UNIVERSIDADE FEDERAL DE SANTA CATARINA - UFSC

CURSO DE GRADUAÇÃO EM ENGENHARIA ELÉTRICA

FELIPE LUIS PROBST

DATA PROCESSING ISSUES IN THE EVALUATION OF ROUNDNESS DEVIATIONS BY SCANNING ON COORDINATE MEASURING MACHINES

Florianópolis

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Trabalho de Curso submetido à Universidade Federal de Santa Catarina - UFSC, como parte dos requisitos necessários para a obtenção do Grau de Engenheiro Eletricista.
Orientadores: Professor Dr. -Ing. Márcio Costa e Professor Dr. -Ing. Robert Schmitt.
Co-orientadores: Professor Dr. -Ing. Gustavo Daniel Donatelli, Dipl. Ing. Susanne Nisch e Eng. Francisco Augusto Arenhart.

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Título: Data processing issues in the evaluation of roundness deviations by scanning on Coordinate Measuring Machines

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Florianópolis, ____ de ____________________ de 2009

Dedico este trabalho à minha mãe Elza, meus irmãos Renan e Rodrigo, minha namorada Sabrina, e em especial ao meu pai Eno (in memorian).

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Platão

ABSTRACT

This report presents the results of a research about signal processing on roundness measurement by scanning with CMMs. In this process, there are three main steps to be realized: elimination of outliers, interpolation and signal filtering. Some concepts regarding the presence of outliers on surface analysis are presented, demonstrating the importance of this topic for a correct form evaluation. Furthermore, a brief discussion about interpolation is realized and some classical and alternative filtering methods are discussed, showing the characteristics and advantages of each one. A computational environment was developed to access important characteristics of the discussed methods, regarding the resulting profile after each step of the process. For a comparative evaluation of the methods of outlier elimination, real profiles containing outliers were analyzed, while for the signal filtering, the methods are analysed regarding some important characteristics present in roundness profiles measured by scanning. Results demonstrate advantages and drawbacks of each method, so conclusions on the performance of the evaluated methods can be outlined.

Keywords: Outlier elimination, roundness measurement, robust filtering.

CONTENT

1 GENERAL INTRODUCTION

1.1 MOTIVATION

The inspection process for evaluating conformance with the Geometrical Product Specification – GPS [1] is one of the most important tasks to the quality assurance of products and processes in the mechanical manufacture industry. In this field, the introduction of the Coordinates Measuring Machines (CMM) represented a great advance, mainly in flexibility and versatility, making possible the integrated evaluation of the geometry of the parts with only one equipment.

The application of CMMs are R&D, tools measurement and standard calibration, that demand high accuracy and adaptability, as well as product inspection, where the measurement time is a very important variable.

The information about the work piece surface can be acquired in different ways, mainly by contact or optical technologies. In the measurement by contact, a classical method is the acquisition of isolated points on the surface, registering the coordinate of each point for further processing and substitute geometry construction. The limitations of this acquisition mode are widely known: high measurement time and limited information about the work piece surface, that difficult the reliable measurement of many geometrical characteristics.

Another method, that has the capability of continuous-contact acquisition, is being progressively introduced by the CMM manufacturers. It is called scanning, where the CMM acquire the coordinates of a big amount of points in a specific trajectory while the sensor remains in contact with the work piece surface. Thus, it is possible to achieve a more accurate knowledge, decreasing the contribution to the uncertainty caused by the sampling limitations, and decreasing the measurement time.

As the scanning technology is not a classical method for evaluation of form deviation in CMMs, there are some challenges to be faced. Many different variables influence the performance of a CMM operating in this mode. Although some of them can be discovered by the knowledge of the machine behaviour in point to point measurement, other are dependent of the scanning velocity and the trajectory of the sensor, that are specific of this mode.

To improve the scanning process, reducing the uncertainty and the measurement time, it is necessary to understand the dynamics of the signal obtained in the measurement and its relation to the causes of errors.

The needs and limitations above constitute a good field of research in dimensional metrology, where the results could have a great value for the user and also for the CMM manufacturers. Thereby, an international cooperation between the CERTI Foundation, a Brazilian reference institute in technology and innovation, and the Laboratory for Machine Tool and Production Engineering (WZL) at RWTH Aachen University – Germany is allowing this research, with the aim of optimizing the form measurement process by scanning.

In the whole process, from the point acquisition to the evaluation of form deviation, there are many intermediary steps, that will be explained in the section 1.2.2. One of these steps is the data processing, that aims to eliminate disturbing influences and separate different characteristics of the work piece. The data processing is exactly the subject of this work, specially the outlier elimination and signal filtering, as will be seen in the following chapters.

1.2 CONTEXTUALIZATION

To understand the scope of this work, some basic concepts of surface metrology must be informed. It is also important to know the whole process of measurement and evaluation of geometrical characteristics.

1.2.1 Surface Metrology – Basic Concepts

One of the most important field on surface metrology is the measurement of the deviations of a work piece from its intended form, that is, from the form specified on the drawing [2]. It ensures that the form and texture are correct for the speed, load and temperatures specified in the project.

An important definition related to surface metrology is the surface characterization, that briefly separate the surface in three essential components: roughness, waviness and form.

The roughness is described by the irregularities that are mainly related to the manufacturing process (e. g. turning, grinding), having the characteristic of short wavelengths. The waviness is characterized by medium wavelengths and may be due to the poor performance of an individual machine. Finally, the form has long wavelengths. The surface characterization with the respective errors sources is presented in the Figure 1.

Form deviation (presented in a profile section)	Example for each deviation	Example of deviation causes
1st order: Form deviation 	Flatness and Roundness deviation	Defect in guides of the machine, wrong fixing of the piece, deformation due to temperature
2nd order: Waviness 	Waves	Eccentric fixation or defect in the form of a cutter, vibration on the machine, tool or the piece
3rd order: Roughness 	Grooves	Form of the cutting tool, advance velocity or depth cut
4th order: Roughness 	Scales Rebounds	Deformation process chip (chip sheared or plucked), deformation of material by sandblasting, rebounds by galvanic treatment
5th order: Roughness Not simple to present grafically	Microstructure	Crystallization process, surface modification by chemical action, corrosion
6th order: Not simple to present grafically	Lattice structure of the material	Physical and chemical processes of the material structure, tensions of the crystalline lattice
Overlapping profiles of 1st to 4th order 		

Figure 1. Surface characterization. Adapted from [3]

Just recalling, the main purpose of this project is the form evaluation, then the profile of interest has only the long wavelength part of the surface. To isolate form deviations, filtering techniques are used, which is one of the subjects of this work.

1.2.2 Form Evaluation Process

The skin model, introduced by the ISO 14460-1 [4], defines the geometrical elements disposed to the piece project as: point, line, plane, circle, sphere, cylinder, cone and torus. According to this model, these elements do not exist in a real work piece and *real surface* is the correct term to be used.

Thus, in the form measurement process, the input signal is the real surface of the work piece that is under scrutiny. This signal is acquired, sampled and saved in digital format for further analysis and processing. During this process, some modifications are made, intentionally or not, so that the output is a distorted representation of the real surface. The measurement errors cause undesirable distortion on the signal, which are not intentional modifications. This first step is normally called *acquisition process*.

Then, the saved signal is purposely modified, to minimize the effects of undesirable transformations occurred in the acquisition process. This is the *processing* step. Finally, the geometric parameters are obtained, allowing the evaluation of the required information, what is called *evaluation process*. The Figure 2 illustrates the process described above.

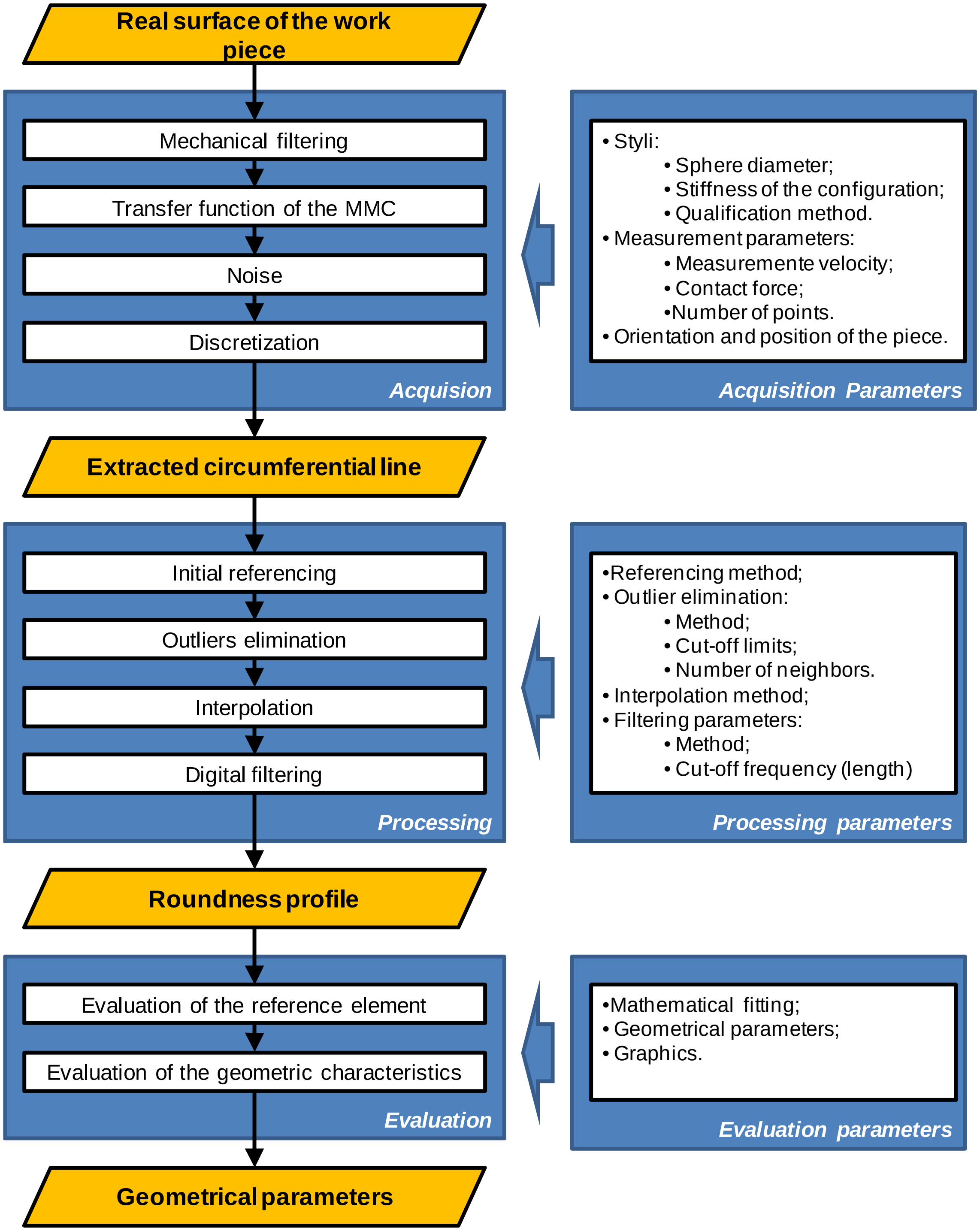

Figure 2. Model of acquisition, processing and evaluation for a real profile, adapted from [5].

