POSITION CONTROL METHOD OF A NON-CONTACTING CONVEYANCE SYSTEM FOR STEEL STRIP

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Abstract: Electromagnetic application system to improve the surface quality of steel strip is getting popular because customers demand better surface quality of steel strip. To realize such a requirement, non-contact conveyance methods by means of air floater and electromagnetic levitation and propulsion were considered. However, air floating method is not easy to control of the position of steel strip since the system is highly nonlinear. And thus, the application of a magnetic levitation and propulsion to steel strip conveyance is suitable. Sensors measuring positions of steel strip also need to be non-contact in order to maintain non-contact and simple characteristics of the system. This paper proposes the method of the spatial position estimation of steel plate without using sensors. This method simplifies non-contact conveyance system and cuts down expenses of the system. Spatial positions of steel strip can be estimated by currents supplied for electromagnet to maintain a fixed air gap. Estimated positions are then fed back into the control system to do position control. Computer simulation and experimental results are provided to verify the suitability of the proposed system performance and concept.

1 INTRODUCTION

In 1990s, various kinds of research activities were conducted to convey steel strips by means of non-contacting methods. One of them was electromagnetic conveyance technology. At first, most researchers were focused on reducing vibration of steel strip. (Liu and Yao, 2002). Later on, University of Tokyo conducted very promising research of levitation and propulsion of steel strip via electromagnetic force. (Hayashiya, and et el, 1999).

Steel making industries produce and treat large amounts of thin steel strips in cold rolling processes to obtain high quality steel strips using various ways. Actually, steel strips are processed at high speed in continuous cold rolling process lines. Because of this, vibration and position deviation of steel strip are the main hazardous problems which cause surface defects and lower productivity. The non-contact operation and the quick response mechanism can be considered to solve the above mentioned problems. Applications of electromagnetic force can be one of the useful technical approaches. (Liu and Yao, 2002).

Electromagnetic application system to improve the surface quality of steel strip is getting popular because customers demand better surface quality of steel strip. To realize such a requirement, non-contact conveyance methods by means of air floater and electromagnetic levitation and propulsion were considered. However, air floating method is not easy to control of the position of steel strip since the system is highly nonlinear. And thus, the application of a magnetic levitation and propulsion to steel strip conveyance is suitable. Sensors measuring positions of steel strip also need to be non-contact in order to maintain non-contact and simple characteristics of the system. This paper proposes the method of the spatial position estimation of steel plate without using sensors. This method simplifies non-contact conveyance system and cuts down expenses of the system. Spatial positions of steel strip can be estimated by currents supplied for electromagnet to

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maintain a fixed air gap. Estimated positions are then fed back into the control system to do position control. Computer simulation and experimental results are provided to verify the suitability of the proposed system performance and concept. (Gerber, 2002)

2 BACKGROUND

Non-contacting conveyance system by means of electromagnetic force can be seen in Figure 1. The system should generate normal, thrust, and guidance forces in order to maintain steel strip under control. The system is now then designed based on the above concept.

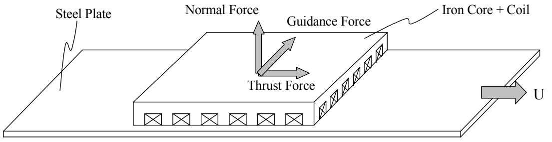

Figure 1: Non-Contacting System Concept.

Figure 2 shows the schematic diagram of the non-contact conveyance system. $N \cdot i$ shows the magnetomotive force and Φ means magnetic flux. Reluctance, $\Re$, can be a clearance at the middle of E-shaped core. Reluctance, $\Re$, can be expressed as equation (1) in terms of the area, A, at the middle of E-shaped core. (Roters, 1951).

$$\Re = \frac{z}{\mu_0 A} \tag{1}$$

where μ_0c is the permeability in the air which can be set as $4\pi \times 10^{-7}$ H/m.

