Feedback control of liquid metal coating

19th ERCOFTAC DaVinci Competition

Fabio Pino

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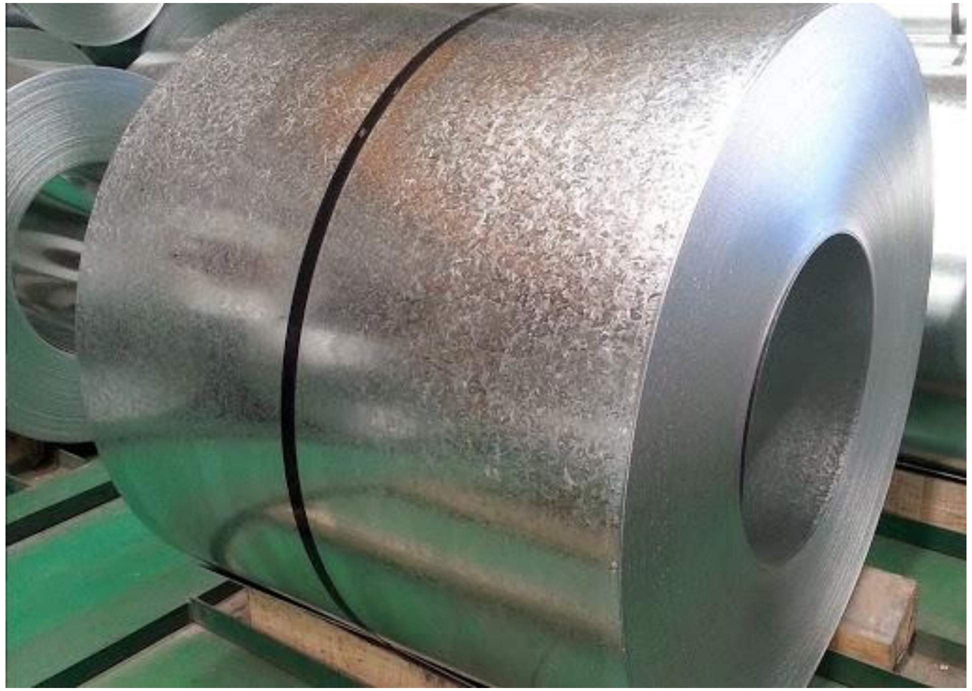
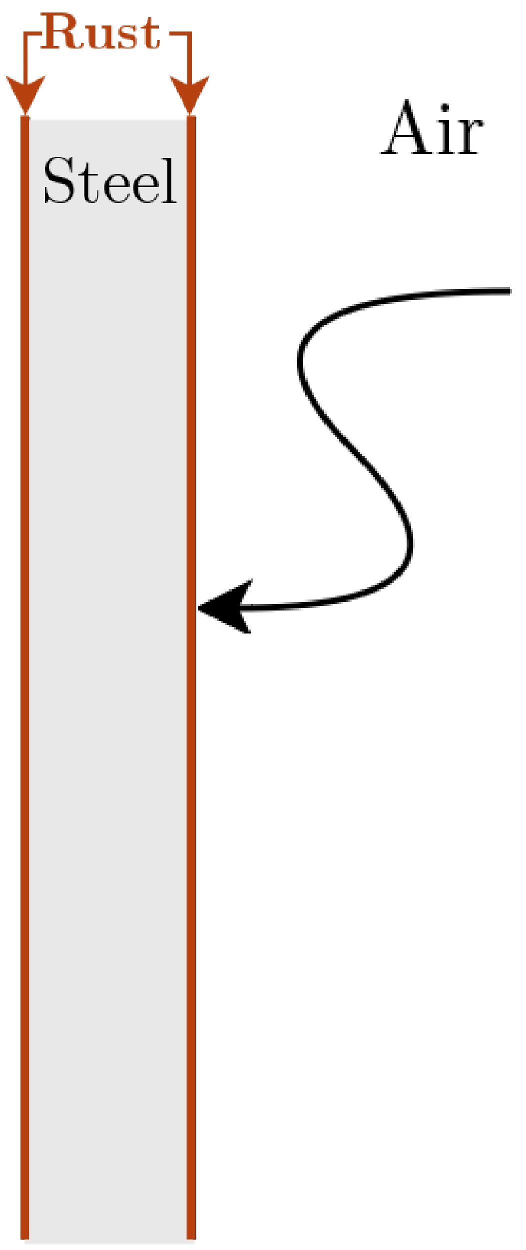
[2] **T**ransfers, **I**nterfaces and **P**rocesse**s** (**TIPs**) laboratory, Université libre de Bruxelles

October 10th, 2024



Hot-Dip Galvanization



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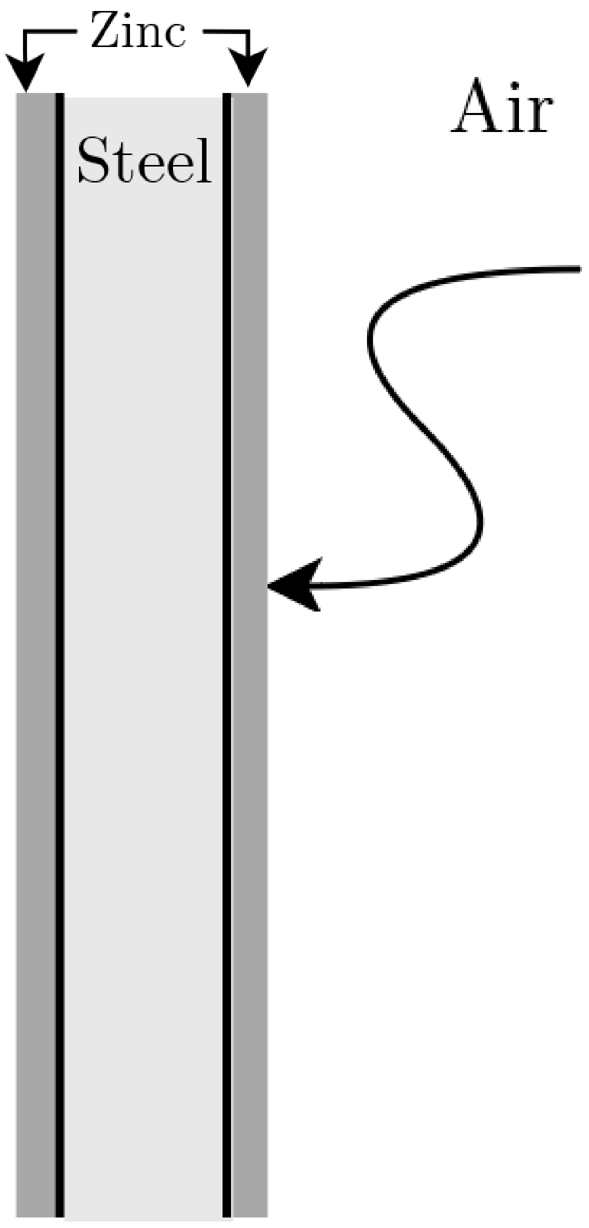

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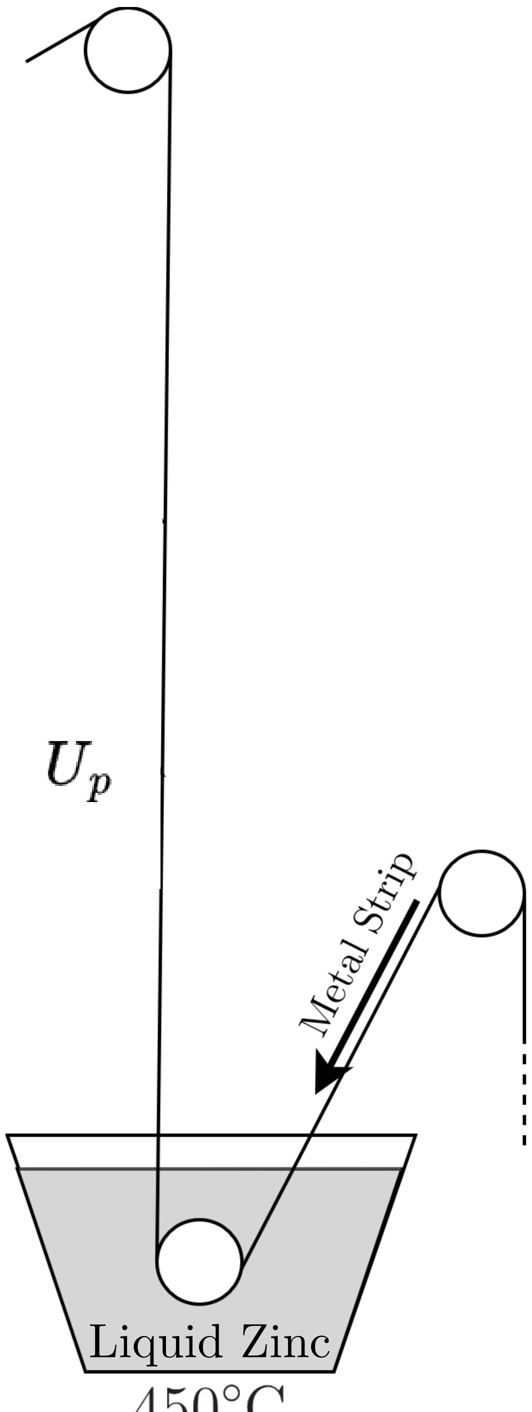
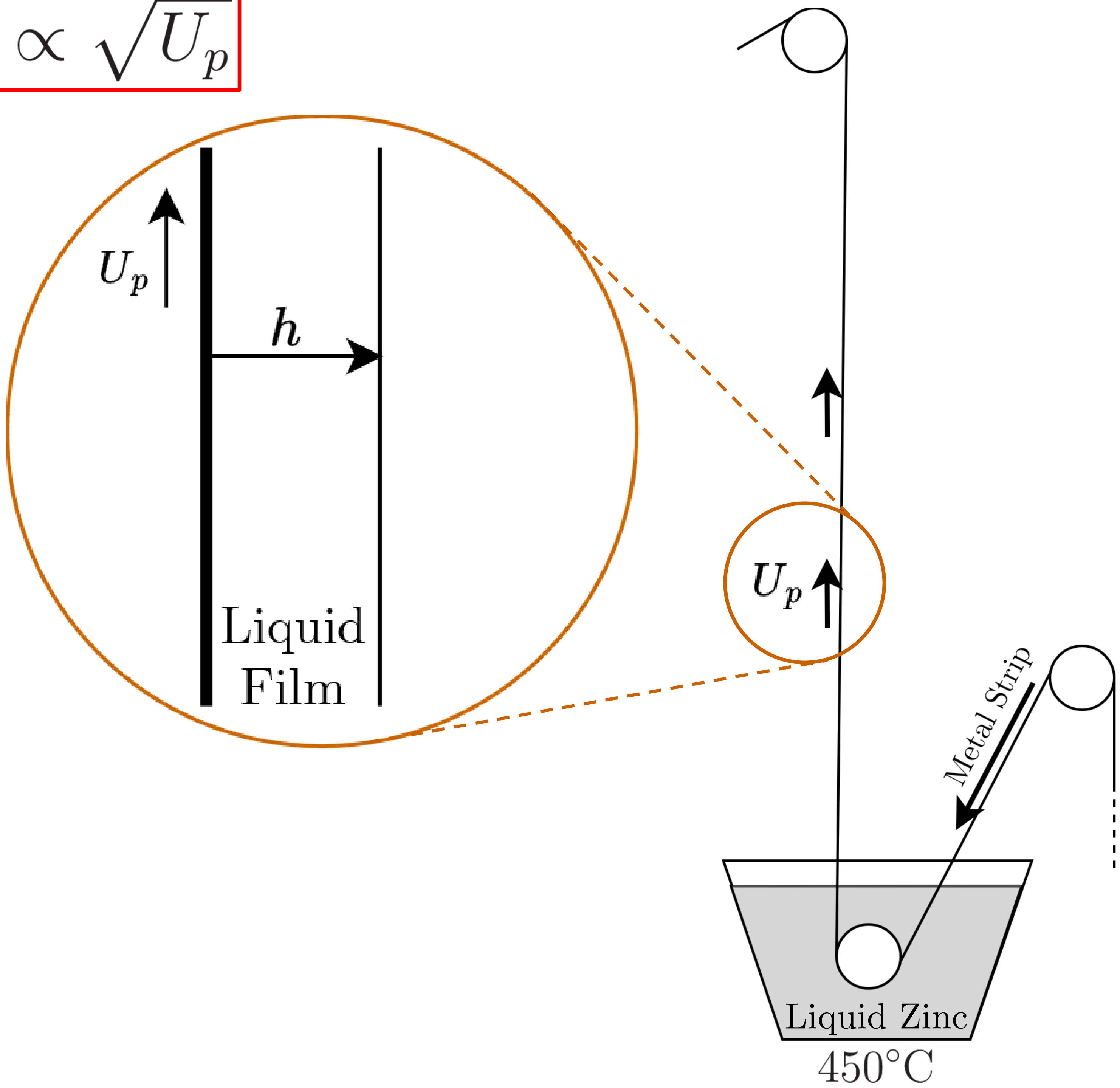


Derjaguin's solution

$$h \propto \sqrt{U_p}$$

Hot-Dip Galvanization



Hot-Dip Galvanization

Derjaguin's solution

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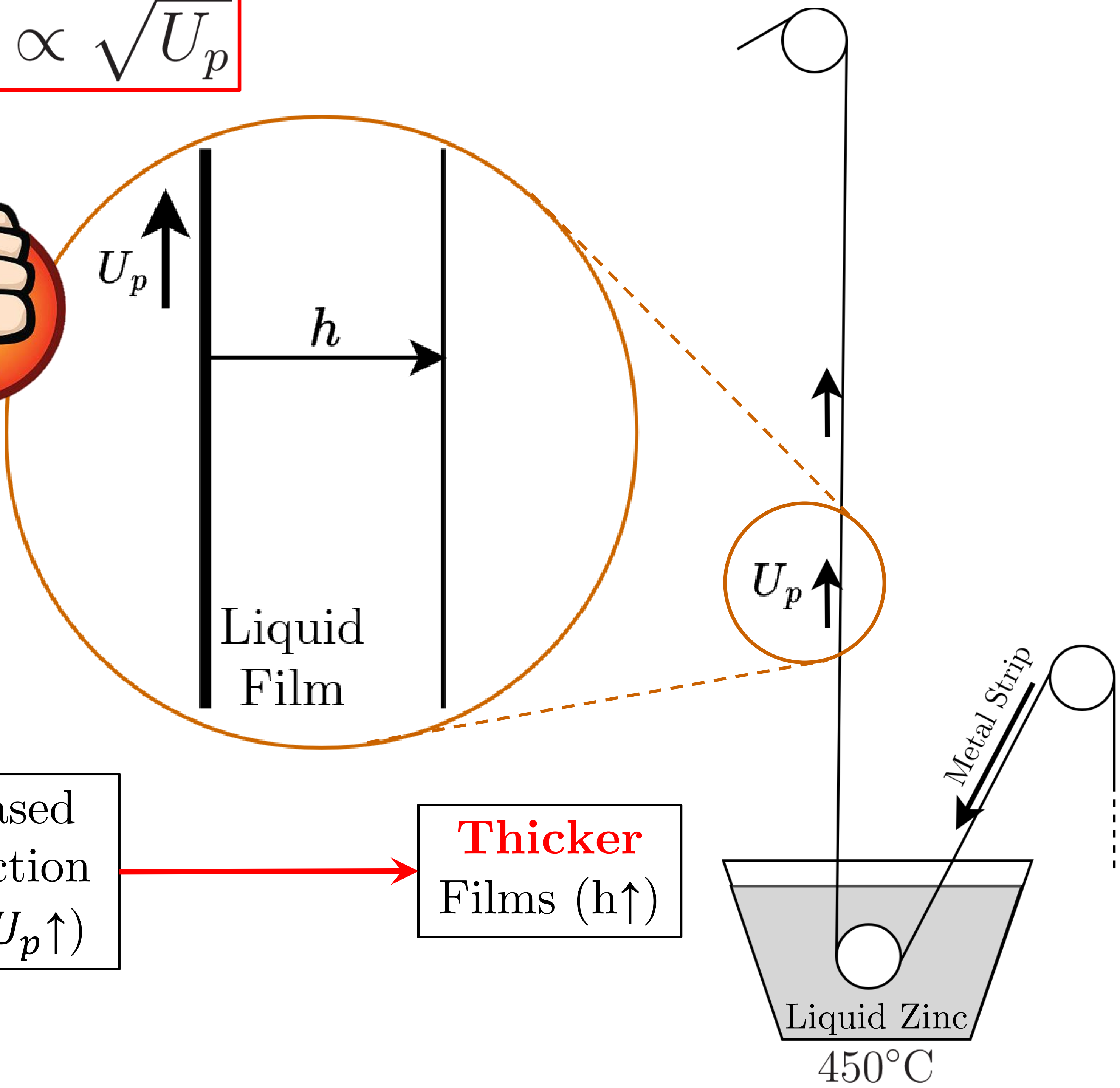
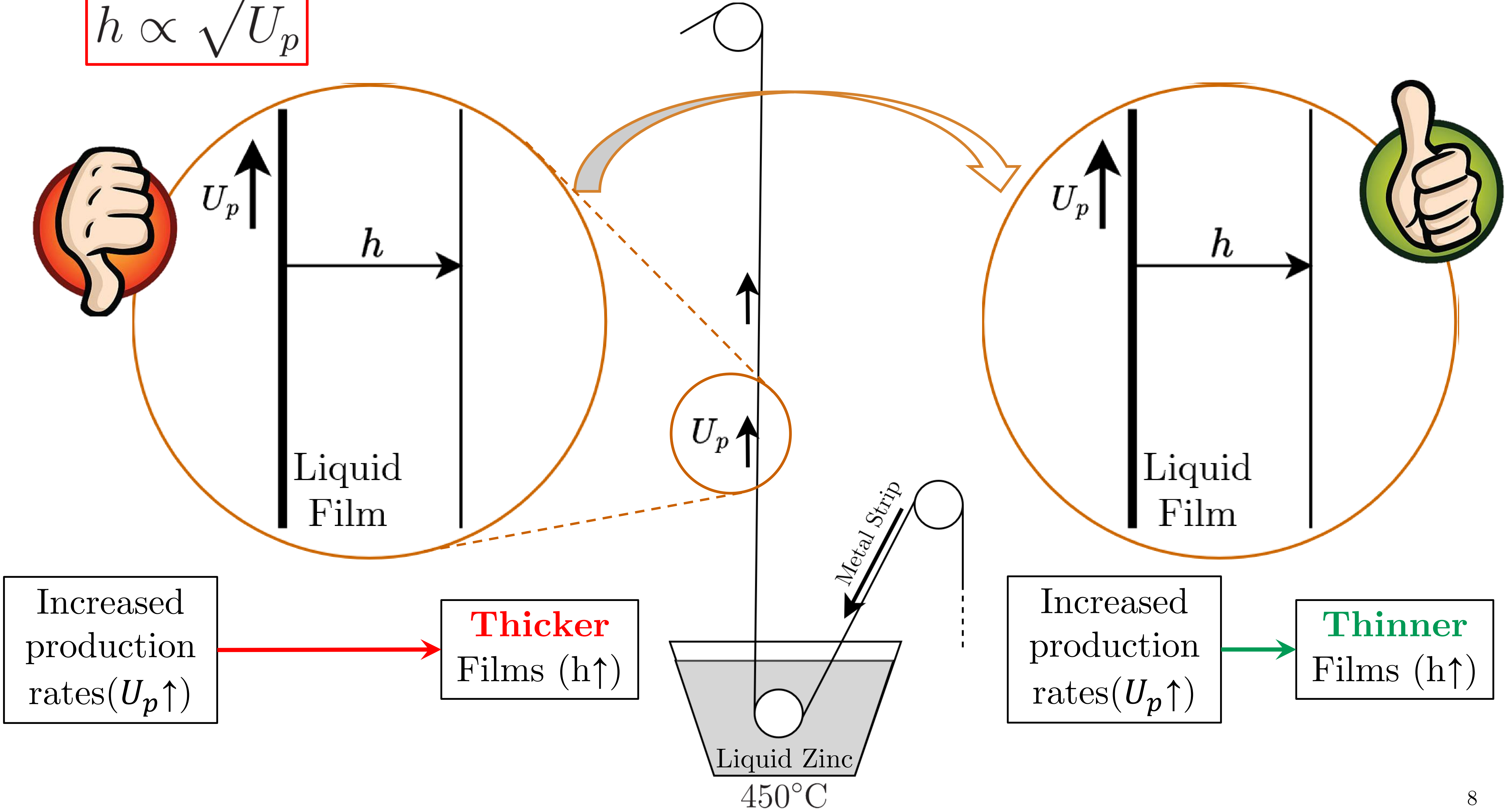


Increased production rates($U_p\uparrow$) → **Thicker** Films (h↑)

