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Towards High Speed Galvanizing – Mastering Wiping Conditions Using Hydrodynamic Pads Strip Stabilization

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Increasing the speed of galvanizing lines for reducing their production costs is challenging while maintaining a high coating quality demanded by steel customers. Several issues arising at bath area prevent such speed increase up to or above 200 m/min. Among these issues, corrosion and wear of the immersed hardware, skimming volumes, and wiping conditions are predominant. Regarding the last limitation, the RFCS European project "High Speed Galvanizing" aimed notably at developing a strip stabilization device that could act directly at the wiping level. During that project, CRM Group and its partners have pushed the limit of strip stabilization under TRL-5 conditions at low industrial speed on its Annealing and Hot-Dip Galvanizing Pilot Line. Thanks to a finite element model coupled to an optimization of damping parameters, both validated by measurements, hydrodynamic pads (WO2017129391), whose effects increase with strip speed, have been tested very close to the wiping level. Consequently, a flat and stable strip could be achieved right between air knives with extremely low residual displacements, even under forced vibrations representative of harsh industrial working conditions. The coated product so-obtained was characterized with a similar reduction of final coating thickness variations.

Keywords: *Hydrodynamic, Strip, Vibrations, Stabilization, Wiping*

1. Introduction

Thanks to the galvanic protection offered by zinc, many common flat commercial products such as commodity steel panels or automotive parts can be produced in continuous industrial sheet-galvanizing lines, along which a thin cold-rolled steel sheet coil is continuously uncoiled, welded to the previous one, degreased, annealed in a high temperature furnace, galvanized in a liquid zinc bath, then cooled, skin-passed, conditioned, recoiled, cut, packed and finally sent to the industrial customer.

The final zinc thickness is imposed by gas wiping knives, yet at the exit of the metal bath where the strip is diverted and shape-corrected by a set of immersed rolls. In the bath, the dissolution of iron fines at strip surface and the slight dissolution of the strip itself, lead also to the formation of micron-sized intermetallic dross particles, possibly polluting the final coating and creating visible defects, but also contributing to the wear of rolls bearings. Nevertheless most of those particles are regularly skimmed from bath surface, together with the oxide film produced by the wiping gas.

In modern galvanizing lines, the limitations to higher productivity include the increased dross production with more frequent related operations at bath, the increased wear of immersed material inducing strip vibrations, the management of strip shape and residual cross-bow at wiping level, and the splashing of liquid metal generated by a necessary higher wiping pressure balancing a thicker liquid wave, leading to coating defects, more skimmings and dirty equipment [1,7,11,12].

Indeed in the hot-dip galvanizing of steel sheet, the stabilization of the moving strip as it emerges from the galvanizing bath is of major importance as high stability and flat shape of the strip in front of wipers is needed for

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efficient wiping and homogeneous coating gauge leading to high quality products [2-4,6,8,9,13].

Hopefully stabilizing the strip with zinc pads can be very effective thanks to the density and the viscosity of liquid zinc. From that basis CRM has tested and patented [14] the concept of hydrodynamic (HD) zinc pads, passively acting like self-aligning tilting-pad thrust bearings surfing on the liquid metal, in order to reach the targeted benefits of stabilizing the strip right under the gas wipers (> 10 mm; maybe complementary to an electromagnetic stabilizer [5,10] acting above such wipers) while adjusting temporarily both strip shape and pass line between gas knives closer to the ideal plane through the elastic deformation of the strip (cf. Fig. 1 and Fig. 2).

2. Numerical Models of Hot-Dip Galvanizing Lines

A first effort started with the development of finite element (FE) numerical models by the LTAS-VIS laboratory of the Aerospace and Mechanical Engineering Department of ULiège, of both the narrow strip CRM Annealing and Hot-Dip Galvanizing Pilot Line, and a full width typical industrial line. The objective was to draw the sensitivity of strip vibrations to defects in immersed hardware, and to highlight the capabilities offered by HD pads. The validation of the first model has been possible based on the analysis of data from former (cf. Fig. 2b) and consecutive CRM pilot trial. Future industrial data are still necessary to validate the corresponding model and to allow the optimization of pads location according notably to line conditions and effective strip format.

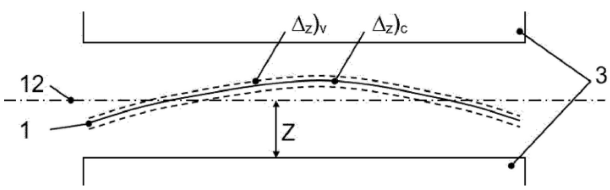


Fig. 1. Strip residual crossbow and vibrations at wiping level (top view)

2.1 Basic model and preliminary trials

The strip was assumed to be free of initial geometric defects (flatness, coil set, crossbow, or waviness) and considered “at rest” (no effect of longitudinal velocity on vibrations). The necessary translation and rotation blockages were given to sink roll, top roll and corrector roll and strip tension was introduced as an initial pre-stress. Cooling sections consists here of two sets of air pads acting on each side of the strip (cf. Fig. 3). Off-trial measurements have highlighted that each single air pad presents an equivalent stiffness, constant and proportional to box pressure. Cooling sections introduce also a stochastic excitations, whose amplitude were tuned in relation to vibrations amplitude at wipers. Finally, an

