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Dr.Durmuş Karayel

Address
Sakarya.University,.Sakarya M.Y.O., Mechatronics Program,
Sakarya, Turkey,

Phone
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Fax
(+90 264 2786518)

(include country and area codes)

Other authors:
Sinan Serdar OZKAN,.Ismet.Kandilli,

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ACTIVE CONTROL OF MACHINE TOOL SPINDLE VIBRATIONS USING AN ELECTROMAGNETIC BEARING

Durmus KARAYEL[*] Sinan Serdar OZKAN[**] İsmet KANDİLLİ[***]

e-mail: d_karayel@hotmail.com e-mail: s_ozkan74@hotmail.com e-mail: kan_67@hotmail.com

[*]*Sakarya University, Sakarya M.Y.O., Mechatronics Program,Sakarya, Turkey*

[**]*Sakarya University, Sakarya M.Y.O., Industrial Electronic Program, Sakarya, Turkey*

[***]*Kocaeli University, K.M.Y.O., Electronic Program, Kocaeli, Turkey*

Key words: Vibration control, Machine tool,Electromagnetic bearing

ABSTRACT

In this study, the three dimensional dynamic model of the milling machine was prepared. The relative displacements on the contact point of the cutting tool and the workpiece were obtained by the forced vibration analysis. This displacements affected the machining accuracy of the milling machine. Therefore, radial and axial electromagnetic bearings were designed for the active control of the system and they were adapted on the spindle of the milling machine. The system was run with active control and without active control and both cases were compared. It was seen that the active control decreased the cutting tool vibration and improve the machining performance.

I. INTRODUCTION

The machining is a very important production method for precision parts. A lot of studies were achieved to increase machine tool performance on cutting tools. So, the cutting tools, which were appropriate for high speed, were manufactured and the cutting capacities of cutting tools were increased. However, vibration which is a very important problem between cutting tool and work piece arised and it reduced the machining accuracy. This problem is very effective for milling machines because milling process' cutting forces, which arise unavoidably, appear a variable character. The response of the system for this kind of cutting force affective directly cutting process and machining accuracy. A lot of studies were achieved to solve this problem by researchers [1,2,3]. These studies consisted of the selection of optimum parameters. The using electromagnetic forces to control shaft vibrations have recently been a subject of attention from a number of researchers and successful applications of bearing. In this study, it is intended that the dynamics effects of the cutting forces on the spindle are decrease and the cutting performance is increased using an electromagnetic bearing. The cutting forces were obtained by the experiment and the simulation. The electromagnetic attraction forces were produced by the electromagnetic bearing according to the cutting forces.

II. THE MODEL OF THE CUTTING SYSTEM

In this study, the asymmetric face milling was considered for the model of the cutting forces. The cutting force components between the cutting tool and the work piece are following.

$$F_T = k_T \times A \tag{1}$$

$$F_R = k_R \times F_T \tag{2}$$

$$F_A = k_A \times F_T \tag{3}$$

These forces are correspond to the cutting tool' insert. If this cutting force components transform Cartesian coordinate (see figure 1). The cutting force components in x, y and z directions can be obtained as following;

