Recent Advances in Separation of Roughness, Waviness and Form

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1 Introduction

A typical engineering surface consists of a range of spatial frequencies. The high frequency or short wavelength components are referred to as roughness, the medium frequencies as waviness and low frequency components as form. Figure 1 illustrates this.

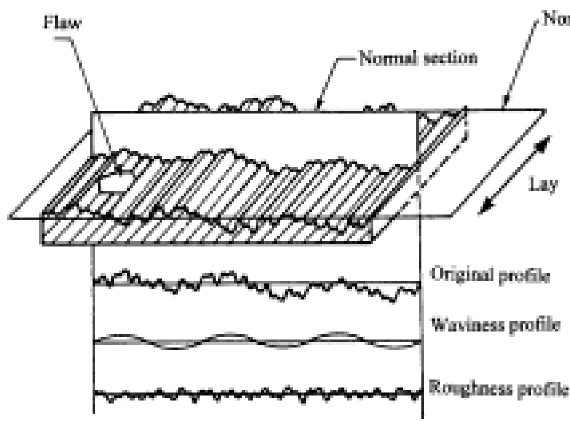

Figure 1 Roughness and waviness in a surface [1]

In the early days, different instruments and measurement techniques were adopted to capture the different wavelength regimes. Visual assessment using microscopy was used to identify any torn material or micro burr, stylus based instruments to obtain roughness and other special instruments to get form information. Today, with the availability of increasingly sophisticated gages and sensors, we have an overlap of measuring capability.

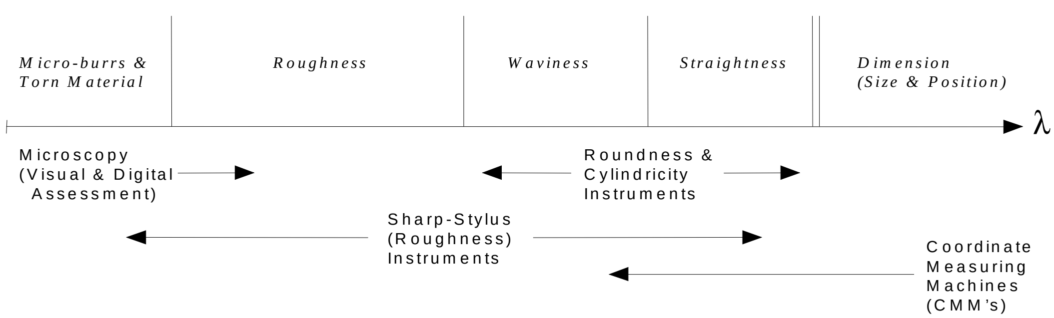

Figure 2 Metrology measurement spectrum [2]

A typical stylus based instrument can capture roughness, waviness and form. A roundness measuring instrument can also gather straightness data and a CMM can get both dimensional information and form. Figure 2 shows the current metrology measurement spectrum. As the bandwidth of measurement instruments increase, it has become essential to separate surface profile data into meaningful wavelength regimes before numerical characterization.

Historically, it has been accepted that different aspects of the manufacturing process generate the different wavelength regimes and these affect the function of the part differently [3]. By separating surface profile into various bands, we can map the frequency spectrum of each band to the manufacturing process that generated it. Thus, filtering of surface profiles serves as a useful tool for process control and diagnostics.

While engineers commonly trace manufacturing process variations based on surface profile data, mapping functional performance of a component based on surface profile information has been a challenge. The different wavelength regimes play a key role in critical parts like crankshafts and bearings. Thus, separation of signal into various bandwidths has to be viewed from a functional standpoint as well.

Digital filtering is a common practice to separate a signal into various regimes [4]. Analog RC filters have been replaced by the now common Gaussian filters. This paper reviews recent advances in filtering surface data including bandpass filters for process specific analysis and functional correlation, multiresolution analysis using wavelets, robust filters and morphological filters.

