Implementation of Cognitive Chips in Machining Error Attenuation

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Abstract: Machining is a complex process that requires a high degree of precision with tight geometrical tolerance and surface finish. Those are confronted by the existence of vibration in the turning machine tool. Overcoming a micro level vibration of a cutting tool using smart materials can save old machines and enhance development in designing new generations of machine tools. Using smart materials to resolve such problems represent one of the challenges in this area. As a continuation from previous work for the transient solution for a tool tip displacement using pulse width modulation (PWM) technique that was implemented for smart material activation to compensate for radial disturbing cutting forces. A Fuzzy algorithm is developed to control the actuator voltage level to improve dynamic performance. Such technique together with the finite element method as dynamic model proved a great successfulness. To implement such results in real life industrial system we may use chips that mimic human brain as developed recently by IBM which is intelligent to learn through incidents, find patterns, generate ideas and understand the outcomes to reduce tool vibration error.

1 INTRODUCTION

Demand for higher productivity in automated manufacturing brought to the attention the control of machine tool dynamics for a better machining accuracy. Economical and ecological factors encouraged the old conventional machines to continue in service by overcoming the tool vibration problem. Various factors might affect machining process (Frankpitt, 1995), some of them are non-measurable and others might change in real-time. However, the wider use and the availability of cost effective microcontrollers encouraged the implementation of intelligent control schemes to overcome such time dependent problems. The tiny unfavorable relative motion between the cutting tool and the working piece that associated with high excitation forces encouraged the use of smart material actuators to counteract such motion errors (Dold, 1996). Rigid fixture is a good choice for minimizing displacements of cutting tools from its nominal position during machining. Unfortunately such a luxury is not available in all applications. The reconfigurable manufacturing era prefer fixtures consumes less space with minimum weight (Gopalakrishnan et al., 2002; Moon and Kota 2002).

Previous dynamic modeling of smart toolpost (Eshete, 1996) is based on linear piezo-ceramic actuator. Derived models are either believed as lumped single rigid mass for tool carrier, tool bit and piezo-actuator or obtained from the most dominant mode of system vibration as an effective mass, stiffness and damping coefficients. Such models then adopted for designing an adaptive controller using the measured current and applied voltage as control signals to the actuator. Based on similar principles (Zhang et al., 1995) derived a mathematical model for such smart tool post using the PMN. A control system, and real time microprocessor implementation was examined (Dold, 1996) and no details are given for the design and selection of actuator, tool holder, and tool bit stiffness, and, actuator switching. In case of future geometrical changes, the validity of using lumped masses in system modeling is questionable. Nature and type of signals controlling smart material and how they affect toolpost dynamic response is suffering from information shortage. Recently (Hurtado, 2001) developed an engineering approach in determining optimum dimension based on stiffness of machining fixtures. However, geometrical dynamic design for smart toolpost requests special attention.

This work presents Fuzzy algorithm using a finite element model (FEM) (Zienkiewicz and Taylor, 2001)

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for flexible smart tool post incorporating PZT actuator, tool holder, holder fixture, and tool bit. The main dimensional variation in the work-piece that might be caused by tool radial motion is emphasized. This endeavor involves a development of a finite element model to evaluate lumped mass modeling approach, toolpost stiffness ratios and to work on a Fuzzy control algorithm for actuator input voltage. A special attention is given for the model to be a robust for large variations in design parameters. Such finite element model offers a methodology for future development in smart toolpost design for limited space and weight environments.

2 BUILDING THE FEM MODEL AND GOVERNING EQUATIONS

In this work Lead Zirconate Titanate (PZT), is employed as intelligent material for smart toolpost actuator. This encouraged by a well-developed theoretical analysis for this material. Also it is the most common used piezoelectric materials. Toolpost model incorporates actuator, tool carrier (holder), supporting diaphragm and tool bit as a spring buffer between tool carrier and the net actuating force at tool tip as shown in Figure 1.

