INNOVATION IN FRACTURE ROUGHNESS CHARACTERIZATION

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ABSTRACT

We describe pore to core scale Berea fracture roughness by using two experimental techniques: high-resolution perthometer profilometry and a new shadow imaging technique. Profiles were analyzed by Fourier spectrometry and a recently proposed average wavelet coefficient method. Shadow images were analyzed using a recent theory for shadows in a self-affine landscape. The methods were consistent. The Fourier method had highest resolution, while the wavelet method had less noise. Imaging is faster than profilometry. The fractures have three distinct roughness regimes: grain shape, self-affine roughness and randomly uncorrelated roughness. Realistic fracture profiles and surfaces were generated numerically.

INTRODUCTION

Traditionally, sandstone fractures are modeled as two flat surfaces. In reality they are rough — similar to cracks in concrete walls. The roughness height depends on the length scale over which the height is measured. Mean roughness height is not meaningful, as it varies with length. Instead, the roughness can be described as a random self-affine surface with a roughness exponent ζ and a scale independent amplitude. A random self-affine surface, with a zero average in the (x,y)-plane, is statistically invariant when $(x, y, z) \to (\lambda x, \lambda y, \lambda^{\zeta} z)$, where $\lambda > 0$. Most studied brittle fractures are self-affine with $\zeta \approx 0.8$.

The aim of this work is to: 1) describe Berea fracture roughness, 2) compare experimental and analysis techniques, and 3) generate numerically realistic three-dimensional Berea fracture surfaces. We used two methods: high-resolution perthometer profilometry (HRPP) and a new shadow imaging technique (SIT) which we have developed. HRPP data were analyzed for the first time by a recently proposed average wavelet coefficient (AWC) method [2] and by a standard Fourier power spectrum. The development of a SIT was motivated by the recent theory in physics for shadow length distribution (SLD) in a self-affine landscape [1]. Based on the experimental results and theoretical analysis, we generated numerically realistic fracture profiles and surfaces numerically.

RESULTS

Profiles were measured with high resolution (length 2.42 μm, height 30.5 nm). Figure 1 shows a typical perthometer profile. Figure 2 shows a Fourier power spectrum which

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is an average over 162 profiles from a fractured Berea sandstone. There are three distinct roughness regimes: grain shape, self-affine, and random uncorrelated noise. Each regime is described by a straight line in a log-log power spectrum. Spectra of grain shape roughness were between analytical spectra we derived for an arc and a half-circle. The average of 162 AWC spectra is shown in Figure 3. The roughness exponent derived for AWC is similar to the one for Fourier spectra. The noise is lower for AWC, and the resolution is higher for Fourier spectra.

For the imaging technique, we first built an experiment, involving a light source, optics and a CCD camera, to sample shadow patterns on fracture surfaces in longitudinally split Berea cores. Images were preprocessed using shadow recognition routines (thresholding), and post processed by calculating histograms of shadow lengths. The self-affine regime was identified in the histograms, such as in Figure 4. Grain shape and random noise regimes were not identified due to low pixel resolution/blurring, and poor statistics, respectively. An advantage of image analysis, is that it is a fast non-contact method.

The three roughness regimes were modeled numerically. Realistic profiles, as shown in Figure 5, were constructed by filtering a self-affine profile. Fourier spectra of synthetic profiles were remarkably similar to the measured profiles (see Figure 6). An image of the Berea fracture surface is shown in Figure 7. A synthesized fracture surface, as shown in Figure 8, was generated by a two-dimensional inverse Fourier transform of spectra including the three roughness regimes. The synthesized fracture surface is very similarr to the real measured surface. Fourier spectra of a cap and a hemisphere were derived analytically and used as end member models for grain scale roughness. The realistic surfaces can be used as input geometry for simulating flow.

CONCLUSIONS

Berea sandstone fractures in core samples had a rough surface which can be described by three roughness regimes: grain shape, self-affine and random uncorrelated noise. The AWC method and the SLD analysis of SIT data are consistent with the Fourier spectrum method. SIT is a fast, non-contact method. Realistic Berea fracture profiles were generated by inducing a correlation length and rounded peaks, and realistic fracture surfaces were generated by an inverse Fourier method.

REFERENCES

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[2] I. Simonsen, A. Hansen, and O. M. Nes. Determination of the Hurst exponent by use of wavelet transforms. *Phys. Rev. E*, 1998, **58**(3):2779-2787.

