Active Control of Sheet Motion for a Hot-Dip Galvanizing Line

Dr. Stuart J. Shelley
Dr. Thomas D. Sharp
Mr. Ronald C. Merkel

Sheet Dynamics, Ltd.
1776 Mentor Avenue, Suite 170
Cincinnati, Ohio 45242

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Abstract

Out-of-plane vibration of the steel sheet during hot-dip galvanizing results in undesirable variations in zinc coating weight thickness. This requires higher nominal coating thickness to avoid underweight conditions, wasting zinc and increasing costs. It also precludes using hot-dip galvanized product in applications requiring low coating weight. This paper details recent active vibration control experiments that have been performed on a segment of steel strip that show significant promise of reducing resonant vibration of the sheet near the air knife box. The contributions of three modes of vibration were reduced resulting in RMS vibration reductions of up to 50 percent.

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Introduction

It has been difficult for hot-dip galvanized steel sheet to compete with electro-galvanized (EG) steel sheet in terms of coating weight uniformity and surface quality. Advances in air knife design, coating thickness measurement techniques, and strip stabilization have improved the coating weight control to the point that hot-dip can compete with EG in demanding applications such as exposed automotive auto-body panels. Further improvements in coating weight uniformity will improve the competitiveness of hot-dip and open up additional markets that are now limited to EG.

Strip stability in the region of the air knives is critical to improving coating weight uniformity. Vibration of the sheet between the air knives leads to non-uniformity in the coating due to the resulting air pressure variations. Non-uniformity in coating thickness cause galvanizers to increase the base coating thickness so that areas of thin coating do not break minimum thresholds. This increases the cost of the final product due to the higher zinc usage and precludes the use of hot-dip galvanized product in applications requiring low coating weight and high coating weight uniformity.

Control of coating thickness is currently limited to closed loop feedback control between a downstream coating thickness gage and the air knife and feed forward compensation for line speed and knife position changes. Regular maintenance on mechanical components also reduces the forcing functions that can drive the out-of-plane motion of the sheet. The addition of an active control system to reduce sheet motion at the air knives can improve the ability of the air knives to maintain uniform coating weight. The resulting zinc savings and improvement in quality could have a significant effect on the hot-dip market.

This paper details active vibration control experiments that were performed on a test stand to determine the effectiveness of various control techniques at reducing out-of-plane resonant sheet motion. The results of the testing show that active control holds significant promise for improving sheet stability and coating weight uniformity for hot-dip galvanized steel. Sheet vibration measurements made on a galvanizing line are also presented.

Control System Development

The out-of-plane vibration of a long strip of steel under tension can be quite complex. The density and complexity of the modes of vibration would make complete control of the strip motion nearly impossible. However, the control required to improve coating thickness uniformity is local to the region around the air knives. If a node line across the width of the strip can be created at the air knife location, there would be no strip motion where the coating thickness is determined.

There are two primary excitation sources for the strip: random flow excitation from the air knives and constant frequency sources from rotating components such as the pot roll. Each of these sources can require a different type of control methodology. Broadband random excitation will result in the highest sheet responses at the resonance frequencies. Therefore, control methods that either add damping to resonant frequencies or perform mode cancellation will be most effective. For constant frequency sources, control methods that can apply control forces 180 degrees out of phase with the mechanical excitation will be required. The majority of this paper will focus on the results achieves with resonant control methods. Preliminary results from rotating component control will also be provided.

Since contact with the strip cannot be made in the region of the air knives, non-contact actuators and sensors must be used for control. In this development, electromagnetic actuators and retro reflective position sensors were used. The test stand used for control system development consisted of a 40” x 80” segment of steel strip under adjustable tension. Out-of-plane strip motion was measured at three locations across the width of the strip with the retro reflective position sensors. Each sensor was located immediately adjacent to an electromagnet pair used to apply the control forces to the sheet. An actuator was attached directly to the sheet to provide the disturbance forces to be controlled. The actuator was located approximately one-third in from the edge of the sheet below the line of control. The test stand is shown in Figure 1.

