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Heat loss optimisation in CNC motors

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ABSTRACT

Purpose: Heat loss plays very important role in CNC systems, especially in suspension systems with permanent load that are usually used for testing, detection and automatic cutting, the adjusting of motor torque in each axis is based on starting by maximum current required to overcome against resistant torque on the motion surface of the system.

Design/methodology/approach: In this research a new control method is introduced for the minimization of heat loss in CNC motors. In these systems the misdirected current that causes magnetic misalignment and reduces the torque is converted to heat in the motor winding, thus reducing the motor continuous torque capability.

Findings: This method is based on an open-architecture of a dynamic control to optimize the input current in order to dissipate the minimal heat loss. So that, it reaches the requested velocity-position condition with the lowest amount of misaligned magnetic field and current converted to heat.

Research limitations/implications: The dynamic performance implications are more important than the steady-state torque disadvantage.

Practical implications: An algorithm for the dynamic torque control is given and a simulation is carried out using this algorithm for a two axis CNC cutting system with two-guider bars suspension. Reaching to the actual requested motor current is practical implication. From this point of view, the enhanced free running of pulse width modulated (PWM) is represented.

Originality/value: Results obtained in this work show that using the proposed procedure the heat loss is minimized while the speed errors are reduced and the surface finish is improved. Finally, the results of this dynamic control method is represented on CNC two axes cutting machine and extended the results on the other systems.

Keywords: Resistant forces; Open-architecture control; Free-running pulse width modulated driver

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Executive applications of CNC systems in machining, inspections and testing, robotics and other manufacturing operations causes numerous architecture in controls regarding to their facility and capability in various branches of times to be established [1]. Increasing in power of microprocessors and invitation of multi-operational systems in one hand and assured protocols connection between industrial hardware and personal computers on the other hand, paves the way for using personal computers to control processes and monitoring pure industrial systems [2]. The extension of open-architecture control to separate CAD/CAM, interpolation, running and simulation layers confirms that the most of CNC manufacturers interest to high flexibility obtained from development of software and replacement of old hardware with powerful software [3].

Nowadays a lot of works have been done to improve the capability of machine tools. The continuing development and trends in manufacturing and operations engineering can not be sustained using current methods and processes [4]. General theory of systems gives general principles of study and reinstatement (design) of all types and varieties of systems.

The development of modern machining centres proceeds towards very high machining speeds and precision. At the same time the static, dynamic and heat loads of machining centres become increasingly complex [5]. The quality of machined parts is assessed against specifications for dimensional and mechanical characteristics [6]. Due to the widespread use of highly automated machine tools in the industry, manufacturing requires reliable monitoring and optimization models and methods [7]. Nowadays discrete-continuous systems are more commonly used in designing methods of mechanical systems. Therefore there has been an increasing interest in such methods of synthesis which could be applied both for systems with converged and continuously distributed parameters [8]. The investigation into the structures of cascade systems was conducted by means of the software method for distributing the dynamic characteristics to the continued fraction based on graphs and structural numbers [9]. Although a large number of different 3-digitization systems has been developed, but common to them all is the presence of noise and measuring errors in the results [10]. Minimization of machining cost via several efforts have been done in the past years to develop techniques for dry machining at present limited to soft materials especially in difficult machining operations. Many different sensor types, coupled with signal processing technologies are now available and many sophisticated signal and information processing techniques have been invented and presented in research papers [11]. The thermal phenomena, which occur in complex machine tools and machining centres, are particularly difficult to model. The systems that completely automate all the activities in technological process preparation usually are working fully separated from product CAD models [12].

Up to now what have been considered about the connection of interpolation layers – as the supplier of the data of motion - and execution layer - as multi-axis motion controller - are all about the motion of axes and their velocity. In fact, the motive conditions in all over the motion range for an axis from start to end is considered to be constant on various points of axis and to overcome with applied forces variations, the motor driver is designed to satisfy the velocity-motion conditions at the worst loading situations [13]. In motion systems with variable loading, as CNC machine tools, the consideration of constant gradient of forces applied to tool is not correct. But in the systems with constant loading as automatic cutting machines and also non-destructive testing systems in which inspections are accomplished by scanning, the consideration of constant gradient of resistance forces is logical. Suspension systems in CNC machines and robots are always designed so that the friction and inertia of the system are minimized. But designing difficulties such as installation problems, out of parallelism and foundation errors, impacts and unpredicted contacts and machine tool's error in total; will affect the design of the suspension system [14].