Special strategies are applied for data processing to eliminate atypical points and separate the form deviation from super positioned roughness and waviness. Existing techniques for outlier elimination and filtering differ in their transmission characteristics and their robustness.

However, there are no strict rules defined in form measurement standards for the use of data processing techniques, because it depends on the structure of the real surface and the influences during the production process. Therefore, the comparison of results of form measurement is only possible by specifying the techniques used for outlier elimination and filtering. In Figure 3, it is showed an example of form measurement and evaluation of form deviation, with a standardised filtering.

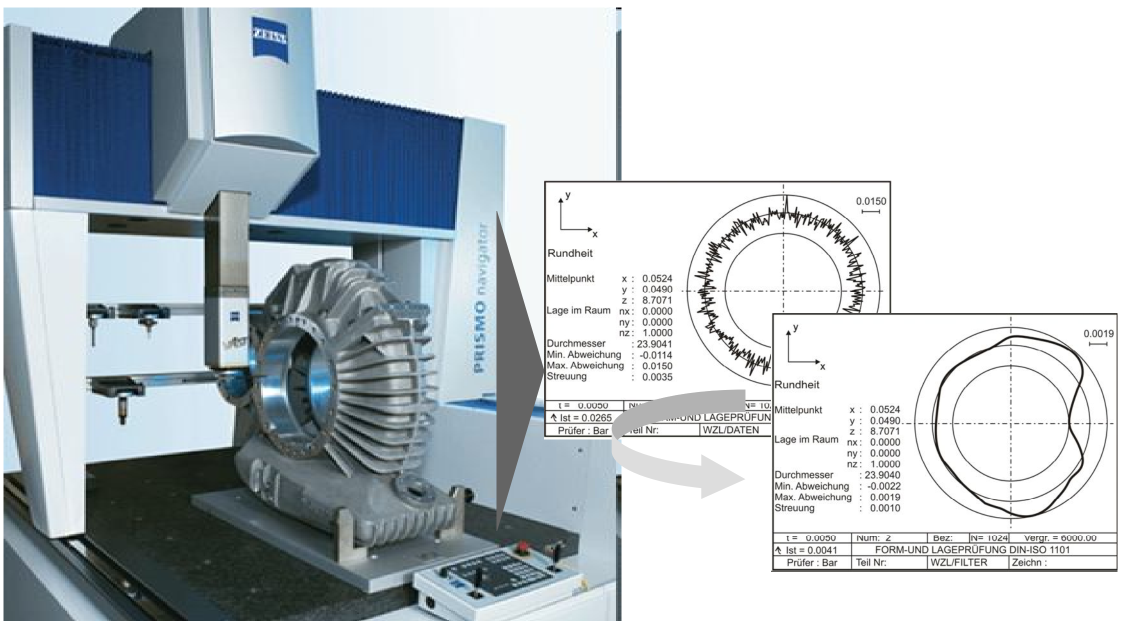

Figure 3. Measurement of form deviation (roundness) in a CMM and evaluation of roundness deviation after using a Gaussian low-pass filter.

The filtering of profiles is defined in some standards for form measurement, like the ISO 16610-1 [6] and the ISO 11562 [7]. These standards impose two main requisites to the filter selection: it must have phase correct properties and 50% transmission at the cut-off. Hence, the Gaussian filter is normally used, notwithstanding it has some adverse effects on profiles. However, there are some alternative filters, that are being used by some CMM software, like Spline and Morphological filter, but to apply different filters on form measurement, the analysis of their characteristics and robustness is necessary.

1.3 OBJECTIVES

Allied to the general context of the project, the main objective of this work is the analysis of classical and alternative techniques for signal processing applied to form measurement by scanning in CMMs. Therefore, some methods for outlier elimination and filtering will be analysed. The other important task of signal processing, the Interpolation, has already been explored in the general project [8], and just a brief description of this subject will be done.

1.4 REPORT STRUCTURE

Chapter 2 will present the theoretical fundaments about signal processing in the evaluation of form, starting with the basic concepts of signal processing, followed by the description of classical and alternative methods of signal filtering. Then, a brief contextualization about interpolation is made and, finally, it is explained the use of filtering techniques for outlier elimination.

Chapter 3 will expose the materials and methods used to evaluate the signal processing methods discussed in the Chapter 2. Afterwards, the results of the evaluation and comparison of the outlier elimination methods and the analysis of filtering techniques will be exposed in the Chapter 4.

Some case studies are presented in Chapter 5, showing important characteristics from the whole process of roundness evaluation that influence the final result. Finally, the Chapter 6 will present the conclusions about the work and the possibilities to start new researches in this subject.

2 THEORETICAL FUNDAMENTS

After a contextualization about the process of form evaluation by scanning in CMMs, the focus of this work is to present the classical and innovative techniques for signal processing applied to this subject. Although, a brief review of basic concepts of signal processing is firstly introduced.

2.1 BASICS

2.1.1 Sampling

Sampling is the process of getting a digital signal from an analog one. This is a necessary step to analyse a signal computationally, since computers are digital machines and can store only digital values [9].

When the signal has a limited bandwidth B at frequency domain, the sampling rate must be greater than twice the bandwidth to be possible reconstruct the original signal. This value is based on Nyquist criterion, defined by (Eq. 1), where f_s is the sampling frequency.

$$f_s \geq 2.B \qquad \text{(Eq. 1)}$$

If the Nyquist criterion is not respected and the signal is sampled by a lower rate, it occurs a distortion called aliasing, illustrated in Figure 4. The aliasing causes a replication of the frequencies greater than the sampling rate in the sampled signal.

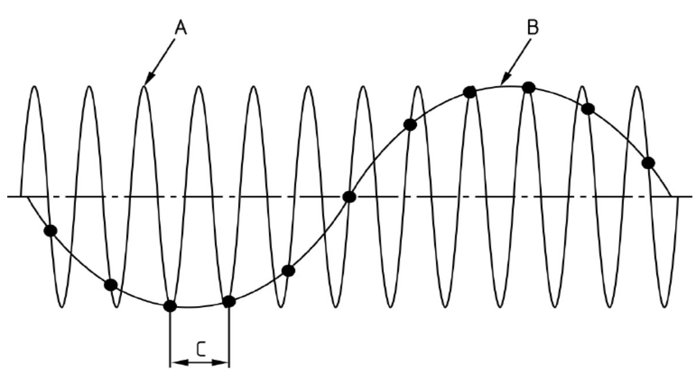

Figure 4. Aliasing (A is the original signal, B is the signal with *aliasing*, C is the sampling interval) [10].

In practice, the signals have large bandwidth and the measurement systems have a limited sampling rate, then it is necessary to limit the bandwidth until the biggest frequency of interest, cancelling the frequencies above. The Standard ISO 12780-2 [10] indicates three different ways to limit the bandwidth: mechanical, analog and digital filtering. However, the mechanical filtering does not avoid the presence of noise in the acquisition system or vibrations in the measurement environment, which can include high frequencies in the signal. Furthermore, the digital filtering can be performed only after the acquisition, when the aliasing has already occurred. Therefore, only the analog filters are able to limit the band before the sampling [2].

2.1.2 Convolution

In linear systems, convolution can be understood as a mathematical operation that relates three different signals of interest: the input signal x[n], the impulse response h[n] and the output signal y[n]. Its symbolic representation is described by (Eq. 2), while the mathematical equation is expressed by (Eq. 3) .

$$x[n] * h[n] = y[n] \quad \text{(Eq. 2)}$$

$$y[n] = \sum_{k=-\infty}^{\infty} x[k].h[n-k] \quad \text{(Eq. 3)}$$

The impulse response is the output of a linear system, e. g., filter, when the input is an impulse (the delta function δ[n]), as shows the Figure 5. If two systems are different, each one has a particular impulse response.

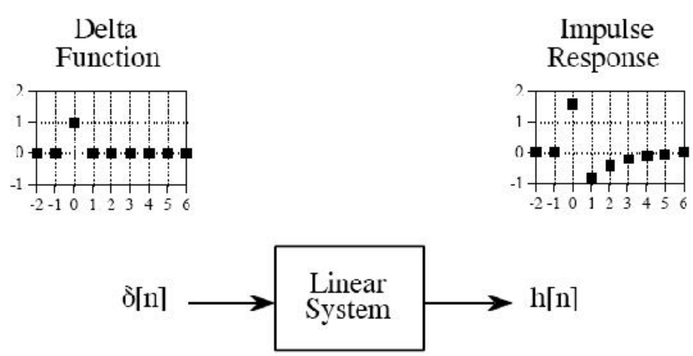

Figure 5. Delta function and impulse response [11].

The convolution can be also described by three steps. First, the signal is decomposed into a set of impulses, where each one can be seen as a scaled and shifted delta function. In sequence, the output resulting from each impulse is a set of scaled and shifted delta. Finally, the output signal can be found by adding these scaled and shifted impulse responses [11]. The convolution here explained is applied only for discrete signals, but it exists also for continuous signals, with another mathematical approach.

2.1.3 Discrete Fourier Transform and Fast Fourier Transform

The Discrete Fourier Transform (DFT) is the application of the Fourier Transform for discrete and periodic signals. For a finite signal that contains N points, it is considered that the same signal is repeated infinitely for the left and right side. The relation between the time/space domain signal and its DFT is given by (Eq. 4),

$$X[k] = \sum_{n=0}^{N-1} x[n].e^{-j2.\pi.k.n/N}, 0 \leq k \leq N-1 \qquad \text{(Eq. 4)}$$

where X[k] is called the DFT of the signal x[n]. X[k] is also a finite signal in the frequency-domain with N points [12].

A very important application of the DFT on signal processing is the DFT convolution, where the convolution can be performed at the frequency domain. At first, the DFT of the input signal x[n] and the impulse response h[n] are taken, followed by a simple multiplication of them, resulting on the signal Y[k], that represents the DFT of the output signal y[n]. Therefore, the Inverse DFT (IDFT) is performed and the output signal is represented at time/space domain. The IDFT is given by the (Eq. 5).

$$x[n] = \frac{1}{N} \sum_{k=0}^{N-1} X[k].e^{j2.\pi.k.n/N} \qquad \text{(Eq. 5)}$$

For the computational implementation of the DFT, the Fast Fourier Transform (FFT) is usually used. It is an efficient algorithm that decompose a DFT with N points into N DFTs [11], each one with a single point, achieving a considerable computational gain that grows up proportionally to the number of points of the signal. With the FFT algorithms, the DFT convolution, for example, is performed much faster than the convolution on time domain.

2.2 FILTERING

Signal filtering is the essential part of signal processing that aims to separate the signal of interest from an input signal with undesired elements, like interference, noise or other signal. These problems can be solved by analog or digital filters, but here just the digital filters are addressed.

Every linear time invariant (LTI) filter has an impulse response, a step response and a frequency response and each of these responses contains complete information about the filter, but in a different form [11]. The impulse and frequency response were already explained, while the step response, as says the name, is the filter output when the input is a step signal. These characteristics are important to know the behaviour of the filter for different inputs.

For linear filters, the filtering process is performed by convolving the input signal with the impulse response of the filter, in the time/space domain, or by the DFT convolution, where the DFT of the input signal is multiplied by the frequency response of the filter. As seen before, this last operation results on the output signal in the frequency domain and, then, an inverse DFT is performed to give the filtered signal.

