

Strip lateral position control using electromagnets in continuous processing line

Yusuke ISHIGAKI* and Yoshiaki NISHINA*

* Mechanical Engineering Research Department, JFE Steel Corporation
1-1 Minamiwatarida-cho, Kawasaki-ku, Kawasaki, Kanagawa 210-0855, Japan
E-mail: y-ishigaki@jfe-steel.co.jp

Received 5 November 2014

Abstract

In continuous metal strip processing lines, such as pickling, annealing and surface treatment lines, lateral instability of strips is a common problem. Strip lateral movement has a bad influence on productivity of the processing lines. A simple and effective device to control a lateral position of a strip is required because conventional preventions such as a steering roll and crown roll are not effective. In this study, a method of controlling a strip lateral position using electromagnets was investigated. First, theoretical equations were derived to predict capability to control a strip. Next, the derived theory was verified compared with lab experiments. The results obtained can be summarized as follows: (1) The theoretical equations of velocity of lateral movement are derived from inclination when the strip is attracted by electromagnet(s). The inclination is calculable from geometric relation. (2) It is found that the theoretical equations are valid by lab experiments in the conditions of changing attracting displacement and line speed. Controlling lateral movement using electromagnets is possible, and the control capability can be estimated by the derived theory. (3) The velocity of lateral movement in the case of attracting the half of strip width is three times as fast in the case of attracting the edge of the strip.

Key words : Strip, Strip position, Lateral dynamics, Electromagnet, Steering device

1. Introduction

In continuous metal strip processing lines, such as pickling, annealing, and surface treatment lines, lateral instability of strips is a common problem. Large-scale lateral movement causes quality defects of a strip like abrasions and elongations, and needs to restrict line speed to avoid line troubles. Strip lateral movement has a bad influence on productivity of the processing lines.

It is important to clarify a mechanism of strip lateral movement in order to prevent strip lateral movement. The mechanism of strip lateral movement has been studied. For example, lateral dynamics of a moving web were studied fundamentally, (Shelton and Reid, 1971). Relationship between strip lateral movement on a roll and a shape of the roll was investigated based on deformation of the strip, (Sasaki, et al., 1984, Fukushima, et al., 1993). A simulator of strip lateral movement was developed considering a strip as a spring-mass system, (Suzuki and Kikuchi, 1991). Control logic was studied based on modeling of strip lateral movement, (Yerashunas, et al., 2003, Shin and Kwon, 2007). In addition, strip lateral movement is important in various fields as well as the field of metal strip processing. In film processing, controlling for edge alignment was investigated, (Huang, et al., 2007). In the field of OA equipments such as printers and facsimiles, paper feed mechanism was studied, (Nishimura, 1981). In a belt conveyor system, simulations based on multibody dynamics were conducted to examine belt mistracking, (Kobayashi and Toya, 2008).

A steering roll and a crown roll are used conventionally to prevent unintentional lateral movement of a strip. But installing a steering roll is costly because a steering device needs much space and a construction range of existing facilities is large. Depending on the situation, an installation may be impossible. In the case of a crown roll, an extreme crown causes quality defects of strips, so the amount of crowns is slight and an effect is also small. Therefore, a simple and effective device to control a lateral position of a strip is required.

In the field of the metal processing, various methods have been developed to prevent lateral movement. For example, it was found that a strip lateral position was controllable by gas blowing, (Matoba and Ataka, 1988). A contactless control system by Lorentz force was developed, (Kamiyama and Uchida, 1993). Pinch rolls to prevent strip lateral movement were proposed and verified by experiments in a processing line, (Masui, et al., 2000, Kaseda, et al., 2001).

In this study, a simple method of controlling a strip lateral position using electromagnets was investigated. First, theoretical equations were derived to predict the capability to control a strip. Next, the derived theory was verified compared with lab experiments.

2. Theoretical study

2.1 Basic concept

Figure 1 shows a schematic diagram to explain a strip lateral position control using electromagnets. Electromagnets are placed at the back of a strip and incline the strip by attracting the one side of the strip lateral position in front of a roll. The inclined strip winds around the roll, and the strip moves to the lateral direction. The lateral movement of the strip occurs in the following procedures:

- (1) When a strip is attracted by an electromagnet at the one side of the lateral position, a new contact surface S occurs.
- (2) In the contact surface S, the strip inclines to the direction of rotation of a roll.
- (3) The strip in contact with the roll travels in the direction of roll rotation according to frictional force with the roll.
- (4) As the result, a point A moves to a point B' instead of a point B, and the point B moves to the point B' seemingly.