2 Current filtering practice

The earliest filter used in surface metrology is the analog RC filter. The 2RC digital filter [1] simulates the characteristics of the analog 2RC network. The transfer functions of the 2RC lowpass filter and highpass filter are

$$\frac{Output}{Input} = \left(1 - ik\,{}^{\lambda}\!/_{\lambda_c}\right)^{-2} \;,\; \frac{Output}{Input} = \left(1 - ik\,{}^{\lambda_c}\!/_{\lambda}\right)^{-2}$$

respectively, where $i = \sqrt{-1}$ and $k = 1/\sqrt{3} = 0.577$. The 2RC filter does not have linear phase characteristics. The digital 2RC filter overcomes many of the shortcomings of the analog RC filter [4]. Whitehouse proposed a new RC filter with linear phase [5]. The most widely used filter today is the Gaussian filter [1]. The weighting function and transmission characteristic of a Gaussain lowpass filter are

$$S(x) = \frac{1}{\alpha\lambda_c}\exp\left[-\pi\left(\frac{x}{\alpha\lambda_c}\right)^2\right]$$

$$\frac{A_{output}}{A_{input}} = \exp\left(\pi\left(\alpha\frac{\lambda_c}{\lambda}\right)^2\right)$$

respectively. Where $\alpha = \sqrt{\ln 2/\pi} = 0.4697$. The important property of Gaussian filter is linear phase characteristics and 50% transmission at the cutoff to simplify analysis of waviness.

3 Recent Developments

The advances in the field of digital signal processing and increasing computational capability have led to new developments in surface filtering.

3.1 Mapping process conditions

To analyze surface texture appropriately, the different wavelength components should be separated reasonably by applying filters with different cutoff, i.e., in figure 3 $\lambda_f, \lambda_c, \lambda_s$ are cutoffs for form, waviness and roughness. Figure 4 is a piston pin bore profile and its power spectral density(PSD). The PSD shows the different wavelengths and their sources. The short wavelengths are generated by tool radius and long wavelengths by guideway error. Chatter is clearly visible in the medium wavelength band.

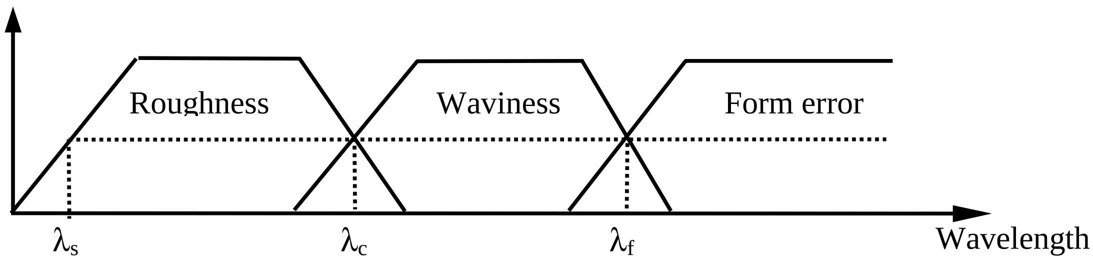

Figure 3 Separation of surface into frequency bands

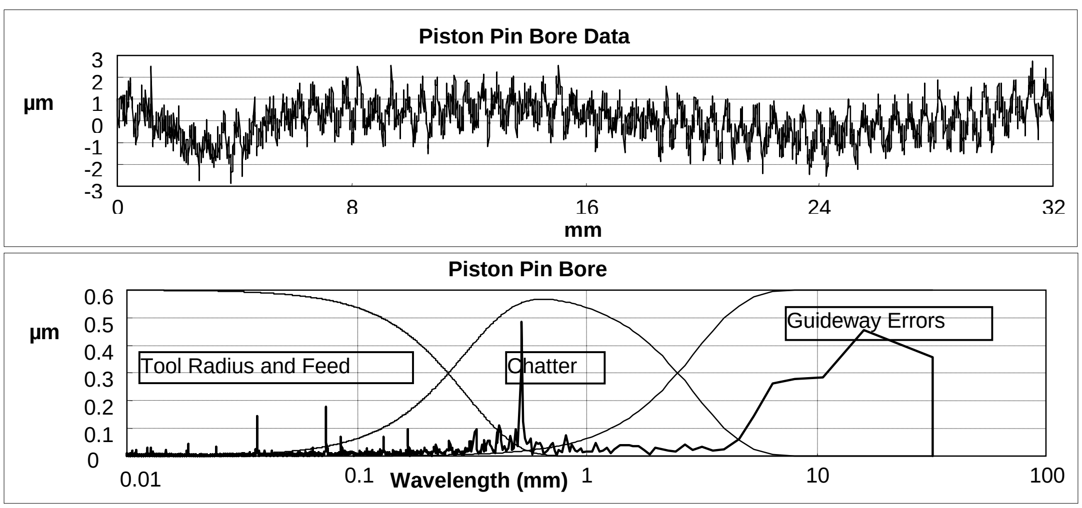

Figure 4 Piston pin bore profile and its PSD

3.2 Function critical components

Functional performance of a part is usually determined by different wavelengths on a surface. From a study by Marlburg [2], the middle wavelength components are critical to a diesel engine crankshaft pin's performance because they are relative to localized loading and ultimate failure of the bearing. It is necessary to control long wavelength aspects in a reasonable level for proper fit and short wavelength components for tribological requirements. Bandpass filtering is needed to separate those function critical wavelength components. Figure 5 shows the result from bandpass filtering of a crankshaft pin profile.