2.2.1 Moving Average Filter

The Moving Average filter is widely used in general filtering, because it has a very good behaviour on noise reduction and signal smoothing. It realizes an average from a determined number of points from the input signal to produce each point in the output signal [11]. This averaging can be performed by a simple arithmetic mean, where all chosen points from the input have the same weight, or it can be made by a weighted mean, according to some weighting functions. The equation for the basic Moving Average filter is described by (Eq. 6),

$$y[i] = \frac{1}{M} \sum_{j=0}^{M-1} x[i+j] \qquad \text{(Eq. 6)}$$

where y is the output signal, x the input and M is the number of points used in the moving average.

When a weighting function is used, it is the impulse response of the Moving Average filter, then the filtering process can be performed as explained in previous sections, by the convolution at space domain or by the DFT convolution. Some well-known weighting functions are the Triangular, the Blackman window and the Gaussian. The Blackman window and the Gaussian functions are showed in the Figure 6.

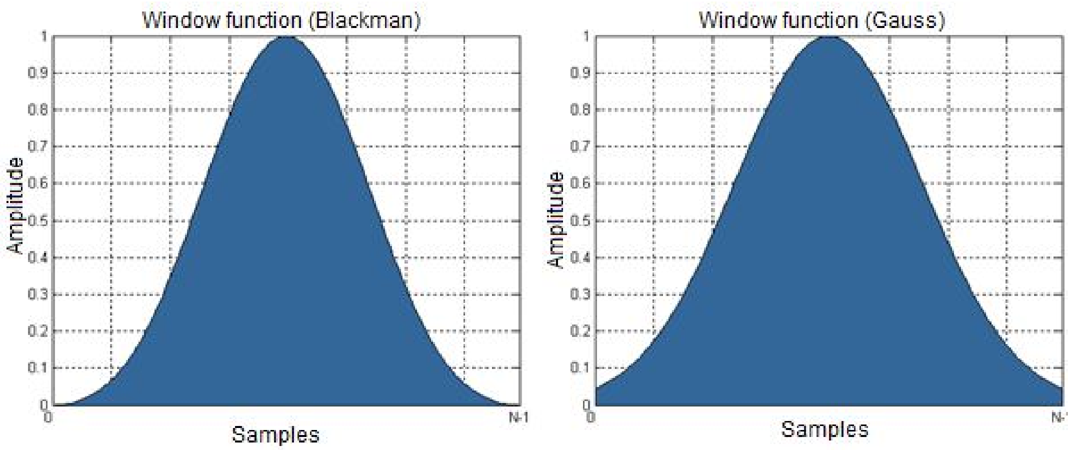

Figure 6. Weighting Blackman and Gaussian functions.

2.2.2 Filtering in Surface Metrology – A Brief Contextualization

In surface metrology, filtering techniques are used to analyze different components of the evaluated profile, such as roughness, waviness or form. The earliest used filter for this propose was the analog two-resistor-capacitor (2RC). As it has memory, its output is function of the input value at a determined time and the prior values, computing a running average of current and previous values. However, while the memory of the network helps in averaging, it also introduce an undesirable phase shift in the output. With the introduction of digital filters, the digital 2RC and the digital 2RC with phase correction were implemented [13] and the last mentioned method was widely used until the Gaussian filter was introduced, that is the preferred method nowadays.

While the 2RC was being developed, an alternative technique was also being studied. It simulates a sphere rolling over the surface, resulting in a profile that represents an envelope of the original signal. This method was a basic morphological filter, that is classified as envelope filter (E system) and depends on the amplitude and wavelength, while the 2RC is a mean line filter (M system), that depends only on the wavelength [14].

The introduction of the Gaussian filter represented a significant advance in signal processing for surface metrology. It is a linear filter and does not cause phase shift in the output signal, unlike the 2RC filter. Furthermore, it has the characteristic of 50% of transmission at the cut-off frequency, making the low-pass complementary to the high-pass filter, for the same cut-off frequency.

However, the Gaussian filter has also some problems, specially with edge distortion for linear profiles and circular open profiles. Thereupon, many alternatives methods for filtering were proposed since the last decade to overcome the restrictions of the Gaussian filter. In the following sections, the Gaussian and some alternative filters will be discussed.

2.2.3 Gaussian Filter

The Gaussian filter is the most used filter in surface metrology, because of the advantages cited above and the simple computational implementation. As seen before, it is a particular case of the Moving Average filter, where the weighting function (in the time or space domain) is described by (Eq. 7),

$$S(x) = \frac{1}{\alpha\lambda_c}\exp\left[-\pi(\frac{x}{\alpha\lambda_c})^2\right] \qquad \text{(Eq. 7)}$$

where $\alpha = [\ln(2)/\pi]^{1/2} = 0,4697$ for 50% of transmission at the cut-off wavelength, x is the position from the origin and λ_c is the wavelength. Figure 7 shows the transmission characteristics for the Gaussian filter used on surface metrology.

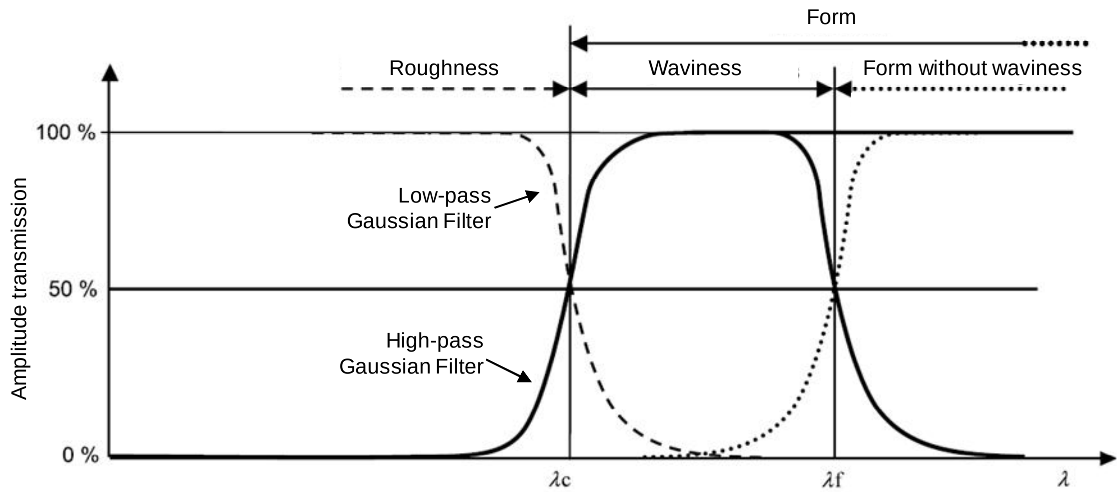

Figure 7. Transmission characteristics for the Gaussian filter used for the separation of a profile in roughness, waviness and form [15].

A peculiar characteristic of the Gaussian filter is that its frequency response is also a Gaussian function, described by (Eq. 8) for the low-pass filter.

$$Sf(\lambda) = \exp\left[-\pi(\frac{a\omega}{\omega_c})^2\right] \quad \text{(Eq. 8)}$$

2.2.4 Spline Filter

The Spline filter was developed by M. Krystek [16], [17], mainly to overcome the edge distortion problem of the Gaussian filter. It can be classified in periodic and non-periodic spline, where the first is used for closed profiles while the second is used for open profiles. As the focus of this work is processing for roundness (closed profiles) evaluation, the method addressed is the periodic spline.

According to the Standard ISO 16610-22 [18], although the spline filter has not a weighting function given by a closed formula, this function can be numerically approximated. Thus, the weighting function based on the cardinal cubic splines can be approximated by the continuous function given by (Eq. 9). The Figure 8 shows the normalized weighting function of the Spline filter.

$$s(x) = \frac{\pi}{\lambda_c}\sin(\sqrt{2}\frac{\pi}{\lambda_c}|x| + \frac{\pi}{4})\exp(-\sqrt{2}\frac{\pi}{\lambda_c}|x|) \quad \text{(Eq. 9)}$$

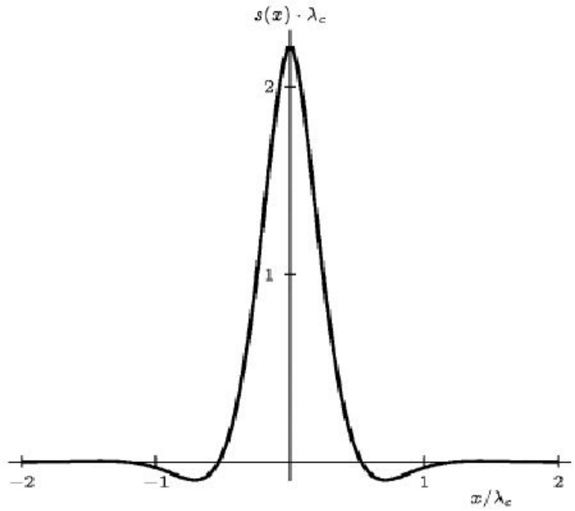

Figure 8. Weighting function of the ideal spline filter, based on cardinal cubic splines [18].

Generally, a filter equation is used instead the approximated weighting function. For the periodic, the filter equation is described by eq 5,

$$\left[1+\beta\alpha^2\tilde{P}+(1-\beta)\alpha^4\tilde{Q}\right]w=z \qquad \text{(Eq. 10)}$$

where:

$$\alpha=\frac{1}{2\sin(\frac{\pi\Delta x}{\lambda_c})} \quad \text{and} \quad 0\le\beta\le1$$

$$\tilde{P}=\begin{pmatrix} 2 & -1 & & & & -1 \\ -1 & 2 & -1 & & & \\ & -1 & 2 & -1 & & \\ & \ddots & \ddots & \ddots & \ddots & \ddots \\ & & -1 & 2 & -1 & \\ & & & -1 & 2 & -1 \\ -1 & & & & -1 & 2 \end{pmatrix} \quad \tilde{Q}=\begin{pmatrix} 6 & -4 & 1 & & & 1 & -4 \\ -4 & 6 & -4 & 1 & & & 1 \\ 1 & -4 & 6 & -4 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \ddots & \\ & & 1 & -4 & 6 & -4 & 1 \\ 1 & & & 1 & -4 & 6 & -4 \\ -4 & 1 & & & 1 & -4 & 6 \end{pmatrix}$$

n = number of extracted data values of the profile

z = vector of dimension n of the profile values before filtering

w = vector of dimension n of the profile values in the filtered profile

λ_c = limiting wavelength of the profile filter

Δx = sampling interval

Figure 9 shows the transmission characteristic in terms of wavelengths for an input signal with amplitude a_0 and the respective filtered signal with amplitude a_1.

