Study on Shape Control and Vibration Absorber of Strip in Steel Process Line

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In a steel process line, the shape controller and vibration absorber are important devices which improve strip quality and line speed. Here, we report on the application of an electromagnetic method of absorbing vibrations and correcting the deformation of strips. We confirmed that the device was beneficial when used in a continuous galvanizing line.

1. Introduction

In steel process lines, shape controlling and vibration absorbing of strips constitute important ways of improving line speed and quality. For example, the coating zinc weight on the strip is adjusted by a wiping nozzle. If there is cross-bowing in the width direction of the strip or vibration at the wiping nozzle position, the coating weight is not uniform and the quality of coated strip is lowered. If the vibration amplitude or cross-bowing deformation is large, the strip may make contact with the process apparatus, causing an adverse effect on the increase in line speed.

Moreover, along with the increase in the production of high-grade steel plates such as coated strips , there is also an increase in production methods in which strip contact with deflector rolls is minimized, yielding strips with fewer flows. As a result of the "roll-less" design employed for this purpose, the roll interval is extended and cross-bowing and vibration are more likely to occur in the strip.

To solve these problems, Mitsubishi Heavy Industries, Ltd. has developed a strip shape controlling and vibration absorbing system employing the contact-free positioning and vibration control techniques which are used in our magnetic bearings[1] and magnetic levitation systems[2]. This paper reports on the results of an element test, and testing in an actual continuous galvanizing line.

2. Method of strip shape control and vibration absorption

Strips transferred in a steel process line are about 600 to 1 800 mm in width and from 0.3 to 6 mm in thickness. Through annealing and galvanizing in the line, the overall line length is extended to several kilometers. In this distance, tension is applied by bridle rolls, and the strip is supported by rolls, although the roll interval is 50 m at most. A strip supported by rolls at such tension can be regarded as a string supported at both its ends, and its natural frequency is expressed in the following Eq.

$$f = \frac{n}{2L}\sqrt{\frac{\sigma}{\rho}} \qquad n=1, 2, \cdots \tag{1}$$

where,

L : roll span (m)
σ : unit tension (N/m^2)
ρ : density of strip (kg/m^3)
f : natural frequency (Hz)

The object of vibration control is to reduce the amplitude by giving damping and stiffness to the natural frequencres.

In actual control, as shown in **Fig. 1**(a), an assembly of a set of electromagnets facing each other àcross a strip, and a sensor for measuring displacement of the strip is formed on one axis. Shape is controlled and vibration is absorbed by disposition of a number of axes in the strip's width direction.

The strip is likely to be deformed in a C-form, that is, the same phase at both ends and the opposite phase in the center. To keep it flat, three axes in the width direction are basically required. However, as measures against W-form deformation are more complicated in shape in the width direction, five or more axes must be arranged in the width direction.

As shown in the block diagram in Fig. 1 (b), a control circuit is a series circuit for PI control and phase compensation of displacement signal. This circuit gives stiffness and damping to the strip while positioning it. A controlled parameter must be determined at this time, in order to avoid static instability and spillover (hunting in higher order mode). As for static instability, we confirmed by a numerical analysis that the dynamic stability arising from control added to stiffness of the strip under tension is greater than the intrinsic unstable force of the electromagnet. (This force tends to be increased as the strip approaches to the electromagnet.) As for spillover, a limit value is determined by experiment, and a constant is determined on the basis of the obtained data. An example of the transmission characteristic from strip displacement to the magnetic force of magnet in an element test mentioned later is shown in Fig. 1 (c).

3. Plant test results

3.1 Confirmation of vibration control effect

A test device for confirming the vibration control effect of strip in a stationary state is shown in **Fig. 2**. A strip 0.5 mm in thickness and 1 000 mm in width was stretched at a roll interval of about 4.1 m. The shape control and vibration absorbers were installed in two rows in the transporting direction, on three axes in the width direction approximately in the center. The test was conducted at a unit tension of 9.8×10^6 N/m^2, and the vibration control effect was evaluated by varying the control constants (proportional gain, integral gain). An example of a control constant is shown in the transfer function characteristic in Fig. 1 (c). The characteristic in Fig. 1 (c) is designed with the purpose of advancing the phase and giving damping in the eigenvalues of the order of 1 to 10. In the test, the primary natural frequency measured by hammering, and damping ratio ζ are shown in **Fig. 3** (a), (b). The natural frequency is raised from 3.2 Hz to 4.5 Hz—5.0 Hz, suggesting that the stiffness is twice as high. The damping ratio is raised from 2% to 6%—15%, and the amplification quality (Q factor)