$$F_x = -F_T \; Sin\theta_i + F_R \; Cos\theta_i \tag{4}$$

$$F_y = F_T \; Cos\theta_i + F_R \; Sin\theta_i \tag{5}$$

$$F_z(i,\phi) = F_A(i,\phi) \tag{6}$$

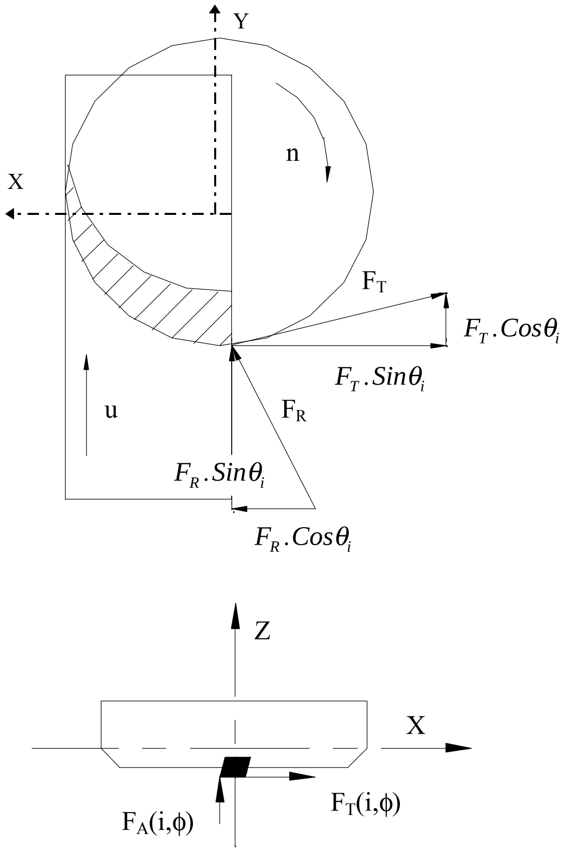

Figure 1. Cutting force components

However, two or more inserts can cut simultaneously. In these cases, the cutting force components are following,

$$\begin{Bmatrix} F_x(\phi) \\ F_y(\phi) \\ F_z(\phi) \end{Bmatrix} = \sum_{i=1}^{Z_c} \begin{bmatrix} -Sin(\theta_i(\phi)) & Cos(\theta_i(\theta)) & 0 \\ Cos(\theta_i(\phi)) & Sin(\theta_i(\phi)) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{Bmatrix} F_T(i,\phi) \\ F_R(i,\phi) \\ F_A(i,\phi) \end{Bmatrix} \tag{7}$$

These cutting force components have variable characteristic. So the cutting system (work piece – cutting tool – spindle) is affected from the forced vibrations. Therefore, the relative displacement between the cutting tool and the work piece arise and so new cutting force components take place. The dynamic model of the system which is consisting of the spindle, the cutting tool and the workpiece has been prepared using mass, spring and damper elements. The dynamic model has three dimension and six degree of freedom (see figure 2). The cutting force components have been obtained by both experiment and simulation. The experimental set up has been present at figure 3. The model has been excited by the cutting force components, which have been applied on (m_1) mass. The compensate electromagnetic forces have been applied on (m_2) mass. For the dynamic model of the cutting system, the equation of the motion;

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{F\} \tag{8}$$

In which [M] is the mass matrix, [C] is the damping matrix and [K] is the stiffness matrix of the system, and vectors $\{U\}$, $\{\dot{U}\}$, $\{\ddot{U}\}$ and $\{F\}$ are the displacements, velocities, accelerations and forces respectively.
Where; {F(t)} is the external force without electromagnetic bearing;

$$\{F(t)\} = \begin{Bmatrix} F_X \\ 0 \\ F_Y \\ 0 \\ F_Z \\ 0 \end{Bmatrix} \tag{9}$$

and with electromagnetic bearing;

$$\{F(t)\} = \begin{Bmatrix} F_x \\ F_x' \\ F_y \\ F_y' \\ F_z \\ F_z' \end{Bmatrix} \tag{10}$$

Cutting force components, which have been obtained by experiment and simulation studies, have been present in figure 4

