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Novel method for evaluating surface roughness by grey dynamic filtering

Zhongyu Wang, Hao Meng *, Jihua Fu

School of Instrumentation Science & Opto-Electronics Engineering, Beihang University, Xueyuan Road 37, Beijing 100191, PR China

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ABSTRACT

The evaluation of surface roughness is of great importance for manufacturing industries as the roughness of a surface has a considerable influence on its quality and the function of products. For surface roughness evaluation, to find an appropriate reference line is of the utmost importance. A smooth grey reference line obtained by grey dynamic filtering is proposed to evaluate surface roughness. The primary sampling data of the measured surface need not obey the typical distributions and the surface profile with less data can also be evaluated without losing primary data. Through sample analysis, the grey reference line is well consistent with ISO Gaussian reference line and their evaluation results for surface roughness are in agreement. The grey reference line can be used as one of complements for Gaussian reference line.

1. Introduction

Surface roughness is microstructure profile error with minor wave pitch on the surface of a workpiece. The performances of workpieces and products, such as wear resistance, corrosion resistance, fatigue strength, sealing properties, heat conductivity and life time, are directly influenced by surface roughness. Besides, surface roughness is greatly sensitive to technical process. The technical factors, such as wear of cutting-tools, change of cutting parameters, vibration of machine tools, manufacturing operation and surface treatment, can result in change of surface roughness [1–3]. Hence, to reasonably measure and evaluate surface roughness is not only the groundwork of assessing the functional performances of workpieces and products, but also the basis of monitoring and controlling the technical process.

For surface roughness evaluation, to find an appropriate reference line is of the utmost importance. The accuracy of roughness evaluation is strongly dependent on the accuracy of the evaluation reference line. In the past few decades, a lot of research efforts have been carried out in the area of surface roughness evaluation [4]. Many kinds of evaluation reference lines, such as the least-squares mean line, the arithmetic mean line, the multinomial regression line, wavelet reference line and Gaussian reference line, have been brought forward [5–8]. The least-squares mean line or the arithmetic mean line is a broken line in the whole evaluation length and discontinuity points can occur on the interfaces between evaluation lengths. Strictly speaking, however, the reference line should be composed of some low-frequency components characterizing the surface profile. Therefore, it should be a smooth curve rather than a broken line. In this sense, both the least-squares mean line and the arithmetic mean line can not describe the form of the surface profile intuitively. The multinomial regression line of a surface profile is described by a special algebraic expression. The special algebraic expression can only approximate the low-frequency components of the surface profile, while its efficiency strongly depends upon the order of the multinomial. As an effective signal analysis method, wavelet analysis is widely used in the field of signal processing. In surface roughness evaluation, wavelet reference line has been used to evaluate surface roughness more effectively. However, how to determine the hierarchy of wavelet decomposition and how to choose wavelet reference line are random to a certain extent. This

* Corresponding author. Tel.: +86 010 82339303; fax: +86 010 82338152.
E-mail address: menghao@aspe.buaa.edu.cn (H. Meng).

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randomness can lead to the uncertainty of the roughness evaluation results. According to ISO 11562 [9], Gaussian reference line, namely a profile line obtained by Gaussian low-pass filtering, is legalized as the reference line for surface roughness evaluation in recent years. Due to the characteristic of linear phase of Gaussian low-pass filtering, the reference line can be extracted without distortion. However, three preconditions [10] are necessary when using Gaussian reference line to evaluate surface roughness. (1) Form errors must be eliminated prior to implementing Gaussian filtering. (2) It is on the assumption that the primary surface profile is composed of harmonic series. (3) Surface roughness should obey Gaussian distribution. At the same time, some primary sampling data can be lost by Gaussian filtering algorithm, thus there must be enough data in the whole evaluation length in order to implement Gaussian filtering.

Additionally, the above-mentioned reference lines strongly depend on prior knowledge and sample size. Unfortunately in some application situations, to obtain large sample size is very difficult in order to improve the measurement speed and sometimes it is hard to learn prior knowledge, these methods are therefore limited in applications. As a typical non-statistical theory, grey system theory is extremely suitable to deal with the less data, little sample, unknown distribution, lack of information and uncertainty [11,12]. In this paper, the grey reference line for surface roughness evaluation based on grey system theory is proposed. A profile line obtained by grey dynamic filtering for the primary surface profile is regard as evaluation reference line for surface roughness evaluation.

2. Grey method for surface roughness evaluation

2.1. Method principle

A typical engineering surface consists of a range of spatial frequencies. The high-frequency or short-wavelength components are referred to as surface roughness, the medium frequency components as surface waviness and low-frequency components as form errors. In surface roughness evaluation, the sum of surface waveness and form errors is usually considered as an evaluation reference line.