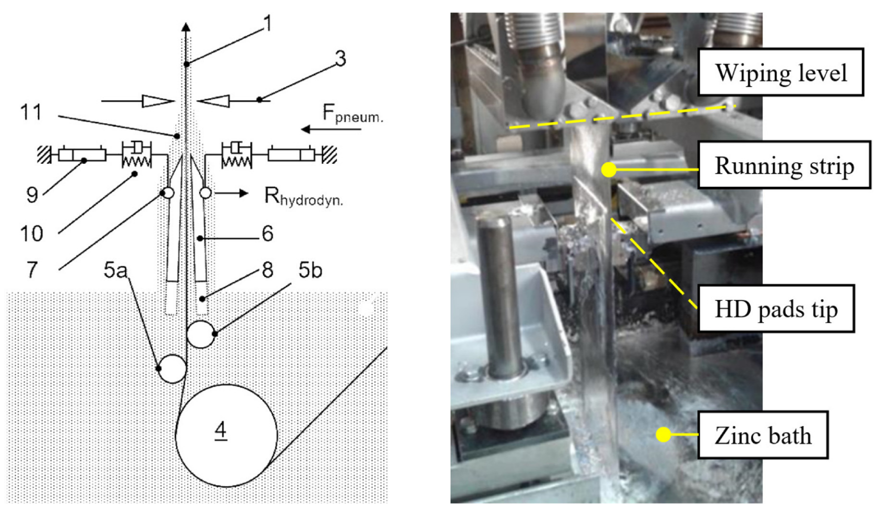


Fig. 2. (a) working principle of HD strip stabilization at wiping level (side view), (b) HD zinc pads in action at CRM pilot line (80 m/min, CW: 10.8 µm / Z145)

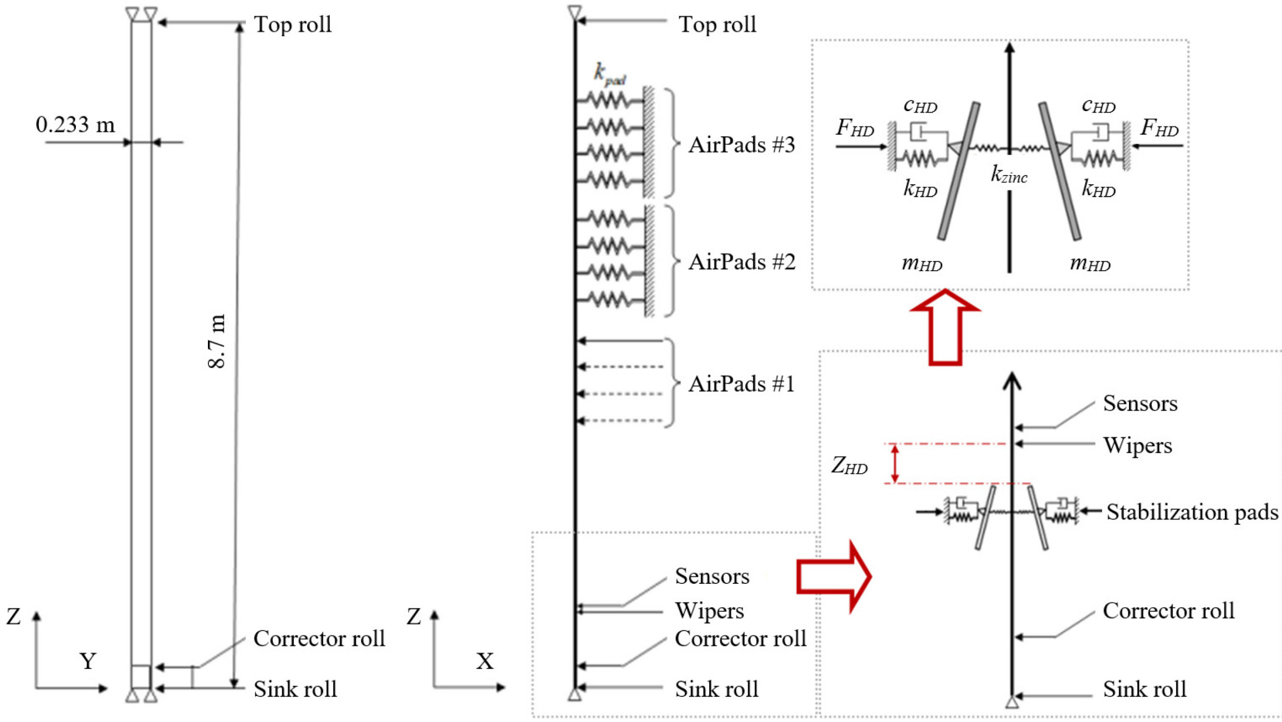


Fig. 3. Layout of the pilot line and HD zinc pads mass-spring model

equivalent rotation stiffness had to be added to consider the influence of the air film on the torsion modes according to the theory.

During former trials, a rotating valve placed in the feeding duct of AP#1 section last box (globally turned off, cf. Fig. 2 and Fig. 3) was used to produce pure harmonic excitations. In contrast, HD pads were located at Z_{HD} distance from wipers, and acting on each strip side. Their pivots were attached to air cylinders, and coupled to a spring-dashpot in a discrete mass-spring system (m_{HD}, k_{HD}, c_{HD}), where the applied force F_{HD} was balanced by the hydrodynamic reaction at pad-strip liquid interface (cf. Fig. 3).

