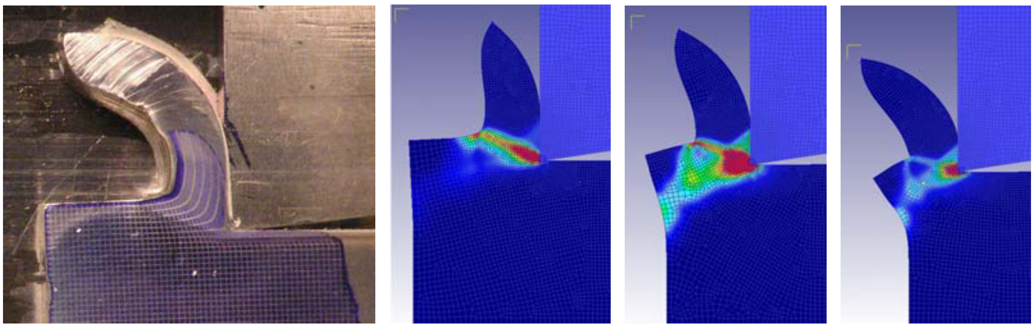
University *of Ljubljana*
Faculty of Mechanical Engineering

Proceedings of the

9th CIRP International Workshop on Modeling of Machining Operations

May 11-12, 2006
Bled, Slovenia



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Foreword

The current Workshop is the 9th in the series sponsored by CIRP and initiated in 1998, in Atlanta, Georgia, USA and is a continuation of the 2005 Workshop held in Chemnitz, Germany.

This Series has its origins in a Working Group on "Modeling of Machining Operations" established in 1995 within the CIRP Scientific Technical Committee for Cutting [STC C]. The aim of this group was to stimulate the development of models capable of quantitatively predicting the performance of metal cutting operations better adapted to the needs of metal cutting industry in the future.

The objectives of the Workshop were to bring together professionals from industry and from academia: firstly to present and discuss recent advances in Modeling of Machining Operations and Cutting Processes, secondly to establish a fruitful dialogue between machining model developers and users, and thirdly to formalize conclusions, recommendations and more useful directions for future research.

In response to the call for papers, 81 abstracts were submitted. After a stringent review of the manuscripts, 60 contributions from 25 countries were accepted and appear in these proceedings after being classified according to the following topics: stability, simulation, cutting force modeling, drilling, grinding, process optimization, tribology, diagnostics, burr formation, tool wear and residual stress, chip formation, and high energy material processing.

The workshop provided a significant advance in knowledge in the field of modelling of machining operations and cutting technologies and we believe that its content will help to stimulate further development in the future.

I. Grabec, E. Govekar (Editors)

A Virtual Test Bed Implementation Using the Precision Model of Feed-Drive System for the Verification of Command Generators

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Abstract

In this paper, a simulation model of a CNC feed-drive's servo-control system, which could be utilized to design and develop CNC controllers, is presented. According to authors knowledge, it is for the first time that a precise model of machine tools components and controller, which may be called a virtual machine, is employed as an experimental aid to carry out practical and economical tests for verifying command generation modules. Therefore, a three-axis CNC machine feed drive is implemented in a Matlab/Simulink environment and its performance will be verified. The effects of some of the main variables on the system's performance such as coulomb friction, viscous friction, feed force and inertia are analyzed and the PID controller is employed and tuned to reach the required performance. Previously generated NURBS commands based on jerk-limited trajectory are used as input to verify the validity of simulation; and the results show that the simulation model is reliable.

1. INTRODUCTION

Feed drive system is one of the most important parts in CNC machines. This is because the accuracy and quality of motion in both single and combined multi-axis depend upon the performance of the feed drive system. Recent method such as Fuzzy, Cross-Coupled, Feed-Forward and ZPETC shows that serious attempts have been made in order to develop new feed drive controllers design for the enhancement of the quality of performance [1-3].

Also a lot of research has been carried out concerning the performance simulation of industrial CNC machines for developing in-process self-adjusting and intelligent servo drive systems which reduce both calculation times required for dynamic implementations and costs of experimental tests [4,5].

In most of the above mentioned research in order to carry out experimental test, the presence of real CNC machine is needed. However, to reduce the cost and the risks associated with the practical test, using the simulation method could be suitable.

