Feedback control of liquid metal coating

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Summary

Hot-dip galvanizing, with a 40 billion dollars market, is an industrial process that protects steel products from corrosion. However, ensuring a uniform coating remains challenging due to a fluid instability known as undulation. This thesis present ground-breaking solutions to this issue, significantly advancing the field of liquid metal coating.

By immersing and then withdrawing a metal sheet from a bath of molten zinc, a liquid film forms on the sheet's surface, which then solidifies into a protective layer. Controlling the final coating's thickness involves using gas jets to remove excess zinc from the bath. At withdrawal speeds above 2 m/s, the jets oscillate, triggering the undulation instability, which leads to uneven coatings and increased environmental impact due to additional surface treatments.

This research project developed a feedback control strategy to mitigate the undulation using gas jets and magnetic actuators with limited liquid film observations. The project followed a multidisciplinary approach, integrating reduced order modelling, numerical methods, linear stability analysis, model predictive control, and machine learning control. An analytical reduced-order model of the three-dimensional (3D) liquid film was developed, with the observation point location based on linear stability findings. Control methods based on linear stability analysis were tested on two-dimensional (2D) unstable waves, demonstrating strong performance and revealing intricate physical control mechanisms. Expertise was developed in machine learning control by comparing various methods on flow control test cases. Based on this knowledge, reinforcement learning algorithms were applied to the undulating problem, reducing the wave amplitude by 10% with jets pushing the crests and magnets rising the troughs.

These findings pave the way for industrial applications of the feedback regulator to reduce undulation instability and deepen the understanding of the liquid film dynamics. Integrating machine learning control methods into a novel workflow alongside analytical approaches and simulations, this research offered significant advancements in industrial coating processes. Owing to its versatility, this new methodology holds promise for applications in other engineering domains, such as combustion flows or turbulence control.

Scientific summary

This research project aimed to develop a control strategy to reduce undulation in the hot-dip galvanizing process using a feedback regulator with gas jets and magnetic actuators (see Figure 1). With the intent to improve the galvanizing process and advance the integration of innovative control techniques in industrial applications, this project answered fundamental and applied research questions: Can a reduced order model accurately replicate liquid film dynamic? Can linear stability analysis define the location of the observation points? Are stability-based control methods (*white box*) effective for film control? Can machine learning control methods (*black box*) discover an optimal control law?

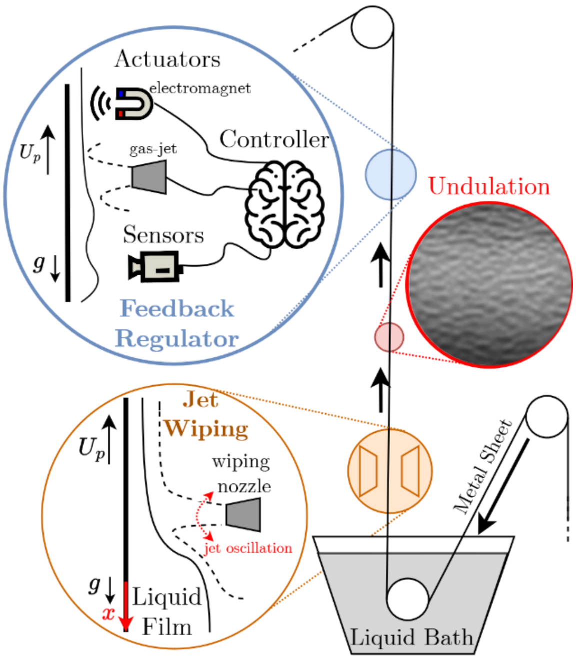


Figure 1 Metal sheet withdrawn at velocity U_p out of molten zinc, wiping jet (orange circle), undulation waves (red circle) and feedback regulator (blue circle).

A novel 3D Integral Boundary Layer (IBL) model was developed to simulate the nonlinear dynamics of the liquid film, incorporating shear stress from gas jets and Lorentz forces from electromagnetic actuators. Numerically implemented with the Fourier pseudo-spectral method and including a perfectly matched layer to reproduces open boundary conditions, the undulation instability was accurately replicated via the actions of forcing gas jets (see Figure 2).

