Magnetic Actuator Design for Strip Stabilizers in Hot-Dip Galvanizing Lines: Examining Rules and Basic Tradeoffs

authored by **L. Marko, M. Saxinger, A. Steinboeck, and A. Kugi**

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Magnetic actuator design for strip stabilizers in hot dip galvanizing lines

Lukas Marko*, Martin Saxinger*, Andreas Steinboeck†, and Andreas Kugi*, *Member, IEEE*
*Christian Doppler Laboratory for Model-Based Process Control in the Steel Industry,
Automation and Control Institute, TU Wien, Vienna, Austria
†Automation and Control Institute (ACIN), TU Wien, Vienna, Austria
Email: {marko, saxinger, steinboeck, kugi}@acin.tuwien.ac.at

***Abstract*—Electromagnetic strip stabilizers are viable tools for controlling the shape of steel strips in hot dip galvanizing lines. Such stabilizers typically consist of multiple electromagnets located at the top and the bottom side of the strip. While the general design of electromagnetic actuators is a well established field of research not all of this expertise is fully utilized in currently installed strip stabilization systems. This work presents typical design trade-offs and rules for the construction and installation of such electromagnets and aims at assisting in the development of future strip stabilization systems. Furthermore, the behavior of thin steel strips in the magnetic field of the actuators is studied in detail. These results are then extended to the multi-actuator setup typically used in hot dip galvanizing lines. Negative effects arising from the magnetic coupling between the actuators are discussed and simple means to prevent these negative effects are presented. Finally, all conclusions made are validated via force measurements carried out in an industrial hot dip galvanizing line.** [1]

***Index Terms*—Steel industry, sheet metal processing, electromagnets, magnetic cores, nonlinear magnetics, finite element analysis**

I. Introduction

In a continuous hot dip galvanizing line, see Fig. 1, an endless steel strip is continuously fed from an annealing furnace into a zinc bath, where it is guided by multiple rolls. After the zinc bath, the strip passes so-called gas wiping dies, which blow off excessive zinc in order to obtain a desired uniform coating thickness. Because the strip is plastically bent around the guiding rolls, residual stresses are induced in the material, which cause deviations from the ideal flat strip shape [2]. These flatness defects lead to non-uniform gap widths between the gas wiping dies and the strip, which results in a non-uniform zinc coating of the steel strip. To avoid these problems, the gap width between the strip and the gas wiping dies has to be actively controlled. In recent years, electromagnetic strip stabilizers have become a promising approach to accomplish this task [3], [4], [5], [6], [7]. Compared to mechanical stabilizers, like touch rolls, electromagnetic systems apply forces to the strip without contact. This prevents surface defects of the strip and of the zinc coating, which is still liquid at this point.

Modeling the mechanical sub-system of the hot dip galvanizing process has attracted considerable research interest over

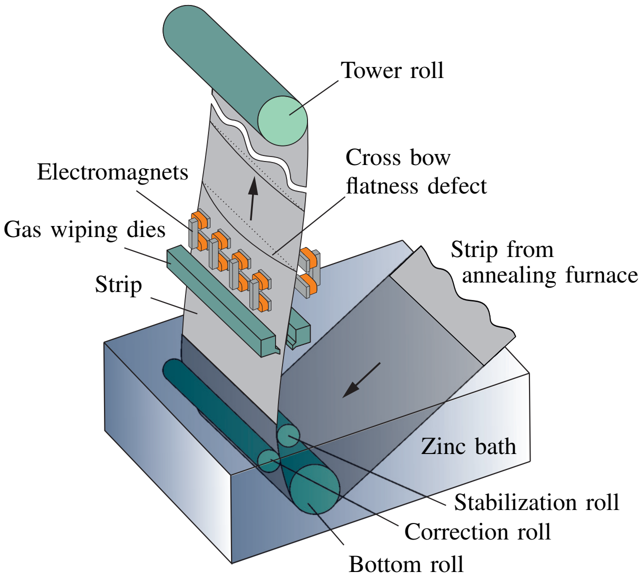

Fig. 1. Hot dip galvanizing line with magnetic strip stabilizer.

the past years. Consequently, the general behavior of this subsystem is quite well understood, see, e. g. , [8], [2]. However, analysis of the magnetic actuators and their interaction with the ferromagnetic strip has received less attention [3], [9]. Thus, many open questions remain, ranging from basic design decisions to more complex issues like the interaction between neighboring magnets.

The aim of this work is to present typical design tradeoffs and recommendations regarding the construction and installation of electromagnetic actuators in hot dip galvanizing lines. While some of the more basic considerations are well established in general magnetic actuator designs [10], [11], not all of them are fully utilized in commercial strip stabilization systems. This work aims at closing this gap and at assisting the development of magnetic actuators for future strip stabilization systems.

The general design of electromagnetic actuators is a well established field of research [12], [13], [10], [14]. In fact, the considered problem shows many similarities to the design of magnetic bearings [11] and the levitation of thin steel plates [15]. However, there are also distinct features of the hot

[1] This is an extended version of the paper presented at the IEEE IAS Annual Meeting 2018 in Portland, OR [1]

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dip galvanizing process demanding additional considerations in the design of magnetic actuators. The air gap variations in the aforementioned systems are typically very small. In magnetic bearings, air gap widths are in the range of $1\,\mathrm{mm}$ with variations of $100\,\mathrm{\mu m}$ or less. Therefore, simple reluctance models or planar field problems, assuming uniform quantities along the axial direction, can be used. Unfortunately, this is not the case for the core geometries in a hot dip galvanizing line. Typical flatness variations of the strip are in the range of $10\,\mathrm{mm}$. To guarantee process stability, i. e. , the strip does not collide with the magnetic cores or their housing, air gap widths are chosen in the range of $30\,\mathrm{mm}$. Furthermore, the aspect ratio of the processed steel strips is very large with typical widths of $1.5\,\mathrm{m}$ and thicknesses of only $1\,\mathrm{mm}$. Thus, multiple electromagnets have to be used in lateral direction for the control of the strip shape. Apart from the difficulties arising from the complex geometry, the magnetic field calculation is further complicated by magnetic saturation effects in the steel strip and the core material. These limitations lead to the necessity of three dimensional field calculations. Thus, modeling and analysis of the magnetic system is a challenging task with high computational effort.