As shown in Figure 1, reluctance on both sides can be twice as much as the center part of E-shaped core, since the area on both sides is half of the middle part. The equivalent reluctance, $\Re_{eq}$, can be obtained as shown in equation (2).

$$\Re_{eq} = \Re + \frac{1}{\frac{1}{2\Re} + \frac{1}{2\Re}} = 2\Re \tag{2}$$

From equation (2) and Ohm's law, applied magnetic field, $\Im$, can be expressed by equation (3),

$$\Im = \int \mathbf{H} \cdot d\mathbf{l} = N \cdot i \tag{3}$$

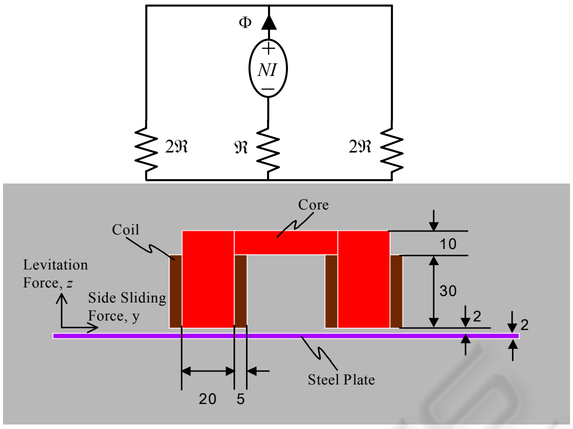

Figure 2: Schematic Diagram of the System.

Where N and i shows number of turns and applied current to the coil. Magnetic flux can be computed by using applied magnetic flux $\Im$ and equivalent reluctance $\Re_{eq}$ with Ohm's law as follows (Trumper, Weng, Ritter, 1999),

$$\Phi = \frac{\Im}{\Re_{eq}} = \frac{Ni}{\Re_{eq}} \tag{4}$$

Hence, flux linkage with N turns of coils can be expressed as shown in equation (5).

$$\lambda = N\Phi = \frac{N^2 i}{\Re_{eq}} \tag{5}$$

Applied current, i, to the electromagnet can induce some amount of force to the steel strip. The induced force to the steel strip can be expressed by magnetic force, f_e.

$$f_e = \frac{\partial W_c}{\partial z} \tag{6}$$

Where magnetic energy, W_c, can be obtained as follows,

$$W_c = \int_0^i \lambda dt \tag{7}$$

Equation (7) can be obtained by integrating equation (5) with respect to time and differentiate partially with respect to the moving direction. f_e is induced force with respect to applied current i and clearance z.

$$f_e = -\frac{\mu_0 A N^2}{4} \cdot \left(\frac{i}{z}\right)^2 \qquad (8)$$

Induced force, $\boldsymbol{f_e}$, can be negative when the electromagnet attracts the thin steel strip. In other words, attractive force caused by the electromagnet can be expressed by negative force comparing with repulsive force (Choi and Baek 2002).

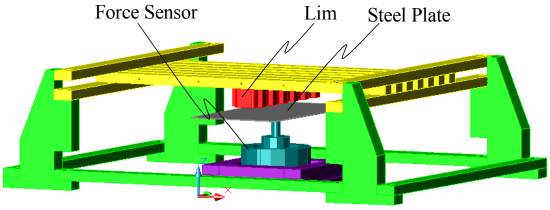

Figure 3: Configuration of the System.

3 SYSTEM DYNAMICS

This paper assumes that the steel strip should keep constant clearance and perpendicular position during its movement. The position estimation of the steel strip cannot be estimated correctly since current applied to the electromagnet is changed according to the inclined steel strip. In this paper, two assumptions were used to derive the equation of motion between the steel strip and the electromagnet. They are as follows: one is that the clearance is always constant, and the other is that the steel strip is always perpendicular to its moving direction.

The initial condition of the system is satisfied when $\boldsymbol{a=0}$. F_A is same as F_B and applied current has also the same amount at the initial condition. If $\boldsymbol{a}$ is not zero, F_A and F_B are not the same and applied current is also not the same, since the distance between the electromagnet and the center of gravity of the steel strip is changed and the force cannot be balanced any more. In other words, the forces applied to the steel strip from the electromagnet should be changed to keep the steel strip perpendicular in accordance with moving distance. The moving distance or the position of the steel strip can be estimated by the above mentioned things. (Nasar and Boldea, 1976).

Figure 4 shows that the steel strip has moved to the amount of $\boldsymbol{a}$ from the initial position toward x-direction.

