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USE OF SYNTHETIC FRACTURES IN THE ANALYSIS OF NATURAL FRACTURE APERTURES

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ABSTRACT

Numerically synthesized models of rough fractures in rocks are promising alternatives to the expensive profilometry process in different applications. The authors present a new powerful and flexible method targeted for the generation of high-quality synthetic fracture models. This method has been implemented in SynFrac^{TM} software, developed by authors. Statistical analysis of suites of synthetic fractures has been performed. As result of the analysis, the dependence of the mean fracture aperture on the main parameters of bounding surfaces has been obtained. This technique and the developed software are not restricted to use with rock surfaces, but can be applied for imaging and modelling of any rough surfaces in any material.

Keywords: numerical modelling, rough fractures.

INTRODUCTION

Computational fluid flow modelling can be effectively applied to flows through rough fractures in rock. In order to do this the geometry of the fracture (2D or 3D) should be described numerically and the flow boundary conditions should be stated. The topography of a real rock fracture can be presented in the form of numerical description obtained using a profiling procedure. This procedure is usually expensive in terms of time, materials, labour and equipment required. An alternative way is to simulate a numerical model of rough fracture, which has properties close to the real fracture. Brown (1995) developed a method of synthesis of numerical models of rough fracture. Synthetic profiles obtained with this method were analysed using statistical and spectral methods. The properties of synthetic profiles were found to be in reasonable agreement with data regarding natural fractures.

Similar numerical model was used later by Glover *et al.* (1998a) in their work on the modelling of fluid flows in rough fractures. Based on this model, we have developed a new method of numerical fracture synthesis. This method is more flexible and has several parameters of synthesis process to be varied in order to achieve a high similarity of the simulated fracture compared to real rock fractures. The input parameters for the method can be obtained with an optical technology (see Ogilvie *et al.* this volume).

High-quality synthetic numerical fracture models can be also used for investigations of the statistical properties of rock fractures. Particularly, the mean fracture aperture dependence on the properties of bounding surfaces can be obtained. It is well known that fluid flow through rough fracture depends essentially on the fracture aperture. On the other hand, roughness of bounding surfaces has also considerable influence on the fluid flow (Brown, 1987). However, the aperture and the roughness are not entirely independent characteristics. In the frame of the present model both of them can be found depending on the model input parameters, which are related closely to the properties of particular rock. For the aim of the present paper we assume that the input parameter can vary continuously, covering the range of discrete values, which correspond to various rocks.

SYNTHESIS METHOD

All three models listed above use the same fractal representation of rough fracture surfaces. Fractal surfaces are composed of a sum of Fourier harmonics, the intensities of which decay gradually as a power of the wave-number, and with phases that are random. After the generation of the Fourier spectrum, an Inverse Fast Fourier Transform (IFFT) is applied in order to obtain the topography of fracture surfaces. This method of generation of a fractal surface is called spectral synthesis (Saupe, 1988).