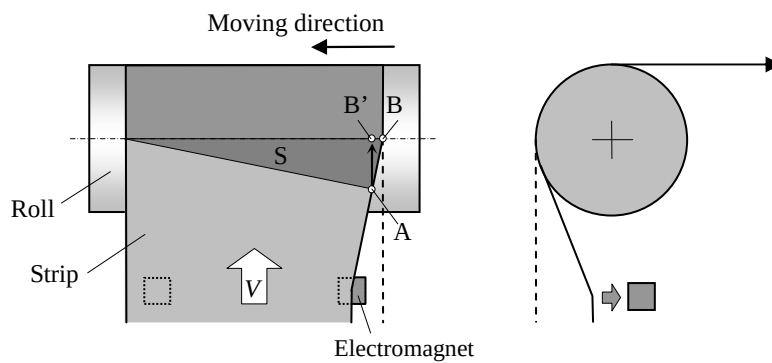


Fig. 1 Schematic diagram of strip lateral position control using electromagnet

It is possible to change the direction of lateral movement by changing electromagnets, and it is possible to change the velocity by changing an electric current of electromagnets.

2.2 Derivation of lateral position control theory

Basically, the lateral strip movement that occurs on continuous processing lines is due to an angle of inclination to the direction of roll rotation, as illustrated in Fig. 2. That is, when a strip rotates together with the roll in the condition where the strip is wound at an angle of inclination to the direction of roll rotation, the strip moves laterally. Velocity of lateral movement v_s can be found from geometric relation between the roll and the strip, and it can be expressed as follows using an average angle of inclination θ_s within the contact surface, line speed V , and strip width w .

$$v_s = V \tan \theta_s \quad (1)$$

$$\theta_s = \frac{1}{w} \int_0^w \theta(x) dx \quad (2)$$

Furthermore, as shown in Fig. 2, when the strip is linearly leaned at an angle of φ by attracting the edge of the strip

in a electromagnet position H , an angle of inclination $\theta(x)$ of the strip in a position of the strip width direction x is derived as

$$\theta(x) \approx \frac{d(x)}{H} = \frac{1 - \cos \varphi}{H} x = \frac{w - \sqrt{w^2 - z^2}}{H \cdot w} x \quad (3)$$

where $d(x)$ is the lateral displacement of the strip in the position of the strip width direction x , and z is the out-of-plane displacement of the strip in the position of the edge. Here, it is assumed that $\theta(x)$ is sufficiently small.