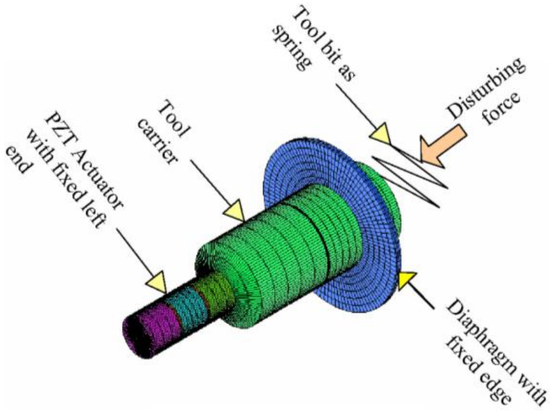

Figure 1: Toolpost Model.

The model incorporated conventional stacked PZT actuator contain polarized ferroelectric ceramic in the direction of actuation, adhesive, supporting structure, and electrodes wired electrically as shown in Figure 2.

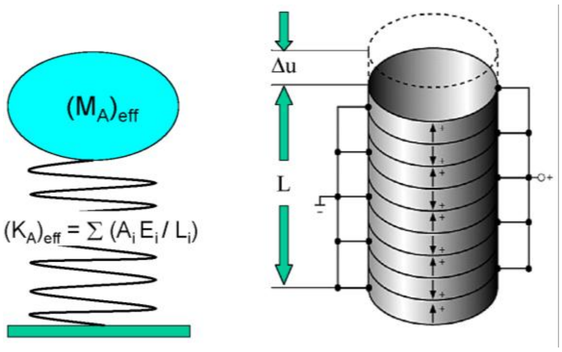

Figure 2: PZT Stacked Actuator.

Finite element modeling of the PZT actuator and toolpost are achieved, through the general constitutive equations of linear piezoelectricity and by equations of mechanical and electrical balance the details are given in (Piefort, 2001 and Abboud et al., 1998). Structural boundary conditions are assigned in Figure 1, where zero displacements is applied at the actuator left end and fixed condition at the outer diaphragm edge. Specifying the applied voltage at actuator electrodes using PWM which accompanying the actuator radial force at tool tip finalizes problem description.

3 TOOLPOST FORCE GENERATION VERSUS DISPLACEMENT

Effectiveness of tool error attenuation depends on PZT actuator capabilities in resisting tool axial force within the limited range of motion. To build such information a force versus displacement curve is developed for the toolpost under investigation in Figure 1. Figure 3 shows the force-displacement characteristics at different values of tool tip (tool bit) to actuator stiffness ratio (KT/KA, coupling spring in Figure 1 at force application). The plotted curves in Figure 3 are emphasizing the importance of increasing (KT/KA) and (KC/KA) ratios. Also the worth of reducing structural support stiffness (diaphragm) in the direction of the PZT activation to increases the actuation movement toward error reduction. As a first guessing a suitable actuator can be selected according to the disturbing force level and the information offered by the force-displacement calculations. A special consideration should be given to the dynamic effects during machining. The smart material data and, the investigated toolpost dimensions are given in Table 1 for both static and dynamic calculations.

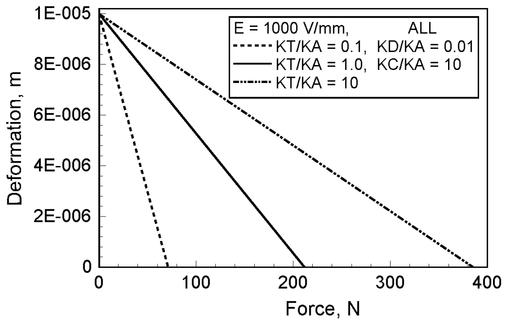

Figure 3: Smart toolpost force generation versus displacement for different tool tip to actuator stiffness ratios.

Table 1: Toolpost dimension and material.