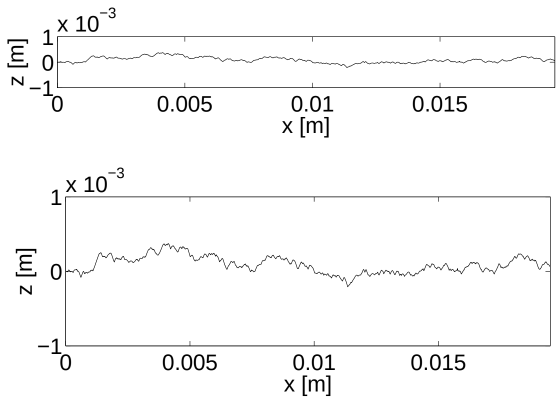

Figure 1: Real profile. (upper) equal axis and (lower) stretched axis

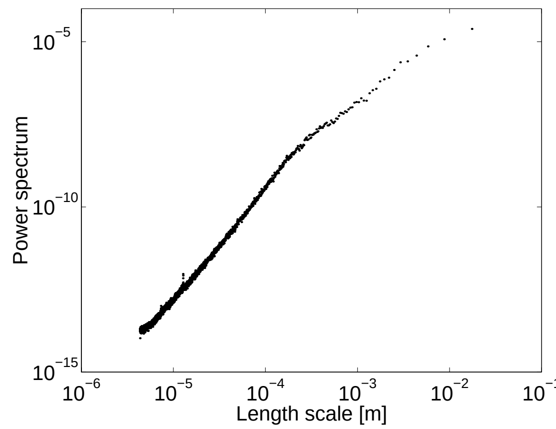

Figure 2: Average of 162 Fourier power spectra of Berea profiles

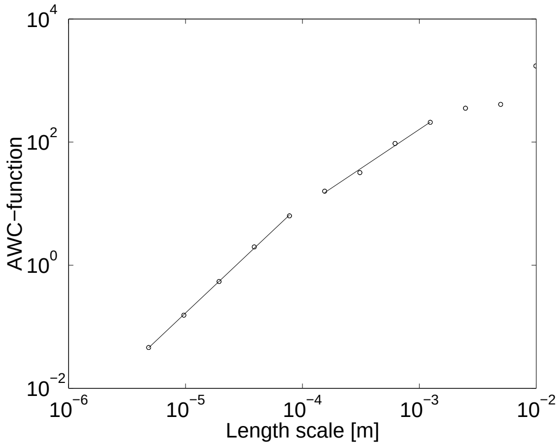

Figure 3: Average of 162 AWC spectra of Berea profiles.

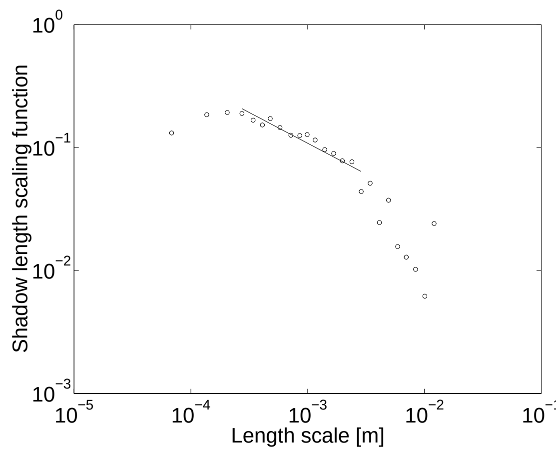

Figure 4: Scaling function (histogram times shadow length) of shadow lengths. Line in self-affine regime

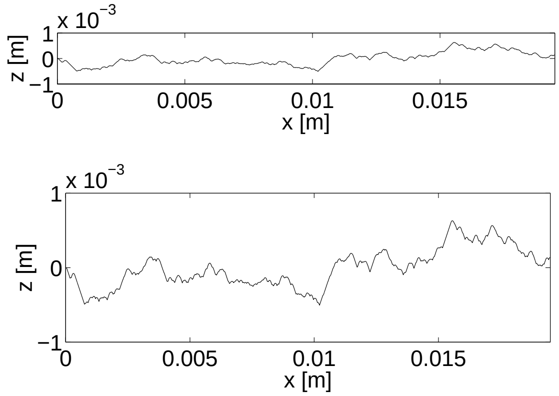

Figure 5: (upper) Typical simulated profile in equal axis, and (lower) with stretched z-axis.

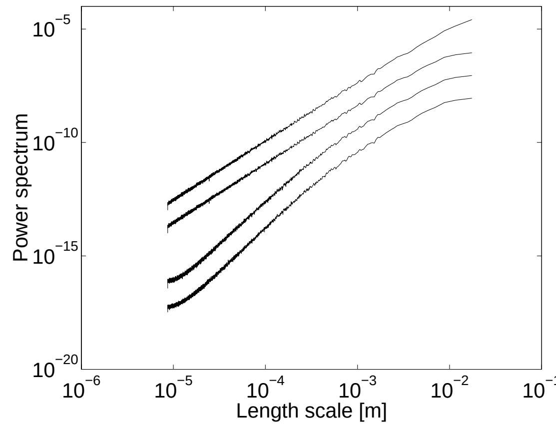

Figure 6: Average Fourier power spectra of 162 simulated profiles. (upper) Self-affine, added correlation length, added grain shape and (lower) added conic distortion.

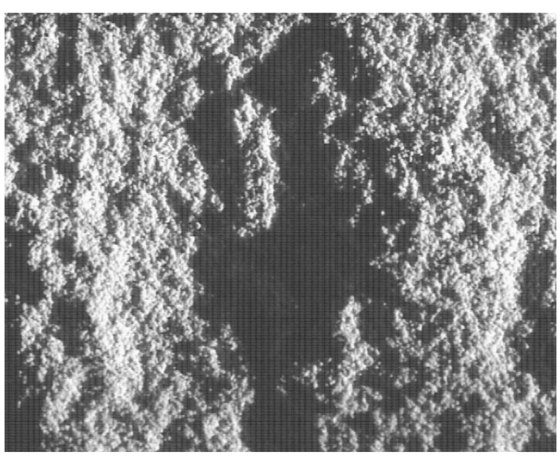

Figure 7: Typical raw shadow image of Berea fractured surface.

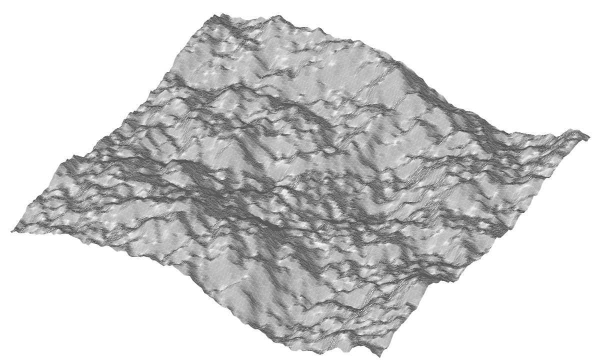

Figure 8: Typical simulated surface with stretched axis.