This model provides deep insights into the coating process dynamics, extensively featuring the intricate multiscale interactions between liquid zinc and control actuators at lower computational cost than Large Eddy Simulations (LES). Beyond its immediate application, the model can be easily adapted to other engineering problems. It can potentially optimize liquid metal films used in contexts ranging from confining plasma in tokamak nuclear fusion reactors to shaping versatile circuitry for next-generation electronic devices.

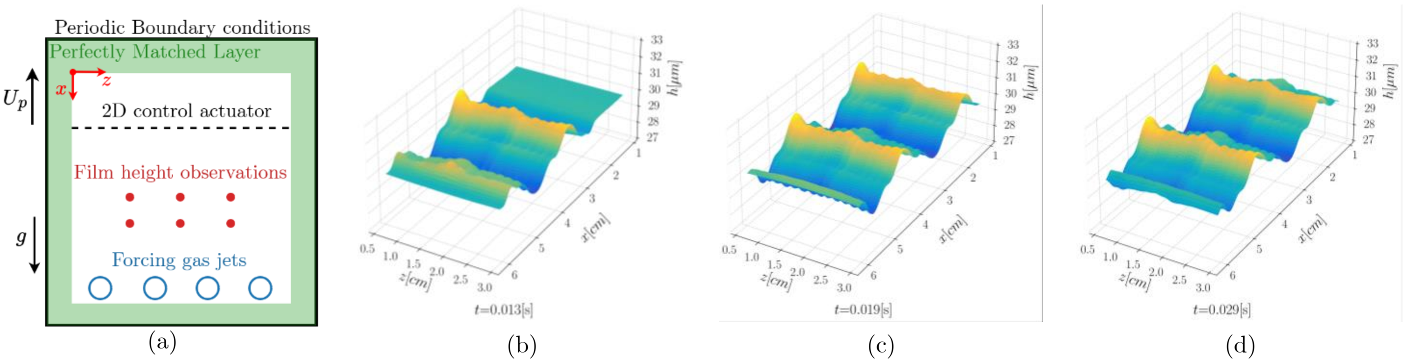


Figure 2 (a) Scheme of the IBL numerical implementation and (b,c,d) evolution of the undulation waves at different points in time

White box methods were tested to control an unstable perturbation over a 2D liquid film (see Figure 3). The optimal linear feedback policy was designed based on analytical and numerical treatments of linearized governing equations and Model Predictive Control (MPC). MPC involved iteratively solving optimization problems at each time step via quadratic programming and then passing of the optimal action to the liquid film model. Using 20 gas jet actuators, the optimal control law damped the unstable waves as they propagated along their characteristic direction. The actuators effectively bring the liquid film to a flat condition, with a gentle redistribution of energy in the liquid, thereby preventing the growth of additional instabilities.

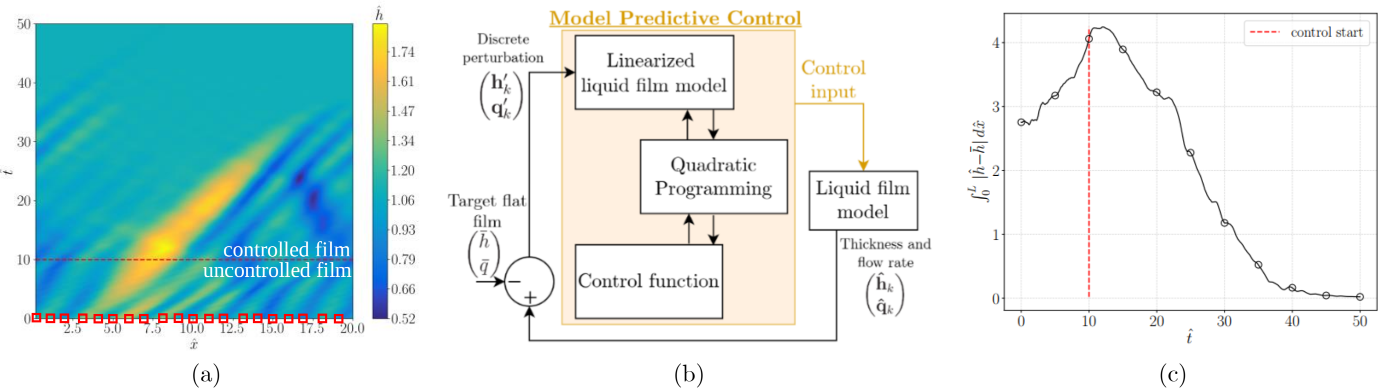


Figure 3(a) Evolution of the 2D liquid film in space-time diagram with control starting at $\hat{t}$=10 (dashed red line) and positions of the control jets (red squares), (b) MPC scheme and (c) evolution of the error norm with respect to the targeted flat film thickness $\bar{h}$

While offering valuable insights into the role of shear and pressure gradient at the free surface, the computational demands of MPC simulations were notably high. They took up to 5 days on a machine with 120 cores, rendering them impractical for addressing the more complex 3D undulation control problem. Therefore, the focus shifted exclusively to *black box* methods.

