Non-linear control variate in δf methods using symplectic neural networks

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We are interested in the numerical simulation of Vlasov-Poissons equations in the context of kinetic plasma simulations. A widely used numerical method to solve such equations is the so-called Particles-in-Cell (PIC) method. One of the main limitations of this method is the inherent statistical noise, which decreases slowly as the number of particles increases.
In order to reduce the statistical noise, PIC methods often follow a so-called δf approach, which consists of decomposing the transported density in two parts, a bulk density f_0 given by an analytical formula and a variation δf represented with numerical particles.
In many practical problems the plasma either remains close to an equilibrium state, which allow to significantly reduce the noise. In some cases however the plasma evolves in an unpredictable way and f_0 needs to be updated by a self-consistent algorithm to better follow the total density. This can be achieved, for instance, using semi-Lagrangian methods [1].
In this work, we propose a new strategy to update the bulk density f_0. We introduce a δf method in which the bulk density is periodically recomputed using symplectic neural networks[2]. These networks are trained on particle trajectories and provide a structure-preserving approximation of the underlying dynamics. This approach allows us to evolve the bulk density without relying on a phase-space grid.
We present results in 1D1V and in 3D3V.

Références

[1] M. Campos Pinto, M. Pelz, and P.-H. Tournier, *A δf PIC method with Forward-Backward Lagrangian reconstructions*, Physics of Plasmas 30.3 (2023).

[2] Jin, P., Zhang, Z., Zhu, A., Tang, Y. and Karniadakis, G. E. (2020), *SympNets : Intrinsic structure-preserving symplectic networks for identifying Hamiltonian systems*, Neural Networks, 132, 166-179.

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