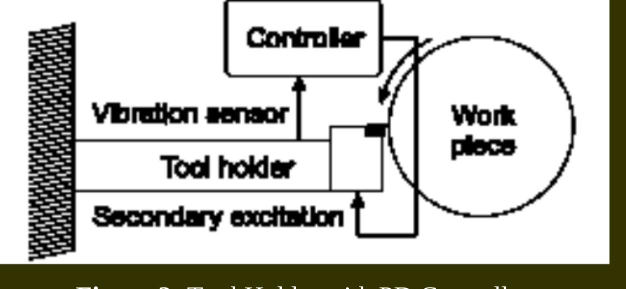

Figure 2: Tool Holder with PD Controller

5. MATHEMATICAL MODEL OF CUTTING SYSTEM

The expression for dynamic cutting force under regenerative chatter condition is given by the equation,

$$dp = K_c(X_t – X_w) + C_c[(dX_t/dt) – (dX_w/dt)]$$

The dynamic cutting force can be modeled, as spring representing effective cutting stiffness and damper representing effective cutting damping. As the value of effective cutting stiffness increases the stability increases and conversely if the value of effective cutting damping decreases then stability increases and settling time decreases. The two-degree of freedom system of workpiece – tool is shown in Figure. 3.

Considering the system displacements, $X_W(t)$ and $X_t(t)$ from the static equilibrium position are positive in the downward direction, the equations of motion of the system is given by,

$$[M_w(d^2X_w/dt^2)] + [(C_w + C_c)(dX_w/dt)] + [(K_w + K_c)X_w] - [C_c(dX_t/dt)] - [K_cX_t] = 0$$

$$[M_t(d^2X_t/dt^2)] + [(C_t + C_c)(dX_t/dt)] + [(K_t + K_c)X_t] - [C_c(dX_w/dt)] - [K_cX_w] = 0$$

The active control of the cutting tool is obtained by introducing a feedback from the output to the cutting tool by means of PD controller. The actuation force for the cutting tool is given by the feedback signal. The two-degree of freedom system with PD controller is as shown in Figure. 4.

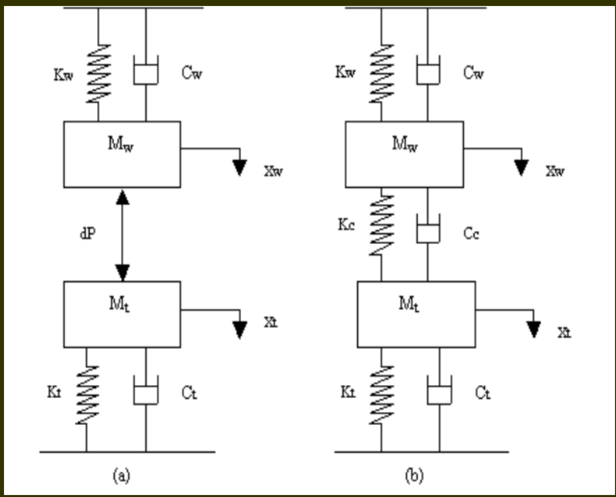

Figure 3: Mathematical Model of the Cutting System

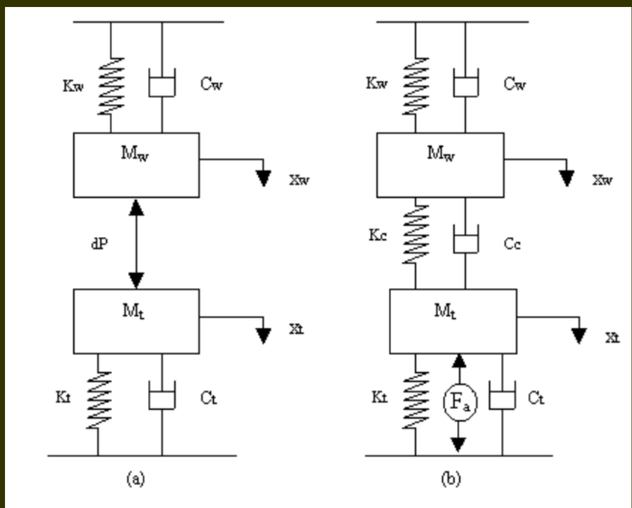

Figure 4: Mathematical Model of the Active Control Cutting System

The equation of motion of the system with controller is given by,

$$[M_w(d^2X_w/dt^2)] + [(C_w + C_c)(dX_w/dt)] + [(K_w + K_c)X_w] - [C_c(dX_t/dt)] - [K_cX_t] = 0$$

$$[M_t(d^2X_t/dt^2)] + [(C_t + C_c)(dX_t/dt)] + [(K_t + K_c)X_t] - [C_c(dX_w/dt)] - [K_cX_w] = F_a$$