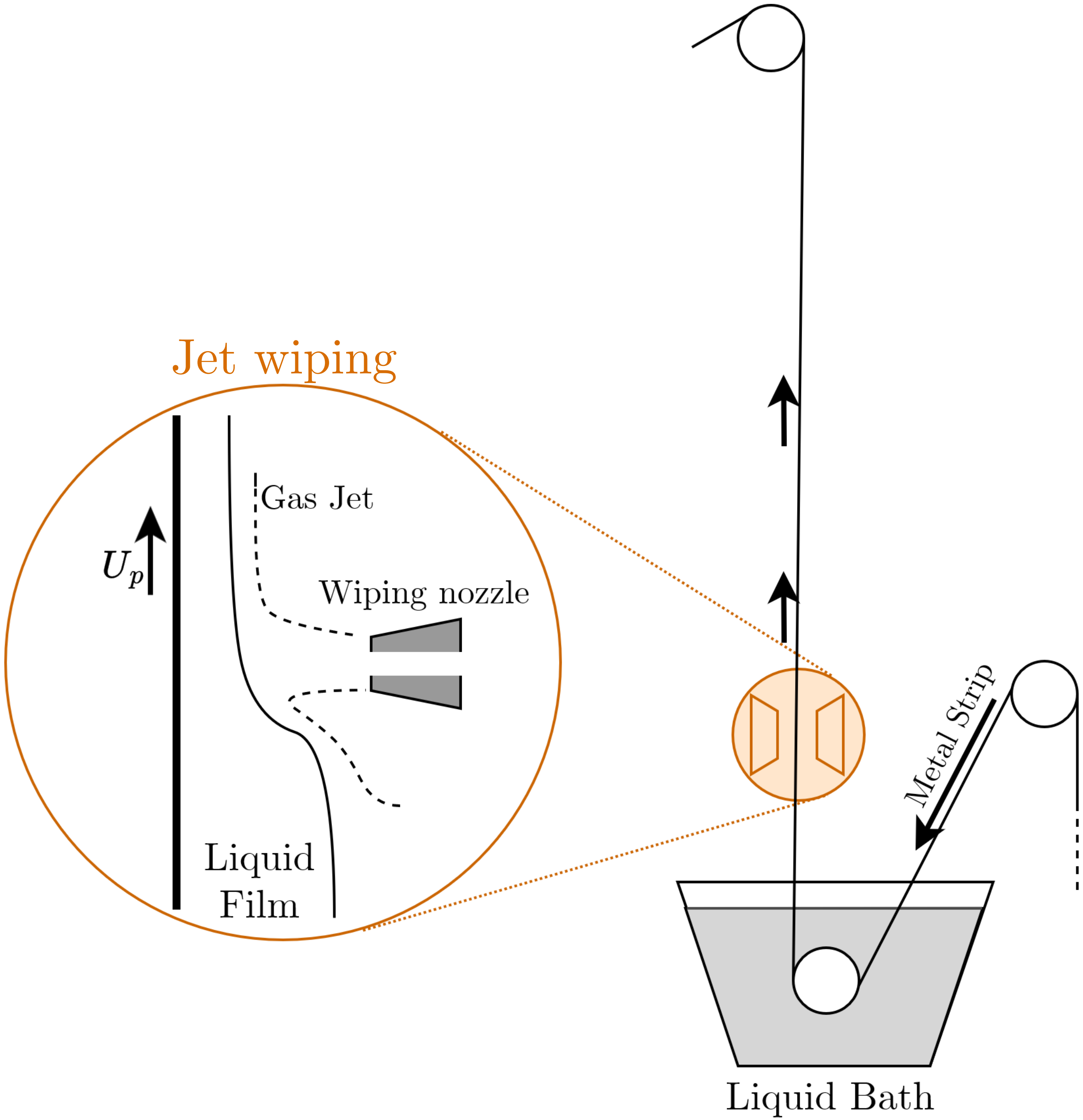
Hot-Dip Galvanization

Derjaguin's solution

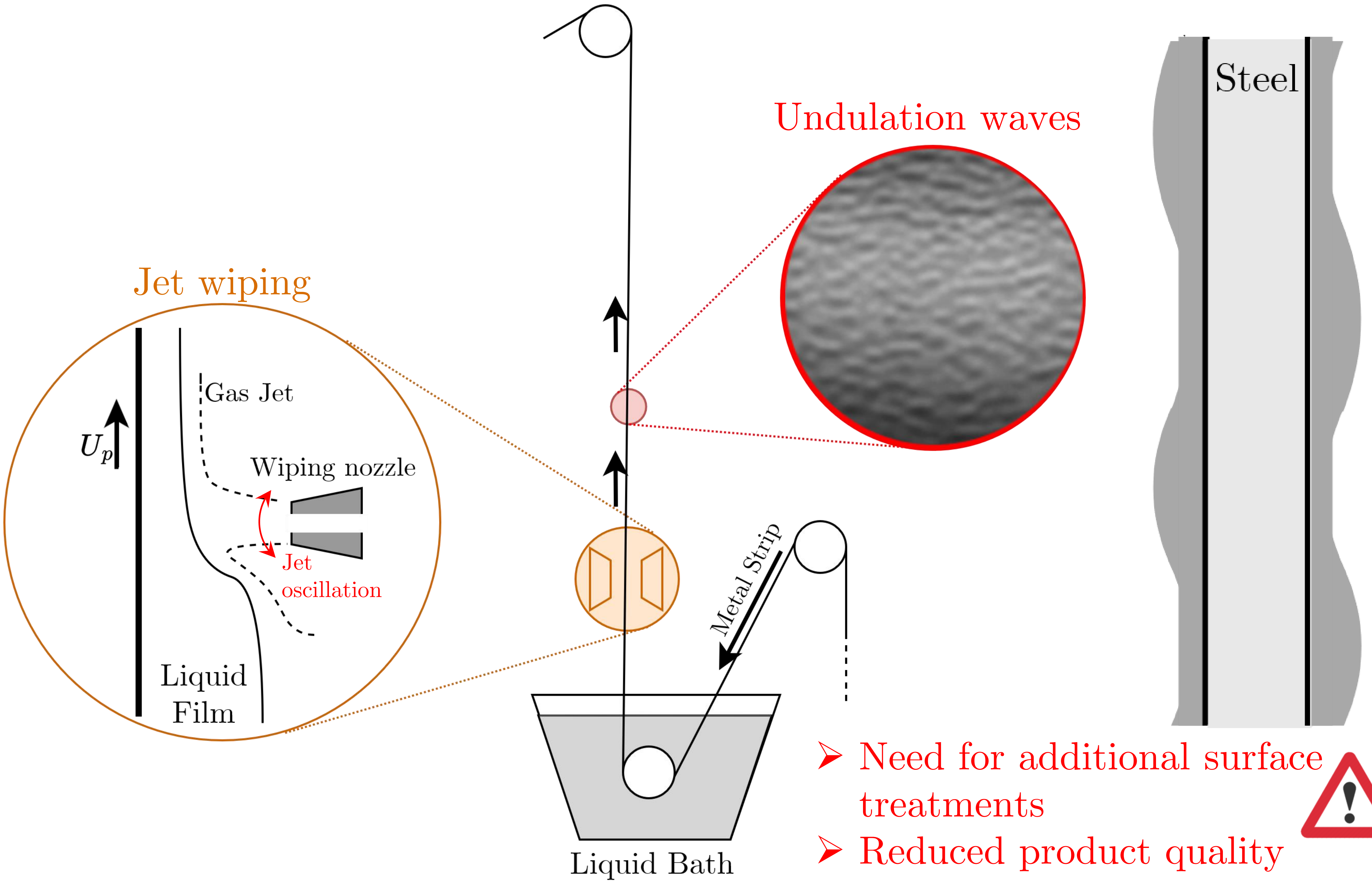
$$h \propto \sqrt{U_p}$$



Hot-Dip Galvanization

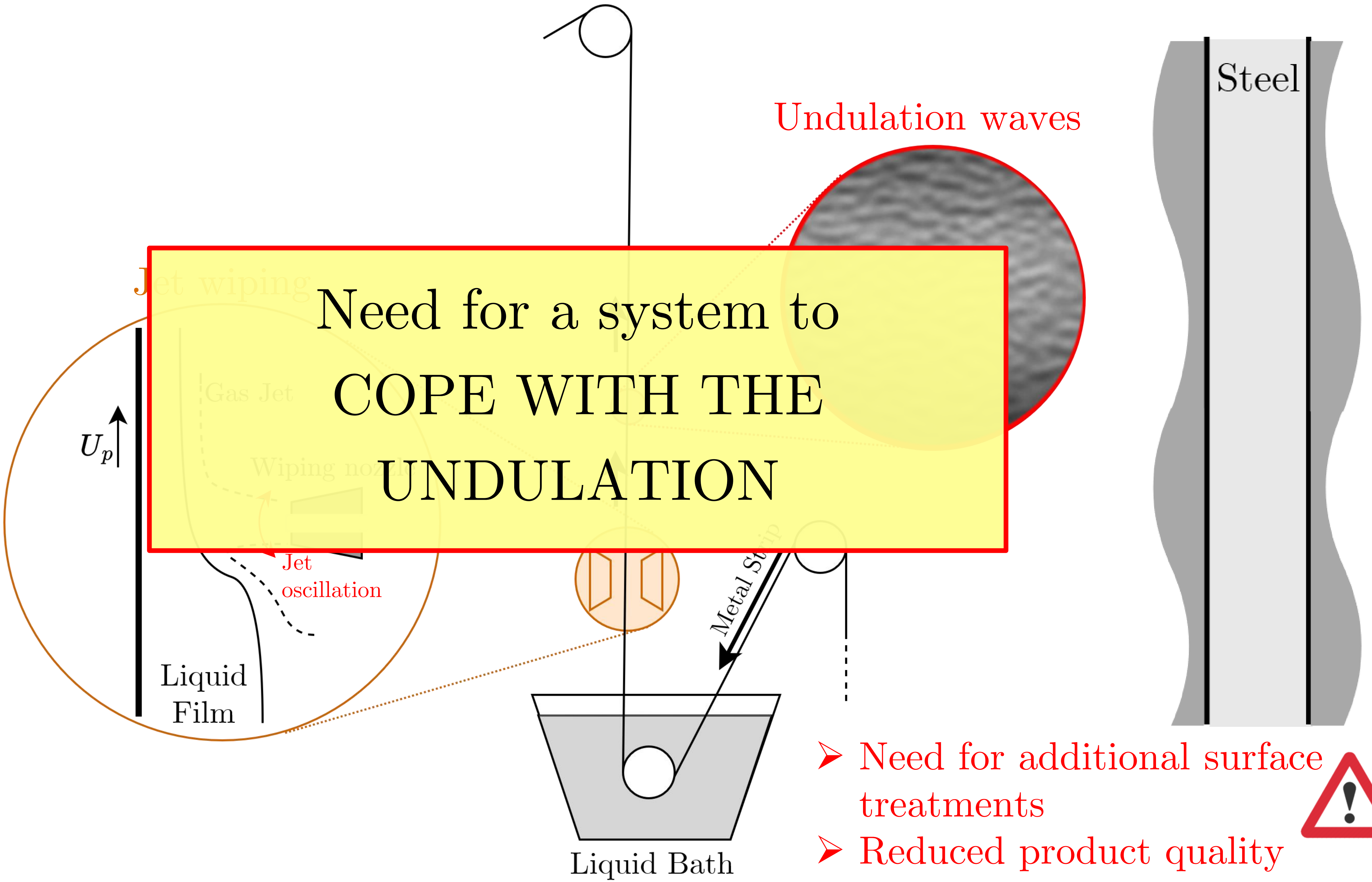


Hot-Dip Galvanization



- Need for additional surface treatments
- Reduced product quality

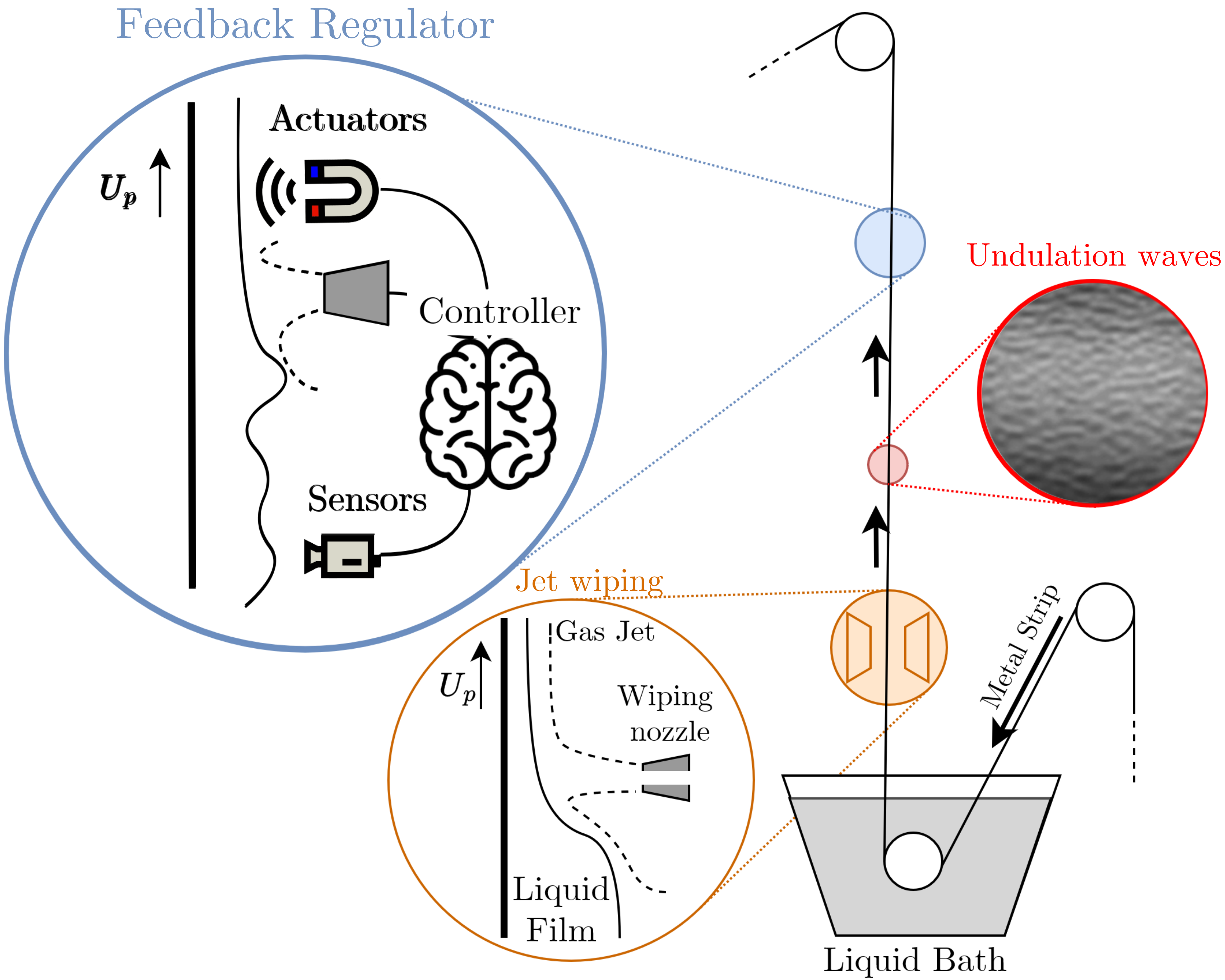
Hot-Dip Galvanization



Need for a system to COPE WITH THE UNDULATION

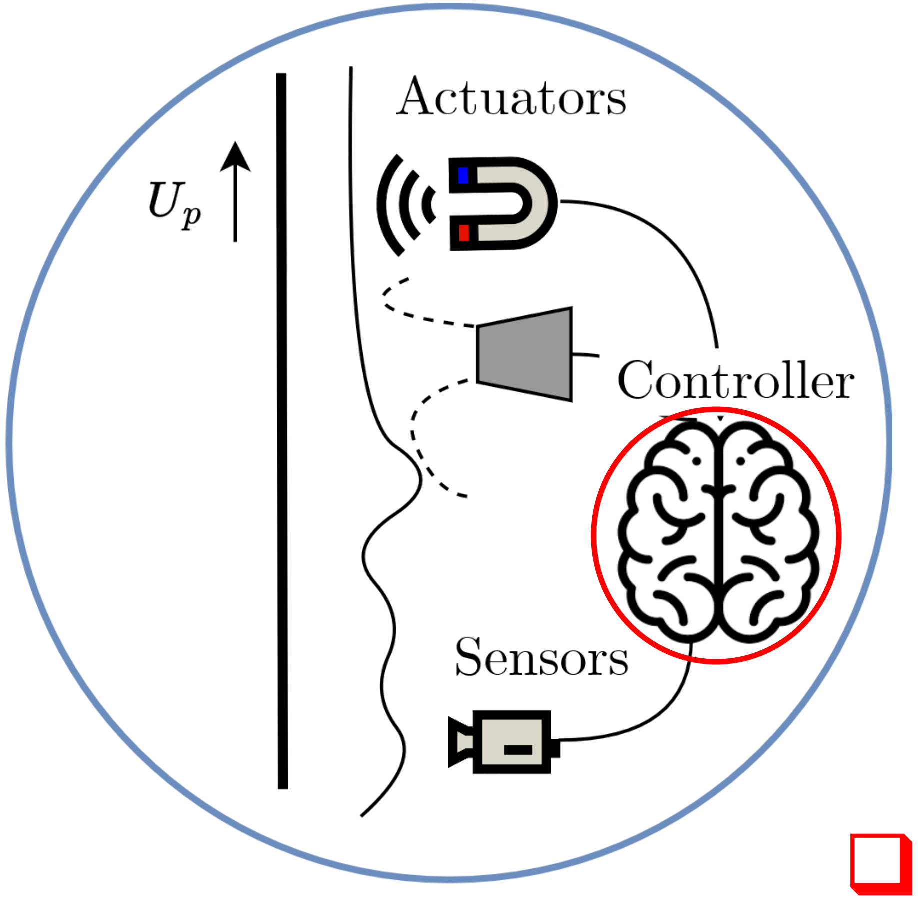
- Need for additional surface treatments
- Reduced product quality

Hot-Dip Galvanization



Aim of the project

Feedback Regulator



Develop an optimal control strategy for a feedback regulator aimed at minimizing undulation waves downstream of the jet-wiping region, using gas jets and electromagnetic actuators.

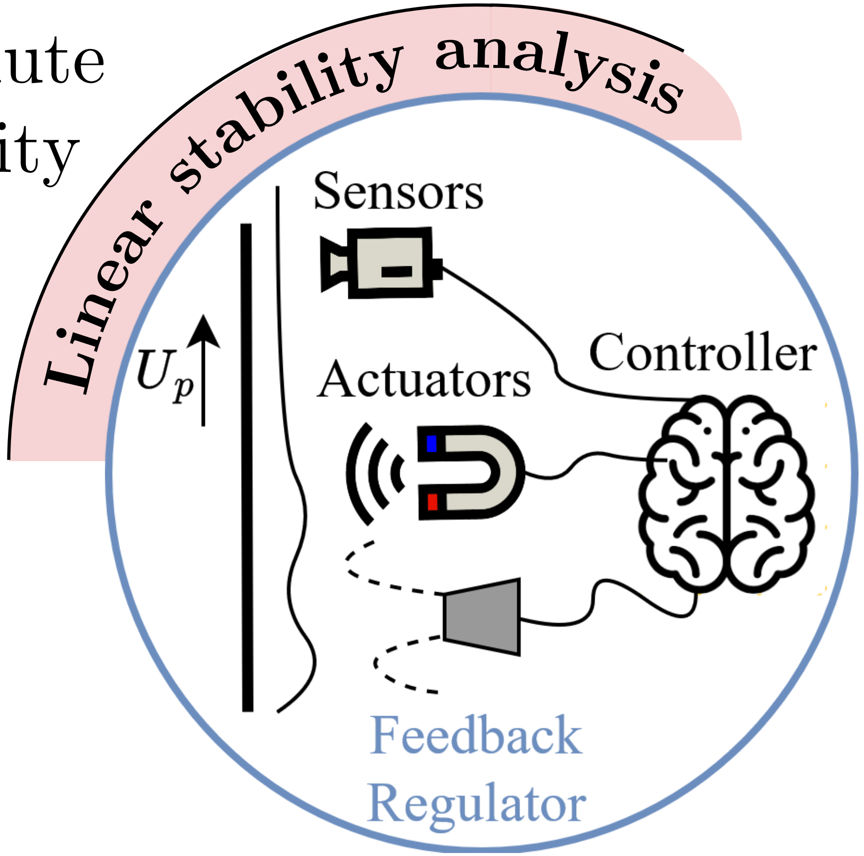
Objectives

- ❑ Carry out a linear stability analysis
- ❑ Derive a simplified model of the liquid film
- ❑ Explore different control methods