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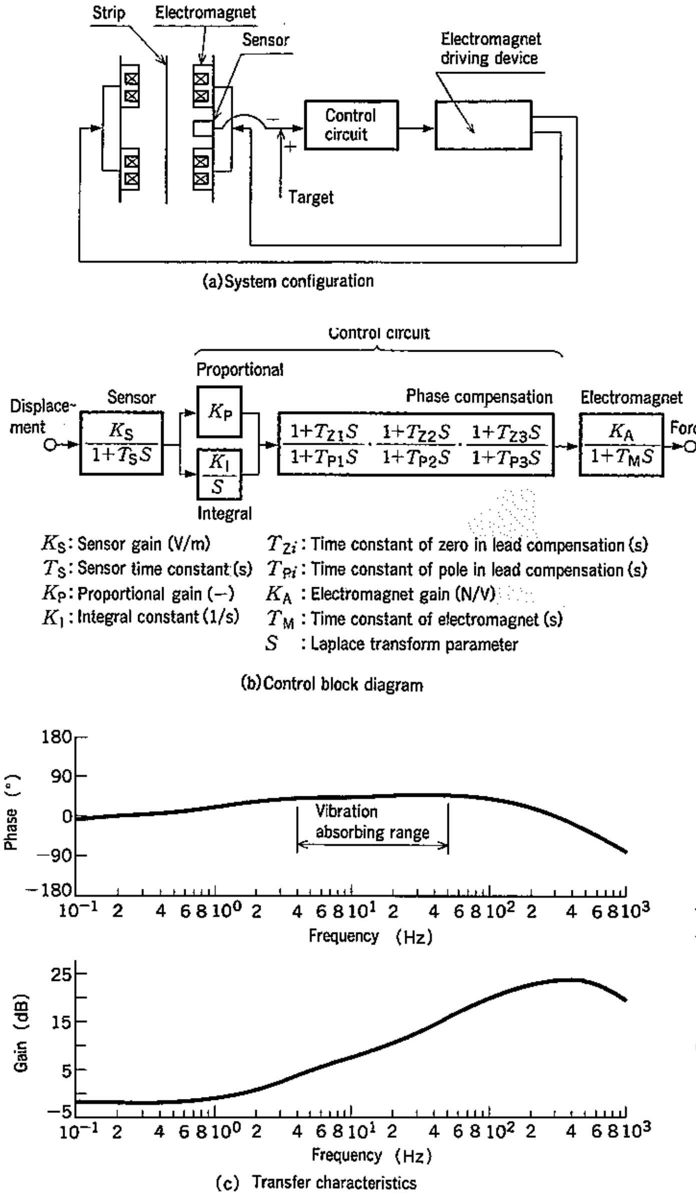


Fig. 1 System and transfer characteristics
Composition of one axis of the device, its block diagram, and an example of transfer characteristics are shown.