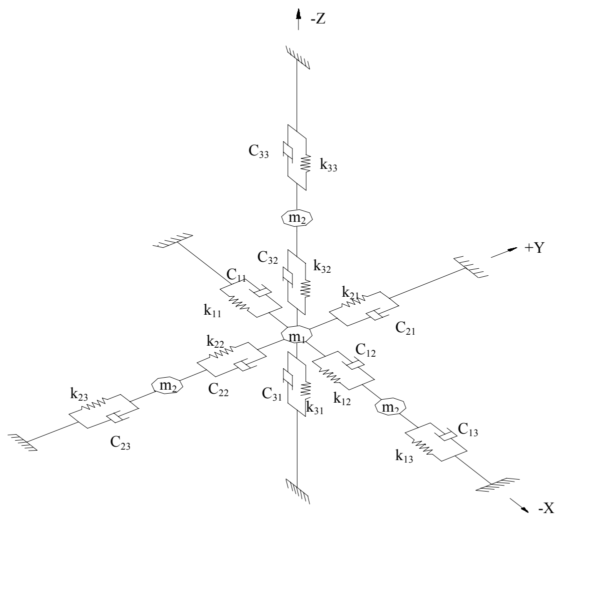

Figure 2. The dynamics model of the system

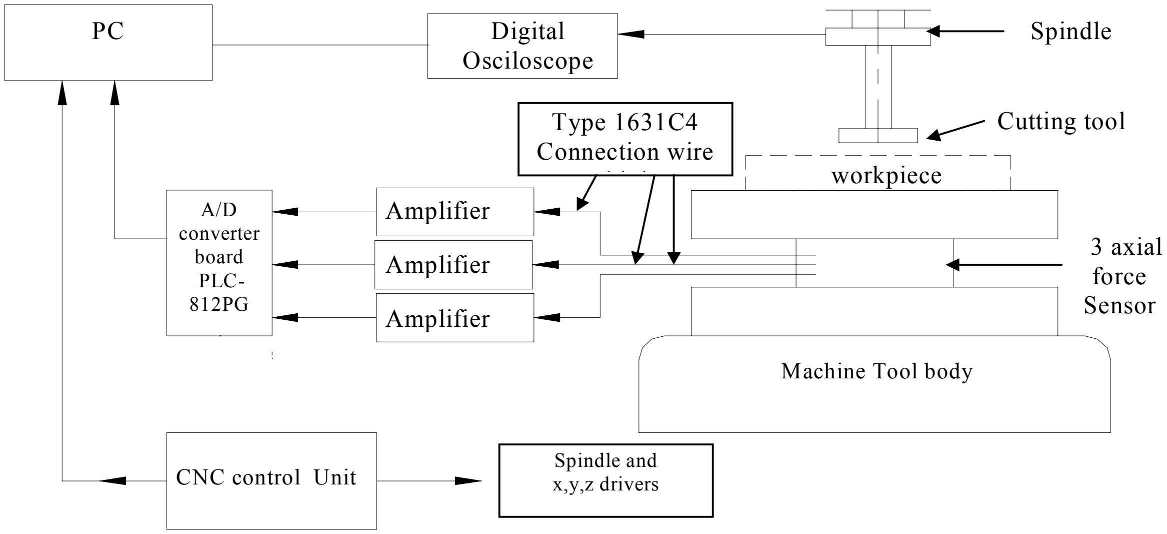

Figure 3. Experimental setup

III. ELECTROMAGNETIC SYSTEMS AND THEIR DRIVE ELECTRONICS

It is necessary that the forces in opposite direction to dynamic force components which effect on the spindle must be produced because the system must be prevented from undesired effects. These improving forces have been produced by electromagnets. The electromagnets configuration is shown in figure 5[7] and the block diagram of the electromagnet system designed for the present study is shown in figure 6 [8]. Each power amplifier, A, which drives a magnet coil, C, is of the

