Introduction of new roughness parameters to quantify rock joints surface using Fourier analysis

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ABSTRACT: Up to now, several parameters and methods such as empirical, statistical method, fractal and spectral methods used to quantify the rock joints surface. Spectral method is the latest and more comprehensive. One of the most useful tool in spectral method is the Fourier transform. Due to the ability of Fourier analysis in separating signals with various amplitudes and frequencies, it can separate the roughness profile to some profiles with specific frequencies and amplitudes. Profiles with high frequencies and low amplitudes represent the small asperities and profiles with low frequencies and high amplitudes represent waviness. In previous investigations, Fourier analysis focused on power spectral curve, and roughness parameters or fractal dimension were calculated by this method. But in this paper by applying Fourier analysis on profiles, filtering different frequencies, and investigating the effect of cutoff frequency in low pass filter of JRC profiles on real length and average dip angle, new parameters (CL & CI) are introduced in order to quantification of rock joints roughness. These parameters have good correlations with JRC. Since CI can quantify the influence of shear direction, it is better than CL.

1. INTRODUCTION

In geomechanics engineering, the engineers are faced with several problems that caused by geotechnical systems, and their structures which are located in or on jointed rocks. In rock masses, joints have complex structures and patterns. Due to this matter and inherited uncertainty in estimating geomechanical properties of intact rocks and joints, predicting properties of rock masses is difficult. On the other hand, the limitation of experimental and field data makes it much worse. In order to predict hydraulic and mechanical properties of rock masses, a) joint network geometry, b) hydraulic and mechanical properties of rock joints, c) hydraulic and mechanical properties of intact rock should be quantified [1].

The shear behavior of unfilled joints is dependent on type of rock, normal stress on joint plate, boundary conditions, geometry of rock joint surface, roughness, rock joint scale, degree of alteration, moisture and water pressure [1].

Strength, deformability and hydraulic properties of rock joints are affected by rock joints roughness. Geometry, scale and strength of rock joints surfaces control the surface mechanical properties. Separation between surfaces or 'aperture' also specifies hydraulic properties. Therefore, accurate quantification of roughness is very important in estimating strength, deformability and hydraulic conductivity of rock joints [2].

The Joint Roughness Coefficient (JRC), various conventional statistical parameters, fractal parameters and spectral method have been suggested for classifying and quantifying roughness of rock joints. Most of these parameters are two-dimensional (2D) and semi three-dimensional (3D) parameters and they are obtained from 2D profiles. Recently, Grasselli and Belem offer different three-dimensional parameters from rock surface for quantifying roughness of rock joints surfaces [2-9].

2. SPECTRAL METHOD

Most of parameters and methods of quantifying the roughness are based on surveying profiles. In other words they are based on the location domain. Parameters such as height or slop of asperities (that are components of surface geometric properties) are used for roughness quantification [1-11].

The signal processing, as a powerful tool for extracting hidden valuable data in location domain, is used in roughness analysis. In this context, many researchers use this tool for roughness analysis of discontinuities surfaces and demonstrated capabilities of this method.

The function of transformations in signal processing is to transform time or location functions into frequency function and extraction of some features that cannot be found in time or location domain. In figure 1 this ability is shown for AC power signal [12].

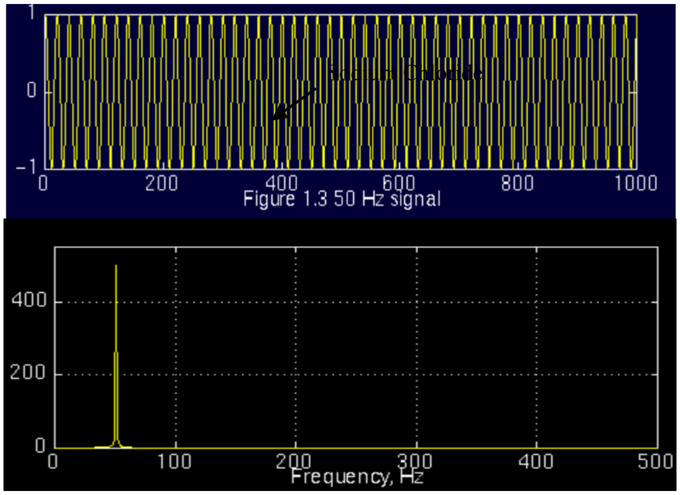

Fig. 1. up) AC power signal; down) furrier transform of AC power signal [12].

