Computational Surface and Roundness Metrology

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To

Prof. V. Radhakrishnan

INAE Distinguished Professor
College of Engineering, Trivandrum, India
and
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Preface

The purpose of this book is to provide insight into computational techniques commonly used in surface and roundness metrology. It is intended to serve as a reference for engineers who routinely use a variety of metrology tools and are interested in understanding the underlying mathematical basis of the data processing from raw data to final parameters. This book can also be used as a text for advanced courses in engineering metrology for students already familiar with measurement methods and practices.

Most of the material is presented with the objective of enabling the reader to not only assimilate the mathematics involved, but also to be able to quickly implement the techniques using a standard math package. For that reason, a number of exercises are included that highlight the implementation of the algorithms using simulated data of surface features. The book employs MATLAB extensively for these exercises. Familiarity with MATLAB will aid in understanding the material.

Also, it should be pointed at the outset that this book assumes a general familiarity with engineering metrology methods; for readers unfamiliar with some of the measurement techniques whose computational aspects are discussed, several excellent textbooks are available and referenced in Chap. 1.

Acknowledgment

N. George Orji carefully reviewed the entire manuscript, offering invaluable comments and suggestions covering both technical and editorial aspects. We are extremely grateful for the generous gift of his time and effort. Numerous colleagues also volunteered to review sections of the text, provided insight into some of the techniques discussed here, and also supplied several excellent references. We express our sincere gratitude to the following people: Christopher Brown, Brian Boudreau, Donald Cohen, David Coleman, Mark Malburg, Abu Mohamed Ali, Eric Novak, Suresh Ramasamy, Jay Ravindran, T. Brian Renegar, Vijay Srinivasan, Eric Stanfield and Theodore Vorburger.

The Center for Precision Metrology at the University of North Carolina at Charlotte offers an extraordinary environment for the education and practice of engineering metrology. The center's incredible intellectual talent, state-of-the-art laboratories, and its web of academic and industrial networks offer students and faculty unique opportunities for research and teaching. This text has benefited greatly from the center's resources and the energy and enthusiasm of its faculty, staff and students. We (the first author as a former graduate, and the second as faculty) thank them for their support.

Contents

Part II Advanced Filtering

Part III Fitting

Notation

Filtering and Parameterization

x, y	spatial location of points (arrays)
z	measured surface heights (either array or matrix)
w	waviness profile points
r	roughness profile points in filtering
n	number of profile points (length of array z) for 2D profiles
nx, ny	number of profile points along x and y for 3D topography data sets
m	number of points in the weighting function (2D profile filtering)
mx, my	number of points in the weighting function (3D topography) along x and y
$x(i)$, $y(i)$	ith element of x and y
$z(i, j)$	(i, j)th element of z
zf	Fourier transform of z
Δx, Δy	spacing along x and y in units of length
l	profile length
lx, ly	profile lengths along x and y
S	weighting function (filter in time/spatial domain)
Sf	transmission characteristics (filter in frequency domain)
λ	sinusoidal wavelength
f	sinusoidal frequency
fx, fy	frequencies along x and y
λc, λf, λs,	cutoff in units of length for 2D profile filtering
λcw, λsw	cutoff in units of length for 2D profile filtering
λxc, λyc	cutoff in units of length for 3D topography filtering along x and y
ω	undulations per revolution (UPR)
ωc	cutoff expressed in UPR
E	objective function to minimize or maximize
x_c, y_c, z_c	center coordinates of a least-squares best-fit circle
d	array of deviations at each of the sampling points from best-fit geometry

R	array of radial distances from center of circle to each sampling point
θ	array of angular positions at each sampling point

Fitting

x, y, z	point coordinates in space (each is an array containing n points)
x_c, y_c, z_c	center coordinates of a least-squares best-fit circle
r	radius of least-squares best-fit circle (limaçon)
d	array of deviations at each of the sampling points from best-fit geometry
R	array of radial distances from center of circle to each sampling point (such as in a roundness profile)
n	number of sampling points
E	objective function to minimize or maximize
θ	array of angular positions at each sampling point
λ	Lagrange multiplier