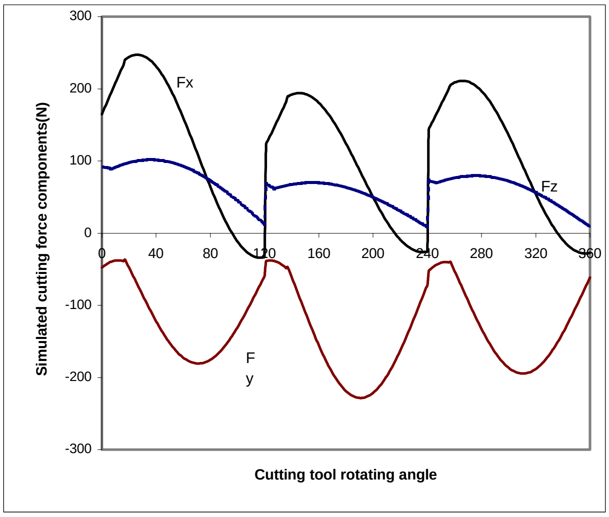

Figure 4(a) Simulated cutting force compenents

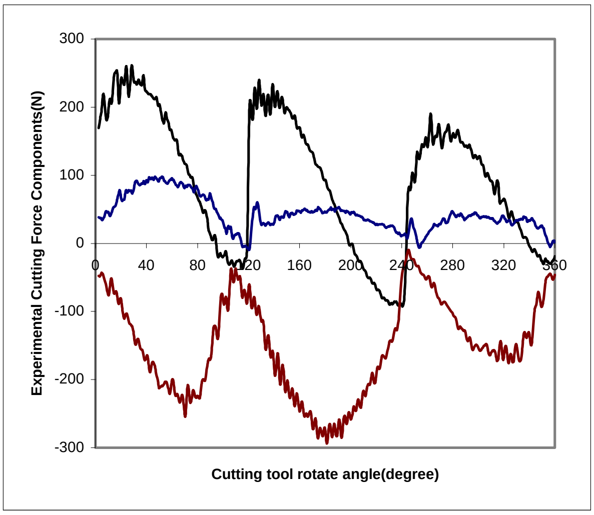

Figure 4(b). Experimental cutting force components

Switching type, employing pulse – width modulation to reduce power losses. There are two electromagnets. One of them is radial and the other is axial. The radial magnet electromagnet consists of four radial poles and the axial electromagnet has one pole.

An electromagnet exerts a force approximately proportional to the square of the magnet flux present at the pole face. It is also unstable in an open loop mode since, as the deflection increases towards a magnet, so does the attractive force from that magnet. The system can, however, be made stable feeding back a signal (V_H) by a Hall probe, which is proportional to the flux at the pole face. For any given coil and its series resistance, R, the supply voltage, V, inductance, L, is given by:

$$V = L\frac{di}{dt} + iR \tag{11}$$

Where (i) is the current passing throught the coil. Thus;

$$\frac{I}{V} = \frac{1/R}{L(L/R)+1} \tag{12}$$

Now, consider the electromagnet in (x) direction;

$$\vartheta_{ix} = S_x - \vartheta_{Hx} \tag{13}$$

Where (Sx) is a signal which takes place in D/A converter output and calculated by PC for the spindle stabilation. ϑ_{ix}

is the input voltage to the corresponding amplifier and ϑ_{Hx} is proportional to the flux ϕ_x at the probe face. This flux is also inversely proportional to the gap (Z_x), between the magnet face and the spidle while the flux is proportional to the current, i_x, in the magnet coil.

So, $\vartheta_{Hx} = K_x \phi_x$ and;

$$\vartheta_{ix} = S_x - K_x \phi_x = S_x - K_x K \frac{i_x}{Z_x} \qquad (14)$$

$$\vartheta_{ix} = S_x - \frac{K_x K}{Z_x} \frac{\vartheta_x / R_x}{(L \quad L_x / R_x + 1)} \qquad (15)$$

$$\vartheta_x = a \vartheta_{ix} \qquad (16)$$

If equation (17) is replaced in equation (14) where (a) is the amplifier gain.
Hence