2.2 Modal analysis and frequency response

A modal analysis of the strand without HD pads has been made using a 3D-Shell finite element (FE) model. The equivalent stiffness of each air cushion was tuned to fit first frequency measured during pre-tests under same tension. Frequencies and shape modes so obtained (cf. Fig. 4) are slightly sensitive to tension but remain unaffected by temperature.

Cooling sections both excite and stabilize strip vibrations. Therefore, modal damping was assumed to increase sharply with frequency. The response over 300 s has been simulated out of any transient effect: calculated amplitudes for a natural excitation were close to the measured values (~0.50 mm-RMS) but with some variations (±10%). The same exercise has been made simulating a pulsating feeding pressure for a single box in AP#1, to produce a harmonic force close to the first natural frequency of the strip. In that case amplitudes were bigger (~1.80 mm-RMS) but variations were lesser (±7%).

Considering the model of HD pads, simulated vibrations at wipers were here close to measured amplitudes. However frequencies and mode shapes are slightly modified compared to the reference case. Consequently, forced vibrations amplitudes close to strip resonance are smaller (~0.55 mm-RMS) and with even less variations (±4%).

Finally, the strip was excited at different frequencies and amplitudes (0 to 8 Hz) using a pulsating pressure at air pad AP#1. Measured and simulated frequency responses are compared hereafter, without and with HD zinc stabilization pads (cf. Fig. 5).

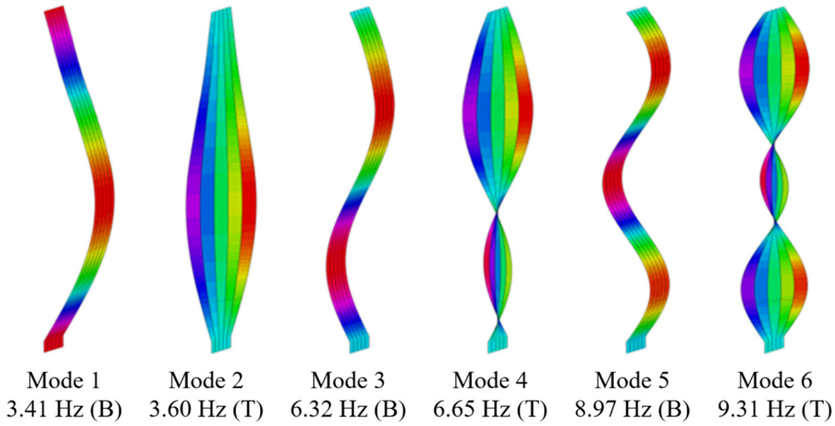


Fig. 4. Mode-shapes of the strip – 3D-shell model, given strip tension (stabilization off)

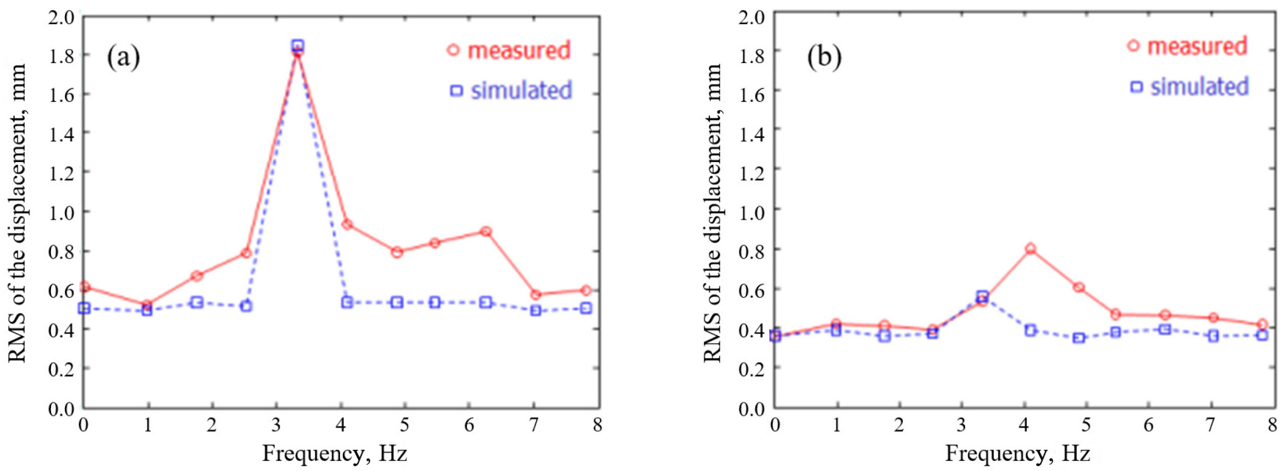


Fig. 5. Frequency responses without (a) and with (b) HD zinc pads

2.3 Influence of strip tension uniformity and damping conditions

Compared to a reference situation, simulations have first confirmed that a non-uniform strip tension alters vibration amplitudes: higher at the loose fiber, smaller at the tensed fiber. Then an optimization of pads parameters has considered successively: distance to wipers Z_{HD}, stiffness k_{HD}, and damping c_{HD}, under uniform strip tension and random excitation at APC sections. Accordingly, HD stabilization performances increase when pads are close to wipers (< Z_{HD}) and when stiffness (> k_{HD}) increases, the latter to be nevertheless limited to avoid problems at pads actuator or even dry contacts between pads and strip with long centers. However damping c_{HD} has a drastic effect on vibrations (÷2.5 to 3 ratio), while it alters strip natural frequencies and bending modes.

