Identification of Optimal Sampling Patterns for Compressed Sensing RARE MRI in Porous Media

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Introduction: The aim of this work is to acquire pore-scale MRI images and flow velocity maps within porous rocks to better understand structure-flow relationships and to aid the development of so-called digital rock (DR) flow simulators. Given the long acquisition times of such high-resolution images, compressed sensing (CS) is used for the MRI data acquisitions. Optimal **k**-space sampling pattern design is a critical aspect of compressed sensing MRI (CS-MRI). Although various **k**-space sampling strategies have been developed, they often require parameter optimisation to obtain optimal **k**-space sampling patterns [1]. We developed a new, parameter-free **k**-space sampling approach using input from high-resolution 3D X-ray micro-computed tomography (µCT) data sets to derive optimal **k**-space sampling patterns for acquiring high spatial resolution 3D MRI images of rocks.

Methods: µCT images (grain space) of 4 mm diameter rock core plugs, routinely acquired as part of a DR workflow, were inverted to obtain pore space images. These were then Fourier transformed into the expected **k**-space for these rocks. From these **k**-space signatures, optimal CS variable-density sampling patterns [1] were generated for each rock type, spatial resolution, and sampling fraction. CS-RARE [2] in combination with the new **k**-space sampling strategy was used to acquire pore-scale structural CS-MRI images of rocks at (isotropic) resolutions as high as 17.6 µm. Pore size analysis in Avizo was used to benchmark the quality of the MRI images relative to a 5 µm µCT image.

Results and discussion: The µCT-based sampling strategy delivers a bespoke **k**-space sampling pattern for each rock type (Fig. 1) according to the morphology of the rock, which was shown to give an optimal CS reconstruction quality for a range of different sampling fractions (0.125–0.375). The pore space analysis revealed excellent agreement between the pore size distributions of the acquired MRI data of Ketton rock using the µCT-based sampling approach and the 5 µm resolution µCT images. These results highlight the advantage of using the µCT-based approach to deliver accurate pore space reconstructions at spatial resolutions for which a fully-sampled acquisition at those resolutions would be prohibitively long to acquire.

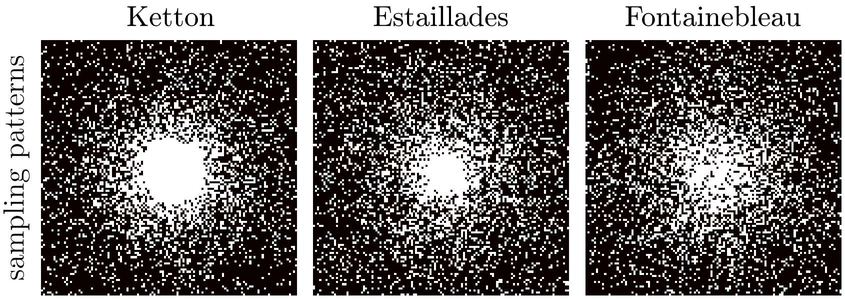

Fig. 1: Sampling patterns of Ketton limestone, Estaillades limestone, and Fontainebleau sandstone as generated by the new, µCT-based sampling approach for a **k**-space sampling fraction of 0.25. The white pixels in the sampling patterns represent the points sampled in both phase-encoding directions. For a 3D CS-RARE experiment, a line in the frequency-encoding direction, orthogonal to both phase-encoding directions, is fully sampled for each of these points.

Conclusion: A novel, robust **k**-space sampling strategy has been demonstrated to generate optimised **k**-space sampling patterns for 3D high spatial resolution microstructural MRI acquisitions from 3D µCT data. This approach can be used to accelerate other MRI acquisitions relevant for DR applications, such as spatially-resolved propagators, fluid velocity maps, and relaxation time maps.

References: [1] Lustig, Magn. Reson. Med. (2007). [2] Ramskill, J. Magn. Reson. (2016).