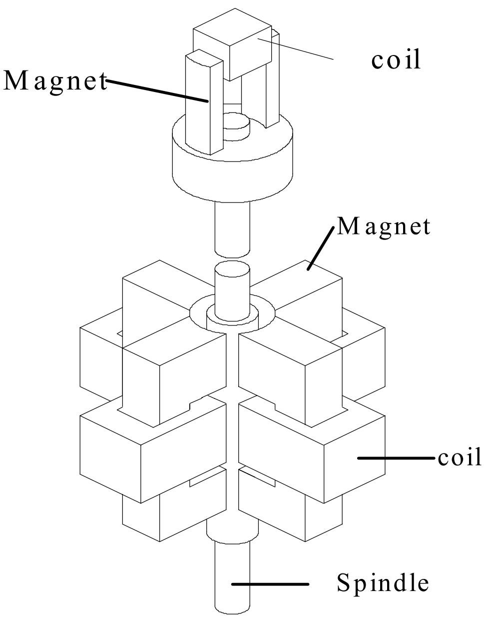

Figure 5. The electromagnetic bearing

$$\vartheta_{ix} = S_x \Big/ \left[1 + \frac{K_x K \ a \ / R_x}{Z_x (L L_x / R_x + 1)} \right] \qquad (17)$$

$$\phi_x = S_x \Big/ \left[K_x + \frac{(L L_x / R_x + 1) Z_x}{a \ K / R_x} \right] \qquad (18)$$

Hence, if (a) is large enough,

$$\phi_x \cong S_x / K_x \qquad (19)$$

The attraction force produced by the magnets can be obtained as following;

$$F'_x = \frac{\phi_x^2}{2 \mu A} \qquad (20)$$

Where μ is magnetic permeability coefficient ($\mu = \mu_0 . \mu_r = 4\pi . 10^{-7}$) and A is the cross – section of magnetic flux route.
If equation (19) is replaced in equation (20)

$$F'_x \cong \frac{Sx^2}{Kx^2 \, 2 \mu A} \qquad (21)$$

is obtained.

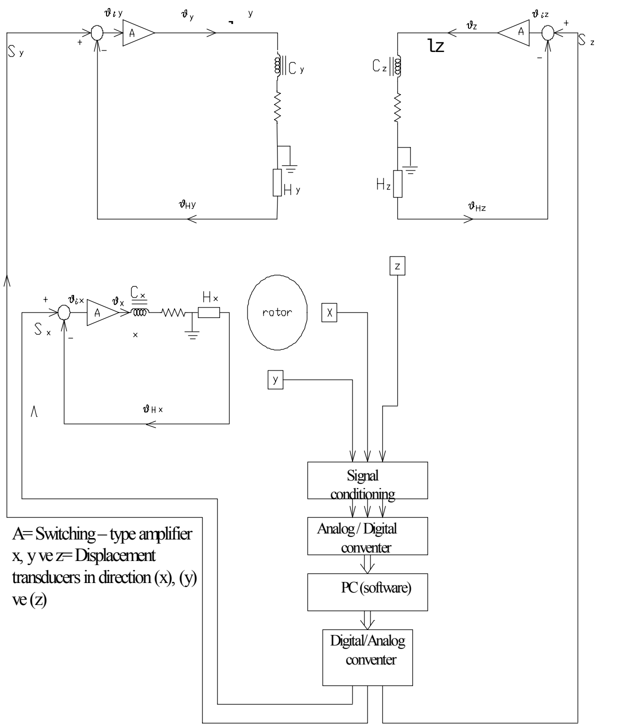

Figure 6. Schematic plot of the control system

From the last equation, it is seen that the attraction force (F'_x) is proportion with square of S_x because K_x, μ and A are constant parameters. The similar equations can be used for y and z axis. The attraction forces obtained by the system simulation have been presented in figure 7.

