Fitting, Filtering and Analysis: Feature Extraction in Dimensional Metrology Applications

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Today's metrology instrumentation is providing an increasing number data points in shorter periods of time. In addition, today's specifications are requiring an increased level of analysis of these data points. In this regard, several new methodologies are being developed as a sort of "toolbox". The challenge to the end user is: "which of these tools is appropriate for a given application".

This presentation looks at some of these data analysis tools in the context of dimensional and surface metrology. Various methods and applications will be explored along with the recommendations for implementing these tools in existing instruments.

Introduction

Typical dimensional measurement approaches rely on some sensing mechanism that converts surface features into discrete data points. These data points are then numerically processed in order to determine the necessary result. Historically, dimensional measurements involved the collection of relatively small numbers of data points and mathematical analyses were directly applied to these points. However with the advent of faster scanning technologies and more affordable data processing capabilities we are now dealing with much larger data sets. These larger data sets bring an increased need for mathematical tools that can "extract" the necessary information from the data set.

Geometry Extraction (Fitting)

Historically, there have been two basic methods for describing a cloud of data: 1. an "envelope" or "zone" method whereby the extremes of the data points are bounded, or 2. a "mean-based" approach wherein a geometry is regressed through the data points and excursions from this "nominal shape" are characterized. These two concepts can be easily illustrated in the measurement of roundness via either a "minimum-zone" based analysis or "least squares" based analysis can be applied to the data points. (See Figure 1.)

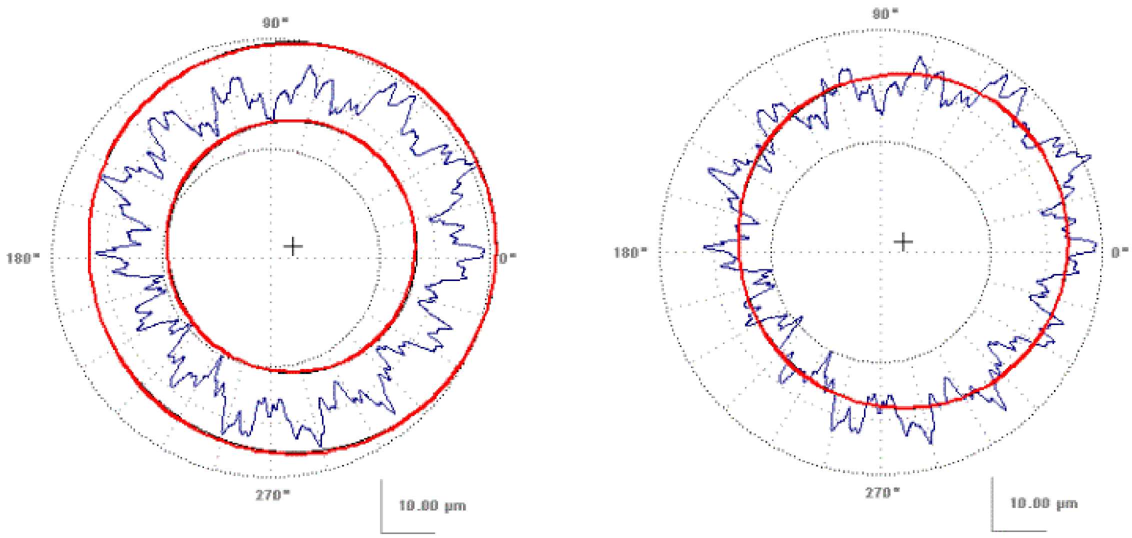

Figure 1. Minimum Zone and Least Squares reference figures for roundness.

The validity or usefulness of either reference figure may depend on the particular application. For example, "zone-based" tolerances and analyses can generally be related to surfaces in contact where "fit" is an important functional criterion. Similarly, "mean-based" tolerances and analyses can often be related to interfaces which tend to "float" and attributes such as vibration or sealing are considered to be important.

Scale-Based Feature Extraction (Filtering)

As stated above, dimensional measurements performed by, for example, a CMM typically include all measured data points in an "as collected" manner. In other words, the raw, measured data points were directly analyzed without any pre-processing. However, as data densities have increased there has been an increased awareness that there is a great deal of "noise" in these "high density" data sets. This "noise" can be the result of such things as the surface roughness of the component being measured or due to errors in the measurement system (for example, vibration or electronic noise). In many cases it is desirable to filter out this "noise" in order to arrive at a more stable data set that is perhaps more indicative of the attributes that are to be assessed.