In other words, the new controller design could be initially simulated and after finalizing the structure and tuning the parameters the final design would be implemented. Additionally, the combination of simulated machine tool components and controller could be used instead of real CNC machine as a virtual one to do some other experiment such as the command generator tests. Altintas [6] introduced a complete model of feed drive system and used it to detect the tool breakage in milling.

In this paper, the feed drive of a vertical milling machine is modeled and used to reveal the feasibility of simulation. Also this proposed simulation is employed as a virtual machine to show the credibility of NURBS-based command generation which is recently available in modern CNC [7].

The aim of this paper is to make an accurate simulation bed of a feed drive system to easily implement experimental tests instead of using costly real CNC machine. It is shown that when the feed drive servo dynamics and the friction in the guide-ways are correctly modeled, a good agreement between simulation and experimental behaviors is obtained.

With the advances of control theory and computer techniques, the computer aided control system design (CACSD) has been developed. Simulink [8] is one of the representatives of high-performance language for the CACSD.

The digital-control model adopted for the simulation of a feed drive is described in this paper and an example of Simulink formulations adopted for implementing the model are provided. A simulation experiment of a feed drive plant is performed by using both continuous and digital control models. The results show that the simulation model is reliable.

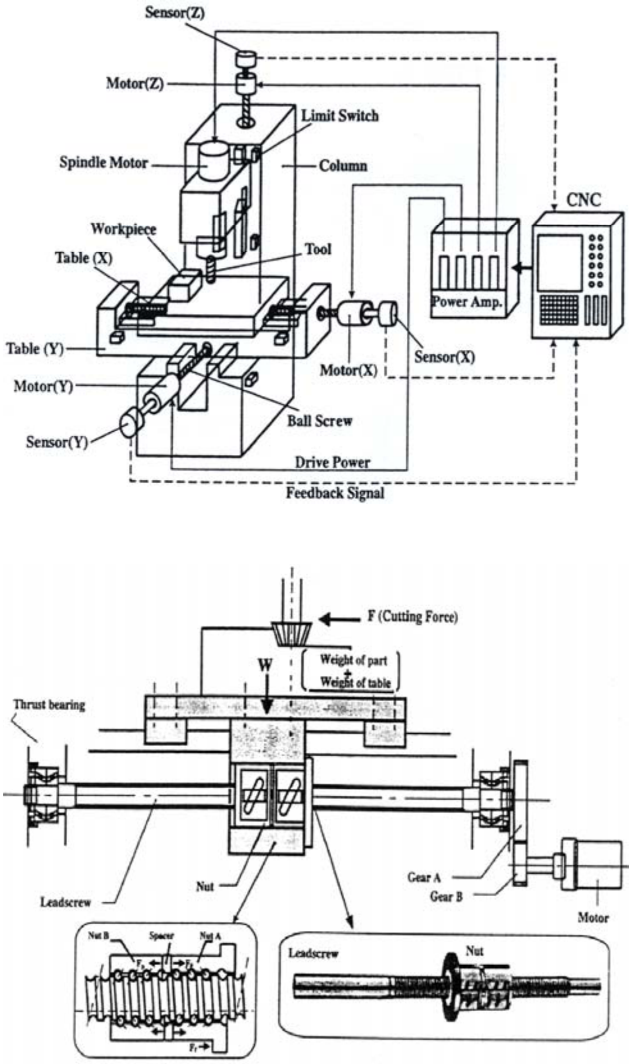


Figure 1: Diagram of a 3-axis CNC machining center and feed drive mechanism with ball screw [11].

2. STATIC AND DYNAMIC MODEL OF THE CNC

The feed drive control system of a CNC machine is made up of the control object (plant) and the controller. The design of a control system requires accurate models of the “plant” to be controlled.

In fact, with the development of modern control equipment and design methods, more accurate, fully dynamic and detailed models are required.

The feed drive system consists both of electrical (i.e., servo amplifier, motor) and mechanical components (i.e., table, ball screw, nut, gear box, guides and bearing). Also inertia and friction characteristics of drive assembly should be considered.

Weck [9] presented detailed information for the behavior of viscous and coulomb damping in different guide-ways. The effects of both electrical and mechanical components of feed drive, on the dynamic performance of the servo, are presented in detailed by Stute and his coworkers [10].

