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Rapid Flow Characterization Measurements Using a Modified CPMG Measurement with Incremented Echo Times, Phase Cycling and Filtering

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Introduction: We present a low-field magnetic resonance (MR) rheology technique for characterizing pipe flows with a simple, low-cost setup [1-3]. By analyzing the phase and magnitude of a series of single spin echoes acquired at varying τ, we extract the average velocity and flow behavior index to reconstruct the flow velocity profile. A modular benchtop system built around ceramic magnets and a pitched magnet sensor design enables flexible operation, including controlled pre-polarization length for slow-polarizing fluids like aqueous solutions. Recent advances include an echo-train acquisition scheme [4] that gathers N echoes per CPMG sequence, reducing experiment time by a factor of 1/N. Phase cycling and filtering improve signal quality by suppressing unwanted coherence pathways.

Methods: Analysis of spin echo phase and magnitude as a function of τ in a constant gradient enables reconstruction of the velocity profile (Fig. 1). An echo-train acquisition scheme with incrementally adjusted τ, combined with 4-step phase cycling and filtering, allows rapid data collection while minimizing coherence pathway artifacts and preserving optimal pulse spacing.

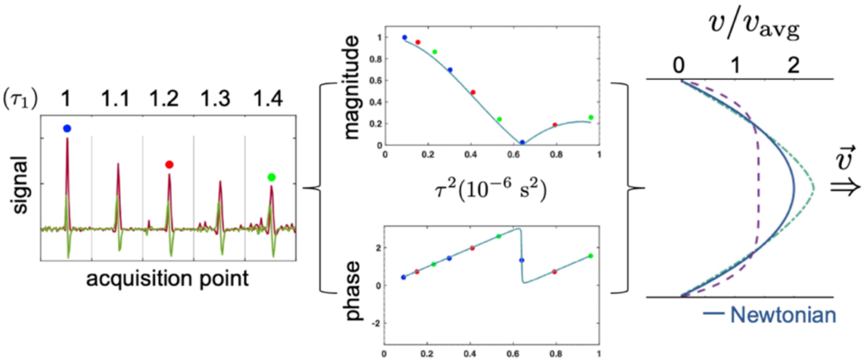

Fig. 1: In a magnetic field gradient, a modified CPMG echo train with variable τ yields flow-sensitive echoes. Phase and magnitude data are fit to a signal model to extract average velocity (v_{avg}) and flow behavior index (n), which define the velocity profile.

Results and Discussion: Validation experiments conducted with Newtonian and shear-thinning fluids confirmed the effectiveness of the methodology. Additionally, the approach reliably distinguishes between laminar and turbulent regimes with high sensitivity. The faster echo-train acquisition scheme produced results consistent with the original method of individual spin echo acquisitions. Our 4-step phase cycling strategy, combined with incremented pulse spacings, enabled acquisition of N = 3 echoes per train in our benchtop apparatus. Incorporating an optional filtering strategy to further mitigate off-resonance effects suggests the approach can be extended to at least N = 5, while also improving echo signal normalization without any requirement to stop the flow.

Conclusion: We developed a simple, low-cost MR method and apparatus for rheological measurements of pipe flow using spin echoes at varying τ. With incremented pulse spacings, phase cycling and optional filtering, we achieve the same flow-sensitive echo response in less time. The modular hardware is easily adapted for industrial use. We anticipate extending this work to a new online viscosity (rheology) measurement, providing a less disruptive alternative to conventional methods and addressing industry need for improved real-time rheological monitoring

References: [1] Guo et al, Phys. Fluids. (2022). [2] Richard et al, Phys. Fluids. (2023). [3] Richard et al. Phys. Fluids. (2024), [4] Richard et al, J. Magn. Reson. (submitted)