6. MODELING USING TRANSFER FUNCTION

Transfer Function of a control system is defined as the ratio of Laplace Transform of the output variable to the Laplace Transform of the input variable assuming all initial conditions as zero. Assuming all initial conditions are zero, taking Laplace Transform of the above equations can express the dynamic equations above in the form of transfer functions. Considering F_a as input, the transfer function G(s) is given by,

G(s) = nump/denp

where,

nump=[- (mw*ct)   - (mw*kt + cw*ct)   - (cw*kt + kw*ct)   - (kw + kt)] denp=[(mw*mt) (mw*(ct + cc) + (cw + cc)*mt) (mw*(kc + kt) + (cw*ct) + (cw*cc) + (cc*ct) + mt*(kw + kc)) (cw*kc + cw*kt + cc*kt + cc*kw + ct*kw + ct*kc) (kw*kt + kw*kc + kc*kt)]

The effect of cutting tool damping on system stability and values are tabulated as shown in Table 2. A generalized program is written by transfer function method using Mat lab. By substituting the tabulated values in the Mat lab program, the step response obtained is shown in Figures. 5 to 12.

Table 2: Cutting Tool Parameters

S. No.	ξ_t	C_c	K_t	Values of Other Parameters
1	0.1754	- 0.5328	5500	M_w = 1.604, K_w = 563, ξ_w = 0.0647, M_t = 2.48, K_c = 1500
2	0.2254	- 0.6481	5000	
3	0.2754	- 0.7864	5000	
4	0.3254	- 0.9247	5000	