2.4 Important additional excitation modes

Additional cases needed to be considered as well as they highlight strong benefits to be gained with HD pads stabilization. Indeed, the presence of a defect on the sink roll such as wear at the bearings can be simulated as a prescribed displacement "d" of the sink roll (assumed < 15 mm) inducing vertical and horizontal harmonic forces on the strip.

$$d = e \sin \Omega t \tag{1}$$

where $\Omega = v/R$ = angular speed, v = strip linear velocity, R = radius of sink roll, e = eccentricity (e.g. due to wear defect)

This first case corresponds to the horizontal component,

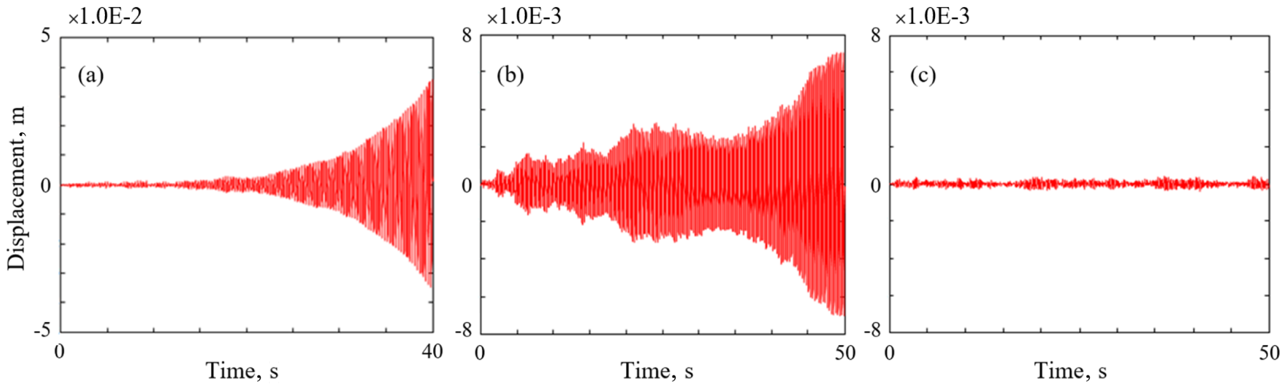


Fig. 6. Simulation results for widthwise uniform tension, 10% timewise variation (a) without stabilization, (b) with stabilization – 0 N.s/mm, (c) with stabilization – 200 N.s/mm

perpendicular to strip plane. Without stabilizer, a small peak appears in the PSD plot at the frequency related to sink roll rotational speed. When the stabilization system is active response amplitudes are consequently smaller and the horizontal influence of any sink roll defect is also minor. The second case corresponds to a timewise variation of strip tension, possibly caused by an imbalanced sink roll, wear defect at roll bearings, vibration of roll supporting arms or even by vibrations induced in the kinematic chain constituting the line itself.

Without stabilizer, and for an excitation frequency two times the first natural bending frequency of the strip, a parametric instability occurs, leading to vibration amplitudes growing to infinity in a truly short lapse of time (cf. Fig. 6a). In the case of CRM pilot line, the excitation frequency for instability corresponds to a critical velocity of 643 m/min. But in the industrial case, the natural frequency is lower and the velocity is about 190 m/min, which is incompatible with a high-speed process.

With stabilizer, the instability disappears when damping is added to the stabilizer (cf. Fig. 6c vs. Fig. 6b). However, the threshold for instability is intricately linked to both the level of the tension modulation and the magnitude of damping.

2.5 Model validation

The validation of the ULiège finite element model described here above was achieved based on recordings from V2i sensors, obtained during off-trial tests and during the pilot trial. The extension of the model to industrial conditions and validation by continuous on-line measurements should provide a complete view of the subject.

At first, the basic modal response of the strip was obtained by off-trial "hammer" shock excitations at various pre-defined locations. A second approach was tested during pilot trial, depending on the nature of vibrations, the presence of stabilization, and the use of a distant laser vibrometer, able to measure strip speed at high frequency (~1 kHz).

To fit the model, recorded displacements have been compared with numerical ones at the laser spot location, along 60 s span time series under natural vibrations and without stabilization. By adjusting damping ratio and modal damping, a precise frequency match has been obtained thanks to an Operational Modal Analysis (OMA) and a Covariance-Driven Stochastic Subspace Identification (SSI) method applied on the recorded signal. That has led also to a good match between simulations and recorded signal, with some differences since the excitation was simulated by a pure sine function, while pilot trial involved one-direction short air pulses creating higher order harmonics.

