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Shared-Feature Branched Mixed PINN for Heterogeneous Neutron Diffusion Eigenvalue Problems

摘要

在非均匀多材料中子扩散特征值问题中，不同材料区域通量场分布特征差异显著，传统物理信息神经网络（PINN）难以同时兼顾全局共享特征与局部介质细节。为此提出了一种共享特征分支式 PINN 方法，该方法通过共享特征提取与材料专属分支相结合的网络结构，在保持全局特征信息的同时增强了对局部介质差异的表达。进一步地，基于混合形式中子扩散方程，联合预测两群中子通量与中子流，将原始二阶扩散方程重构为通量-中子流耦合的一阶残差系统，并采用基于梯度范数反馈的自适应平衡策略，以缓解各损失项间的梯度失衡。针对特征值问题，构建源项迭代框架，实现 keff 与通量场的协同求解。在二维两群 BIBLIS 基准题上的数值结果表明，该方法在 keff 预测精度、通量分布误差以及训练速度上均优于普通 PINN，keff 误差为 1.9 pcm，两群中子通量 L2 误差为 0.815% 和 0.837%，训练提速 274%，表明该方法在复杂非均匀多材料中子扩散特征值问题的 PINN 求解中具有较好的应用潜力。

关键词

物理信息神经网络；中子扩散特征值问题；源项迭代框架

Abstract

In heterogeneous neutron diffusion eigenvalue problems, the flux-field characteristics differ significantly among material regions, making it difficult for conventional physics-informed neural networks (PINN) to simultaneously capture globally shared features and local material-specific details. To address this issue, a shared-feature branched Mixed PINN is proposed. By combining shared feature extraction with material-specific branches, the proposed network preserves global feature information while enhancing the representation of local material heterogeneity.Furthermore, based on the mixed formulation of the neutron diffusion equation, the two-group neutron fluxes and neutron currents are jointly predicted. The original second-order diffusion equations are reformulated into a first-order residual system coupling neutron fluxes and currents. A gradient-norm-feedback-based adaptive balancing strategy is introduced to alleviate gradient imbalance among different loss terms. For the eigenvalue problem, a source-iteration framework is constructed to achieve the coupled solution of keff and the neutron flux field.Numerical results on the two-dimensional two-group BIBLIS benchmark show that the proposed method outperforms conventional PINN in keff prediction accuracy, flux-distribution error, and training efficiency. The keff error is reduced to 1.9 pcm, the relative L2 errors of the two-group neutron fluxes are 0.815% and 0.837%, respectively, and the training speed is improved by 274%. These results indicate that the proposed method has good potential for PINN-based solutions of complex heterogeneous neutron diffusion eigenvalue problems.

Keywords

Physics-informed neural networks; Neutron diffusion eigenvalue problem; Source-iteration framework

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