Precision Engineering 44 (2016) 55–61

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

The filtering method to calculate the transmission characteristics of the low-pass filters using actual measurement data

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ARTICLE INFO

Article history:
Received 24 September 2015
Accepted 27 September 2015
Available online 24 October 2015

Keywords:
Roughness
Low-pass filter
Gaussian filter
Spline filter
Transmission characteristics

ABSTRACT

The Gaussian filter and spline filter are low-pass filters used in surface roughness estimation methods, and their transmission characteristics are well known. However, the transmission characteristics of the Gaussian filter and spline filter used at actual sites may not be in agreement with their theoretical characteristics. Generally, the spline filter is used with an open profile. Although the transmission characteristics of the periodic spline filter are well known, these transmission characteristics are not those of a nonperiodic spline filter used with an open profile. In the case of a Gaussian filter, the filter width of the theoretical transmission characteristics is ∞. However, a Gaussian filter of filter width λ_c is used at actual sites. This fact is a major problem. To solve this problem, it is necessary that the transmission characteristics of a low-pass filter are obtained from actual measurement data and the filter output. However, it is not possible to calculate the transmission characteristics from actual measurement data owing to the end effect and the discontinuity at each end of the data, etc. In this paper, we propose a new method for exactly calculating the transmission characteristics of a low-pass filter. This method involves the process in which the open profile is considered as a closed profile by repeating it periodically. The transmission characteristics of a nonperiodic spline filter and a Gaussian filter (filter width λ_c) used at actual sites were confirmed by the proposed method. The transmission characteristics of the Gaussian filter of filter width λ_c were almost the same as the theoretical characteristics. However, the transmission characteristics of the nonperiodic spline filter were considerably different from those of a periodic spline filter with well-known characteristics. Moreover, the transmission characteristics of the nonperiodic spline filter were found not to be unique.

1. Introduction

The surface roughness profile of an object to be measured is obtained by extracting a mean line for the long-wavelength component from a primary profile using a low-pass filter and subtracting it from the primary profile. This mean line is usually determined by convolving a Gaussian low-pass filter with the primary profile [1]. The filter is a phase-corrected filter established on the basis of ISO11562 [2]. However, ISO11562 was replaced with ISO16610-21 [3] in 2011, and it will be necessary for the transmission characteristics to be exactly the same as the Gaussian function. The Gaussian filter is the low-pass filter that transmission characteristics are the Gaussian function. However, when the Gaussian filter is applied to an open profile [4], it causes unanticipated distortion to the ends of the data called the end effect [5].

The theoretical transmission characteristics of the Gaussian filter are well known. However, the transmission characteristics of the Gaussian filter used at actual sites may not be in agreement with the theoretical characteristics. The filter width of the theoretical transmission characteristics is ∞. And yet, a Gaussian filter of filter width λ_c is used at actual sites. Probably deviation of filter width ∞ and λ_c is very few. However, it is necessary to confirm the transmission characteristics deviation of filter width ∞ and λ_c quantitatively.

On the other hand, a spline filter [6,7] is one of the low-pass filter, too. The spline filter applies a cubic smoothing spline curve to the measurement data. A nonperiodic spline is used with an open

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http://dx.doi.org/10.1016/j.precisioneng.2015.09.020
0141-6359/

profile and a periodic spline is used with a closed profile [4]. If a nonperiodic spline is used, the end effect does not occur. Also, the attenuation slope of the spline filter is slightly steeper than that of the Gaussian filter. Although the theoretical transmission characteristics of the spline filter are also well known, the transmission characteristics of the spline filter used at actual sites not be in agreement with the theoretical characteristics. Generally, the spline filter is used with an open profile. And, an open profile uses the nonperiodic spline. However, the transmission characteristics of the spline filter well known as the theoretical transmission characteristics of the spline filter are periodic spline's one. And, the transmission characteristics of the nonperiodic spline filter are not same as those of the periodic spline filter. However, the transmission characteristics of the nonperiodic spline filter are unknown.

To solve these problems of differing condition of the filters that is used at actual sites and the theoretical characteristics, it is necessary to calculate the transmission characteristics of an applied low-pass filter obtained from actual measurement data and the filter output.

Therefore, the authors previously established a method for obtaining the transmission characteristics from model data [8]. In this method, the transmission ratio is obtained as the quotient of the discrete Fourier transform of the input data and the discrete Fourier transform of the output data without using a filter with a weighting function in the Fourier transform. However, the transmission characteristics were not obtained using actual measurement data. This method requires model data that satisfy a specific condition.

In this paper, this method is expanded and transmission characteristics are obtained using actual measurement data. The rest of the paper is organized as follows. In Section 2, the transmission characteristics are calculated for various conditions, and we outline the problems that arise from such calculations. Section 3 shows the calculation method for the transmission characteristics when using actual measurement data. In Section 4, the experimental results of the expanded method are reported, and Section 5 gives a summary of this paper.