In the following, Sec. II deals with general design considerations for magnetic actuators in hot dip galvanizing lines. Section III is concerned with a single magnetic actuator at the top and bottom side of a steel strip. In Sec. IV, the results from Sec. III are extended to a multi-actuator setup typically found in hot dip galvanizing lines. The interaction between neighboring actuators is analyzed in detail and simple design improvements are proposed to reduce the negative effects of this interaction. Section V presents force measurements which were carried out at an industrial hot dip galvanizing line. These results verify the accuracy of the computational models used in the previous sections.

Throughout this work, a finite element software is utilized to analyze the behavior of the magnetic actuators. All core geometries are based on data from commercially available strip stabilization systems and the electrical steel M330-50A is used as core material. If not noted otherwise, the strip thickness is set to $1\,\mathrm{mm}$ and the dual-phase steel CR850Y1180T-DH is considered as strip material. The lateral and transversal dimensions of the strip are chosen large enough to ensure that edge effects have no influence on the simulation results. Utilizing all geometric symmetries, the setups in Sec. III can be calculated using quarter-space models. Contrary, there is only one plane of symmetry in the multi-actuator setup. Thus, a half-space model is used for all simulations in Sec. IV.

To remain consistent with the measurement results from Sec. V, all calculations are based on magnetization curves measured at room temperature for strip samples taken from the industrial plant. The typical the strip temperature of up to $450\,^\circ\mathrm{C}$ during normal operation of the plant may alter the magnetization behavior of the strip material. However, since the strip temperature is significantly below the Curie-temperature of the material, the elevated temperature causes only a reduced saturation flux density and an increased initial permeability [16], [10]. Thus, the basic magnetic saturation behavior remains the same and all statements and results obtained in this work are equally valid for strip temperatures up to $450\,^\circ\mathrm{C}$.

II. General design considerations

While different actuator designs may have distinct features, there are some basic constraints and trade-offs which should be considered in every design approach:

- In general, each core should have a constant cross sectional area along its main flux path. This ensures equal flux densities in the whole core and thus an optimal material utilization.
- To ensure a reliable control of the distance between the strip and the gas wiping dies, the magnetic actuators should be placed as close as possible to the gas wiping dies. At the same time, the gas stream controlling the coating thickness should not be obstructed by the presence of the magnetic actuators. Thus, the magnets should be built as small and geometrically compact as possible.
- The desired core to strip distance dictates the minimum pole to pole distance of a magnet. As the pole to pole distance is decreased, stray fluxes become more dominant. These stray fluxes do not contribute to the electromagnetic force on the strip. However, they increase the overall inductance seen by the driving circuit. As a consequence, the maximum rate of change of the current through the coils is limited.
- Since the magnetomotive force generated by a coil scales linearly with its number of windings N, a large value of N leads to high force per current values. However, the inductance of the electromagnet scales with N^2 [10]. Thus, a large number of windings limits the current dynamics. While this limitation can be mitigated by high DC driving voltages, a basic trade-off between force per current and maximum rate of change of the coil current remains.
- Though high rates of change in the coil current are desirable, they do not necessarily translate to high rates of change in the magnetic force exerted on the strip. A varying coil current is always related to a time varying magnetic field. According to Faraday's law of induction, the varying magnetic field induces eddy currents in the core and in the steel strip. These eddy currents can have a drastic negative effect on the force dynamics of the actuator [5], [17]. Although eddy currents in the strip are unavoidable, eddy currents in the magnetic core can be significantly reduced by lamination [14].
- The typical temperature of the zinc coating process ranges up to $450\,^\circ\mathrm{C}$. This elevated process temperature has to be considered in the design of the magnetic actuators. To guarantee a stable operation of the magnetic actuators, their temperature should be kept at a reasonable level, typically below $100\,^\circ\mathrm{C}$. Depending on the desired distance between the zinc bath and the electromagnetic strip stabilizer, it can be necessary to use heat shields together with forced cooling of the cores. Apart from the danger of overheating, the elevated temperatures also affect the magnetic properties of the core and the strip material and thus, the magnetic forces exerted on the strip.

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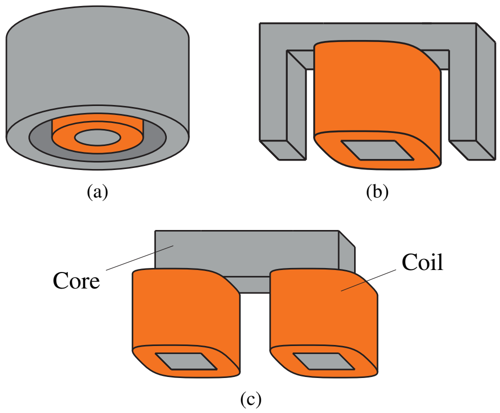

Fig. 2. Different core designs for strip stabilization systems: (a) axisymmetric core, (b) E-shaped core and (c) U-shaped core.

- The gas wiping process leads to fine zinc dust in the vicinity of the zinc bath. To prevent the magnetic actuators from unwanted pollution, they have to be placed in some housing.

III. Single-Actuator Setup

Different magnetic actuator designs, as shown in Fig. 2, can be utilized in strip stabilization systems. As discussed in detail in [1], a U-shaped core according to Fig. 2c minimizes stray fluxes for a given installation space and can be easily built from sheets of electrical steel. Thus, the U-shaped design is best suited for strip stabilization applications and magnetic actuators based on this design will be discussed in detail in this section.