F_A and F_B means the attractive forces to the points A and B, respectively. In this case, following two equations can be derived from the force and moment balance equations.

$$\sum F_z = 0\,;\; F_A + F_B = F_{steel} \qquad (9)$$

$$\sum M_y = 0\,;\; F_B(n+a) - F_A(n-a) = 0 \qquad (10)$$

The above two equations can be expressed in equation (11), where F_{steel} is steel strip weight, M_{steel} steel strip mass, and g the acceleration of gravity.

$$F_{steel} = M_{steel} \times g \qquad (11)$$

From equations (9) and (10), the following equation can be derived with respect to a,

$$a = q \cdot \frac{F_B - F_A}{F_{steel}} \qquad (12)$$

The equations about the applied current to each coil can be derived by using equation (13),

$$F_n = \frac{\mu_0 A N^2}{4}\left(\frac{i_n}{z}\right)^2 \qquad (n = A, B) \qquad (13)$$

By substituting equation (13) into equation (12), the moving position $\boldsymbol{a}$ can be expressed with respect to the applied current as shown in equation (13),

$$a = \frac{\mu_0 A N^2 q}{4} \cdot \frac{i_B^2 - i_A^2}{F_{steel}} \qquad (14)$$

or the following equation can be derived from equation (8),

$$a = q \cdot \frac{i_B^2 - i_A^2}{i_B^2 + i_A^2} \qquad (15)$$

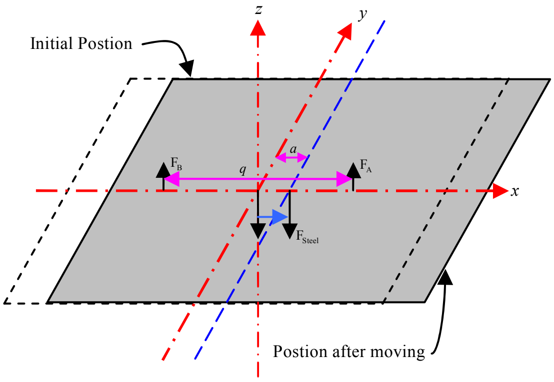

Figure 4: Movement of the Strip.

4 CONTROL SYSTEM

Levitation force (Normal force) can be described by ***y*** and ***i**_pc_*, where ***y*** is the air gap between electromagnetic core and steel strip and ***i**_pc_* is DC offset, respectively. Thrust force can be expressed by equation (16) and (17), by assuming that the frequency of power is fixed and AC power alone takes charge of control. (Fujisaki, 2001).

$$F_y = f(y, i_{DC}) \tag{16}$$

$$F_y = f(i_{AC}) \tag{17}$$

where, i_{AC} is the maximum value of AC current.

Equations of motion can be obtained by the following:

$$\begin{aligned} M\ddot{x} &= F_x - K_{dx}\dot{x} \\ M\ddot{y} &= F_y - Mg - K_{dy}\dot{y} \end{aligned} \tag{18}$$

Where, M is the mass of the strip, F_x is thrust force, g is graivity, K_{dx} is the friction coefficient in the x direction, K_{dy} is the friction coefficient in the y direction.

From equations of motion, the following equation can be obtained.

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{d} \tag{19}$$

where,

$$\boldsymbol{x} = \begin{bmatrix} x \\ v_x \\ y \\ v_y \end{bmatrix}, \quad \boldsymbol{u} = \begin{bmatrix} F_x \\ F_y \end{bmatrix}, \quad \boldsymbol{d} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -g \end{bmatrix},$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\frac{K_{dx}}{M} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\frac{K_{dy}}{M} \end{bmatrix}, \quad \boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ \frac{1}{M} & 0 \\ 0 & 0 \\ 0 & \frac{1}{M} \end{bmatrix} \tag{20}$$

Control inputs can be derived by the following equations:

$$F_x = K_{xP}(x_d - x) + K_{xD}(v_{xd} - v_x) + K_{xI}\int(x_d - x)dt + M_x a_{xd} + K_{dx}v_{xd} \tag{21}$$

$$F_y = K_{yP}(y_d - y) + K_{yD}(v_{yd} - v_y) + K_{yI}\int(y_d - y)dt + Mg + M_y a_{yd} + K_{dy}v_{yd} \tag{22}$$

where, v_x and v_y are velocities in the direction of x and y, respectively. Feedback gains are as follows: (Choi and Baek, 2002)

$$K_P = \begin{bmatrix} K_{xP} & 0 & 0 & 0 \\ 0 & 0 & K_{yP} & 0 \end{bmatrix},$$

$$K_I = \begin{bmatrix} K_{xI} & 0 & 0 & 0 \\ 0 & 0 & K_{yI} & 0 \end{bmatrix},$$

and

$$K_D = \begin{bmatrix} K_{xD} & 0 & 0 & 0 \\ 0 & 0 & K_{yD} & 0 \end{bmatrix} \tag{23}$$

