The Control of Sheet Motion in a Hot-Dip Galvanizing Line by Electromagnetic Actuator

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***Abstract* – Control of steel sheet shape and vibration at the air knives can increase the quality, save zinc and reduce costs. In this paper, an electromagnetic actuator set is designed to evaluate the feasibility of using active magnetic levitation technology to control vibration of the steel sheet at the air knives. Electromagnetic actuators and eddy-current position sensors are used. Because there are welding lines on the steel sheet causing the unsmooth thickness of steel sheet, multi sensor technology is adopted to make the performance calculation result reflect the steel sheet's real status. For the proper sensor placement, the modal analysis of the steel strip is applied. In addition, the location of the electromagnetic actuator is designed according to the principle of "equal rigidity". So the control parameters used in laboratory can be referenced to that of the workplace. Then PID controller is used to control the sheet motion. In order to get enough forces to control vibration, cross-section within the magnetic loop is increased, and one kind of new material with more saturation flux is selected. Through experimental verification and galvanizing line test, the set can stabilize the sheet motion greatly, improve the galvanizing quality and save zinc.**

***Index Terms* – Electromagnetic Actuator. Vibration Control. Steel Sheet. Hot-Dip Galvanizing Line.**

I. INTRODUCTION

High-pressure air knives, roll eccentricity, flowing air and a long free path cause vibration in hot-dip galvanizing lines. Vibration of steel sheets leads to non-uniformity of galvanized coating thickness, zinc splash between air knives and scratches on the coating. Non-uniformity in coating thickness increases the base coating thickness so that areas of thin coating do not break minimum thresholds. This increases the cost of final product due to the higher zinc usage. Advances in air knife design, coating thickness measurement techniques, and strip stabilization have improved the quality and throughput of the process and reduce costs [1~4].

Active magnetic levitation technology has developed for more than one hundred years and been used in many fields [5]. In this paper an electromagnetic actuator set is designed to control the vibration of steel sheet. The set consists of several pairs of electromagnetic actuators, eddy-current position sensors and controller. The essential problems of the electromagnetic actuator set design needed to solve are the big air gap and thin steel sheet that will lead to control force not enough. This paper details sensor placement, the structure and the controller of the system.

II. THE STEEL STRIP MODAL ANALYSIS AND SENSOR PLACEMENT

In active vibration control, actuator and sensor placement is a very significant issue, since it has a direct effect on the control efficiency and cost. An arbitrary choice of actuator positions can seriously degrade the system performance. In cases where an analytical model of a structure is available before the modal test, it is good practice to use the model to design the sensor configuration. Sensor locations should be chosen in such a way that they produce reliable and sensitive information on the all modal shapes of the structural system.

It is difficult to do the experiment with this type of device on a production line without any tests in laboratory. So a small experimental steel sheet set is built to evaluate the feasibility of using an active control system to control the steel sheet at the air knives firstly.

Fig. 1 is the dynamic model of the steel sheet. F denotes the interference force exerting on the steel sheet which included random excitation from the air knives and harmonic frequency excitation from rotating components such as the sink roll.

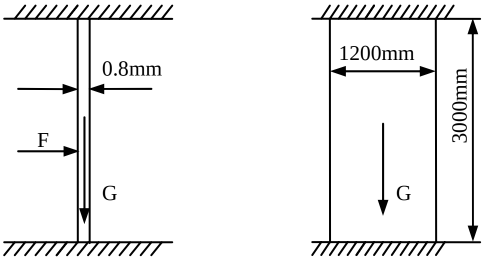


Fig. 1 The dynamic model of steel sheet.

The parameter of the steel strip is as follows: the material is galvanized steel sheet, the density is $7.8\times 10^3 kg/m^3$, the thickness is 0.8mm, the elastic modulus is 2.06×10^{11}Pa, Poisson's ratio is 0.3,1.2m in width and 3m in length. Both the top and bottom of the steel sheet are fixed restriction. Since the thickness of the steel sheet is only 0.8mm, the modal analysis is based on shell structure with Elastic 4 node 63 shell element. Using the MESHING of ANSYS, the finite element model of the steel sheet is shown in Fig. 2.