The nonlinearities in the friction and amplifiers circuit have been considered in simulation. In this paper a feed drive of three-axis CNC machining center as shown in Figure 1 is taken as an example to create a virtual machine feed drive system by modeling of physical structure and servo-drive controller.

2-1. Static and Dynamics equation of physical component

The feed drive system has to overcome both the static and dynamic loads in machine tools. There are three sources of static loads: the friction in the guide-ways, the friction in the bearing, and cutting forces.

Machine tools feed motors also require high torque during acceleration/ deceleration. The effective dynamic loads is rely on J_e, the total reflected inertia on the motor’s shaft consist of the inertia of the table, workpiece, lead-screw, gears and motor’s shaft. The viscous friction torque is another part of dynamic loads in feed drive that is proportional to the velocity.

The total torque T_t required to accelerate or decelerate the inertia J_e and to overcome viscous friction and static loads is given as follows:

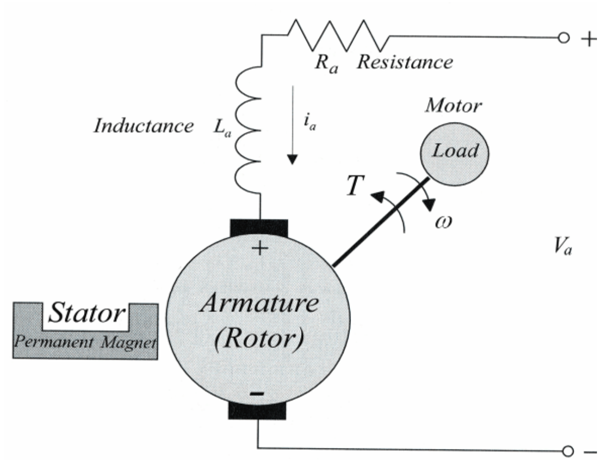
$$T_t = J_e \dot{\omega}(t) + B\omega(t) + T_s(t) \qquad (1)$$

where T_s is the sampling time, B is the Viscous damping coefficient and ω is the angular velocity. Note that only static load is taken as an external force and considered as a part of disturbances in simulations. Noise and un-modeled forces are another kind of disturbance.

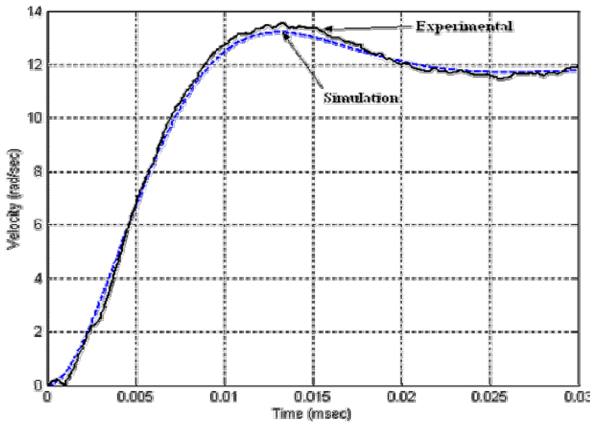
2-2. Electrical Components

The feed drive can be powered by either electrical or hydraulic motors. The most common motors used in the feed drives are direct current (DC) motors since they allow a wide range of operating speeds with the sufficiently large torque delivery required by machine tools.

The use of alternating current (AC) motors is also common in CNC machines.



(a)



(b)

Figure 2: a) Electrical diagram of a PMDC motor [12], b) Step response of the velocity loop.

In this section analysis of a permanent magnet DC motor is explained. However, the analysis and modeling procedures are similar for both DC and AC servomotors.

The motors must have a sufficiently high continuous torque delivery range and sufficient peak torque with a period of 2-3 second to overcome the static and dynamic loads introduced in previous section [11].

As shown in Figure 2(a), the speed of the DC motor is controlled by feeding a DC voltage V_a to the armature of the motor which produces a variable DC current I_a. Note the current drawn by the armature can not exceed the maximum current supply capacity of the power amplifier.

The current limit is treated as a non-linearity in the control system and should be considered in simulated model. The power amplifier mentioned in this paper is a pulse width modulated (PWM), current-controlled amplifier [14].