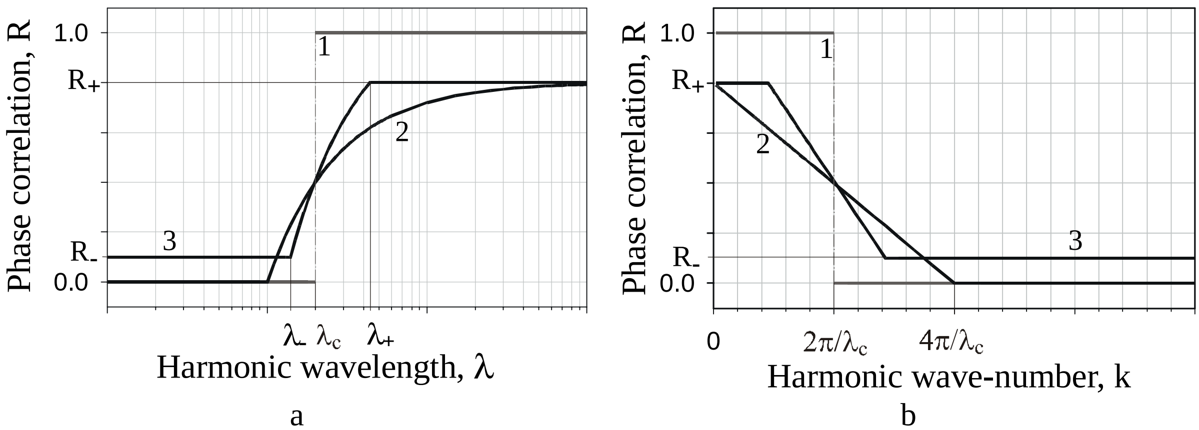


Fig. 1. *Correlation between phases of harmonic components vs. a: harmonic wavelength, b: harmonic wave-number. (1) Brown, 1995; (2) Glover et al., 1998; (3) New model.*

The two surfaces bounding the fracture are not exactly the same, and they are not completely independent. So the random phases of Fourier harmonics of these surfaces should be partially correlated. Brown (1995) proposed that harmonics having wavelength greater than some mismatch length λ_c are perfectly correlated (the correlation coefficient, $R = 1$), while harmonics having shorter wavelength are independent ($R = 0$, Fig. 1a). Later Glover *et al.* (1998b) showed that the discontinuity of the correlation function at the mismatch length λ_c causes an unphysical behaviour of synthetic fractures produced with this method. They proposed a linear variation of the correlation coefficient in the Fourier space within the interval from the wave-number $k = 0$ (infinite wavelength) to $k = 4\pi / \lambda_c$ (wavelength $\lambda_c / 2$, Fig. 1b, the corresponding non-linear dependence on the wavelengths is also shown in Fig. 1a). Glover *et al.* (1998b) also introduced the maximum fractional matching parameter $R_+ \le 1$, which reflects the correlation between fracture surfaces at the largest wavelength used. In order to obtain correlated random phases, two independent random numbers φ_1 and φ_2 were mixed

$$\varphi_3 = R\varphi_1 + (1 - R)\varphi_2 . \tag{1}$$

The resulting random number φ_3 and the initial random number φ_1 are correlated with the coefficient R. However, the random number φ_3 is not uniformly distributed (Fig. 2a), as it should be. For this reason, surfaces synthesized with this method were distorted at the corners (Fig. 2b).

We have developed a new method of numerical synthesis of rough fractures, which is based on the method of Glover *et al.*, and avoids inaccuracies of the Brown and Glover *et al.* methods. The proposed correlation function is shown in Fig. 1. Two new parameters were introduced in order to increase the flexibility of the method. The first one is the minimum fractional matching parameter $R_-(\ge 0)$, which reflects the correlation between surfaces at smallest wavelength used. The second is the length of transition τ from the minimum correlation scale λ_- to the maximum correlation scale λ_+

$$\tau = \lambda_+ - \lambda_- , \quad \lambda_- = \lambda_c \frac{2\lambda_c + \tau}{2(\lambda_c + \tau)} , \quad \lambda_+ = \lambda_- + \tau . \tag{2}$$

The flexibility of new method allows the simulation of both the method of Brown ($R_- = 0, R_+ = 1, \tau = 0$) and the method of Glover *et al.* ($R_- = 0,\ \tau \to \infty$).