IV. CONCLUSIONS

The displacements of (m_l) node have been obtained in directions x, y and z replacing the cutting force components in figure 7. Because the displacements of 1.node (m_1) are criteria which express machining quality according to cutting dynamics. As know, if the relative displacement in the cutting area increase, machining quality is negatively effected and on the contrary machining quality is positively effected. The displacement components which have been obtained for (m_1) node have been presented in figure 8 without the electromagnetic bearing and in figure 9 with the electromagnetic bearing. It has been observed that the electromagnetic bearing has affected the response of the system when figure 8 and figure 9 are compared.

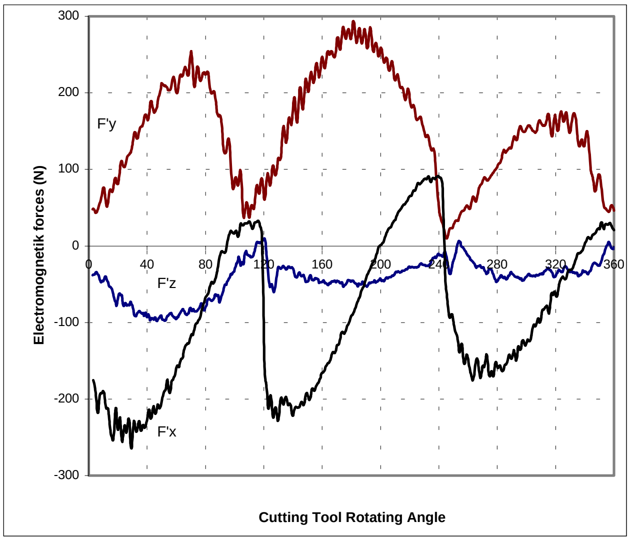

Figure 7. Electromagnetic forces corresponding experimental excitation forces

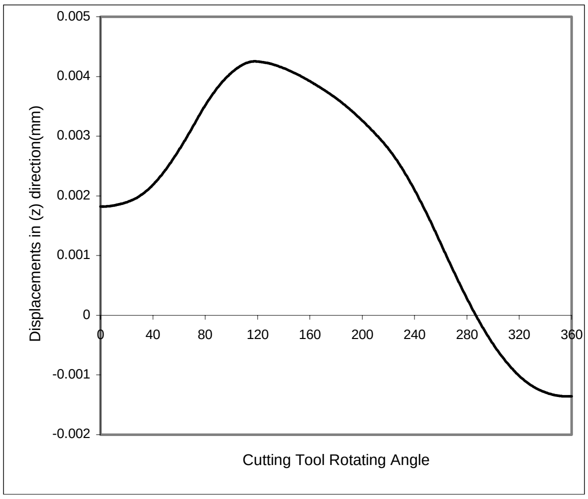

Figure 8. Displacements without electromagnetic bearing

As a result, it is possible that a machine tool with electromagnetic bearing has high cutting capacity. This case means to increase the machine tool performance. Active control of machine tools spindle vibrations using an electromagnetic bearing is a very suitable control for precision manufacture.

It is expected that this active control method will be applicable to a variety of machine tools.

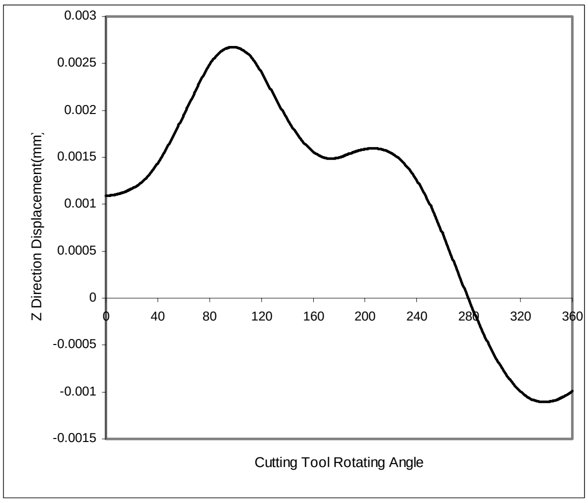

Figure 9. Displacements with electromagnetic bearing

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