7. STEP RESPONSE FOR THE EFFECT OF CUTTING TOOL DAMPING ON SYSTEM STABILITY (WITHOUT CONTROLLER)

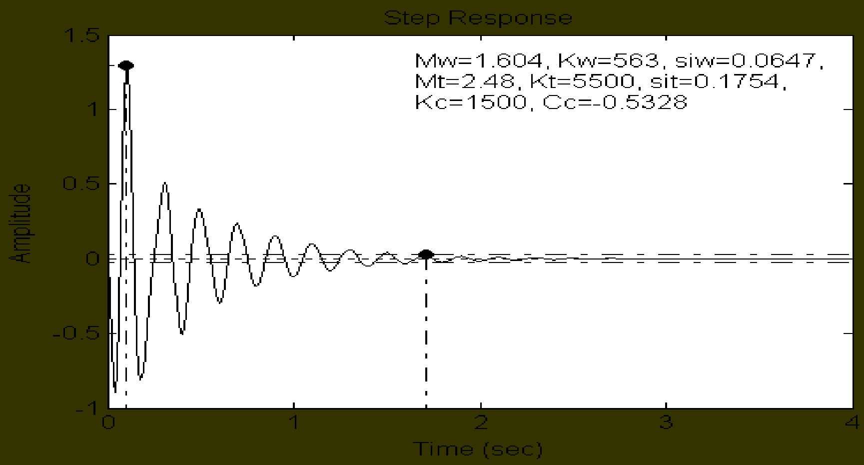

Figure 5

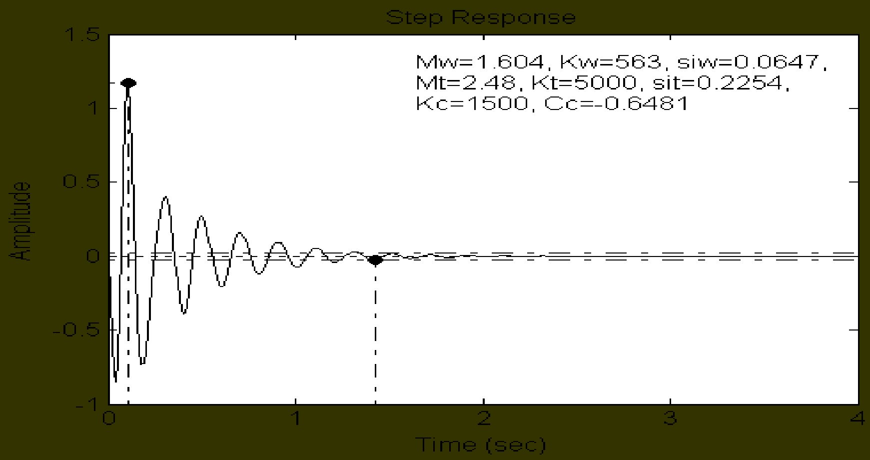

Figure 6

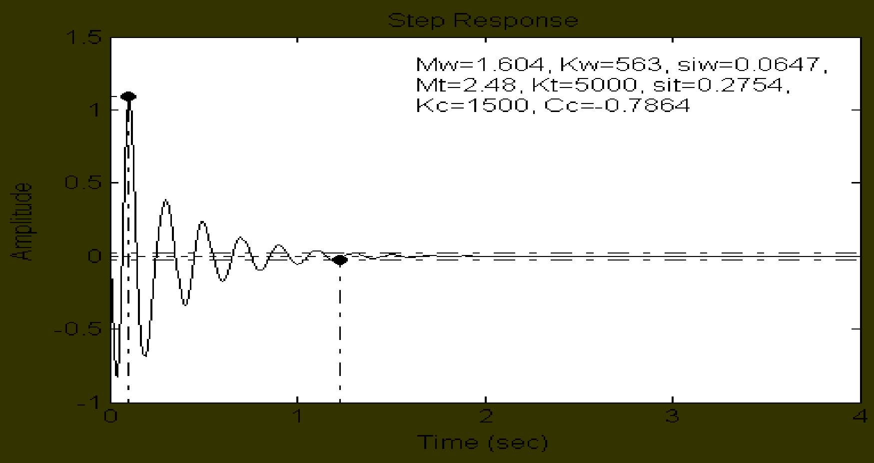

Figure 7

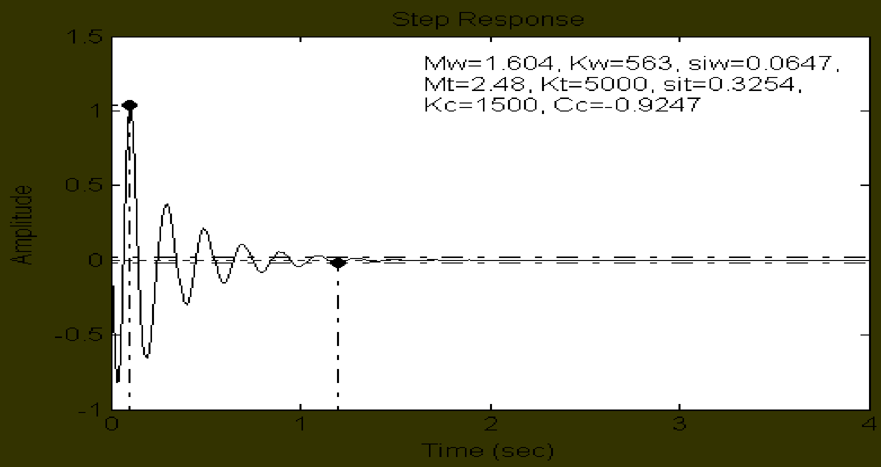

Figure 8

8. STEP RESPONSE FOR THE EFFECT OF CUTTING TOOL DAMPING ON SYSTEM STABILITY (WITH PD CONTROLLER)

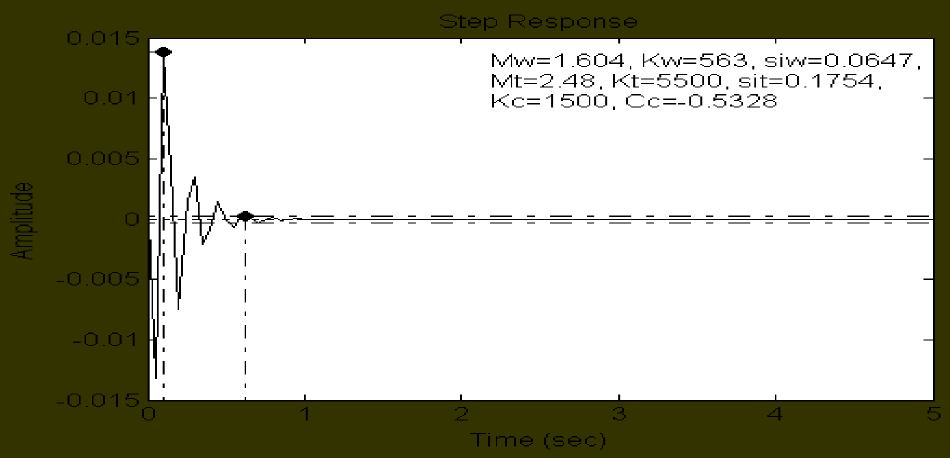

Figure 9

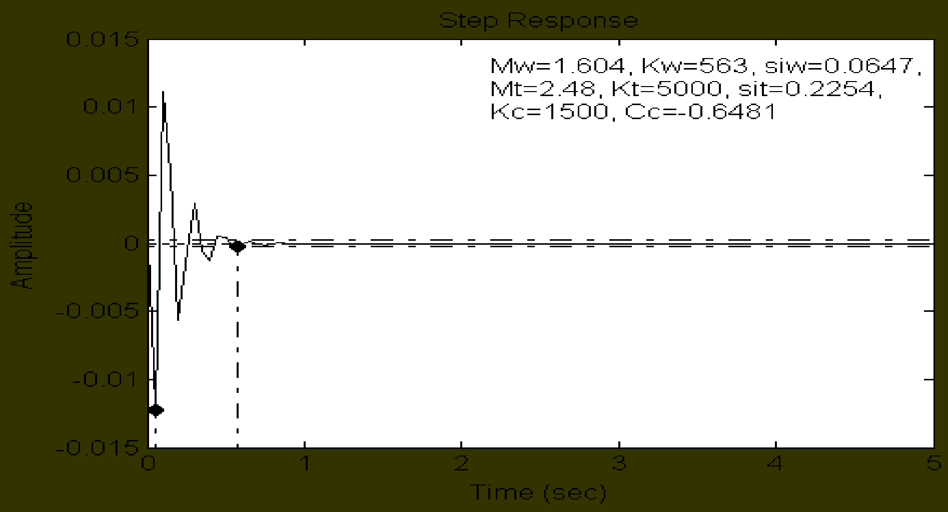

Figure 10

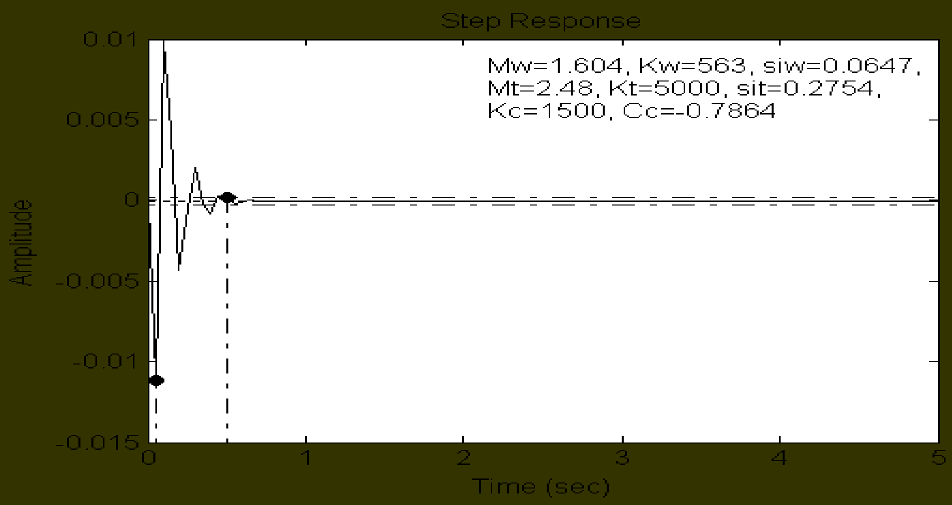

Figure 11

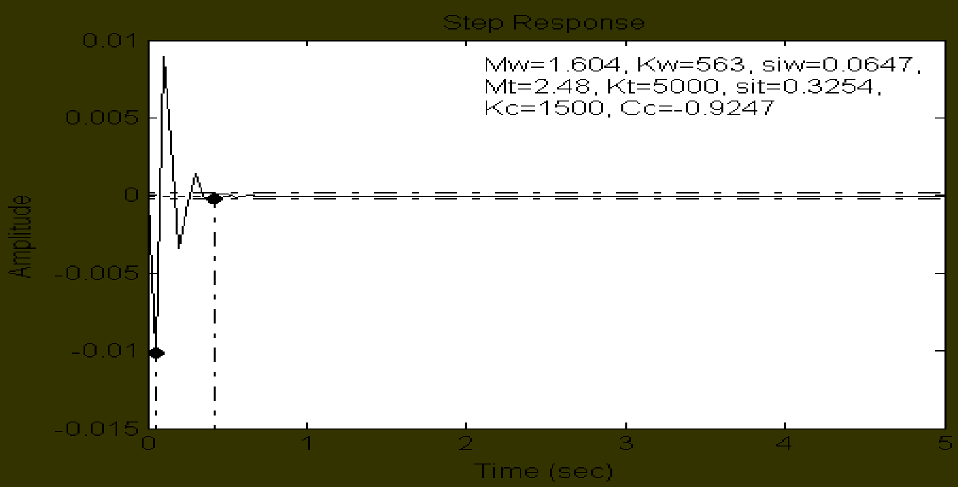

Figure 12

9. CONCLUSIONS

The dynamic analysis of workpiece – tool system with PD controller for turning operation has been performed. The cutting tool parameters are analyzed for various cutting tool damping. The effect of damping of cutting tool on system stability has been analyzed. The generalized program is written by transfer function method using Mat lab software. The analysis is performed with PD controller. The values of settling time and peak amplitude for different values of cutting tool stiffness, effective cutting damping and damping of cutting tool (with and without PD controller) are shown in Table 3.

Table 3: Step Response Values

Figure	Without Controller		With PD Controller	
	Settling Time (sec)	Peak Amplitude (Microns)	Settling Time (sec)	Peak Amplitude (Microns)
5 & 9	1.71	1.29	0.62	0.01
6 & 10	1.42	1.17	0.57	- 0.01
