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Low-pass filter without the end effect for estimating transmission characteristics—Simultaneous attaining of the end effect problem and guarantee of the transmission characteristics

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ABSTRACT

A Gaussian filter (GF) is the most commonly used low-pass filter of measuring surface roughness. However, undesirable distortions, called “end effects,öccur near the end points of the data ends in GF. The transmission characteristics are one of the most important indicators that show the quality of a filter. Previously, it was only possible to obtain theoretical values for the transmission characteristics of filters whose weights were given by an explicit function. In recent years, it has also become possible to obtain the transmission characteristics of a filter whose weights are given by an implicit function. However, this method has a problem in that the values near the end points of the measurement data become significantly different from each other. The consequence is that end effects may occur in the filter outputs due to side effects of the periodic extension. In the case of a spline filter (SF) applied to open profiles, the transmission characteristics of a periodic SF with an end effect can be obtained uniquely. However, the transmission characteristics of a nonperiodic SF, which has no end effect, cannot be uniquely obtained. This results in a trade-off between the two states: end effects exist in a filter whose transmission characteristics can be obtained, and the transmission characteristics of a filter without end effects cannot be uniquely obtained. To address this problem, we propose a method for the GF processing that uses shearing, point symmetric extension, and periodic extension, and produces no end effect but allows the transmission characteristics to be obtained. Previously, there was a problem with the proposed method in that the rationale was unclear regarding how to determine the reference points for point symmetric extension. We resolved this and optimized the reference points. As a result, the proposed method was shown to be successful in not only resolving the end effects in the GF, but also obtaining the transmission characteristics.

1. Introduction

The roughness profile [1] of the surface of an object to be measured can be obtained by extracting a mean line from the primary profile using a low-pass filter whose cut-off value is λc, and then subtracting it from the primary profile. A Gaussian filter (GF) as defined in ISO16610-21 [2] is the most common low-pass filter used to obtain the mean line. However, when the Gaussian filter is applied to open contours in order to calculate a mean line, an unexpected oscillation or waviness occurs near the end points of the data series. This is called an end effect [3]. Fig. 1 shows the results of applying the Gaussian filter of 1 mm width to a 5 mm length of primary profile data. Over the area covering half of the filter width from each of the end points, end effects occurred in the mean line. A Gaussian regression filter of 0th order (GR0) and a Gaussian regression filter of 2nd order (GR2) were proposed to resolve this problem; however, since the weighting function of GR2 was different than that of the Gaussian filter, the output of GR2 was also different from that of the Gaussian filter. Therefore, now that ISO16610-21 precisely requires the weighting function of the low-pass filter to be the Gaussian function, the GR2 is not compatible with the Gaussian filter and is no longer applicable. In addition, although the output of GR0 is equal to the output of the Gaussian filter in an area outside the end effect area, if a slope exists in the

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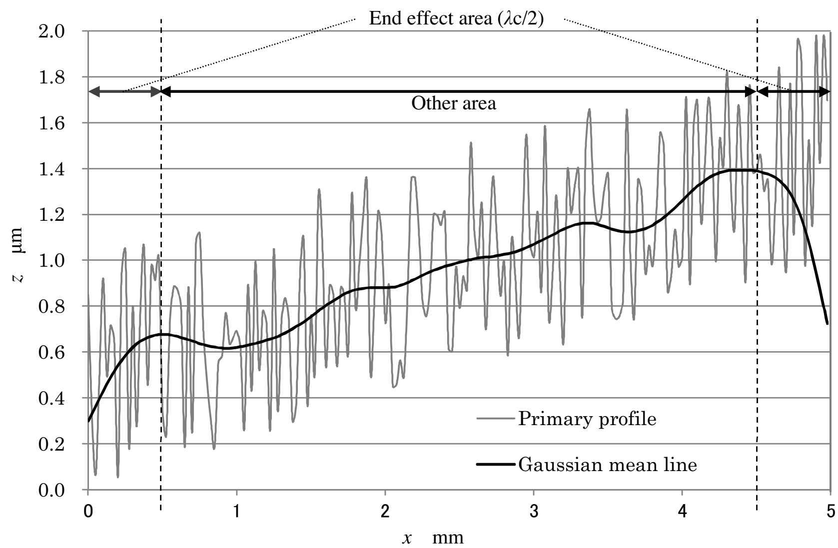

Fig. 1. End effect in mean line of Gaussian filter.

vicinity of both of the end points in the data series, then the end effects cannot be resolved.