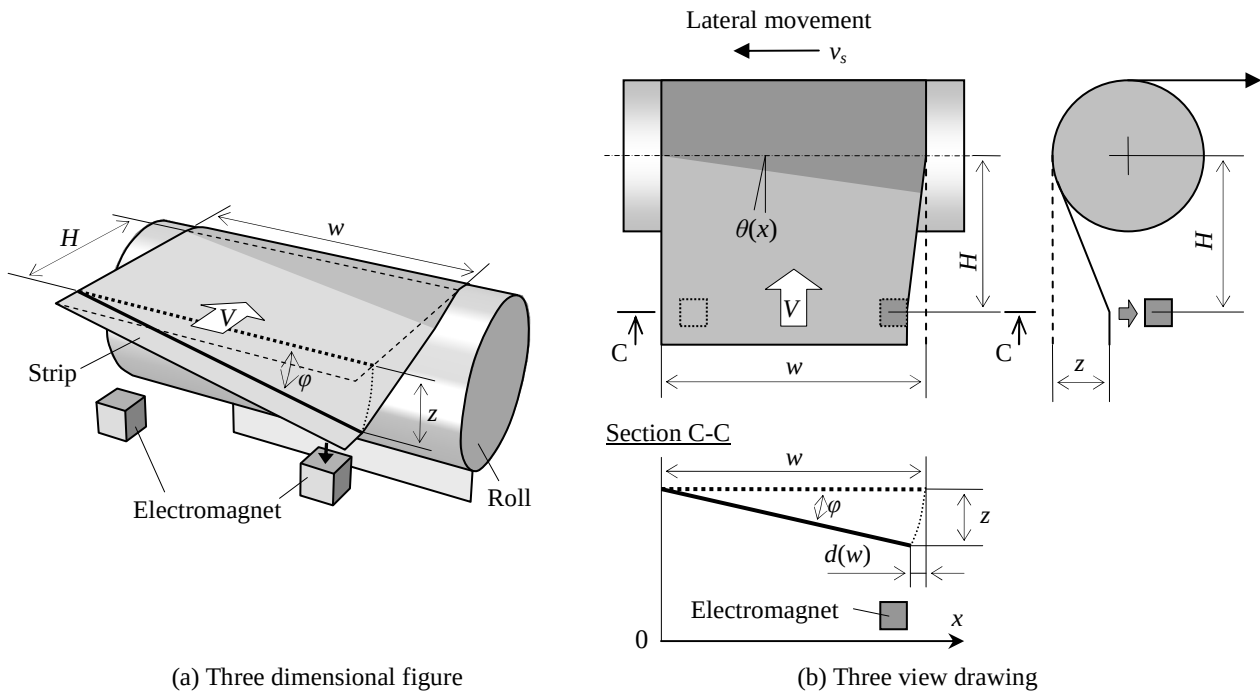


Fig. 2 Geometric relation in the case where the strip is linearly leaned by attracting the edge of the strip

Accordingly, an average angle of inclination θ_s is calculated by a following equation from Eq. (2).

$$\theta_s = \frac{w - \sqrt{w^2 - z^2}}{2H} \quad (4)$$

As mentioned above, velocity of lateral movement v_s is expressed with a following equation if θ_s is sufficiently small.

$$v_s \approx \frac{V}{2H} \left(w - \sqrt{w^2 - z^2} \right) \quad (5)$$

2.3 Enhancement of control capability

It is found that the lateral control capability can be enlarged by increase of the amount of attraction from Eq. (5). If force of the electromagnet is large, the strip is allowed to deform on a large scale. But it is difficult to enlarge the force of the electromagnet because of restrictions of electromagnet heating or installing space of electromagnets. Here, the case where the half of width is deformed in the out-of-plane direction as shown in Fig. 3 is considered to enhance the control capability. In this case an angle of inclination $\theta(x)$ is expressed with following equations by a position of the width direction x from geometric relation if $\theta(x)$ is sufficiently small.

$$\begin{aligned}\theta(x) &\approx \frac{w - \sqrt{w^2 - 4z^2}}{H \cdot w} \cdot x & \left(0 \leq x < \frac{w}{2}\right) \\ \theta(x) &\approx \frac{w - \sqrt{w^2 - 4z^2}}{2H} & \left(\frac{w}{2} \leq x \leq w\right)\end{aligned}\quad (6)$$

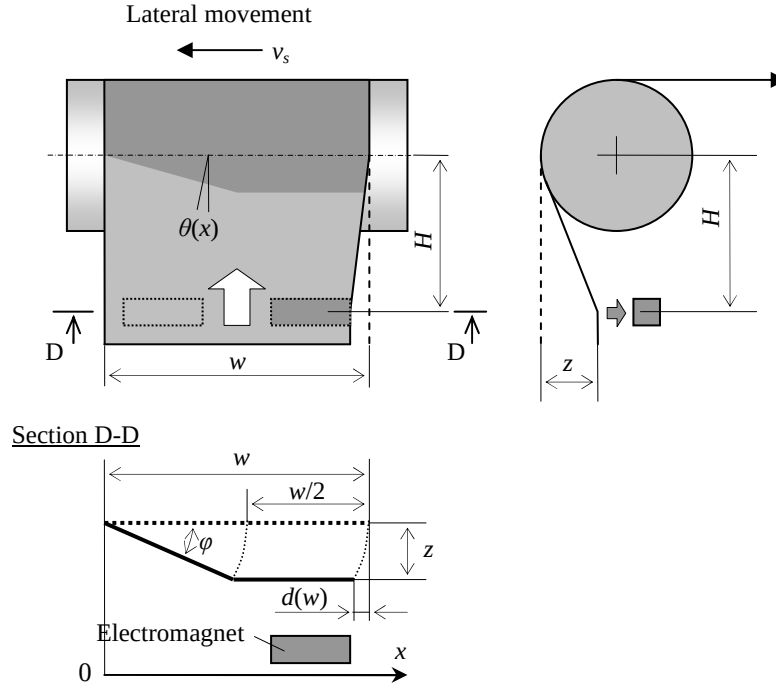


Fig. 3 Geometric relation in the case where the half of width is deformed in the out-of-plane direction