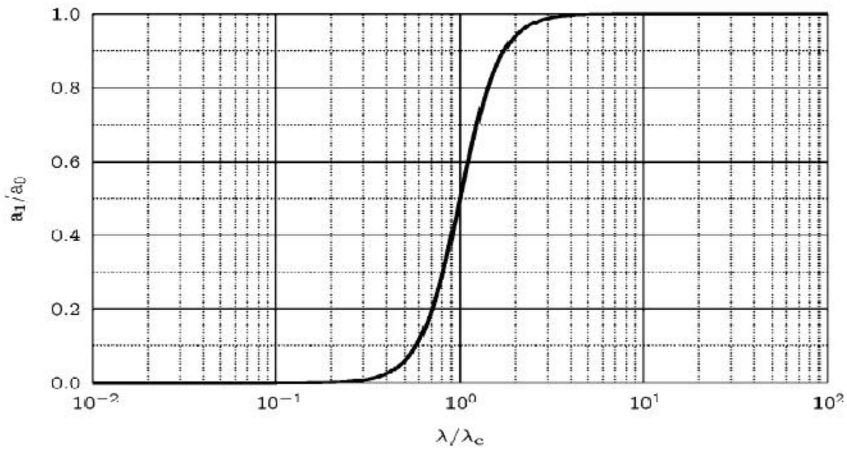

Figure 9. Transmission characteristic for the long wave profile component (β=0 and $\Delta x = \lambda c/ 200$) [18].

2.2.5 Brick-wall Filter

The brick-wall method is based in the theoretical ideal filter. Although it is not realizable in analogical and digital filtering, because its impulse response in time (space) domain extends to all past and future times (or has an infinite length), it can be used when the digital signal has been stored and this process can be classified as an offline-application. For a better understanding, an overview about the ideal filter is presented.

An Ideal filter allows a specified frequency range of interest to pass through while attenuating a specified unwanted frequency range [12]. In fact, it completely eliminates the frequencies in the stop-band, while multiplies the pass-band by a factor k (in general k=1). Therefore, its frequency response is a rectangular function, what gives it the name brick-wall filter. Figure 10 illustrates this frequency characteristic of the ideal filter.

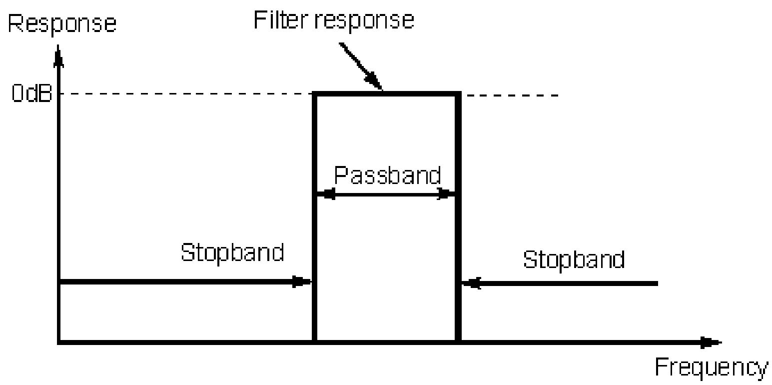

Figure 10. Frequency response of an ideal band-pass filter [19].

In that way, the transition region present in practical filters does not exist in an ideal filter, that is theoretically the best solution for signal filtering. For example, an ideal low-pass filter can be re realized mathematically by multiplying a signal by the rectangular function in the frequency domain or, equivalently, convolution with its impulse response, a Sinc function, at time/space domain [11].

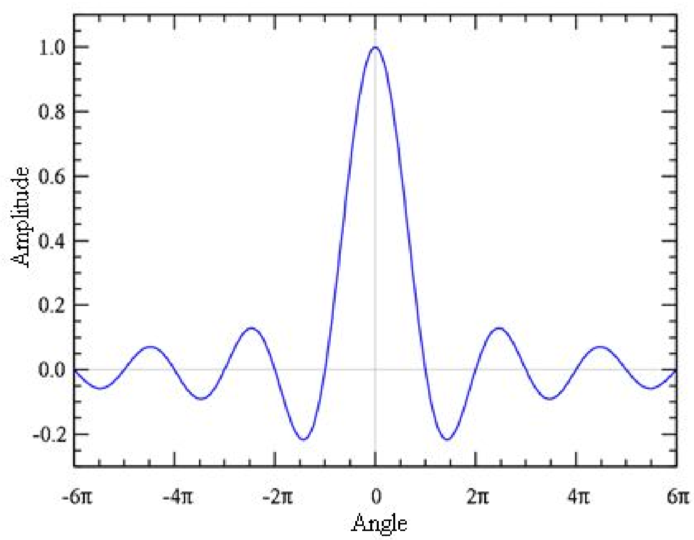

Figure 11. Sinc function [20].

As the Sinc function (Figure 11) has an infinite length, the ideal filter is impossible to realize without also having signals of infinite length. The filter would therefore need to have infinite delay, or knowledge of the infinite future and past, in order to perform the convolution. The solution is to perform an approximation of the Sinc function by windowing, that can be considered a truncation if the used window is a rectangular function (gain = 1). Other window functions can be used, as explained in [21], generating different approximations.

2.2.6 Robust Spline Filter

The Robust Spline Filter was created to use all the benefits of the Spline filter, adding the capability of be robust against outliers. For surface metrology, it is standardized by the ISO 16610-32 [22] and a very interesting model is proposed in [23].

In fact, the Robust Spline filter uses the concepts of the Weighted Spline filter that can be defined by a matrix notation as:

$$(W + \alpha Q)S = WZ \qquad \text{(Eq. 11)}$$

where W is the diagonal matrix of weights, Z is the input signal, S is the output signal, α is the constant value determined by the cut-off wavelength and Q is the coefficient matrix depending on the boundary conditions [23]. For periodic signals Q has the values presented in (Eq. 12) and, for a decay of 50%, α is described by (Eq. 13).

$$Q = \begin{bmatrix} 6 & -4 & 1 & & & 1 & -4 \\ -4 & 6 & -4 & 1 & & & 1 \\ 1 & -4 & 6 & -4 & 1 & & \\ & \ddots & \ddots & \ddots & \ddots & \ddots & \\ & & 1 & -4 & 6 & -4 & 1 \\ 1 & & & 1 & -4 & 6 & -4 \\ -4 & 1 & & & 1 & -4 & \end{bmatrix} \qquad \text{(Eq. 12)}$$

$$\alpha = \frac{1}{16.\sin\left(\frac{\pi \Delta x}{\lambda_c}\right)^4} \qquad \text{(Eq. 13)}$$

The goal of the Robust Spline filter is perform the Weighted Spline filter iteratively, modifying the weight matrix W according to some statistical parameters, until satisfying a determined convergence condition. Goto et al. (2005) proposed a convergence condition of 2% in the ratio of relative change in the overall weights. The first iteration is made by the basic Spline filter and the filtering algorithm is represented in Figure 12.

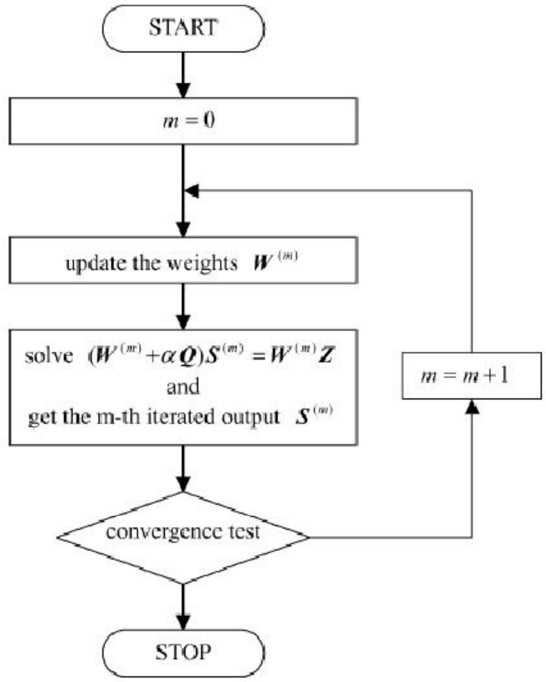

Figure 12. Algorithm of the Robust Spline Filter [23].

2.2.7 Robust Gaussian Regression Filter

The Robust Gaussian Regression filter is already included in the standards for Geometrical Product Specification. Described by the ISO 16610-31 [24], it is based on the concepts of Gaussian regression filter, that is applied iteratively until the filtering is satisfactory. This regression filter can evaluate the entire length of the profile, so overcoming the problem of edge effects present in the Gaussian filter. It is possible because the weighting function is calculated for every point, by (Eq. 14),

$$s_{kl} = \frac{1}{\lambda_c \sqrt{\ln(2)}} \exp\left[-\frac{\pi^2}{\ln(2)} \frac{((k-l)\Delta x)^2}{\lambda_c^2} \right] \qquad \text{(Eq. 14)}$$

where k is the index for the location of the weighting function (centre) and l is the index for profile points [14], [25]. Figure 13 illustrates the progression of the weighting function for the Gaussian regression filter.

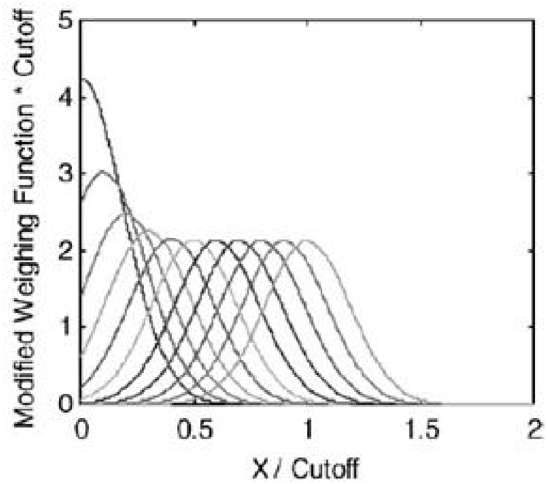

Figure 13. Progression of the weighting function for the Gaussian regression filter.

This filter is applied iteratively with a control variable determined by a median statistic of the difference between the signals after and before the filtering. Brinkmann [26,27] reported a good approach about the Regression and the Robust Gaussian Regression filter, highlighting their benefits, if compared to the classical Gaussian filter.

2.2.8 Wavelet Filter

The Wavelet filter is a promising method that is being evaluated in surface analysis [28]. It is based on the Wavelet Transform, that overcomes one specific problem of the Fourier transform, the only frequency resolution and no time/space resolution. This means that in the Fourier transform, although it is possible to determine all the frequencies present in a signal, it is not possible to know where they are present. So, the wavelet analysis is able to represent a signal in the space and frequency domain at the same time.

The idea behind the space-frequency representation (generally called space-scale representation) is to divide the signal into several parts and then analyze each one separately. This is made by the use of a fully scalable modulated window, that is shifted along the signal and for every position the spectrum is calculated. Then this process is repeated many times with a slightly shorter (or longer) window for every new cycle. The final result will be a collection of time-frequency representations of the signal, all with different resolutions [29]. To achieve efficient implementation, a dyadic scaling is usually used, as will be explained below.

Not addressing the mathematical details, the multi-band analysis can be performed by feeding the signal into a bank of band-pass filters where each filter has, for the dyadic scaling, a half bandwidth of the right neighbor, and a low-pass filter to cover the remainder spectrum. The band-pass functions are called *Wavelets*, while the low-pass is called *Scaling function*. Figure 14 shows the subdivision of the signal in multiples bands and Figure 15 illustrates the wavelets and the scaling function.

