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Exploiting locality and translational invariance to design effective Deep Reinforcement Learning control of the 1-dimensional unstable falling liquid film

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Instabilities arise in a number of flow configurations. One such manifestation is the development of interfacial waves in multiphase flows, such as those observed in the falling liquid film problem. Controlling the development of such instabilities is a problem of both academic and industrial interest. However, this has proven challenging in most cases due to the strong nonlinearity and high dimensionality of the underlying equations. In the present work, we successfully apply Deep Reinforcement Learning (DRL) for the control of the one-dimensional (1D) depth-integrated falling liquid film. In addition, we introduce for the first time translational invariance in the architecture of the DRL agent, and we exploit locality of the control problem to define a dense reward function. This allows to both speed up learning considerably, and to easily control an arbitrary large number of jets and overcome the curse of dimensionality on the control output size that would take place using a naive approach. This illustrates the importance of the architecture of the agent for successful DRL control, and we believe this will be an important element in the effective application of DRL to large two-dimensional (2D) or three-dimensional (3D) systems featuring translational, axisymmetric or other invariance.

I. INTRODUCTION

Falling liquid films are a common phenomenon both in industry and nature¹⁻⁴. Such flows are highly complex due to their nonlinearity, and the presence of an interface between the liquid and gas phases. In addition, there are many instabilities taking place in such flows as highlighted by the previous references. These are both a challenge and an attraction for engineers and scientists. Progressing towards effective strategies for the control of instabilities in falling liquid films, is therefore a relevant and interesting problem. Some work has been performed in the case of falling liquid flows⁵⁻⁷, but the design of general, robust control methods that can be adapted to specific applications in a flexible way without user expertise is still a relevant problem. Finding such general control laws is made complex due to the combination of strong non-linearity, high dimensionality, and time-dependence of those systems.

However, in recent years, methods based on data-driven approaches inspired by recent results from the Machine Learning community have proven increasingly successful. Those include several classes of methods, such as Genetic Programming (GP)^{8,9}, and Deep Reinforcement Learning (DRL)^{10,11}. These methods are now being applied to Fluid Mechanics, with a series of recent successes that include, for example,

controlling complex wake dynamics in two-dimensional (2D) simulations^{12,13}, controlling chaotic model Partial Differential Equations (PDE) systems^{14,15}, and a number of drag and vortex shedding control strategies¹⁶⁻¹⁸. However, one must be able to scale up those methods, both in terms of number of simulations and number of control outputs, in order to envision control of realistic situations. While the first scaling problem has recently been tackled and proven to work well¹³, demonstrating the ability of such methods to handle well a large number of outputs without hitting the curse of dimensionality remains a critical open problem.

In the present work, we consider the 1D falling liquid film problem and its optimal control through a DRL approach using small localized actuators. This problem is well suited for exploring optimal control of systems with many actuators, as it is both strongly nonlinear, featuring the development of large unstable interfacial waves, as well as inexpensive and quick to solve. Therefore, it is an excellent model problem to explore the potential of DRL applied to systems with many control signals, as it allows fast prototyping, training, and assessment of different methodologies. Our contribution in this article is double: first, we show that this system can be very efficiently controlled using DRL. Second, we discuss different variations around how DRL can be applied in practice to such a problem with a potentially large control space dimensionality. There, we show that different approaches are possible to take advantage of the invariance by translation of the equations describing the system, and that the choice of the method used has a large impact on the quality of the control strategy obtained as well as on the speed of learning. In addition, we observe that the locality (both spatial and temporal) of the system allows to define a dense reward function, which provides

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a fine-grained training signal and there also allows both better and faster training.

The organization of this manuscript is as follows. First, we present the methodology used for both the 1D falling liquid film simulation, and the DRL methodology including the different strategies to effectively implement multiple-output control. Then, we present the results obtained controlling the system, and we compare the efficiency of these different strategies. Finally, we discuss the applicability of our findings to different control problems, both within Fluid Mechanics and at large.

II. METHODOLOGY

A. Falling liquid film simulation

In this work, we consider a liquid film that flows down an inclined plane, as illustrated in Fig. 1. The x coordinate is chosen along the streamwise direction, i.e. following the inclined plane. The formulation of the problem and the numerical scheme implemented to solve it are similar to that in¹⁹. More specifically, the liquid chosen is an incompressible, Newtonian fluid with constant properties. Those are its surface tension σ , viscosity μ , and density ρ . As a model for the falling film, we use the dimensionless, depth-integrated system²⁰:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0, \quad (1)$$

$$\frac{\partial q}{\partial t} + \frac{6}{5} \frac{\partial}{\partial x} \left(\frac{q^2}{h} \right) = \frac{1}{5\delta} \left(h \frac{\partial^3 h}{\partial x^3} + h - \frac{q}{h^2} \right), \quad (2)$$

where h is the non-dimensional local film thickness, q the non-dimensional local flow rate, $\delta = (\rho H_c^{11} g^4 / \sigma)^{1/3} / 45 v^2$, with H_c the film thickness without waves, $g = 9.81 \text{ m/s}^2$ the acceleration of gravity, and $v = \mu / \rho$. In practise, we will use $\delta = 0.1$ in the following, similar to¹⁹. This formulation resorts on a semiparabolic velocity profile and satisfies the no-slip boundary condition at the wall, as well as the zero stress boundary condition at the gas-liquid interface. The boundary conditions at the inlet and outlet are:

$$h = 1, q = 1 \text{ at } x = 0, \quad (3)$$

$$\frac{\partial h}{\partial x} = 0, \frac{\partial q}{\partial x} = 0 \text{ at } x = L, \quad (4)$$

where $L = 300$ is the length of the domain. This value of L is long enough for the development of different types of waves to take place in the case without control. The initial condition in time is obtained by simulating a uniform liquid film of thickness and mass flow rate unity ($h = 1$ and $q = 1$) until the waves are fully developed.

Similarly to¹⁹, the equations (1) and (2) are discretized using the finite difference method. The transient terms are integrated using the third order Runge-Kutta method (RK-3)²¹. Convective terms are discretized using the Total Variation Diminishing (TVD) scheme²². The grid size is $\Delta x = 0.1$ and the time step is $\Delta t = 0.001$. In addition, we use a similar technique to¹⁹ and add noise on the h variable at the inlet of the domain ($x = 0$) to trigger the appearance of waves. This is done by replacing (3) with:

$$h(t) = 1 + r(t) \text{ at } x = 0, \quad (5)$$

where $r(t)$ is random, uniformly distributed in $[-5 \times 10^{-4}; 5 \times 10^{-4}]$. In their work,¹⁹ have studied the influence of the white noise input and found that its amplitude and distribution does not have a significant effect on the overall behavior of the waves due to the amplifier nature of the flow at specific frequencies.