Accordingly, an average angle of inclination θ_s is calculated by a following equation from Eq. (2).

$$\theta_s = \frac{1}{w} \left\{ \int_0^{w/2} \frac{w - \sqrt{w^2 - 4z^2}}{H \cdot w} x dx + \int_{w/2}^w \frac{w - \sqrt{w^2 - 4z^2}}{2H} dx \right\} = \frac{3}{8} \frac{w - \sqrt{w^2 - 4z^2}}{H} \quad (7)$$

As mentioned above, velocity of lateral movement v_s is expressed with a following equation if θ_s is sufficiently small.

$$v_s \approx \frac{3V}{8H} \left(w - \sqrt{w^2 - 4z^2} \right) \quad (8)$$

When the ratio of velocity of lateral movement in half-width attraction to velocity of lateral movement in edge attraction is defined as α , α is expressed with a following equation from Eq. (5) and (8).

$$\alpha = \frac{3}{4} \frac{w - \sqrt{w^2 - 4z^2}}{w - \sqrt{w^2 - z^2}} = \frac{3}{4} \frac{1 - \sqrt{1 - \frac{4z^2}{w^2}}}{1 - \sqrt{1 - \frac{z^2}{w^2}}} \quad (9)$$

Because $4z^2/w^2$ and z^2/w^2 become very small values when displacement z is smaller than strip width w , a following approximation is possible.

$$\sqrt{1 - \frac{4z^2}{w^2}} \approx 1 - \frac{2z^2}{w^2} \quad (10)$$

$$\sqrt{1 - \frac{z^2}{w^2}} \approx 1 - \frac{z^2}{2w^2} \quad (11)$$

Therefore, Eq. (9) is calculable as follows.

$$\alpha \approx \frac{3}{4} \frac{1 - \left(1 - \frac{2z^2}{w^2}\right)}{1 - \left(1 - \frac{z^2}{2w^2}\right)} = 3 \quad (12)$$

That is, the velocity of lateral movement in the case of attracting the half of strip width becomes three times as fast in the case of attracting the edge of the strip, and lateral control capability can be raised.

3. Experiment for verification

3.1 Experimental setup

Lab experiments were conducted to verify whether the lateral movement would be controllable using electromagnets. Figure 4 shows a experimental setup. A steel strip traveled endlessly in this apparatus. Three electromagnets (E_1 , E_2 and E_3) are arranged near a top roll across width of the strip to evaluate an influence of electromagnet arrangement. Using the electromagnet E_1 or E_3 simulates a condition of edge attraction like Fig. 2. Using the electromagnets E_1 and E_2 simulates a condition of attracting the half of strip width like Fig. 3. A sensor of lateral movement measures a position of the strip when the strip is attracted by some electromagnets. Also sensors of displacement measure displacement that each electromagnet attracts. Table 1 shows experimental conditions. The width of the strip w is 866 mm. The line speed V is adjustable and up to 0.75 m/s.