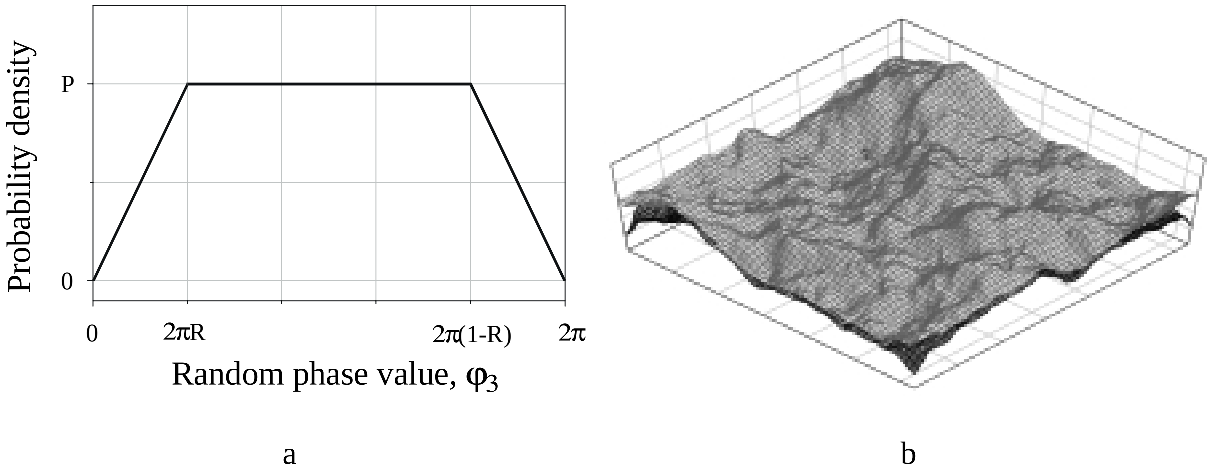
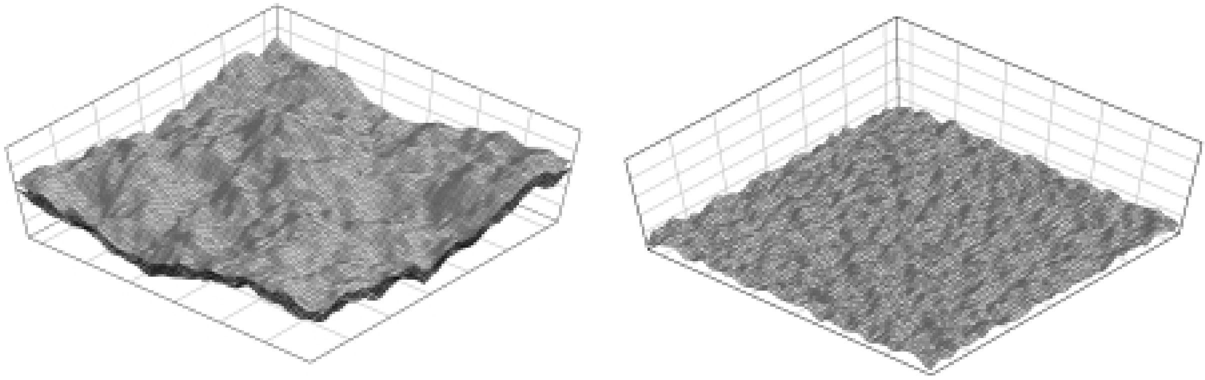


Fig. 2. *Numerical model of rough fractures by Glover et al. (1998). a: Non-uniform probability density distribution of random phase* φ_3. *b: Sample of synthesized numerical fracture. Non-uniform distribution of phases causes aperture increasing at the corners.*

Partially correlated random phases of Fourier harmonics were produced with a kind of Monte Carlo method. Two random sequences φ_1 and φ_2 of a considerable length ($10^4 - 10^6$ of random numbers) were generated. Then the sequence φ_2 was rearranged in a random way until the correlation between sequences reaches the desired value R. It is quite obvious that this procedure does not affect the distribution of random value φ_2, however it may introduce some autocorrelation to the sequence φ_2. In order to avoid this effect, authors picked up random pairs from sequences (φ_1, φ_2) instead of taking these pairs in order, one by one.

We have implemented this new method of numerical synthesis of rough fracture model as a software algorithm (SynFrac^{TM}). This program is able to generate effectively sets of high-quality synthetic fracture models (Fig. 3) automatically or under manual control. SynFrac^{TM} software has a graphical user interface (GUI), which makes program easy to understand and use.