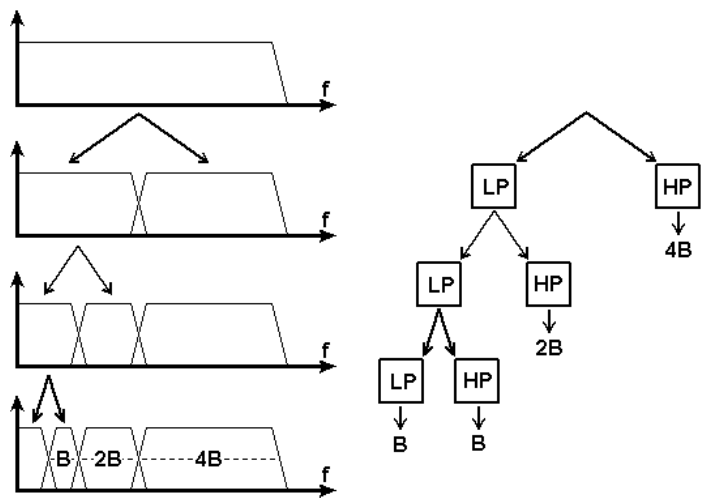

Figure 14. Splitting the signal spectrum with an filter bank [29].

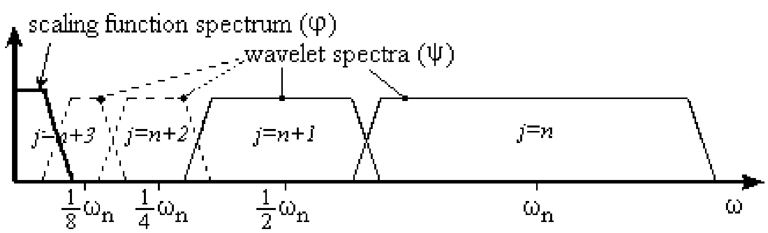

Figure 15. Wavelets and Scaling functions. Adapted from [29].

In the last decades, many scaling and wavelets functions were developed. They represent the scalable modulated window that, as seen previously, is the core of Wavelet analysis. A primary consideration in applying wavelets for surface profile analysis is the characteristic of amplitude and phase transmission of the wavelet and scaling function. Current standards on surface texture, such as the ASME B46.1 [30], specify non-linear phase as not desirable because it introduces distortion in filtered profiles. Thus, a combination of good amplitude and linear phase transmission is always desired.

From this perspective, some functions with regards to their adequacy for surface analyses were analysed [31]. The summarized results are shown in the Table 1.

	Haar	Db6	Coif4	Bior5.5	Bior6.8
Amplitude	Poorest	Good	Good	Poor	Good
Phase	Linear	Poor	Near Linear	Linear	Linear

Table 1. Amplitude and phase characteristics for Wavelet bases [**Error! Bookmark not defined.**].

Therefore, comparing the amplitude and phase characteristics, the functions Coif4 and Bior6.8 seems to be good choices. They are derived from the Coiflet and Biorthogonal Wavelet families, with many references in the literature. This functions are shown in Figure 16 and Figure 17, respectively.

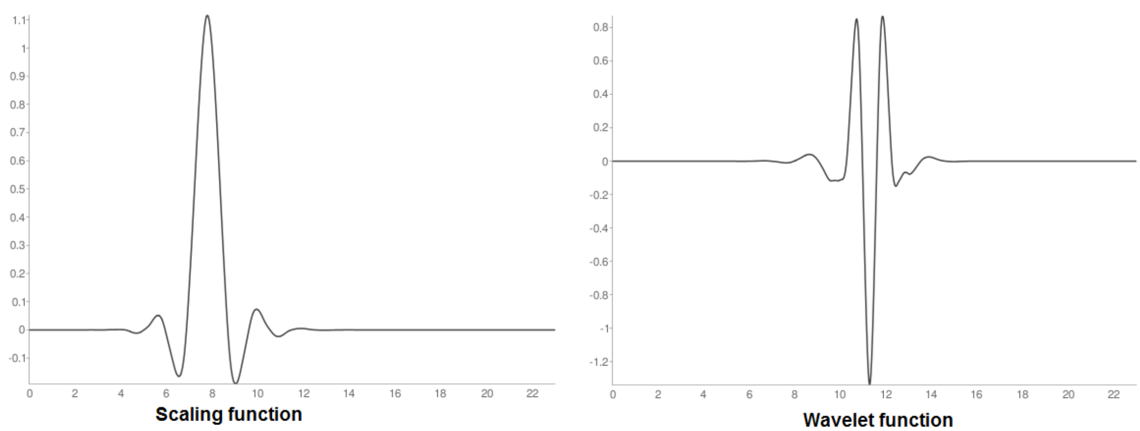

Figure 16. Scaling and Wavelet functions for the Coif4 base [32].

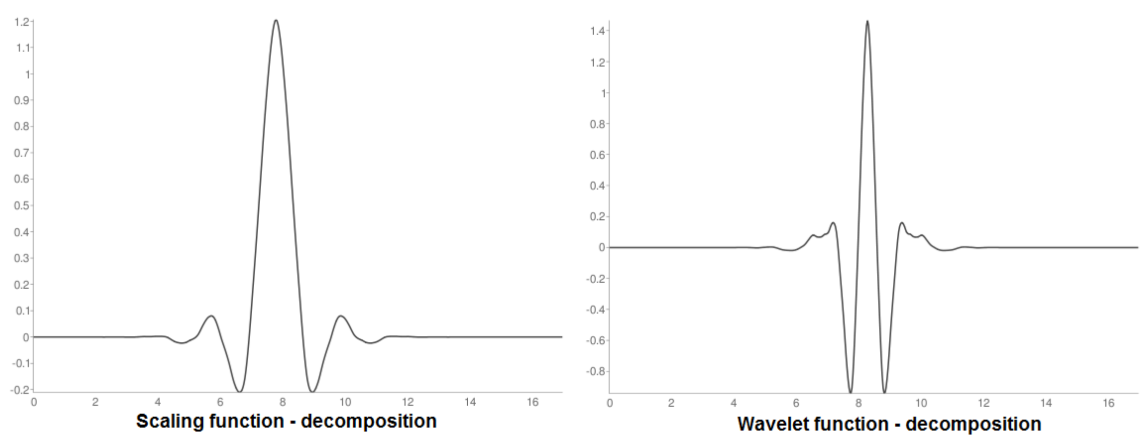

Figure 17. Scaling and Wavelet functions for the Bior6.8 base [33].

2.2.9 Morphological Filter

The principle of the Morphological filter is to simulate a geometrical element, in general a circle, rolling over the signal. Not so simple as this, it is based in the Minkowski sums [34], that even consists on a sweep of one set over other set. Figure 18 illustrates a Minkowski addition and subtraction, respectively, that is the basis for the filtering operations in Morphological filters.

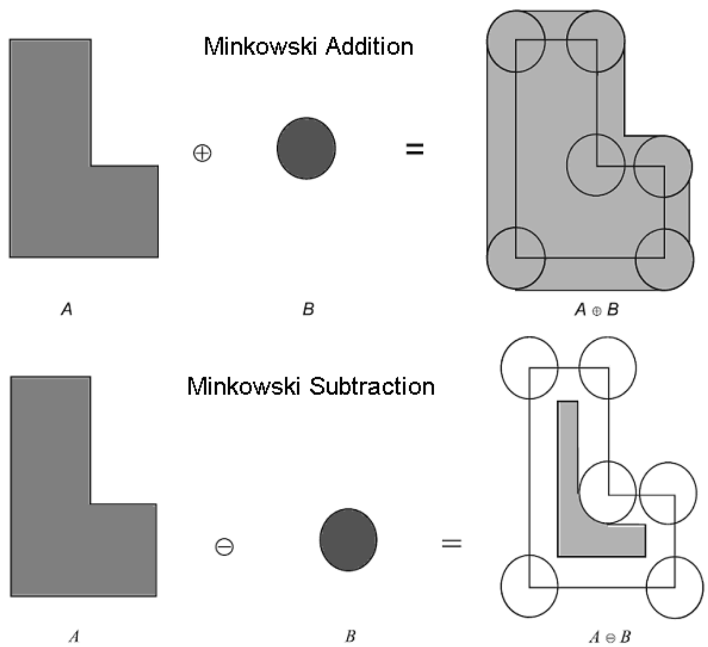

Figure 18. Minkowski addition and subtraction of two sets [35].

Based in these fundaments, four important operations are introduced:

- Dilation – Consists in a Minkowski addition of the signal (A) with the structuring element (B) reflected through its origin, in other words, B' = *{-b:b ϵ B}*. As the structuring element in this case is a circle, the Dilation is the same that a Minkowski addition.
- Erosion – Consists in a Minkowski subtraction of the signal (A) with the structuring element (B) reflected through its origin, or, B' = *{-b:b ϵ B}*. Whit a circle, the Erosion is the same that a Minkowski subtraction.
- Opening – Is a Erosion followed by a Dilation (the sequence is important). Using a round structuring element, sharp convex corners of the input set A can be rounded.

- Closing – Is a Dilation followed by the Erosion (the sequence is important). Using a round structuring element, concave corners of the input set A can be filleted.

The Figure 19 shows the Opening and Closing operations.

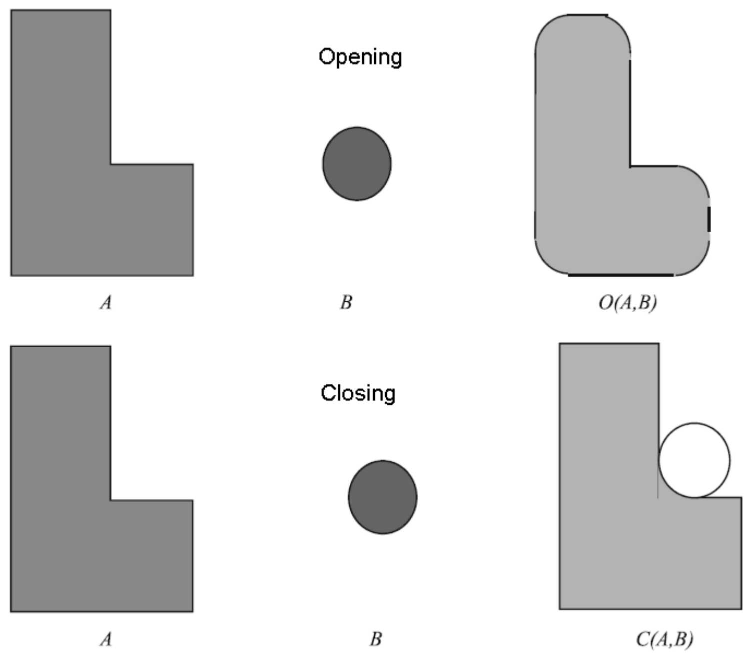

Figure 19. Opening and Closing operations [35].

Applying these morphological operations in an appropriate combination, it is possible to suppress all signal features smaller than the used structuring element. In other words, this operations can be compared to a low-pass filter, where the cut-off frequency is related to the radius of the structuring element.

The standard ISO 16610-41 [36] describes the use of morphological filter for surface metrology and propose some size of radius to be used. However, it is necessary to be careful when comparing the Morphological to the other filtering methods, because the result of the filtering is not dependent only on the frequencies or wavelengths of the input signal, but also on its amplitudes. Figure 20 shows the four described morphological operations applied to a simulated signal.