The following fundamental dynamic equations govern the motion of DC motors. According to the Figure 2(a), the applied armature voltage V_a is derived by applying Kirchoff's law to the motor circuit as follows:

$$V_a(t) = R_a I_a(t) + L_a \dot{I}_a(t) + K_b \omega(t) \qquad (2)$$

where K_b is The back electro motive force (EMF) constant and is determined by the ratio of voltage generated in the winding to the speed of the rotor. Also R_a and L_a are the resistance and inductance of the armature respectively.

The magnetic field produces a useful motor torque T_m, which is spent in accelerating the reflected inertia on the motor's shaft, overcoming the friction in the motor's bearing and sideways, and resisting against feed cutting forces and friction loads reflected as disturbance torque on the motor's shaft. Thus:

$$T_m(t) = K_t I_a(t) = J_e \dot{\omega}(t) + B\omega(t) + T_s(t) \qquad (3)$$

where K_t is the torque constant (torque sensitivity) for a servomotor and is determined by dividing the developed torque by the current to produce that torque. Since both K_b and K_t are determined by the same factors, K_b is directly proportional to K_t. The motion is starting when T_m reaches the value of T_t as define in Eq.(1). The properties of the simulated vertical milling machine are given with full description in Table 1.

3. CONTROL SYSTEM MODELING

In Previous section, a detailed, dynamic model of feed drive system is obtained. The linear feed drive model adopted for calculations was developed by Altintas [6,11]. The complete physical parts of a CNC control loop are shown in Figure 3(a).

The overall representation of a specific feed drive is carried out by identifying the necessary modules and connecting them appropriately by means of electrical and mechanical links. Also the control diagram of these physical parts is presented as a type of transfer function in Figure 3(b).

It shows a feed drive layout as control objects by assembling the modules on the computer screen via Matlab/Simulink.