The actuators/sensor assembly is built as two parts. The sensor/actuator assembly was designed so that it could be directly mounted onto an existing hot-dip line immediately above the air knife box. This assembly has been designed to withstand the harsh environment present on the galvanizing line. The assembly includes mechanisms that:

1. Insure that sensors and actuator temperature limits are not exceeded;
2. Insure laser displacement sensors are not fouled;
3. Protect the assembly from furnace buckles

The magnetic actuators are cooled with vortex air-cooling units. Additionally, they are coated with a ceramic insulator that reduces the heat loading. The position sensors are enclosed by a steel housing with a glass lens. Compressed nitrogen is fed into the sensor housing and exits around the lens providing a clean local environment that prevents dust buildup.

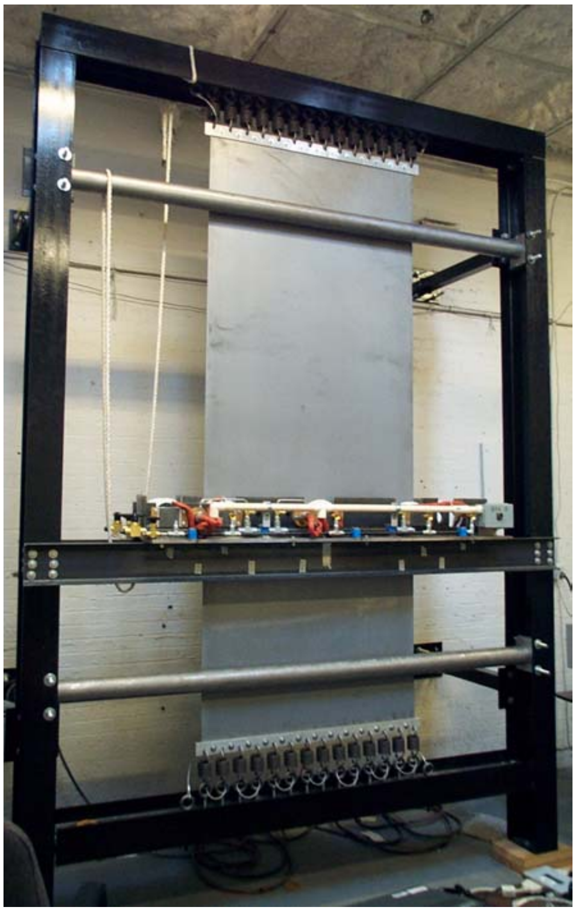

Figure 1: SDL steel sheet test stand.

This test stand configuration does not attempt to replicate the sheet velocity, the actual length of the sheet between zinc bath and tower support points, the elevated sheet temperature, or tension variations in the system. These were not viewed as significant restrictions on the testing because these would have their greatest effect on the resonant frequencies of the system which are accounted for in the controller design.

The baseline sheet dynamics were characterized by measuring frequency response functions (FRFs) between the sheet actuator and each sensor position as well as between each of the three magnet pairs and each position sensor. The corresponding power spectral density (PSD) plots of the sensor signals are shown in Figure 2. They show the relative magnitudes of the sheet responses due to broadband random excitation from the sheet actuator.