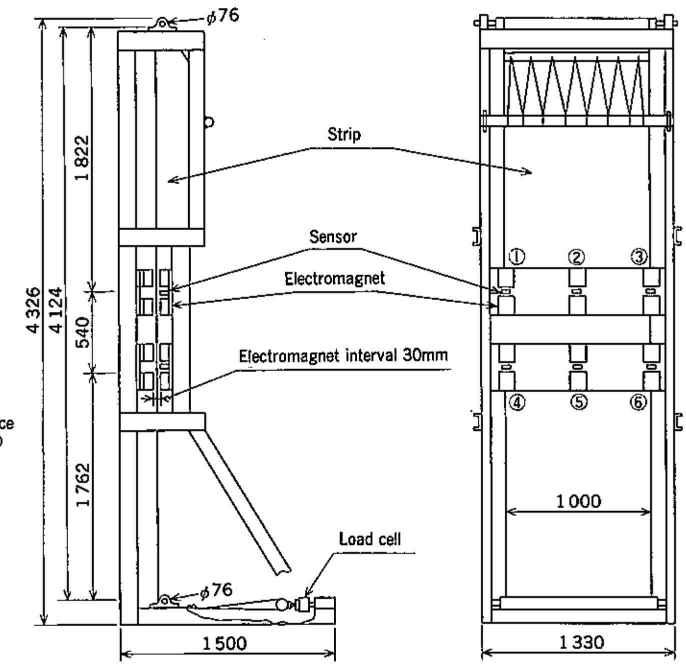


Fig. 2 Test device of suspended strip
Test device of roll span of about 4.1 m used in element test.

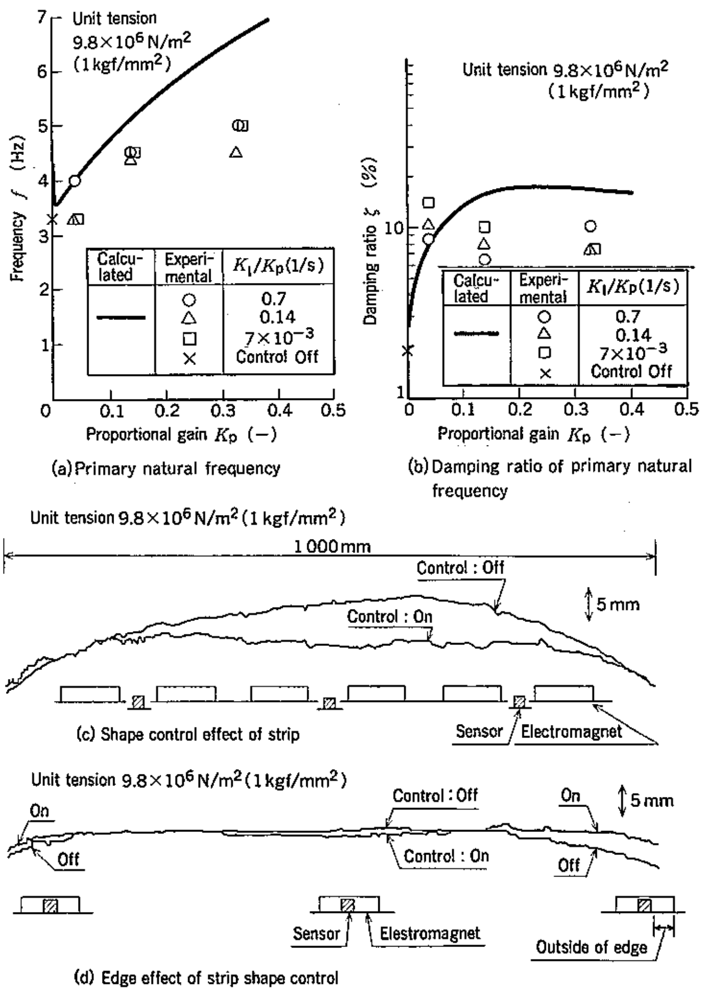


Fig. 3 Natural frequency and damping ratio, and shape control
In the strip suspended state, primary natural frequency, damping ratio, and shape control results are shown.

that can be about expressed as $1/(2\xi)$ is reduced to the maximum of 1/7. It is thus known, by properly selecting the parameters, that the amplitude in resonance can be reduced to the maximum of 1/14.

Fig. 3 (a), (b) also shows the calculated values in numerical analysis. Of the primary fundamental natural frequency, in control off state, the calculated value is about 1.3 times higher than the experimental data, and the tendency is the same when the control is on. This seems to be because both ends of the strip stretched in the vertical direction are calculated at fixed ends, and the stiffness is estimated as higher than the actual level. The tendency of the natural frequency to rise along with elevation of gain agrees with the experimental value, and it is therefore considered possible to predict when the roll diameter is large and the stiffness is high, as in the actual line. Also, the fact that the calculated value of natural frequency near gain 0 is smaller than that of control off state, can be explained as the unstable force of the electromagnet is greater for the dynami-