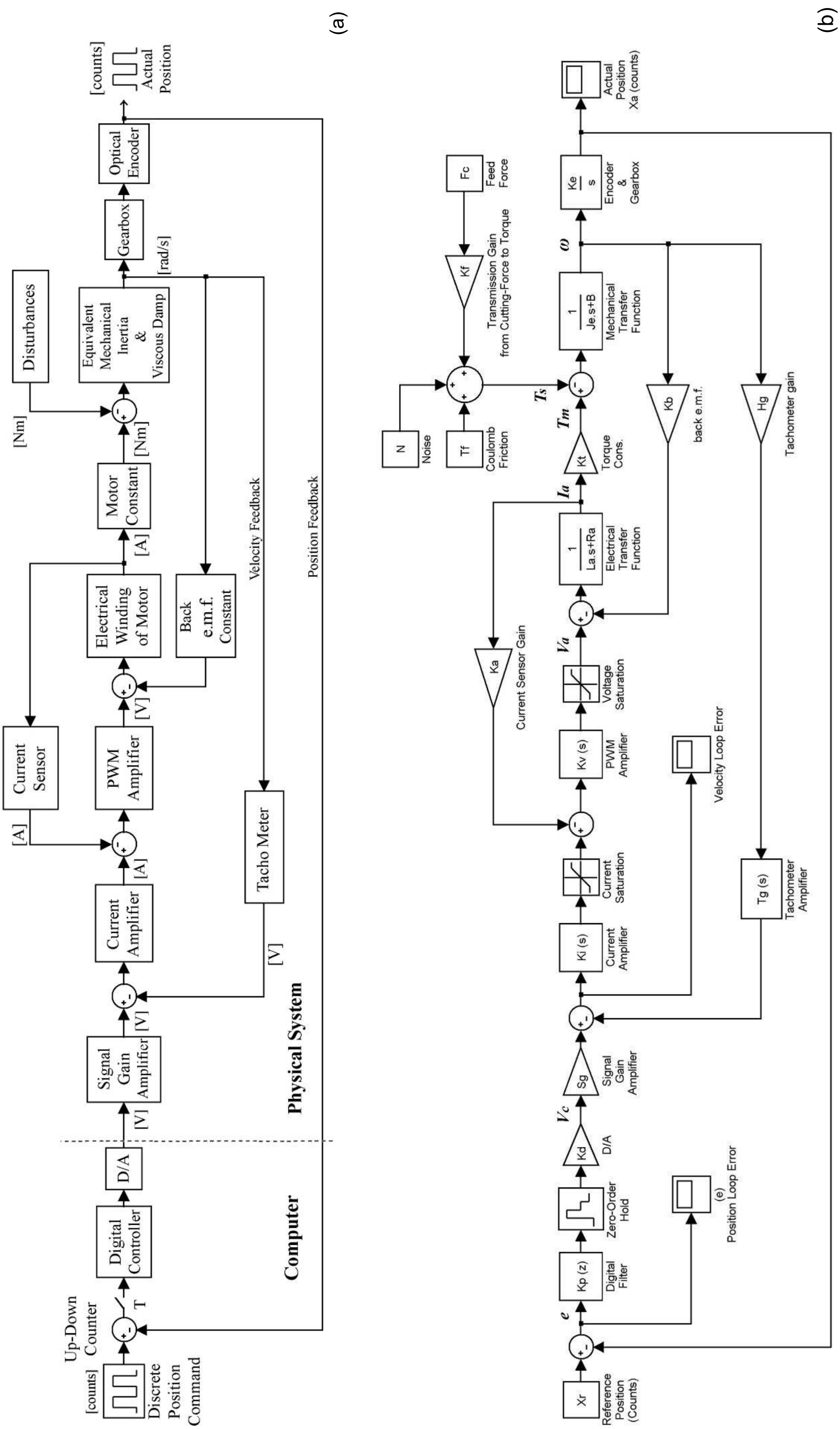


Figure 3: Block diagram of a CNC feed-drive servo-control in Simulink. a) Physical parts. b) Transfer function.

Table 1: Simulated machine tool properties [6].

m_w = 180 kg	Table mass
m_t = 200 kg	Max. mass for workpiece
m_l = 8.15 kg	Lead-screw mass
h_p = 0.00508m/rev	Pitch of feed-screw
d_p = 0.0445 m	Feed-screw diameter
J_m = 1501 g · m^2	Motor's shaft inertia
r_g = 1.0	Gear reduction ratio
μ_s = 0.10	Friction coef. in guides
μ_b = 0.005	Friction coef. in bearings
F_f = 8000 N	Max. feed force
F_p = 5000 N	Preload force in bearing
F_z = 2000 N	Max. vertical force
B=0.002256 Nm/rad·sec^{-1}	Viscous damping coef.
Ke = 0.00127 mm/counts	Encoder gain

There are three control loops appear in the servo controller: Position, Velocity and Current. Taking the Laplace transform of Eqs. (1), (2), and (3) yields the transfer functions Eq.(4) which have the same physical interpretations. The dynamic behavior of each module is described by means of equations representing the electrical transformations and kinematics balance. The continuous and discreet control loops is applied in this simulation model.

$$I_a(s) = (V_a(s) - K_b\omega(s))/(L_a s + R_a), \; T_m(s) = K_t I_a(s), \omega(s) = (T_m(s) - T_s(s))/(J_e s + B) \quad (4)$$

3-1. Velocity control loop

The feed drive servo velocity controller is designed to have a fast rise time with zero overshoot at step changes in the velocity. Typical design value for feed drive velocity control loop may be a damping ratio of 0.707 and a peak time of 10ms so cause the natural frequency of 88 Hz. By some manipulation, the complete velocity transfer function is obtained relies on Figure 3(b) and Eqs. (4) as follows:

$$\omega(s) = \frac{K_1}{s^2 + K_2 s + K_3} V_c(s) - \frac{(1/J_e)[s + (R_a + K_v K_a)/L_a]}{s^2 + K_2 s + K_3} T_s(s) \quad (5)$$

where,

$$K_1 = \frac{K_t S_g K_I K_v}{L_a J_e}, K_2 = \frac{B}{J_e} + \frac{R_a + K_v K_a}{L_a},$$

$$K_3 = \frac{B(R_a + K_v K_a) + K_t(K_b + H_g T_g K_v K_I)}{J_e L_a}$$

3-2. Position control loop

The position loop consists of an up-down counter, an encoder, a digital compensation filter, and a digital to analog converter.

The instantaneous content of the counter represents the integrated position error within digital servo control interval *T*. The D/A converter is modeled as a zero order hold (ZOH) and has a gain K_d. The digital filter is programmable and resides in servo motion controller. The filter's parameters are tuned to provide a desired transient response of the position control loop.