An ideal multi-axis suspension system is the system with constant gradient resistance forces (especially friction forces). But in real suspension systems this does not happen. What is presented in this research is a multi-axis controller with open-architecture control method and capability of adaptive control of the motors input current regarding the motive situations so that the motor is able to reach the required current for the motion. The goal of motor input current limitation is to prevent heating loss, increasing the motor life and its elements, and also preventing shocks due to impact and unwanted contacts.

Application of free-running PWM motor drivers as a chopper of power generator and the method of setting parameters regarding to friction loads and angular speed of motor which is illustrated due to database by a system with open-architecture control and also the calculation method of gradient resistance forces on axis are introduced here.

2. Databases and control flexibility

Using personal computers as supplier of motion data for the next software and hardware layers, gives the capability to CNC designer to update controlling and optimization of motion parameters, velocity and other necessary data by using and improving databases. They can also provide some special possibilities to save and recover a group of localized information to satisfy some temporal and local conditions. Multi-tasking of operating system of the personal computer's core guarantees the continuous reading and writing on database contemporaneous with the control of velocity and interpolator program outputs. Updating capability of database information with regard to the calculations or measurements ensures the user to improve system at the least hardware optimization with the changes of loading conditions of user's need.

3. Open-architecture controllers

Open-architecture control is a new model to create complex control systems with software/hardware flexibility based on using personal computers as calculators and digital signal processors as executers. The structure of such systems is layered with connection bridge of transmission protocols for data and instructions to different layers. At the highest layer, there are a computer, CAD/CAM software and perhaps an editing environment to input G (or production) codes. The next layer includes interpolation unit, velocity controller and co-drivers. There are motion and velocity hardware controllers, which are at the last layer. I/O hardware and data transmission protocols are interfaces between these layers. An open-architecture controller related to motion system contains the following sections at the highest layer:

- CAD/CAM software written with a high-level programming language such as C/C++, Pascal or Visual Basic.
- Operating system corresponding to software as MS-DOS, Windows NT or UNIX.
- Hardware based on a processor such as 80x86/Pentium® or PowerPC®.

On the next layer, there are interpolator and velocity controller programs which are written by one of the mentioned languages working under corresponding operating system. Various portions of a CNC machine with open-architecture control and their serial arrangements are shown in Figure1.

4. Nature and effect of resistive forces

In any controlled motion, estimating of resistive forces is one of the most basic problems in motor parameter's determination of any engaged axis. It is said that the inertia of the system is one of the most resistive nature against the variation of motive velocity.

Although the optimized design in motion systems is based on reduction in inertia across all displacement axes, but by any velocity variation, the motor has to collate against momentum variations of motive parts in any way. The most generally damping control method against linear and angular momentum variations is acceleration-constant velocity-deceleration to reduce jerks causing by momentum variations.

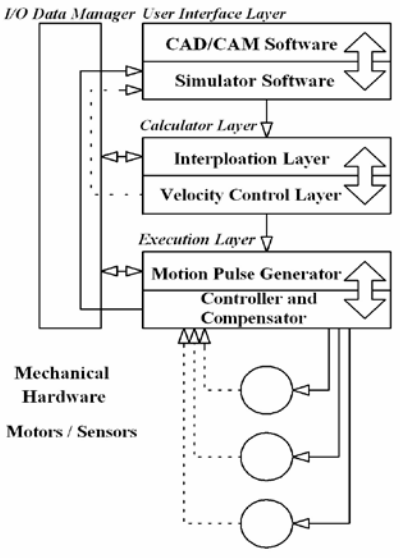

Fig. 1. Serial arrangement of an open-architecture controller

The inclinations of acceleration and deceleration regions are determined by a set of kinetic and cinematic parameters of the system. Friction is an unavoidable factor on the motion. The amount of frictional forces is directly dependent to the quality of contact surfaces in accordance with the weights of motive set parts. Engineering experiences confirm that the consideration of constant/zero friction of an ideal suspension system are incorrect. The error in machine tools is another independent damping factor that appears as various shapes in different systems. Figure 2 shows two guider bars of third axis of an ultrasonic non-destructive testing system.

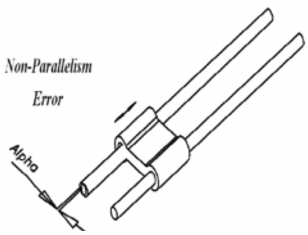

Fig. 2. Non-parallelism error of guider bars

Considering the parallelism of these two bars as a default, the existence of even a very small angle between them, causes exponential increase in the motive forces along the guiding axis. Although calculation and compensation of these forces is very difficult, but they can be measured in stabilized state.