As mentioned above, synthetic numerical fractures can be used in computational fluid flow modelling. However, this is not the only application of synthetic fractures. As synthetic models have a high similarity to real fractures in rock, they may be used for collection of statistical data, when there is a lack of real profiling data. In this work we use synthetic fractures to emphasize the relationship between the properties of rock surfaces bounding the fracture and the mean fracture aperture. Indeed, this methodology and software can be applied whenever a rough surface or fracture is required in any medium. For example, this software has recently been used to provide large-scale (10 km × 10 km) rough surfaces for use in satellite image modelling.



a b

Fig. 3. *Typical synthetic fracture models produced with SynFrac™ software. a: Upper and lower bounding surfaces of the fracture. b: Resulting aperture variation across the fracture. Note that the lack of long wavelength in the aperture. This is the result of the fracture surfaces being matched at the larger wavelength.*

RESULTS

A large number of synthetic rough fractures (100×100 mm) in rocks were created using SynFrac™ as a function of fractal dimension (from 2 to 2.4), standard deviation of bounding surfaces (from 0.01 to 5 mm), mismatch length (from 1 to 50 mm), and minimum and maximum matching fractions (from 0 to 20% and from 80% to 100%, respectively). For each set of parameters a suite of 10-30 fractures was created. Each fracture was analysed to ascertain whether the resulting synthetic fractures had parameters, which matched the synthesizing parameters. In this way we verified the synthesizing algorithms and their implementation in SynFrac™ software.

The mean arithmetic apertures of the resulting fractures were obtained for each suite of fractures, and have been examined as a function of (i) surface asperity distribution (standard deviation), (ii) fractal dimension, (iii) anisotropy, and (iv) mismatch parameters.

Dependence of mean fracture aperture on the standard deviation of bounding surfaces is shown in Fig. 4 (isotropic fractal dimension 2.2, mismatch length $\lambda_c = 10$ mm, transition length $\tau = 20$ mm). It is quite obvious that there is a strong proportionality relation between these values, as seen in Fig. 4. The scattering in the mean fracture aperture increases as well as the mean fracture aperture increases, so the relative scattering values are constant.

As expected, the fracture aperture depends non-linearly upon the fractal dimension (Fig. 5). Two data sets are presented in this figure, symbols Δ and ∇ correspond to surface standard deviations of 0.3 mm and 0.6 mm, respectively, and other parameters are the same as in Fig. 4. One can see that the change of the standard deviation causes a proportional change of fracture aperture again. It appears also that the fracture aperture increases with fractal dimension as the roughness of fracture surfaces increases.

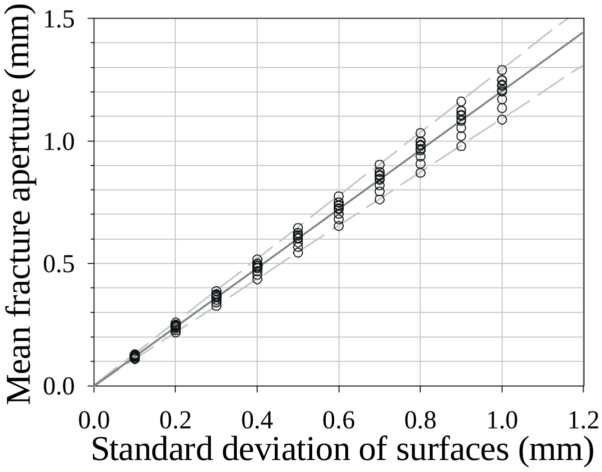


Fig. 4. *Mean synthetic fracture aperture as a function of the standard deviation of surfaces. Fractal dimension 2.2, mismatch length 10 mm, transition length 20 mm.*