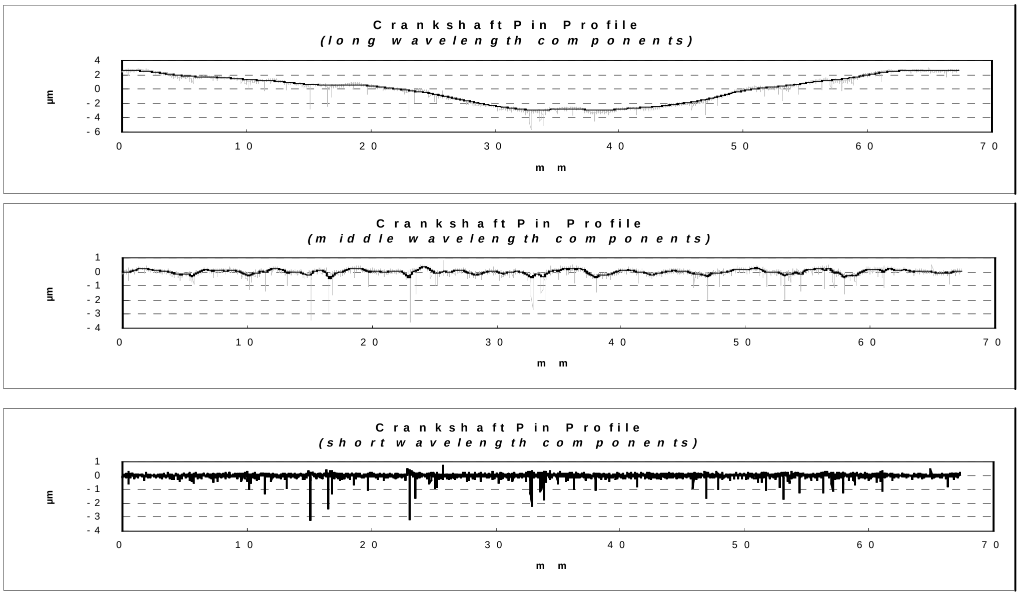

Figure 5 Bandpass filtering of a crankshaft pin profile

3.3 Filtering with wavelet transform

The fundamental idea behind wavelet analysis is to analyze signal according to scale. Wavelet analysis provides a flexible time-scale window localized on time-scale plane. If we look at a signal with a large window, we would notice gross features. Similarly, if we look at a signal with a small window, we would notice fine features. The result in wavelet analysis is to see both the fine and the gross features. This makes wavelets interesting and useful.

The primary study on the application of multiresolution analysis (MRA) for analyzing multi-scale engineering surfaces are presented by Chen, Liu and Raja [6][7]. As octave filter banks, wavelets can be used to decompose signal into different bands with different scales, which is also called multiresolution analysis of signal [8]. In MRA, the dyadically dilated wavelets constitute a bank of octave band pass filters and the dilated scaling functions form a low pass filter bank. The efficient implementation of discrete wavelet transform (DWT) is to get successive approximations of signal by applying the low pass filter bank and successive details of signal by applying the band pass filter bank. DWT appears to have great potential for analyzing multi-scale features in engineering surfaces due to its properties of good time-scale localization and flexible time-scale resolution. In order to analyze engineering surface texture, multi-scale approximations of original texture at different resolution levels will be extracted by DWT. This will give us a clear overview of the multi-scale features of surface texture. Then the separation of multi-scale features based on wavelength can be made according to the information provide by the multi-scale approximations. A polished surface profile is considered for wavelet filtering. In the multi-resolution approximation shown in figure

6, only long wavelengths in the profile are seen below level 5. The rougher structure appears from level 5 to 9. In approximations over level 9, more and more fine structures are added. We can reconstruct the profiles by combining the levels 1~5, levels 5~9 and levels 9~13. Various families of wavelets can be used for MRA. Each one has its own advantages and limits. Spline wavelets are recommended to be used in ISO/TS 16610-4 [9].