In addition, we introduce forcing terms in the equations at several user-tunable positions. In the following, we will refer to these individual forcings as ‘jets’. The strength of the jets is set by the DRL algorithm (see next paragraph) when applying control on the system. For simplicity, the forcing is performed on the mass flow rate q , by adding the following parabolic profile suction/blowing forcing δq_i at each time step in the numerical solver:

$$\delta q_i(x, t) = \begin{cases} A_i(t) \cdot (x - l_i)(r_i - x) & \text{if } l_i < x < r_i, \\ 0 & \text{otherwise,} \end{cases} \quad (6)$$

where i (integer between 1 and N , the total number of jets) is the index of the jet currently considered, which is located between x -positions $l_i < x < r_i$, and $A_i(t)$ is the strength of the corresponding jet at time t . As visible in (6), this corresponds to using a small jet following a parabolic profile, going to zero on the right and left edges of each of the forcing areas, with the centers being located at positions $c_i = (l_i + r_i)/2$ and the jets having half-widths $w_i = (r_i - l_i)/2$. In the following, the maximum strength of the jets, as well as their widths and locations, will be used as physical meta-parameters of the flow configuration. Note that both injection of mass (positive forcing corresponding to an increase of the local mass flow rate, i.e. blowing) and removal of mass (negative forcing, corresponding to a reduction in the local mass flow rate, i.e. suction) are possible.

Those numerics are implemented in highly tuned C++ code for optimizing the speed of execution, and made available to the high-level Python DRL library (see next paragraph) through the use of C++/Boost Python bindings. All the implementation is made available as Open Source (see the Appendix A). Using our implementation, a simulation covering non-dimensional times $t = 0$ to $t = 200$ typically takes less than 30 seconds on a modern CPU using a single core. The problem is small enough that a large part of it can reside purely in CPU cache, which also greatly improves performance. Typical converged simulation results, with the inlet perturbation but without jet control, are illustrated in Fig. 2.

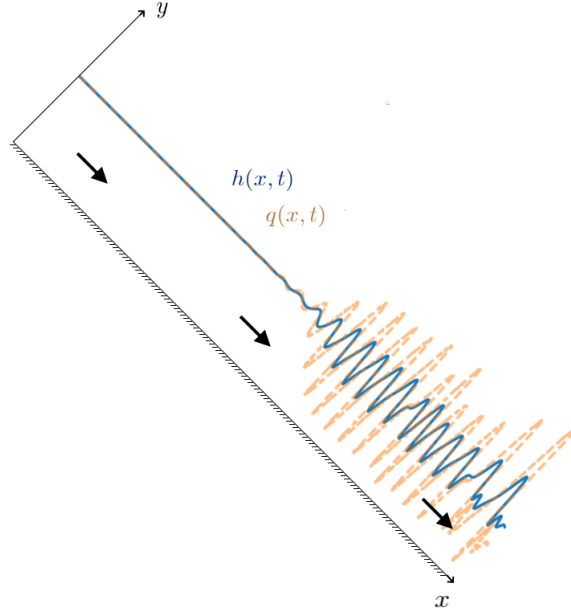


Figure 1. Schematic representation of the flow. $h(x,t)$ is the local transient film thickness, $q(x,t)$ is the local transient flow rate.

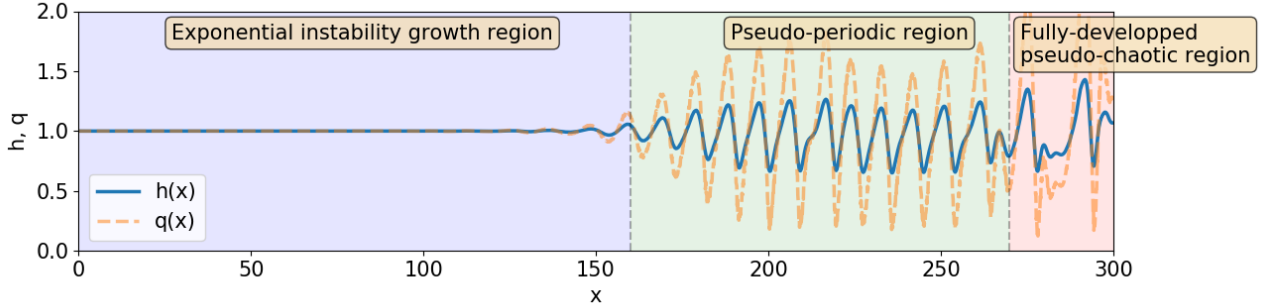


Figure 2. Illustration of a converged falling liquid film simulation performed with zero control but with inlet disturbances. Three areas are clearly visible: first, a region where the flow disturbances induced by the inlet boundary condition perturbations grow exponentially. Second, a region where the waves are pseudo periodic and get unstable. Third, a region where fully-developed pseudo-chaotic behavior of the waves is observed. This pseudo-chaotic domain is defined as the region where large amplitude solitary waves are observed, and there is no longer a pseudo-periodic pattern.

In order to provide the input (or state observation) and reward to the DRL agent, we use small regions in the neighborhood of each jet. The state is obtained by reading from the simulation both h and q and considering them as two different input channels. In all the following, unless stated otherwise, both h and q are sampled in an area $A_{obs,i} = [r_i - L_{obs}; r_i]$, where L_{obs} is the size of the observation area. Similarly, the reward is computed either locally on the right of each jet based on an area $A_{reward,i} = [l_i; l_i + L_{reward}]$, or globally on the union of these areas $\bigcup_{i=1}^N A_{reward,i}$. Typical values are $L_{obs} = 25$ and $L_{reward} = 10$ in the following.

The formula for the reward is:

$$R(A_{reward}, t) = 1 - \frac{\chi}{\sqrt{L_{reward}}} \cdot \|h - 1\|_2 \quad (7)$$

where A_{reward} is the domain where we compute our reward, it can either be $A_{reward,i}$ or $\bigcup_{i=1}^N A_{reward,i}$ depending on what method we use (see next section), L_{reward} is the total length of the domain, $\|\cdot\|_2$ is the L^2 -norm, and χ is a parameter chosen so that the reward calculated in the pseudo-periodic region of Fig. 2, without any control, is close to 0. Empirically, we use $\chi = 5.7$. Applying such reward renormalization is a common technique in DRL. The reward can therefore be expressed as an integral over the domain:

$$R(A_{reward}, t) = 1 - \chi \cdot \left(\frac{1}{L_{reward}} \cdot \int_{A_{reward}} (h(x, t) - 1)^2 dx \right)^{\frac{1}{2}} \quad (8)$$

while in our discretized simulation, the calculated reward becomes:

$$R(A_{reward}, t) = 1 - \chi \cdot \sqrt{\frac{\sum_{x \in A_{reward}} (h(x, t) - 1)^2}{\text{card}(A_{reward})}}, \quad (9)$$

where $\text{card}(A)$ is the number of elements in the finite discrete set A .

Using this reward, the network gets an incitation towards killing waves (or, more mathematically, the reward functions is increased when the wave fluctuations are reduced by the control), and a perfect reward is obtained when no waves at all are present ($h = 1$ uniformly on the whole reward domain), while any fluctuations in h get penalized.

L_{obs} and L_{reward} are to be chosen carefully. The reward being a single value, it is essential for it to encapsulate relevant information about how our action impacted the environment. We can suspect that a too large reward space makes the reward less relevant about the effect of our actuation, while a too small reward space may have difficulties capturing the effect of the control behind of the jet.