Features and benefits of transformations, which are developing every day, spread use of this tool in other non-electrical fields such as medicine, biology, geoscience and etc. One of the interesting fields, which uses this method, is the analysis of surface roughness. Fourier transform, fast Fourier transform and wavelet transform are famous transformations used in signal processing.

The most important and basic transformation in signal processing is the Fourier transform. Josef Fourier showed that many of periodic signals could be written as a linear combination of complex exponential functions with harmonic relationship. General form of complex exponential function is $e^{i\omega t}$. Where ω is the frequency of the function which is related to fundamental period (T) by $\omega = \frac{2\pi}{T}$. Besides, $i = \sqrt{-1}$ is the imaginary unit. In figure 2, a hypothetical periodic signal and frequency component of it are illustrated [11, 12].

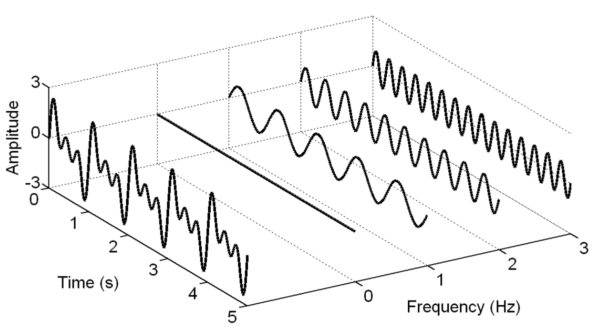

Fig. 2. A hypothetical periodic signal and frequency component [12].

Furrier transform assumes signal is periodic and calculates magnitude and phase for different frequencies of signal. Thus, when the Fourier transform is taken on a limited signal, assumes the length of input signal is a fundamental period of signal. On the other words, this method repeats the signal in an unlimited way on both sides of signal, and then calculates frequencies of the signal [12].

3. NEW METHOD

The shear mechanism includes break asperities and slip on each other, which this break rate is dependent to normal stress and boundary conditions. In low normal stresses, the smaller and steepest asperities and in higher normal stresses, the largest asperities are damaged. Because of the ability of Fourier transform in separation of signals with different amplitude and frequency, it can classify roughness profiles into different profiles like signal classification. Actually, the classified profile with smaller amplitude and upper frequency indicates small asperities and vice versa, which the classified profile with larger amplitude and lower frequency indicates large asperities (figure 2).

In previous researches, Fourier transforms focused on calculating roughness parameters or fractal dimension by analyzing power spectral [10], but in this paper, the new parameters are defined by imposing low pass filters with different cutoff frequencies and studying the changes in real length of profiles and average dip angle of profile's elements that face the shear with changing the cutoff grade.

In order to define new parameters, the JRC profiles are analyzed with Fourier transform. The amplitude and phase of each frequency for profile of JRC 14-16 that calculated with FFT (Fast Fourier Transform) are shown in figure 3. For FFT analysis, digitized JRC profiles are used with 0.5mm accuracy, therefore the frequency of sampling is 2000 samples per meter and the maximum frequency that is obtained from FFT is 1000 Hz.