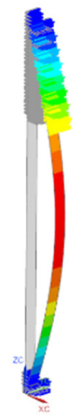
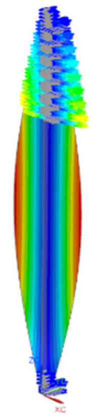
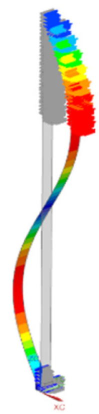
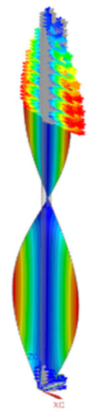
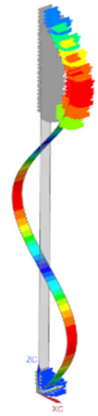
2.6 Upscaling to industrial dimensions

To simulate the dynamic response of an actual line, the initial model has been scaled up to the following industrial strip formats: 1.0 × 1500 mm / 0.5 × 2000 mm / 2 × 1000 mm.

Same strip tension than previously was applied, HD and APC parameters were kept the same, all leading to the modal analysis of the vertical strand (cf. Table 1).

Particularly, the results obtained for the thinner-wider case present a second bending mode along strip width. But also, asides from splashing problems at highest speed,

Table 1. Five first modes of the scaled line model (strip format: 1.0 × 1500 mm)

Mode 1 First bending f_1 = 0.57 Hz	Mode 2 First torsion f_2 = 0.58 Hz	Mode 3 Second bending f_3 = 1.12 Hz	Mode 4 Second torsion f_4 = 1.13 Hz	Mode 5 Third bending f_5 = 1.63 Hz
				

the risk of instability in that case forces the need of a HD stabilizer under the air knives.

As a conclusion, the preparation of any prospective industrial trial will demand first to study their integration in the process specifications, but also to identify the optimal relative location of few HD pads along strip width, in various industrial conditions.

3. Zinc Pilot Trial

The trial at CRM pilot line was prepared as summarized hereafter and described by the following set-up at bath and overall layout (Fig. 7 and Fig. 8):

· Strip vibrations were induced using a set of electronic air-pulse actuators placed under the APC section and tuned to obtain suitable amplitude at wipers;

· Pads support damping parameters (k_{HD}, c_{HD}) and distance to wiping line (Z_{HD}) were optimized aiming at minimized vibration amplitudes at wiping level;

· In addition to low frequency line signals (1 Hz), various signals associated to strip vibrations were sampled at moderate sampling rate 50 Hz: strip tension at top roll, strip displacements at wiping level (inductive sensors: motor, center and operator sides), pad actuators temperature, and pads temperature;

· A distant high frequency laser vibrometer (1 kHz) was also placed at mid-height of the strand (cf. Fig. 8) to measure strip speed perpendicular to its plane for further validation of the finite element model of the line.

Considering low industrial speed (80 m/min) and moderate coating gauge (10 μm/side) the conditions assessed during this pilot trial were:

· Natural strip vibrations vs. Forced vibrations, close to strip resonance;

· No stabilization vs. With HD stabilization, at 40 mm from wiping line.

3.1 Strip tension at top roll

During that trial, tension variations were notably increased under forced strip vibrations (+36%). But thanks to the correcting and dampening action of HD stabilization, those variations are brought back to the natural case.

3.2 Strip vibrations at vibrometer

We have observed a large decrease of strip vibrations amplitude at laser spot level (i.e. at mid-height of AP#2 section, cf. Fig. 8) in the case of forced vibrations with HD stabilization. From that base, the validation of the FE model has been confirmed and its extension to industrial conditions on wide formats have been pursued (cf. Table 1).

3.3 Strip vibrations

Strip displacements have been recorded slightly above wiping level using inductive sensors, then reported at wiping level. The damping performances obtained (cf. Fig. 9) using HD stabilization have led to about –80% reduction (÷5 ratio) of natural strip vibrations and up to