Item	Value	Units
Cylindrical PZT-8 Stack		
PZT Thickness	0.09e-03	m
Electrode Thickness (Nickel)	0.03e-03	m
Structural support (Stainless)	0.03e-03	m
Adhesive Thickness	10.0e-06	m
Number of layers	500	
Effective Radius	5.0e-3	m
Steel Cylindrical Tool Carrier (holder)		
Radius	10.0e-3	m
Length	55.0e--3	m
Steel Tool Bit Effective Length		
Assumed Effective Length	20.0e-3	m
Steel Diaphragm		
Thickness	0.5e-3	m
Outside Radius	20.0e-3	m

4 FUZZY ALGORITHM FOR VOLTAGE ACTIVATION

Obtained results in (Rashid, 2004) prove significant deviation of lumped mass modeling from the finite element solution especially in the range of low (KD/KA) and high (KC/KA) where the PZT actuation is maximum as pointed out in Figure 3. Therefore the finite element method is the reliable tool of assessing switching methodology and system damping in smart toolpost during error reduction. Transient solution for tool displacement in time domain for system shown in Figure 1 is given in (Rashid, 2004 and Rashid, 2011). Smart toolpost configuration and associated data are given in table 1.

4.1 PWM Modeling

Tool tip position error is reduced by appropriate voltage activation to the smart material. An economical way for smart material activation in vibration attenuation is by using Pulse Width Modulation (PWM). It is a common technique available on microcontroller units (MCU) to govern the time average of power input to actuators. The time dependent motion accompanying the tool vibration attenuation using the PWM for the smart material activation is the next step.

The smart material voltage activation is either triggered by a piezo stack with force sensing layer or by using a suitable type of displacement sensor. In both methods sensing location should reflect cutting tool position error correctly. Switching circuits (Luan and Lee, 1998) are not investigated in this work. But the level of the required activation voltage for the piezo stack is carefully discussed.

Representation of switching voltage as a series of PWM cycles is based on the peak cutting force level at the measured frequency (ω_f), where, the initial peak voltage is estimated accordingly from Fig. 3. A complete period of force cycle (T_f) is then divided into number of duty cycles (N_{PWM}). At any of these divisions, the time duration of the PWM high DC-voltage is calculated according to the obtained voltage factor from the fuzzy algorithm discussed next. A time delay in voltage activation can be incorporated as a function of force period. Two switching are associated with each PWM cycle segment, therefore switching rate is $2N_{PWM}\omega_f$. Effects of switching voltage input, forcing frequency ω_f, and, damping level upon toolpost time response are parameters to be discussed in smart toolpost transient solution. A harmonic force waveform is assumed for all presented results.

4.2 The Fuzzy Algorithm

For such a nonlinear problem a fuzzy modeling algorithm (Passino, 1998) is launched to extract rules that relate actuator voltage factor (a multiplication factor to the estimated voltage from Figure 3) to the toolpost position error and the time rate of change of error as shown in Figure 4. Five linguistic values are used, namely L=‘‘Low’’, M/L=‘‘Medium to low’’, M=‘‘Medium’’, M/H=‘‘Medium to High’’ and H=‘‘High’’.

The algorithm considers each input and output variables to be equally divided by symmetric membership functions of triangular type, and the algorithm uses the t-norm max to select the degree to which two fuzzy sets match. The output of each fuzzy inference system is derived using the standard Zadeh–Mamdani's min–max gravity reasoning method. The rules in the fuzzy model have the following form:

$$\begin{aligned} R^{(i)}: &\text{IF } x_1 \text{ is } A_1^{(i)} \text{and } x_2 \text{ is } A_2^{(i)} \ldots \\ &\text{and } x_m \text{ is } A_m^{(i)} \text{ THEN } z \text{ is } B^{(i)} \end{aligned} \tag{1}$$

Where, $R^{(i)}$ is the ith rule, x_j are the antecedent variables, and z is the consequent variable. For the toolpost, x_j will be the error and, the rate of change of error as obtained from the FEM model, and z will be the actuator voltage factor. Symbols $A_j^{(i)}$ represent the fuzzy sets, and, $B^{(i)}$ are the rules conclusion of the fuzzy system. The inference operation and the defuzzification formula of the fuzzy algorithm are described in various literatures (Passino, 1998). A number of calculations and fine-tuning are pursued to obtain the final membership functions and the rule-base for the voltage factor of the controller as given in table 2.

Table 2: The controller rule base.