For the undulation control problem, the positions for observation points were identified by analysing the threshold between absolute and convective instabilities [1-3]. This was achieved by solving the Orr-Sommerfeld eigenvalue problem using the Chebyshev-Tau spectral method and Rayleigth quotient iterations. Our investigation revealed a window of absolute instability in the space of nondimensional thickness ($\bar{h}$) and Reynolds number (Re) (highlighted in grey in Figure 3a), which significantly deviate from the typical galvanizing conditions (depicted in light blue).

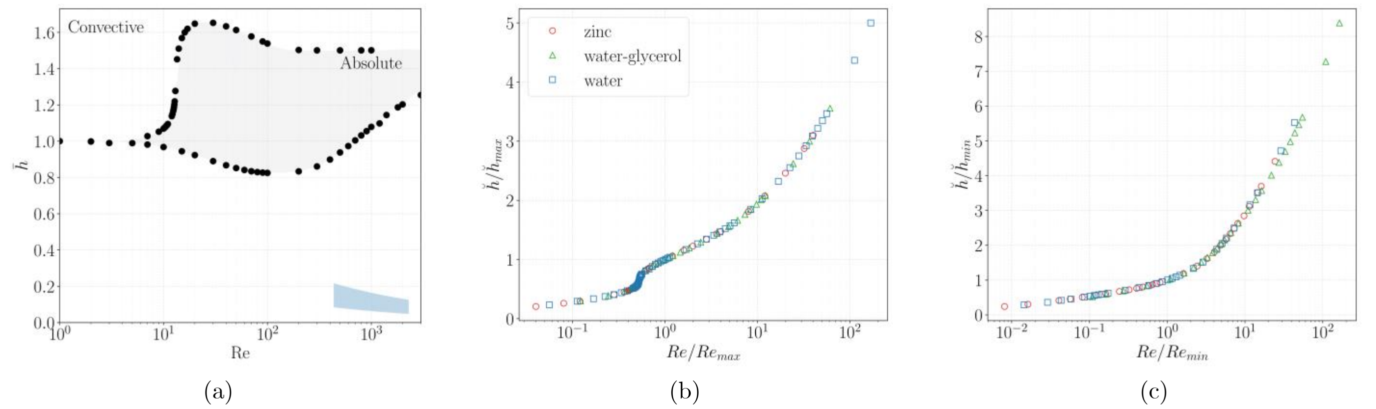
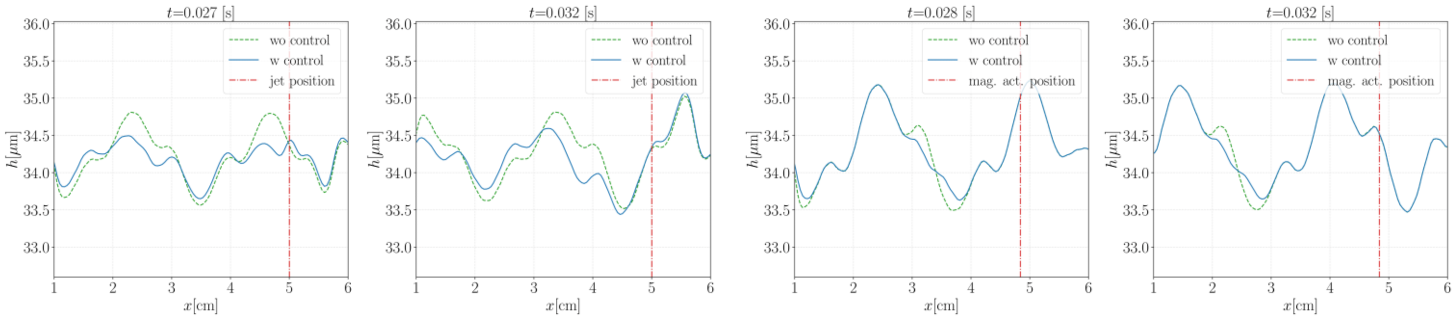


Figure 4 (a) Absolute-convective threshold in the nondimensional liquid film thickness ($\bar{h}$) and Reynolds (Re) space and (b-c) scaled upper and lower bounds for water (blue squared) water-glycerol (green triangles) and zinc (red circle) in the rescale thickness $\check{h}$.