In this regard, filtering methodologies, such as the Gaussian filter, have been put forth. These methodologies have been very common in the context of roughness and roundness measurement and are now making their way into other dimensional metrology applications. (See Figure 2.)

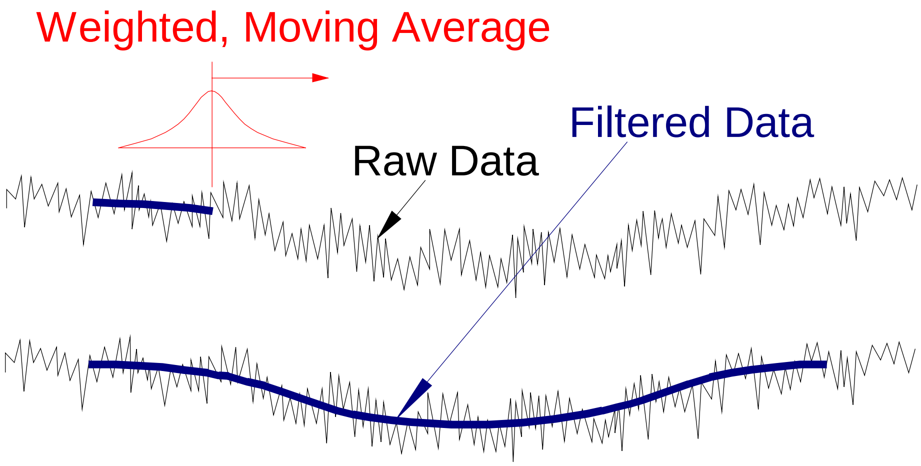

Figure 2. *The application of a Gaussian filter.*

Another common filtering approach is that of "morphological filtering" whereby a structuring element is applied to the data set. The contact points between the data set and structuring element establish a limiting condition. Given these limiting conditions, then the inner or outer envelope of the structuring element can be used to generate a reference figure. A common morphological operation is that of a "closing filter" whereby a mathematical shape is moved over a data set in the same what that a probe or stylus would move over a surface. The resulting data set is based on profile peaks and all point of nearest approach of the stylus. (See, for example, Figure 3.)

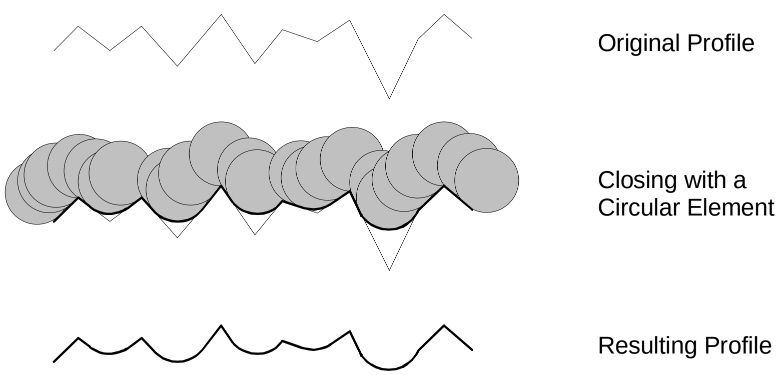

Figure 3. *A morphological closing filter.*

A "Toolbox" for Extraction

The evolution of mathematical tools in metrology has resulted in a set of methods or "toolbox" for extracting information from measured data sets. In this regard, four categories of tools appear to be emerging. Many of these methods are presented in the documents that are being produced by ISO TC213/AG9 "GPS Extraction Methods". Under this system, various tools can be selected and applied based on the specific analysis needs.

Reference Geometry Fitting Methodologies
In terms of "fitting" methodologies, the measurement of roundness provides four approaches for determining a reference center/circle:

- Minimum Zone (MZ)
- Least Squares (LS)
- Maximum Inscribed (MI)
- Minimum Circumscribed (MC)

Similar approaches can be constructed for a wide range of non-circular geometries. Recently, a great deal of work has been done regarding the application of convex and alpha hulls to as means of achieving these reference geometries as well defining new reference geometries.