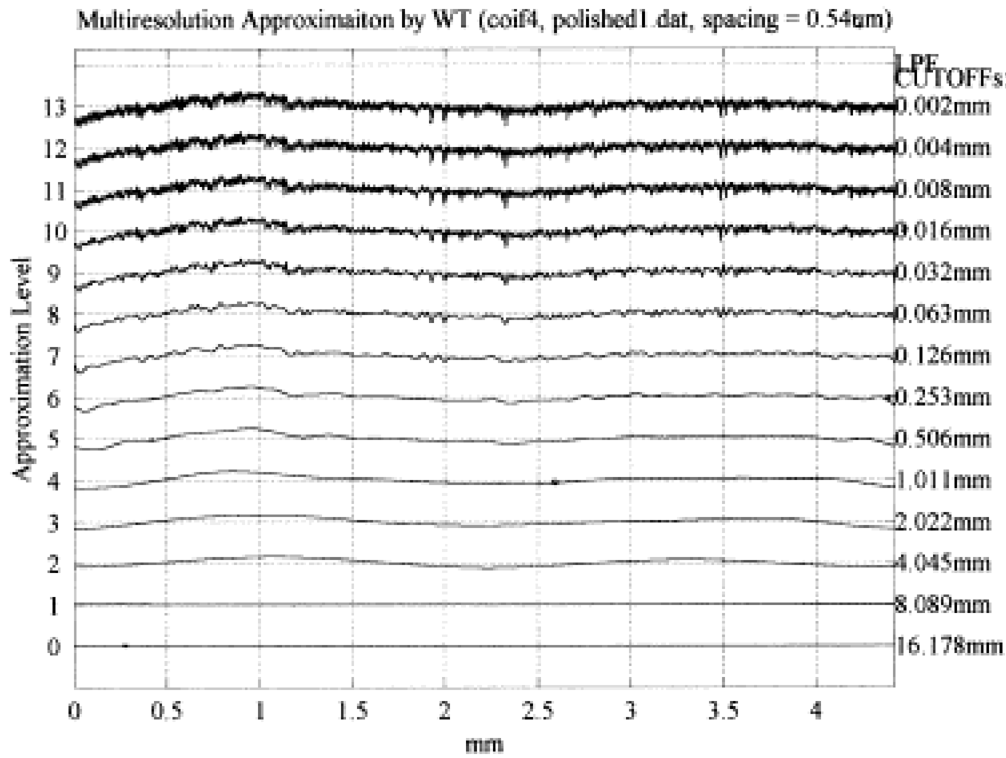

Figure 6 Wavelet decomposition of polished surface profile

3.4 Robust filters

Robust filters are filters that are tolerant against outliers. There are two types of robust spline filters : non-periodic robust filters for filtering open profiles and periodic robust filters for closed profiles. Since robust spline filters are non-linear, the weighting function can not be given. The filter equation for both kinds of robust spline filters are specified in ISO/TS 16610-8 [10]. Another robust filter that has been proposed is the robust Gaussian regression filter, the definition for which can be found in ISO/TR 16610-10[11]. With its regression approach and robust algorithm this filter evaluates measured surface profiles without loss of data in the marginal sections.

3.5 Morphological filters

Mathematically, morphological filters are defined using Minkowski sums. There are two major morphological operations (dilation and erosion) and two secondary morphological operations (opening and closing). The basic concepts of morphological operations and filters are addressed in ISO/TS 16610-5[12]. The computation part is defined in ISO/TS 16610-6[13] and the scale space techniques is described in ISO/TS16610-7[14].

4 Conclusions

Advances in filtering techniques enable us today to separate the different wavelength regimes without any distortions. It is easy to specify and implement well defined bandwidths using digital filters. Current research emphasis is in the area of multiresolution analysis and more robust filters. The need to establish stable manufacturing process and provide functional correlation for components will require finer bandwidth analysis in the future. Case studies to demonstrate process control and functional analysis with these new and powerful tools will be a task for the future.

5 References

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13 ISO/TS 16610-6, Geometrical Product Specification (GPS) – Data extraction techniques by sampling and filtration – Part 6: Morphological operations and filters.
14 ISO/TS 16610-7, Geometrical Product Specification (GPS) – Data extraction techniques by sampling and filtration – Part 7: Morphological scale space techniques.