Uncertainty

x, y	spatial location of points (arrays)
z	measured surface heights (either array or matrix)
w	waviness profile points
r	roughness profile points
u	standard uncertainty
X	input quantity, may be an array
Y	output quantity
R	part form error (array containing n points), roundness profile
Rf	Fourier transform of part profile
Sx , Sy	spindle error (array containing n points) along x and y directions
Sfx , Sfy	Fourier transform of spindle errors
θ	array of angular positions at each sampling point
ω	array of frequencies (UPRs)
n	number of sampling points in a roundness trace
Hf	transfer function (in frequency domain)
ϕ	angle between probes in multi-probe or angle between positions in multi-position methods
m_i	the ith measured profile or probe reading (in multiple probes or position methods), an array of n points
m	a combination of measured profiles
mf	Fourier transform of m

Chapter 1
Introduction

1.1 Surface and Roundness Metrology

Surface finish is a crucial link between a component, the manufacturing process that generated it, and the functionality that is expected of it (Whitehouse 1994). This relationship between surface finish, part functionality, and manufacturing process parameters is the primary reason for the measurement, characterization, and study of surface texture.

The science of surface metrology can be traced back to the 1940s, to the seminal work of researchers at the Rank Taylor Hobson Company in UK (Reason *et al*., 1944). Stylus-based techniques for surface texture measurements have been in use since that time. Reason (1979) and Sherrington and Smith (1988a) survey the progress made in surface topography measurements especially using the stylus method. Optical techniques are also used for surface texture measurement. Sherrington and Smith (1988b) review optical techniques in surface metrology. Roundness measurements were performed in the 1960s and Reason (1966) presents an early report. Whitehouse (1994, 1997, 2004), Thomas (1999), Smith (2002), and Jiang *et al*. (2007) trace the evolution of surface metrology and the different measurement techniques used.

1.2 Scope and Objectives

A surface texture or roundness profile, as acquired by any metrology instrumentation, is a discrete data set. That is, the deviations from the nominal geometry are expressed as a function of spacing coordinates. Although real surfaces are continuous, metrology instrumentation can only acquire a finite digital sample. This finite dimensional array collected by typical commercial instruments is still a fairly large volume of data; a typical surface profile can contain 8,000 to 25,000 data points while a roundness trace can contain 360 to 7,200 points. An area map of a surface can contain $1{,}024 \times 1{,}024$ points or more.

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Such a large array or matrix of data is "processed" by software in commercial instrumentation to provide parameters that we are familiar with. These parameters are the link between the component's surface texture, the functionality expected of it, and the manufacturing process that created this surface finish in the first place.

But what does "processing" really mean?

A surface, even after careful alignment with the measurement instrument, may have some residual slope during profile or topography measurement. In some instances, the nominal geometry may be curved, such as when extracting a profile from a surface of a sphere or cylinder. In roundness metrology, the measurement is often superimposed by an eccentricity between the part and the spindle. These measurement setup and part-induced errors can be rectified in software by a process known as *fitting*. Fitting substitute geometry, such as a line, plane, circle, sphere or cylinder is quite common, and we use linear algebra, matrix methods, and non-linear optimization techniques for this purpose. Fitting is therefore one "processing" technique in engineering metrology data analysis. It should be pointed out that fitting is a critical analysis step in coordinate metrology, where features of interest such as size, parallelism, perpendicularity *etc.* are determined from substitute geometry; fitting is used primarily as a preprocessing step in surface texture analysis.

Subsequent to any preprocessing by fitting, the data undergoes an information extraction phase, where suitable surface features are extracted because of their relevance to functional properties of the component. This step is referred to as *filtering*. The underlying assumption here is that engineering surfaces are comprised of surface wavelengths, and that certain wavelength bandwidths have specific bearings on certain aspects of a component's functionality. Therefore, filtering involves partitioning a profile or topography into different wavelength bandwidths. The fundamental basis for filtering lies in signal-processing theory.

Parameters are then computed on fitted and filtered surface and roundness data. These parameters are toleranced during design, and as mentioned before, they are inspected during quality control. A variety of parameters exists, some trivial to compute and others not. Therefore *parameterization* is a third topic of computational relevance.

Finally, in numerical computations, *uncertainty* in the inputs propagates through the chain of computations, and is impacted by the algorithms used, and the type and nature of the computations themselves. This is an important area in metrology and has its bearing in probability and statistics. Uncertainty analysis is generally not provided by commercial instrumentation, but national measurement labs do provide such analysis with their reference software.