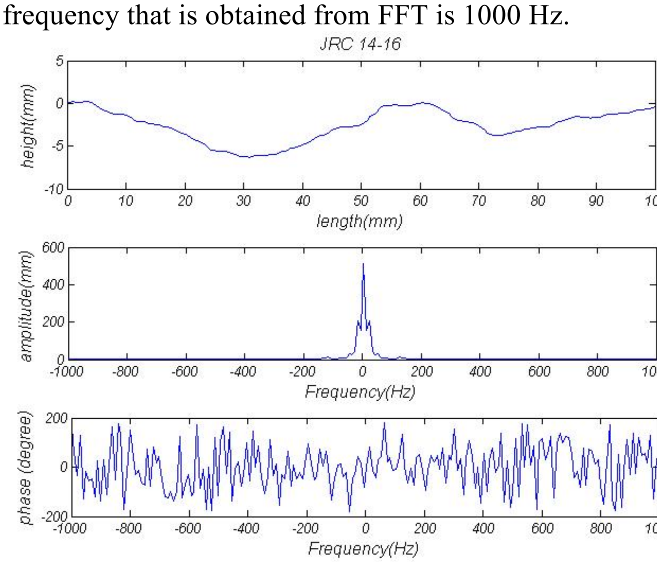

Fig. 3. a) Profile of JRC 14-16 b) amplitude vs. frequency diagram for FFT analysis of JRC 14-16 c) phase vs. frequency diagram for FFT analysis of JRC 14-16.

A low-pass filter is a filter that allows signals with a frequency lower than a certain cutoff frequency pass and stops signals with frequencies higher than the cutoff frequency [11]. By applying a low pass filter on the profile, its roughness is reduced. Therefore, it can be assumed that during rock joints shearing, the frequencies, which are higher than a cutoff frequency, are removed. This specific frequency depends on roughness, normal stress and boundary conditions. Thus, by low pass filtering with different cutoff frequencies on each profile and analyzing the changes which are made on the profile, the appropriate parameters can be defined for roughness quantification.

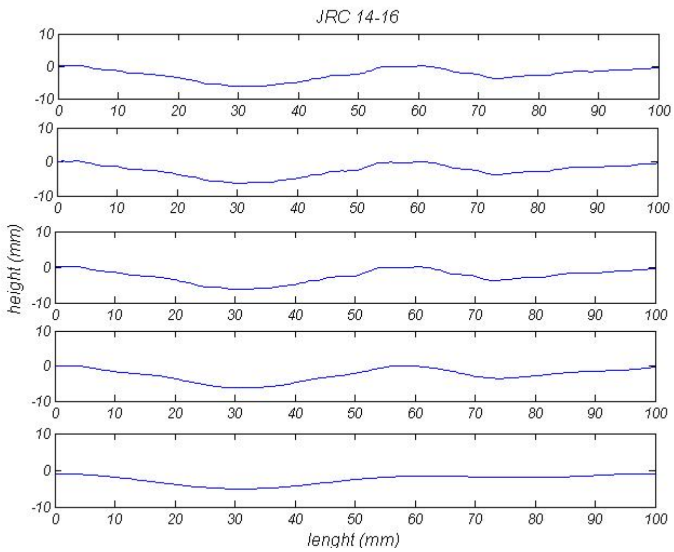

Fig. 4. The first diagram is 14-16 JRC profile and the others up to down are low pass filtered profiles with cutoff frequencies 990, 495, 100 and 20 Hz.

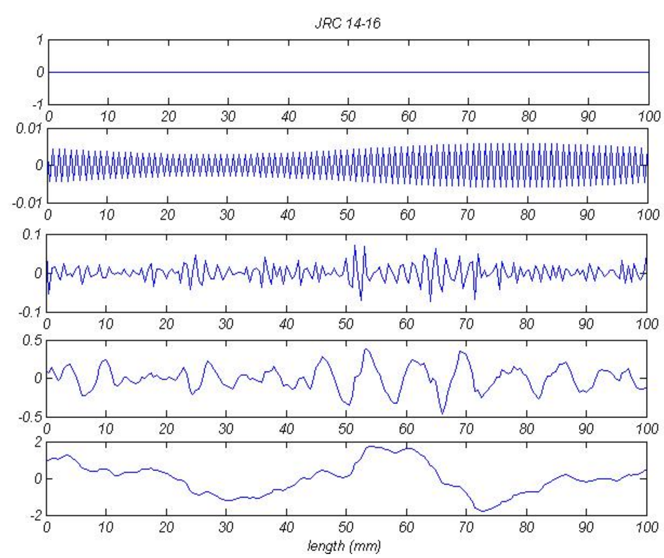

Fig. 5. the removed signals from figure 4 (in the same order of figure 4).