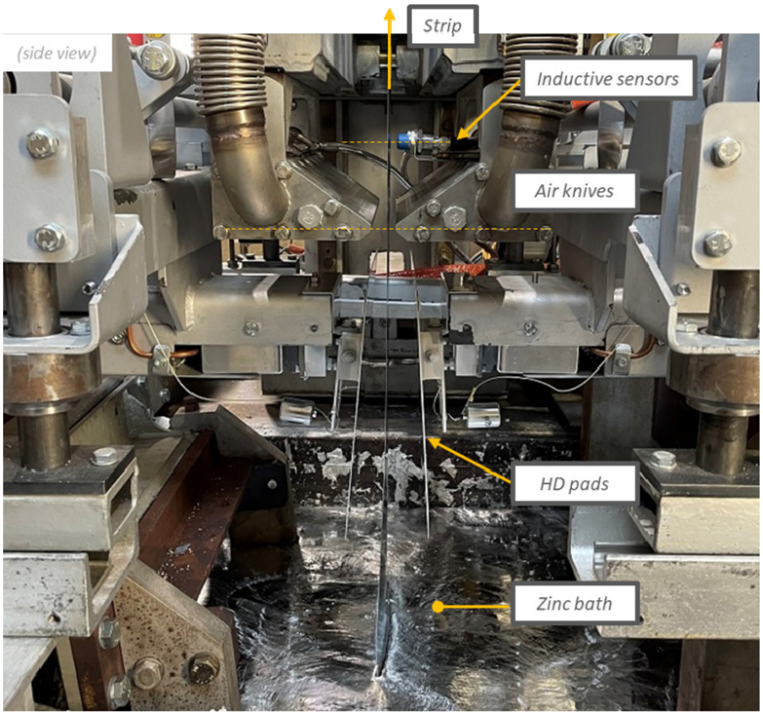


Fig. 7. Set-up at the zinc bath

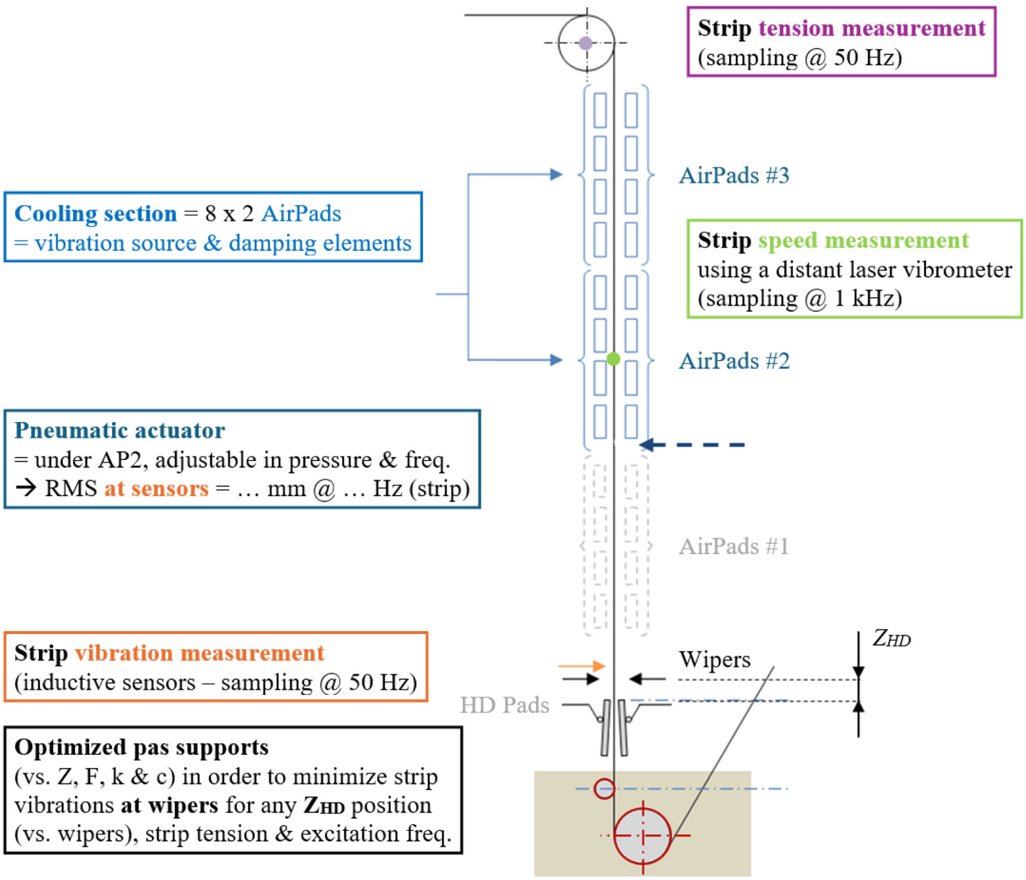


Fig. 8. General layout at CRM Annealing and Hot-Dip Galvanizing Pilot Line

–87.5% reduction (÷8 ratio) of forced strip vibrations, close to strip resonance, representative of harsh industrial conditions (e.g. high APC blowing power).

3.4 Performances achieved

HD stabilization performances achieved during that pilot trial are expressed here as the comparison between recorded displacements of strip center reported at wiping line, and strip-length manual coating thickness measurements on top side, and their standard deviation, under both forced and natural vibrations (cf. Fig. 10).