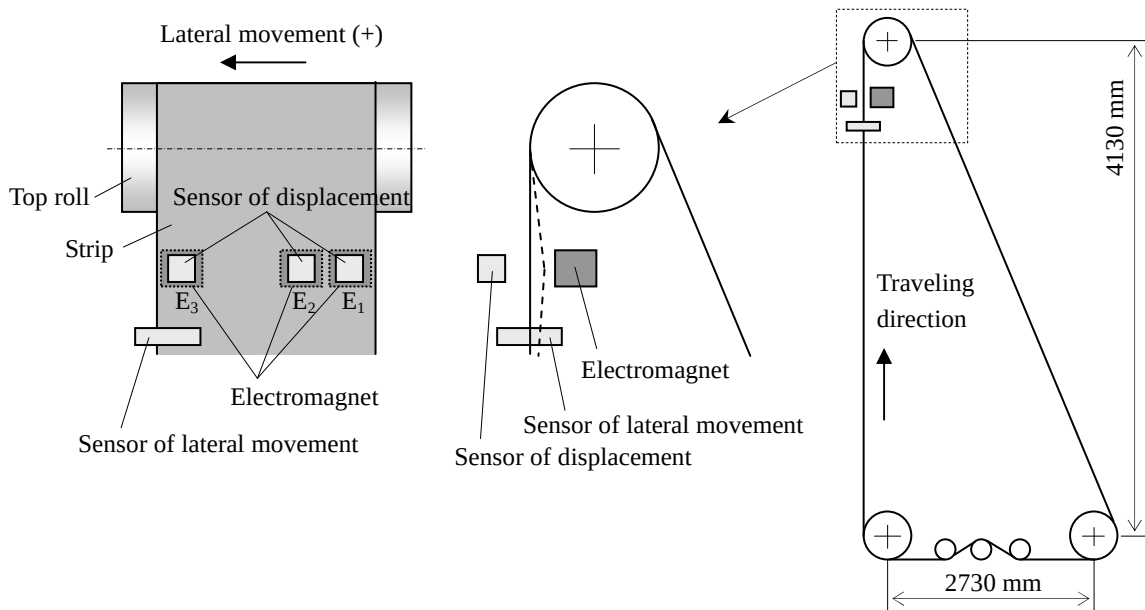


Fig. 4 Experimental setup

Table 1 Experimental conditions

Line speed	Max 0.75 m/s
Tension	1000 N
Strip width	866 mm
Strip thickness	0.4 mm
Roll diameter	400 mm

The velocity of lateral movement is measured by following methods.

- (1) Investigate a condition to realize specific displacement of electromagnet attraction in advance.
- (2) Run the strip at constant line speed.
- (3) Turn on electricity to the electromagnet.
- (4) Measure time series data of a strip lateral position using the sensor of lateral movement. Figure 5 shows an example of strip lateral movement. In this case, the strip is attracted by the electromagnet in the range of 84 s to 408 s.
- (5) Derive velocity of lateral movement from inclination of the measured time series data. v_{off1} , v_{on} , and v_{off2} are velocity of lateral movement before attraction, under attraction, and after attraction. Net velocity of lateral movement using the electromagnet can be evaluated by taking difference between v_{on} and v_{off} (an average of v_{off1} and v_{off2}).

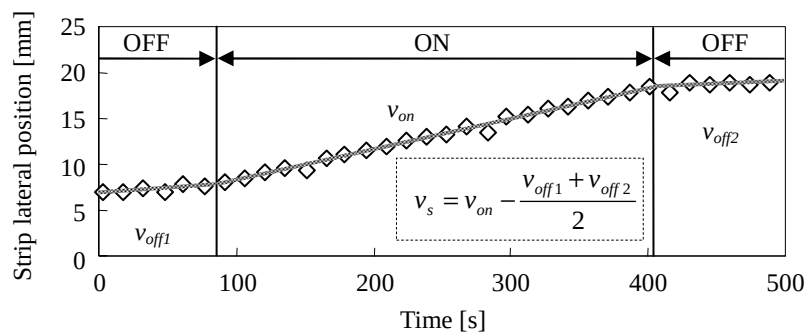


Fig. 5 Example of strip lateral movement

3.2 Experimental results

Figure 6 shows experimental results when the electromagnet is changed. The strip moves to the positive lateral direction in the case where the electromagnet E_1 is used. On the other hand, the strip moves to the negative lateral direction in the case where the electromagnet E_3 is used. These are results according to the supposed mechanism of the strip lateral movement. And these results show that a direction of lateral movement is controllable by changing electromagnets.