As seen in figures 4 and 5, by reducing the cutoff frequency in low pass filter, the amplitude of removed signal is increased and the profile becomes smoother.

3.1. Parameter of CL

After FFT analysis on profiles, real length variation of the profile are investigated due to applying low pass filter with different filtering frequencies. As expected, the real length of filtered profile decreases with reducing the cutoff frequency of low pass filter. In figure 6 "actual length of filtered JRC 14-16 profile vs. cutoff frequency of low pass filter" is shown.

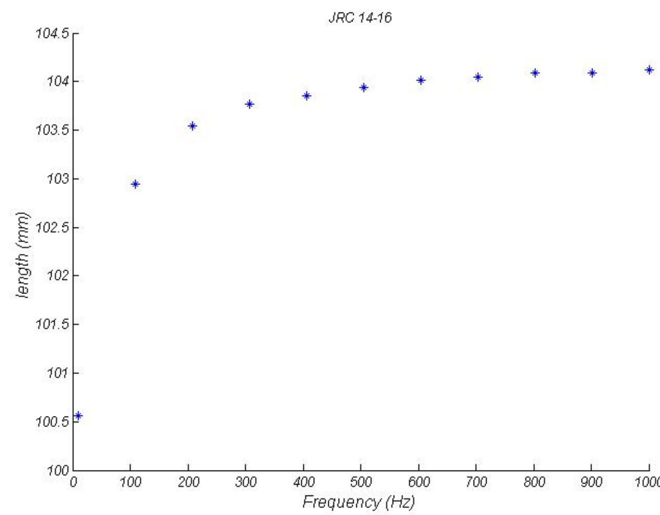

Fig. 6. Variation of actual length of profile vs. cutoff frequency of low pass filter for 14-16 JRC profile.

As illustrated in figure 6, variation of actual length with frequency, follows an exponential equation and an exponential diagram can be fitted on this diagram. In order to compare different profiles, the actual lengths of different filtering frequencies are divided into the actual length of unfiltered profile, then the following relation is fitted on it.

$$L = CL_1 Fr^{CL_2} \quad (1)$$

In this equation, L represents the actual length of profiles for specific cutoff frequency of low pass filter (Fr) and CL_1, CL_2 are exponential coefficients, which are different for each profile. It seems that these coefficients can be utilized for quantifying joint roughness. To investigate this idea, CL_1, CL_2 are calculated for all JRC profiles (table 1).

In equation 1 the first coefficient of exponential equation (CL_1) represents the variation of roughness length. The lower CL_1 results in the higher roughness and shows that the profile includes signals with higher amplitude. The second coefficient (CL_2) represents the convexity of the curve of actual length variation vs. cutoff frequency of low pass filter. Thus the higher CL_2 leads to the higher roughness. Actually this coefficient shows the effect of signals with different frequencies.

These coefficients cannot quantify the roughness lonely. Therefore the new parameter (CL) with the following equation is introduced:

$$CL = CL_1 \times (1 - CL_2) \quad (2)$$

The value of CL is calculated for all JRC profiles (table 1). In figure 7 the relation of JRC and CL is illustrated and the relationship between these two parameters is shown in the following equation:

$$JRC = 2.7239\, ln\, CL + 35.076 \quad (3)$$

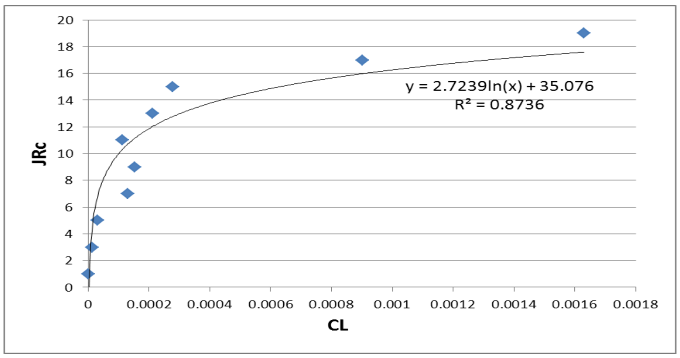

Fig. 7. Relation between JRC and CL for JRC profiles.

Table 1. The value of new parameters for each JRC profiles.

JRC	CL_1	CL_2	*CL*	Ci_1	Ci_2	*Ci*
1-2	0.997	0.0004	1.2E-06	0.24	0.386	0.085
2-4	0.990	0.0015	1.3E-05	0.57	0.347	0.175
4-6	0.986	0.0022	3.0E-05	1.13	0.248	0.280
6-8	0.970	0.0044	0.00012	0.87	0.346	0.303
8-10	0.970	0.0052	0.00015	2.62	0.201	0.459
10-12	0.974	0.0044	0.00011	5.13	0.100	0.515
12-14	0.964	0.0059	0.00021	3.37	0.164	0.557
14-16	0.959	0.0068	0.00027	7.21	0.081	0.588
16-18	0.927	0.0124	0.00090	3.97	0.197	0.771
18-20	0.901	0.0165	0.00162	3.25	0.243	0.792

3.2. *Parameter of CI*

After studying the variation of real length of the profile, due to the cutoff frequency of low pass filter, the variation of asperities' average dip angel that face with shear direction is investigated. Hence, if the shear direction is left to right then the average dip angel of elements that face to the left is calculated and vice versa. Therefore, for each profile, two different behaviors can be predicted.

For this purpose, for each JRC profiles, variation of average dip angle for two different directions are calculated, due to changes in cutoff frequency of low pass filter. In figure 8 the variation of average dip angle in two different directions is illustrated. As shown in this figure, with decreasing the cutoff frequency of low pass filter, average dip is reduced and exponential equation can be fitted on this data.

Figure 9 shows the exponential equation fitted on average dip angles (left to right). This equation can be written as below:

$$D = CI_1 Fr^{CI_2} \quad (4)$$

Where D represents the average dip angle of profiles for specific cutoff frequency of low pass filter (Fr) and CI_1, CI_2 are exponential coefficients that are different for each profile. It seems that these coefficients cannot be used to quantify joint roughness lonely, like the previous part. To investigate this idea, CI_1, CI_2 are calculated for all JRC profiles (table 1).

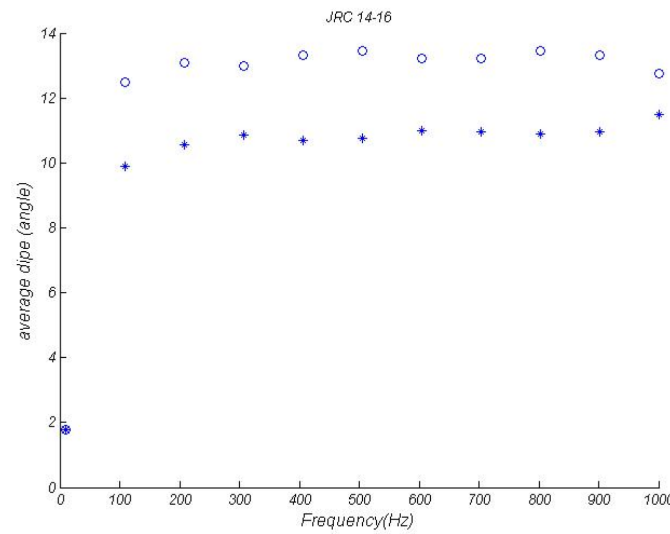

Fig. 8. Variation of average dip angle of profile vs. frequency of low pass filter for two different directions of 14-16 JRC profile (star: left to right; circle: right to left).

