Chapter 2
A Brief History of Filtering

2.1 Introduction

Engineering surfaces are viewed as having fine texture called roughness, superimposed on more general curvature called waviness, and long-range deviations called form. This has been recognized from the early days of surface texture measurement. The motivation for such classification comes from the fact that roughness, waviness, and form have different origins and affect part functionality in different ways (Whitehouse 1994). Therefore, partitioning a profile into roughness, waviness, and form is of primary significance and an important aspect of surface texture analysis. This partitioning is achieved through a process called filtering.

In the infancy of surface texture measurements, profile data was filtered graphically (Whitehouse and Reason 1965). The raw profile was divided into segments of equal length, and in each segment, a mean line was drawn that captured the slope of the profile in that segment. The roughness profile was obtained by considering the deviations of the points from these mean lines. The graphical approach was cumbersome and time-consuming. An automated way to deriving the mean line became necessary and electrical filters were soon adopted for surface texture filtering.

2.2 Electrical Filters

In electrical filtering, a voltage proportional to the profile is passed through a two-resistor-capacitor (2RC) network. Because the 2RC network has memory, the output is not only a function of the input at any instant of time, but also a function of prior values. In effect, the 2RC network computes a running average of current and previous voltages, but gives reduced weights to voltages more distant in the past. While the memory of the network helps in averaging, by remembering past values only, it introduces an undesired phase in the output.

2.3 Digital Filters

To understand this phase behavior and to rectify the problem, Whitehouse and Reason (1965) simulated the 2RC filter digitally. They described the filter using a weighting function that depended on the cutoff. A cutoff serves a similar purpose as the size of a segment in graphical analysis, namely to separate the short-wavelength components from the long-wavelength components.

They were able to show that the weighting function can be convolved with the raw profile to produce a running average mean line. The digital mean line thus obtained was identical to the hardware electrical filter mean line. The digital implementation of the 2RC filter was a significant step forward. With increasing computing capabilities, the electrical filter quickly became obsolete and filtering began to be accomplished using computers. Raja and Radhakrishnan (1977, 1979a, 1979b) have explored digital filtering technique extensively. They have used the Fourier transform for filtering surface profiles and also demonstrated filtering in the time domain using impulse response (the *finite impulse response* of a filter), in several early papers noted previously.

With the advent of digital filtering, researchers also began to address the primary shortcoming of the 2RC filter, namely its non-linear phase. A phase-correct 2RC filter was designed (Whitehouse and Reason 1965; Whitehouse 1967). Subsequently, the Gaussian filter was introduced, and it remains the preferred choice of filter to this day. Vorburger and Raja (1990) discuss some of these developments in their report.

2.4 The Envelope Method

Around the time that researchers at Rank Taylor Hobson were developing the 2RC filter, Von Weingraber (1956, 1957) in Germany was working on an alternative technique to separate the fine texture from the overall form. In many applications, surface texture plays an important role during contact between mating surfaces. Therefore, on a measured profile, he simulated this contact by determining the envelope of a ball rolling on a surface. The deviations from the envelope would be the fine texture or roughness.

This system came to be known as the E system, while the electrical filter-based technique came to be termed the M system. Over the years, the M system became the *de-facto* filtering choice. More recently, the E system has re-emerged and found prominence as part of a larger group of techniques referred to as morphological filters.

2.5 The Gaussian Filter

The next major development in surface texture filtering can be attributed to the arrival of the Gaussian filter (ISO 11562:1996, ASME B46.1-2002). It solved the problem of non-linear phase of the 2RC and could be implemented digitally quite easily.

2.6 Overlap of Measurement Techniques

Today, with the availability of increasingly sophisticated gages, sensors, and powerful data-processing capabilities using personal computers, there is an overlap of measuring capability. A typical stylus-based instrument can capture roughness, waviness, and form. A roundness-measuring instrument can also gather straightness data and a coordinate measuring machine (CMM) can acquire both dimensional information and form. Figure 2.1 shows the current metrology measurement spectrum. As the bandwidth of measurement instruments increases, it becomes essential to separate surface profile data into meaningful wavelength regimes before numerical characterization.

2.7 Recent Advances in Filtering

In the last decade, there have been some significant advances in filtering techniques; reviews can be found in Raja *et al.* (2002) and Muralikrishnan (2003). The Gaussian filter, which is widely used today, suffers from several shortcomings. First, the waviness profile has distortion near the edges (this is true for open profiles, not for roundness). In fact, a length equal to half a cutoff or one cutoff is typically removed from the beginning and from the end of both the roughness and waviness profiles to limit the effect of edge distortion. For already-short traces, discarding an additional one cutoff at both ends is not an acceptable solution.

Another issue with the Gaussian filter is that the waviness profile does not follow the texture in the presence of large form, such as when measuring on nominally

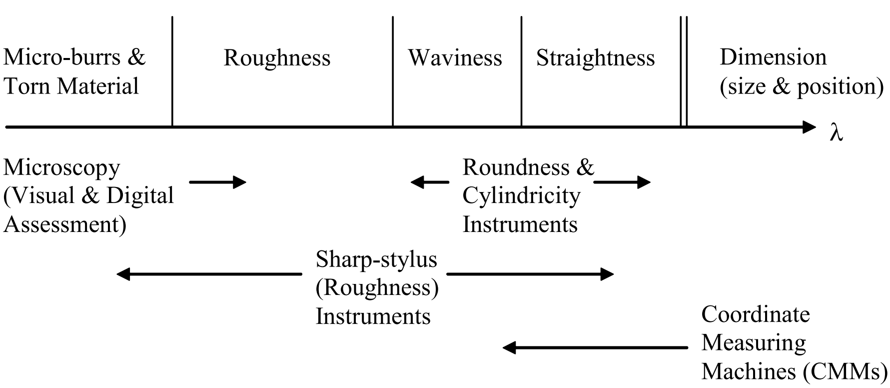

Fig. 2.1 Overlap of measurement instruments (Malburg 1996)

cylindrical or spherical geometry. It is quite common to first remove the best-fit nominal surface before applying the filter for this purpose. A third drawback of the Gaussian filter is that it is not robust against outliers. A large peak or valley will distort the waviness profile in the vicinity of an outlier.

The spline and Gaussian regression filters overcome the problems of edge distortion and poor performance in the presence of large form, while the robust spline and robust Gaussian regression filters overcome all three problems. Wavelet-based filters are also finding increasing applications in surface texture measurement because they provide an efficient way to partition a profile into multiple- and narrow-wavelength bands, something not feasible with the Gaussian filter. And as mentioned earlier, morphological filters and scale-space techniques provide an entirely different perspective to filtering, and are finding new and exciting applications. We will discuss these techniques in later chapters.

2.8 Summary

We have briefly traced the evolution of filtering techniques in surface metrology. In this and subsequent parts, we will discuss many of these topics in considerable detail. In the next few chapters, we discuss some elementary concepts in filtering with the objective of allowing the reader to comprehend the mathematics and perform implementations of commonly used filters such as the Gaussian or the 2RC. In Part II, we discuss more recent advances such as the Gaussian regression, spline, morphological, and multi-scale filters.

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