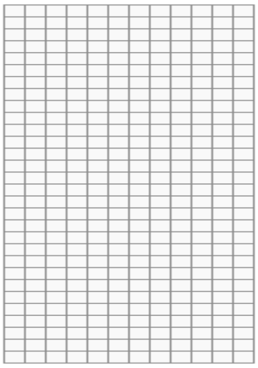
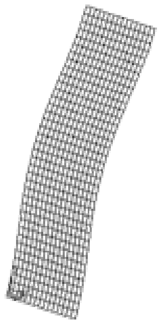


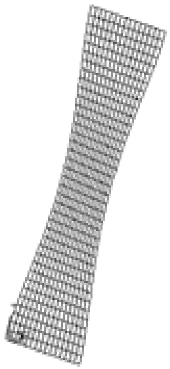
Fig. 2 The finite element model of the strip steel.

ANSYS software provides seven model extraction methods, that is Subspace、Block Lane、Power Dynamics、Reduced、Unsymmetric、Damp and QR Damp. The Block Lanczos method has the advantages of quick speed and exact calculation when seeking natural frequency in a designed range of eigenvalue spectrum of a given system. So this method is adopted. The first three mode shapes are shown in Fig. 3.

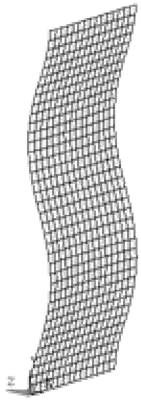
The vibration is the linear combination of all the modes of vibration, but the low natural frequency vibration plays more important role than the high frequency vibration. So the first three modes of vibration determine the dynamic characteristic of the steel strip. The result of modal analysis is listed in Table I.



(a) 1st mode shape.



(b) 2nd mode shape.



(c) 3rd mode shape.

Fig. 3 Mode shape.

TABLE I
THE RESULT OF MODAL ANALYSIS

Mode	Frequency（Hz）	Characteristic of the vibration	The number of nodal line
Mode 1	0.484	Flexural	None
Mode 2	0.916	Bending and torsional	1
Mode 3	1.335	Flexural	1

The description of vibration mode is as follows: the 1st mode of vibration is mainly flexural vibrations in vertical direction and the 1st mode shape is that of a bowed sheet with the entire sheet in phase. The 2nd mode of vibration is coupled bending and torsional vibration. The mode shape corresponding to mode 2 has the left and right sides moving out of phase with very little centre motion (twisting about the vertical centreline of the sheet).The 3rd mode of vibration is flexural vibrations as be the first mode but with two sections. The magnetic actuators and sensors couldn’t be located near the nodal line of the steel strip, making sure that the steel strip vibration displacement could be detected by sensors and controlled by electromagnetic actuators.

III. STRUCTURE DESIGN

A. Design Principle of Steel Sheet Test Stand

The sheet is suspended approximately 50 meters between the sinker roll and the tower roll in steel factory, but the height of the experimental steel sheet is limited by the laboratory. The location of the electromagnetic actuator is designed according to the principle of “equal rigidity”. The definition of “equal rigidity” is to keep the sheet rigidity of test stand being equal with that of the steel factory. So the control parameter used in laboratory can be referenced to that of the workplace. The displacement of laboratory steel strip under unit force can be calculated by (1).

$$z = \frac{y^2 (L-y)^2}{3LEI} \quad . \qquad (1)$$

Where $\boldsymbol{z}$ is the displacement, y is the location height of electromagnetic actuator, L is the length of the steel sheet, EI is the bending modulus.