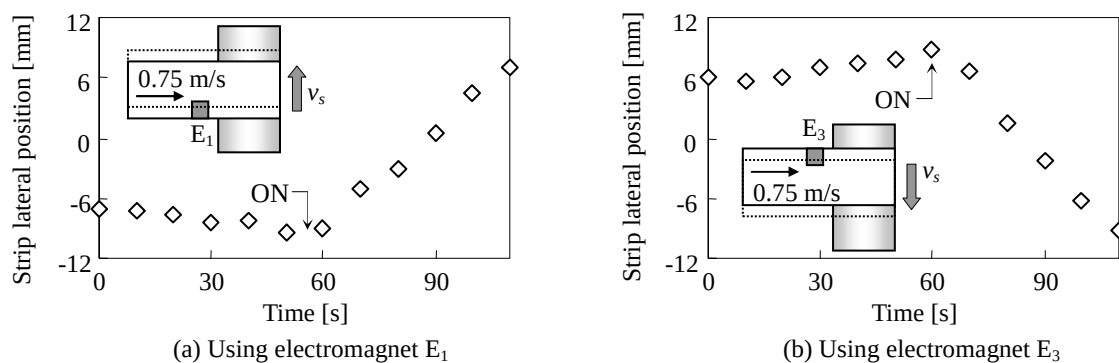


Fig. 6 Result of experiment of strip lateral movement by electromagnet

Lab experiments were conducted in various conditions to validate the derived theoretical equation. The experimental results and theoretical curve derived from Eq. (5) are shown in Fig. 7 and Fig. 8. Figure 7 shows the relationship between the out-of-plane displacement of the strip in the position of the edge and the velocity of lateral movement at constant line speed ($V=0.75$ m/s). Figure 8 shows the relationship between the line speed and the velocity of lateral movement at constant strip displacement ($z=12$ mm). In each figure, experimental results show the average of three experiments and error bars represent the standard deviation.

Here, the experimental results are agreed with the theoretical curve. These results show that the derived theory from geometric relation is valid. It means that a slip of the strip on the roll hardly occurs in the conditions this time. The design of a device for controlling strip lateral movement using electromagnets is possible because control capability can be estimated by the derived theory.

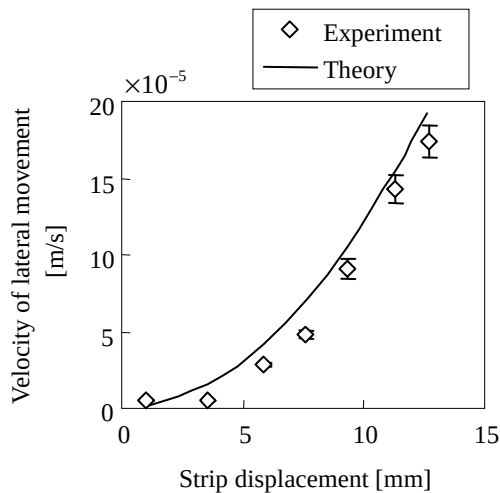


Fig. 7 Relationship between velocity of lateral movement and strip displacement

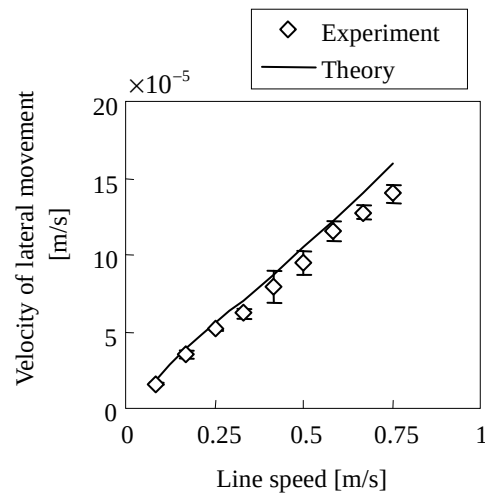


Fig. 8 Relationship between velocity of lateral movement and line speed

Figure 9 shows experimental results when electromagnet arrangement is changed. Here, these results show the average of three experiments and error bars represent the standard deviation. The velocity of lateral movement in the case of using electromagnets E_1 and E_2 is three times as fast in the case of using electromagnet E_1 only. This experimental result is agreed with the examination result calculated by Eq. (12). This shows that the theory of the velocity of lateral movement of Eq. (8) derived from geometric relation is valid.

From the above result, it is thought that deriving the velocity of lateral movement from an angle of inclination to the roll of the strip is an appropriate approach to the strip lateral movement. Attracting the half of width is effective for enhancement of the control capability.