A. Force distribution on the strip

In a magnetic field, the resulting electromagnetic force $\mathbf{F}_{\mathrm{mag}}$ on any body surrounded by air and enclosed by the surface $\mathcal{S}$ can be calculated by

$$\mathbf{F}_{\mathrm{mag}} = \frac{1}{\mu_0} \int_{\mathcal{S}} \left(\mathbf{n} \cdot \mathbf{B}\mathbf{B} - \frac{1}{2} \mathbf{n} \mathbf{B} \cdot \mathbf{B} \right) \mathrm{d}S, \tag{1}$$

with the magnetic permeability of vacuum μ_0, the outward surface normal $\mathbf{n}$, and the magnetic flux density vector $\mathbf{B}$ [18]. Due to the high permeability difference between the steel strip and the surrounding air, the magnetic field at the surface of the strip is almost parallel to $\mathbf{n}$. Thus, the total electromagnetic force on a steel strip is governed by the magnetic flux entering and leaving the strip.

Because of the elastic behavior of the strip, the force distribution on the strip is also of interest. In general, the magnetic field leads to a volumetric force density in the steel strip and a surface force density on the strip surface [18]. For thin elastic media, like the steel strip in the given application, the force distribution is well approximated by a two-dimensional distribution acting on the middle plane of the strip [19], [20]. This approximation is used in the following to analyze the setups shown in Fig. 3. Although the position of the strip z_{strip} between the magnetic cores has a significant influence on the achievable magnetic forces, all qualitative statements and conclusions drawn in the following sections are equally true for arbitrary strip positions. Thus, in the following calculations the steel strip will always be considered to be in the center between the top and the bottom core at $z_{\mathrm{strip}} = 0$.

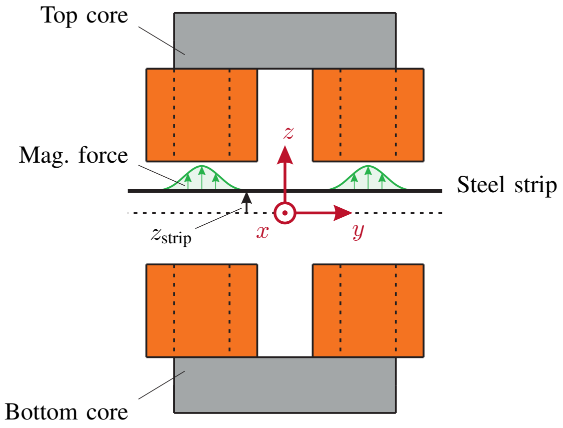

Fig. 3. Simulation setup for a single actuator pair.

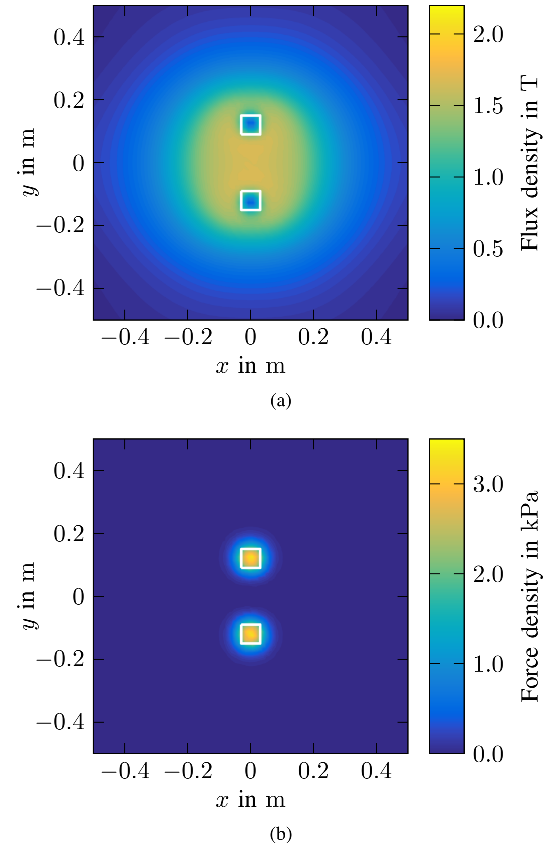

Fig. 4. Typical density distributions for a U-shaped core: (a) magnetic flux density in the steel strip and (b) force distribution on the strip.

Fig. 4a shows the typical magnetic flux density in the center plane of the steel strip for the U-core setup from Fig. 3. Herein, the current in the top coils is set to $i_{\mathrm{top}} = 50\,\%$ of

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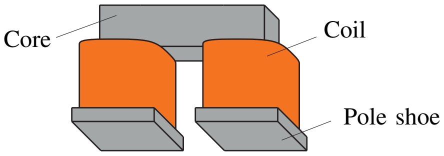


Fig. 5. U-shaped core with pole shoes.

the maximum value, while the current in the bottom coils is kept at $i_{bot} = 0$. White lines show the contours of the core above and below the strip. Due to the small cross section of the strip, large areas of the strip are magnetically saturated and the magnetic flux in the strip spreads over a large area. However, the magnetic flux mainly enters and leaves the strip directly below both pole areas. This leads to a concentrated force density under both poles, as shown in Fig. 4b.