7 & 11	1.23	1.09	0.50	- 0.01
8 & 12	1.20	1.03	0.42	- 0.01

It is observed that when the damping of cutting tool is increased, settling time and peak amplitude is decreased proportionately. Also, it is observed that settling time and peak amplitude is considerably decreased when PD controller is used than that of without controller.

10. REFERENCES

[1] Alwarsamy T, Balasubramanian R, Raja Kumar K, Sankarasubramanian B, "Improvement of Stability by Optimal Parameters using Genetic Algorithm", Advances in Vibration Engineering, vol. 2. no. 4, pp. 388-404, 2003.

[2] Harpreet Singh, Singh S. P, Agarwal V. P, "Active Vibration Control of a Beam using Virtual Instrumentation Software", International Conference on Smart Materials, Structures and Systems, India, pp. 443–448, 1999.

[3] John L. Yang, Joseph C. Chen, "A Systematic Approach for Identifying Optimum Surface Roughness Performance in End-Milling Operations", Journal of Industrial Technology, vol. 17, no. 2, 2001.

[4] Keraita J. N, Oyango H. J, Misoi G. K., "Lathe Stability Charts via Acoustic Emission Monitoring", African Journal of Science and Technology, 2001.

[5] Lipski J, Litak G, Rusinek R, Szabelski K, Teter A, Warminski J, Zaleski K, "Surface Quality of a Work Material Influence on Vibrations in a Cutting Process", Journal of Sound and Vibration, 2000.

[6] Luke Huang, Joseph C. Chen, "A Multiple Regression Model to Predict In-Process Surface Roughness in Turning Operation Via Accelerometer", Journal of Industrial Technology, vol. 17, no. 2, 2001.