5. Driving CNC motors

The last control–execution layer in open-architecture control systems is driving of the motor of any axis. Increment of frequency synchronous to increment in voltage and switching current in switching elements, which are the main elements of driving circuit, causes an increase driving precision in torque and rotational speed of motors and improves the adaptability with the microprocessors. Figure 3 shows schematic diagram of driving a DC motor.

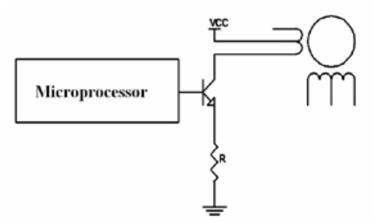

Fig. 3. General idea of driving a DC motor

Optimization in driver's circuit design to switch more voltage and current with the higher frequency from power supply to motor, improves motor's mechanical characteristics such as torque and better control of angular speed.

In CNC systems as a special case, the capability of producing higher torque with the least volume of motor, maximum velocity controllability and decreasing of heat loss energy are the desired properties of a motor.

6. Mathematical model for DC motor

To analyse the DC motors that are used in control systems, their mathematical modelling is necessary. The models with permanent magnet and separate magnetic excitation are only different in characteristics of magnetic fields. Figure 4 shows the equivalent circuit of a DC motor including; a coil as a resistance R_a in series with inductance L_a and e.m.f. Voltage e_b .

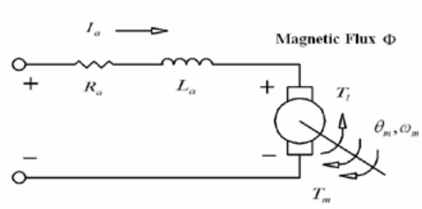

Fig. 4. A DC motor equivalent circuit

The output instantaneous torque of rotor $T_m(t)$, is directly proportional to magnetic flux (Φ) and the current in coil ($I_a(t)$), so:

$$T_m(t) = K_m.\Phi.I_a(t) = K_i.I_a(t) \quad (1)$$

The current appearance rate in coil is:

$$\frac{dI_a(t)}{dt} = \frac{1}{L_a}.e_a(t) - \frac{R_a}{L_a}.I_a(t) - \frac{1}{L_a}e_b(t) \qquad (2)$$

In which $e_a(t)$ is instantaneous voltage of coil. The e.m.f. Voltage $e_b(t)$ is given as:

$$e_b(t) = K_b \frac{d\theta_m(t)}{dt} = K_b \omega_m(t) \qquad (3)$$

$\theta_m(t)$ and $\omega_m(t)$ are instantaneous displacement and angular speed of motor respectively.

Angular acceleration of the motor is a function of resistive factors (such as angular moment of inertia J_m, loading torque $T_l(t)$, the viscous friction coefficient of air gap B_m) and motive factors, so that:

$$\frac{d^2\theta_m(t)}{dt^2} = \frac{1}{J_m}.T_m(t) - \frac{1}{J_m}.T_l(t) - \frac{B_m}{J_m}.\frac{d\theta_m(t)}{d(t)} \qquad (4)$$

With definition of $I_a(t)$, $\omega_m(t)$ and $\theta_m(t)$ as the variable parameters of system we have:

$$\begin{bmatrix} \frac{dI_a(t)}{dt} \\ \frac{d\omega_m(t)}{dt} \\ \frac{d\theta_m(t)}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & -\frac{K_b}{L_a} & 0 \\ \frac{K_i}{J_m} & -\frac{B_m}{J_m} & 0 \\ 0 & 1 & 0 \end{bmatrix} . \begin{bmatrix} I_a(t) \\ \omega_m(t) \\ \theta_m(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \\ 0 \end{bmatrix} .e_a(t) - \begin{bmatrix} 0 \\ \frac{1}{J_m} \\ 0 \end{bmatrix} .T_l(t) \qquad (5)$$

From this equation the transformation function of rotor displacement and input voltage can be calculated:

$$\frac{\Theta_m(s)}{E_a(s)} = \frac{K_i}{L_a J_m s^3 + (R_a J_m + B_m L_a)s^2 + (K_b K_i + R_a B_m)s} \qquad (6)$$