Some new researches are proposing Morphological filters based on different combinations of the morphological operations. As an example, [37] proposes the filter described by (Eq. 15), that performs a mean line filtering.

z(x) = mean[(first closing, than opening),(first opening, than closing)]   (Eq. 15)

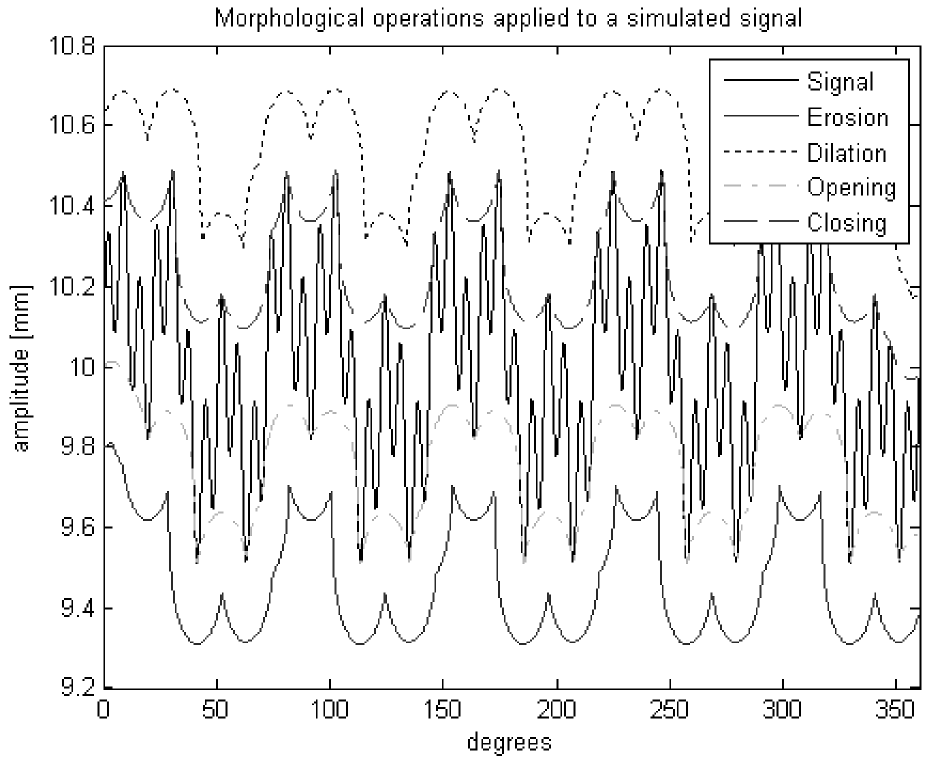

Figure 20. Morphological operations applied to a simulated signal.

2.2.10 Filtering Roundness Profiles

For roundness measurement, it is common to express the filter parameters in terms of frequency, in Undulations per Revolution (UPR). The relation between the frequency in UPR and the wavelength is described by (Eq. 16), where Ø is the nominal diameter of the part.

$$\omega(UPR) = \frac{\pi.\varnothing}{\lambda} \qquad \text{(Eq. 16)}$$

When the filtering of a roundness profile is made in the space domain by convolution, care must be taken to avoid edge effects. As the profile is closed, it is necessary to perform the circular convolution [38] instead the linear convolution, because there are not zeros before and after the signal, but the signal itself, that is periodic. If the length of the weighting function is m and that of the profile is n, increase the length of the profile to n+2m by adding the first m profile points to its end and the last m points to the beginning. Now, a simple linear convolution will produce a profile of length n+2m+m−1. The central n points represent the filtered profile [14].

However, the circular convolution is not computationally efficient because it requires much memory. When the filtering is realized by the DFT, this problem does not exist because the DFT already supposes a periodic signal and performing the IDFT to the weighting function and the signal would be equivalent to a circular convolution.

2.2.11 Selection of Filter and Filtering Parameters

Selecting the filtering parameters is not an easy task. There is a specific standard that proposes this parameters for roundness measurement, the ISO 12181-2 [39], which uses only the diameter of the evaluated part as variable, with a defined cut-off wavelength of 0,8 mm, from the (Eq. 16). Table 2 shows the cut-off selection according to this standard.

Reference circle diameter [mm]	Undulations per revolution, UPR
$d \leq 8$	15
$8 < d \leq 25$	50
$25 < d \leq 80$	150
$80 < d \leq 250$	500
$250 < d$	1 500

Table 2. Approximation of linear cut-off frequencies with λc = 0,8 mm [40].

However, the standard VDI/VDE 2617-2.2 [40] says that the definition of filtering parameters should include not only the cut-off frequency (or wavelength) but also the tip diameter and filtering method [5].

With the advancements in signal filtering, some researches (e.g. [25] and [27]) and the standard VDI/VDE 2631-3 [15] propose the so called functional filtering, where the selection of filtering methods and parameters are based mainly on the manufacturing process and the function of the work-piece.

A typical case which the manufacturing process is determinant to specify the filter to be used is the *plateau honed* profile. It has many valleys in the side of the material, what is very important in some application, as for example, preserving the work-piece lubricated. In general, to evaluate the form of these profiles, it is not necessary to consider the valleys and robust filters are more indicated for the filtering. Figure 21 shows a plateau honed profile, evaluated in [27], filtered by the Gaussian filter and the Robust Gaussian, showing the difference on the result and how the evaluation can be wrong, depending on the selection of the filtering method.

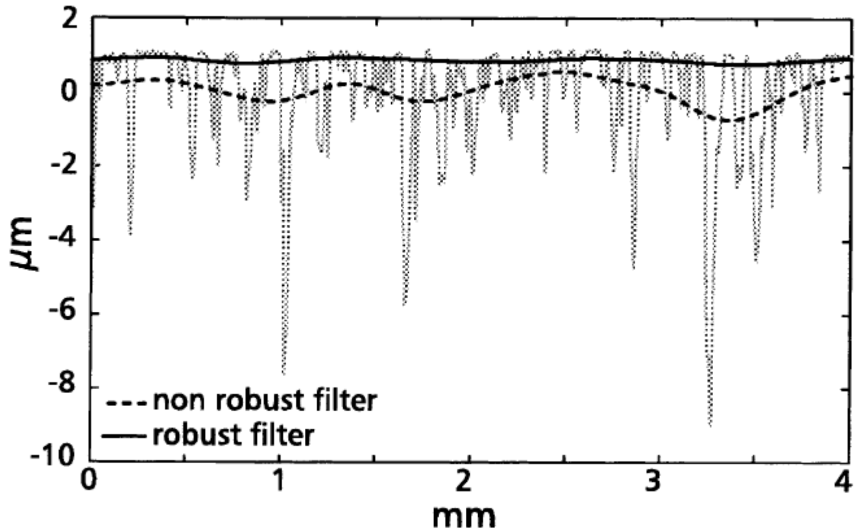

Figure 21. Profile extraction of a plateau honed surface with a non robust and a robust filter line [27].

Regarding the function of the work-piece, the observation made above, that the valleys are not important for the form evaluation, is valid for many cases, specially for sliding and assembly surfaces, where the most important is the contact surface. However, in some cases these valleys must be considered in the evaluation of the profile, as for example the sealing surfaces of a duct, where the pits can allow leaks.

These addressed issues reinforce the idea that the filtering method and parameters should be specified by the designer, regarding the manufacturing process, the function and the frequencies present in the part. Otherwise, the metrologist does not have enough information and can reach a wrong evaluation of the surface.

2.3 OUTLIER RECOGNITION AND ELIMINATION

One of the most critic problems in the measurement of form deviation is the presence of outlier in the acquired profiles. Specifically on measurement by scanning in CMMs, the outlier presence is more prospective, because the vibrations in the ground caused by production machines, electrical noises or other unknown causes. Figure 22 exhibits an outlier in the roundness measurement of a real profile.

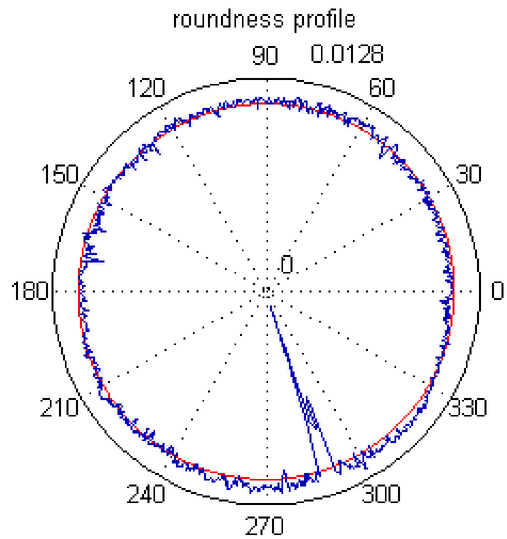

Figure 22. Outlier in the roundness measurement of a real profile.

There is not great knowledge about outlier elimination in form measurement and there are no specific standards for this subject. However, The ISO 16610-1 [6] define an outlier as:

“Local portion in a data set that is not representative or not typical for the partitioned integral feature and characterized by magnitude and scale”.

It relates also that *“not all outliers can be determined using data alone, except for outliers that are physically inconsistent with stylus tip geometry*”.

In the metrology literature, besides the classical Gaussian filter, some recent methods of outlier elimination have been proposed, based on the concept of multi-scale analysis [14], [28]. The fundament of this technique is to separate the signal in many narrow bands and analyse each one separately. Different ways can be used to separate the signal, as the Brick-wall filter, the Morphological filter or the Wavelet filter. The process of outlier elimination is made as explained below.

Gaussian filter: First, the signal is filtered by a low-pass Gaussian filter. This filtered profile is shifted by the safety coefficient of 4 times the standard deviation (sigma) of the signal, defining the upper and lower limits to discriminate the outlier from the original profile. Considering a Normal distribution, it is guaranteed that the probability of any point to be inside this limits is about 99.994 % [41].Finally, the points that are external of the limits are considered outliers. Figure 23 shows a real signal filtered by a Gaussian filter and the 4 sigma limits.

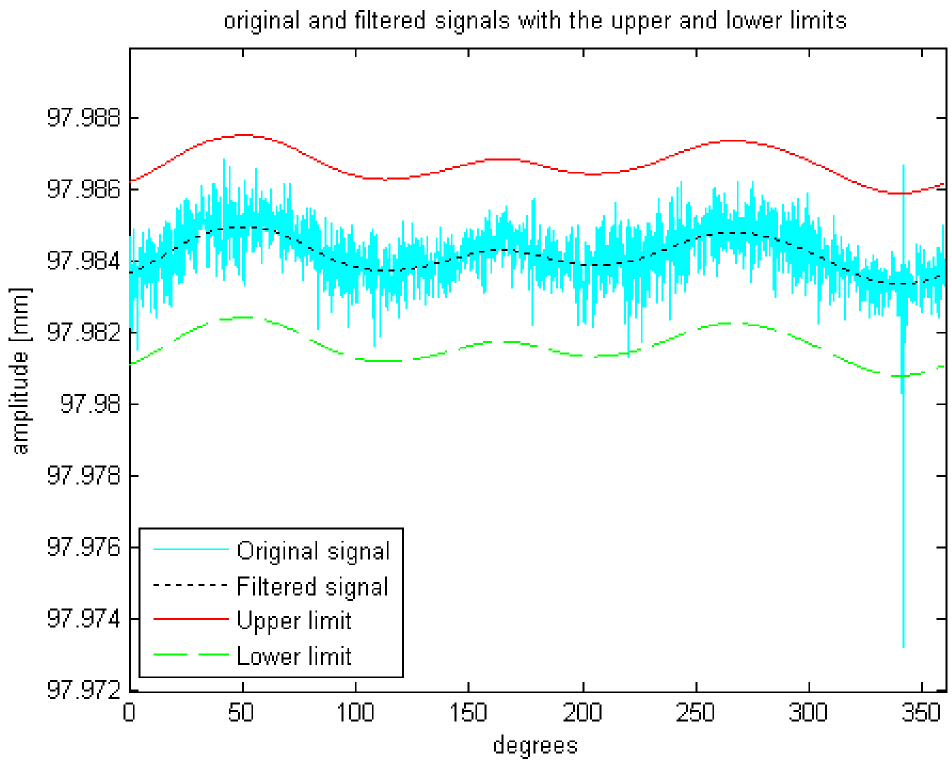

Figure 23. Original and filtered profiles with the 4 sigma limits.