B. Influence of bottom core

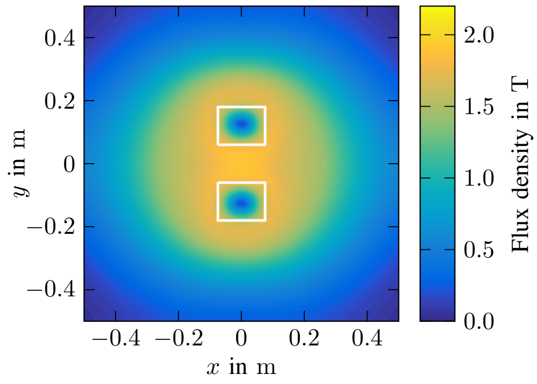
Our simulations suggest that the influence of the bottom core on the achievable magnetic force is rather small (see [1]). From this point of view the bottom core could be removed to reduce costs. However, the main goals of the strip stabilizer are the compensation of flatness defects and the rejection of disturbances and strip oscillations. In general, the accomplishment of these goals requires forces acting towards the top and bottom side of the strip. Therefore, since a single core can only pull the strip in its direction, magnetic cores are required on both sides of the strip.

With the arguments above the question remains whether these cores should be assembled in pairs, i. e., with equal lateral positions on both sides of the strip, or if they can be independently positioned. While the latter setup gives more flexibility, it would increase the complexity of the control task because the current and force restrictions of each core have to be taken into account individually. Contrary, if top and bottom side cores are assembled in pairs (placed directly opposite to each other), they can be considered as one magnetic actuator which can pull the strip in both directions. This allows for the implementation of simpler and more robust control algorithms.

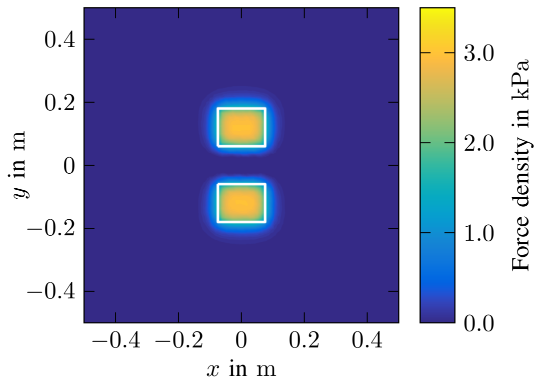
C. Influence of pole shoes

As can be inferred from (1), the total magnetic force on the strip is mainly determined by the magnetic flux entering and leaving the steel strip. To increase the magnetic flux through the strip surface, it can be advantageous to extend the pole area. However, for U-shaped cores as shown in Fig. 2c, the flux through the strip is typically only limited by the pole area but not by the saturation of the core. Thus, it is not necessary to increase the cross sectional area of the core itself.

To increase the pole area without changing the cross sectional area of the core, a pole shoe extension, as shown in Fig. 5, can be used. Fig. 6 shows the flux density in the center of the steel strip and the corresponding force distribution for this setup. A comparison of Figs. 4a and 6a shows that the pole shoe extension considerably increases the flux level in the steel strip. Furthermore, as shown in Fig. 6b, the magnetic



(a)



(b)

Fig. 6. Typical density distributions for a U-shaped core with pole shoes (white lines indicate their contour): (a) magnetic flux density in the steel strip and (b) force distribution on the strip.

force density is still concentrated below the pole area, which is now increased. Finally, Fig. 7 shows the positive effect of pole shoes on the resulting total magnetic force on the strip. Contrary to the simulation without pole shoes, in the simulation with pole shoes, the core starts to saturate at $i_{top} \approx 60\,\%$, which may also be inferred from the force characteristics given in Fig. 7. This shows the limits of pole shoe extensions. At some point, a further increase of the pole shoe area is not beneficial because the cross section of the core becomes the limiting factor. Furthermore, the utilization of pole shoes reduces the effective pole to pole distance. This increases the amount of stray fluxes and thus the overall inductivity of the magnetic actuator.

D. Influence of strip material

The steel grade of the strip and in particular its magnetic properties can significantly vary during production in a hot dip galvanizing line. The main reason for this lies in varying carbon contents, and thus a varying micro-structure [16]. In the following, the influence of the magnetic material properties on the force exerted on the strip is studied in more detail.

Figure 8 shows magnetization curves for two strip materials, with the magnetic flux density B and the magnetic field strength H, as well as the achievable magnetic force on the

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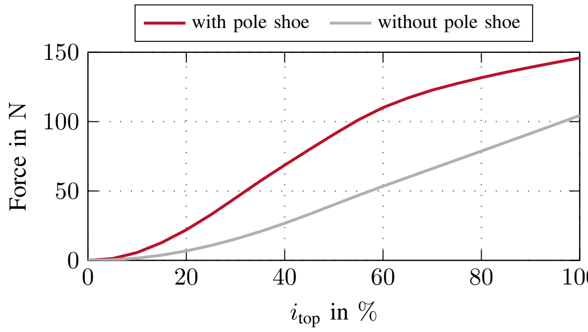
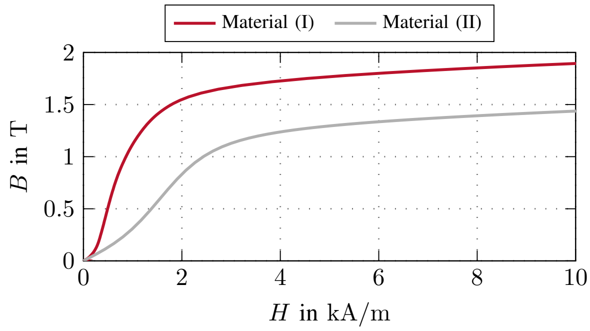
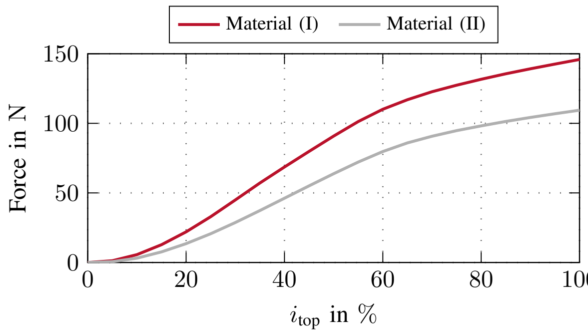


Fig. 7. Influence of pole shoes on the magnetic force in the U-shaped core setup shown in Fig. 3. For both simulations, the current in the bottom coils i_{bot} is set to zero.