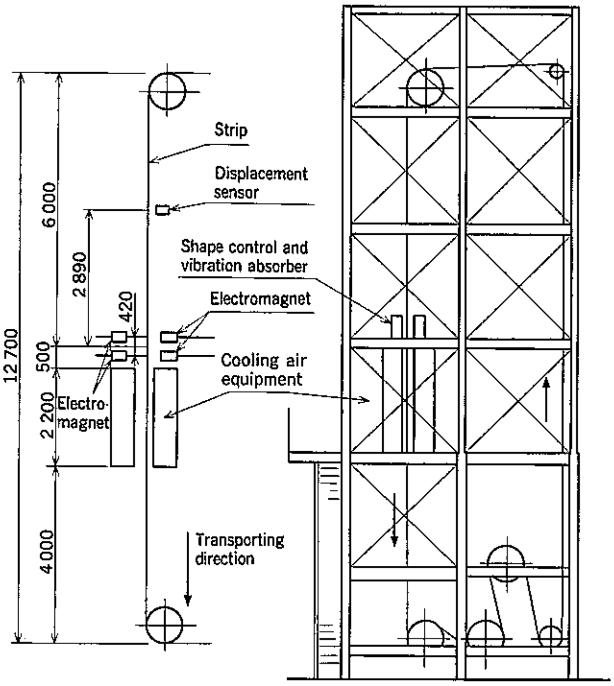


Fig. 4 Test device in process test line
A test device of roll span 12.7 m of testing by transporting strip.

Table 1 Damping ratio of primary natural frequency

Vibration absorption \ Line speed	15.5 m/min	44.6 m/min	0 m/min
Off	3.3%	2.9%	1.9%
On	11%	11%	5.5%

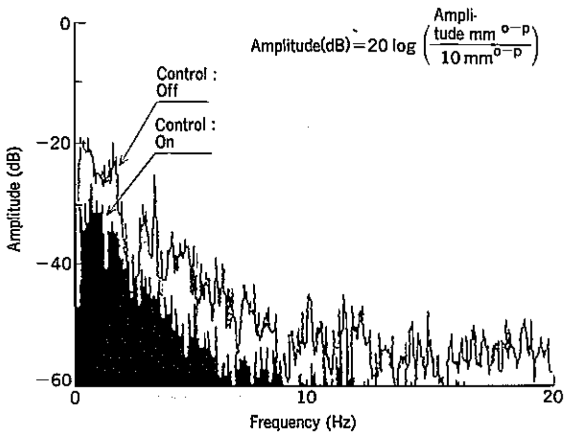


Fig. 5 Frequency spectrum of exciter test by cooling air
Strip exciting test by cooling air; amplitude was decreased by about 10 dB.

cal stability caused by control. The calculated value of the damping ratio is close to the experimental data in the order of magnitude, and it is considered to be reasonably effective for approximating the magnitude of damping when setting the control constant.

3.2 Confirmation of shape control effect

The effects of shape control by varying the disposition of electromagnets and sensors are shown in Fig. 3 (c), (d). In the disposition of electromagnets and sensors shown in Fig. 3 (c), bowing of about 15 mm could be decreased to about 2 mm between the sensors at both edges. Outside the sensors at both ends, however, bowing increases due to the force of the electromagnet. Accordingly, as shown in Fig. 3 (d), one axis was composed by placing two electromagnets vertically and putting a sensor between them (the disposition of electromagnets and sensors in Fig. 2). The position in the width direction was extended so that the sensor could reach the edge of the strip. In this disposition, the shape can be controlled up to the edge, and the efficacy of placing the sensor at the edge has been confirmed.

3.3 Process line test results

To confirm the vibration absorbing effect on the transporting strip, the shape control and vibration absorbers were installed in the company's steel process test line, and a test of transporting state was conducted. An outline of the test line is shown in **Fig.** 4. The strip used in the test has the same specifications as that used in the stationary state test, but the roll span is extended to 12.7 m. Hence, the control constants were changed according to Eq. (1) of the natural frequency of string.

To investigate the effect of absorbing vibration, hammering was conducted at the position of the device, and the stationary state and transporting state were compared. The results are shown in **Table 1**. The damping ratio of the natural frequency was about 3 times in the stationary state, and also about 3 to 4 times in the transporting state, thus confirming the effect of absorbing vibration in the transporting state.