In summary, data processing generally falls into the four categories discussed above, namely, fitting, filtering, parameterization, and uncertainty (Fig. 1.1), and this book exclusively addresses these topics. Some of the material presented here is available in the literature in journals and conference proceedings, some as early as 1944, and some as recent as 2007. Many of the details are buried in personal communications that researchers have had with colleagues over the last several decades. Some mathematics may be discussed in other textbooks, and in national and international Standards, but in a manner that is sometimes abstract and unsuitable for immediate implementation.

After more than six decades of the practice of surface and roundness metrology, there is still no single detailed compilation of the mathematical techniques used. We felt the need for such a book during our research and teaching activities and our effort here hopefully addresses some of that need. In each of the chapters, we describe the mathematics and illustrate the concepts through worked examples. We also provide end-of-chapter exercises with answers at the end of the text. We use MATLAB (a product of The MathWorks) extensively through out the text. Several excellent tutorials are available for those unfamiliar with MATLAB; the MathWorks website is a good reference (MATLAB).

1.3 Organization

We have organized the remaining chapters into five parts. Although fitting precedes filtering in the analysis hierarchy, we discuss filtering first (Part I) because of its significance to the ultimate goal of surface texture analysis, namely, the correlation of surface texture parameters and functional behavior of components. In Chaps. 2, 3, and 4, we present a historical context to filtering and then discuss implementation aspects from both a frequency- and time-domain perspective. Chapters 5 and 6 are devoted to the Gaussian and the two-resistor-capacitor (2RC) filters. In each case, we illustrate filter characteristics through discussions and worked examples. Then, we extend the filtering ideas to two cases: roundness and 3D data analysis in Chaps. 7 and 8 respectively.

In Part II, we discuss some recent advances in filtering techniques, such as the Gaussian regression filter, the spline filter, robust filters, morphological filters, and multi-scale filters. Each has its own unique advantages and disadvantages; we illustrate these with worked examples using simulated surface profile data.

Part III is devoted to the next computational topic of importance, namely, fitting. Fitting reference circles is a critical aspect of roundness analysis. Fitting lines,

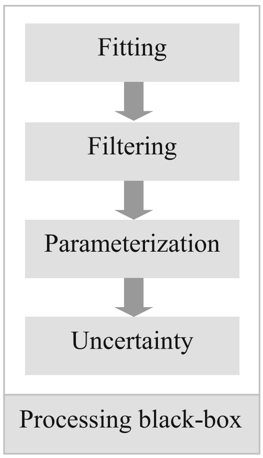

Fig. 1.1 Data processing in surface and roundness metrology

planes, circles, spheres, and cylinders may sometimes be used in preprocessing surface texture data as well. We discuss these topics in this part. After a brief introductory chapter (Chap. 14), we elaborate procedures for fitting least-squares lines and planes (Chap. 15). Non-linear methods that are useful for circles, spheres, and cylinders are presented in Chaps. 16 and 17. Then, a linear approximation for circles useful for roundness analysis is illustrated (Chap. 18), followed by a discussion on exchange algorithms for minimum-zone lines, planes, and circles (Chap. 19). Finally, we wrap up Part III with Chap. 20, a discussion of linear-programming-based simplex for circle fitting and illustrate how this method is linked to exchange algorithms discussed in the previous chapter, Chap. 19.

The focus of Part IV is on parameters that can be computed from surface profiles. These include amplitude, spatial, and hybrid parameters. We also illustrate the computation of statistical functions such as the autocorrelation function, the power spectral density, and the bearing area curve. The final chapter, Chap. 23 in this part is devoted to parameters and statistical functions computed from 3D topography.

In Part V, we discuss topics concerning error and uncertainty. We first discuss concepts related to uncertainty propagation and its implications in surface profile filtering and surface fitting (Chaps. 24 and 25). In Chap. 26, we discuss methods for separating spindle error from part error in roundness analysis. Finally, in the concluding Chap. 27, we take a look at some emerging computational topics that are finding relevance in surface and roundness metrology.

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Part I
Filtering

We discuss filtering techniques as applied to 2D surface profiles, roundness profiles, and 3D surface topography in this part. We trace the evolution of different filtering methods in Chap. 2. In the Chaps. 3 and 4, we introduce basic ideas involved in frequency- and time-domain filtering. In Chaps. 5 and 6, we focus our attention on two commonly used filters: the Gaussian and the 2RC filter. In the final two chapters in this part, Chaps. 7 and 8, we describe filtering as applied to roundness profiles and 3D surface topography.