In addition to this definition of the state and actions, a renormalization is applied before the data are fed to the agent. The aim of this renormalization is to make sure that the resting value of our data is 0 instead of 1, and that it does not exceed a certain threshold in absolute value (typically, the maximum output to the Artificial Neural Network (ANN) should be approximately between 1 and 10), which is a necessary condition for the DRL control to perform well. This renormalization is performed by defining the state s effectively given to the ANN as:

$$s = h_{\text{norm}}(A_{obs}, t) \cup q_{\text{norm}}(A_{obs}, t), \quad (10)$$

where

$$h_{\text{norm}}(x, t) = \text{clip}(\gamma_h \cdot [h(x, t) - 1], -S_{max}, S_{max}), \quad (11)$$

and

$$q_{\text{norm}}(x, t) = \text{clip}(\gamma_q \cdot [q(x, t) - 1], -S_{max}, S_{max}), \quad (12)$$

where $\gamma_h \approx 1.0$ and $\gamma_q \approx 1.0$ are normalization parameters, and $S_{max} \approx 5.0$ is the maximum value we are ready to feed our ANN. The *clip* function is a saturation function defined as $\text{clip}(x, \alpha, \beta) = \max(\min(x, \beta), \alpha)$. Similarly the action effectively applied on the simulation is:

$$A_i(t) = \frac{M \cdot b_i}{w_i^2} \quad (13)$$

where b_i is the action effectively produced by the ANN, which is in the range $[-1, 1]$, and M is a hyperparameter defining the maximum strength of the jets, typically $M = 5$. w_i is the half-width of the jets, as previously defined.

A typical illustration of the positioning of jets, as well as the associated state and reward areas, is presented in Fig. 3. In Fig. 3, as in similar figures in the following of the paper, we present snapshots of the state of the system (q, h) together with snapshots of the outputs $b_i, i = 1..N$, provided by the ANN. Those outputs are between 1 and -1, and displayed shifted by an offset of +1 relatively to the vertical axis for clarity. Observe that the control effectively applied is obtained by applying scaling proportional to M , as indicated in Eqn. (13).

In all the following, trainings are always started from a well-converged state of the system, with fully developed waves being present. This corresponds to an initial configuration of the system similar to what is visible in Fig. 2. The maximum jet intensity is large enough that bad choices of the instantaneous strength of the jets can create numerical blowup of the simulation. In this case, the simulation is terminated, a negative reward of -500 is provided to the ANN to ‘punish’ it, i.e. from a mathematical point of view reduce the probability of following a trajectory in the phase space that leads to numerical breakup, and the simulation is resetted to the initial converged state before training is resumed. Of course, such blowup is strictly a consequence of the numerics used, and a real-world experiment would not need to worry about such problems.

B. DRL algorithm and strategies for multiple controls

Machine Learning has become very attractive in the recent years following several high-impact results of deep ANNs across a variety of fields. Results include, for example, attaining super-human performance at image labeling²³, winning against human professionals at the game of Go²⁴, or achieving control of complex robots²⁵. Those successes have demonstrated the ability of ANNs to solve a wide range of strongly nonlinear, high dimensionality problems that were resisting investigation using traditional methods. Following these developments, ANNs are now being applied to other fields of science including Fluid Dynamics. Recent developments in this domain include, to name but a few, analyzing laboratory data^{26,27}, formulation of reduced order models²⁸, active flow control¹², the control of stochastic systems from only partial observations¹⁵, shape optimization²⁹, and closure models for LES and RANS simulations³⁰.

More specifically, several of these applications rely on the use of Deep Reinforcement Learning (DRL). This approach consists in finding, through trial and error, the solution to a complex problem for which no theoretical or algorithmic solution is known otherwise. DRL takes advantage of the universal approximator³¹ property of ANNs to optimize interaction with the system it should control through three channels: an observation of the state of the system, an action taken to control the system, and a reward function giving feedback on its current performance. This framework is adapted to cases

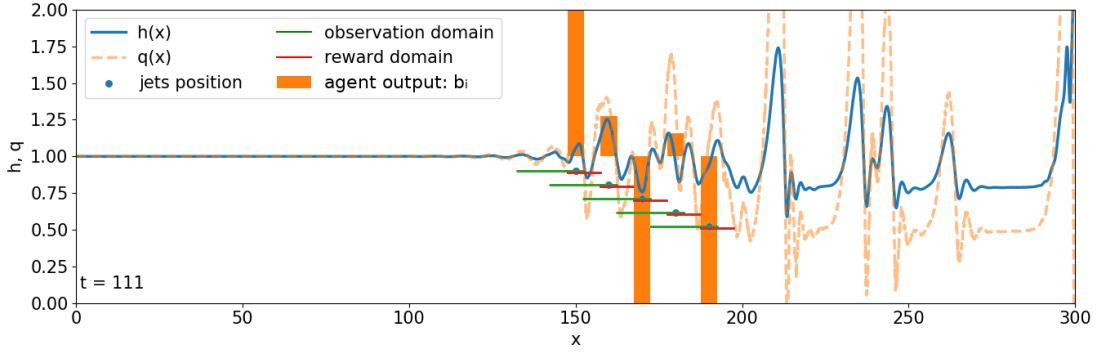


Figure 3. Illustration of the observation space, reward space, and jet position during training, here with 5 jets. The forcing by the agent is illustrated by plotting directly the output of the Artificial Neural Network (ANN), which is between -1 and 1 and used to compute the control following Eqn. (13). For clarity of the figure, the ANN output b_i is shifted by an offset of +1 relatively to the vertical axis used for h and q .

Method	states	network	reward
M1: concatenated jets as a single environment	concatenated and flattened	MLP	one global reward
M2: convolutional network	concatenated	CNN - equivalent to a MLP on each row of input	one global reward
M3: each jet as a separate environment	kept separate	MLP, shared between jets	N rewards

Table I. Comparison of the 3 different methods for the design of the DRL agent and its interaction with the thin liquid film simulation.

MLP = Multi Layer Perceptron, an ANN where every layer is fully connected.

CNN = Convolutional Neural Network.

where only partial, noisy observations of a stochastic system are available. Therefore, choosing a good reward function is critical as this is what guides the ANN towards solving a specific problem. In the following, we will use a specific DRL algorithm known as the Proximal Policy Optimization (PPO³²). This algorithm belongs to a wider class of algorithms called the Policy Gradient Methods³³, and is often regarded as the state-of-the-art algorithm to be used for control problems where a continuous action space is present.

As the PPO algorithm has been described in details by its initial authors³², and has been discussed also in the Fluid Mechanics literature at several occasions^{12,34}, we refer the reader curious of more details about the inner working of this algorithm to these references for further information, and in the following we only provide a high level overview of the algorithm.

The general idea behind the Policy Gradient method on which PPO is based consists in parametrizing the policy function $\pi_{\theta}(b|s)$ with an ANN having the set of weights θ . Therefore, given in input a state observation s , the ANN used to parametrize the policy π produces a set of moments that describe a distribution (possibly multidimensional) from which the individual actions b are sampled. Therefore, the policy function describes the probability, provided a state observation s , that the next action to be taken is b . Following this definition, one can find an expression for the estimation of the gradient of the actualized reward function relatively to the set of weights θ used in the ANN, following Monte Carlo

sampling of phase space trajectories under control by the policy π_{θ} . In the case of the PPO algorithm, several additional technical improvements are used. First, a critic network is in charge of estimating the actualized reward function. This is especially useful when stochastic, noisy reward functions are present. Second, a limit is set on the maximum update allowed to the policy at each training step. This allows to avoid overfitting the policy to randomly occurring ‘lucky’ events. Several high-quality implementations of the PPO algorithm are available open source from public software repositories, and in the following we will use one of these to provide us with a well-tested implementation (see Appendix A for further details).