Furthermore, the vibration absorbing effect on disturbance of cooling air, which is a typical example of excitation in a steel process line, was confirmed. The results are shown in **Fig. 5**. The overall amplitude decreased to about 10 dB, that is, 1/3. On the forced vibration also, the effect corresponding to the increment of stiffness was recognized. It is also effective in high order frequency, as can be seen from Fig. 5.

4. Real line test

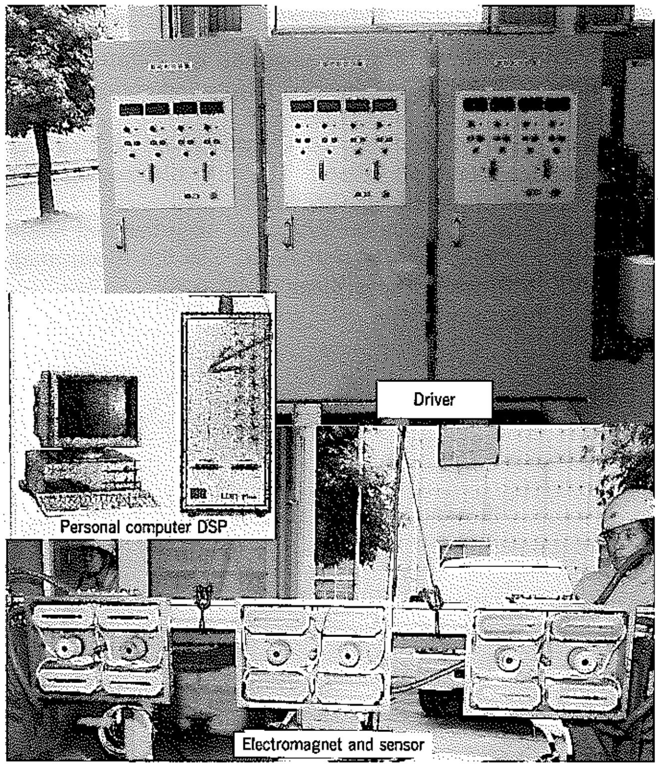
4.1 Apparatus for real line

An apparatus configuration of 6th axis control for continuous galvanizing line is shown in **Fig.** 6 (a). Using a DSP (Digital Signal Processor) in the control unit, a function of an automatic level of compensation could be assigned for optimum control constants, depending on line conditions such as plate thickness and tension. An electromagnet driver independently drives six axes by PWM control. The disposition of electromagnets and sensor comprises upper and lower electromagnets for each axis, with a sensor disposed between them. The electromagnets are designed to have sufficient magnetic force even on a thin steel strip. When applying a magnetic force to a thin plate such as strip, the magnetic flux density is likely to be saturated in the cross section of the strip, and the magnetic force obtained may not be sufficient. The characteristic of the magnetic force is shown in Fig. 6 (b). In a thin plate of 0.58 to 0.98 mm, a magnetic force of 10 kgf/axis or more is presented.

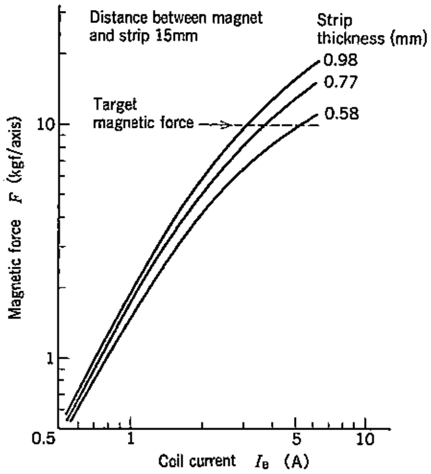
4.2 Real line test results

The test device was installed in the continuous galvanizing line No. 4 of Yawata Works of Nippon Steel Corp., and an experiment was conducted.