B. Electromagnetic Actuator Structure and Material

Let x_0 be the air gap, x_1 be the width of the iron core. Usually magnetic circuit as shown in Fig. 4 requires (2).

$$\frac{x_1}{x_0} \ge 20, \quad x_1 \ge 10\,mm, \quad x_0 < 0.5\,mm \quad . \qquad (2)$$

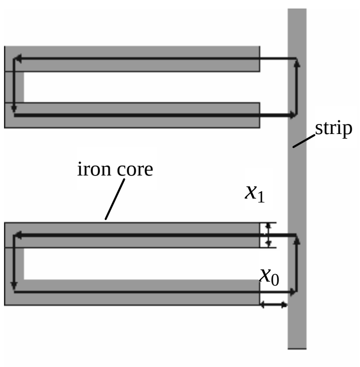


Fig. 4 Normal magnetic circuit

In this system, the magnets are positioned with sufficient air gap (10mm~20mm) to take into account maximum transverse sheet displacement and possible warpage. Furthermore, the thickness of steel sheet is very thin varying from 0.3mm to 2mm. Because the cross section within the magnetic loop is equal to that in steel strip, the magnetic forces can’t reach set value for the leakage flux (see fig. 5). Through increasing the cross section area of iron core, the magnetic flux can be increased while the leakage flux is decreased. So, the “E” type iron core is adopted. In order to get enough forces to control vibration, perm alloy which has more saturation flux is selected as the material of iron core.

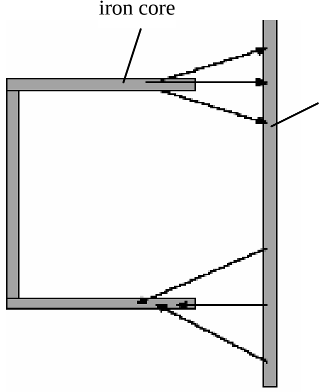


Fig. 5 Magnetic circuit with leakage flux

The vibration of the steel sheet is measured by eddy-current position sensors which are fixed above the electromagnetic actuators pairs. Seven electromagnetic actuators pairs are designed in line across the width of the steel sheet to provide force controlling the steel sheet motion. The test stand is shown in Fig. 6.

Fig. 6 The test stand of sheet motion control

C. Going through welding line by multisensor fusion technology

In hot-dip galvanizing line, there is one welding line on the steel sheet every 10000 meters. Welding line will cause the unsmooth thickness of steel sheet. So it will affect the accuracy of sensor measurement. In this system six sensors are used to detect one signal. Arithmetic means of six sensors can make the performance calculation result reflect the steel sheet's real status well and exactly. The algorithm is simple and reliable.

IV. VIBRATION CONTROL

Because the dynamic of steel sheet is complex, PID controller is used to control the sheet motion. Fig. 7 describes the active control method of sheet motion. This method is often used in magnetic suspensions system. A sensor measures the displacement of the sheet from its equilibrium position. A controller derives a control signal from the measurement, a power amplifier transforms this control signal into a control current, and the control current generates the magnetic forces within the actuating magnet in such a way that the sheet remains in its equilibrium position.

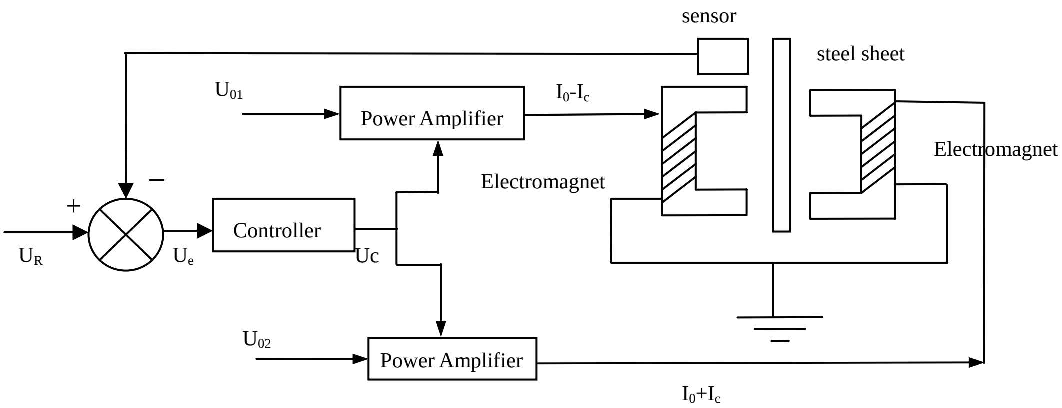


Fig. 7 Sheet motion control system.