Now, currents can be applied as follows:

$$I_A = F_y + F_x \cdot a \cdot \cos(2\pi ft + 0) \tag{24}$$

$$I_B = F_y + F_x \cdot a \cdot \cos\left(2\pi ft + \frac{\pi}{3}\right) \tag{25}$$

$$I_C = F_y + F_x \cdot a \cdot \cos\left(2\pi ft + \frac{2\pi}{3}\right) \tag{26}$$

where, a is AC magnitude weighting factor.
The overall control system can be designed as shown in figure 5.

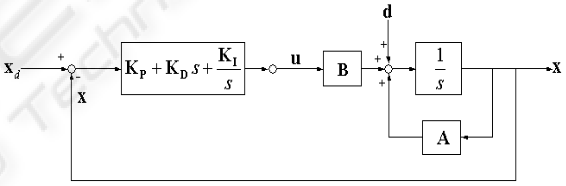

Figure 5: Control System Diagram.

5 POSITION ESTIMATION OF STEEL STRIP

The center of gravity of the steel strip is positioned in the middle of two equal spaced electromagnets. In this experiment, the steel strip is moving to the x-axis while it is lifted. Figures 6 through 8 show the experimental results. Figure 6 shows that the lifted steel strip can keep the constant clearance and stable. Figure 7 depicts the fluctuating current during the steel strip movements to the x-axis. Figure 8 is the compared positions of the steel strip as the steel strip moves to the x-axis. These graphs are the estimated position, the measured and filtered value by laser position sensor. (Nakagawa, 2000).

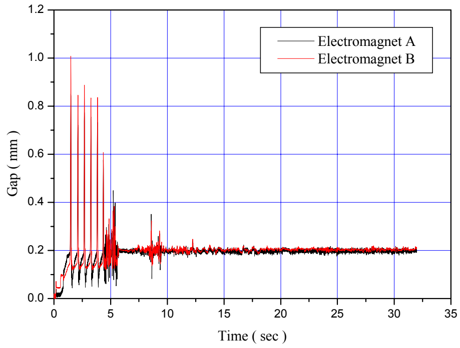

Figure 6: Air gap.

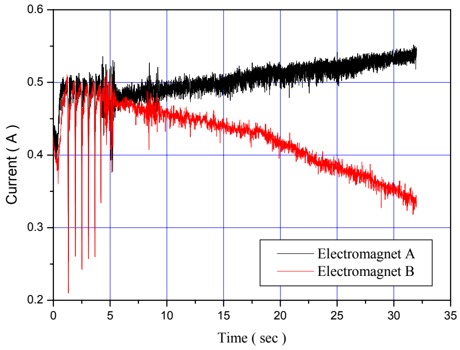

Figure 7: Current.

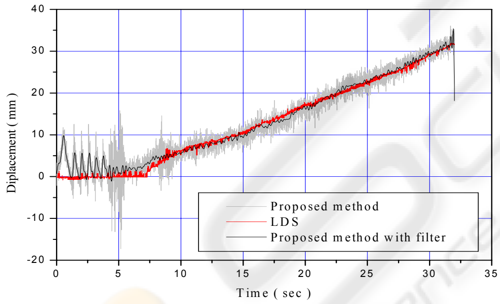

Figure 8: Position of a Moving Steel Strip.

6 RESULTS

A non-contact conveyance of the steel strip by electromagnets has been proposed to show that the applied current can be changed in accordance with the movement of the levitated steel strip. The position estimation method of the steel strip by the applied current has also been proposed and tested in the constructed non-contact steel strip conveyance system. The estimated position of the steel strip has been compared the measured one by a laser position sensor. The estimated position of the steel strip shows satisfactory results comparing with the measured one. Non-contact sensors are very expensive and some of them make system complicated. To eliminate sensors, this paper proposes the method of the spatial position estimation of steel strip without sensors. This method simplifies non-contact conveyance system and cuts down expenses. The spatial position of steel strip with currents supplied for electromagnet was estimated and used to maintain a fixed air gap. And the theoretical analysis was verified by experiments and shows good control performance.

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