Let $x(t)$ be primary profile curve, then $x(t)$ can be described by

$$x(t) = r(t) + s(t) \tag{1}$$

where, $r(t)$ is a reference line for surface roughness evaluation and $s(t)$ is surface roughness.

For the measured surface, its profile curve $x(t)$ can be regarded as a random quantity superposed on its profile form. In the grey system theory, all the random quantities are considered as grey quantities varying in a certain range. To deal with the grey quantities is not to find probability distribution or statistical characteristics, but to find the law between the primary data through grey generating. And then modeling based on the grey system theory can be carried out [13,14]. Grey dynamic filtering is a new filtering technique on the basis of rolling grey model $RGM(1,1)$. As one of methods for grey modeling, $RGM(1,1)$ reconstructs itself whenever a new data rolls in. Consequently the built model is provided with the function of metastasis. The obtained model curve varies with the new data rolling in. Thus the obtained evaluation reference line has good consistency with the general trend of the surface profile. In the process of building $RGM(1,1)$, the high-frequency components in the primary profile curve can be suppressed and the low-frequency components can be obtained through grey generating. Therefore, $RGM(1,1)$ is extremely suitable to obtain the solution of $r(t)$ in the Eq. (1).

In the process of buding $RGM(1,1)$, for each sampling point, several grey model curves can be used to describe it. After synthesizing all the model curves in the evaluation length, the grey reference line $r_{GM}(t)$ for surface roughness evaluation can be obtained. This can be described by

$$r_{GM}(t) = RGM(x(t))$$

where, $RGM(x(t))$ is the rolling grey model of $x(t)$.

2.2. Grey dynamic filtering

Given data sequence $x^{(0)} = \{x^{(0)}(1), x^{(0)}(2), \ldots, x^{(0)}(k), \ldots, x^{(0)}(N)\}$ is the time series of the primary sampling data of the surface profile in the whole evaluation length, where $x^{(0)}(k)$ is positive for all k. Supposing the data length in a sampling length, namely the length of rolling grey modeling interval, is n. And at the m moment, the data series is $x_m^{(0)} = \{x^{(0)}(m), x^{(0)}(m+1), \ldots, x^{(0)}(m+n-1)\} = \{x_m^{(0)}(1), x_m^{(0)}(2), \ldots, x_m^{(0)}(n)\}$, then the sequence of 1-AGO (1-Accumulated Generating Operation) can be obtained by

$$x_m^{(1)} = \{x_m^{(1)}(1), x_m^{(1)}(2), \ldots, x_m^{(1)}(n)\}$$

where, $x_m^{(1)}(k) = \sum_{i=1}^{k} x_m^{(0)}(i),\ k = 1, 2, \ldots, n.$

The MEAN data sequence of $x_m^{(1)}$ is described by

$$z_m^{(1)} = \{z_m^{(1)}(1), z_m^{(1)}(2), \ldots, z_m^{(1)}(n)\}$$

where, $z_m^{(1)}(k) = \begin{cases} x_m^{(1)}(1), & k = 1 \\ \frac{1}{2}\left(x_m^{(1)}(k) + x_m^{(1)}(k-1)\right), & k = 2, 3, \ldots, n \end{cases}.$

The first order grey differential equation concerning the sequence $x_m^{(0)}$ is

$$x_m^{(0)}(k) + a_m z_m^{(1)}(k) = b_m \tag{2}$$

where, a_m and b_m are the undetermined coefficients of the grey differential equation.

The Eq. (2) can be described as a matrix equation,

$$Y_m = \phi_m \theta_m \tag{3}$$

where,

$$Y_m = \begin{pmatrix} x_m^{(0)}(2) \\ x_m^{(0)}(3) \\ \vdots \\ x_m^{(0)}(n) \end{pmatrix},\ \phi_m = \begin{pmatrix} -z_m^{(1)}(2) & 1 \\ -z_m^{(1)}(3) & 1 \\ \vdots & 1 \\ -z_m^{(1)}(n) & 1 \end{pmatrix},\ \theta_m = \begin{pmatrix} a_m \\ b_m \end{pmatrix}.$$

Among these parameters, Y_m, ϕ_m are known and θ_m is undetermined.