Data Filtering Methodologies
The application of filters in metrology is a primary concern in the measurement of surface roughness. However, with increased data densities in many other forms of metrology, filters are being applied across a wide range of applications as a means of controlling the wavelength or frequency content of measured data sets. Historically, filtering was performed via analog electronics that were integrated in the measurement apparatus. Today, with the integration of computers in metrology, digital filtering is typically performed on numerical data sets after the measurement. To this end several approaches are available:

- Electronic (2CR) Filtering
- Phase Correct 2CR Filtering
- Gaussian Filtering
- Spline-based Gaussian Filtering
- Valley Suppression Filtering
- Morphological Filtering
- Wavelet Filtering
- Robust Filtering

Outlier Removal Methodologies
High-density data sets will often include extraneous data points (or "outliers") that may not reflect the actual geometry of the surface. In many cases, it is useful to apply mathematical methods to remove these data points rather than manually remove the points or re-measure the component. In this regard several approaches have been developed.

- Threshold-based Detection
- Statistically-based Detection
- Morphological Filter Methods
- Alternating Sequence Filters
- Wavelet-based Detection

Analysis Methodologies
Once the measured data points are pre-processed and the reference geometry is applied, it is necessary to quantify the deviations with respect to the ideal geometry. Often in GD&T applications a simple peak to valley measure is sufficient. However, in many other applications, additional analyses are necessary in order to describe the functionality of a component. Many numerical parameters are available to accomplish this and these parameters cover areas such as:

- Worst-case Peak-To-Valley Deviations
- Averaged Peak-To-Valley Deviations
- Statistical Analysis
- Volumetric Analysis
- Slope/Fractal/Spacing Analyses
- Wavelet/Fourier Analysis

Fitting and Filtering for Complex Geometries

When encountering a noisy data, one may be inclined to simply filter the data and then proceed with applying the desired fitting method. However, caution should be taken as this approach may cause unwanted distortions in the data. This problem can be demonstrated in the analysis of complex geometries such as those found on cam lobes or airfoils. If a Gaussian filter is directly applied to the measured data points of a cam lobe, the underlying lobe geometry (particularly around the "nose") can be distorted due to the averaging effect of the filter. (See Figure 4.)

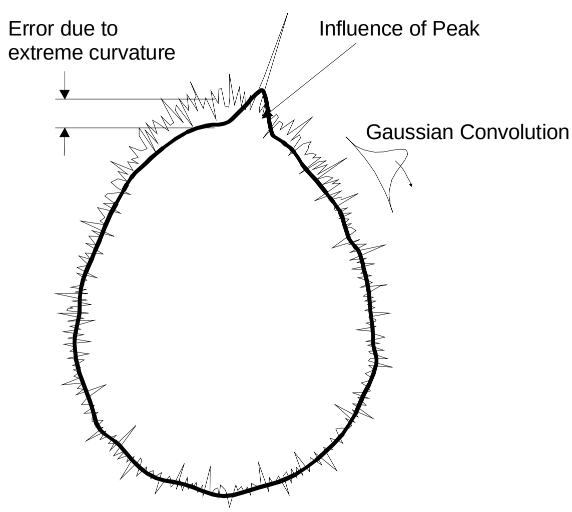

Figure 4. Distortion of a cam lobe due to the Gaussian filter.

In the case of the cam lobe, the Gaussian filter "smoothes out" the nose radius and gives a misrepresentation of the actual measured lobe. In many cases, this filtering effect can be significant enough to make the measured data fall outside the tolerance limits for the lobe geometry. In addition, the outlying data point (or "unwanted asperity") is reduced in magnitude, but becomes much wider upon filtering.

These effects combine to cause the subsequent analysis of the profile to be erroneous in terms of a rotation of the geometry and an overly large consumption of the tolerance zone. (See Figure 5.)

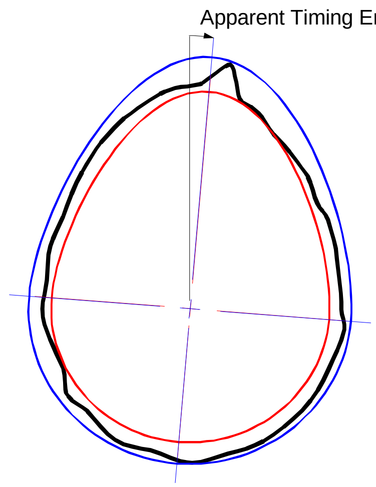

Figure 5. Analysis of distorted cam lobe.