Presently, a slight uncorrected strip pass line change at

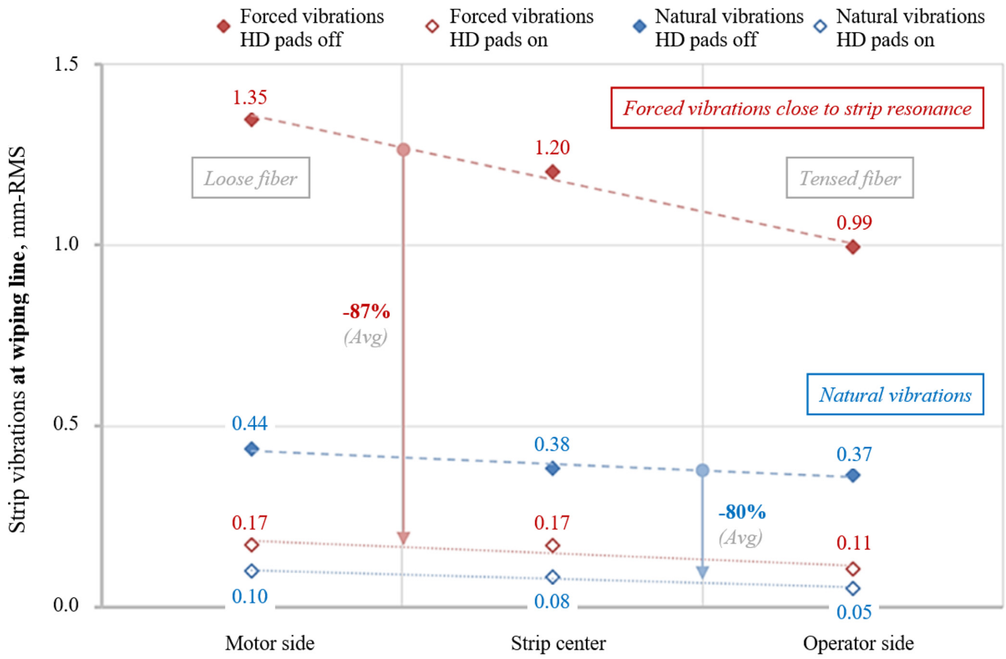


Fig. 9. Performances achieved on strip vibrations reported at wiping line

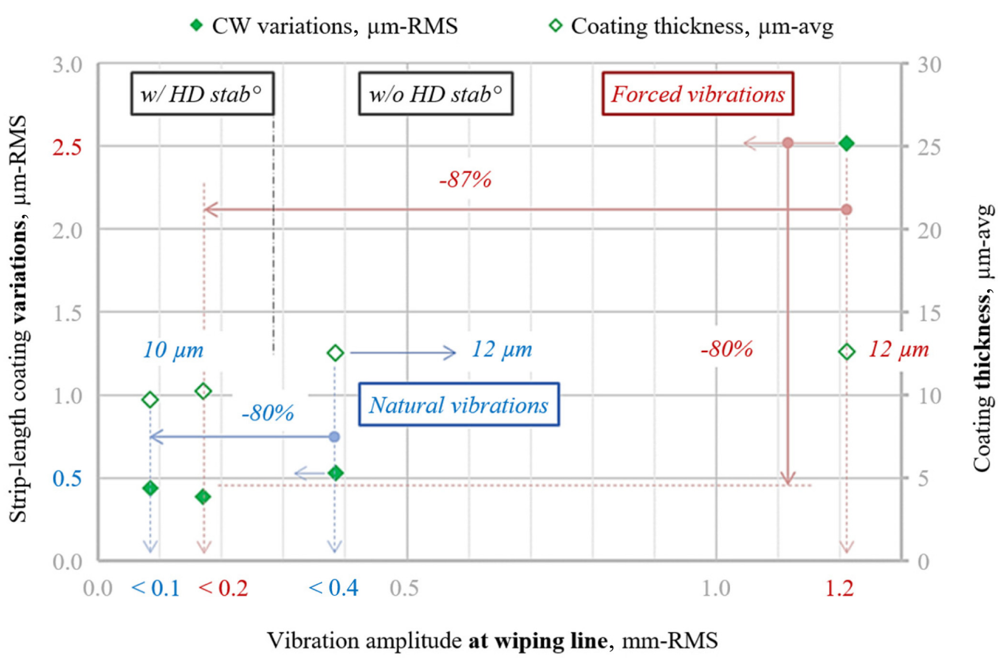


Fig. 10. Performances achieved on lengthwise coating uniformity (top side)

pads closure (w/o → w/ HD stabilization), has led to a 2 μm change of the average coating thickness. Comparatively, a former trial highlighted a robust sensitivity of 1 μm on the average coating thickness per 10 mm displacement of the frame supporting the air cylinders (cf. Fig. 2a), strengthening the industrial feasibility of the system, at the price of a closed-loop control, possibly coupled with a strip profile measurement [15,16].

Here again, that small change was proportionally far below the effective damping of coating thickness variations achieved thanks to HD stabilization, particularly under forced strip vibrations, whose amplitude at wiping line were representative of industrial conditions:

Forced "industrial" strip vibrations: –87%
→ top side forced coating variations: –80%
Natural "pilot" strip vibrations:–80%
→ top side natural coating variations: –17%

4. Industrial Point of View

According to the performances obtained at pilot level, the industrial application of HD zinc pads to the stabilization, the elastic shape correction and the fine pass-line tuning of the running strip at wiping level suggests an innovative solution to an old problem, possibly leading to process improvements while somewhat disturbing habits in that area.

Nevertheless, before any implementation on any industrial line, many points still need to be addressed, notably regarding the optimal distribution of HD pads across strip width depending on process working conditions and strip format, the long-term sustainable use of pads regarding liquid metal corrosion and dross build-up, or even the automation of such system regarding weld passages and format changes. The preparation of industrial trials will thus demand additional team efforts including numerical simulations, FMEA study, … etc.

5. Conclusions

Based on an intensive preparation involving numerical modelling by ULiège, validated by frequency and modal analyses by V2i, a TRL-5 pilot trial has been conducted with success on the CRM Annealing and Hot-Dip Galvanizing Pilot Line, aiming at evaluating performances of HD stabilization at low industrial speed (80 m/min), leading in all cases to a flat and stable strip in front of air knives:

· A strong reduction of strip vibrations at wiping level, under extreme "industrial" forced conditions, close to strip resonance (-87%) or softer "pilot" natural conditions (-80%).