Note that the position control loop has continuous and discrete components. For any given discrete time input $X_r(kT)$, the position response $X_a(kT)$ can be found by Eq. (6). The parameter of both nominator and denominator of the position closed-loop can be obtained by some manipulation.

$$X_a(k) = -(\alpha_3 z^{-1} + \alpha_2 z^{-2} + \alpha_1 z^{-3} + \alpha_0 z^{-4}) X_a(z^{-1}) + K_{cl}(z^{-1} + \beta_2 z^{-2} + \beta_1 z^{-3} + \beta_0 z^{-4}) X_r(z^{-1}) \quad (6)$$

Table 2: Control Parameters of feed drive system.

Components	Symbol	Definition	Value (Units)	Transfer Func.
PMDC Motor Assembly	B	Viscous damping	0.002256 (Nm/rad·sec^{-1})	$\frac{1}{J_e s + B}$
	J_e	Equivalent inertial	0.003767 (Nm/sec)	
	L_a	Inductance	0.002 (H)	$\frac{1}{L_a s + R_a}$
	R_a	Resistance	0.4 (Ω)	
	K_t	Torque constant	0.3 (Nm/amp)	
	K_b	Vol cons. (e.m.v)	0.3 (vol/rad·sec^{-1})	
Tacho Gain	H_g	Tachometer constant	0.08872 (vol/rad·sec^{-1})	
Current Feedback	K_a		0.3264 (vol/amp)	
Signal Amplifier	S_g	Adjustable gain	0.335 (vol/vol)	

Tacho Amplifier $T_g(s)$	T_g	Tacho gain	0.3183 (vol/vol)	$\frac{T_g(T_{t1}s+1)}{T_{t2}s+1}$
	T_{t1}		0.003979 (sec)	
	T_{t2}		0.00014 (sec)	
Current Amplifier $K_i(s)$	K_i		2113.5 (vol/vol)	$\frac{K_i}{T_{ki}s+1}$
	T_{ki}		0.1788	
	V_{im}		9.2 (vol)	Saturation Limit
Voltage Amplifier $K_v(s)$	K_v		203 (vol/vol)	$\frac{K_v(s+\omega_{kv})}{s}$
	ω_{kv}		313 (rad/sec)	
	V_{vm}		78 (vol)	Saturation Limit
Encoder & Gearbox	K_e	Encoder gain	636.62 (counts · rad^{-1} · sec)	
D/A	K_d	Adjustable gain	0.0781 (vol/counts)	
ZOH	T	Time interval	0.001 (sec)	$\frac{1-e^{-Ts}}{s}$
Digital position control Filter $D(z)$	K_p	Position control filter gain	2.45	$K_p\left(\frac{z+a}{z+b}\right)$
	a	Position zero	-0.879	
	b	Position pole	-0.564	

3-3. Controller module

For a feed drive system, despite the multi-variable control synthesis, the displacement and velocity control are still the main controls. For the control process to operate smoothly, it is important to induce a displacement error control loop in the digital-control strategy.

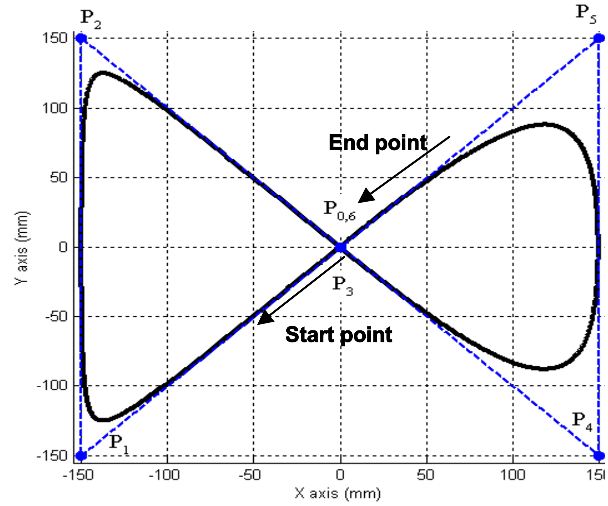
Therefore, a feedback control consisting of the direct PID control function in the forepart and velocity feedback and position feedback at the rear is adopted. The effects of the main variables on the system performance are introduced by Eq. (5) and Eq. (6).

The optimum values of the control parameters are obtained by Ziegler-Nichols' method as listed in Table 2. However, although new designs of modern controllers have been introduced by researchers [1-5], the PID controllers are still being widely used in many CNC machines as control system and are suitable for use in advanced control system development [13].