Similarly to¹³, we will in the following use the word ‘action’ to describe the value provided by the ANN based on a state input, while ‘control’ describes the value effectively used in the simulation. This distinction is especially important as the choice of the duration of an action, which may extend over several control time steps, is critical for obtaining good learning (see Figs. 2 and 6 of¹³). In the following, we use linear interpolation to determine the value of the control at each time step in-between of action updates. Since the frequency of action update is set to be about 10 time higher than the typical frequency of the evolution of the system, this linear interpolation does not limit in practise the effective control quality.

In the present work, the system to control is characterized by the high dimensionality of its output. More specifically, it is natural to use several jets (up to 20 jets in our simulations,

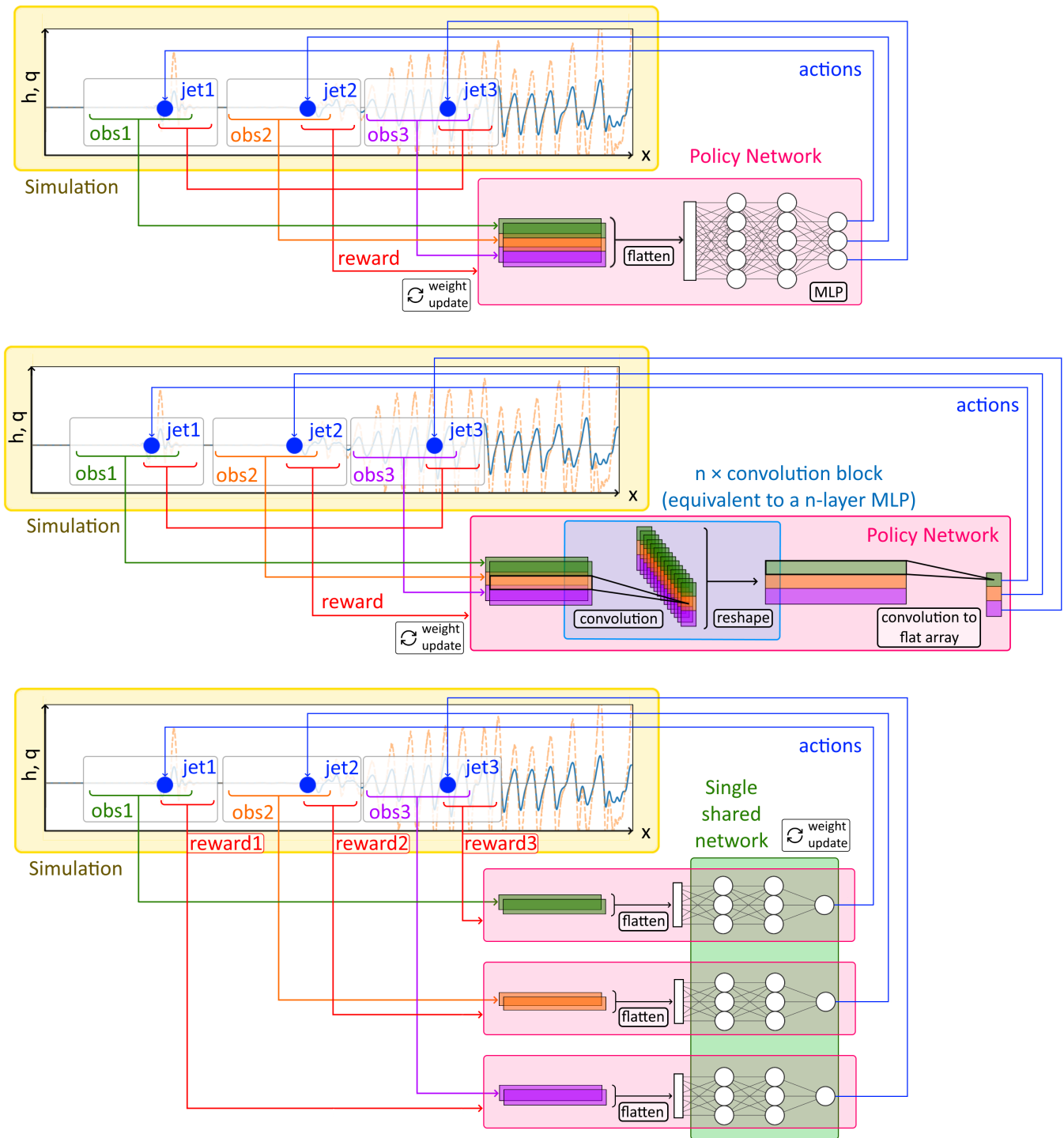


Figure 4. Illustration of the 3 different methods for control of a system with translational invariance and locality. From top to bottom: M1, M2, and M3. M1 is the naive implementation of the DRL framework. M2 takes advantage of translation invariance of the system to re-use the network coefficients for the control of an arbitrary number of jets. M3 both exploits the translation invariance, and the locality of the system by using a dense reward signal. Details are available in Table I.

but a larger domain could feature even more jets). Therefore, using the PPO algorithm effectively becomes challenging. Indeed, the naive approach which consists in using a single network with several outputs does not scale well to an increasing number of jets, as the combined combinatorial size of the output domain for N jets grows as a power of N , and therefore the curse of dimensionality is a threat to finding effective control strategies. However, one can observe that the system to control features a translation invariance along the x -axis. Therefore, one should be able to take advantage of this property to optimize learning, in the same way that Convolutional Neural Networks (CNNs) take advantage of translational invariance of 2D images across the x - and y -directions to share convolutional kernels across the whole image and therefore reduce the number of weights needed and improve learning performance^{35,36}.

Following this observation, we design three different methods for performing control of the system:

- First, a ‘naive’ method in which the input regions from all jets are concatenated and flattened before being provided to the network, and the dimensionality of the output is equal to the number of jets. In this case, the reward is evaluated over the whole combined reward region. This method will be referred to as the Method 1 (‘M1’) in the following.
- Second, we apply control following a method that is a direct analogy of the CNN used in image analysis. In this case, the inputs from the regions around different jets are concatenated without flattening, and fed into a purely convolutional network. This allows to apply the exact same weights, and therefore the same policy, on all inputs to generate the individual jet values. There also, only one global reward is available, similar to M1. Due to purely technical implementations difficulties and the exact architecture of the DRL framework, this is however not implemented as a CNN in practise, but as a formally equivalent cloned network. This method will be referred to as the Method 2 (‘M2’).
- Third, we apply control by splitting the simulation into several DRL environments, i.e we consider each triplet [jet observation domain, jet value, jet reward domain] as a separate environment. A unique agent is sampling trajectories from these environments as if they were clones of the same environment, taking advantage of the translational invariance of the system. Similarly to M2, the same policy is applied on all the jets. However, in contrast to both M1 and M2, this method effectively ‘densifies’ the reward: instead of performing learning based on 1 single global reward, many individual rewards are obtained (one for each jet), providing more granularity in the learning process. This will be referred to as the method 3 (‘M3’).

Those 3 different methods for controlling several jets are summarized in table I, and presented in Fig. 4. Note that in all cases the architecture of the network is kept equivalent

(except for the output layer in case M1 vs. M2 and M3), and only the translational invariance and reward densification differ between those methods.

As visible in Table I and Fig. 4, the methods M1, M2, and M3 reflect increasingly the structure of the underlying system to control, and therefore we expect in terms of learning speed and performance that $M1 < M2 < M3$, where the order relation describes ‘how good’ and ‘how fast’ the policies and trainings are. This hypothesis is confirmed experimentally in the next section.