In this equation the amount of torque of the load ($T_l(t)$) is negligible, then, $\Omega_m(s)$ the speed of motor will be as follows:

$$\Theta_m(s) = \frac{1}{s}\Omega_m(s) \qquad (7)$$

Apart from the creation of magnetic field, suppose the value of Φ as magnetic flux of the gap is constant, then the output torque of motor will be:

$$T_m(t) = K_m.\Phi.I_a(t) = K_i.I_a(t) \qquad (8)$$

K_i is constant so the variations of output torque of DC motor with input current will be linear (Fig. 5).
In steady state condition the self-inductance will be zero, so, the output torque of rotor will be:

$$T_m = K_i I_a = \frac{K_i(E_a - K_b.\Omega_m)}{R_a} \qquad (9)$$

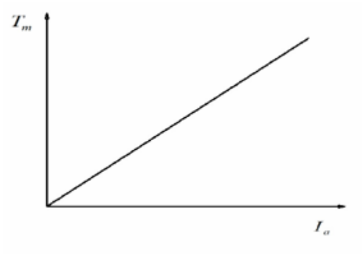

Fig. 5. Diagram of Torque/Current for a DC motor

The inclination of torque-angular speed curve is (see Figure 6):

$$\frac{dT_m}{d\Omega_m} = -\frac{K_i K_b}{R_a} \qquad (10)$$

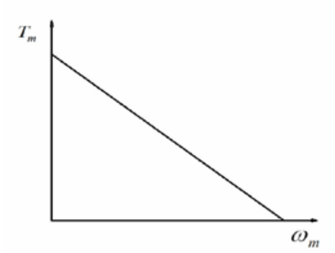

Fig. 6. Diagram of Torque/Angular Speed for a DC motor

7. PWM circuit and current control

In usual methods reaching the desirable torque and motor speed is related to the nominal amount of current in coil. In pulse width modulation method, the speed control method of DC motors, with a high frequency switching element, which may usually be a kind of FET or MOSFET, is used to drive the motor. Control signals with determined frequencies are delivered from a microprocessor circuit to driver. The ratio of duty cycle of pulses determines the input motor voltage and its rotary speed [15].

When the duty cycle ratio of driving circuit pulse controller is determined by the sampling of current of coil, then the coil's current can be controlled on line. The schematic of this system is shown in Fig. 7.

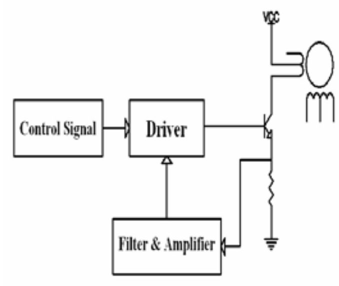

Fig. 7. Block-diagram of a free-running PWM driver

Determination of instantaneous coil current is important since the amount of current needed can be delivered to the motor regarding to the loading conditions. The first benefit of such a system is the reduction of electrical energy losses as heating and also long lasting of fixed magnet in motor structure.

A PWM free-running circuit uses a resistance with high current transmission capability as a current sampler that is in conjunction with current phase to earth. The phase current can be defined after voltage determination between two ends of resistance. This voltage is compared with a reference one after amplification and filtration. In fact, this reference voltage determines the allowable current of phase and can be controlled on time from output of microprocessor by a digital to analogue converter. A phase diagram of DC/stepper motor, which is controlled with free-running PWM circuit at constant current, is shown in Fig. 8.

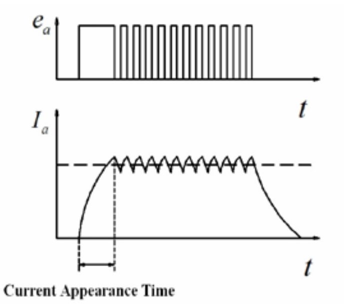

Fig. 8. Current effect of a free-running PWM driver

8. Resistive force along axis

To determine the gradient of resistance forces in a motive system, a PWM free-running circuit is used. It is supposed that digital positioning sensors define the situation of axis at anytime. The least OAC system requirements that can organize a database of positioning/resistive torque of any axis are:

1. PWM free-running circuit with variable reference voltage for every motor axis driving;
2. Input/output software to set up PWM parameters and catch the position of any point;
3. Data transmission protocol from/to personal computer.