· An improved lengthwise coating uniformity in the common 10 μm thickness industrial target range by significantly reducing both forced (-80%) and natural coating variations (-17%).

Consequently, based on V2i laser spot vibrometer measurements in the after-pot cooling section, the ULiège finite element model of CRM pilot line has been extended to the industrial case with various strip format and target line speeds, confirming the benefits to be gained from HD Pads strip stabilization right under the wiping line.

In the future, industrial trials might confirm those performances, depending on damping conditions and optimal distribution of few pairs of HD pads along strip width.

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References

1. M. Dubois, M. L. Riethmuller, J. -M. Buchlin, M. Arnalsteen, *Proc. Galvatech Conf.*, pp. 667-674, The Gas-Jet Wiping Limit: the Splashing Phenomenon, Chicago (1995).
2. O. Brüls, J. C. Golinval, *Proc. 21st Benelux Meeting on Systems & Control*, p. 24, Active Control of the Steel Strip in a Hot-Dip Galvanizing Line, Veldhoven, The Netherlands (2002). https://pure.tue.nl/ws/portalfiles/portal/3079152/555518.pdf
3. O. Brüls, J. C. Golinval, Simulation of an Active Control System in a Hot-Dip Galvanizing Line, pp. 39 - 44, NATO Advanced Study Institute on Virtual Nonlinear Multibody Systems, Prague (2002). https://apps.dtic.mil/sti/tr/pdf/ADA409218.pdf
4. S. Dubois, M. Dubois, *Proc. GALVATECH 2004 Conf.*,

pp. 207 – 216, Characterization of Strip Vibration at the Wiping Nozzles, Chicago, IL, USA (2004). https://www.tib.eu/en/search/id/tema:TEMA20040904855/Characterization-of-strip-vibration-at-the-wiping?cHash=b05e26b7b156b0f36df8494b75855378

5. Löfgren, *Proc. 97th Meeting Conf.*, EM Strip Stabilizer for Hot-Dip Galvanizing Lines (2005).
6. Hennion, Hot-Dip Galvanizing – Stabilizing and Cooling the Strip in the Wiping Area, RFCS study 2004 – EUR 22035 (2004).
7. K. Zhang, *Proc. AISTech 2005 Conf.*, p. 475, On the Selection of Materials for Improved Performance of Pot Bearings (2005). https://www.researchgate.net/profile/K-Zhang-5/publication/237763687_On_the_Selection_of_Materials_for_Improved_Performance_of_Pot_Bearings/links/55130e7e0cf2eda0df2e4f03/On-the-Selection-of-Materials-for-Improved-Performance-of-Pot-Bearings.pdf
8. O. Brégand, J. Crahay, P. Gerkens, New Wiping Techniques to Efficiently Produce Suitable Coating Layers at High Speed in the Hot-Dip Galvanizing Process, RFCS study 2008 – EUR 24208 (2008). https://data.europa.eu/doi/10.2777/86670
9. K. Beaujard, M. Renard, A. Cano, K. Willems, Improvement of Productivity on Hot-Dip Galvanizing Line by Decreasing Strip Variations in Gas-Jet Cooling Systems, RFCS study 2010 – EUR 25317 (2013). https://data.europa.eu/doi/10.2777/92028
10. S. Dombrowski, A. Pereira, *Proc. 50th Rolling Seminar*, pp. 252 - 260, Electromagnetic Strip Stabilization: EMG-EMASS® – Technology, Results, Customer Experiences, and Future Development, Brazil (2013). https://abmproceedings.com.br/en/article/electromagnetic-strip-stabilization-emg-emassr-technology-results-customer-experiences-and-future-development
11. F. Ajersch, F. Ilinca, F. E. Goodwin, *Proc. Galvatech 2015 Conf.*, pp. 537 - 544, Experimental Study of Skimmings Generation in Galvanizing Baths With Variable Al and Mg Compositions, Canada (2015). https://www.researchgate.net/publication/344825722_Experimental_Study_of_Skimmings_Generation_in_Galvanizing_Baths_With_Variable_Al_and_Mg_Compositions
12. M. Dubois, *Proc. Galvatech 2015 Conf.*, Pot Roll Rotation, a Challenge for High Line Speeds, Canada (2015). https://www.researchgate.net/profile/Michel-Dubois-4/publication/329983190_Pot_roll_Rotation_Challenge_High_Line_speed_Galvatech_2015_corrected/links/5c273a3da6fdccfc706f8fb0/Pot-roll-Rotation-Challenge-High-Line-speed-Galvatech-2015-corrected.pdf
13. M. Dubois, J. Callegari, Methodology to Quantify Objectively the Coating Weight Uniformity, pp. 142-148, AISTech (2016). https://www.millennium-steel.com/wp-content/uploads/2021/05/pp142-148_ms17.pdf
14. O. Brégand, Y. Hardy, P. Gerkens, M. Larnicol, Device for Hydrodynamic Stabilization of a Continuously Travelling Metal Strip, WO2017129391 (2017).
15. Schyns & Mathy, Method and Device for Measuring Distances on Bright Metal Strips, WO03019114 (2003).
16. M. Dubois, J. Callegari, Method for Controlling a Coating Weight Uniformity in Industrial Galvanizing Lines, WO2020083682 (2020).