III. RESULTS

A. Physical metaparameters and successful learning

Using the methodology presented in the previous sections, together with a consistent set of metaparameters, satisfactory learning is obtained. We find that tuning the metaparameters of the PPO algorithms is not crucial to obtain learning, and in all the following we will use the default PPO metaparameters recommended by the package used (this include for example the decay constant γ used for calculating the actualized reward, the batch size, the learning rates, and several other parameters specific of PPO such as the likelihood ratio clipping, and the entropy regularization). In addition, a simple network composed of three hidden layers containing, going deeper in the network, 128, 64, and 64 neurons (corresponding to an equal number of convolutional kernels of individual size 1×1 in the case using a CNN) is used. This is in good agreement with other studies, that have generally observed that the PPO algorithm is quite robust to the exact value of its metaparameters. By contrast, the ‘physical’ metaparameters of the simulation setup are important. In the following, the parameters used (unless stated otherwise) correspond to a duration of action $\Delta t_{action} = 0.05$, i.e. 50 steps of the numerical solver are performed between each action update, which corresponds to a typical propagation of the waves by a distance of the order of $\Delta x = 0.2$. This is typically 10 percents of the half-width of a jet, $w_i = 2$, which itself is typically around 10 percent of the wavelength of big fully developed waves $\lambda = 20$. The duration of an episode, which dictates the number of actions performed between learnings, is set to $\Delta t_{episode} = 20$. This allows to sample trajectories in the phase space that are long enough that the effect of policy updates can be observed. Finally, the reference maximum strength of a jet is set to be $M = 5$. While the exact numerical relation between these quantities is not critical, their relative orders of magnitudes must be respected to be able to control the system. For example, using too wide jets (larger than the typical size of the waves) obviously does not allow to perform control. Similarly, too small jets are not enough to significantly alter the propagating waves. The choice of Δt is also critical to allow the discovery of a valid policy through trial and error, similarly to what has been discussed in for example¹³ and is illustrated later in this section.

In this section, we only present results obtained with the training method M3, which is the best performing one (see discussion in section III.B). Successful learning, correspond-

ing to the default parameters, is illustrated in Fig. 5. There, the method M3 is used to train 10 jets to perform active control of the incoming waves. As visible in Fig. 5, the ANN can effectively kill waves on the control region.

As visible on Fig. 5, the placement of the jets in the physical domain is there such that, upon control of the system, the waves never get the possibility to fully develop into a pseudo-chaotic regime. This means that, upon successful control, the problem becomes even simpler for future actuation as only small waves are present, which are less nonlinear than large pseudo-chaotic waves. To test the ability of the system to learn and control also large, pseudo-chaotic waves, we run trainings with a strong perturbation jet added at $x = 20$. The perturbation jet is sampled from a uniform distribution on the range $[-5; 5]$. Typical results are visible in Fig. 6. One can see that, in this case, satisfactory control can also be obtained (Fig. 6, top). However, this holds only if the jets are made strong enough (no satisfactory control is obtained for Fig. 6 bottom), while with the configuration of Fig. 5 even weak jets were enough to exert effective control (see next paragraph).

The effect of more metaparameter experimentations are presented in Fig. 7. There, we present learning curves based on evaluation from the reward function Eqn. (7), even in the case when another reward function is used during training. As visible in Fig. 7, the exact size of the observation domain for each jet is not critical for the learning. This is consistent with previous reports that DRL is usually good at filtering out unnecessary information. Similarly, in the default configuration, the maximum strength of the jets is not too critical. This has already been discussed, and corresponds to the fact that upon discovery of a successful strategy by the ANN, waves can be killed before they fully develop - therefore, requiring only weak jets for successful control. However, as was illustrated in Fig. 6, this is not the case if the incoming waves are strong enough. By contrast, the choice of the reward domain, reward function, and action update frequency are much more important to obtain successful and efficient training, as illustrated by the second plot of Fig. 7. This is, there also, consistent with previous reports, such as^{12,13}, and can be easily understood in each of the cases presented. Indeed, using a too large reward domain means that, until the waves are successfully killed on a large region, a lot of the reward signal is uncorrelated with the individual action of each jet - as it incorporates many waves from far downstream each individual jet. Similarly, using the standard deviation of the water height $\text{std}(h)$, instead of the deviation to the reference water $\sum_{x \in A_{\text{reward}}} [h(x,t) - 1]^2$ in Eqn. (7), means that the agent may try to reduce the waves fluctuations around a different mean water level as forcing locally changes the mean value of the water height. Therefore, this confuses the agent during learning. Finally, the most drastic effect on learning is observed when the action period is reduced to be equal to the numerical timestep. Similarly to^{12,13}, this means that only white noise forcing is applied in general to the system, which fails at finding any consistent strategy.

B. Comparison of the three training methods M1, M2, and M3

Learning curves for a varying number of jets (1, 5, 10, and 20 jets) and the three different methods are presented in Fig. 8. In addition, since several actions are obtained for each numerical advancement of the simulation in the case M3, the data in this later case are presented again in Fig. 9, but showing on the horizontal axis both the number of actions and the number of numerical advancements. It is visible there also that the DRL agent is able to apply effective control on the system. The evolution of the reward during training indicates that several phases take place. As should be expected, control with a random policy (as takes place at the beginning of each training) degrades the reward compared with the case without control (the reward without control is around 0, and in the first phase of training a reward as low as -0.5 can be observed, corresponding to larger waves being obtained when bad control is applied). However, as training takes place, the reward starts to increase at least in the cases when training is successful. Finally, a plateau in performance is reached upon successful training (or failure of training). The value of the reward, that is close to 1 in several cases, indicates that the system is controllable, and that this control is close to perfect in the sense that it manages to kill close to all fluctuations in h (see Eqn. (7)), i.e. all waves are canceled.

However, it is clear that there are large variations between the efficiency of the different methods. While all methods perform similarly in the case with one single jet, which is really a consistency test for the 3 methods as they are all equivalent in this particular case, differences appear when the number of jets starts to be increased. More specifically, one can observe that as the number of jets increases, methods M1 and M2 see a reduction of their efficiency regarding both the speed of convergence, and the quality of the control strategy asymptotically found. It appears that the method M1 is performing worst, while method M2 is doing slightly better though also degrading with increasing number of jets. By contrast, method M3 sees close to no reduction in performance when increasing the number of jets (at least normalizing by the number of simulation advances as shown in Fig. 9, which is proportional to the CPU cost, instead of the number of actions taken). Generally, this confirms experimentally that here we clearly observe that $M1 < M2 < M3$, where the ordering relation describes effectiveness of the methods.

The difference in efficiency between these 3 methods can easily be understood, as hinted in the previous section, by considering both the invariance of the system by translation and how this compares to the architecture of the DRL agent, as well as the amount of fine-grained reward signal received.