Brick-wall filter: This method uses the concepts presented in section 2.2.5 and a bank of band-pass filters is applied to a signal, separating it in many sub-bands in the frequency domain. Figure 24 illustrates the application of a Brick-wall multi-scale filter. All bands have the same width, unless the last that is defined by the difference between the Nyquist frequency and the previous frequency (in the figure, *Bn = Nyquist freq. – f3*). For the elimination of outlier, the standard deviation of each band is calculated and a limit of 4 sigma (upper and lower) is defined. After this, the points that fall outside these limits are considered outlier points and are substituted by the mean value of that band. After the outlier elimination in all bands, the profile is reconstructed.

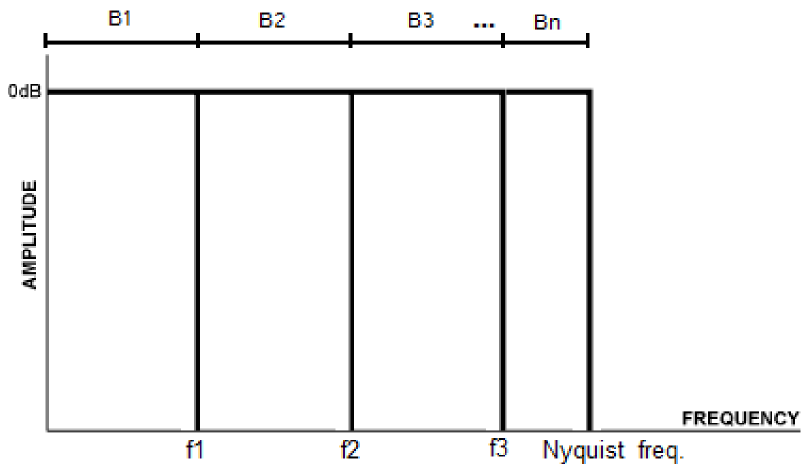

Figure 24. Multi-scale brick-wall filter.

Morphological: The profile is filtered by a combination of opening and closing operations, varying the size of the structuring element, so doing a signal separation in a space-scale. The first structuring element has the size of the smaller feature discernible in the signal, normally just larger than the sampling interval. The resulting profile is termed *approximation profile* and the difference between the original profile and the approximation is called *difference profile*. The next step is the filtering of the approximation profile, with a bigger structuring element, generating new approximation and difference profiles. This process is extended for many levels and the size of the structuring element is arbitrary and depends of the application. The process of outlier elimination is performed as for the Brick-wall filter. Figure 25 shows a Morphological multi-scale separation, with respective Approximation and Difference profiles.

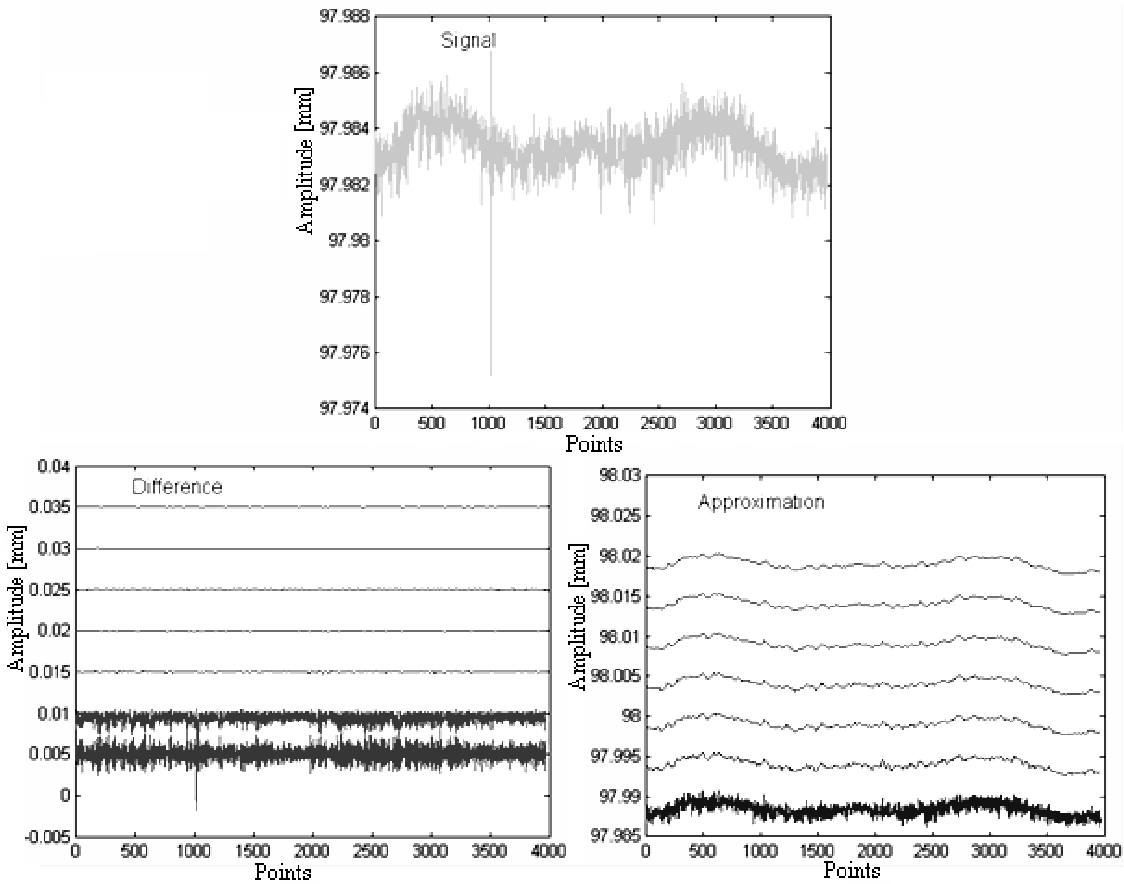

Figure 25. Morphological Approximation and Difference profiles (without outlier elimination).

Wavelet: The wavelet has already the characteristic of multi-scale separation, as seen in the section 2.2.8 and, after the decomposition of the signal in many sub-bands, the elimination of the outlier is performed at the same form as described for the Brick-wall filter and the Morphological filter.

2.3.1 Outlier Elimination in Coordinate Measuring Machines

The main CMMs have in their measurement software a specific function to eliminate outliers. However, for roundness measurement, there are some information that are necessary and are not given by these software. In general, the software does not give both before and after profile. In other words, it is only possible to see the acquired profile or the profile after the outlier elimination. Thus, it is not possible to analyze the effects of the elimination in the whole signal.

The measurement software must point the outliers, with their location, but should also allow the operator to decide if the elimination is satisfactory or if is necessary a new measurement with some modified conditions, that were supposedly the cause of these abnormalities. This is another reason that shows how important is the graphical comparison between the signals before and after the outlier elimination.

About the used methods, there is little information. Usually, the operator must select some parameters, like number of standard deviation for the limits, and the outlier elimination is performed. Figure 26 shows the configuration screen for outlier elimination of the Calypso®, a measurement software from Carl Zeiss Inc.

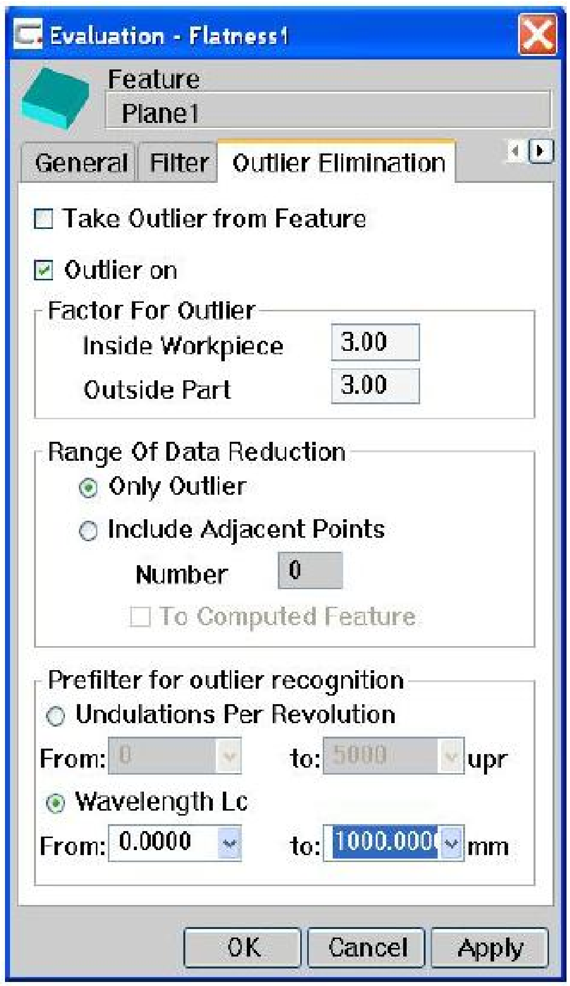

Figure 26. Outlier elimination from Calypso®.

2.4 INTERPOLATION

On roundness measurement by scanning in CMMs, occurs the displacement of at least two axis from the machine to be obtained the circular trajectory. This characteristic implies in some effects that are not existent in equipments specifics for form measurement, where the axis of the rotating table defines the referencing circle. One of these effects, as explained in [42], is the uneven spacing in the data acquisition. Figure 27 shows the angular spacing of a real measurement.

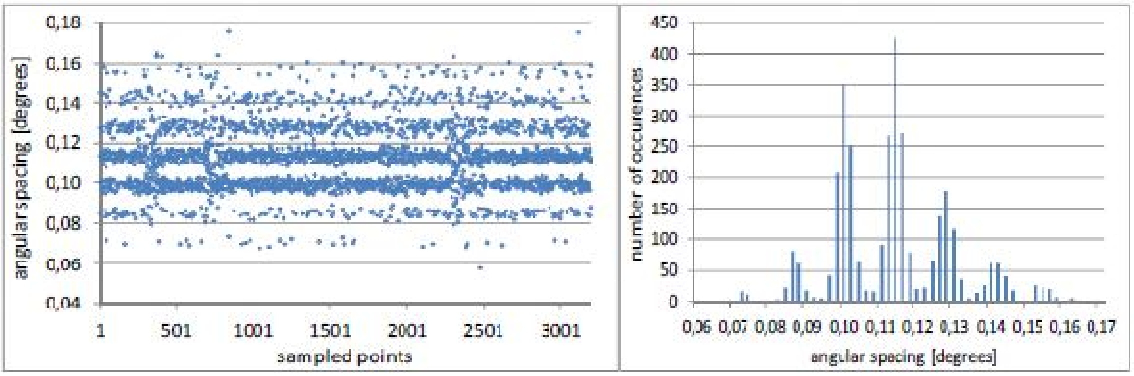

Figure 27. Uneven spacing of a real measurement (left) and the respective multimodal distribution (right) [8].