An alternative approach for the filtering of complex geometries is based on a combination of fitting and filtering. This alternative method retains the underlying geometry, while smoothing out the deviations via the following steps:

1. Fit the nominal geometry to the data set via the least squares method.
2. Subtract (and store) the least squares reference, such that the remaining data points are only the deviations relative to the least squares fit.
3. Filter these deviations and remove outliers.
4. Superimpose the filtered deviations upon the stored least squares geometry.
5. Analyze the data set compared to the tolerance.

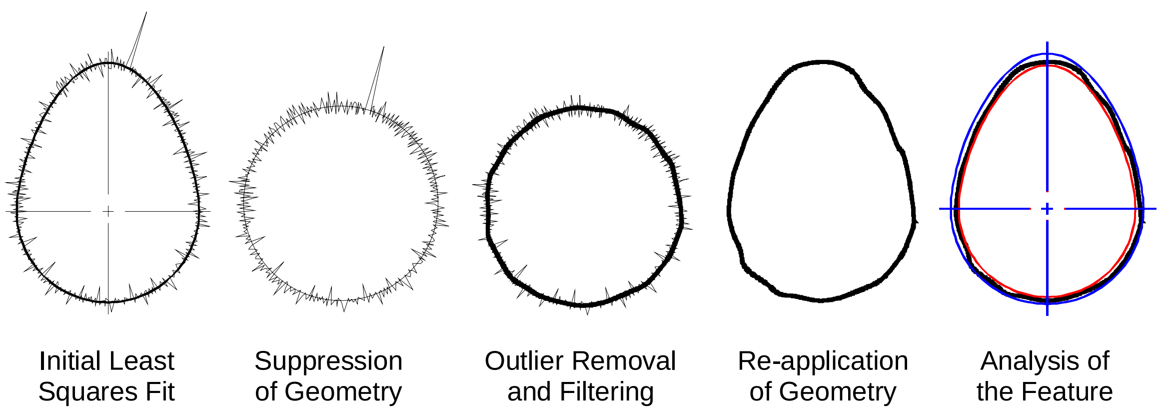

Figure 6. Distortion-free analysis of cam lobe.

Filtering for Functional Simulation

Many common sealing interfaces incorporate a conformable component in contact with a rigid component. In these cases, the conformable component is designed such that it can tolerate some geometry and positional errors in the rigid component. However, this ability to conform relates to the surface features in the rigid component. For example, a gasket may be able to conform to long wavelengths (Figure 7), but it may not be able to conform to shorter wavelengths even though the amplitude of the short wavelengths is considerable less (Figure 8).

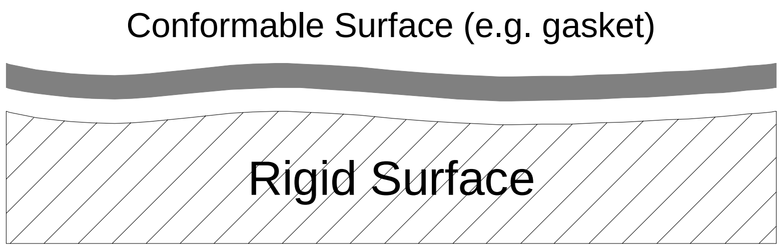

Figure 7. *A conformable interface with long wavelengths.*

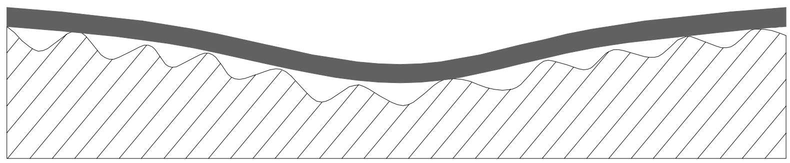

Figure 8. *A conformable interface with shorter wavelengths.*

To simulate the conformability of the gasket, a combination of robust Gaussian and morphological filtering methodologies can be employed as shown in Figure 9.