(a)



(b)

Fig. 8. Influence of the strip material on the magnetic force: (a) magnetization curves and (b) resulting forces. The current in the bottom coil i_{bot} is set to zero for all simulations.

strip. The magnetization curves of material (I) and material (II) are obtained via measurements on samples from the industrial plant. These materials are chosen in this study because they can be seen as upper and lower bound on the material-dependent magnetization curves, which occur in the considered industrial plant. It can be inferred from Fig. 8 that the strip material has a significant influence on the magnetic force. In fact the force characteristics for the two different materials vary up to 50 %.

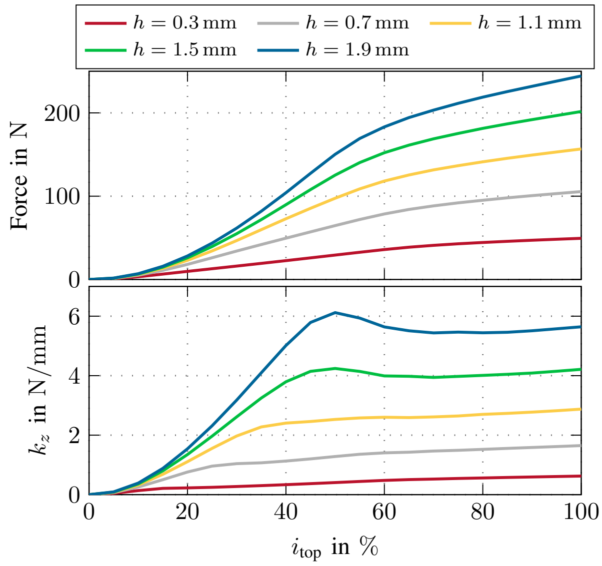


Fig. 9. Influence of the strip thickness h on the magnetic force and its sensitivity k_z to changes of the position. The current in the bottom coil i_{bot} is set to zero for all simulations.

E. Influence of strip thickness

Apart form the strip material, the thickness of steel strips processed in hot dip galvanizing can also vary significantly between individual strips. This variation of the strip thickness alters the force characteristics of the electromagnetic actuators. Since the dynamics of the strip movement is considerably slower than the dynamics of the electrical system, the magnetic force exerted on the strip can be described by the nonlinear steady-state force characteristic

$$F_{\text{mag}} = f(i_{\text{top}}, i_{\text{bot}}, z_{\text{strip}}), \tag{2}$$

where z_{strip} denotes the strip position.

For the design of position control algorithms, the nonlinear magnetic force characteristic is typically linearized at a desired set-point. This yields the approximation

$$F_{\text{mag}} \approx k_i \left(i_{\text{top}} - i_{\text{bot}}\right) + k_z z_{\text{strip}}, \tag{3}$$

where k_i denotes the sensitivity to changes of the difference between i_{top} and i_{bot} and k_z is the sensitivity to changes of the strip position z_{strip}. Since k_z appears as a negative stiffness in the feedback loop, it has a direct influence on the closed-loop stability of the strip position control system [11].

Figure 9 shows the effect of variations in the strip thickness on the magnetic force exerted on the strip as well as on the sensitivity k_z. Clearly, the strip thickness has a significant influence on both quantities. For small coil currents, k_z increases quadratically, which is also predicted by simple reluctance models [11]. However, for higher coil currents, the nonlinear magnetization effects in the core as well as in the strip material limit a further increase of the sensitivity.

The results from Fig. 9 together with the influence of varying strip materials from the previous sections indicate that the force characteristics of the magnetic actuators can

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significantly vary during production in a hot dip galvanizing line. Therefore, control algorithms based on (3) may lead to unsatisfactory control performance of the strip stabilization system. In this case, the performance of the closed-loop system may be improved by utilizing a nonlinear model of the force characteristic (2) in the control algorithm [21], [22].

IV. Multi-actuator setup

So far, only a single magnetic actuator at the top and bottom side of the steel strip was considered. However, strip stabilizers in hot dip galvanizing lines typically utilize multiple magnetic actuators for strip shape and disturbance control. Therefore, this section extends the results from the previous section to the multi-actuator setups shown in Fig. 10.

A. Necessity of multiple actuators

To effectively compensate flatness defects, multiple pairs of magnetic cores have to be used as indicated in Fig. 1. The required minimum number of core pairs depends on the initial flatness defects of the strip and the desired compensation accuracy. The maximum number of core pairs depends on the lateral dimensions of the magnetic actuators and the strip. Generally, the strip cannot be perfectly flattened out using a finite number of actuators. From a practical point of view, up to seven magnetic actuator pairs are usually enough to reduce flatness defects to amplitudes below 1 mm [12], [23]. Furthermore, it is useful to assemble the cores on linear axes orientated along the lateral direction to shift them in case of lateral strip movements and to guarantee the desired coverage of the strip with magnets for various strip widths.

While these considerations show the advantages and the necessity of a multi-magnet setup, this setup may entail unwanted interactions between the individual actuators. A single active magnet causes large areas of the steel strip to saturate. Using multiple magnets, an overlap of these saturated regions and thus an interaction between the magnetic fields of the individual actuators is unavoidable. Depending on the strip to pole distances, the pole to pole distances, and the currents in the individual magnets, this magnetic coupling can significantly decrease the forces exerted on the strip.

B. Reduction of magnetic coupling

One strategy to reduce the negative effects of the magnetic coupling would be to utilize a model in the control algorithm to compensate for this effect. However, due to the rather complex geometry and the nonlinear magnetic behavior of the core and strip material, this may entail considerable computational effort. Hence, this strategy may be infeasible in real-time implementations. Furthermore, due to uncertainties in the magnetic properties of the strip material or the strip temperature, this strategy may fail to adequately decouple the actuators.

