A Self-Supervised Inversion Framework for Low-Field 2D NMR Relaxation Spectra with Embedded Fluid-Specific Physical Priors

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Introduction

Low-field nuclear magnetic resonance (NMR) is a key technique in downhole logging for non-invasive characterization of fluid composition. Two-dimensional spectra (T_1-T_2, D-T_2) enhance sensitivity to fluid differentiation and reservoir evaluation [1]. However, limited acquisition time and tool mobility in low-field environments often lead to sparsely sampled, noisy data, making the inverse Laplace transform highly ill-posed. Conventional regularized methods struggle to provide stable, high-resolution spectra, especially in systems with overlapping relaxation components. These challenges highlight the need for inversion frameworks that embed fluid-specific physical priors and leverage data-driven approaches to improve stability and interpretability under sparse acquisition conditions.

Methods

This study introduces a self-supervised deep learning framework for 2D NMR relaxation spectrum inversion (Fig.1), integrating physical priors of fluid relaxation behavior. The model is composed of three modules: (1) a multi-scale convolutional encoder with positional encoding for hierarchical feature extraction; (2) a self-attention mechanism to enhance recognition of long-delay and weak signals; and (3) a physics-informed module that embeds a multi-exponential decay forward model, enabling spectrum-to-echo reconstruction as part of a self-supervised loss. Additionally, fluid-relaxation priors [2] (e.g., for bound water and hydrocarbons) are introduced as spectral priors, guiding the network toward physically consistent outputs.

Results and discussion

Experiments show that the method achieves stable, high-fidelity spectrum reconstruction under sparse and low-SNR conditions, with enhanced peak localization and reduced artifacts compared to traditional methods. The integration of physical relaxation priors further improves interpretability and robustness in realistic measurement situation.

Conclusion

This work presents a novel self-supervised inversion framework for 2D low-field NMR data, integrating fluid-specific physical priors to enhance spectral resolution, stability, and interpretability. The approach is particularly effective in complex environments and holds strong potential for extension to multi-dimensional relaxation analysis and complex reservoir evaluation.

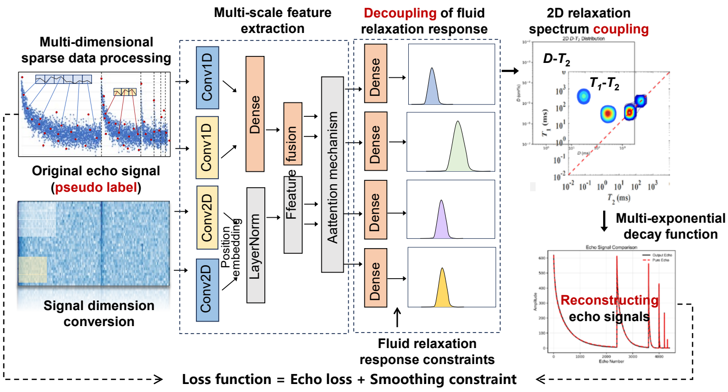

Fig. 1: A Self-Supervised Inversion Framework for 2D NMR Relaxation Spectra with Embedded Fluid Response Coupling.

References:

[1] Lizhi Xiao. Practical NMR for Oil and Gas Exploration. Royal Society of Chemistry, (2023).
[2] Yi-Qiao Song, Ravinath Kausik. NMR application in unconventional shale reservoirs – A new porousmedia research frontier. Progress in Nuclear Magnetic Resonance Spectroscopy. (2019).