Firstly, the methods 1 does not reflect whatsoever the invariance by translation of the physical system. While this has no consequences in the case when only 1 jet is used, this drastically reduces the ability of the agent to learn when more jets are present. Indeed, this means that the network has to ‘learn from scratch’ by trial and error the policy applied to each jet, and there is no sharing of the weights of policies found at different locations. Therefore, the method 1 is subject to the curse of

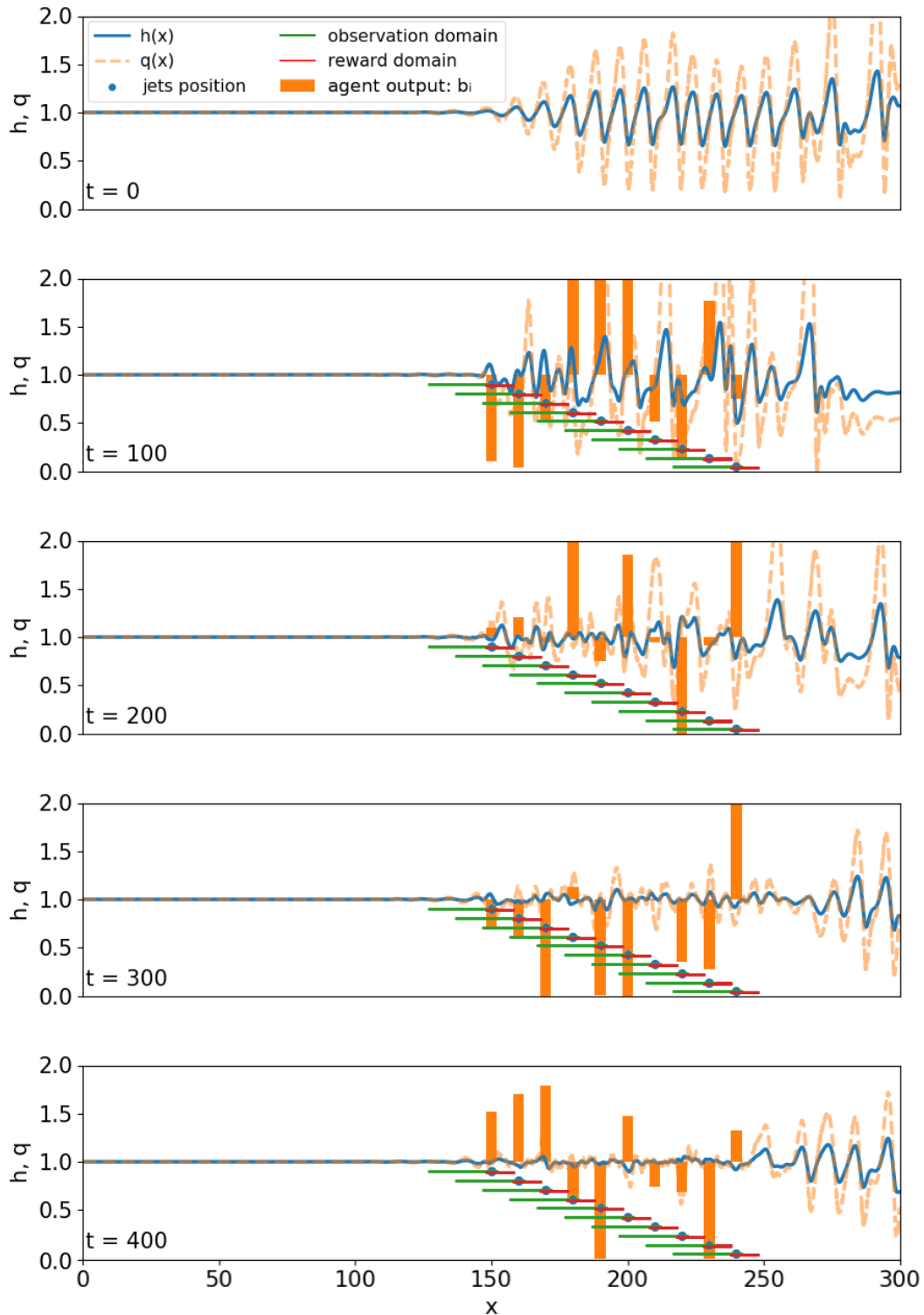


Figure 5. Evolution of the simulation during the training phase. Here we are using the method M3 with 10 jets, coupled to one single simulation, and default physical metaparameters (see discussion in the text). We can see that an efficient policy has been found already for a non-dimensional time of around $t = 400$. This typically takes less than three minutes on a recent CPU, using a single core. This model was trained on an Intel(R) Core(TM) i7-8565U.

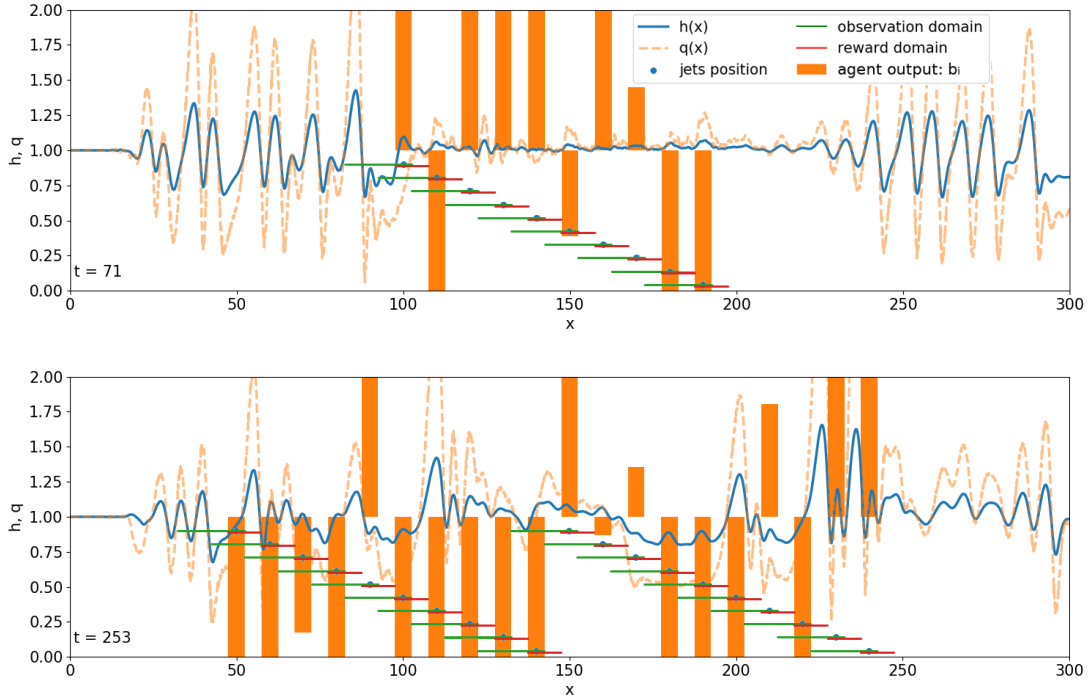


Figure 6. Illustration that control can be successfully applied even when pseudo-chaotic, fully developed waves are used as an input to the control region, as long as the physical metaparameters used are relevant. Top: render of a policy trained over 150 episodes, acting while a stochastic perturbation jet is present at $x = 20$, creating a pseudo-chaotic region. There we are using the method M3 with 10 jets, and the standard jet strength. We can see that large incoming waves are effectively controlled. Bottom: render of a policy trained during 740 episodes, using the same method and with the same perturbation jet at $x = 20$. We use twice as many jets as in the previous trainings (top), but each jet is 10 times less powerful (reduction of M by a factor of 10). We observe that the policy fails to fully dissipate the large waves (some level of control is still achieved, though), as the control strength is not sufficient to compensate for the wave growth.

dimensionality. If, for the sake of a thought experiment, one considers that the action space for each jet is a discrete set of p values in the admissible range, then the method 1 may need typically up to $C \times p^N$ trials to sample effectively the policy in the case where N jets are used, where C is a constant. By contrast, methods 2 and 3 use the exact same set of weights to link the state and jet control at each position, either it is by using a fully convolutional network or a shared agent, and therefore they escape this curse of dimensionality.