Alternatively, a significant reduction of the interaction between neighboring magnets can be achieved by a thoughtful selection of the polarization of the magnetic actuators. Consider the two polarization patterns in Fig. 10. The pattern

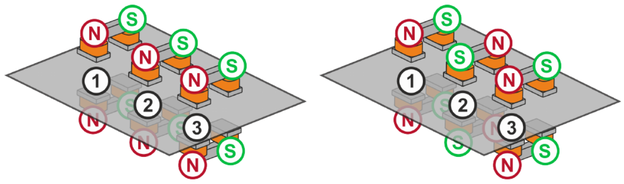

Fig. 10. Considered polarization patterns: (a) Same polarization for all cores and (b) alternating polarization of cores.

in Fig. 10a is the standard configuration used in commercial strip stabilization systems. The alternating pattern shown in Fig. 10b is carefully chosen and performs far better in terms of magnetic interaction. Both configurations lead to a distinct magnetic interaction between the magnetic fields of the individual cores. However, for both configurations, the force distribution on the strip remains concentrated below the respective pole areas, similar to Fig. 6b. Thus, there still exists a clear correspondence between the individual actuators and the magnetic forces acting on the strip.

Fig. 11 shows the positive effect of the alternating polarization pattern for $i_{1,\mathrm{top}} = 100\,\%$, varying values of $i_{2,\mathrm{top}}$, and $i_{3,\mathrm{top}} = 100\,\%$. All currents on the bottom side are set to zero. The calculation reveals that the alternating polarization pattern can produce a drastically higher magnetic force F_2. Furthermore, the influence of $i_{2,\mathrm{top}}$ on the forces F_1 and F_3 is significantly reduced. In addition, F_2 shows a much better agreement with the force characteristics of an actuator pair without active neighbors. The test case from Fig. 11 demonstrates the positive influence of the polarization change in a rather extreme scenario. Thus, Fig. 12 shows simulation results for a more standard test case with $i_{1,\mathrm{top}} = 50\,\%$, $i_{2,\mathrm{top}} = 50\,\%$, and various values of $i_{3,\mathrm{top}}$. Again all currents on the bottom side are equal to zero. As in the previous scenario, the alternating polarization leads to a clear reduction of the interaction between the magnets. Furthermore, the magnetic force almost perfectly resembles the characteristics of the single actuator pair.

The reason for the increased magnetic forces due to the new polarization pattern can be easily understood based on the flux density and flux line distribution in the steel strip shown in Fig. 13. If neighboring magnets are equally polarized, as in Fig. 10a, the nonlinear saturation effect in the strip limits the magnetic flux that flows through the strip region directly below the magnets. Thus, as indicated by the flux lines in Fig. 13a, a significant amount of flux has to go outside around. This limits the total flux into and out of the strip and thus, the magnetic forces exerted on the strip. Contrary, if the alternating polarization pattern from Fig. 10b is used, there is a direct interchange of flux between the poles of different magnets, see Fig. 13b. This decreases the total area of magnetic saturation in the steel strip as well as the length of the individual flux lines. Therefore, more flux enters and leaves the strip, which yields higher magnetic forces compared to the previous setup.

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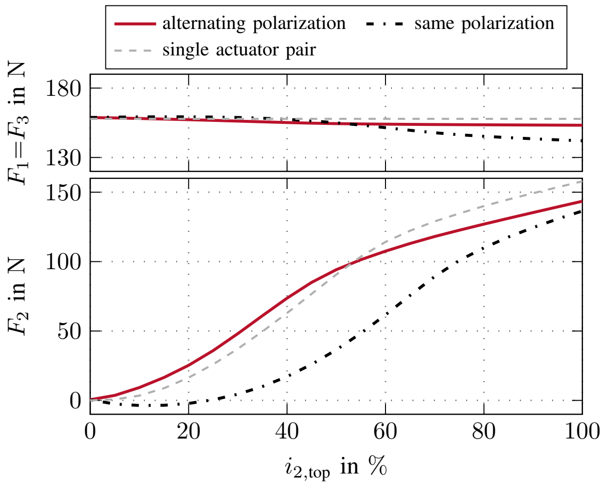


Fig. 11. Calculated magnetic forces with $i_{1,\text{top}} = i_{3,\text{top}} = 100\,\%$ and various values of $i_{2,\text{top}}$. All currents at the bottom side were set to zero.

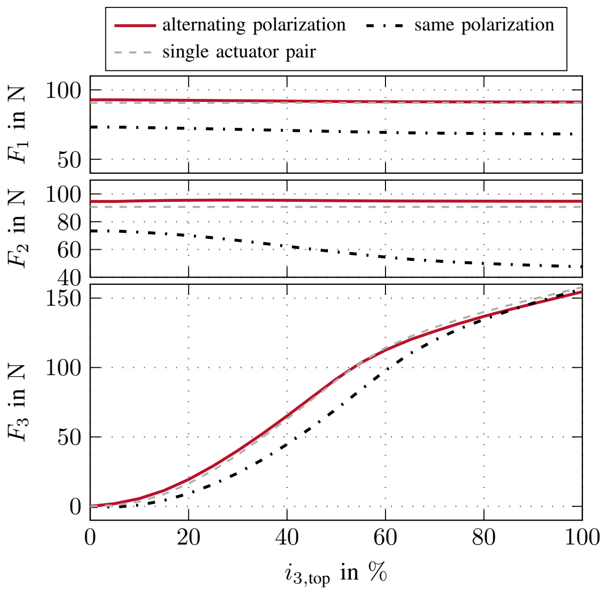
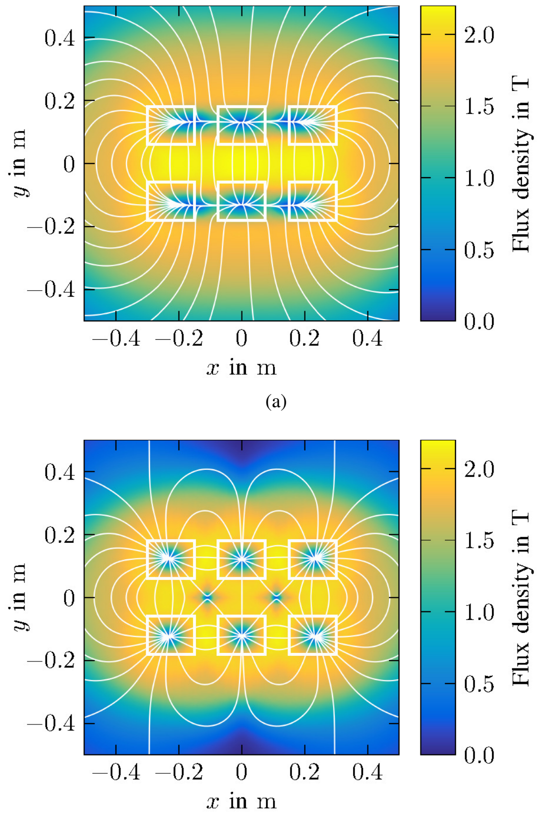