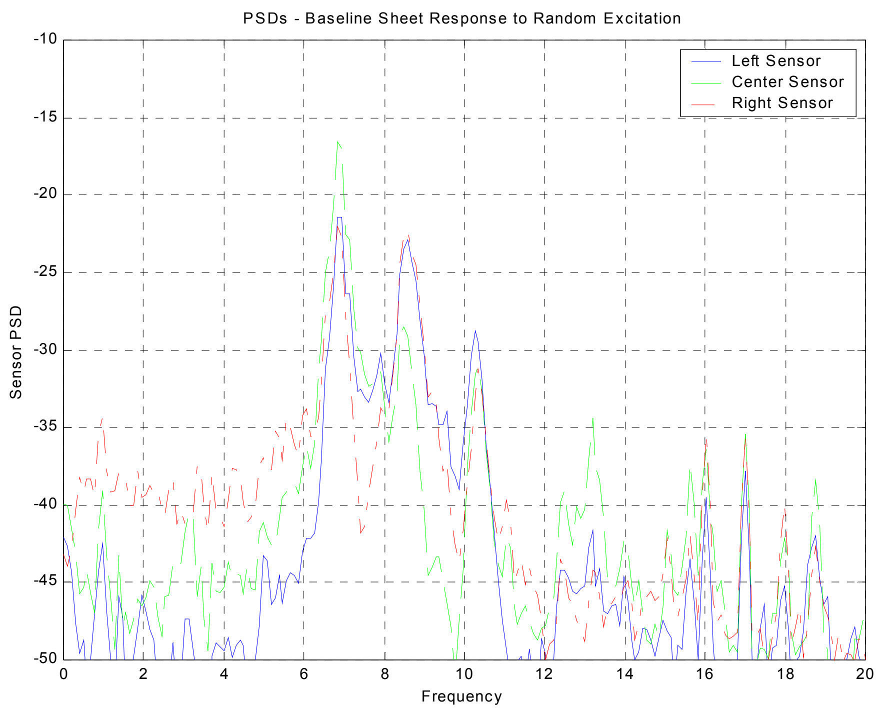

Figure 2: PSD plots of sheet motion under random excitation.

There are three modes of vibration that dominate the response of the sheet at the simulated air knife location: 6.8, 8.5, and 10.1 Hz. The mode shape of the 6.8 Hz peak is that of a bowed sheet with the entire sheet in phase. The 8.5 Hz mode has the left and right sides moving out of phase with very little center motion. The 10.1 Hz mode is a bowed sheet as was the first mode but with the center out of phase with the edges.

The motion at the center of the sheet is dominated by Mode 1 with Modes 2 and 3 having nearly equal contributions at more than 10dB down from the primary peak. The left and right positions on the sheet show nearly equal contributions from Modes 1 and 2 and a Mode 3 contribution approximately 5-8dB lower. Controlling these three modes will have a significant effect on the overall sheet motion due to broadband excitation and thus the amount of zinc used in the hot dip galvanizing process. The efforts made to control these modes are detailed in the following sections.

Modal Control

The approach used to address the controls problem was to divide and conquer. From data taken on the sheet it was determined that the lower frequency vibration modes had distinct vibration 'shapes'. By intelligently using the set of actuators and sensors, the response of individual modes can be isolated, greatly simplifying the control problem. Once the system was simplified into separate modal responses, a simple PID controller was used to control each of the significant modes. Details of this procedure are given below.

The baseline FRFs taken on the sheet and the PSDs of the individual sensors showed that the center sensor response is dominated by Mode 1. The peak in the PSD is over 10dB larger than the next highest peak. The corresponding motion at the left and right sensors is relatively small in comparison (5dB lower). Therefore, control of Mode 1 was attempted by using only the center sensor as the input to the feedback controller. The controller output was then used to drive the three actuators in proportion to the relative FRF magnitude and phase values. This method of developing the controller input was viewed as realistic since the resonant frequencies are likely to shift as a function of many operating variables but the mode shapes should not vary significantly for a given setup.

The most effective PID controller tested on the sheet for Mode 1 was proportional feedback only. The results of the proportional control are shown in Figure 3.