As the least-squares estimate value for θ_m, $\hat{\theta}_m$ can be obtained by solving the Eq. (3). Namely,

$$\hat{\theta}_m = (\phi_m^T \phi_m)^{-1} \phi_m^T Y_m$$

With $\hat{\theta}_m$ as the parameter, the whitenization differential equation corresponding to the Eq. (2) can be obtained by

$$\frac{dx_m^{(1)}}{dt} + a_m x_m^{(1)} = b_m \quad (4)$$

By solving the Eq. (4), the solution of the Eq. (2) is given by

$$\hat{x}_m^{(1)}(k) = (x_m^{(0)}(1) - \frac{b_m}{a_m})e^{-a_m(k-1)} + \frac{b_m}{a_m}$$

where, $k = 1, 2, \ldots, n$.

After IAGO (Inverse Accumulated Generating Operation), the grey model value sequence corresponding to $x_m^{(0)}$ can be obtained by

$$\hat{x}_m^{(0)}(k+1) = \hat{x}_m^{(1)}(k+1) - \hat{x}_m^{(1)}(k) \quad (5)$$

where, $k = 1, 2, \ldots, n$.

The grey model curve corresponding to the moment m can be obtained by the Eq. (5). In the process of building $RGM(1,1)$, $N - n + 1$ grey model curves are obtained in the whole evaluation length. With m changing, these grey model curves slide along the profile of the measured surface accordingly. For the sampling point j, there are totally T_j grey model curves to describe this point. Supposing the weight of these model curves is the same, the mean $\overline{\hat{x}_j}$ of all the model curves at the sampling point j is regarded as the amplitude of the point j. Namely,

$$\overline{\hat{x}_j} = \begin{cases} \frac{1}{T_j} \sum\limits_{m=0}^{T_j-1} \hat{x}_m(j-m), & 1 \leqslant j < n \\ \frac{1}{T_j} \sum\limits_{m=j-n}^{j-n+T_j-1} \hat{x}_m(j-m), & n \leqslant j \leqslant N \end{cases} \quad (6)$$

$$\text{where, } T_j = \begin{cases} 1, & j = 1 \\ j-1, & 1 < j \leqslant n \\ n-1, & n < j \leqslant N-n+2 \\ N-j+1, & N-n+2 < j \leqslant N, \end{cases} \quad j = 1, 2, \ldots, N.$$

The smooth curve connecting each of $\overline{\hat{x}_j}$ in the Eq. (6) is regarded as the grey reference line for surface roughness evaluation.

3. Sample analysis

In order to validate the grey reference line for evaluating surface roughness, grey dynamic filtering arithmetic and Gaussian filtering arithmetic [15] are carried out by Matlab7.0 in this paper separately. Surface roughness of some measured surfaces is evaluation by the two different methods.

3.1. Surface roughness evaluation for standard templets of flat grinding

The same standard templet of flat grinding for surface roughness is evaluated by Gaussian reference line and grey reference line, respectively. The profile arithmetic average error of the templet R_a is 0.2 μm. The sampling length of the templet is taken as 0.08 mm and the evaluation length consists of five sampling lengths. In the whole evaluation length, the number of the sampling points N is 675. As shown in Fig. 1, the obtained grey reference line has good consistency with Gaussian reference line. In contrast, the grey reference line can describe the surface profile in the whole evaluation length, while a part of the primary sampling data is lost by Gaussian reference line due to the edge effects of Gaussian filtering.

Although a part of the primary sampling data is lost by Gaussian reference line, Gaussian reference line is a continuous curve and is still authorized by ISO 11562. Hence Gaussian reference line is usually regarded as the standard to assess other reference lines. As shown in Fig. 2 (a) and (b), the roughness profile by the grey reference line is very close to the one by Gaussian reference line in their common evaluation length. A part of roughness profile data and the profile arithmetic average error R_a by the two methods are given by Table 1. As shown in Table 1, the R_a by the two methods is close to 0.2 μm. The relative error of the R_a by the grey reference line to the R_a by Gaussian reference line is merely −0.103%. The results show that surface roughness can be reasonably evaluated by the obtained grey reference line.

Table 2 shows the results of surface roughness evaluation for five standard templets of plat grinding with different R_a. The nominal R_a of the five standard templets is shown as the first column of Table 2. The obtained R_a by the two methods is respectively, shown in the second column and the third column of Table 2. The relative errors of the R_a by the grey reference line to the R_a by Gaussian reference line are given by the fourth column of Table 2. As shown in Table 2, the R_a by the two methods is in agreement. For all the five standard templets, comparatively the R_a by Gaussian reference line is a little more than the R_a by the grey reference line, which shows that the components of the measured surface can not be completely separated by Gaussian filtering and there are still some low-frequency components left in surface roughness profiles. In contrast, the components of the measured surface can be separated by grey dynamic filtering more completely and grey reference line can describe the surface profiles more effectively.