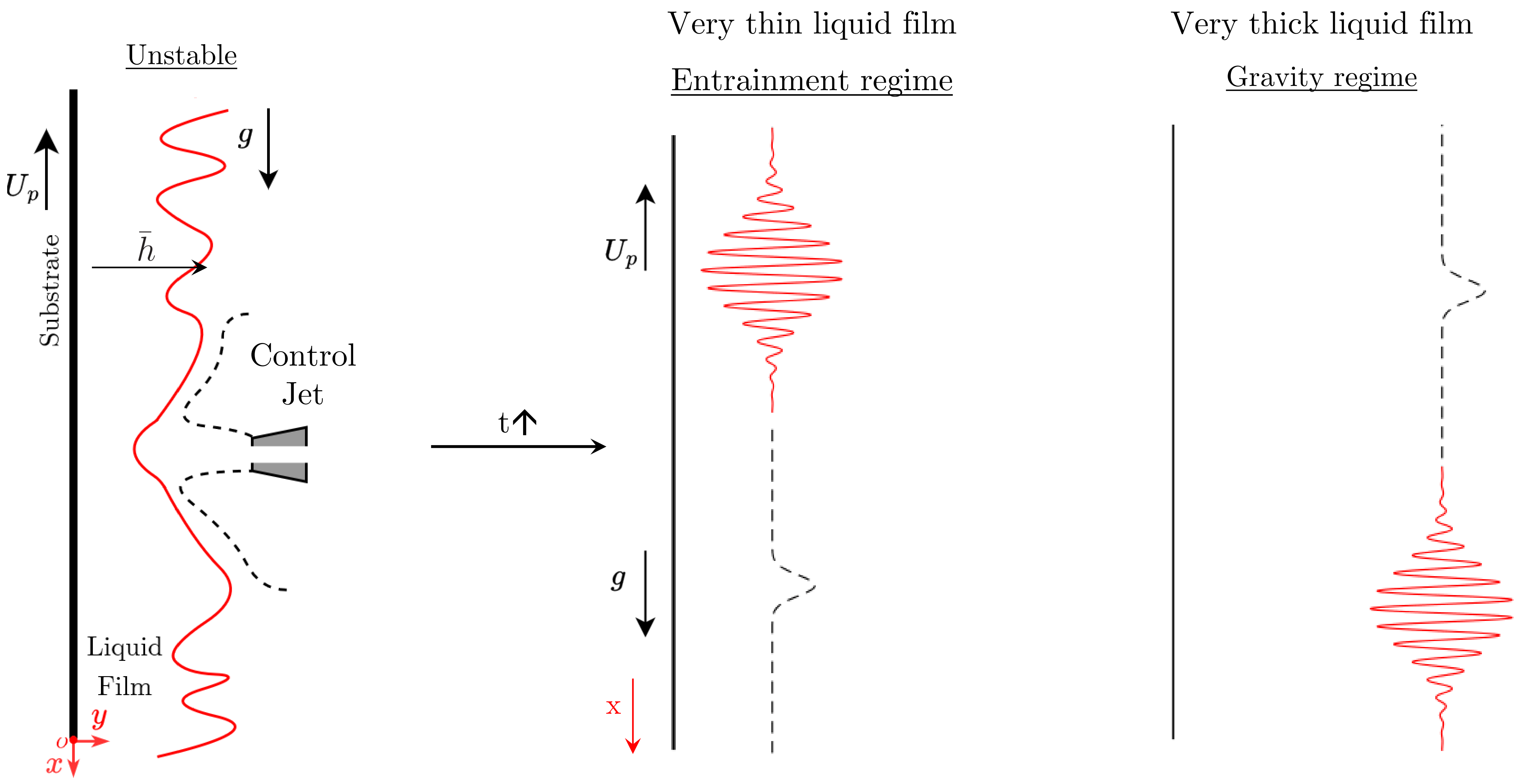
Contents

Linear stability analysis

Computation of the threshold between absolute and convective instability



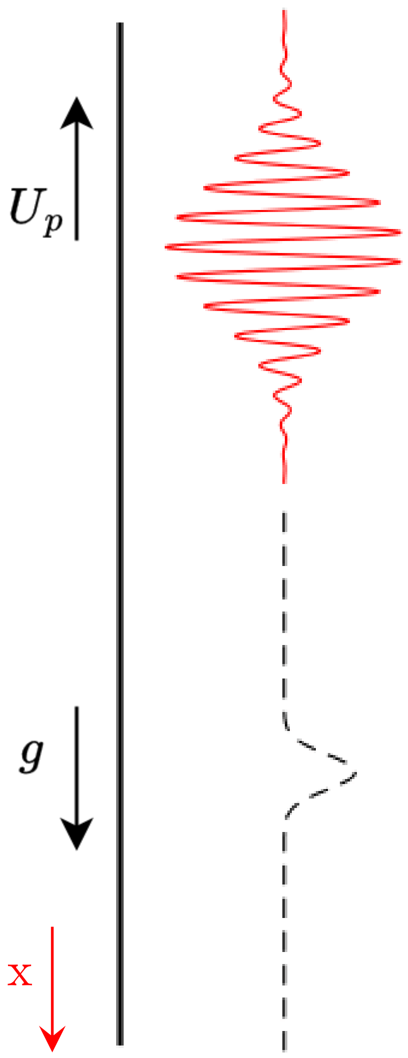
Dynamic of the liquid film



Dynamic of the liquid film

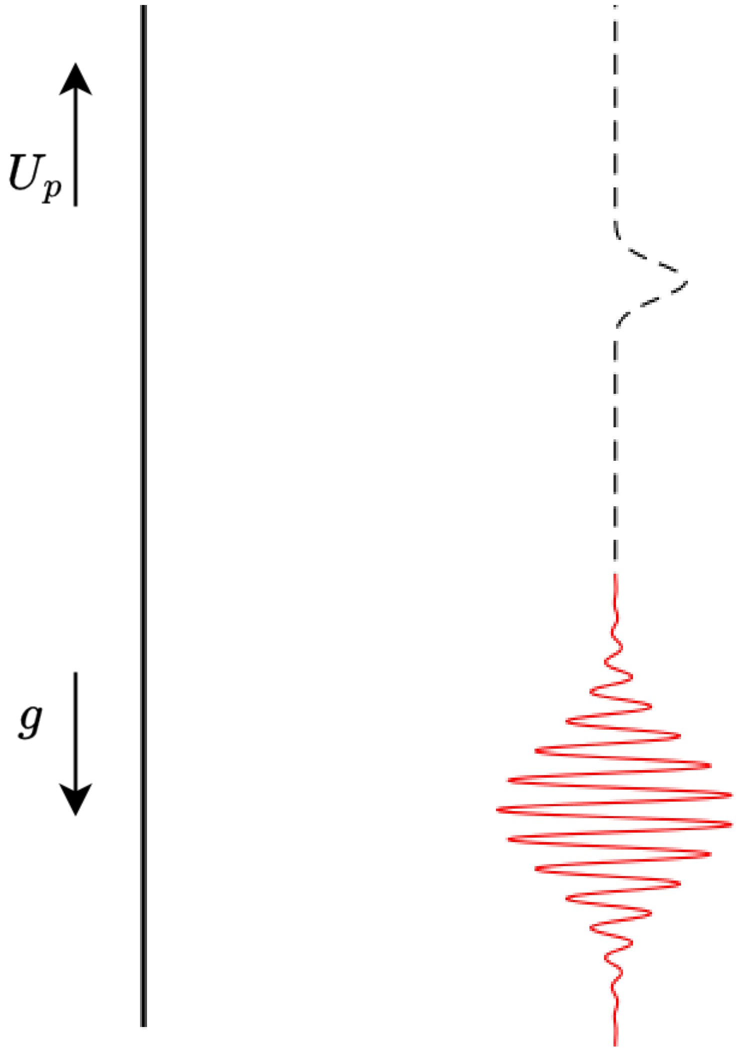
Very thin liquid film

Entrainment regime



Very thick liquid film

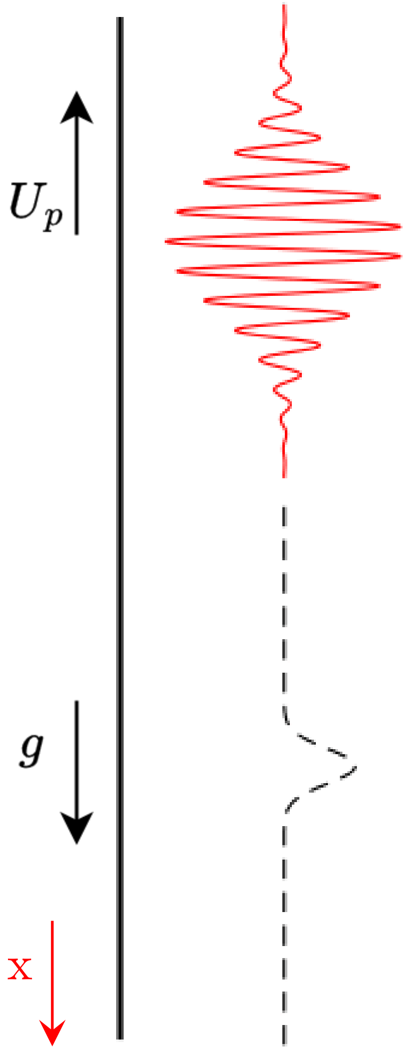
Gravity regime



Dynamic of the liquid film

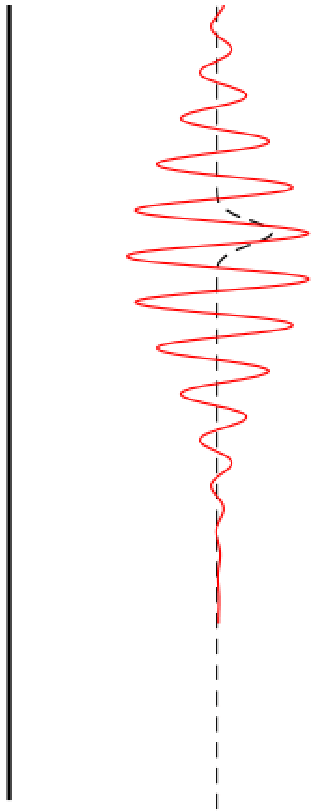
Very thin liquid film

Entrainment regime



Equilibrium between gravity and entrainment

Region of absolute instability



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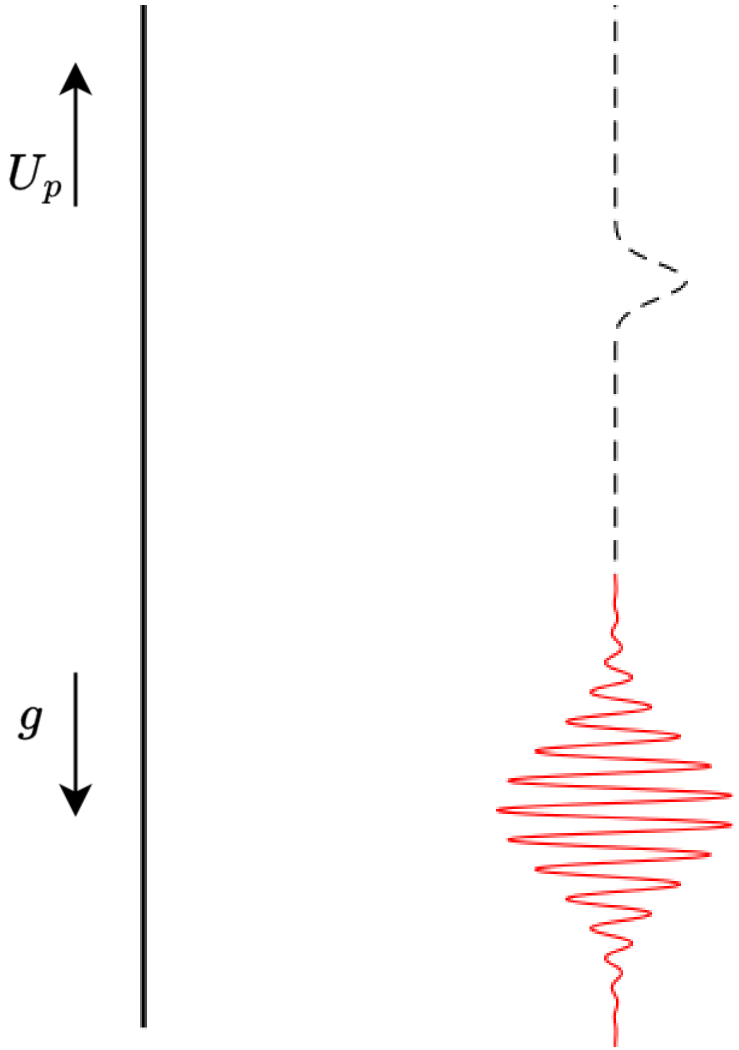
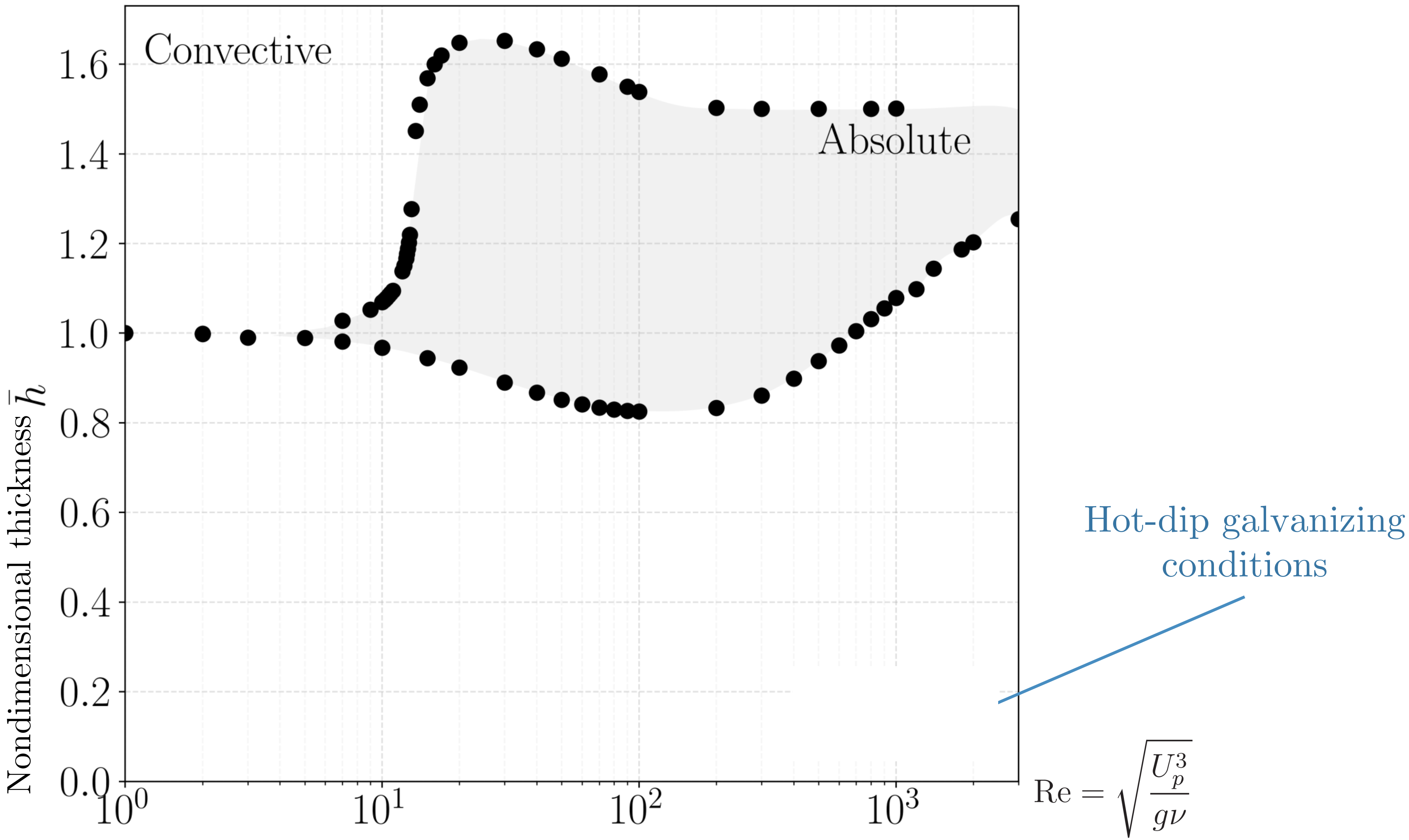


Dynamic of the liquid film

We found the region of absolute instability studying the linearized 2D Navier-Stokes equations

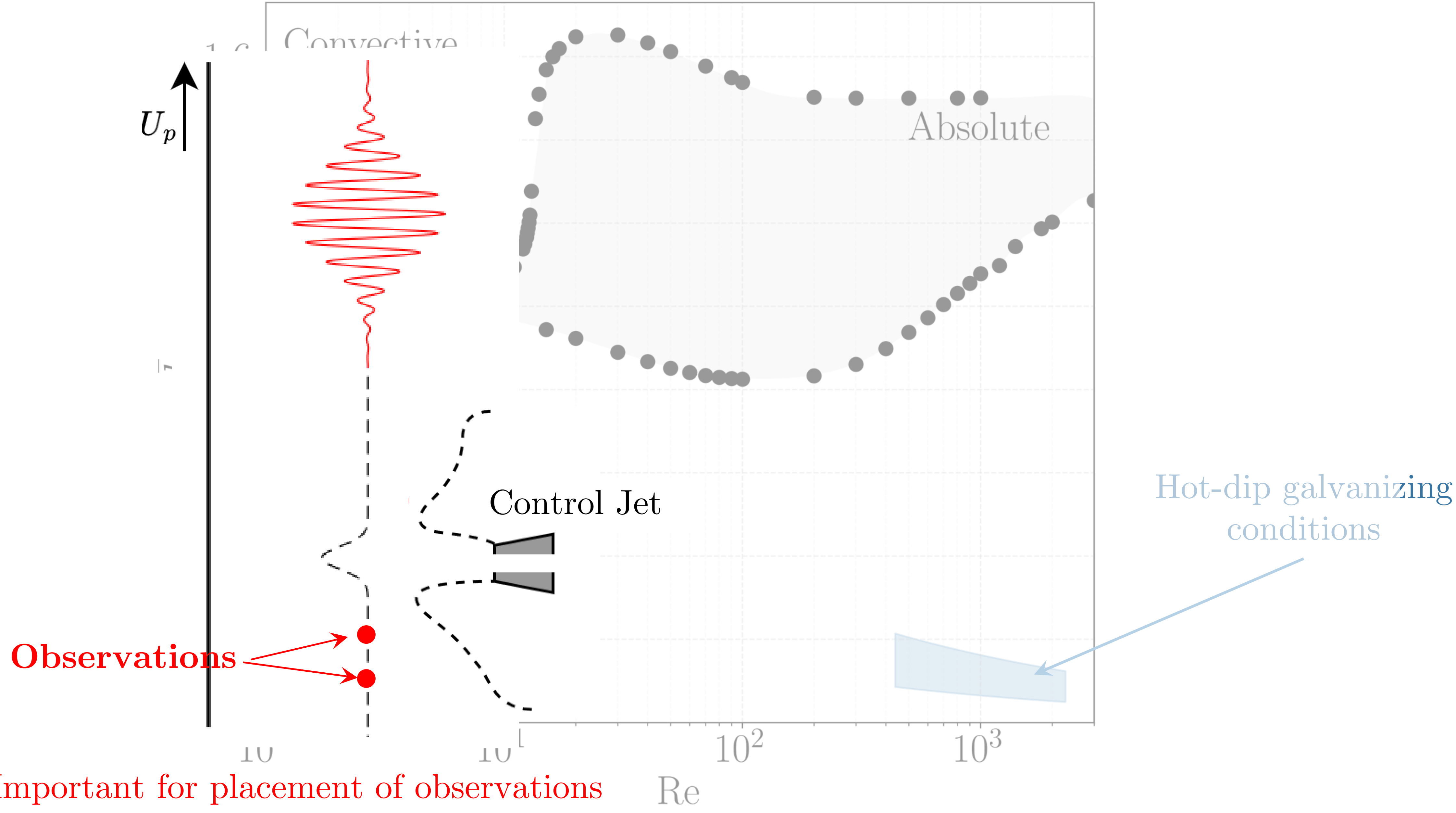


Pino, Fabio, Miguel Alfonso Mendez, and Benoit Scheid. "Absolute and convective instabilities in a liquid film over a substrate moving against gravity." *arXiv preprint*

Pino, Fabio, Miguel Alfonso Mendez, and Benoit Scheid. "Linear stability analysis of a vertical liquid film over a moving substrate." *Journal of Fluid Mechanics* (2024).

Dynamic of the liquid film

We found the region of absolute instability studying the linearized Navier-Stokes equations



Important for placement of observations

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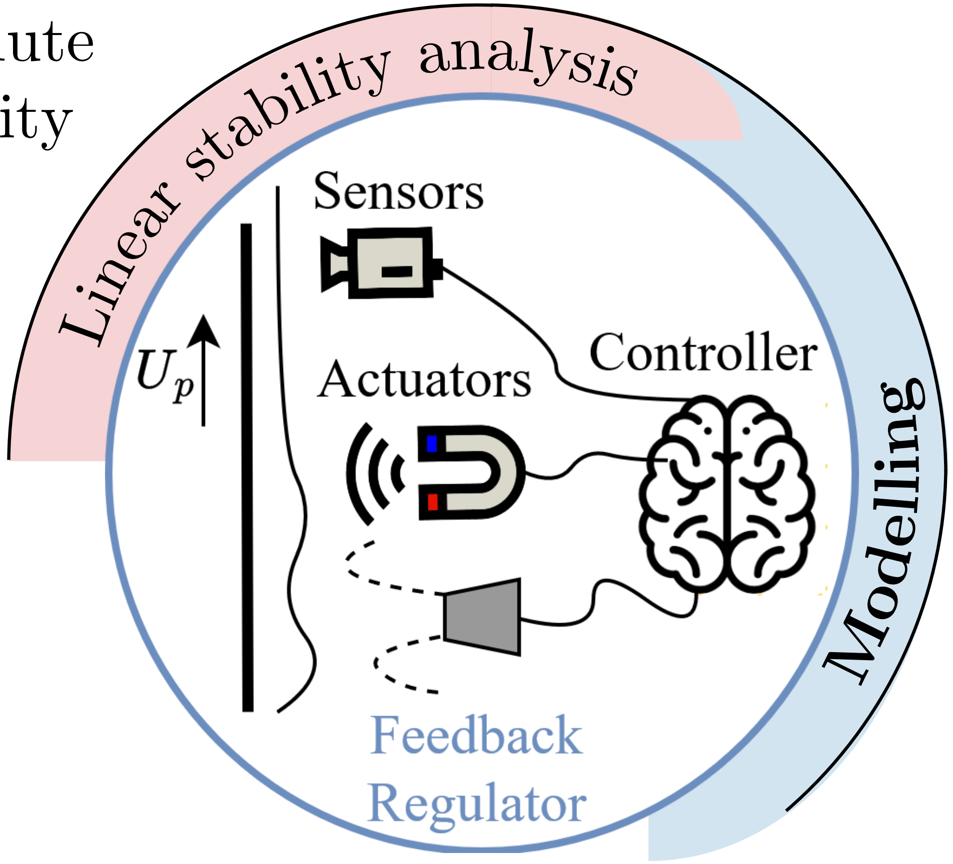
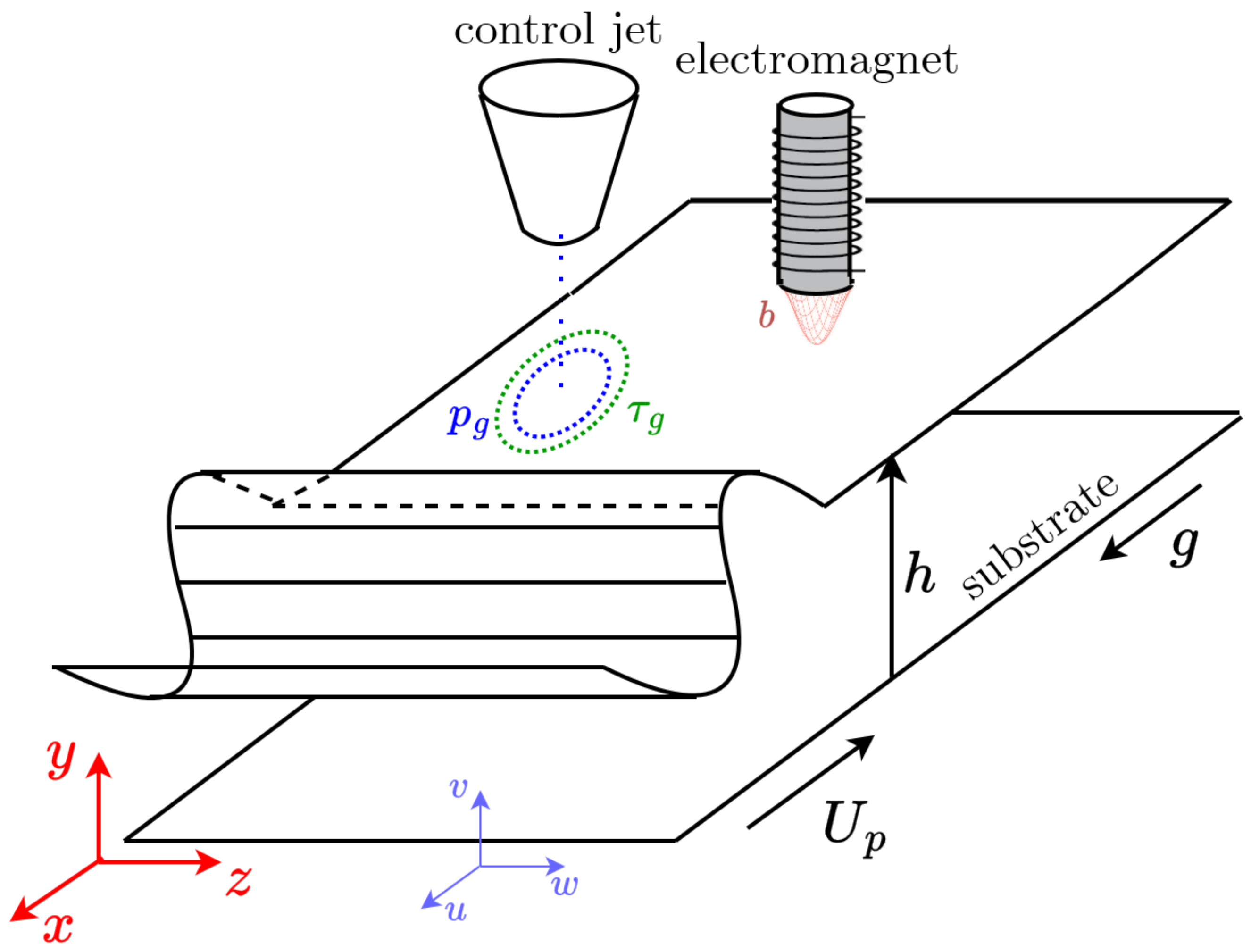