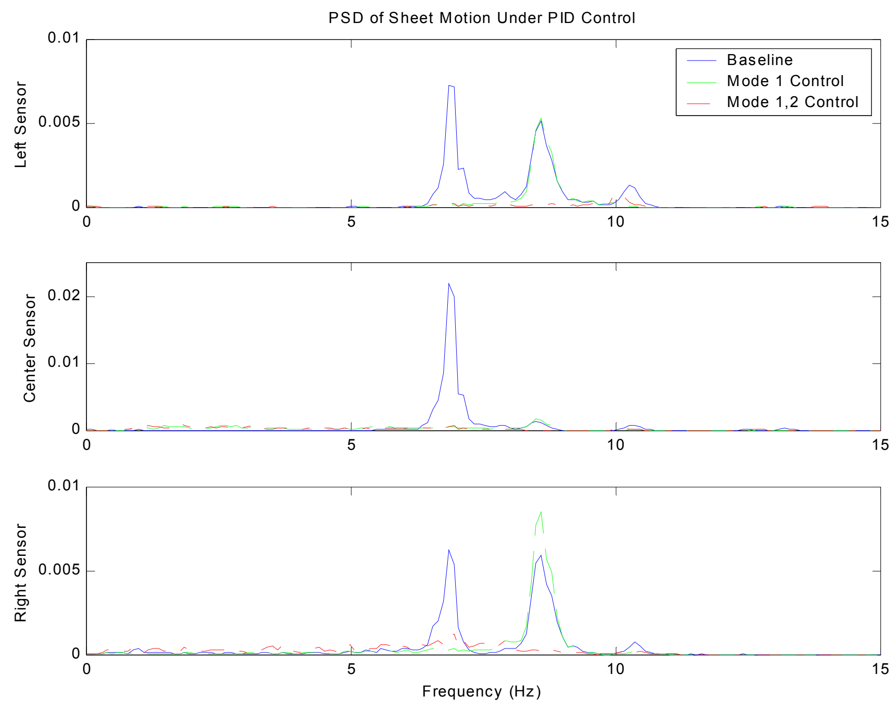

Figure 3: PSD plots of sheet motion under PID control.

The effect of Mode 1 is removed from the response of the controlled sheet. Additionally, Mode 3 is reduced by the Mode 1 controller. This is the result of the similarity in the shapes of the two modes.

The Mode 2 controller was evaluated in combination with the Mode 1 controller. The mode shape corresponding to Mode 2 shows little center motion with the left and right sides of the sheet out of phase with each other (twisting about the vertical centerline of the sheet). The left and right sensor signals were subtracted and used as the input to a PID controller. The feedback voltage to the left and right actuators were equal and opposite while no feedback was given to the center sensor. The results of implementing these two controllers are shown in Figure 3 for the PSDs and Figure 4 for the time response. The results shown are for proportional feedback only. As was the case with Mode 1, derivative and integral terms had no positive affect on the performance of the controller. Mode 3 is still reduced from baseline levels with Mode 1 and 2 control. Due to similarity in the mode shapes for Modes 1 and 3 no attempts were made to further reduce Mode 3.

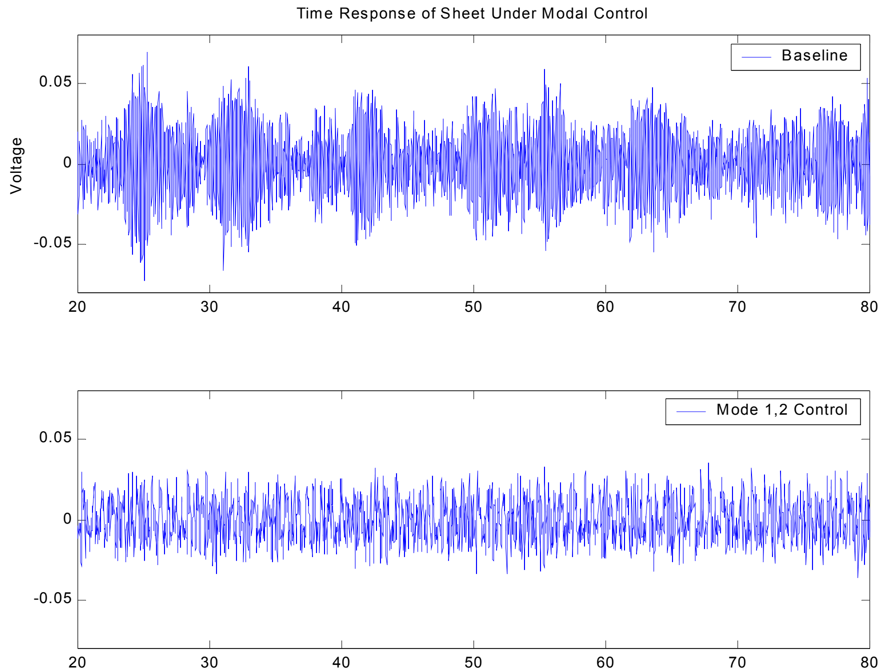

Figure 4: Sheet response under modal control.