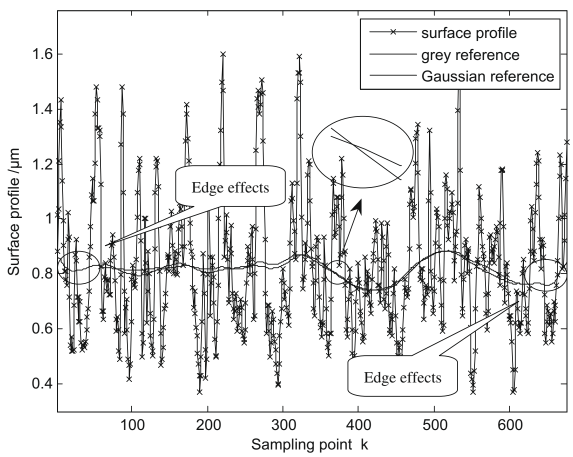

Fig. 1. Surface profile, the grey reference line and Gaussian reference line of the standard templet.

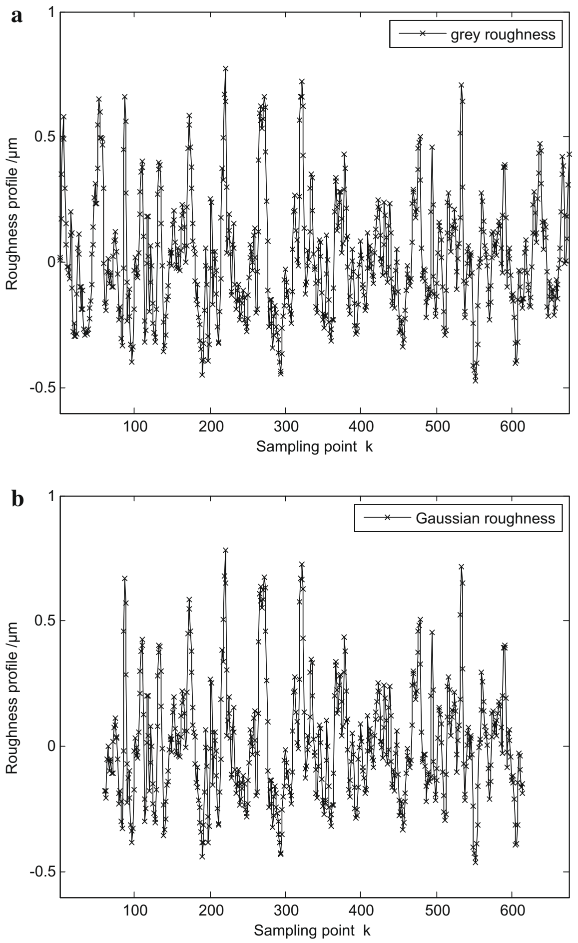

Fig. 2. Results of evaluating the standard templet by grey reference line and Gaussian reference line: (a) surface roughness profile by the grey reference line and (b) surface roughness profile by Gaussian reference line.

Table 1
Roughness profile data by the two methods/μm.

k	Gaussian reference line	Grey reference line
136	0.1612	0.1590
137	−0.0077	−0.0086
138	−0.2350	−0.2367
139	−0.3528	−0.3533
140	−0.3323	−0.3323
141	−0.2902	−0.2892
142	−0.2187	−0.2161
143	−0.1545	−0.1499
144	−0.1411	−0.1388
145	−0.0986	−0.0941
146	−0.0121	−0.0128
147	0.0312	0.0307
148	0.0381	0.0401
149	−0.0206	−0.0210
150	0.0300	0.0328
151	0.1389	0.1389
152	0.1967	0.2019
153	0.1597	0.1532
154	0.0716	0.0723
155	−0.0313	−0.0302
⋮	⋮	⋮
R_a	0.1948	0.1946
relative error	–	−0.103%

Table 2
Contrast of surface roughness evaluation results by the two methods/μm.

Nominal R_a	Gaussian reference line	Grey reference line	Relative error (%)
0.1	0.0972	0.0969	−0.309
0.2	0.1948	0.1946	−0.103
0.4	0.3925	0.3917	−0.204
0.8	0.7909	0.7901	−0.101
1.6	1.5910	1.5902	−0.050

3.2. Surface roughness evaluation for a real workpiece

In order to further validate the grey reference line for evaluating surface roughness, a real workpiece is also evaluated by the grey reference line and Gaussian reference line separately. The sampling length of the real workpiece is also taken as 0.08 mm and its evaluation length consists of five sampling lengths. As shown in Fig. 3, although the number of the sampling points N is less than 200 in the whole evaluation length, the obtained grey reference line has still better consistency with the primary surface profile. In contrast, Gaussian reference line deviates from the primary surface profile at some sampling points. The roughness profiles by the two methods are respectively, shown in Fig. 4 (a) and (b). As evaluation results, the R_a by Gaussian reference line is 0.0751 and the R_a by the grey reference line is 0.0748. The relative error of the latter to the former is merely −0.399%. The results further validate the obtained grey reference line in surface roughness evaluation even for the measured surface with less data.