Secondly, both methods 1 and 2 fail to take into account that the system presents some locality that allows, if exploited correctly, to ‘densify’ the reward. By contrast, the method M3 takes into account this locality, and is therefore able to extract N reward signals instead of 1, therefore collecting much more information driving the gradient descent. What is meant here is that, while the output flow conditions obtained after the jet number j do influence what happens at the area around the jet number $j + 1$, the actuation has first and foremost a short term effect on the flow around the position where it is applied. Therefore, it does make sense to consider the neighborhood of each jet independently, and use it in an individual DRL control loop. The approach chosen in M3, which consists in having an agent learn from the observation and reward of each jet, takes therefore full advantage of both the invariance and loc-

ality properties of the system. As visible in Fig. 9 this means that, while more actions are needed to learn a valid policy as the number of jets N is increased using the method M3, since at the same time the number of actions executed by numerical advancement of the simulation is N , the learning takes place in constant number of numerical advancements, i.e. constant CPU time when the simulation is the leading computational cost (which is usually the case in Fluid Mechanics, see the discussion in¹³). By contrast, the methods M1 and M2 are at a double disadvantage: first, they receive less volume of reward, which is the signal allowing to perform training, i.e. less information is fed into the DRL algorithm. Second, the reward in the cases M1 and M2 covers a very large area, which encompasses several jets, and therefore the feedback information gets less representative of the actual state of the system. Indeed, if one jet performs a ‘good’ action and another a ‘bad’ one at the same time, as a result the reward will be average, and the DRL algorithm has no way to know that it actually performed well on one jet, and poorly on the other.

However, one may argue that the densification of the reward used in method M3 may also be a potential problem for the optimality of the solution found. Indeed, it means that all rewards are obtained on a local, rather than a global, basis. In our case, this is not a problem, as the optimal strategy at a

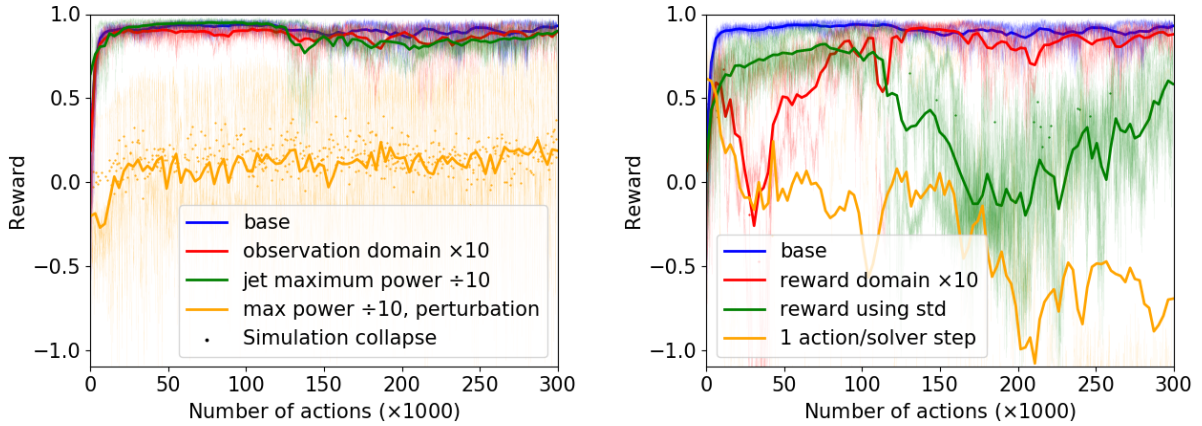


Figure 7. Analysis of the effect of both physical and DRL metaparameters on the strategies found, using the method M3. The left panel focuses on the effect of physical metaparameters such as the size of the observation domain and the maximum jet strength, while the right panel focuses on the effect of metaparameters of the DRL setup such as action update frequency and definition of the reward domain. The baseline configuration corresponds to 4 evenly-spaced jets, $w_i = 2.5$, $L_{obs} = 10$, $L_{reward} = 10$, and the agent being trained with method M3. The first jet is located at $x = 150$, and the spacing between the jets is 10. The reward on vertical axis is computed with the same function on the same reward domain for all the trainings. There is no perturbation jet in the base case. The ‘simulation collapse’ label corresponds to points where bad choice of jet strength by the ANN leads to numerical instability of the simulation, in which case the simulation is reset. Each thick learning curve is the average of 3 trainings (individually shown as thin colored curves). On the left, we investigate the effect of the observation domain size and jet strength on the learning quality. We observe that the size of the observation domain has little effect on the learning, as the ANN is able to select the relevant information. Similarly, in the case with no perturbation jet, the waves are small enough that the strength of the jets can be reduced and control is still obtained. By contrast, if a perturbation jet is used, the waves are too big to be controlled with the weakest jets. On the right, we investigate the effect of the reward parameters and the number of solver steps per action. We observed that using a reward domain that is too large, i.e. includes a large region that is too far away from the jets to be initially controlled, disturbs the learning and that more time is needed in this case to find a good policy. Similarly, a reward function based on using a standard deviation works less well, as the ANN can try to change the mean level of the flow. Finally, using a duration for actions that is far smaller than the natural period of the system (1 numerical timestep per action) completely stops the learning, similarly to what had been observed in¹³.

local level is also the optimal strategy at a global one. However, this may be a problem for method M3, if it is used exactly as deployed here, in a more complex system where the local and global optimization processes are in conflict with each other. One could, however, easily mitigate such an issue, by defining each local reward as a weighted average of the true local reward, and the global reward taken over the whole system. Such approach will therefore require expert knowledge from the user, in order to define relevant reward spaces and help guide the algorithm. While this means that further work will be needed to apply this approach to more sophisticated situations, the results presented so far suggest that the DRL methodology is robust to the exact domain chosen, as long as it encompasses the regions where important physics are happening.

IV. CONCLUSION

We present the first successful control of the falling liquid film flow through a 1D simulation, using DRL. In addition to proving that the system is controllable, we show that the DRL methodology can be used in such a way that it handles an arbitrary number of jets. Therefore, one can effectively escape the curse of dimensionality on the control output size.

This relies on satisfactorily exploiting invariance and locality properties of the underlying system. Failing to exploit one, or several, of these properties leads to reduced quality of the learning and of the final policy. While this is the first time, to our knowledge, that this methodology is proposed for the optimal control of physical systems, it is deeply inspired by the success of CNNs in image analysis. Indeed, CNNs prove efficient in such tasks by similarly taking advantage of translation invariance of image semantic content.