Fig. 12. Calculated magnetic forces with $i_{1,\text{top}} = 50\,\%$, $i_{2,\text{top}} = 50\,\%$, and various values of $i_{3,\text{top}}$. All currents at the bottom side were set to zero.



(a)

(b)

Fig. 13. Magnetic flux density distribution and flux lines for $i_{1,\text{top}} = i_{2,\text{top}} = i_{3,\text{top}} = 100\,\%$. All currents at the bottom side were set to zero. (a) Same polarization for all cores and (b) alternating polarization of cores.

V. Measurements and Verification

So far, all conclusions were drawn based on finite element calculations. To verify the results from the previous sections, experimental measurements of the magnetic forces were conducted in an industrial hot dip galvanizing line. Since the magnetic actuators are not equipped with force sensors, it is impossible to conduct force measurements during normal plant operation, see Fig. 14a. Thus, a dedicated mechanical apparatus was constructed to experimentally measure the magnetic forces during a scheduled downtime of the plant. As indicated in Fig. 14b, the experimental measurement apparatus is assembled directly on the magnetic stabilizer equipment in the industrial plant. This ensures that all measurements are performed with a geometric setting equal to normal plant operation. However, with the devised setup it is not possible to heat the strip. Thus, all measurements were conducted at room temperature.

The measurement apparatus consists of a frame which is supported via rotary joints. The frame holds a tempered glass plate with a thickness of 12 mm, where the strip specimen is glued upon. This design avoids a significant deformation of the strip specimen by the magnetic forces and ensures consistent air gaps between the strip and the poles during the measurement campaign. Furthermore, the air gaps at the individual cores are measured by the distance sensors of the strip stabilizer. Due to the rotary joint, magnetic forces acting on the specimen result in a load on the force sensor at the top of the apparatus. From this experimental force measurement, the magnetic force exerted on the strip specimen can be calculated using the known geometry of the frame.

In [1], measurement results for a pair of U-shaped cores corresponding to the single magnet setup from Fig. 3 and the strip material CR850Y1180T-DH were presented. To confirm the validity of the finite element model utilized in the previous sections, Fig. 15 compares the measured and the calculated magnetic force for the considered single actuator setup, for varying positions of the measurement frame z_{strip} and the high-

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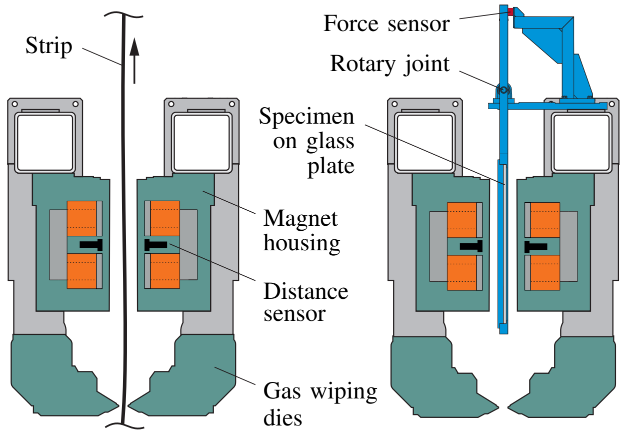

(a) (b)

Fig. 14. Strip stabilization system in the industrial hot dip galvanizing line: (a) Setup during normal production (b) Experimental setup with measurement apparatus to determine magnetic forces exerted on the strip.

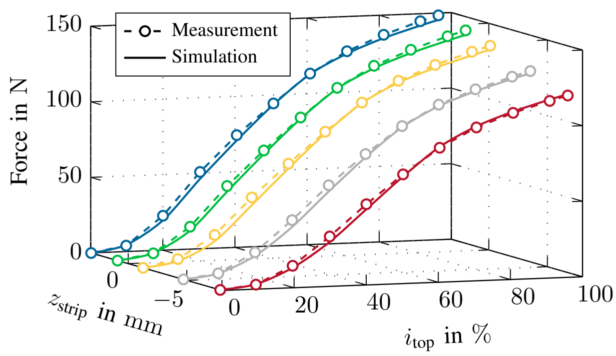

Fig. 15. Comparison between measured and calculated forces exerted on a HX300LAD strip specimen for a single pair of U-shaped cores. The current of the bottom core coil was kept at $i_{\text{bot}} = 0$.