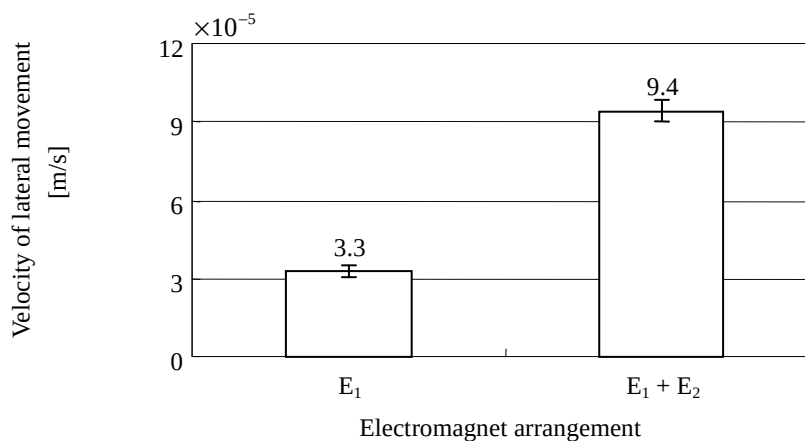


Fig. 9 Influence of electromagnet arrangement on strip lateral movement ($V=0.75$ m/s)

4. Conclusion

In this study, a method of controlling a strip lateral position using electromagnets was investigated by theoretical studies and lab experiments. The results obtained can be summarized as follows:

- (1) The theoretical equations of velocity of lateral movement are derived from inclination when the strip is attracted by electromagnet(s). The inclination is calculable from geometrical relation.
- (2) It is found that the theoretical equations are valid by lab experiments in the conditions of changing attracting displacement and line speed. Controlling lateral movement using electromagnets is possible, and the control capability can be estimated by the derived theory.
- (3) The velocity of lateral movement in the case of attracting the half of strip width is three times as fast in the case of attracting the edge of the strip.

References

- Fukushima, T., Yanagi, K., Mihara, K., Hashimoto, R., Mizuta, K. and Wada, K., Theoretical study for strip walking on a roll, Transactions of the Japan Society of Mechanical Engineers, Series B, Vol.59, No.558 (1993), pp.585–592 (in Japanese).
- Huang, C.-C. Wu, H.-Y. and Tang, T.-T., Adaptive control for edge alignment in polyester film processing, Advances in Polymer Technology, Vol.26, No.3 (2007), pp.153-162.
- Kamiyama, T. and Uchida, H., Development of strip walk control system by Lorentz force, Current Advances in Materials and Processes, Vol.6, No.5 (1993), p.1379 (in Japanese).
- Kaseda, Y., Masui, T., Hirooka, E. and Nonaka, A., Development of pinch rolls to control strip wandering in strip processing lines, ISIJ International, Vol.41, No.11 (2001), pp.1366-1372.
- Kobayashi, Y. and Toya, K., Fundamental study of belt mistracking affected by rotation speed and other factors, Toshiba Review, Vol.63, No.1 (2008), pp.47-50 (in Japanese).
- Masui, T., Kaseda, Y. and Isaka, K., Basic examination on strip wandering in processing plants, ISIJ International, Vol.40, No.10 (2000), pp.1019-1023.
- Matoba, T. and Ataka, M., Control of zigzag walk of strip in continuous annealing line by gas blowing, Current Advances in Materials and Processes, Vol.1, No.2 (1988), p.556 (in Japanese).
- Nishimura, K., Skew correction in roller paper feed mechanism, Journal of the Japan Society of Precision Engineering, Vol.47, No.4 (1981), pp.418-423 (in Japanese).
- Sasaki, T., Hira, T., Abe, H., Yanagishima, F., Shimoyama, Y. and Tahara, K., Control of strip buckling and snaking in continuous annealing furnace, Kawasaki Steel Technical Report, No.9 (1984), pp.36-46.
- Shelton, J. J. and Reid, K. N., Lateral dynamics of a real moving web, Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control, Vol.93, No.3 (1971), pp.180-186.
- Shin, K.-H. and Kwon, S.-O., The effect of tension on the lateral dynamics and control of a moving web, IEEE Transactions on Industry Applications, Vol.43, No.2 (2007), pp.403-411.
- Suzuki, N. and Kikuchi, A., Development of strip walk simulator by spring-mass system, Nippon Steel Technical Report, No.342 (1991), pp.23-27.
- Yerashunas, J. B., De Abreu-Garcia, J. A. and Hartley, T. T., Control of lateral motion in moving webs, IEEE Transactions on Control Systems Technology, Vol.11, No.5 (2003), pp.684-693.