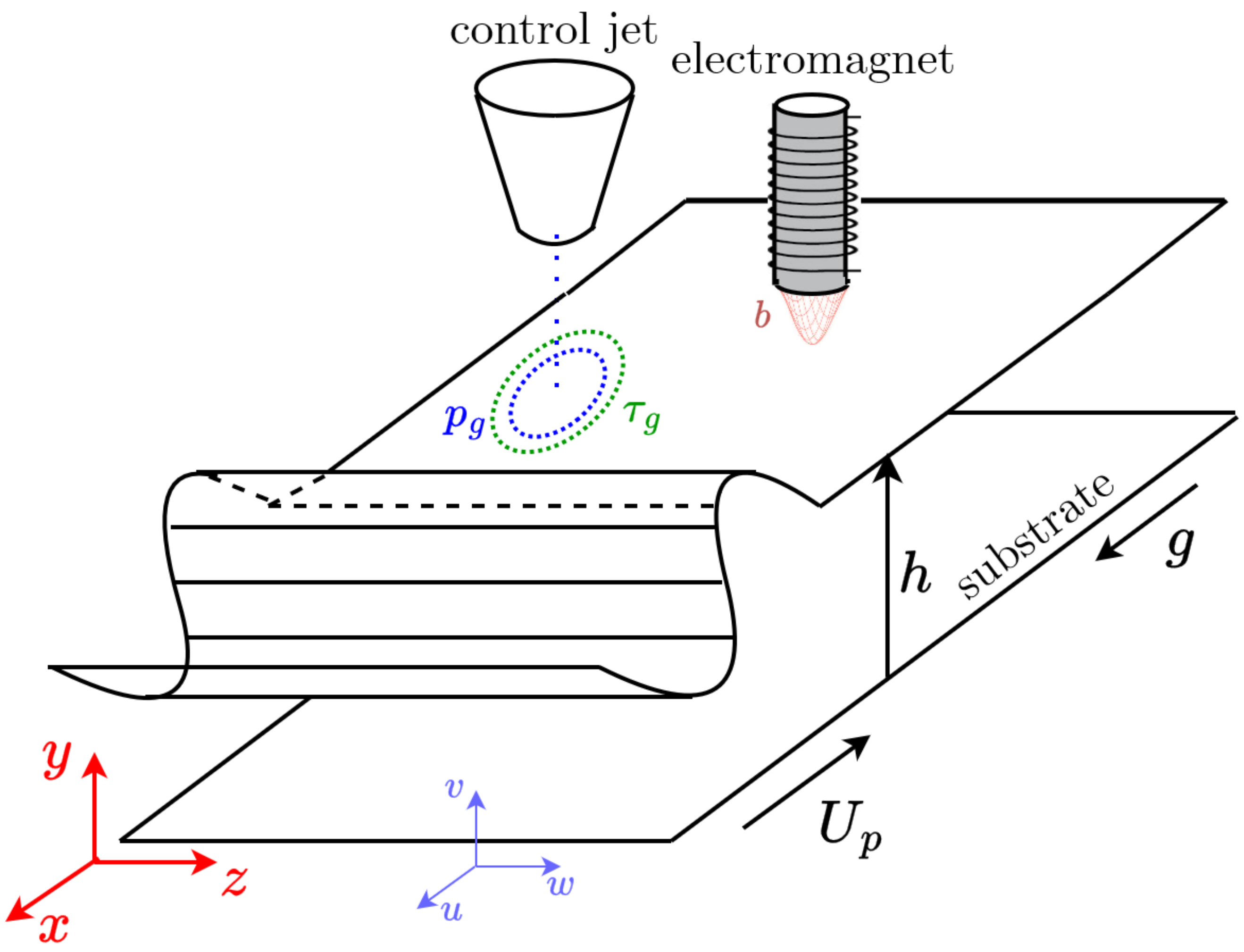
<u>Derive simplified model</u>

Derivation liquid film reduced order model with actuators modelling

Liquid film modelling



Liquid film modelling

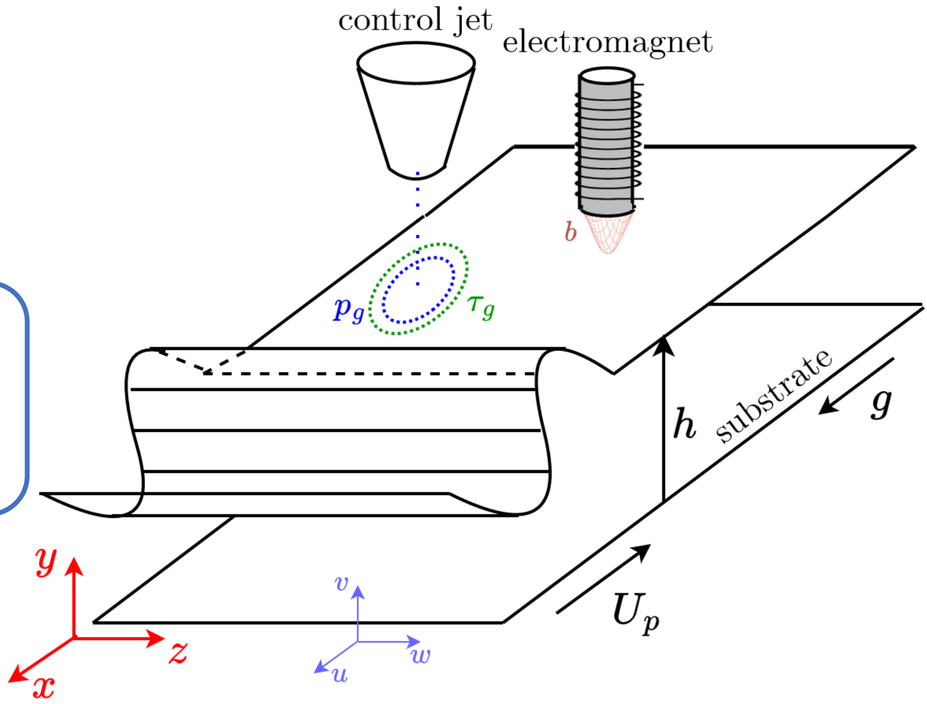


Liquid film modelling

Long-wave assumption $h_{\text{ref}}/x_{\text{ref}} = \varepsilon \ll 1$

Integrate over liquid film thickness

Navier-Stokes equations → Boundary-Layer equations → Integral Boundary-Layer (IBL) model



Liquid film modelling

3D Nondimensional Integral Boundary Layer model

Long-wave assumption

$h_{\mathrm{ref}}/x_{\mathrm{ref}} = \varepsilon \ll 1$

Integrate over liquid film thickness

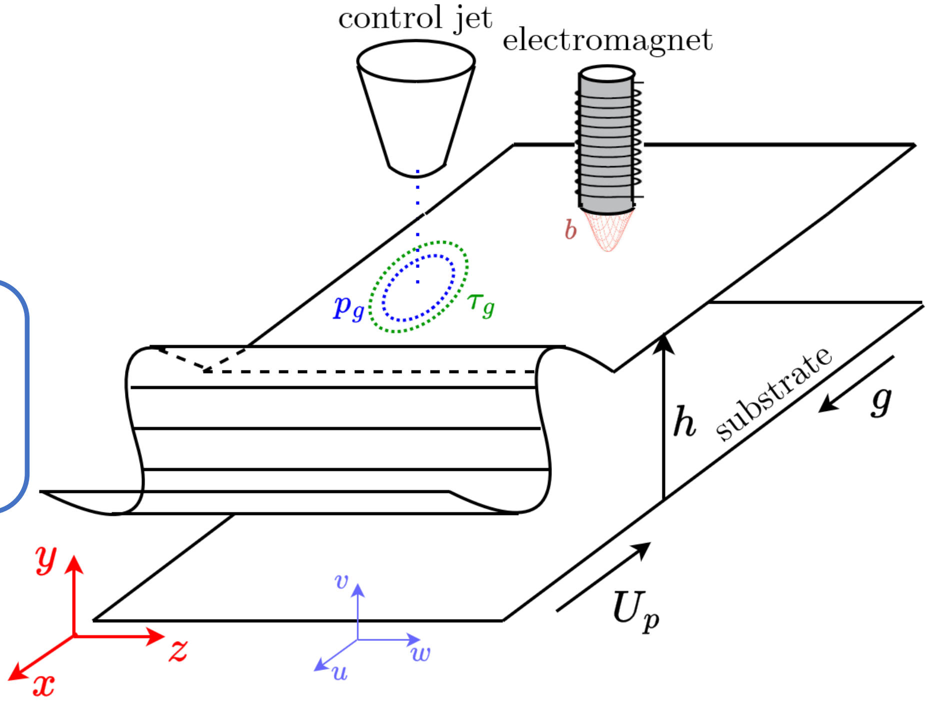
Navier-Stokes equations → Boundary-Layer equations → Integral Boundary-Layer (IBL) model

$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{S}$$

$\hat{h}$ Film thickness

$\hat{q}_x$ Streamwise flow rate

$\hat{q}_z$ Spanwise flow rate



Ivanova, T., Pino, F., Scheid, B., & Mendez, M. A. (2023). Evolution of waves in liquid films on moving substrates. *Physics of Fluids*, *35*(1).

Liquid film modelling

3D nondimensional Integral Boundary Layer model

$\hat{h}$ Film thickness
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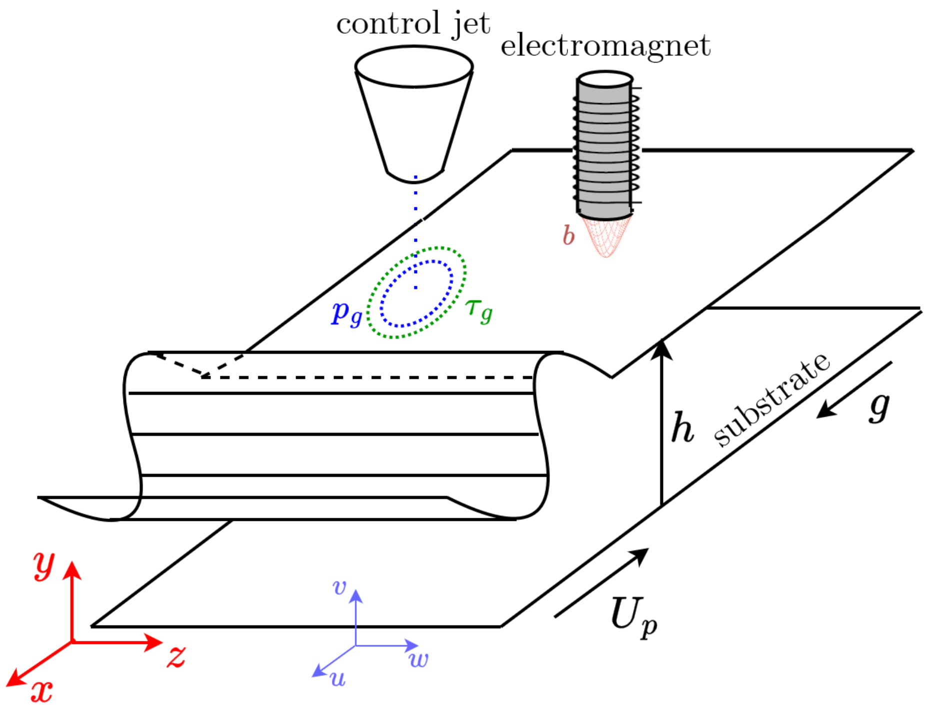

Flux matrix

$$\mathbf{F} = \begin{pmatrix} \hat{q}_x & \int_0^{\hat{h}} \hat{u}^2 d\hat{y} & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} \\ \hat{q}_z & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} & \int_0^{\hat{h}} \hat{w}^2 d\hat{y} \end{pmatrix}$$

Source term

$$\mathbf{s} = \begin{pmatrix} 0 \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{x}}\hat{p} + \partial_{\hat{x}\hat{x}\hat{x}}\hat{h} + \partial_{\hat{x}\hat{z}\hat{z}}\hat{h} + 1\right) + \hat{\tau}_{g,x} + \hat{\tau}_{w,x} - \mathrm{Ha}^2\hat{b}^2\hat{q}_x\right] \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{z}}\hat{p} + \partial_{\hat{z}\hat{z}\hat{z}}\hat{h} + \partial_{\hat{z}\hat{x}\hat{x}}\hat{h}\right) + \hat{\tau}_{g,z} + \hat{\tau}_{w,z} - \mathrm{Ha}^2\hat{b}^2\hat{q}_z\right] \end{pmatrix}$$

Reduced Reynolds number

Hartmann number (ratio electromagnetic forces to viscous forces)

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Liquid film modelling

3D nondimensional Integral Boundary Layer model

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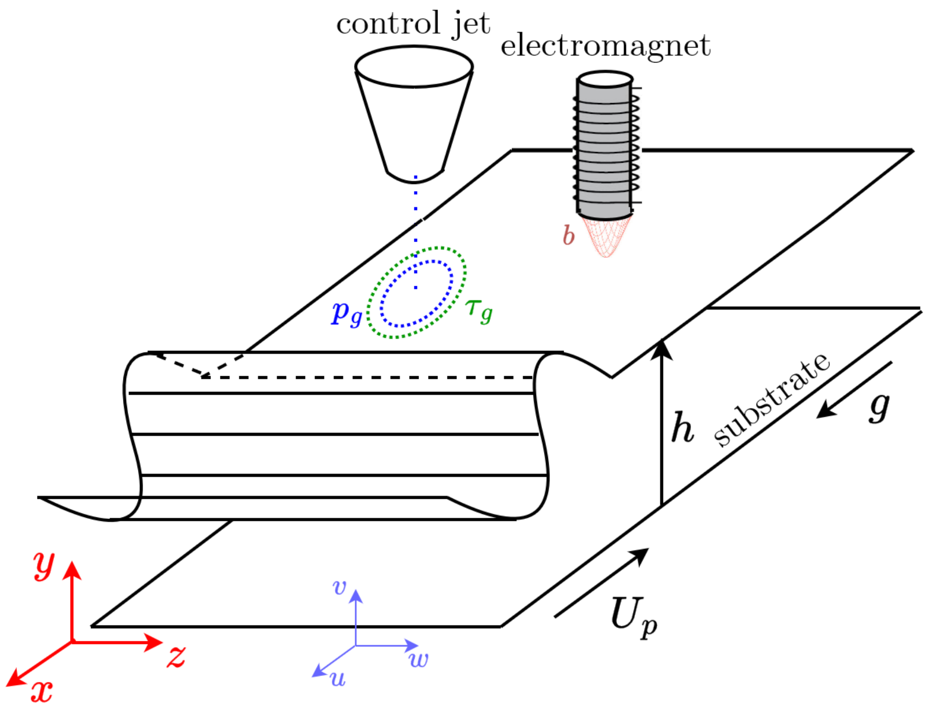

Flux matrix

$$\mathbf{F} = \begin{pmatrix} \hat{q}_x & \int_0^{\hat{h}} \hat{u}^2 d\hat{y} & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} \\ \hat{q}_z & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} & \int_0^{\hat{h}} \hat{w}^2 d\hat{y} \end{pmatrix}$$

Source term

Gravity

$$\mathbf{s} = \begin{pmatrix} 0 \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{x}}\hat{p} + \partial_{\hat{x}\hat{x}\hat{x}}\hat{h} + \partial_{\hat{x}\hat{z}\hat{z}}\hat{h} + \boxed{1}\right) + \hat{\tau}_{g,x} + \hat{\tau}_{w,x} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{x}\right] \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{z}}\hat{p} + \partial_{\hat{z}\hat{z}\hat{z}}\hat{h} + \partial_{\hat{z}\hat{x}\hat{x}}\hat{h}\right) + \hat{\tau}_{g,z} + \hat{\tau}_{w,z} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{z}\right] \end{pmatrix}$$

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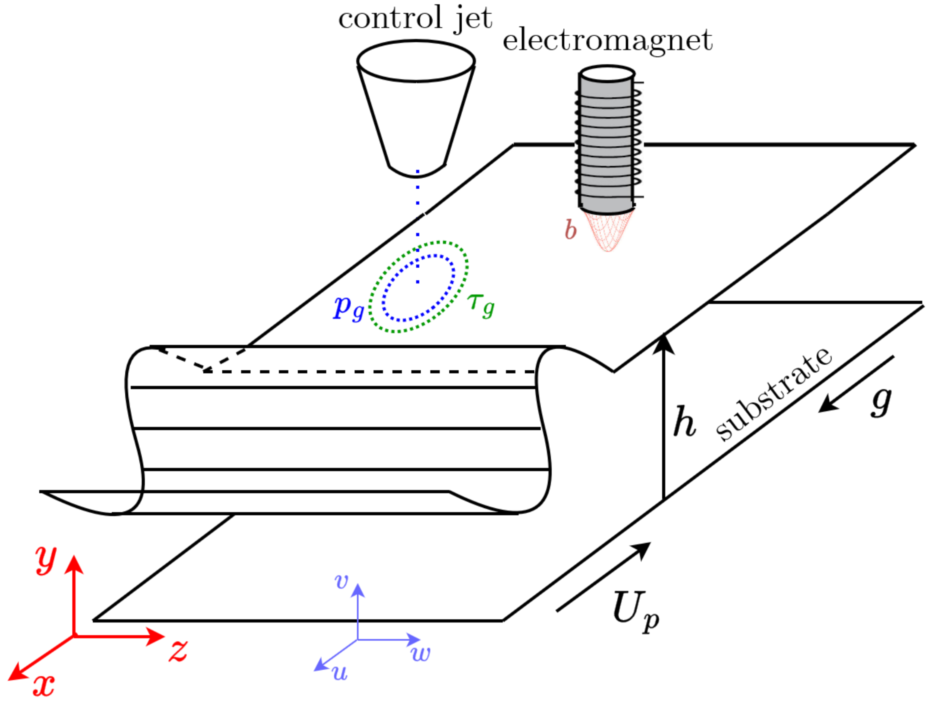
Liquid film modelling



3D nondimensional Integral Boundary Layer model

$\hat{h}$ Film thickness
$\hat{q}_x$ Streamwise flow rate
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$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{s}$$

Flux matrix

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Gravity

Shear at the substrate

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Liquid film modelling

3D nondimensional Integral Boundary Layer model

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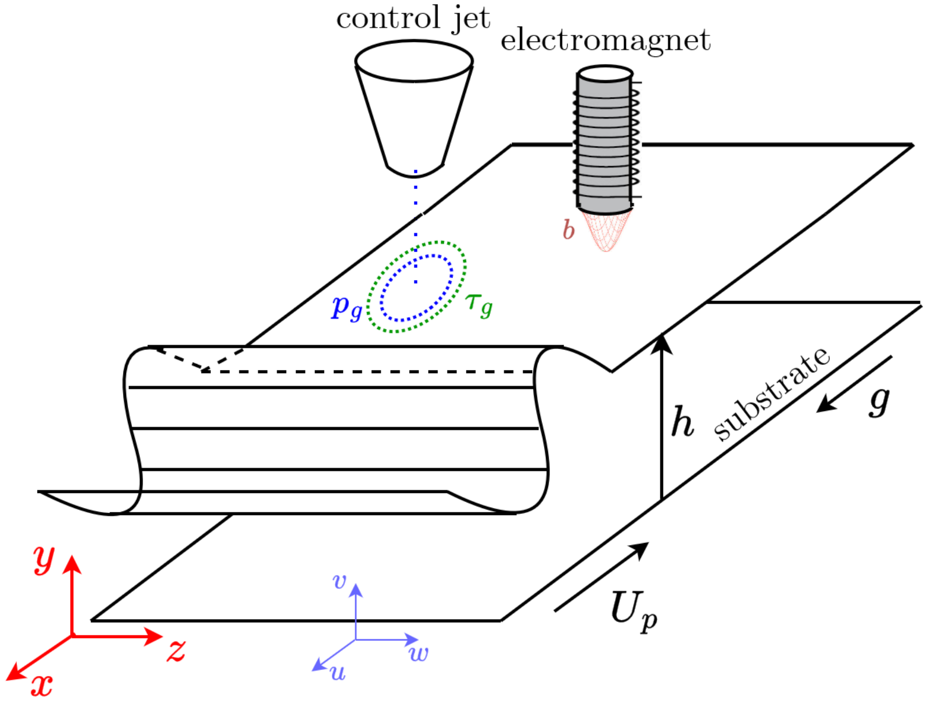

Flux matrix

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Gravity

Surface Tension

Shear at the substrate

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Liquid film modelling

3D nondimensional Integral Boundary Layer model

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$\hat{q}_x$ Streamwise flow rate

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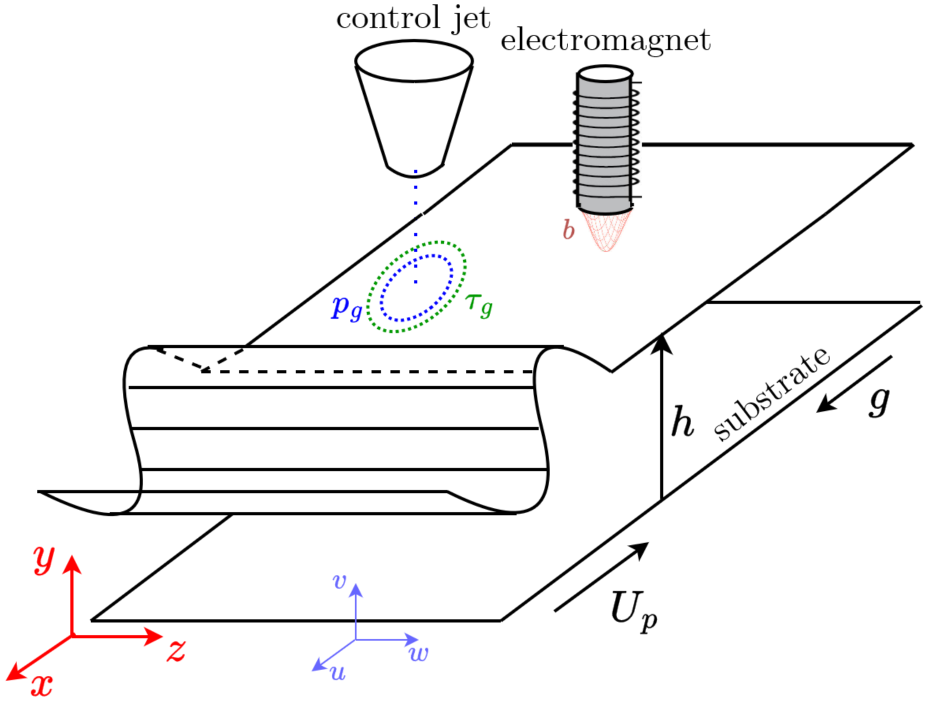
$$\partial_{\hat{t}}\begin{pmatrix}\hat{h}\\ \hat{q}_x\\ \hat{q}_z\end{pmatrix} + \nabla\cdot\mathbf{F} = \mathbf{s}$$



Flux matrix

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Source term

Gas-jets · Gravity · Lorentz Force

$$\mathbf{s} = \begin{pmatrix} 0 \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{x}}\hat{p} + \partial_{\hat{x}\hat{x}\hat{x}}\hat{h} + \partial_{\hat{x}\hat{z}\hat{z}}\hat{h} + 1\right) + \hat{\tau}_{g,x} + \hat{\tau}_{w,x} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_x\right] \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{z}}\hat{p} + \partial_{\hat{z}\hat{z}\hat{z}}\hat{h} + \partial_{\hat{z}\hat{x}\hat{x}}\hat{h}\right) + \hat{\tau}_{g,z} + \hat{\tau}_{w,z} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_z\right]\end{pmatrix}$$

Surface Tension · Shear at the substrate

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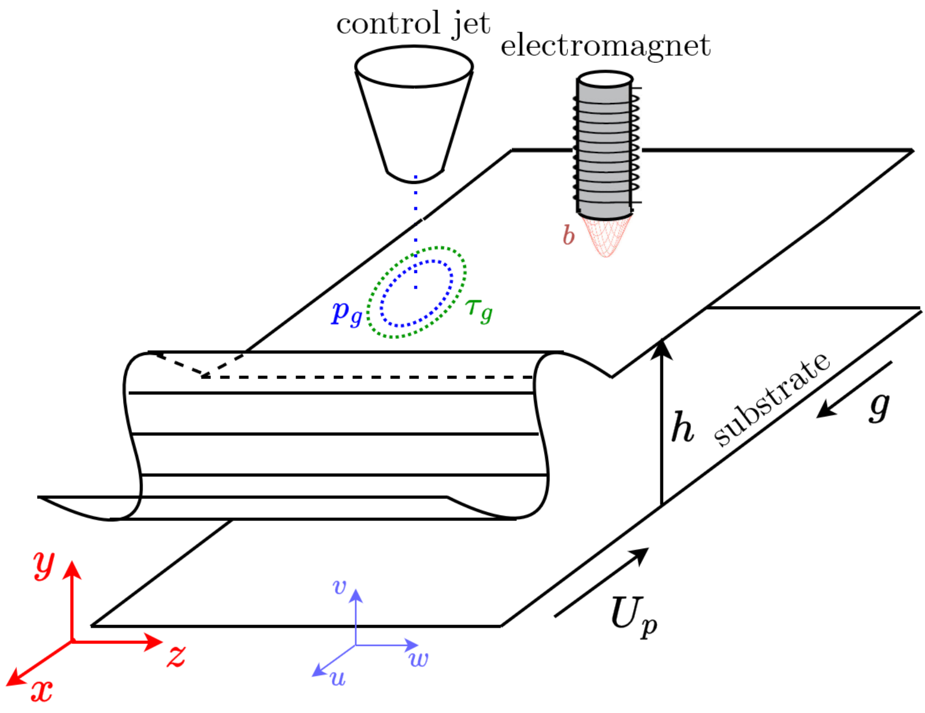
Liquid film modelling