PID controller structure which is commonly used in CNC is simulated in Simulink as CACSD software and verified by step response method as shown in Figure 2(b). The electrical control subsystem and the mechanical control subsystem are, as shown in Figure 3.

The above analysis is presented for the horizontal x-axis drive, and its parameters which are used in simulation modeling are given in Table 2.

For the simplicity and without prejudice to the general concept, all axis properties are considered the same as presented for x-axis.



Seq. no.	G-Code	Knot vector	Weight	X axis Mm	Y axis mm	Feedrate mm/min
N10	G 06.3	K0.0	W1.0	X0.0	Y0.0	F6000
N20		K0.0	W25.0	X-150	Y-150	
N30		K0.0	W25.0	X-150	Y150	
N40		K0.25	W1.0	X0.0	Y0.0	
N45		K0.5	W2.0	X150	Y-150	
N46		K0.5	W2.0	X150	Y150	
N47		K0.75	W1.0	X0.0	Y0.0	
N51		K1.0				
N52		K1.0				
N53		K1.0				

Figure 4: Sample tool-path and corresponding NURBS G-code used for command generation.

4. RESULT AND DISCUSTION

A simulation experiment upon a real CNC plant is performed using the SIMULINK modeling. In this simulation study, the command generator programs are written by VC++ 6.0 and are executed on a personal computer with Pentium IV 2.66 GHz CPU.

The commands are generated as set points and sent to the servo control system with 2ms of sampling period. A NURBS curve shown in

Figure 4 by considering a jerk-limited kinematics profile was used as example to test the feasibility of the proposed virtual CNC machine during milling operation.

