Submission code: JN50DLKQA0

See this and other abstracts on our website: https://home.sbgf.org.br/Pages/resumos.php

A Comparative Analysis of Physics-Informed Neural Network Architectures for Wave Propagation in Heterogeneous Media

Leonardo Moreira (IMPA / Centro Pi), Daniel Yukimura (IMPA / Centro Pi), Arthur Bizzi (IMPA / Centro Pi), Márcio Marques (IMPA / Centro Pi), Leonardo Mendonça (IMPA / Centro Pi), Christian Oliveira (IMPA / Centro Pi), Vitor Balestro (IMPA / Centro Pi), Lucas Fernandez (IMPA / Centro Pi), João Pereira (IMPA / Centro Pi), Tiago Novello (IMPA / Centro Pi), Pavel Petrov (IMPA / Centro Pi), Lucas Nissenbaum (IMPA / Centro Pi)

A Comparative Analysis of Physics-Informed Neural Network Architectures for Wave Propagation in Heterogeneous Media

Introduction

Neural networks have been successfully applied to a wide-variety of problems, in areas such as computer vision and language models. Scientific machine learning is an emerging field whose goal is to apply artificial intelligence to the solution of different problems, typically associated with physics. Physics-Informed Neural Networks (PINNs) is one such method, where a neural network is trained to minimize a weighted loss function given by the residue in a differential equation, as well as in the respective initial and boundary conditions. This leads to meshless models that can easily assimilate external data, overcoming common limitations of numerical methods.

Despite promising results in such fields as fluid dynamics, climate modeling, biomedical simulations, and material science, PINNs still struggle with certain important problem classes. Specifically, PINNs tend to violate causality (i.e., time consistency), often converging to trivial solutions, and sometimes distort the solution spectra by truncating high-frequency components. These challenges are especially significant when PINNs are used to model wave propagation through complex heterogeneous media, where the loss computed from the wave equation residue is harder to characterize, and the high-frequencies could be important in determining the solution to the inverse problem. Our objective is to analyze and compare state-of-the-art PINN architectures on the task of simulating wave propagation in heterogeneous media.

Method

We present a comparative analysis of four well-established PINN architectures: the classic PINN model, Quadratic Residual Networks (QRes), First-Layer Sine (FLS), and a transformers based model (PINNsFormer). Moreover, we compare the approximations obtained by these models with traditional numerical methods, such as finite difference and spectral methods. We also propose some experimental hybrid architectures that can be considered a combination of numerical methods and PINNs and apply them to the solution of the forward problem of wave propagation.

The performance of each model is evaluated against a reference solution generated by using a high-precision numerical method. We assess the accuracy of PINNs solutions by estimating their discrepancy from the reference solutions in relative L2 (rMSE) and relative L1 error (rMAE) metrics. Additionally, we measure the time each model takes to converge to its best approximation, determined by the moment at which the validation rMSE stabilizes. Comparisons are carried out for various geoacoustic environments, ranging from simple two- and four-layered waveguides to more complex models.

Results and Conclusions

Our analysis indicates that, among the evaluated PINNs architectures, QRes is the only one capable of obtaining enough training precision in reasonable time to reliably reproduce multiple reflections at media interfaces. Many existing models still lack the ability to surpass the causality violation problem that collapses the learned wave to the trivial solution of its equation and loses the information of reflected waves. We have also found evidence that, beyond these models, there are hybrid machine learning and numerical algorithms that are possible alternatives.