In order to quantify the overall effect of the controllers that were evaluated, the RMS vibration levels were calculated from the time histories. The results are shown in Table 1.

Sensor	PID Baseline	PID Mode 1	Reduction %	PID Mode1,2	Reduction %
Left	0.0159	0.0116	27.0%	0.0091	42.8%
Center	0.0196	0.0128	34.7%	0.0121	38.3%
Right	0.0163	0.0148	9.2%	0.0129	20.9%

Table 1: Reduction in RMS vibration levels for various controllers.

The best performance was achieved by proportional control of Modes 1 and 2. Reductions of 20 to 42 percent were measured which could lead to a substantial zinc savings if the nominal coating weight can be reduced proportionally. The variation in reduction with sensor position was a function of the participation of the location in each of the mode shapes. Some of the mode shapes were not symmetric so some locations experienced higher vibration and therefore, higher potential reductions.

Implementation of the controller would require the development and use of a run-time lookup table of control parameters so that different material widths, grades, and speeds could be supported as the modes of vibration change. As an alternative, adaptive estimation methods have been evaluated for tracking modes of vibration during operation. Either of these methods would be able to adjust for the change is system dynamics that will occur with material parameters as well as changes in temperature, lubrication, and tension. It may also be possible to develop a closed-form solution for the first few modes of vibration so that the controller could be updated based on the current operating parameters.

Adaptive Feedforward (AFFW) Control

Modal control has been shown to be effective in controlling resonant sheet response. Adaptive feed-forward techniques were then evaluated to control fixed frequency sources such as bearing faults, roll eccentricity, or unbalance. Adaptive feedforward control is an effective technique for canceling a disturbance for which some measurement of the source is available. It has been successfully used in applications such as acoustic noise cancellation[1] and structural control[2]. In feedforward control, the measured disturbance is fed into the controller to produce the control actuator command signals. This measured disturbance is called the reference signal, and it is usually derived from the primary disturbance (e.g. a tachometer signal from rotating machinery) although a sensor whose output is colored by the plant can also be used. Typically, an adaptive FIR filter is used for the controller. The plant output(s) is used as the error signal to update the coefficients in the FIR filter.

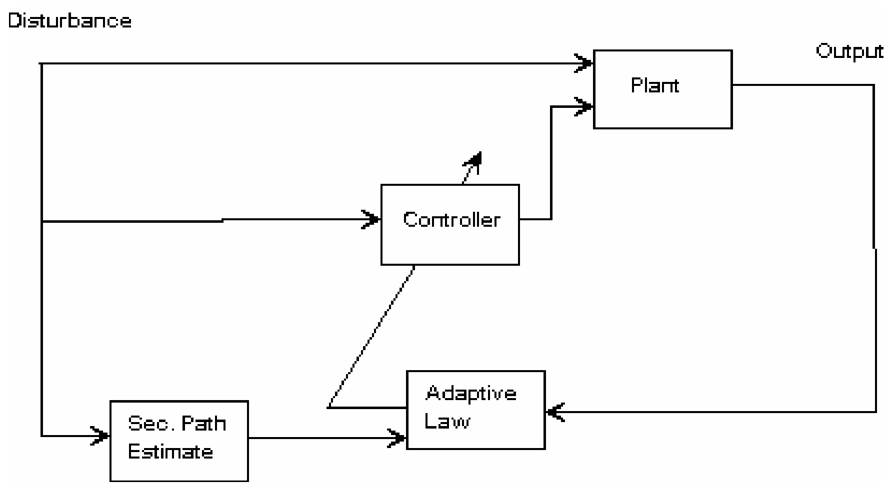

Figure 5: Simple adaptive feedforward control system.