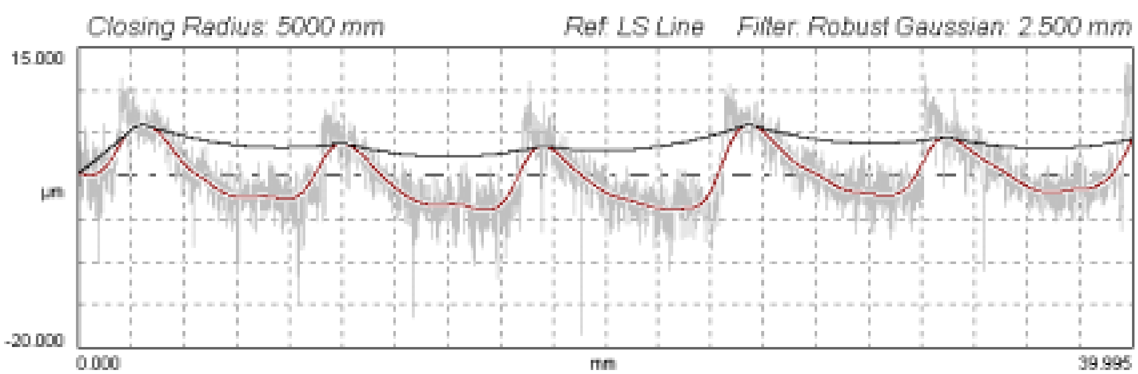

Figure 9. *A combination Gaussian/Morphological filtering approach for conformable surfaces.*

The robust Gaussian provides a stable profile indicative of the underlying "shape" of the profile while the morphological filter simulates the conformability of the mating component. The difference between these profiles can be analyzed in terms of cross sectional area and an assessment of "leak potential" can be determined.

Implementing the "Tools"

There is a common perception that in order to obtain the benefits of new methodologies one must purchase new instrumentation. This is no longer the case given the possibilities of software retrofits/upgrades and "add-ons". Several instrument manufacturers now provide retrofits whereby newer operating systems and controllers can be incorporated into older metrology structures. These retrofits can range from a simple software update, to a full overhaul of the hardware, electronics and software.

Another, although less common, approach for incorporating new analysis tools into existing equipment involves the development of "add-on" software. In many cases software applications can be developed that can easily "co-exist" with the native software and yet provide an enormous amount of additional flexibility. Depending on the operating system and native instrument software, several options exist for incorporating "add-on" software. Many of these approaches provide for the development of custom analyses without additional operator intervention. Furthermore, many of these methods can be provided in an manner that does not affect the instrument's operation or native software; thereby allowing for normal calibration and service of the instrument.

Analog Interface
Many older surface-measuring instruments (e.g. roughness, roundness, etc.) provided electronic processing of data and the only available output was to a strip chart recorder. As newer filters and parameters were introduced and standardized it became desirable to incorporate these new capabilities. This has been accomplished in many cases through the use of an analog-to-digital (A/D) converter board installed in a personal computer. Through this approach, the probe signal can be digitized and captured directly into the computer where the necessary processing can be performed.

Port Based Access
Some instrument manufacturers have recognized the need for external analysis and have provided for the transmission of measured points out a communications port. The most common of these approaches incorporates an RS-232 port whereby measured data points and supplemental information can be transmitted. In some cases, the instrumentation can be completely controlled by an external computer via the communications port – thereby allowing for a "turn-key" software application.

"Shell" Based Execution
In earlier operating systems, for example with some DOS-based instruments, provisions are included for executing another program from within the native instrument software. This mechanism provides a relatively smooth transition between the native data collection software and the custom "add-on" software. Often this process can be automated such that no operator intervention is required between the two processes.

Dynamic Data Exchange (DDE)
Several metrology applications running under "multiple-application operating systems" such as Windows™ can directly send or receive data to and from other programs that are running simultaneously with the native instrument software. This approach has been adopted by many statistical process control (SPC) packages and is a useful methodology for transferring measurement data to an external application.

File-Based Data Transfer
The file-based approach is a very useful method for multi-application operating systems such as Windows™. In this approach the "add-on" software runs alongside the native software. The native software window can be maximized and the instrument can be used as if the add-on is not even present. The data transfer occurs when the native software stores data points to a file that the add-on software is monitoring. When the add-on software detects the presence of new data, it can automatically load the data, analyze the data points and bring the custom display to the front (topmost window).

Summary

There is a wealth of analytical tools that are becoming available for metrology applications. These tools allow for a better understanding of measured data and ultimately can provide additional "value" to the measurements. New tools are available and are being developed in the areas of fitting, filtering, outlier removal and analysis, however these don't require the purchase of new instruments in order to achieve the benefits. There are several methodologies for incorporating these tools in existing measurement systems as a means of providing a relatively low-cost, yet high value-added solution.