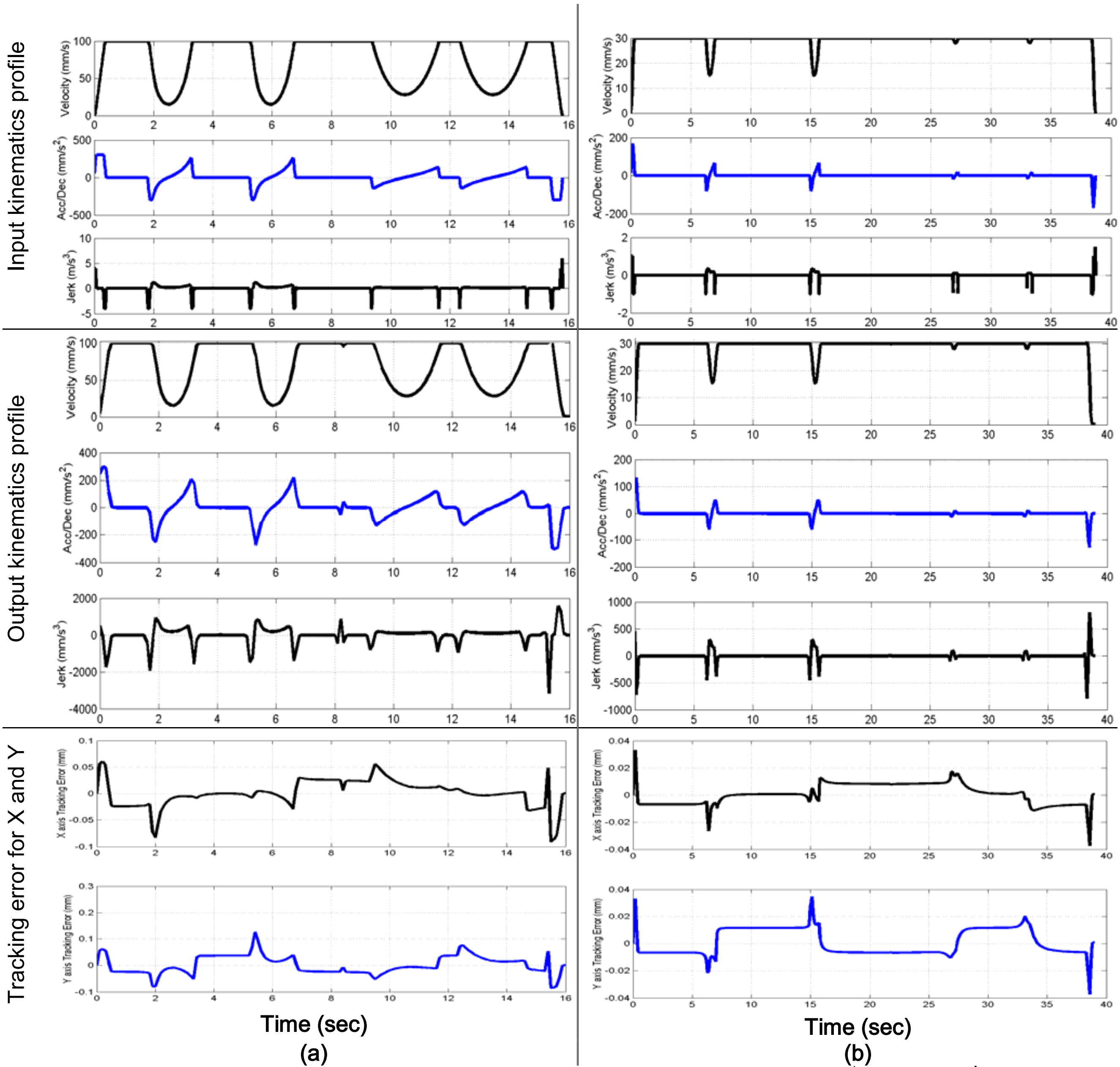


Figure 5: In/Out kinematics profiles of simulations and tracking error. a)1st test. b)2nd test.

Figure 5(a) shows a first simulation result in which, kinematics behavior along the curves in the case of a given feedrate command of 100mm/s are jerk limit of 4000mm/s^3 and maximum Acc/Dec of 300mm/s^2. The generated trajectory has a trapezoidal acceleration profile with smooth variation of feedrate.

In order to decrease the tracking error at the sharp corners of the curve, the power of servo control system should be increased or feedrate should be decreased. To reveal this fact another simulation as shown in Figure 5(b) is performed with feedrate command of 30mm/s, jerk limit of 1000mm/s^3 and maximum Acc/Dec of 200mm/s^2. Other conditions are the same as previous test. According to the result depicted in Figure 5, the pick of tracking error for each axis is occurring at such points that the direction of motion is changed. This is because of the presence of the inertia and frictions in feed drive system. Tool-path was so selected that the inversion of direction occurred twice for x-axis and four times for y-axis.

Tracking errors diagrams as shown in Figure 5 confirm this point. In other word, in these figures, the error is seemed with both positive and negative values. When the motion is towards the positive direction of the axis, negative tracking error reveals that the actual position in relation to the input command is delayed. So to, when the motion is towards the negative direction of the axis, positive tracking error illustrates that the actual position in relation to the input command (set points) is delayed. In these figures, also two and four specific points of change in error sign for x-axis and y-axis have been recorded respectively.

Considering the enforcement of Acc/Dec in motion commands, transient conditions are exist at both the start and the end part of the tool-path. In order to obtain the tracking errors in Figure 5, it would be necessary to shift backward the output values in time domain by utilizing the discreet function of z^{-23} as backward time shift operator [14]. As a result, the whole output profile is shifted backward by $\Delta t = 0.023$ sec.

As expected, with decreased of feedrate in the second test, the tracking error of each axis is decreased. Any significant imprecision in modeling and implementation would cause unstable response or over-damp oscillations at the output. However, for the purpose of increasing the performance of the controller in HSM, it would be possible to use more advanced algorithms such as ZPETC, feed-forward, crossed-coupled, adaptive and fuzzy control.

5. CONCLUSION

The development of the computer has made it possible to set up a feed drive and servo control system based on the Simulink. In this paper, a simulation model of a CNC machine system is presented. The simulation experiment of this model is performed using the continuous and digital control model. The simulation parameters are obtained by means of a simulation experiment. The comparison of measurement data with simulation results shows that the servo-control system model is reliable.

Feed drive and its controller are simulated via a Matlab/Simulink program. The effects of some of the main variables on the system's performance such as coulomb friction, viscous friction, feed force and inertia has been considered and the PID controller is employed and tuned to reach the required performance.

The test results revealed the advantages and capabilities of the purposed simulated feed drive model. Also it could be a convenient test bed for other experimental purpose in application of CNC feed drive and controller.

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