Based on this result, the observation points were positioned only upstream of the actuator's locations, as their actions generate waves that propagate only downstream. We also found a window of absolute instability for water and water-glycerol. Normalizing these windows with their maximum and minimum values and using a rescaled thickness ($\breve{h}$), all the curves aligned almost perfectly (see Figure 4b and c). This generalizes our results to fluid with any Kapitza number, simplifying the analysis of the absolute/convective threshold for liquid film in dip-coating applications, further extending the impact of this analysis.

Machine learning methods were chosen among the various approaches for designing the control logic. They proved robust in handling uncertainties and noise and demonstrated the ability to derive complex control strategies without knowledge of the governing equations, making them ideal for real-world galvanizing applications.



(a) (b) (c) (d)

Figure 5 Evolution of the controller liquid film over a line along x for (a-b) single 2D gas jet and (c-d) single 2D magnet

Before addressing the undulation instability control, we compared different black box methods on representative flow control test cases [4]. Based on the knowledge developed in this phase, we addressed the undulation control problem with the reinforcement learning Proximal Policy Optimization (PPO) algorithm. We found that a proportional control with 2D gas jet and electromagnet can reduce the waves' amplitude (see Figure 5). For the gas jet, the optimal solution has open-loop and closed-loop components. The closed-loop component makes the agent act on the crest and not on the valleys. The open loop component is a constant function of time that generates extra wiping, pushing the film below the desired flat state. For the electromagnetic actuators, the controller acts only on the troughs, creating a resisting volumetric force which pushes the liquid to accumulate upstream, hence levelling the valleys.

This thesis significantly advanced liquid metal coating by introducing cutting-edge feedback control strategies that significantly enhance coating quality, reduce costs, and promote sustainability. The novel use of gas jets and magnetic actuators underscores the ground-breaking nature of this thesis and its ability to set new standards across various engineering applications. This research addressed real-world challenges with transformative potential by integrating robust theoretical frameworks with advanced machine-learning methods. Furthermore, the adaptable methodology developed here promises broad applicability in diverse engineering fields, from 3D metal printing, flexible electronics, and tuneable metamaterials to microfluidic devices using Galinstan. This work demonstrated the power of multidisciplinary approaches in solving complex industrial problems and opened new avenues for future research and application.

Publications and Thesis's output

This thesis resulted in 6 peer-reviewed articles, with 2 more in preparation. The outcomes were showcased through posters and presentations at 9 conferences, 3 VKI PhD symposia, 2 winter and 2 summer schools. In addition, the expertise gained in reinforcement learning was disseminated through 2 lectures in the VKI research master's program and 2 sessions in the VKI lecture series "*Hands-on Machine Learning for Fluid Dynamics.*" This extensive outreach underscored the significant impact of this research, highlighted by the five key publications listed below:

[1] Pino, F., Scheid, B., & Mendez, M. A. (2024, June). Absolute/convective instability threshold in inverted falling film through linear stability analysis. *In AIP Conference Proceedings (Vol. 3094, No. 1). AIP Publishing.*

[2] Pino, F., Mendez, M. A., & Scheid, B. (2024). Absolute and convective instabilities in a liquid film over a substrate moving against gravity. *Physical Review Fluids, 9(10), 104002.*

[3] Pino, F., Mendez, M. A., & Scheid, B. (2024). Linear stability analysis of a vertical liquid film over a moving substrate. *Journal of Fluid Mechanics (under review)*

[4] Pino, F., Schena, L., Rabault, J., & Mendez, M. A. (2023). Comparative analysis of machine learning methods for active flow control. *Journal of Fluid Mechanics, 958, A39.*

[5] Pino, F., Scheid, B., & Mendez, M. A.. (2024). Multi-objective optimization of the magnetic wiping process in dip-coating. *Journal of Engineering Mathematics (under review)*