Another type of low-pass filter that is commonly used is a spline filter [5,6]. There are two types of spline filters: the first is periodic, and the second is nonperiodic. A periodic spline filter is used for closed profile, such as the circumference of a pipe. Since closed profiles have no end points, end effects do not occur. However, if the periodic spline filter is applied to open profile with end points, then end effects do occur. For this reason, a nonperiodic spline filter is used for open profile because they do not have an end effect. The theoretical transmission characteristics of the periodic spline filter are published in the data sheets of standards and technical literature, although these theoretical transmission characteristics are not of the nonperiodic spline filter without end effect, but those of periodic spline filter. Recently, a method was proposed that uses the periodic extension of finite-length data to obtain the transmission characteristics of low-pass filters actually used in measurements based on the discrete Fourier transform (DFT) ratio of the filter input and output data [7]. When the characteristics of the Gaussian filter and the periodic spline filter were measured using this method, the results almost matched the corresponding theoretical values. However, these filters have end effects. In contrast, when the transmission characteristics of the nonperiodic spline filter with no end effects were calculated, the results were found to be significantly different than the published transmission characteristics of the periodic spline filter.

As this shows, the transmission characteristics of low-pass filters that have end effects, such as the Gaussian filter and the periodic spline filter, match the theoretical values that are published in data sheets. In contrast, the transmission characteristics of low-pass filters that have no end effects, such as the nonperiodic spline filter, do not match the theoretical values in data sheets. Therefore, there is a trade-off between guaranteeing of the transmission characteristics and resolving the end effects.

This trade-off can be solved by two methods. First is point symmetric extension that is an effective method for resolving end effects. Fig. 2 shows point symmetric extension. Black points are measurement data, white points are after the point symmetric extension. Second is periodic extension that is needed to calculate the transmission characteristics of low-pass filters [7]. The point symmetric extension method resolves end effects by extrapolating the input data that is close to the end points of the data series. There are two techniques used to implement point symmetric extension. The first is to obtain the reference points while minimizing the sum of the squared filtering output and input data calculated by using the data after extension [8]. The second is to obtain the reference points while minimizing the sum obtained by adding the bending energy to the method [8,9] It was confirmed that both techniques were able to resolve the end effects in normal filtering. Next, periodic extension causes side effect that is one of the end effects (Fig. 3). However, combining the point symmetric extension method with shearing [9], it is expected that this end effects by periodic extension can also be resolved.

However, point symmetric extension has three problems. The first problem (Problem A) is that there is no explanation of how this method is able to resolve the end effects. The second problem (Problem B) is that, although the bending energy corresponds to the case in which the order of the smoothing spline is of the 3rd order, no explanation is given as to why a cubic smoothing spline should be used instead of a higher order spline, such as a spline of 5th order or higher [10]. The third problem (Problem C) is the evaluation criterion. It is necessary to confirm the best ratio of the bending energy and the sum of the squares. In the methods for implementing the point symmetric extension as described in [8,9], the smoothing parameter μ is assumed to be constant. (In this paper, default μ value is setted as the μ of the spline filter) However, this needs to be verified because the optimal value for μ may vary depending on the low-pass filter.

Therefore, this paper solves the above three listed problems (A–C) and the side effects of periodic extension, using the essentials of the method described in [9] (a method of obtaining the reference points for the point symmetric extension method by using the sum of squares and bending energy as evaluation parameters). A calculation method is then proposed regarding the transmission characteristics of a low-pass filter that is applicable to open profile and does not produce end effects. Chapter 2 outlines the point symmetric extension method. Chapter 3 describes the proposed method that solve end effects and can calculate the transmission characteristics without waviness. Chapter 4 describes the experiments. Finally, chapter 5 provides a summary of this paper.

2. Point symmetric extension and shearing

End effects are the unexpected oscillations and waviness that occur close to the both data ends when calculating a mean line. When an interpolation is performed on mean line data using the

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