As the first step, the whole axes except the one engaged in resistive force measuring process are mechanically fixed to a point. For resistive force measurement, which is relevant to a resistive torque on the shaft of motor, first of all, a low level voltage as PWM reference voltage is written on engaged motor. Then the system waits for a standard response from positioning sensors, which can be considered as a number of pulses in a period of time. After passing through a short distance the system will be stopped and the lowest level of the voltage according to the lowest motor's output torque will be written to PWM reference voltage again. If the system does not give a standard response, the reference voltage increases slowly until desirable motion conditions will be obtained. The data sets as reference voltage, situation of axis and motion instructions will be handled by input/output hardware and corresponding software between personal computer in one hand and DSP hardware, the controller of motion, speed and torque on the other hand. Finally, a simple database consisting of the position of axis and PWM reference voltage will be created in the personal computer and ready for processing. In execution of this algorithm, a decrease in measuring limits means an increase in measurement accuracy.

9. Obtained data processing

The results obtained from measurement can be used as a raw data to determine needed coil's current at corresponding positions. So that the motor coil's current axis (i), which is linearly proportional to motor's output torque, according to the motor's necessity at any point, can be determined by PWM reference voltage of motor driving circuit and applying a safety coefficient factor. It is necessary to mention that the control of speed is quite different from the control of the torque, and it is being done by continuous variation of coil voltage. Since decreasing in coil voltage causes dropping in nominal current appearance and afterwards decreasing in desired torque, it is necessary to use a control method for coil's mean voltage without any decreasing in power supply voltage. PWM is the best velocity control method due to the mentioned conditions. In this method a series of frequency constant pulses are used for coil's mean voltage determination, so that; final mean voltage defines by the duty cycle of these pulses. Synchronous execution of this method is not in contradiction with the philosophy of power voltage cutting, which is accomplished by PWM free-running circuit to determine the coil current. Pulse feeding is considered to be the same as continuous power supply.

We can use a theoretical relationship between reference voltage and position instead of continuous referring to database. For example the theoretical equation of reference voltage and position can be based on Lagrange formula of extrapolation of $N-1$ degrees polynomial as:

$$V_i = F(x_i) \quad : i = 1,2,...,N \tag{11}$$

$$V(x) = \sum_{j=1}^{N} P_j(x).F(x_j) \tag{12}$$

$$P_j(x) = \prod_{\substack{n=1 \\ (n \neq j)}}^{N} \left(\frac{x - x_N}{x_j - x_N} \right) \tag{13}$$

If N is very large, then calculation will be very complex and direct use of database may be justified. Figure 9 is a schematic diagram of measured reference voltage on a typical axis.

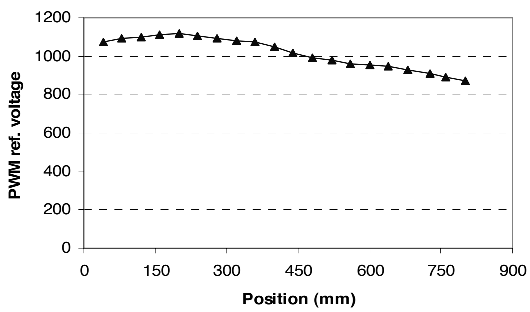

Fig. 9. Diagram of measured ref. voltage along an axis

Flow chart (Fig. 10) also shows the execution method of control process of motor current.

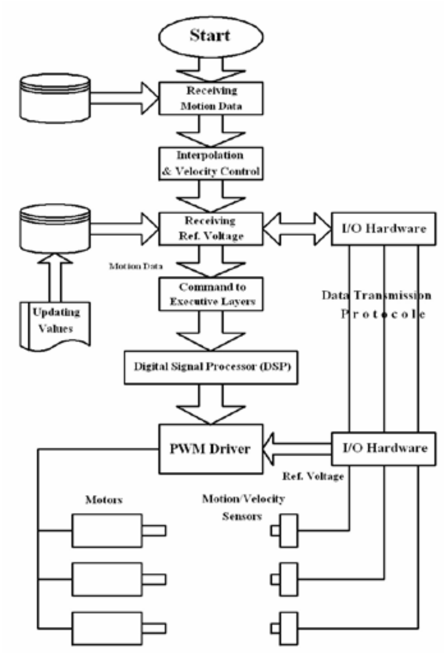

Fig. 10. Execution flowchart of dynamic torque control algorithm

10. Simulation and execution

The control algorithm of motor torque for a two axis CNC cutting system with two- guider bars suspension system used to prepare metal sheets for tension test is designed and executed on an open-architecture control system (Fig. 11).