A block diagram of a simple adaptive feedforward control system is shown in Figure 5. The method used here is called Filtered-X or Filtered-Reference because the reference signal is filtered by an estimate of the secondary path, or the transfer function between the control input and the sensor (error signal) output.

A broadband feedforward control scheme was implemented on the SDL sheet test stand. The system was disturbed with a 1 Hz sine wave on the disturbance actuator. A representative plot of the motion of the strip as a function of time is shown in Figure 6 for the open loop case and for AFFW control. The sheet motion is reduced by nearly an order of magnitude.

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[1] Kuo, Sen M., and Dennis R. Morgan. *Active Noise Control Systems: Algorithms and DSP Implementations*. John Wiley, New York, 1996.
[2] Vipperman J. S., and R. A. Burdisso. "Adaptive Feedforward Control of Non-Minimum Phase Structural Systems." *Journal of Sound and Vibration*, Vol. 183 No. 3, 1995, pp. 369-382.

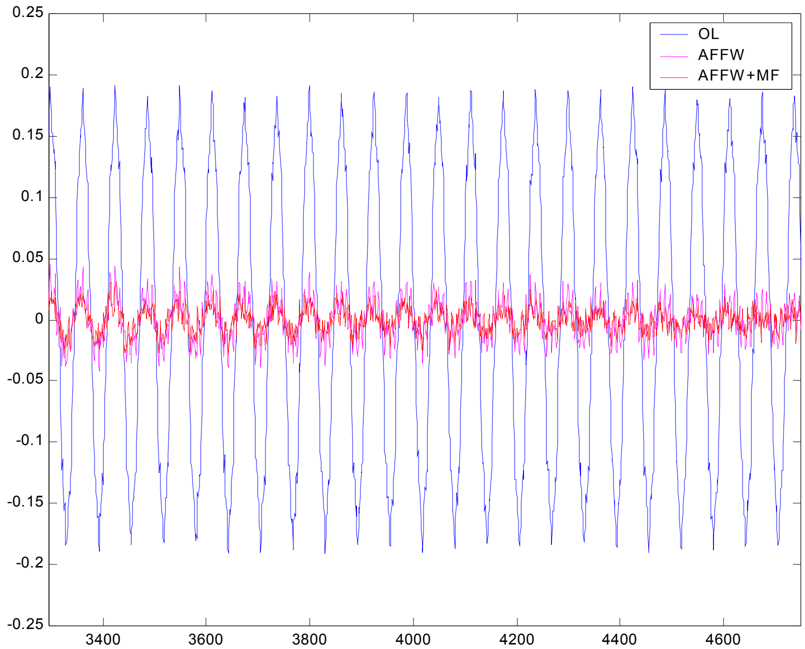

Figure 6: Sheet response to sinusoidal input with AFFW control.

This control method would require tachometer signals from the major rotating components so that the most significant discrete frequency sources are known. The control of multiple discrete frequency sources has not been evaluated.

Galvanizing Line Testing

Data was acquired on a hot dip galvanizing line to characterize the operating environment and the nature of the sheet motion that can be expected. A magnet, position sensor, and cooling fixturing were placed at several positions across the width of the strip above the air knives during line operation. Displacement and temperature data was measured for several line speeds and material grades.

A typical displacement spectrum is shown in Figure 7. The major peaks present in the spectrum are harmonics of a rotating component with a 1.75 Hz fundamental. This result shows that for this line the majority of the strip motion is forced response as opposed to resonant response. However, resonant amplification can be seen around 2, 5, and 8 Hz. This suggests that resonant control can have a positive affect on sheet motion. An FRF of the sheet could not be made to confirm that these were sheet resonances and to determine their mode shapes since the galvanizing line could not be stopped.

The sheet displacement is nearly a decade down from the peak values by 10 Hz. This suggests that controlling forced and resonant response over a small frequency span as was done on the test sheet can have a significant effect on the overall strip motion. This is especially true if the mechanical forcing functions can be kept small through regular maintenance.