The test results of shape control and vibration absorption are shown in the example of strip measuring 0.8 mm in

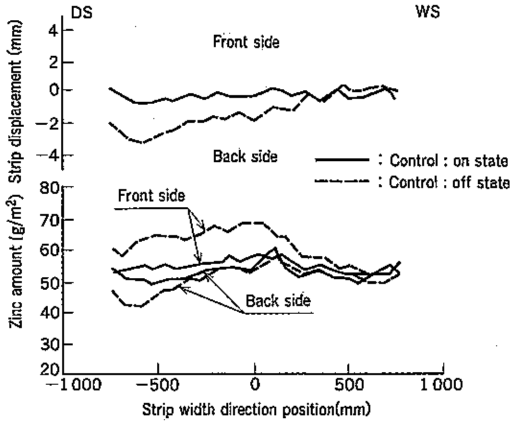


(a) Apparatus configuration

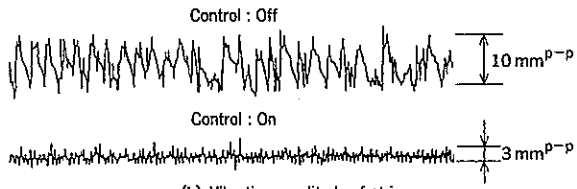


(b) Magnetic force characteristics of electromagnet

Fig. 6 Devices for CGL
Devices for use in CGL and magnetic force characteristics of the electromagnet.



(a) Cross section shape of strip and zinc amount



(b) Vibration amplitude of strip

Fig. 7 Effect of application test in CGL
An example of application in CGL; fluctuations in the amount of zinc on the steel are decreased to 10 g/m².

thickness and 1 700 mm in width. The shape control result is shown in **Fig. 7** (a). In the control off state, the strip was transported by inclining in the width direction, and a state of displacement of 3.5 mm between the two edges was set up. At this time, fluctuations in the amount of zinc coating on the strip were about 20 g/m^2 in the width direction. By its shape control, the shape in the width direction was made flat, and the strip was then moved parallel from the back side to the front side. By this operation, the displacement of the strip in the width direction could be kept within 1 mm, and fluctuations in the amount of zinc coating on the strip in the width direction were halved to 10 g/m^2. In addition, the galvanizing amount was equalized on the front and back sides.

Vibration absorbing results are shown in Fig. 7 (b). It refers to the vibration near the strip edge, and the amplitude corresponds to the control on and off state in Fig. 7 (a). As can be seen from the figure, the overall amplitude is decreased from 10 mm^{P-P} to 3 mm^{P-P}. Comprehensively considered together with other data, the effect of decreasing the vibration of 6 to 18 mm^{P-P} to 3 mm^{P-P} could be confirmed.

By changing the support rolls above the device from the closed to the open state, another test was conducted in a long roll span. Shape control was also excellent in long roll span as well. However, as the position of the device was too close to the support roll in the galvanizing pot, the effect was small for the absorption of the vibration on the long span strip.

5. Conclusions

A device for controlling the strip shape and absorbing vibration was developed, its performance was tested, and the following results were obtained:

(1) In the element test of vibration absorbing effect, the resonance amplitude was decreased to the maximum of 1/14, and the amplitude was reduced to 1/3 even with disturbance by cooling air.

(2) In the element test of shape control, for a strip width of 1 000 mm, the effect of reducing the strip C-form by 15 mm to 2 mm was confirmed.

(3) As a result of the test in an actual continuous galvanizing line, fluctuations in the amount of zinc weight on the strip in the width direction were decreased from 20 g/m^2 to 10 g/m^2. The amount of zinc weight on the front and back sides was also equalized. The vibration absorbing effect was also recognized, as the vibration of 6 to 18 mm^{P-P} was reduced to about 3 mm^{P-P}.

Accordingly, this device is considered to have reached a level of practical use. Henceforth, it is planned to improve it further as a practical device reinforcing, for example, the automatic parameter changing function, depending on the operating conditions

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References

(1) Katayama, K. et al., Development of Totally Active Magnetic Bearings, Mitsubishi Heavy Industries Technical Review Vol.26 No.1 (1989) p.12

(2) Kawada, N. et al., Study on Characteristic of Magnetic Levitation for Thin Plate, The 4th Electromagnetics Symposium Proceedings (1990) p.59

(3) Morii, S. et al, Study on Vibration Absorber and Shape Control of Strip by Electromagnet, The 5th Electromagnetics Symposium Proceedings (1992) p.429