$d\dot{\varepsilon}\backslash\varepsilon$	H	M/H	M	M/L	L
H	**H**	**M/H**	**M**	**M**	**M**
M/H	**M/H**	**M**	**M/L**	**M/L**	**M/L**
M	**M/L**	**M/L**	**M/L**	**L**	**L**
M/L	**L**	**L**	**L**	**L**	**L**
L	**L**	**L**	**L**	**L**	**L**

Figure 4 shows the control surface of the fuzzy controller, offering a correlation between the voltage factor VF as a function of the normalized error ε and the normalized rate of change in error $\dot{\varepsilon}$. By considering the negative error is the tool tip displacement away from the work piece axis then ε is the negative of the normalized tool tip error with respect to the maximum static displacement of the peak radial cutting force? The universe of discourse of the input variable ε is defined to be within the range [0, 1] where the voltage is only applied when the tool has an inward motion away from the work piece axis. While $\dot{\varepsilon}$ is the time rate of change of error ε calculated every one tenth of the force period and given a universe of discourse [-0.2, 0.2]. Finally VF is a multiplication factor for the estimated voltage from the static tool force-displacement chart in Fig. 4 and given a universe of discourse [0, 1].

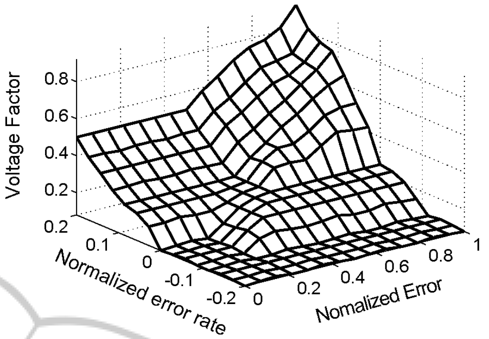

Figure 4: Fuzzy control surface for voltage factor.

5 RESULTS OF FUZZY CONTROLLED RESPONSE FOR INTEGRATED TOOLPOST

Requirements to reduce tool holder size and weight encourage developing new tactics of using smart actuators to attain high precision by compensating unfavorable motion errors.

Estimation of cutting tool radial force might involve several variables. In general the static force relation (Frankpitt, 1995) which expressed in terms of depth of cut (d , mm), cutting speed (V , mm/s), feed (f , mm/rev), and, coefficients describing the nonlinear relationships ($\kappa, \lambda, and, \gamma$) can be used as a first guess in error attenuation:

$$F_r = K_r d^{\lambda} V^{\gamma} f^{\kappa}(t) \qquad K_r \text{ a general constant} \tag{2}$$

K_r , λ , γ and, κ are to be calibrated for each tool-workpiece, tool-work material combinations, process types, tool-wear condition, workpiece hardness, tool geometry and speed. For presented results both Eq. (2) and Figure 3 deliver the first estimate of the force and applied voltage to the actuator. Following force values are obtained according to the Fuzzy control surface in response to error and rate of error. Data for the produced results are given in Table 1. Using a few PWM cycles per force period can cause unfavorable switching dynamic excitation by actuator to tool post as shown in Figure 5 for ten PWM cycles. Twenty PWM cycles per force period produce more favorable results but more than twenty have little effect. For comparison, the outcome of increasing β by ten folds from selected datum of 1% damping ratio for first mode and 5% for second mode produce significant reduction in tool tip normalized error. Both damping and voltage activation are contributed to reduction in normalized error as shown in Figure 5. Using a high damping only does not solve error attenuation problem as indicated in Figure 6.

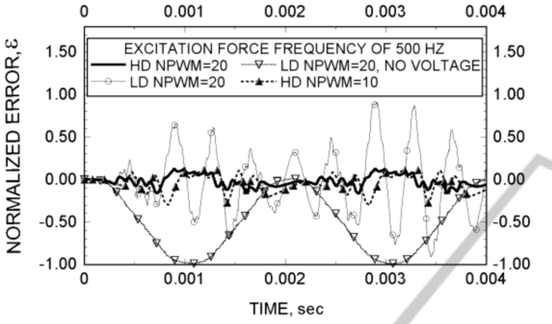

Figure 5: Normalized tool tip error versus time for KT/KA = 10, KC/KA = 10 and KD/KA = 0,01 for high damping (HD), low damping (LD) and N_{PWM} of 20 or 10.