3D nondimensional Integral Boundary Layer model

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Flux matrix

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Source term

Gas-jets, Gravity, Lorentz Force, Surface Tension, Shear at the substrate

$$\mathbf{s} = \begin{pmatrix} \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{x}}\hat{p} + \partial_{\hat{x}\hat{x}\hat{x}}\hat{h} + \partial_{\hat{x}\hat{z}\hat{z}}\hat{h} + \overset{0}{1}\right) + \hat{\tau}_{g,x} + \hat{\tau}_{w,x} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{x}\right] \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{z}}\hat{p} + \partial_{\hat{z}\hat{z}\hat{z}}\hat{h} + \partial_{\hat{z}\hat{x}\hat{x}}\hat{h}\right) + \hat{\tau}_{g,z} + \hat{\tau}_{w,z} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{z}\right] \end{pmatrix}$$

Closures relations

$$\hat{u} = \hat{u}(\hat{y}; \hat{h}, \hat{q}_x, \hat{q}_z) \qquad \hat{w} = \hat{w}(\hat{y}; \hat{h}, \hat{q}_x, \hat{q}_z)$$

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Liquid film modelling

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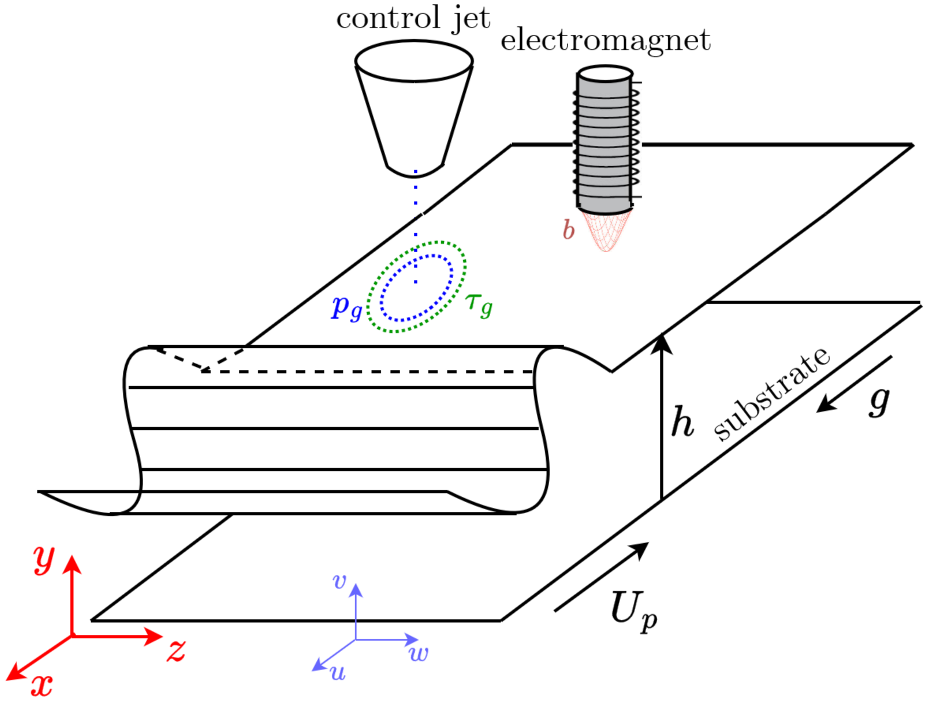

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Source term

Gas-jets, Gravity, Lorentz Force

$$\mathbf{s} = \begin{pmatrix} 0 \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{x}}\hat{p} + \partial_{\hat{x}\hat{x}\hat{x}}\hat{h} + \partial_{\hat{x}\hat{z}\hat{z}}\hat{h} + 1\right) + \hat{\tau}_{g,x} + \hat{\tau}_{w,x} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{x}\right] \\ \delta^{-1}\left[\hat{h}\left(-\partial_{\hat{z}}\hat{p} + \partial_{\hat{z}\hat{z}\hat{z}}\hat{h} + \partial_{\hat{z}\hat{x}\hat{x}}\hat{h}\right) + \hat{\tau}_{g,z} + \hat{\tau}_{w,z} - \mathrm{Ha}^2\hat{\mathrm{b}}^2\hat{\mathrm{q}}_\mathrm{z}\right] \end{pmatrix}$$

Surface Tension, Shear at the substrate

Closures relations

$$\hat{u} = \hat{u}(\hat{y}; \hat{h}, \hat{q}_x, \hat{q}_z) \qquad \hat{w} = \hat{w}(\hat{y}; \hat{h}, \hat{q}_x, \hat{q}_z)$$

Self-similarity hypothesis

The velocity profile is everywhere parabolic and self-similar.

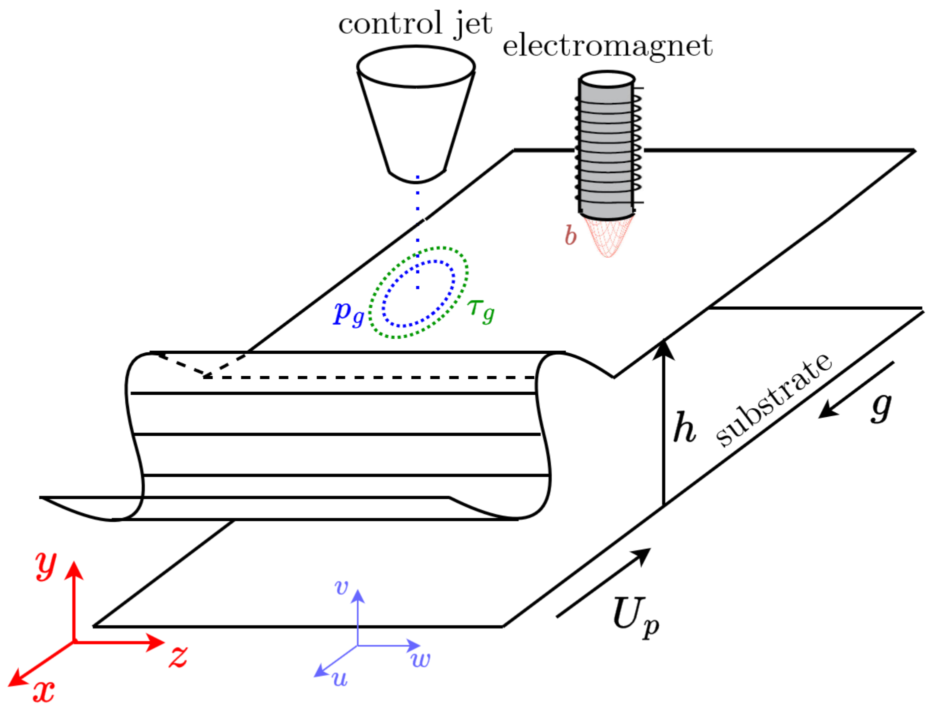
Ivanova, T., Pino, F., Scheid, B., & Mendez, M. A. (2023). Evolution of waves in liquid films on moving substrates. *Physics of Fluids*, *35*(1).

Liquid film modelling

3D nondimensional Integral Boundary Layer model

$\hat{h}$ Film thickness
$\hat{q}_x$ Streamwise flow rate
$\hat{q}_z$ Spanwise flow rate

$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{s}$$



Flux matrix

$$\mathbf{F} = \begin{pmatrix} \hat{q}_x & \int_0^{\hat{h}} \hat{u}^2 d\hat{y} & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} \\ \hat{q}_z & \int_0^{\hat{h}} \hat{u}\hat{w} d\hat{y} & \int_0^{\hat{h}} \hat{w}^2 d\hat{y} \end{pmatrix}$$

Source term

Gas-jets, Gravity, Lorentz Force

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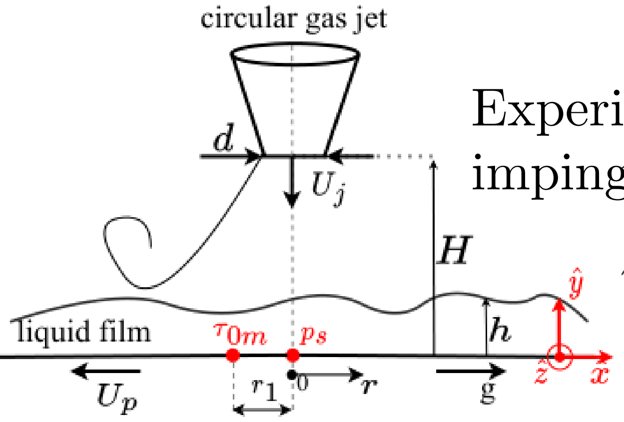
Surface Tension, Shear at the substrate

Modelling actuators



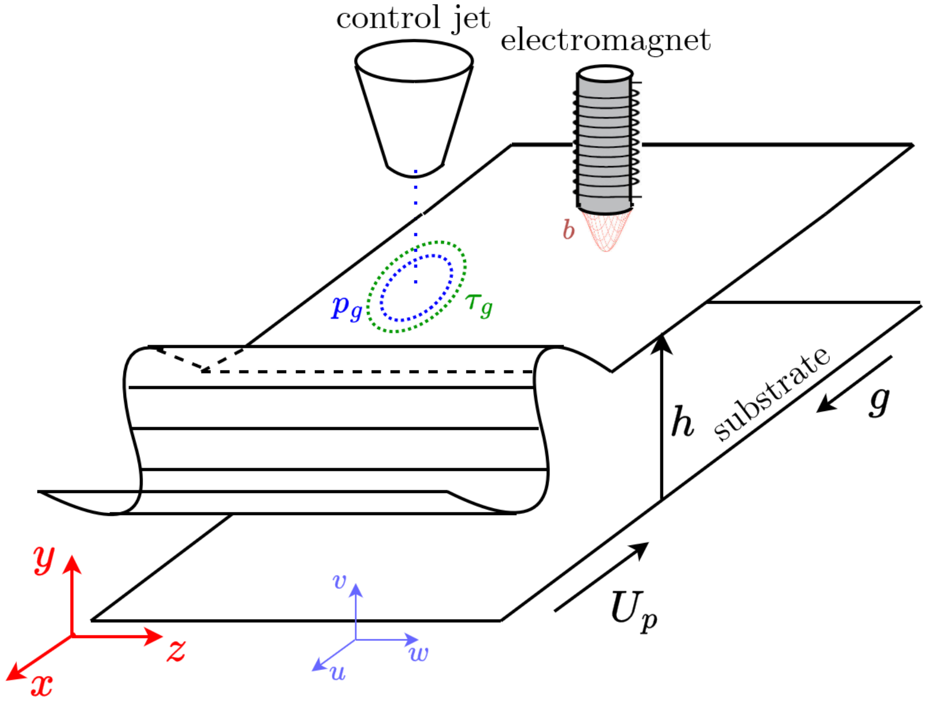
Experimental correlations of impinging gas jets

$$\tau_g = f_\tau(\lambda)\tau_{0m} \quad p = f_p(\lambda)p_s$$

$$\lambda = r/H$$

Liquid film modelling

3D nondimensional Integral Boundary Layer model



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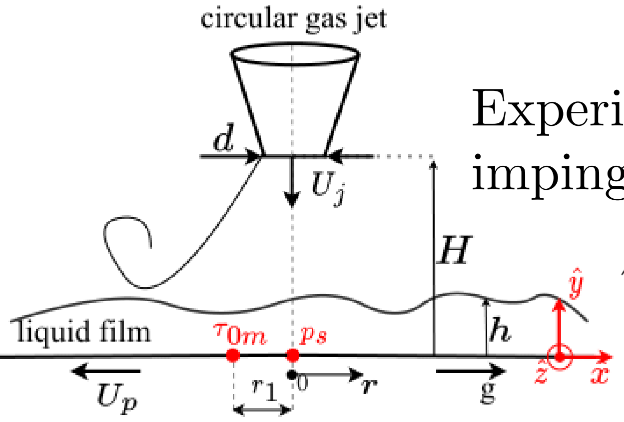
Surface Tension, Shear at the substrate

Modelling actuators



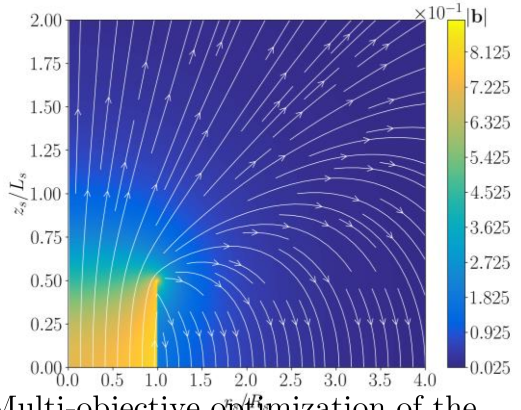
Experimental correlations of impinging gas jets

$$\tau_g = f_\tau(\lambda)\tau_{0m} \quad p = f_p(\lambda)p_s$$

$$\lambda = r/H$$

Approximation magnetic field of a solenoid

$$b(x,z,t) = b_t(t)e^{\frac{-(\hat{x}-\hat{x}_0)^2}{2\gamma_x^2} + \frac{-(\hat{z}-\hat{z}_0)^2}{2\gamma_z^2}}$$



Pino, Fabio, Benoit Scheid, and Miguel Alfonso Mendez. "Multi-objective optimization of the magnetic wiping process in dip-coating." *arXiv preprinr*

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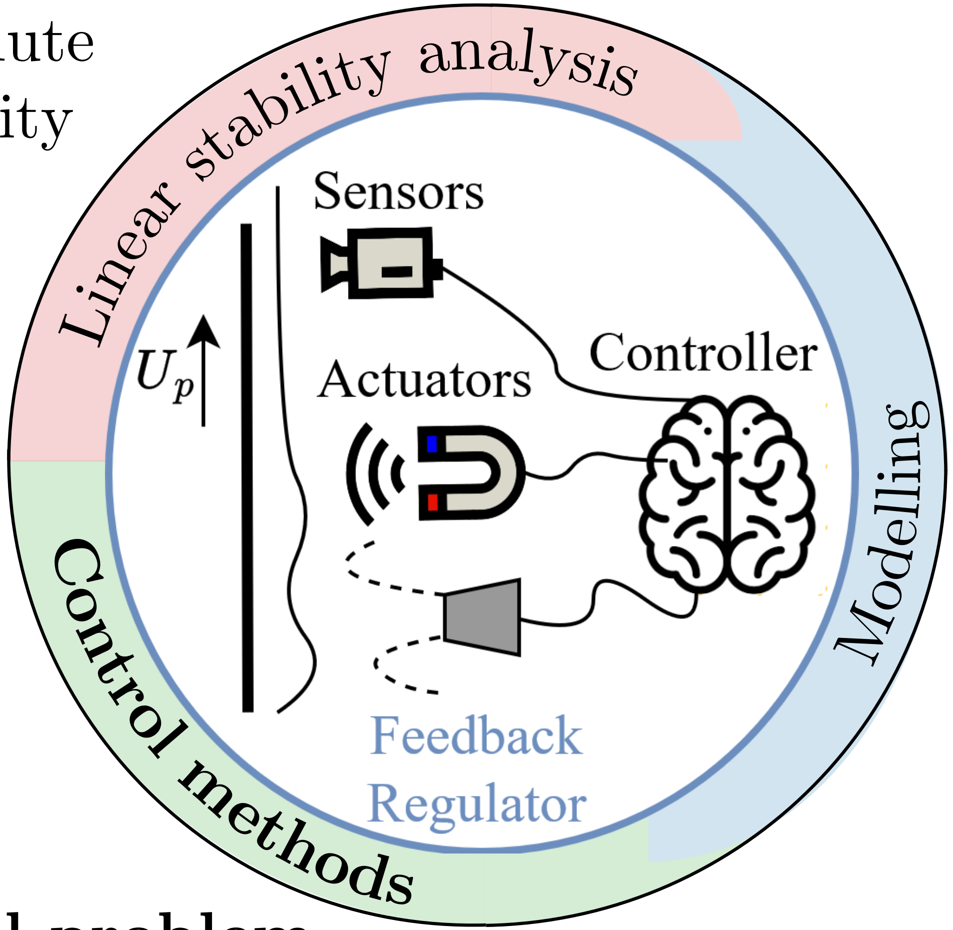


Derive simplified model

Derivation liquid film reduced order model with actuators modelling

Control methods

- ❑ **Definition optimal control problem**

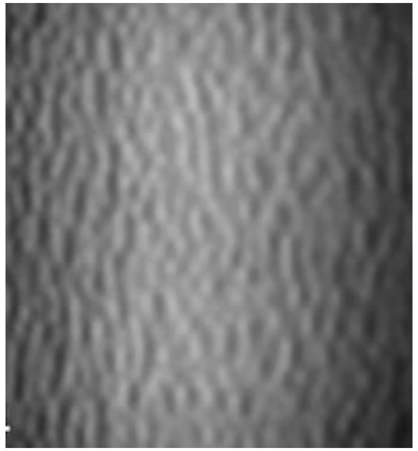
Definition optimal control problem

Definition optimal control problem

Integral Boundary Layer model

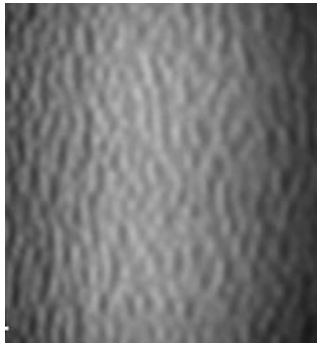
$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{s}$$

Undulation waves



Definition optimal control problem

Undulation waves



Integral Boundary Layer model

$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{s}$$

Performance measure

Liquid film as flat as possible in the reward area around target thickness $\bar{h}$

$\mathbf{a}$ *Control Parameter*

$$\max_{\mathbf{a}} \int_0^T \int_{\Omega_r} \underbrace{\mathcal{L}(\hat{h}(\hat{x},\hat{t}) - \bar{h})}_{Running\,Cost} \, d\hat{x} d\hat{t}$$

Ω_r Reward area

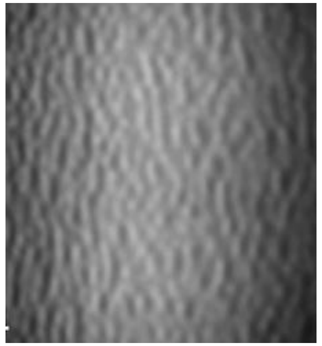
U_j nozzle exit velocity

p_s jet's impingement pressure

$\hat{b}$ Intensity magnetic field

Definition optimal control problem

Undulation waves



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Ω_r Reward area

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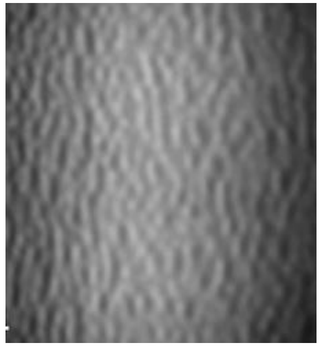
Model based control approach (White box)

Governing equations

- ❑ Full knowledge of the Integral Boundary Layer equations
- ❑ Linearization around desired flat state $\bar{h}$
- ❑ Identify feedback gains that maintain the system within the stable region.

Definition optimal control problem

Undulation waves



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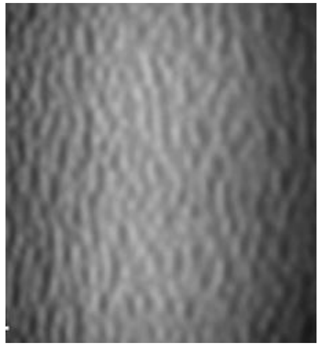
Machine learning approach (Black box)

Pino, Fabio, et al. "Comparative analysis of machine learning methods for active flow control." *Journal of Fluid Mechanics* 958 (2023): A39.

Definition optimal control problem

Undulation waves



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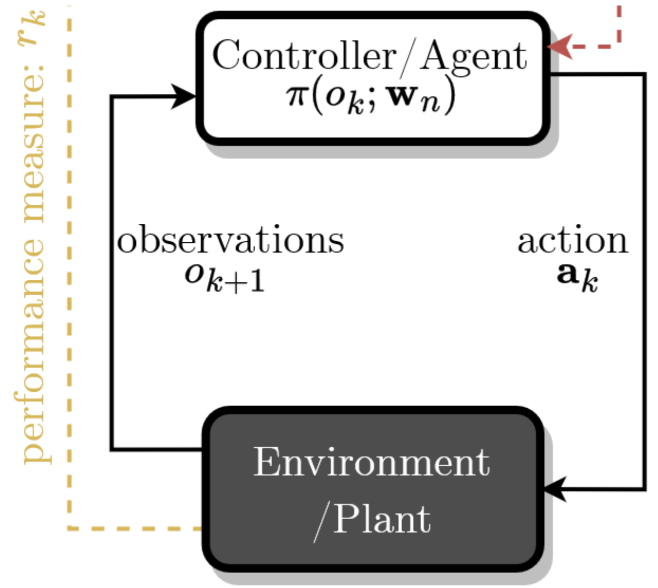

Free surface observations

$$o_k = m(\hat{h}(\hat{x}, \hat{t}_k))$$

Instantaneous reward

$$r_k = \int_{\Omega_r} \mathcal{L}(\hat{h}(\hat{x}, \hat{t}_k) - \bar{h}) \, d\hat{x}$$

Pino, Fabio, et al. "Comparative analysis of machine learning methods for active flow control." *Journal of Fluid Mechanics* 958 (2023): A39.

Definition optimal control problem

Integral Boundary Layer model

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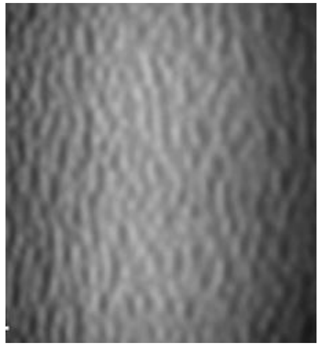

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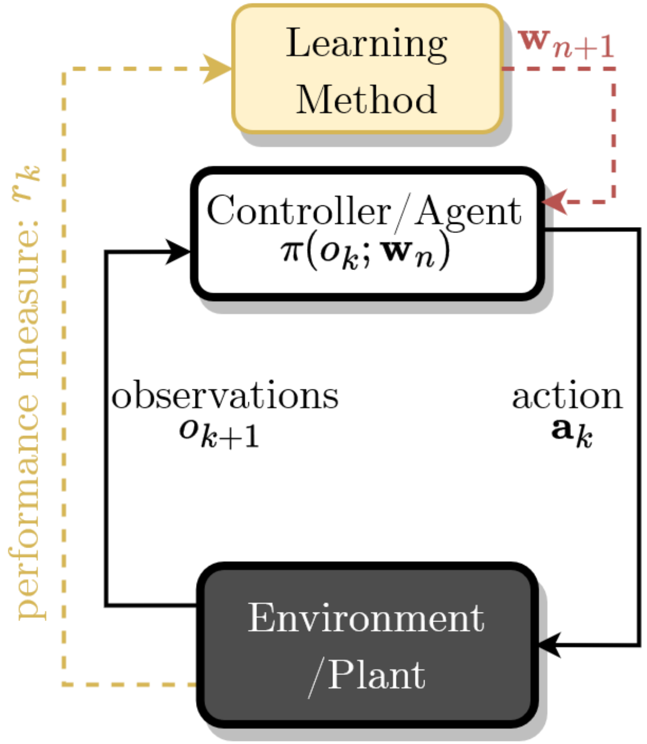

Machine learning approach (Black box)

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$$o_k = m(\hat{h}(\hat{x},\hat{t}_k))$$

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$$r_k = \int_{\Omega_r} \mathcal{L}(\hat{h}(\hat{x},\hat{t}_k) - \bar{h}) \, d\hat{x}$$

Feedback control action

$$\mathbf{a} = \pi(o_k|\mathbf{w}_n)$$

Control action parameters

$$\mathbf{w}_n$$

Machine learning control methods vary in the way they adjust the controller action parameters.