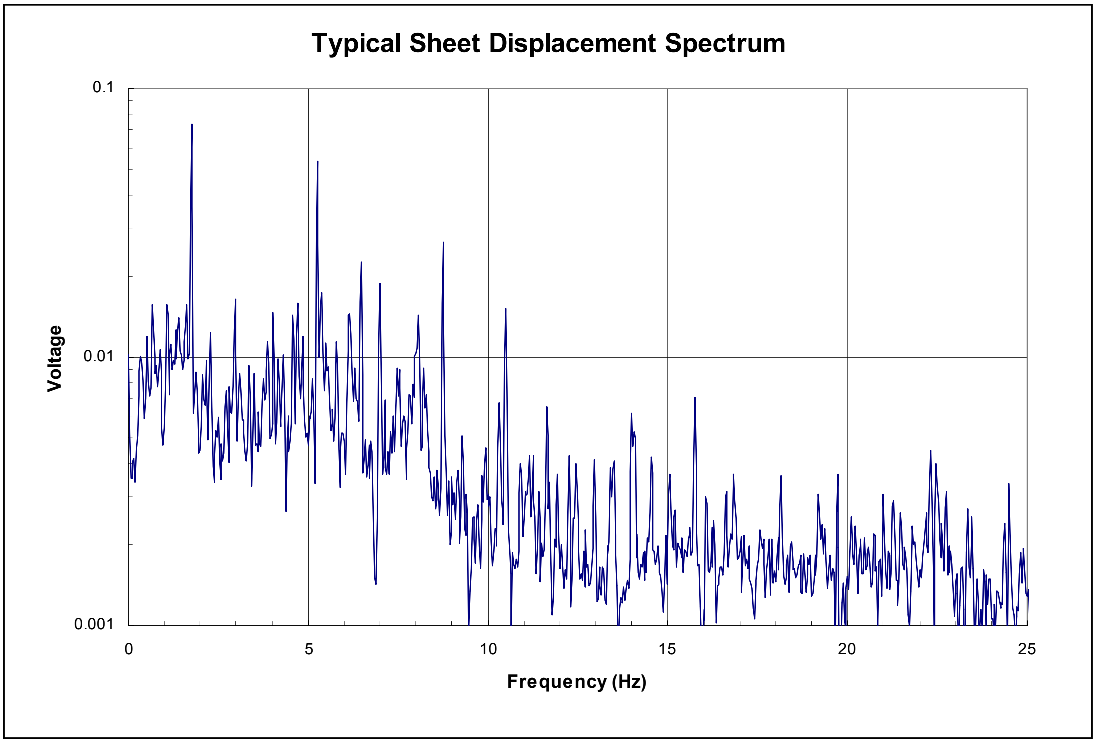

Figure 7: Out-of-plane sheet motion above air knife.

While this data was acquired, thermocouple data was taken for various sensor locations across the width of the galvanizing line with varying air supply pressures. This basic testing showed that a reasonable temperature range can be maintained with typical shop air pressure levels. Depending on the position of the test unit, temperatures varied between 85 and 120 degrees F.

Conclusions & Future Work

Control of the resonant and forced vibration of tensioned steel strip has shown to be realizable and effective. Adaptive feed-forward control was demonstrated to significantly reduce the response of the sheet to forced vibration. Modal control significantly reduced the contribution of the three most significant out-of-plane sheet modes with a resulting reduction of nearly fifty percent in overall sheet motion. This reduction in sheet motion should achieve an equivalent reduction in the nominal zinc coating thickness necessary to maintain minimum coating thickness requirements.

Additionally, this system has the potential to also control sheet bow. The current investigation focused on controlling out-of-plane strip motion without evaluating the ability to maintain a required static curvature. The only limitation that may occur with the current actuator arrangement is the heat that will be generated by the electromagnets if high force levels are required to remove sheet bow. The current test stand setup does not allow for bowing of the sheet so modifications will be required prior to evaluation.

Further development of the control system will involve additional survivability tests of the physical components in the mill environment. Initial evaluations appeared promising but maintenance requirements must be verified in order to assure survivability and maintainability.