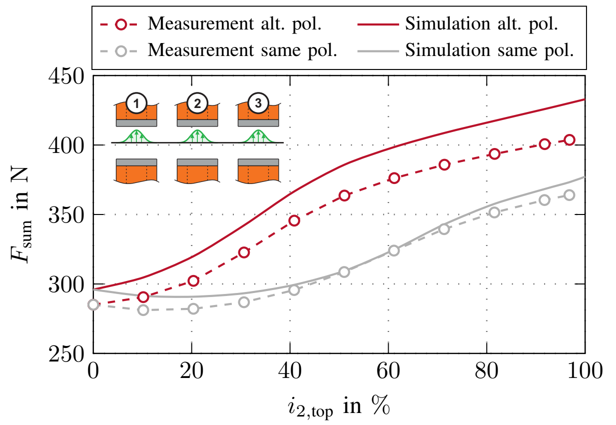

Fig. 16. Measured and calculated total force exerted on a CR850Y1180T-DH strip specimen for different polarization patterns. The actuator currents were set to $i_{1,\text{top}} = i_{3,\text{top}} = 100\,\%$, various values of $i_{2,\text{top}}$, and $i_{1,\text{bot}} = i_{2,\text{bot}} = i_{3,\text{bot}} = 0$.

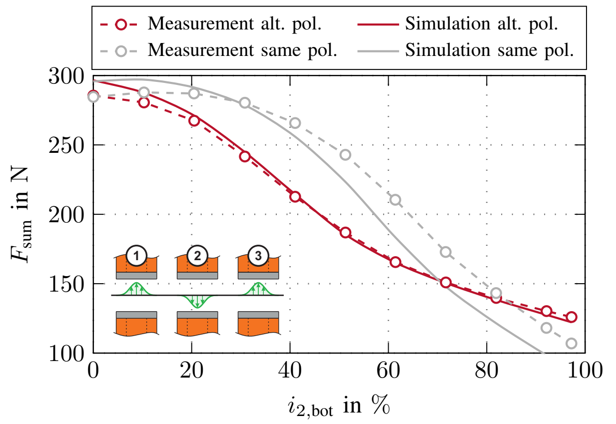

Fig. 17. Measured and calculated total force exerted on a CR850Y1180T-DH strip specimen for different polarization patterns. The actuator currents were set to $i_{1,\text{top}} = 100\,\%$, $i_{2,\text{top}} = 0$, $i_{3,\text{top}} = 100\,\%$, $i_{1,\text{bot}} = i_{3,\text{bot}} = 0$. and various values of $i_{2,\text{bot}}$.

strength low-alloy steel HX300LAD as strip material. Similar to the results in [1], these simulations accurately predict the measured forces exerted on the strip even for varying positions z_{strip}.

To validate the proposed alternating polarization scheme from Sec. IV, experimental measurements for the multi-actuator setups from Fig. 10 were carried out. Here, the outer top side magnets were fully magnetized ($i_{1,\text{top}} = i_{3,\text{top}} = 100\,\%$) while the current in the top center magnet, see Fig. 16, or in the bottom center magnet, see Fig. 17, were varied. Due to the principle of operation of the measurement apparatus, it was only possible to measure the total force F_{sum} exerted on the strip specimen. However, the positive effect of the alternating polarization pattern is clearly visible in the simulation and in the measurement results shown in Fig. 16 and Fig. 17.

In the case of Fig. 16, all magnetic forces act in the same direction. Due to the alternating polarization pattern, the negative interaction between the individual actuators is reduced and thus, the total force exerted on the strip specimen is considerably increased. For the measurements in Fig. 17 the magnetic force due to the center actuator acts opposed to the magnetic forces of the outer magnets. Thus, an increase in $i_{2,\text{bot}}$ decreases the total force exerted on the strip specimen. As in the previous measurement, the negative interaction between the individual actuators is reduced due to the alternating polarization pattern. Therefore, the central actuator is able to exert a significantly higher force on the strip, which leads to a smaller total force on the strip.

The results in Fig. 16 and Fig. 17 show that the calculated forces and the actual measurement agree quite well. Hence, the model is capable of accurately describing the complex behavior of the magnetic field even in the multi-actuator setup. The small differences can be explained by uncertainties in the magnetization curve used in the calculation.

Clearly, the new alternating polarization pattern in Fig. 10b can be easily obtained from the pattern in Fig. 10a by swapping the electrical connectors of individual coils. This, new alternating polarization pattern is now in continuous

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operation at the industrial plant for almost one year.

VI. Conclusions

In this work, basic trade-offs and rules for the design of electromagnetic actuators in strip stabilization devices for hot dip galvanizing lines were discussed. It was shown in finite element calculations that the forces exerted on the steel strip are concentrated below the pole areas of the actuators. At the same time, a significantly larger area of the strip suffers from magnetic saturation. Furthermore, our simulations indicate that the strip thickness as well as the magnetization properties of the strip material have a significant influence on the magnetic force that is exerted on the strip. These variations of the actuator characteristics have to be considered in any controller design for strip stabilization systems, to guarantee high performance of the closed-loop system for varying steel grades and strip thicknesses.

In the multi-actuator setup, the areas of magnetic saturation caused by the individual actuators can overlap. This may entail unwanted interactions between neighboring magnet pairs and a reduction of the magnetic forces. In order to reduce the coupling between actuators, an alternating polarization pattern was suggested, which allows to treat each actuator separately in future control algorithms. Finally, the positive effect of this change in polarization is shown in simulations as well as measurements from an industrial plant.

To conclude, an ideal magnetic strip stabilizer features the following properties:

- The actuators should be built from laminated, U-shaped cores, which maximize the pole to pole distance for the given installation space.
- The pole to strip distances should be large enough to guarantee sufficient process safety. Furthermore, the pole to pole distance of the individual cores should be larger than the pole to strip distances.
- The actuators should be positioned equally in lateral strip direction at the top and bottom side of the steel strip.
- Neighboring magnets should be alternately polarized.
- The actuator positions should be variable to be able to react to lateral strip movements and varying strip widths.

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