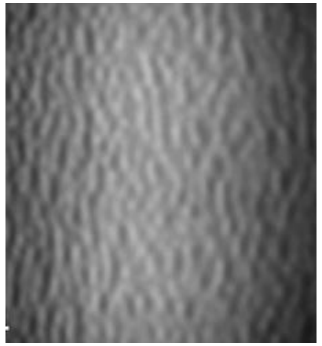
Pino, Fabio, et al. "Comparative analysis of machine learning methods for active flow control." *Journal of Fluid Mechanics* 958 (2023): A39.

Definition optimal control problem

Liquid film Governing Equations

$$\partial_{\hat{t}} \begin{pmatrix} \hat{h} \\ \hat{q}_x \\ \hat{q}_z \end{pmatrix} + \nabla \cdot \mathbf{F} = \mathbf{s}$$

Undulation waves



Performance measure

Liquid film as flat as possible in the reward area around target thickness $\bar{h}$

$$\max_{\mathbf{a}} \int_0^T \int_{\Omega_r} \underbrace{\mathcal{L}(\hat{h}(\hat{x},\hat{t}) - \bar{h})}_{Running\,Cost} \, d\hat{x}d\hat{t}$$

Ω_r Reward area

$\mathbf{a}$ *Control Parameter*

U_j nozzle exit velocity

p_s jet's impingement pressure

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Model based control approach (White box)

Advantages

- Fast and Efficient
- Stability Guarantees
- Established literature

Disadvantages

- Linear Systems Limitation
- Model Dependency
- Difficulty with uncertainties and noise

Governing equations

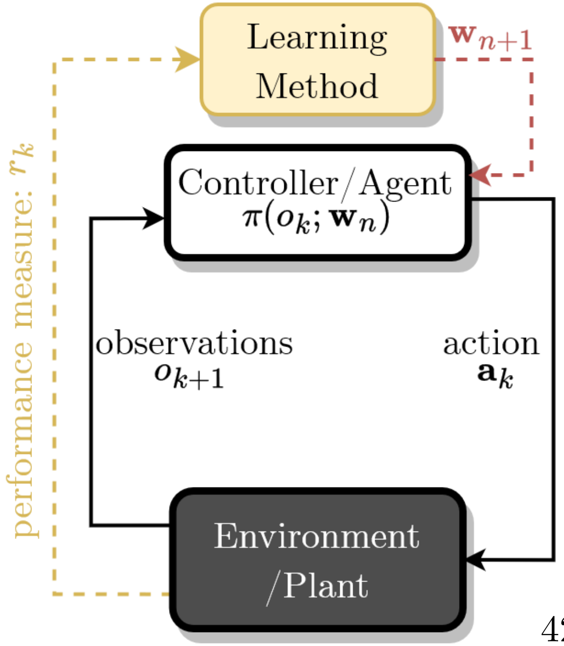
Machine learning approach (Black box)

Advantages

- Model-Free Learning
- Nonlinear Systems
- Adaptability

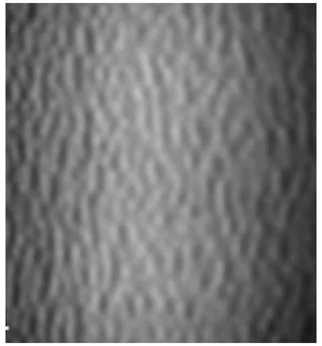
Disadvantages

- No Stability Guarantees
- Sample Inefficiency
- Computational Complexity



Definition optimal control problem

Undulation waves



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$$\max_{\mathbf{a}} \int_0^T \int_{\Omega_r} \underbrace{\mathcal{L}(\hat{h}(\hat{x},\hat{t}) - \bar{h})}_{Running\,Cost} \, d\hat{x} d\hat{t}$$

Ω_r Reward area

$\mathbf{a}$ *Control Parameter*

- U_j nozzle exit velocity
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Model based control approach (White box)

Advantages

- Fast and Efficient
- Stability Guarantees
- Established literature

Control small amplitude waves

- Linear Systems Limitation
- Model Dependency
- Difficulty with uncertainties and noise

Governing equations

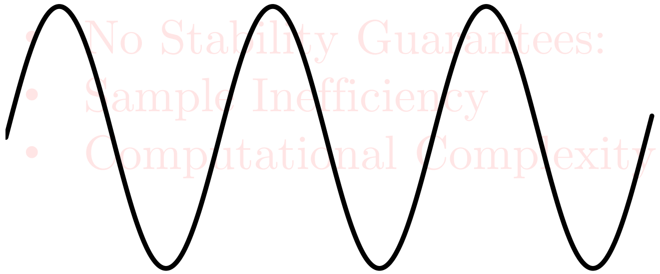
Machine learning approach (Black box)

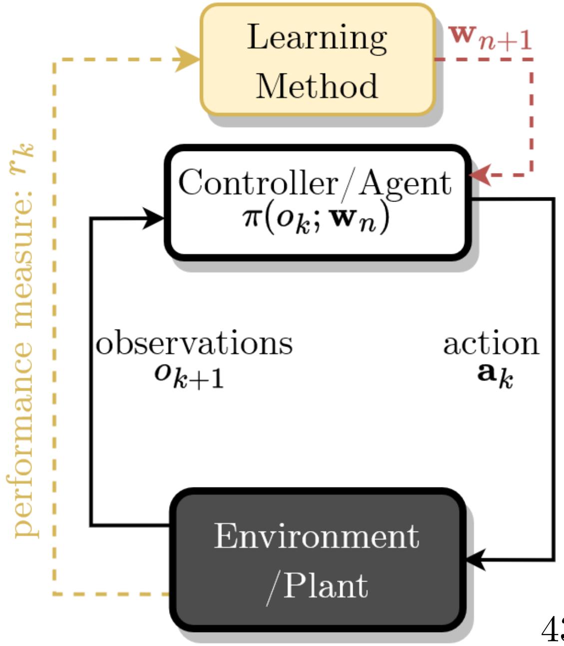
Advantages

- Model-Free Learning
- Nonlinear and Complex Systems
- Adaptability

Control large amplitude waves

- No Stability Guarantees:
- Sample Inefficiency
- Computational Complexity





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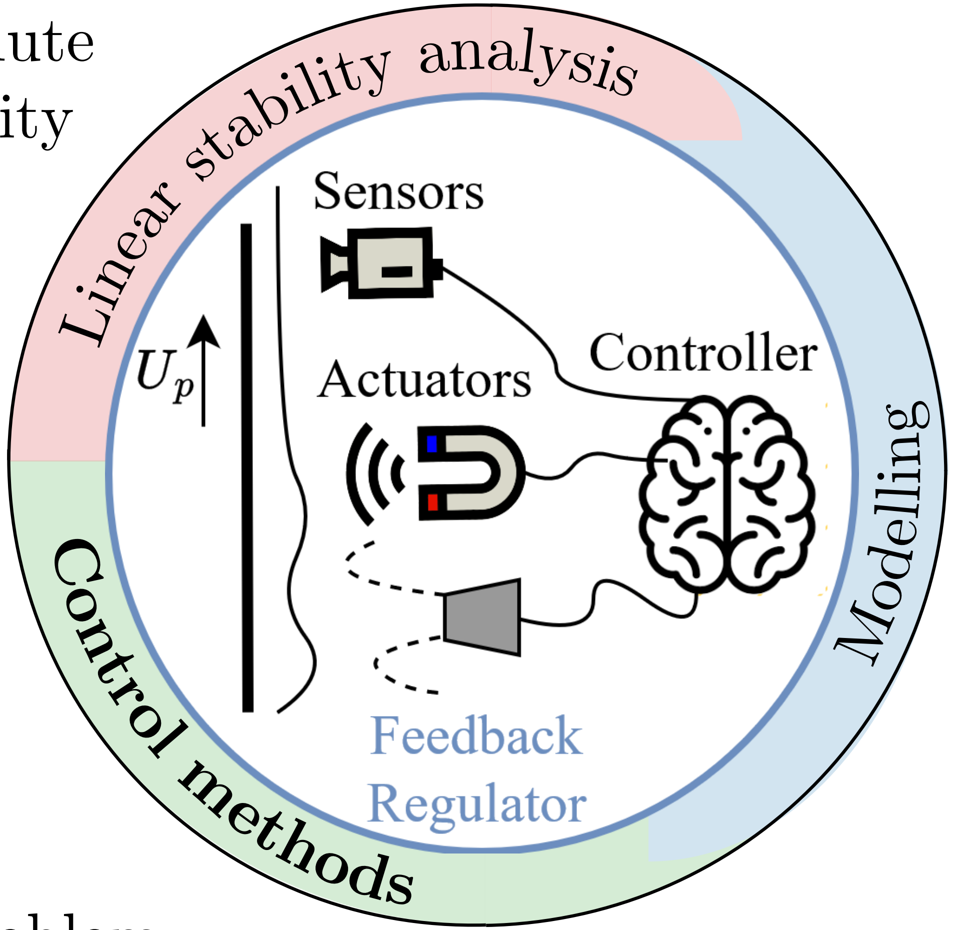


Derive simplified model

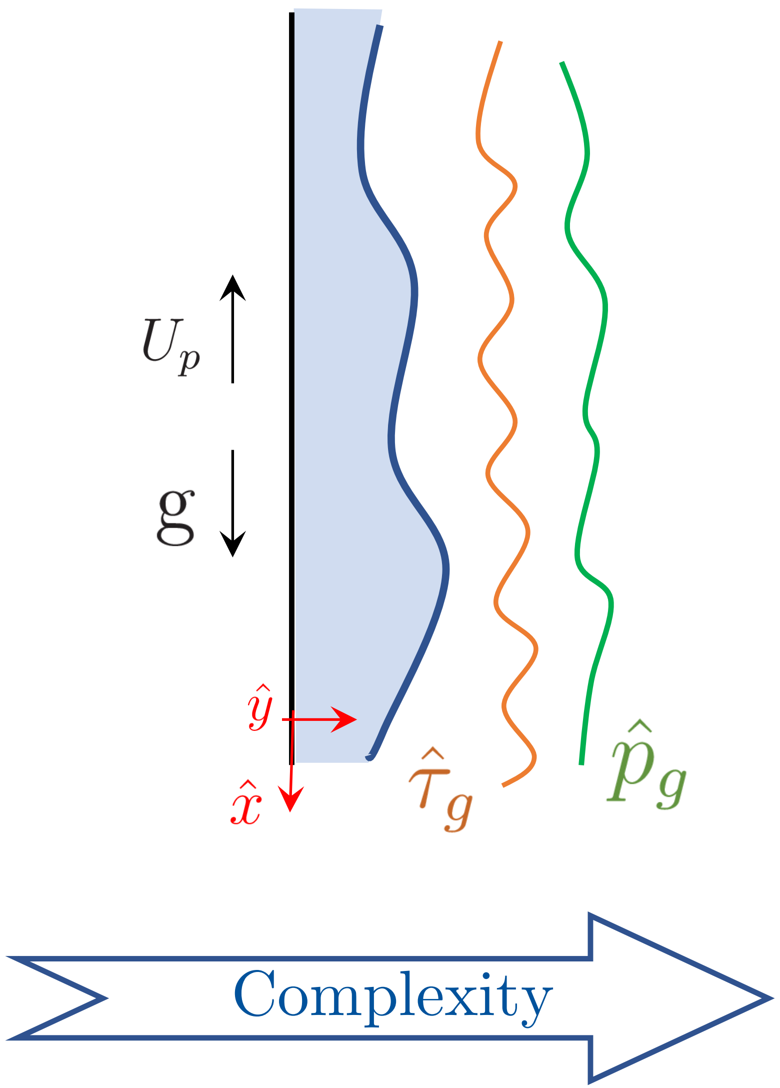
Derivation liquid film reduced order model with actuators modelling

Control methods

- ❑ Definition optimal control problem
- ❑ **Small-amplitude control via linear stability methods**
- ❑ Large-amplitude control via machine learning methods

Linear stability based control

Independent pressure and shear stress distributions at the free surface



Linear stability based control

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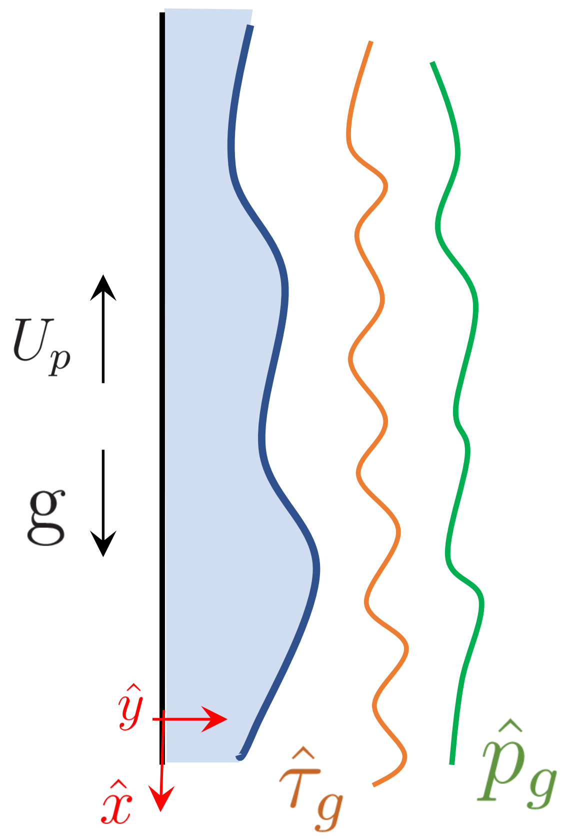
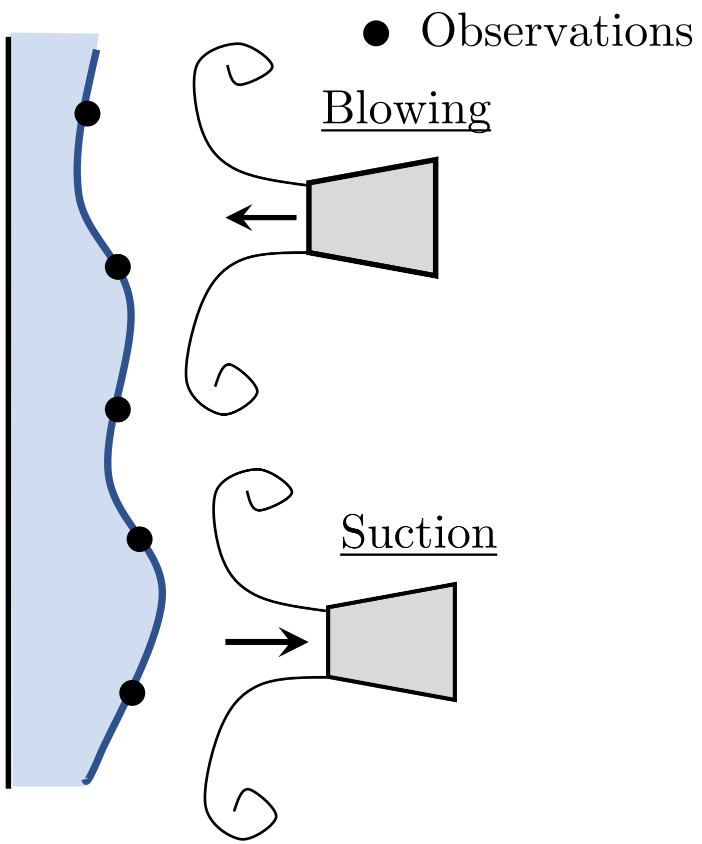