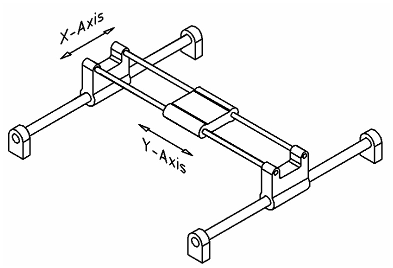

Fig. 11. A two-guider bars suspension system

A control board based on Intel® 8051 micro controller, which is connected to computer by RS232 protocol, as DSP hardware. The software of trajectory interpolation, speed control and also connecting interface to databases containing coordinates and PWM reference voltage is written in Visual BASIC. In execution layer two DC servomotors to axes driving and PWM circuits to drive any phase are used (Fig. 12).

For example 5V in PWM reference results in 2Amp. /phase feeding current in cutting. Voltage control method in coil for a desired speed is PWM control method with a frequency of 26.8 KHz. With regard to the usage of two guider bars for suspension of every axis, the non-parallelism error of these two guider bars is obvious on y-axis (Fig. 13).

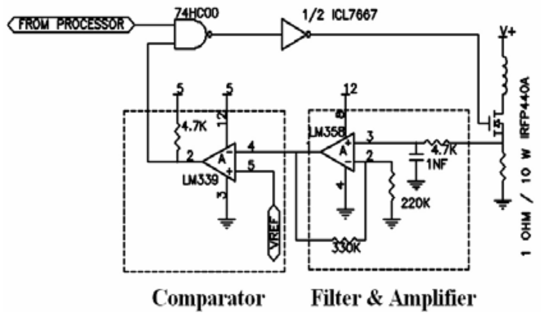

Fig. 12. The test bed PWM driver circuit

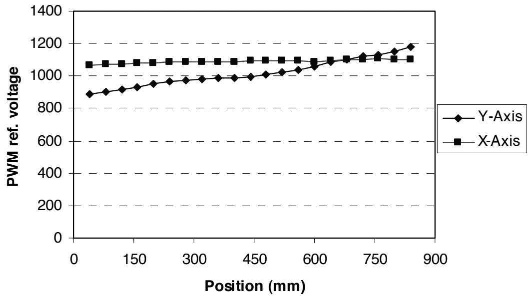

Fig. 13. Diagram of measured ref. voltage along two axes of a CNC cutting system

Figure 14 shows motive speed error across y-axis with and without using control algorithm of motor current.

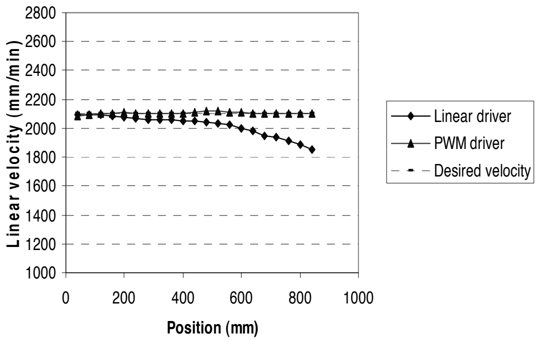

Fig. 14. Velocity of Y-axis driven with linear and PWM drivers

11. Conclusions

In this research a new control method for the current of motor coils in CNC systems has been presented. The results from measuring, simulation of motion and analysis of error diagrams are as follows:

- The advantages of a CNC system with open architecture controller such as simplicity in structure, independence of units and flexibility of software help the designer to execute simple and powerful algorithms with sufficient accuracy and speed. The schematic of such a system is introduced and has been manufactured as a sample.
- The current is being controlled by data output of positioning sensors and reference voltage is calculated from voltage/distance function. The distance, which is obtained from database, is interpolated with the mentioned data simultaneously. The data needed for rotation the calculated angle and rotational speed of each motor, are delivered to DSP hardware simultaneously with reference voltage in accordance to motive position. So, these multi-tasking cause no delay on control process on open-architecture CNC system.
- Regarding the database updating of resistance force versus the distance of each axis, it is possible to define a periodic control method to determine resistance forces of suspension CNC systems. With this method, it seems that, the accuracy of motion system especially the linear velocity will remain in an acceptable range.
- Analysis of linear speed's error in a system of two axes which are executed by free-running PWM driver circuit with constant and variable reference voltages shows that the continuous control of PWM reference voltage and afterwards the coil instantaneous current on each axis causes improvements in speed error and also increases the machined surface quality. Finally, increasing the working efficiency, decreases energy loss and motor drives life is improved.

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