V. EXPERIMENTAL VERIFICATION AND GALVANIZING LINE TESTING

The good performance has been achieved by PID controller in the laboratory. One typical corresponding power spectral density (PSD) plot of the sensor signals under PID control vs. no control is shown in Fig. 8.

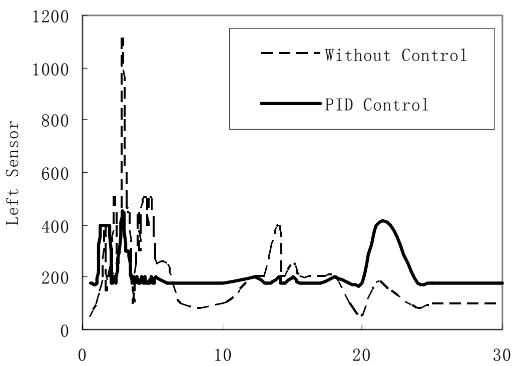


Fig. 8 PSD plot of sheet motion under PID control vs. no control.

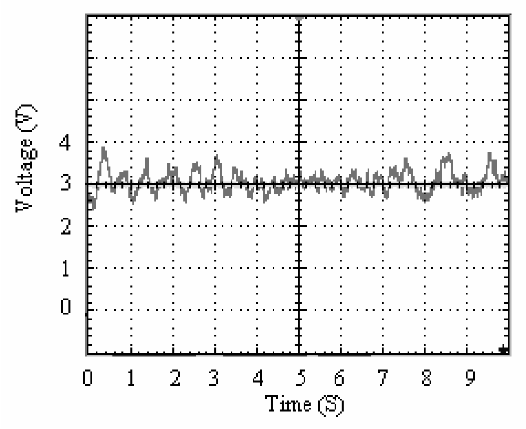
The displacement at the 2.8 Hz was nearly 85 percent down from the peak values. The steel achieved stable levitation. In order to quantify the overall effect of the controllers, the root mean square (RMS) vibration levels were calculated. The results are shown in Table II.

TABLE II
REDUCTION IN RMS VIBRATION

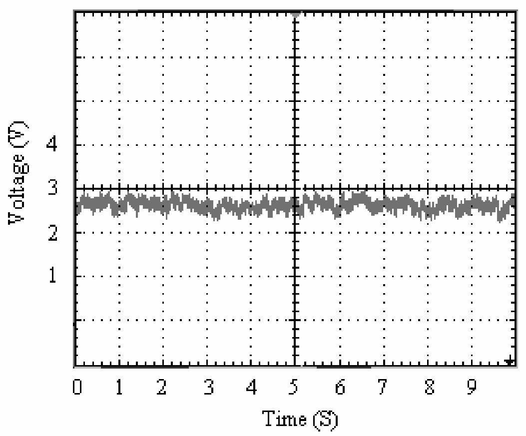
Sensor	Without control	PID control	Reduce(%）
1#	2714.6	1987.3	26.7
2#	4087.7	1589.7	61.1
3#	2983.8	1544.5	48.2

The electromagnetic magnet set has been placed across the width of the strip above the air knives during line operation in the galvanizing line of Shanghai Baosteel Corporation (see Fig. 9). Data was acquired to characterize the nature of the sheet motion. One typical sheet response under sheet motion control vs. no control is shown in fig. 10.

Fig. 9 Test in the galvanizing line



(a) No control



(b) Under control

Fig. 10 Sheet response under sheet motion control vs. no control

When the electromagnet actuator didn't work, peak to peak value of virbration amplititude was about 1.40 minimeters. It was 0.40 minimeters decreased by 71% comparing with above, when the steel sheet was controlled by electromagnetic actuator. Steel sheet worked more smoothly and welding line went across the set safely.

VI. Conclusion and Future Work

In this paper, an electromagnetic actuator set is designed to control the steel sheet vibration at the air knives. Through experimental verification and galvanizing line test, the set can stabilize the sheet motion greatly, improve the galvanizing quality and save zinc. However the forces are subject to the properties, dimensions, and speed of the strip as well, some further investigation is needed.

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