Control jets with blowing and suction

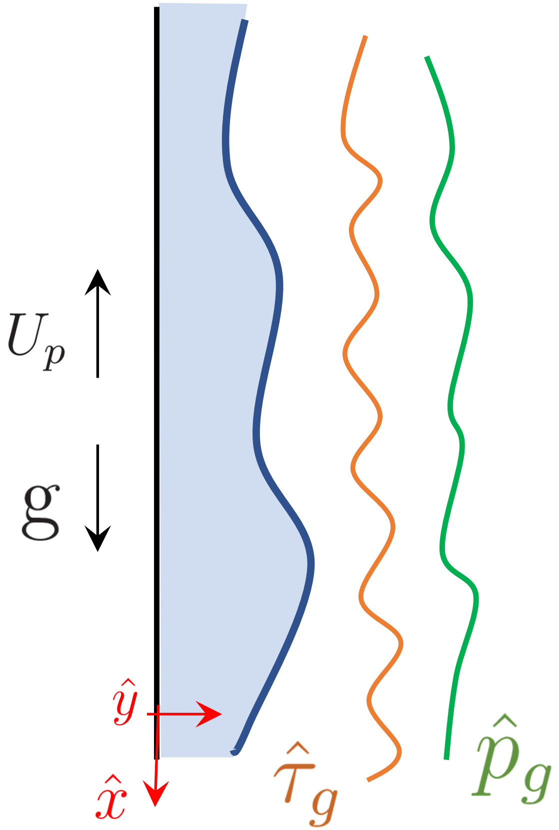
$$\hat{\tau}_g = f(\hat{p}_g)$$



Complexity

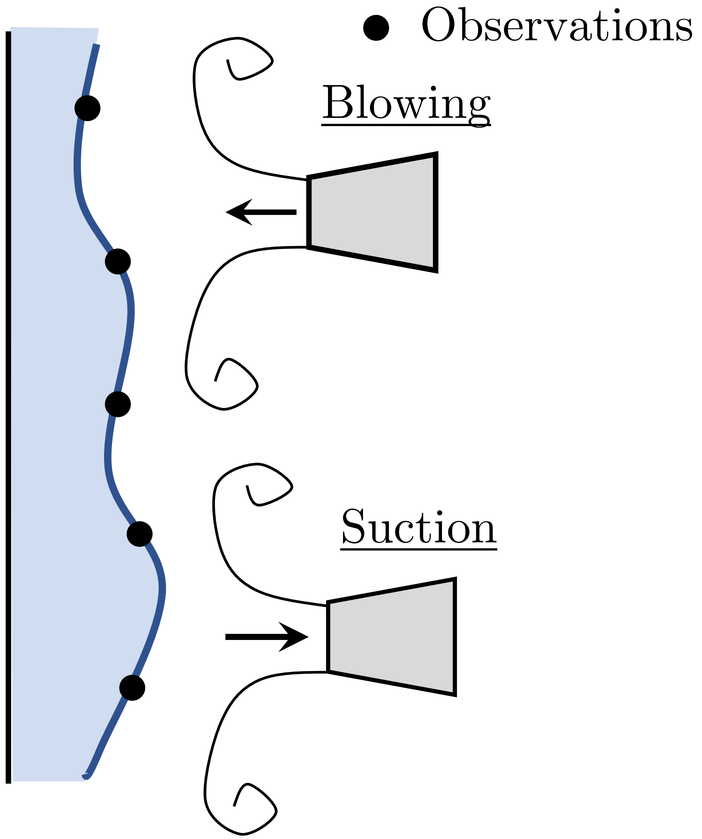
Linear stability based control

Independent pressure and shear stress distributions at the free surface

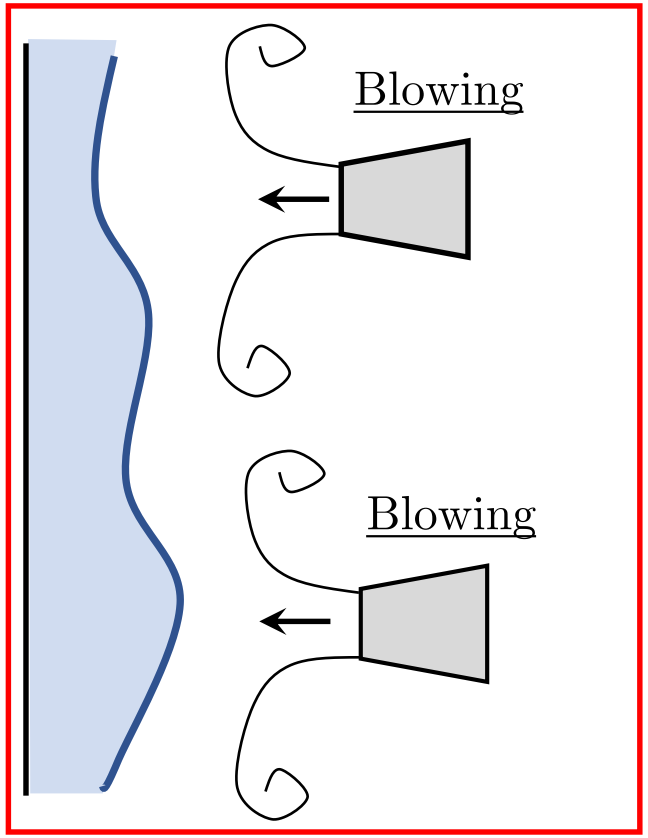


Control jets with blowing and suction

$$\hat{\tau}_g = f(\hat{p}_g)$$



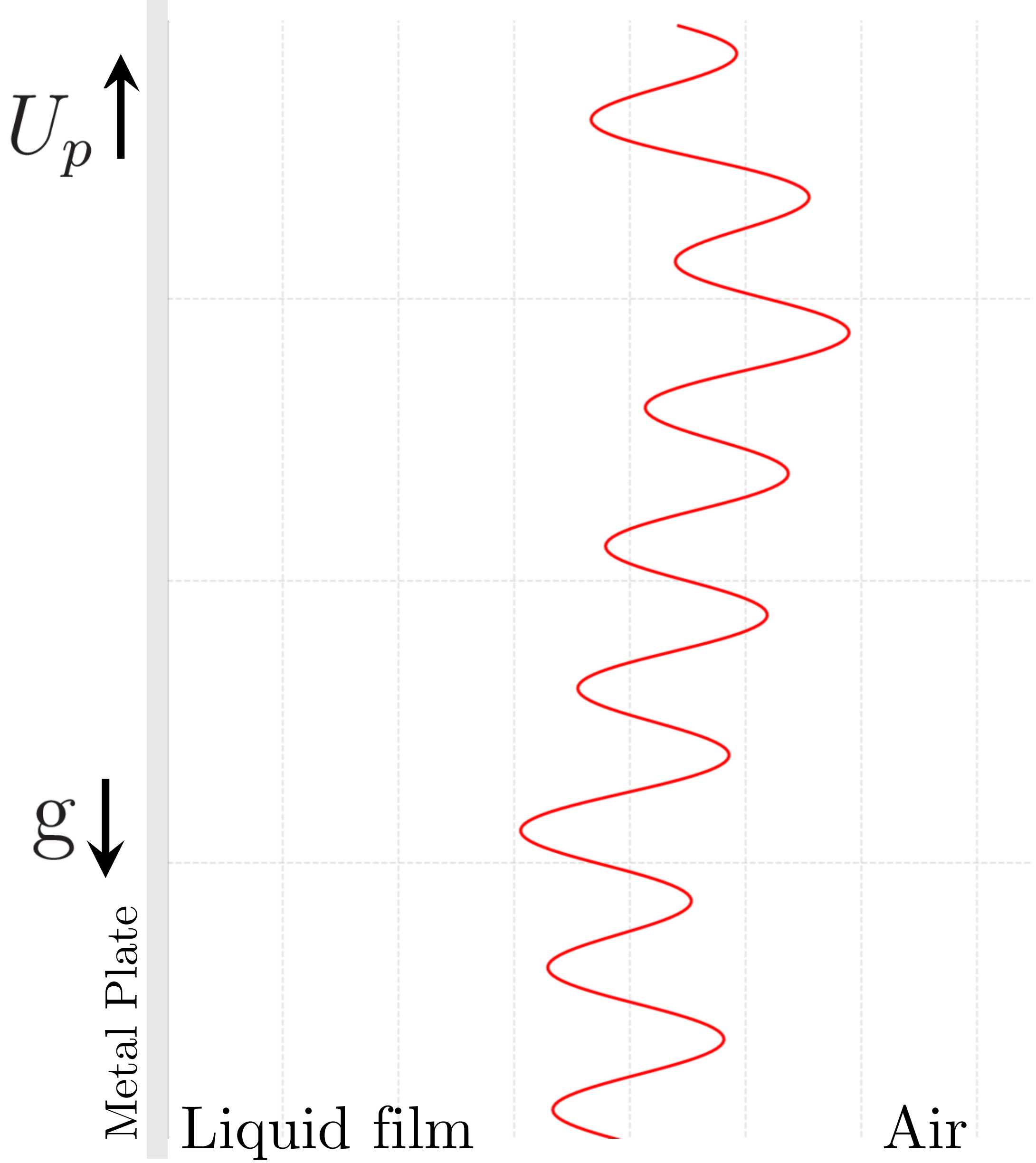
Blowing control jets



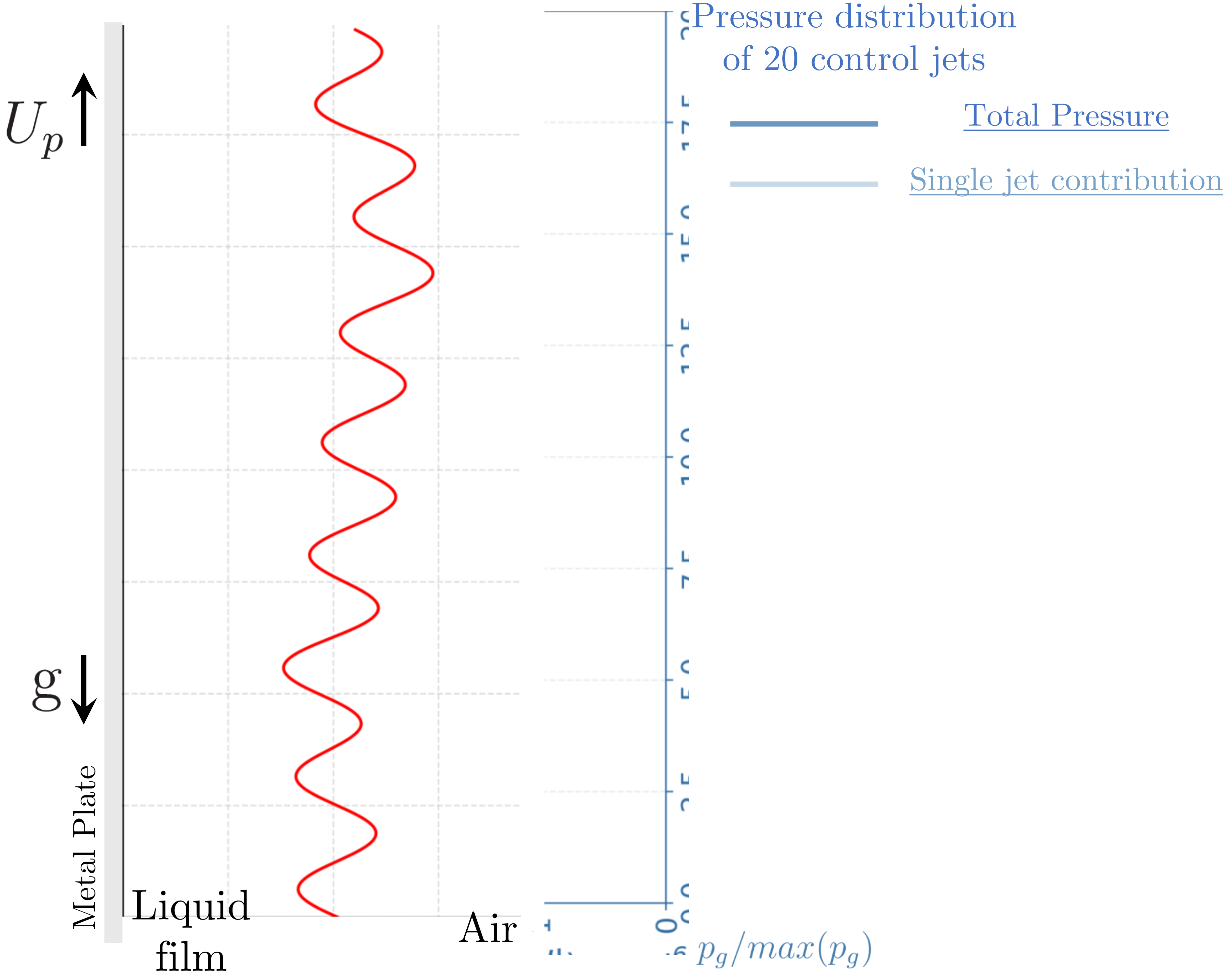
Complexity

Linear stability based control

The controller was tested in the stabilization of a highly unstable liquid film



Model predictive control



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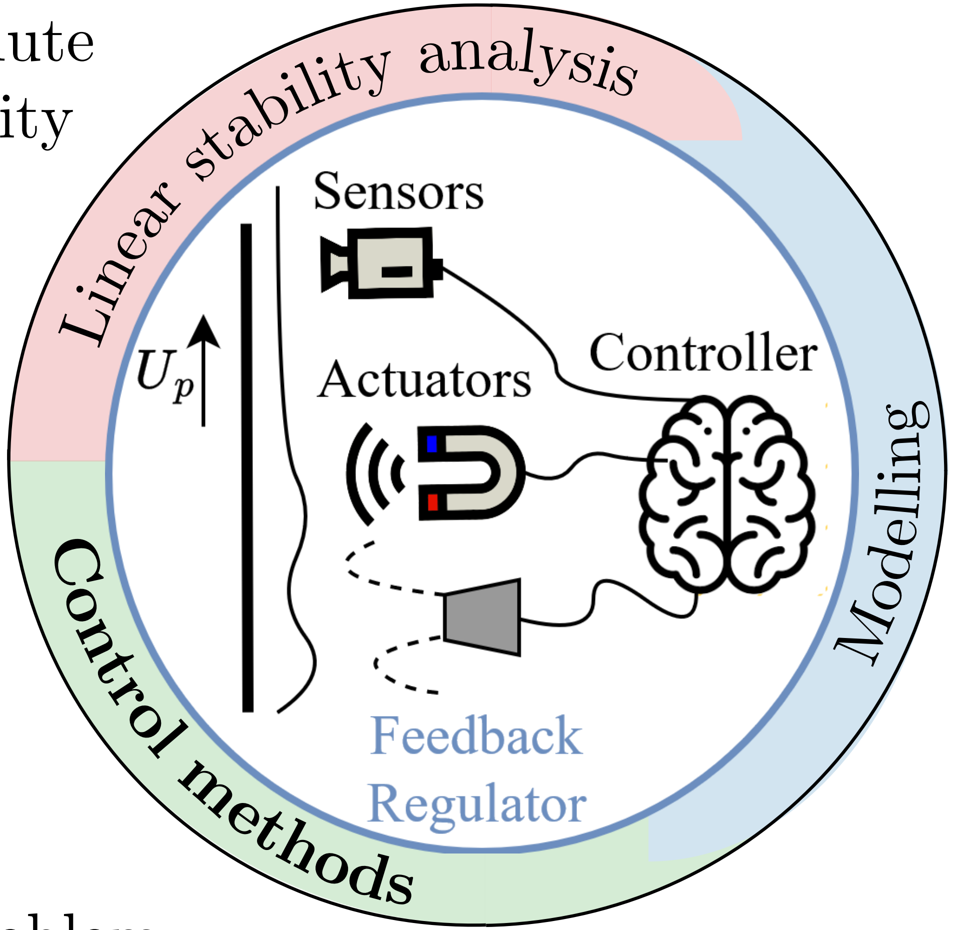

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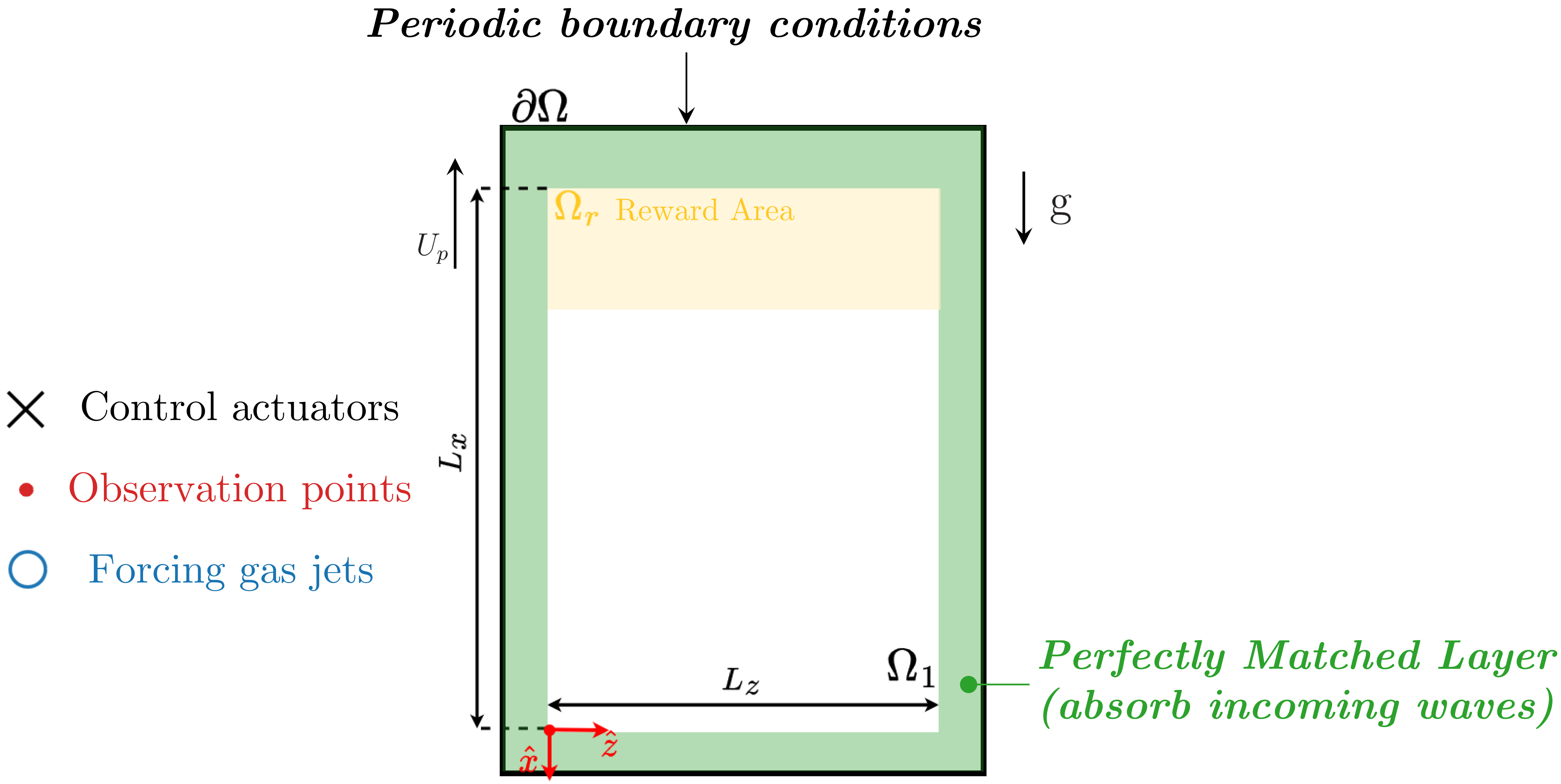
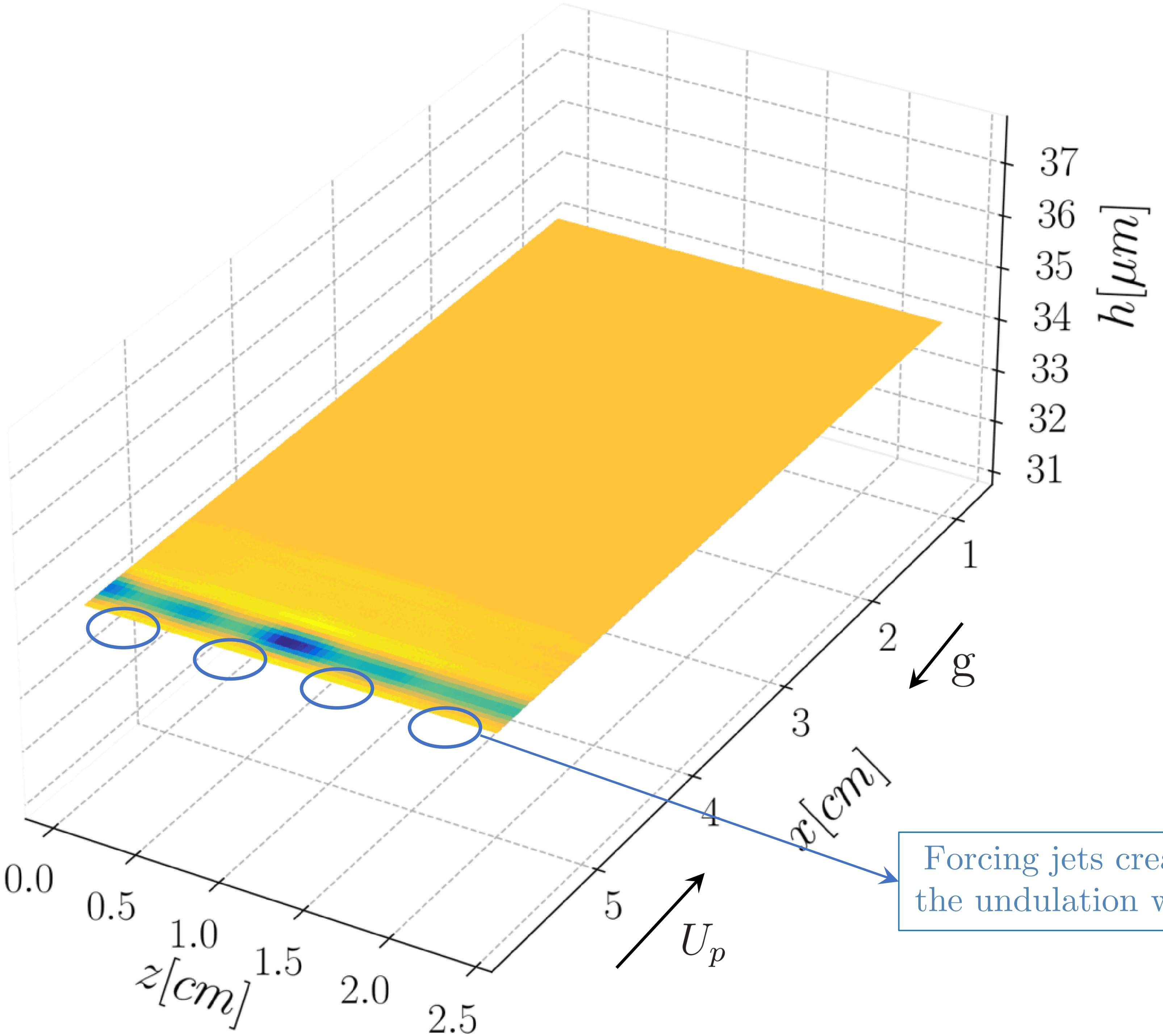
Undulation control with machine learning methods

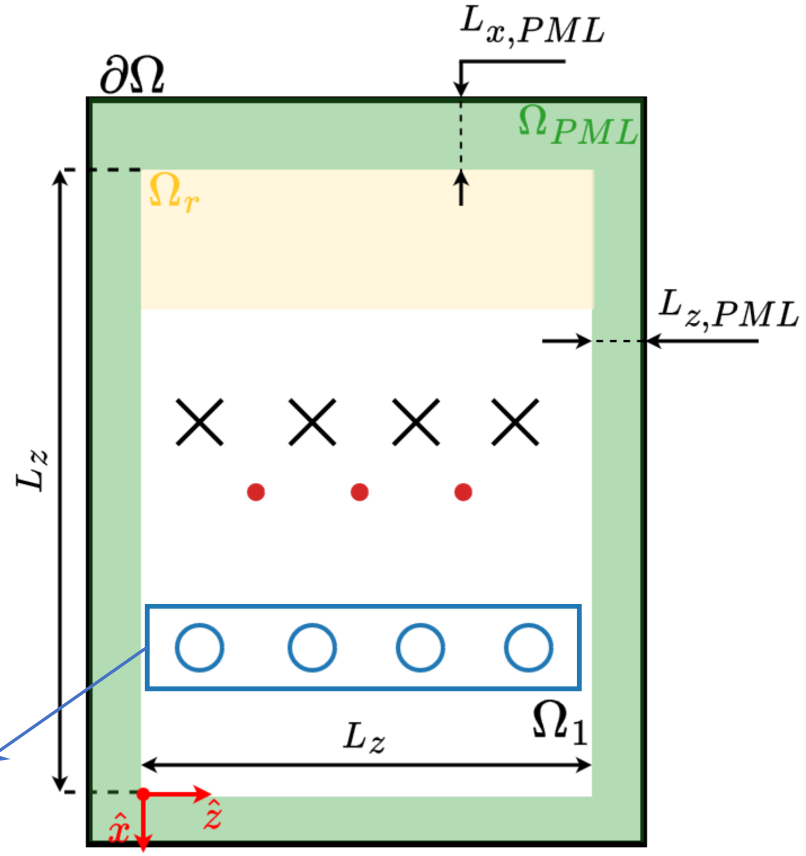
Fourier pseudo-spectral implementation



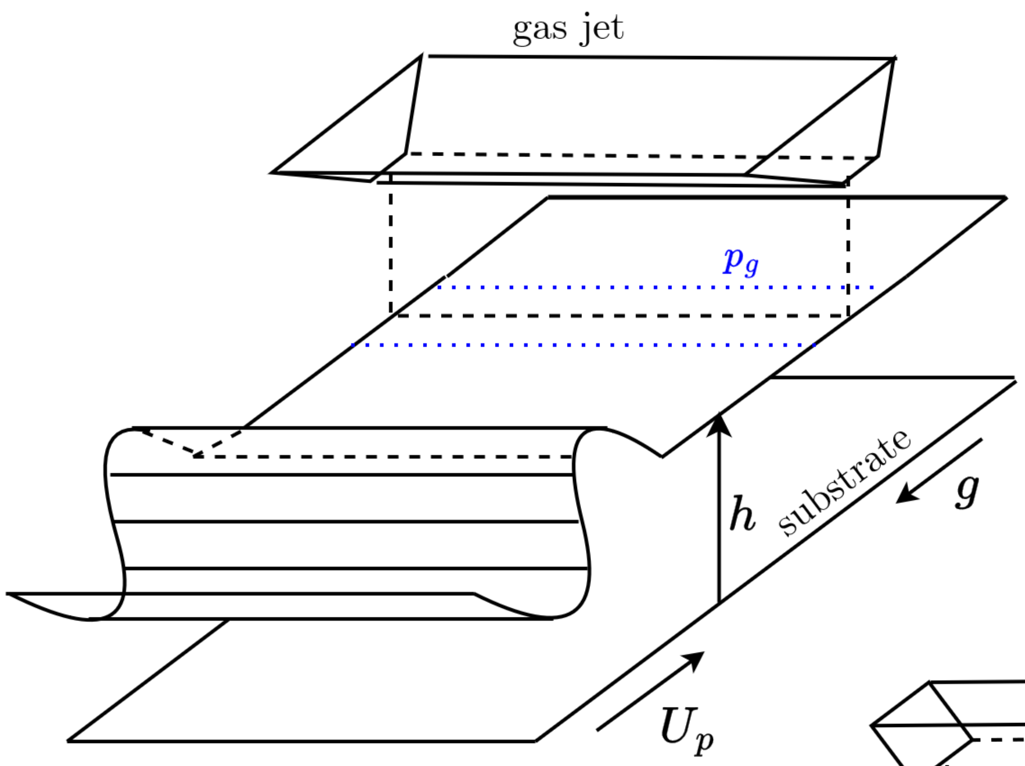
Undulation control with machine learning methods

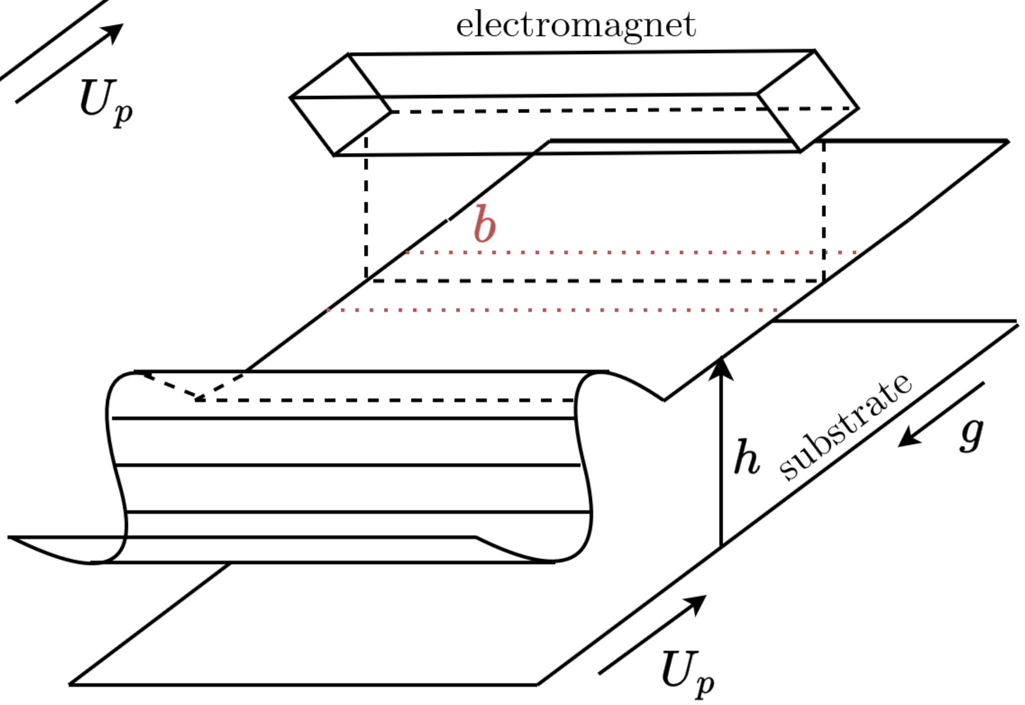


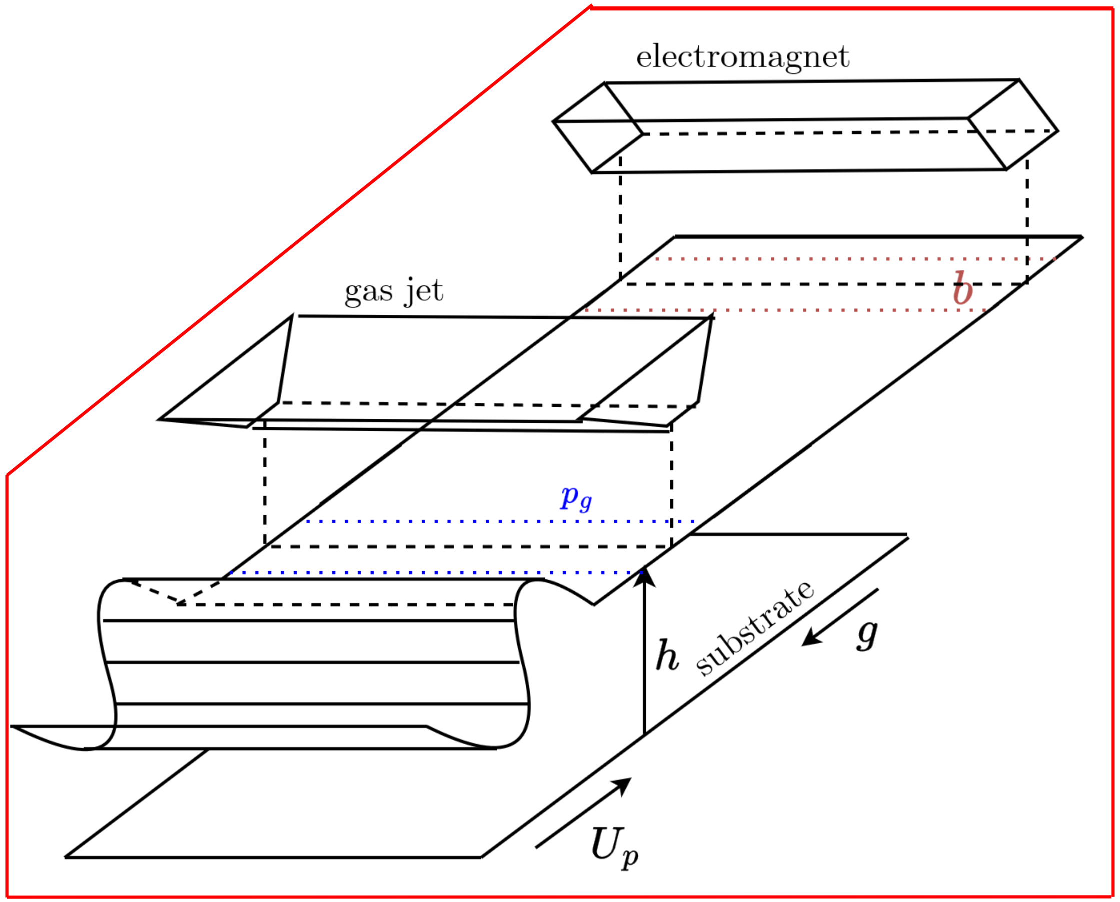
Forcing jets creates the undulation waves