2. Problems in calculation of transmission characteristics

2.1. Basic computational model

Here, N items of measurement data are expressed as $f(i)$, the weighting function of the discretized low-pass filter is $l(i)$, and the mean line of the output obtained by convolution of the weighting function with $f(i)$ is $h(i)$. Provided that, i is measurement points of the equal interval of measurement direction x.

$$h(i) = \sum_k f(k)l(i-k) = (f \otimes l)(i) \tag{1}$$

$\tilde{F}(u_k)$, $\tilde{L}(u_k)$ and $\tilde{H}(u_k)$ are the discrete Fourier transforms of $f(i)$, $l(i)$, and $h(i)$, respectively, where $u_k = k/N$, which satisfy the following.

$$\tilde{H}(u_k) = \tilde{F}(u_k)\tilde{L}(u_k) \tag{2}$$

Then, transmission characteristics of low-pass filter $|\tilde{L}(u_k)|$ (spectrum) is given by following equation.

$$|\tilde{L}(u_k)| = \left|\frac{\tilde{H}(u_k)}{\tilde{F}(u_k)}\right| \tag{3}$$

2.2. Calculation of the transmission characteristics of a Gaussian filter

It is confirmed whether Eq. (3) can calculate the transmission characteristics from actual measurement data. Even if the transmission characteristics are calculated from actual measurement data that similar to model data, new proposed method has no value. Fig. 1 is a model data that could calculate the transmission characteristics [8]. As one of the conditions for the model data, the input data and filter output must be connected smoothly at the ends of the data [9]. Thus, actual measurement data do not satisfy this condition. Fig. 2 shows actual measurement data $f(i)$ of a glass surface, where the difference in the values at the ends of the data is large. The experiments reported later use these data.

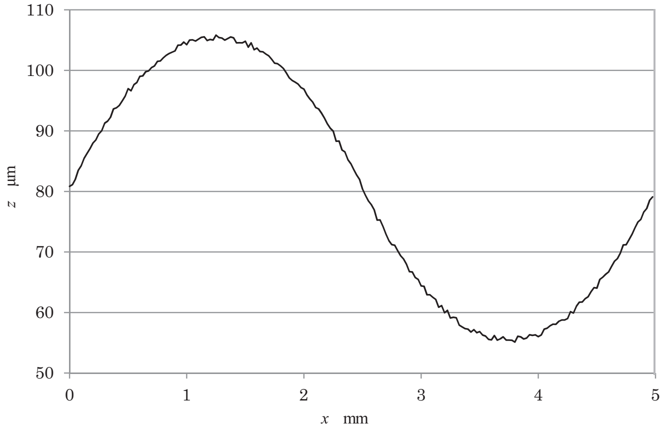

Fig. 1. Input data (model data).

First, the case of the Gaussian filter is confirmed. A problem of the Gaussian filter is how to deal with the end effect, which changes the filter output $h(i)$. The following three cases are investigated to deal with the end effect. In the first case, data over the entire area including the end effect area are used. In the second case, the GR0 filter [10] is used. In the third case, only data from the central part are used, with the end effect areas removed. In addition, a window function is confirmed to deal with discontinuities. These four cases are investigated.

Fig. 3 shows the outputs of the Gaussian filter and GR0 that are denoted as $h(i)$. Other than at the end effect areas, the output of the GR0 is the same as that of the Gaussian filter.

2.2.1. Case that the end effect areas are included

First, the transmission characteristics are calculated from the discrete Fourier transform of all the input data $f(i)$ and the Gaussian filter output $h(i)$ including the end effect areas. Fig. 4 shows the transmission characteristics of the Gaussian filter in this case. The transmission characteristics obtained from the model data are the same as the theoretical characteristics. However, the transmission

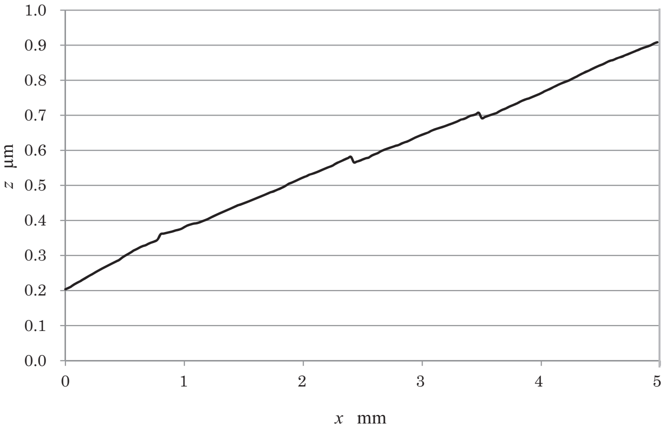

Fig. 2. Input data $f(i)$ (actual measurement data).