This work, possibly combined together with the results previously obtained in¹³, opens the way to applying DRL to more realistic, complex physical systems. Indeed, such systems may require many control outputs to be manipulated, which is a difficulty in itself due to the curse of dimensionality. In addition, using DRL may be a promising avenue in situations where the combination of several competing mechanisms such as friction drag, wake drag, or the influence of adverse pressure gradients, are competing and defy traditional optimization methods³⁷. However, those same systems usually present many properties of locality (either strong or weak) and invariance, therefore the kind of techniques presented here can be envisioned as a solution to this dimensionality problem. We expect that such trainings, that will resort on the use of both several independent simulations in parallel similar to¹³, and environment splitting and / or convolutional policy

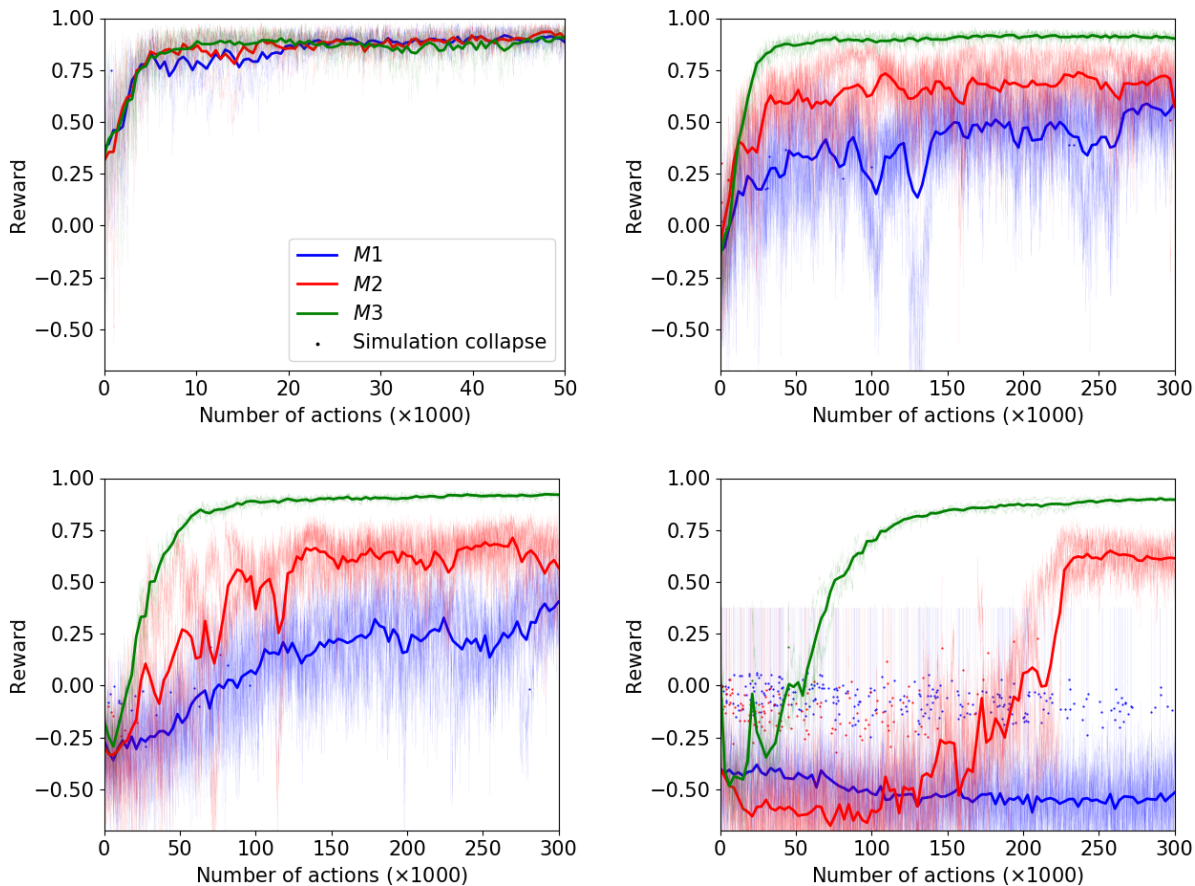


Figure 8. Comparison of the efficiency of the learning (both speed and quality of the final policy) for the methods M1, M2, M3 (varying color) and an increasing number of jets from left to right, top to bottom (respectively 1, 5, 10 and 20 jets). The ‘simulation collapse’ label corresponds to points where bad choice of jet strength by the ANN leads to numerical instability of the simulation, in which case the simulation is resetted. Each thick learning curve is the average of 3 trainings (individually shown as thin colored curves). As visible here, the method M3 is best, with increasing advantage over both M2 (second best) and M1 (worst) as the number of jets increases.

as presented in the present work, may be able to scale to several thousands of CPUs during training and become a tool for the study of realistic flow configurations.

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APPENDIX A: OPEN SOURCE CODE RELEASE

The source code of this project, together with a docker container that enforces full reproducibility of our results, is released as open-source on GitHub [NOTE: the repository is empty for now, the code will be released upon publication in the peer-reviewed literature]: <https://github.com/vbelus/falling-liquid-film-drl>. The PPO agent is based on the open-source implementation provided by stable-baselines³⁸, which builds on top of the Tensorflow framework³⁹. We are using the RL toolkit OpenAI Gym to build custom environments and interact with the agent⁴⁰.

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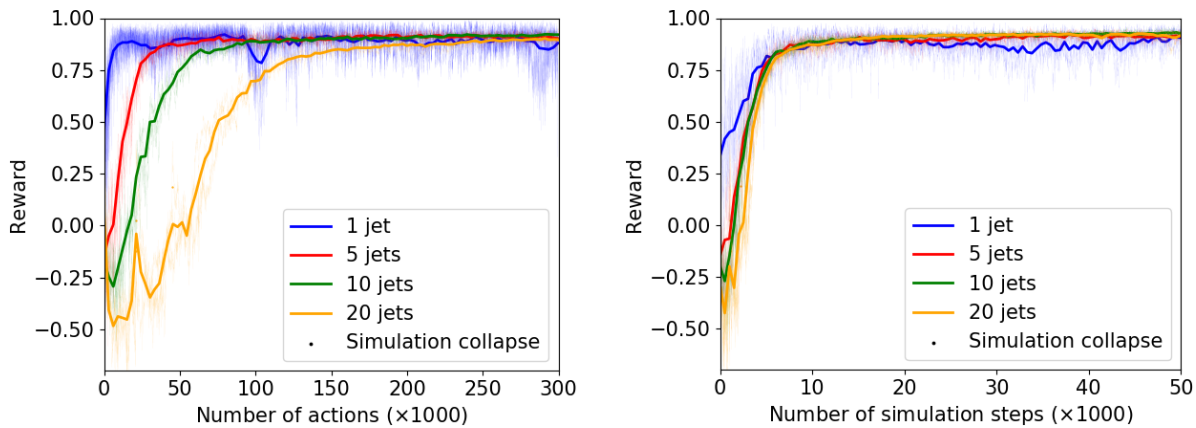


Figure 9. Detailed overview of the training of the DRL agent following the method M3. On the left, the same data as in Fig. 8 are reproduced, showing that more actions are needed to perform satisfactory learning with increasing number of jets. However, we show on the right that the learning as a function of the number of simulation steps, i.e. advancement in time of the simulation, remains equivalent between all cases. This is because, with method M3, the number of actions per advancement in time of the simulation is proportional to the number of jets, i.e. ‘number of actions $\propto N \times$ number of steps’, and therefore using more jets allows to extract more individual triplets of (state, action, reward) out of each advancement in time of the simulation. More specifically, we observe that learning with the method M3 uses constant CPU resources (which is proportional to the number of steps rather than the number of actions), independently of the number of jets used.

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