4. Conclusions

The grey system theory is applied in the area of surface roughness evaluation. The primary profile curve is regarded as a grey quantity superposed on the profile form of the measured surface and grey dynamic filtering is used to obtain the reference line for surface roughness evaluation. Beside the existing methods, the proposed method has the following advantages.

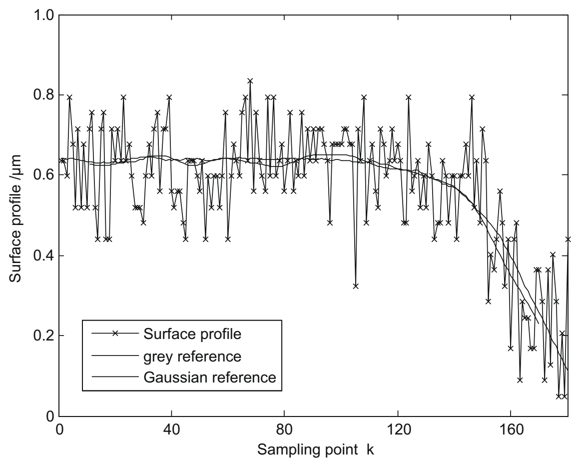

Fig. 3. Surface profile, the grey reference line and Gaussian reference line of the real workpiece.

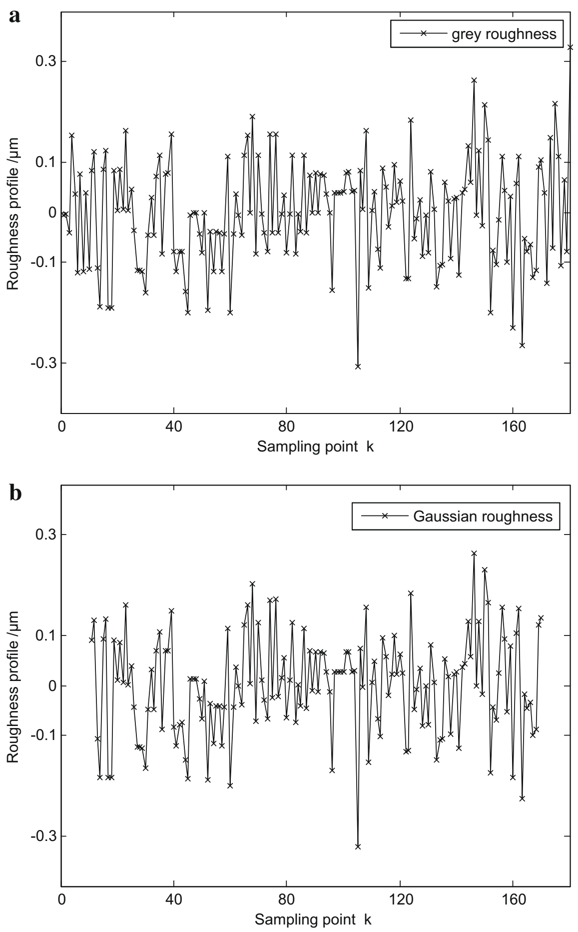

Fig. 4. Results of evaluating the real workpiece by grey reference line and Gaussian reference line: (a) surface roughness profile by the grey reference line and (b) surface roughness profile by Gaussian reference line.

(1) The grey system theory is extremely suitable to deal with the less data, little sample, unknown distribution, lack of information and uncertainty. Hence grey dynamic filtering based on *RGM*(1,1) can be implemented even though less primary sampling data of the measured surface are available.
(2) In the process of implementing grey dynamic filtering, the primary sampling data of the measured surface can be independent of the typical distributions such as Gaussian distribution.
(3) In the process of building *RGM*(1,1), the data concerned with modeling are updated without cease. Thereby the model curve can accord with the trend of the surface profile. Thus the reference line for surface roughness evaluation as low-frequency components can be effectively obtained.
(4) There are no edge effects in the process of grey dynamic filtering, so in the whole evaluation length surface roughness can be evaluated by the obtained grey reference line.
(5) The grey reference line is well consistent ISO Gaussian reference line and their evaluation results for surface roughness are in agreement. The grey reference line can be one of complements for Gaussian reference line in use.

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