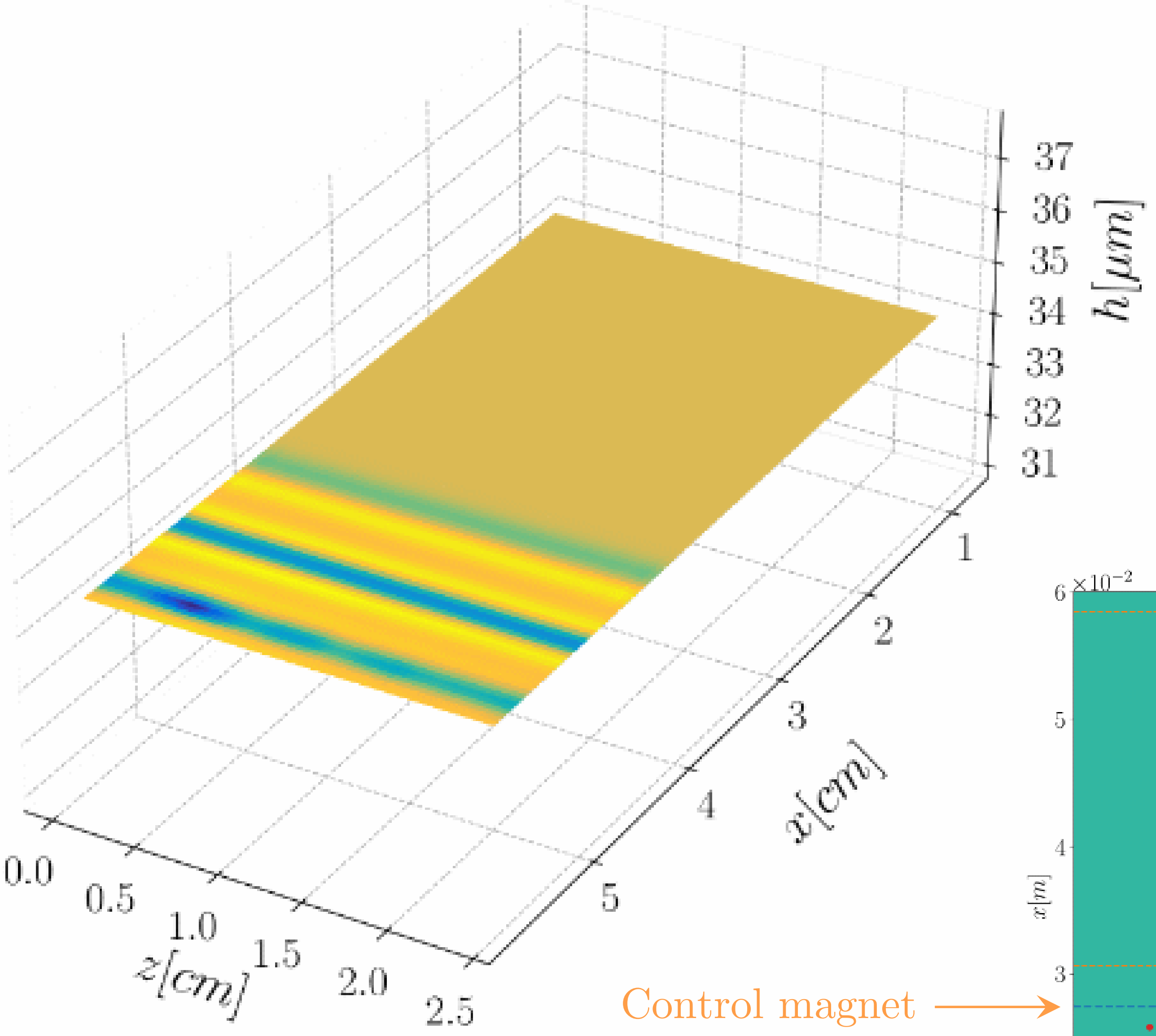
Undulation control with machine learning methods

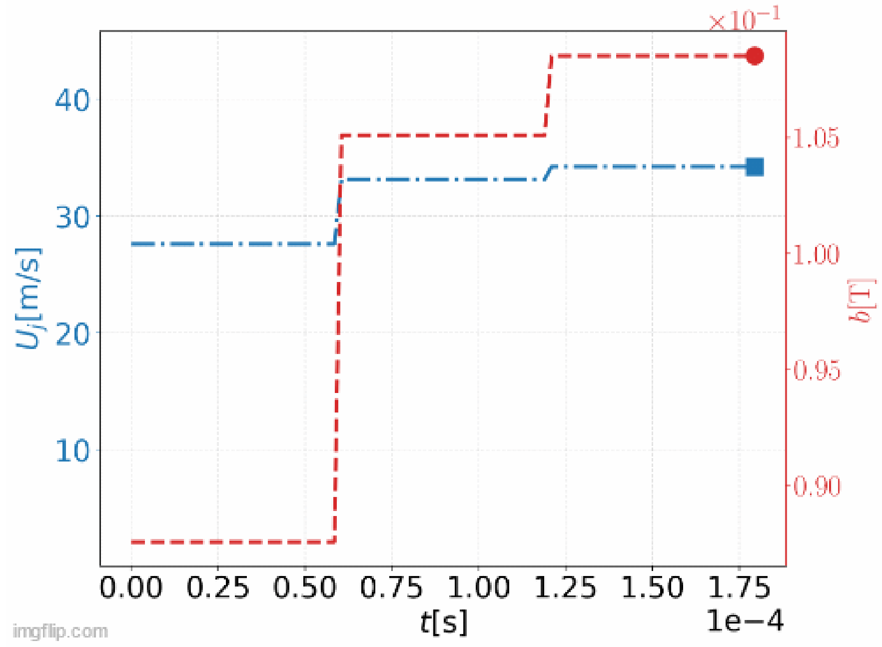






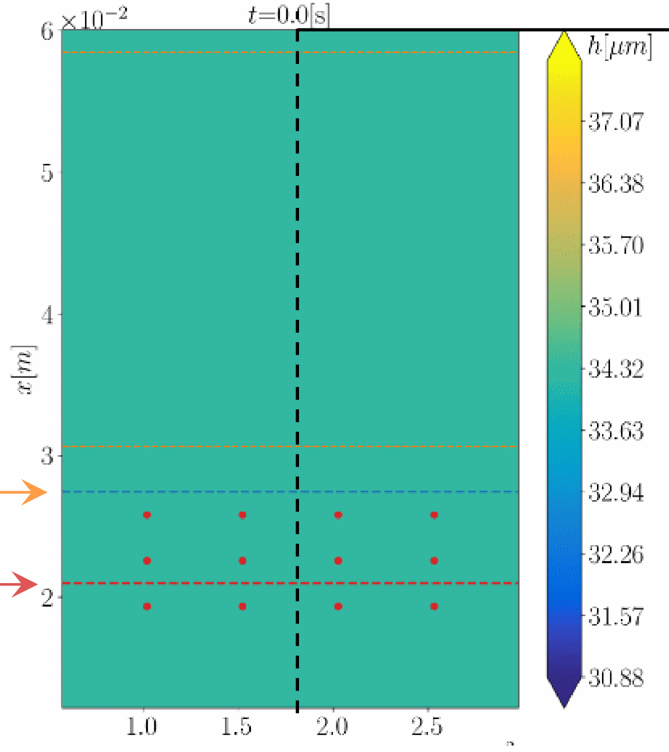
Undulation control with zinc

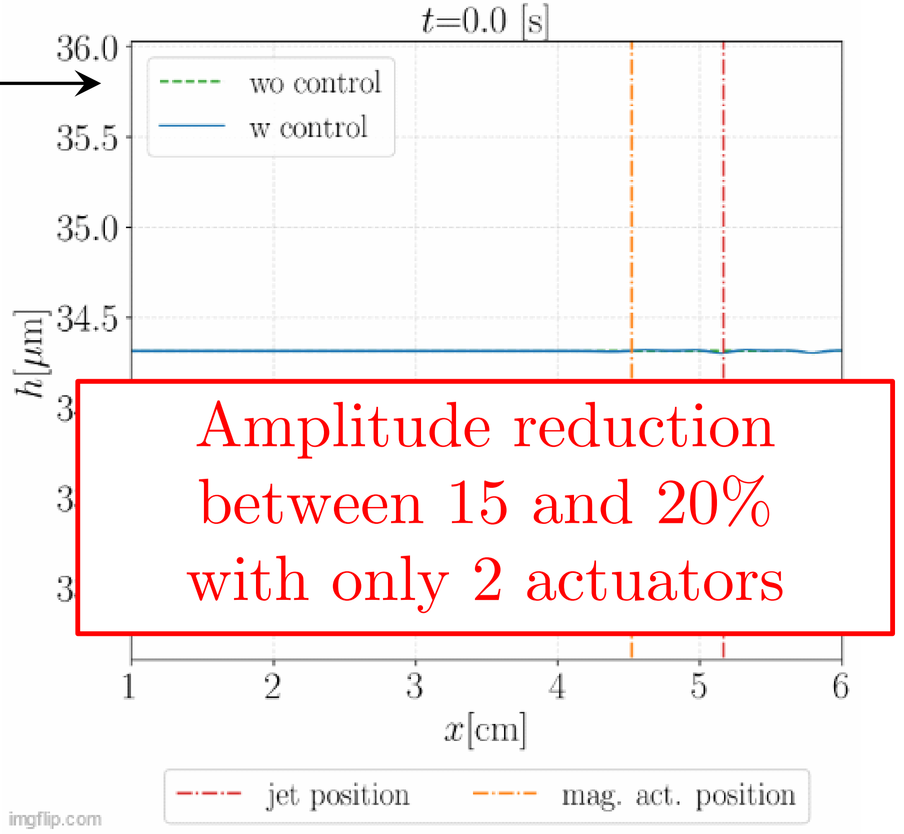




Control magnet

Control jet



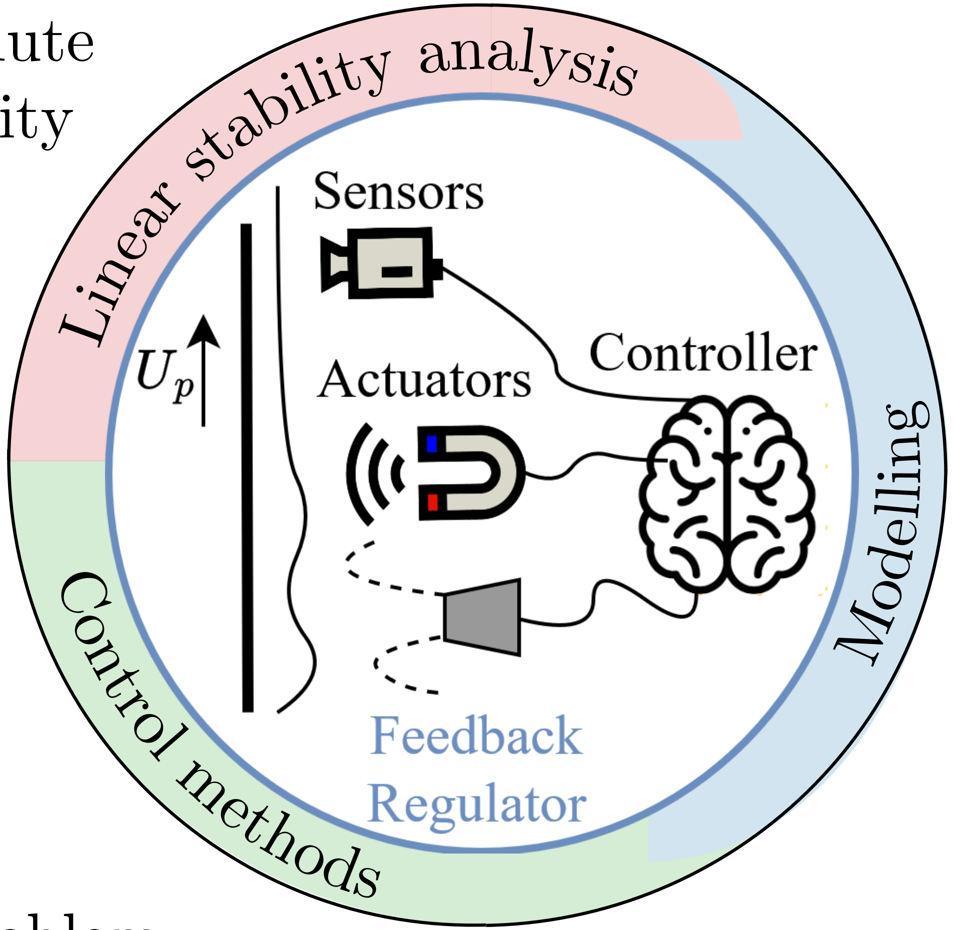


Amplitude reduction between 15 and 20% with only 2 actuators

Contents

Linear stability analysis

Computation of the threshold between absolute and convective instability



Derive simplified model

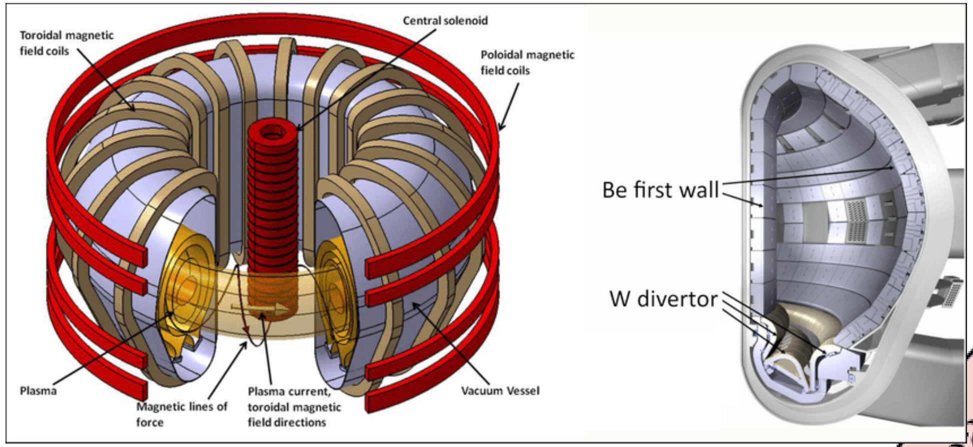
Derivation liquid film reduced order model with actuators modelling

Control methods

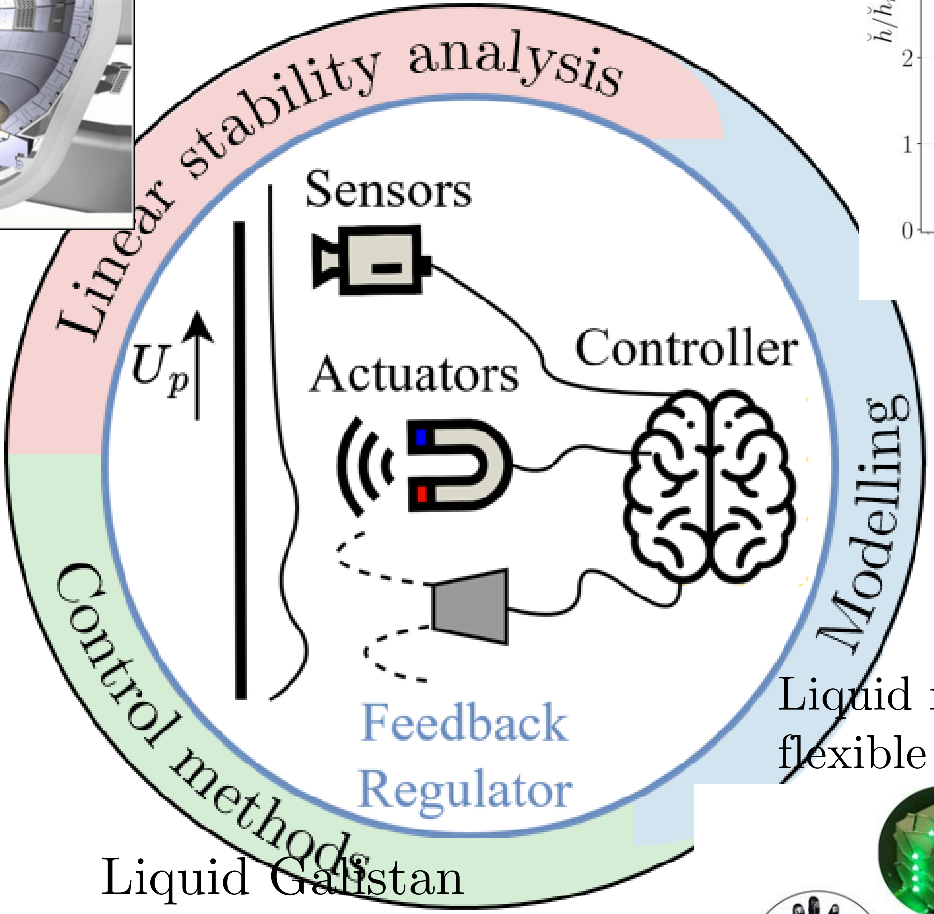
- ❑ Definition optimal control problem
- ❑ Small-amplitude control via linear stability methods
- ❑ Large-amplitude control via machine learning methods

Prospects

Modelling metal liquid film in tokamak fusion reactors

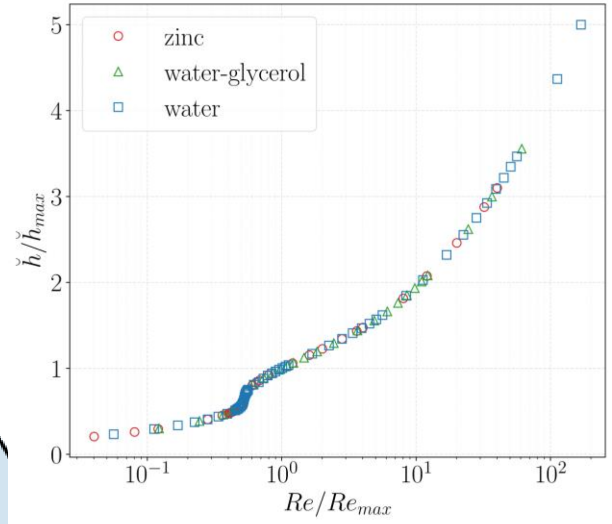


Active MagnEtic control of LIquid mEtal (AMELIE) facility

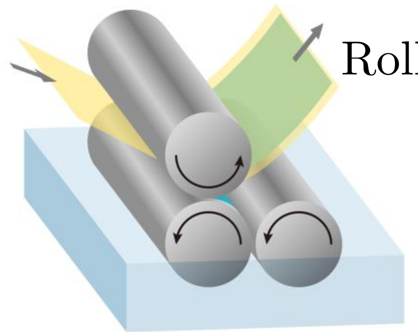


Liquid Galinstan

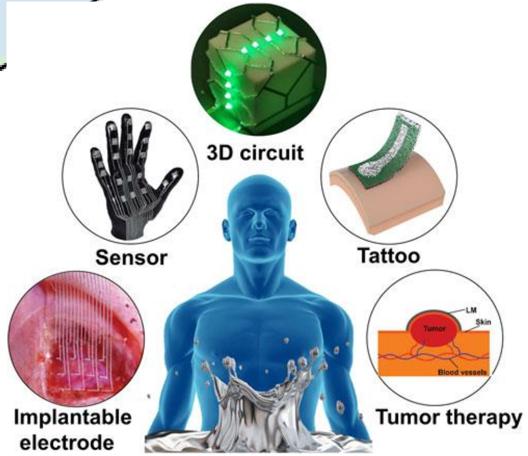
Generalization of the absolute instability window



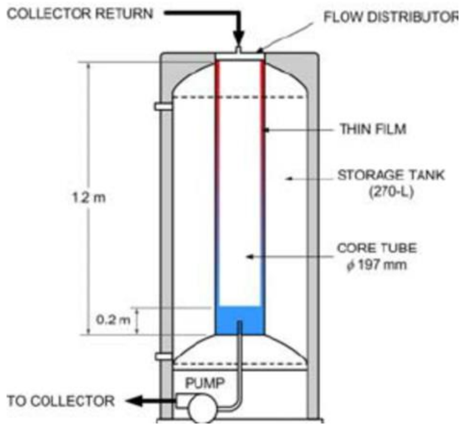
Roll-coating



Liquid metal for flexible electronics



Falling film heater exchanger



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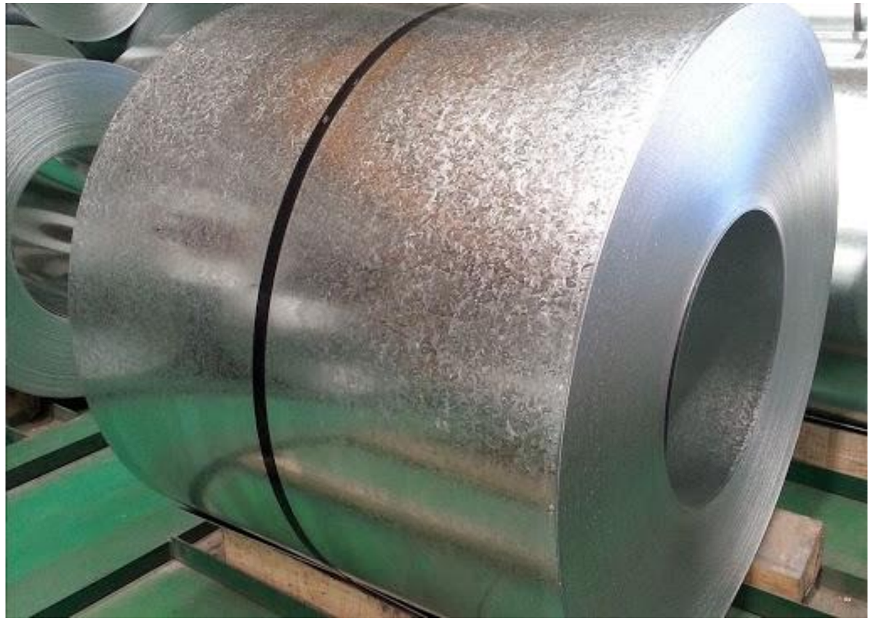


Thank you for your kind attention.

The larger the island of knowledge, the longer the shoreline of wonder

Credit: Oleg Riabcuk