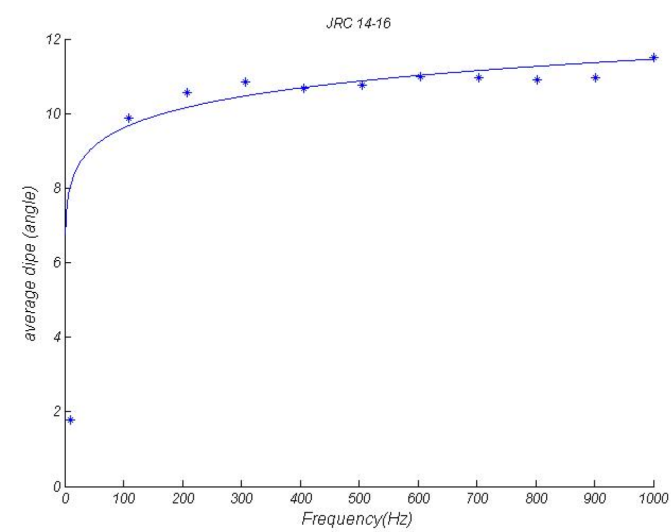

Fig. 9. The exponential equation that is fitted on variation average dip angles for 14-16 JRC profile (left to right).

In equation 4 the first coefficient of exponential equation (CI_1) represents the variation of average dip angle. Thus the lower CI_1, indicates the higher roughness. The second coefficient (CI_2) represents the convexity of the curve of average dip angle variation with low pass filter frequency. Therefore the higher CI_2, indicates the higher roughness. Actually this coefficient shows the effect of signals with different cutoff frequencies.
The new parameter (*CI*) is defined with following equation is introduced:

$$CI = CI_1 \times (1 - CI_2) \quad (5)$$

The value of *CI* is calculated for each JRC profile (table 1). In figure 10 the relation between JRC and CI is illustrated and the relationship between these two parameters is shown in the following equation:

$$JRC = 25.077CI + 1.3597 \quad (6)$$

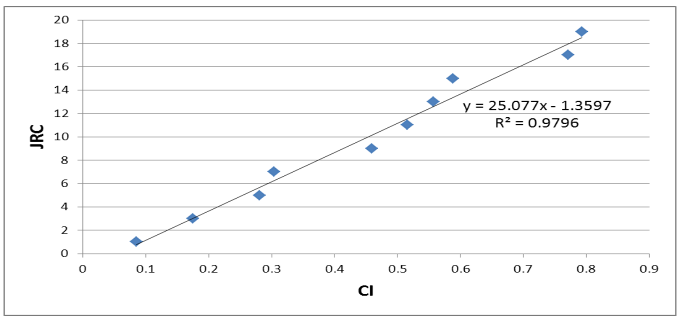

Fig. 10. Relation between JRC and CI for JRC profiles.

4. CONCLUSIONS

The JRC profiles are digitized with 0.5 mm accuracy and for these profiles more accuracy is not reasonable. Therefore, if the rock profiles digitize with different accuracy to 0.5mm, these equations have more errors in predicting JRC value. Actually the accuracy of rock joints surface sampling affects all previous methods like the method in this paper, but this method can be less sensitive than other methods because of using Fourier analysis.
CI and CL have good correlation with JRC but CI is better than CL because CI could represent the shear direction.
In this paper the new method is used to calculate JRC but it is better to use this method and these parameters directly in rock joint shear criteria. On the other hand, these parameters are two-dimensional and it is one of the weaknesses of this method. To resolve this issue, the surface of rock joints can be divided into many parallel profiles that are parallel to the shear direction, and then these parameters are calculated for each profile and are averaged to achieve a number. Besides, this method can be used for surfaces similar to profiles and directly calculate three-dimensional parameters that will be presented in the future article.

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