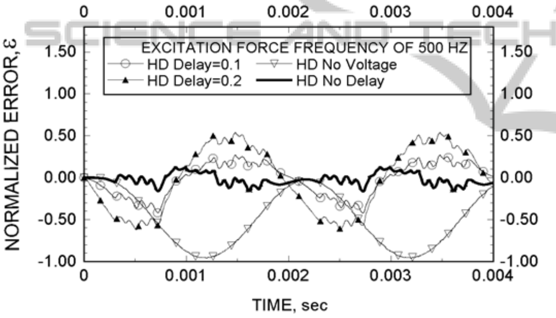

Figure 6: Normalized tool tip error versus time for KT/KA=10, KC/KA=10, KD/KA=0,01, high damping (HD), delay of 0,1, delay of 0,2 and N_{PWM} of 20 or 10.

Negative normalized error in Figures 5-6 indicates outward tool tip retraction away from the workpiece axis. Tool bit to actuator stiffness ratio (KT/KA) has importance in terms of force availability for tool tip error elimination and accurate displacement sensing as shown in Figure 3. For a stiffness ratio greater than ten identical displacements produced between tool tip and tool carrier main body. Taking into consideration the geometrical factors, deviation starts to be noticeable when stiffness ratio (KT/KA) drops below one. Importance of such parameter depends on required final error limits and type of application. Time delay in voltage activation has a significant effect if the delay is exceed 10% of the force frequency period as shown in Figure 6.

6 CONTROLLER CONFIGURATION USING COGNITIVE CHIP

It is difficult to acquire a controller that ensures continuous error tracking under stabilized condition for smart toolpost under continuous exposal to an erratic real time force inputs. The idea of using an intelligent controller is generated by the random nature of system excitations which largely depends on unpredictable parameters such as structural properties, friction, and other variable dynamic forces (Rashid, 2011). A neural network can model the response of such system by means of a nonlinear regression in the discrete time domain. The result is a network, with adjustable weights, that might approximate the system dynamics. Though it is a problem since the knowledge is stored in an opaque fashion and the learning results in a large set of parameter values which almost impossible to be interpreted in words. Conversely using a fuzzy rule based controller that consists of readable if-then statements which is almost a natural language, cannot learn new rules alone.

The structure of using intelligent controller is shown in Figure 7 (Rashid, 2011) where MF is the membership function. The idea of implementing the cognitive chip is described in Figure 8.

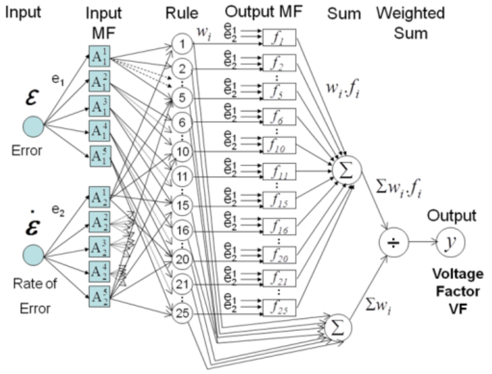

Figure 7: Intelligent controller architecture (Rashid, 2011).

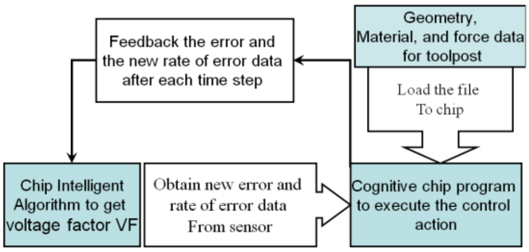

Figure 8: Flow chart for cognitive chip implementation.

7 CONCLUSIONS

Reducing machining error in old turning machines using smart material can reduce industrial waste, save money and, improve design flexibility for new cutting tools. The outcome of this work show stiffness ratios in toolpost structural design have a major rule in actuator selection and design. Support stiffness in the direction of actuation should be minimal. Tool bit to actuator stiffness should be higher than one and to the extents that make tool error is acceptable. Tool bit to actuator stiffness and tool carrier (holder) to actuator stiffness both are preferred to be high. The developed fuzzy algorithm for voltage activation factor based on normalized error and its rate proved a significant effectiveness in error attenuation. Implementation if intelligent scheme proved effectiveness during FEM simulation. Using cognitive chips in real application as in Figure 8 is the idea of future development.

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