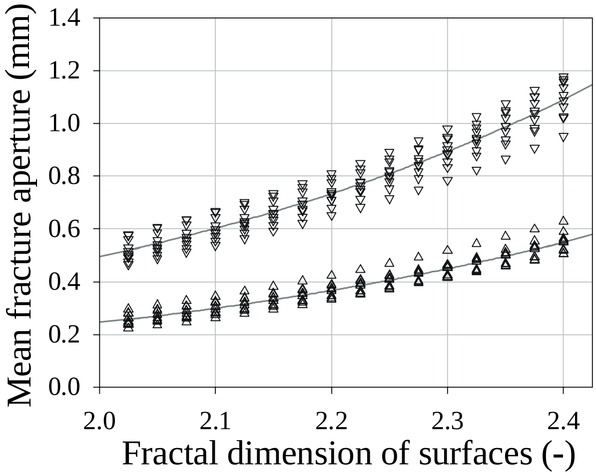


Fig. 5. *Mean synthetic fracture aperture as a function of the fractal dimension of surfaces. Mismatch length 10 mm, transition length 20 mm, standard deviation of surfaces 0.3 mm (Δ) and 0.6 mm (∇).*

It was found, that isotropic fractures have the least mean aperture, if all other parameters remaining constant (Fig. 6, fractal dimension 2.1, standard deviation 0.5 mm, other parameters are the same as in Figs. 4 and 5). The mean aperture increases as anisotropy appears.

It was mentioned above, that variation of the transition length parameter yields smooth transition between Brown and Glover *et al.* methods. The variation of the mean fracture aperture during this transition is shown in Fig. 7. The method of Brown gives the smallest values of fracture aperture and can underestimate it. The mean aperture of the synthetic fracture increases as the transition length increases up to 80 mm. As the transition length become comparable to the size of whole fracture (100 mm), further increasing of the transition length does not affect the fracture properties. A large transitional length causes considerable scattering of mean aperture values, because the correlation between long-wave harmonics with highest amplitude becomes random.

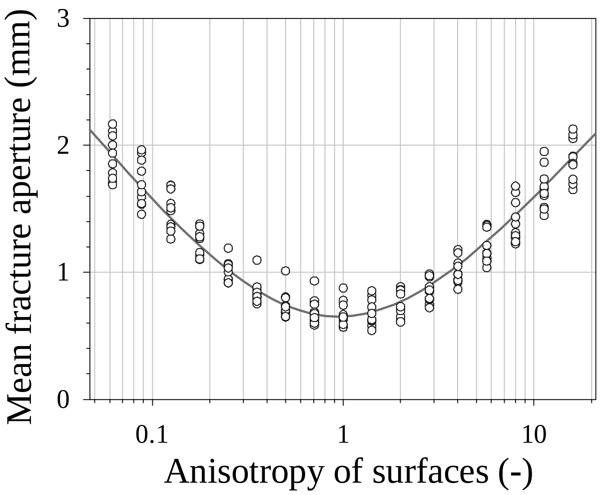


Fig. 6. Mean synthetic fracture aperture as a function of the anisotropy of surfaces. Fractal dimension 2.1, mismatch length 10 mm, transition length 20 mm, standard deviation of surfaces 0.5 mm.

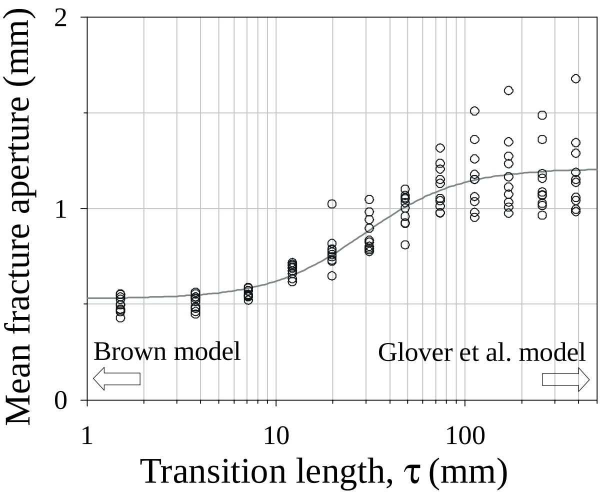


Fig. 7. *Mean synthetic fracture aperture as a function of the transition length. Fractal dimension 2.2, mismatch length 10 mm, transition length 20 mm, standard deviation of surfaces 0.5 mm.*

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