[7] Karkosch H. J, Preumont A, "Recent Advances in Active Damping and Vibration Control", Actuator 2002: 8th International Conference on New Actuators, Germany, pp. 248–253, 2002.

[8] Mauri E, Kato S, Hashimoto M, "The Mechanism of Chatter Vibration in a Spindle-Workpiece System: Part 1– Properties of Self-Excited Chatter Vibration in Spindle-Workpiece System", Journal of Engineering for Industry, vol. 110, pp. 236-241, 1988.

[9] Mauri E, Kato S, Hashimoto M, "The Mechanism of Chatter Vibration in a Spindle-Workpiece System: Part 2- Characteristics of Dynamic Cutting Force and Vibration Energy", Journal of Engineering for Industry, vol. 110, pp. 242-247, 1988.

[10] Mauri E, Kato S, Hashimoto M, "The Mechanism of Chatter Vibration in a Spindle-Workpiece System: Part 3- Analytical Considerations", Journal of Engineering for Industry, vol. 110, pp. 248-253, 1988.

[11] Lago T. L, Lars Hakansson, "Performance of a Chatter Control System for Turning and Boring Applications", 4th GRACM Congress on Computational Mechanics, 2002.

[12] Andren L, Hakansson L, Claesson I, "Active Vibration Control of Boring Bar Vibrations", Blekinge Institute of Technology, Sweden, pp. 139–196, 2004.

[13] Tobias S. A, Machine Tool Vibration, John Wiley, New York, 1965.

[14] Willis M. J, Proportional–Integral-Derivative Control, University of Newcastle, 1999.