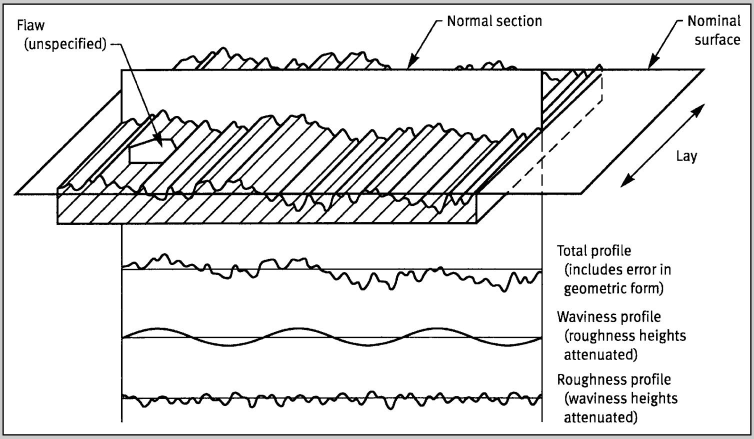

Fig. I Surface roughness and waviness. Reprinted from ASME B46.1-2002, by permission of the American Society for Mechanical Engineers.

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.

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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

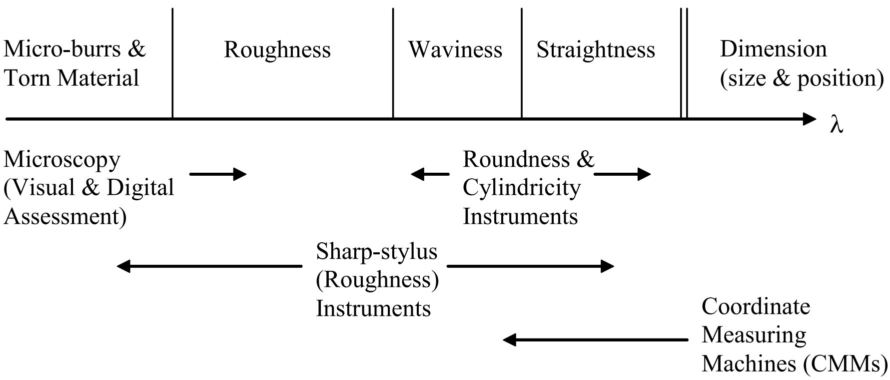

Fig. 2.1 Overlap of measurement instruments (Malburg 1996)

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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Chapter 3
Filtering in the Frequency Domain

3.1 Surface Wavelengths

Every engineering surface can be viewed as comprising of sinusoidal functions of different amplitudes and wavelengths. In fact, roughness is simply a collection of all high-frequency or small-wavelength sinusoidal components of a surface, waviness is a collection of all medium-wavelength components, and form consists of all large-wavelength components.

The transition from roughness to waviness, or from waviness to form is determined by user-defined wavelength cutoffs. Because roughness, waviness, and form represent certain defined wavelength bandwidths, two cutoffs are required to properly establish each band, one for the lower bound and another for the upper bound. Thus, cutoffs λcw (waviness long-wavelength cutoff) and λsw (waviness short-wavelength cutoff) (ASME B46.1-2002) define waviness while λc (roughness long-wavelength cutoff) and λs (roughness short-wavelength cutoff) define roughness. The values chosen for the cutoffs depend on the application; the ASME B46.1 Standard (American Society of Mechanical Engineers 2002) provides some guidelines for selection of cutoff ratios, stylus tip sizes, and traverse lengths.

In practice, however, the measurement instrument capability or measurement setup itself applies a filter that establishes one of these cutoffs. Therefore only one cutoff is specified to define roughness or waviness. For example, the finite stylus size may establish the roughness short-wavelength cutoff through mechanical filtering. Therefore, a roughness long-wavelength cutoff applied to the measured profile may be sufficient to obtain roughness.

A surface profile, like most other digitized signals of observable physical quantities (voltage, current etc), exists in the time or spatial domain, because the signal is monitored as a function of time (plot of voltage as a function of time) or spatial location (plot of surface profile as a function of spatial location). From Fourier theory, we know that such signals can be viewed as comprising of sinusoids of varying frequencies, amplitudes, and phases. In other words, by transforming a surface profile signal to the frequency domain using the Fourier transform, we can clearly identify the amplitude and phase of sinusoids of specific wavelengths.