A direct consequence of the uneven spacing in the acquisition is the attenuation and spreading of the frequencies in the DFT, which can influence the evaluation of profiles by the frequency spectrum and the filtering results. The evaluation in the space domain is also influenced by the uneven spacing, since the difference between profiles can be severely overestimated. Figure 28 presents the evaluation of the frequency spectrum of a simulated signal with even and uneven spacing, respectively.

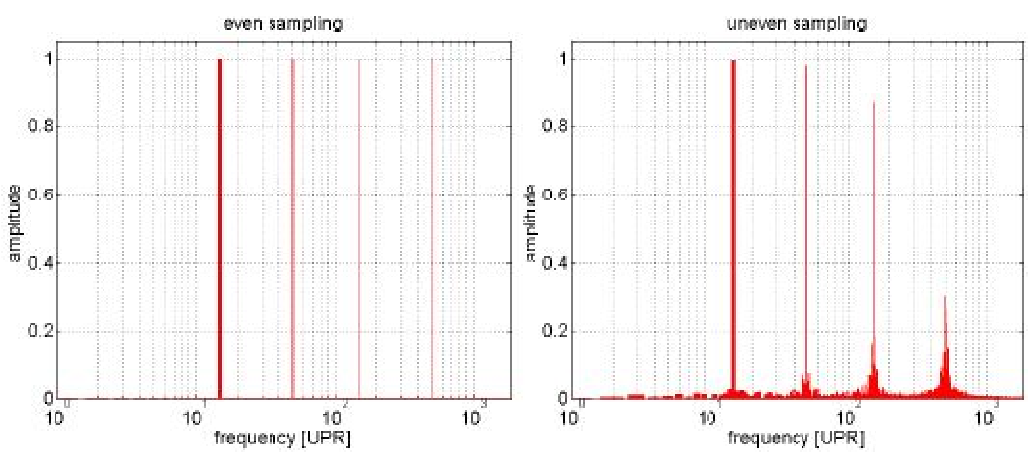

Figure 28. Frequency spectrum and amplitudes of a simulated profile with four frequency components (15,50, 150 and 500 UPR, unity amplitudes), evaluated by a even spacing (left) and an uneven spacing (right) [8].

A recent solution for the problems caused by the uneven spacing, typical in CMMs measuring on high velocities, is the interpolation by cubic splines. The effects on the frequency spectrum were almost eliminated and the evaluation of profiles in the space domain were also improved [8].

2.5 TIP RADIUS CORRECTION

Measurement of roundness profile by mechanical probing is done using spheres with different radii and the extracted profile refers to the centre of the sphere. Therefore, the result is a distorted profile [43], as shown in Figure 29. For assembly work-pieces, the influence of the distortion caused by the sphere is negligible, but for other functional examples such as sliding and sealing, it can lead to a wrong evaluation of the functional properties.

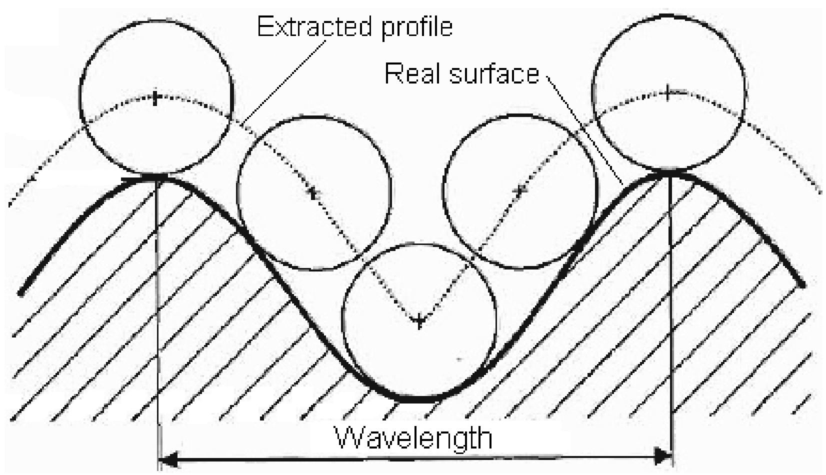

Figure 29. Extracted profile with a spherical probe.

For external surfaces, the mechanical effect explained above can be considered a Dilation, a morphological operation explained in the section 2.2.9. Therefore, the best approximation of the real surface is obtained performing the opposite operation, the Erosion, with the same radius used in the measurement process. Figure XX illustrates this correction.

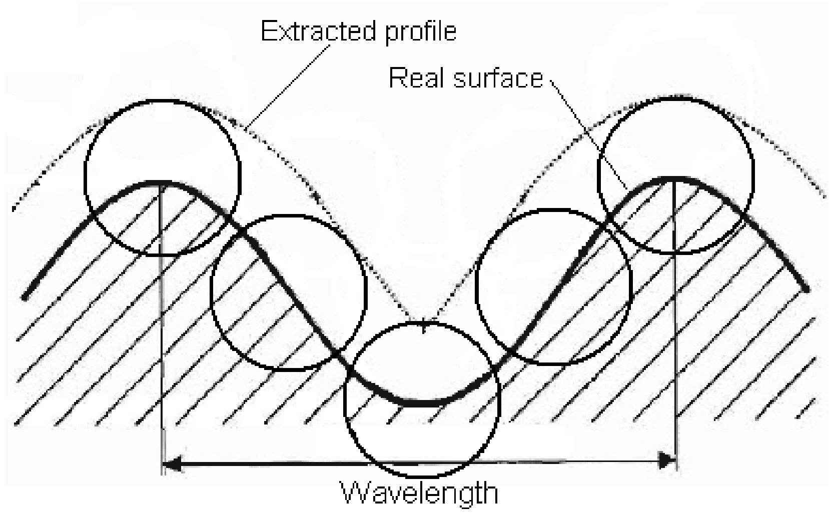

Figure 30. Tip radius correction by Erosion.

2.6 STATUS OF SIGNAL PROCESSING TECHNIQUES

In this chapter, the main techniques and issues of signal processing have been presented. Even though they are present in the literature of surface metrology, most of the methods are not widely applied in industry. Therefore, it is interesting to do a work of evaluation of these processing techniques, presenting the advantages and disadvantages, so they can be definitely applied.

3 MATERIALS AND METHODS

This chapter introduces the equipments, work-pieces and standards used in the acquisition of experimental data, besides the implemented algorithms for signal simulation. Furthermore, describes the environments for evaluation of the techniques of outlier elimination and signal filtering.

3.1 EXPERIMENTAL DATA

An experimental collection was acquired from work-pieces of the automotive industry and, from these experiments, the evaluation of signal processing methods was realized.

3.1.1 CMMs

The measurements were all realized by Coordinate Measuring Machines from the Manufacturer Carl Zeiss INC, but different models. Table 3 shows the technical specification of the three CMMs.

Specification of the used CMMs and their probing systems			
CMM Number	CMM 1	CMM 2	CMM 3
CMM			
Manufacturer	Zeiss	Zeiss	Zeiss
Model	ZMC 550	Accura	Prismo Navigator
Measurement Volume (mm^3)	550x500x450	900x1500x700	1200x1800x1000
MPE_E (ISO 10360-2) (L in mm)	3.0 + L/200 µm	1.6 + L/333 µm	1.5 + L/350 µm
Probing System			
Manufacturer	Zeiss	Zeiss	Zeiss
Model	HSS	VAST xt Gold	VAST
Environment			
Temperature (^oC)	20.0 ± 0.3	20.0 ± 2.0	20.0 ± 2.0

Table 3. Technical specification of the CMMs used to acquire the experimental data.

3.1.2 Work-pieces

As said before, the parts measured were, basically, from the automotive industry. For this work, it was selected two special work-pieces, a brake drum and an axle hub. Figure 31 shows the measurement of a brake drum and the respective calibration and Figure 32 shows the measurement of an axle hub.

Figure 31. Measurement (left) and calibration (right) of a brake drum.

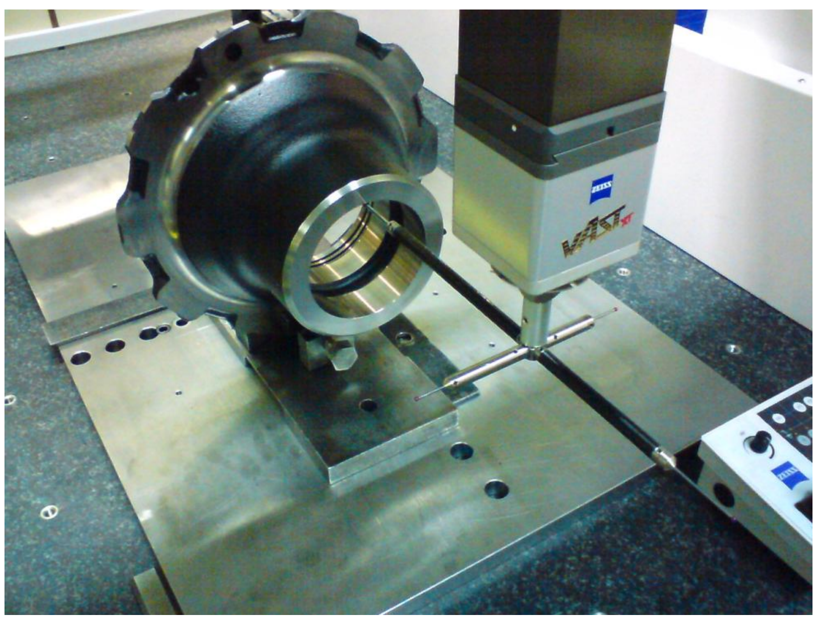

Figure 32. Measurement of an axle hub.

Some measurements were done on environments with disturbs and, therefore, many acquired signals have outlier or big amount of noise, what represents a good experimental data for this work.

3.1.3 The Multi-wave Standard

In addition to the work pieces mentioned above, it was also used a multi-wave standard (MWN), that is a special standard used to improve the calibration of form-measuring instruments [44]. It has some very accurate frequencies for roundness, straightness and flatness measurement and, therefore, it was used at this work for the evaluation of the filtering methods. Figure 33 shows a multi-wave standard being measured on different surfaces.

Figure 33. Measurement of a multi-wave standard [45].

The used multi-wave standard was developed at the Laboratory for Machine Tools and Production Engineering from the Technical University of Aachen (Germany) and manufactured in the Fraunhofer Institute for Production Technology – IPT, in Aachen. It has the name Kombi MWN 1 and its technical characteristics are presented in the Table 4. Figure 27 shows a measurement (on a form measurement machine) of the used multi-wave standard and the respective frequency spectrum, that theoretically has the frequencies of 5, 15, 50, 150 and 500 UPR, with the same amplitudes. For the evaluation of the filtering methods, the external cylinder was used (and simulated).

Kombi - MWN 1			
Surface functions	External cylinder	Internal cylinder	Flat
Diameter [mm]	80	40	-
Maximum number of undulations [UPR]	500	500	500
Maximum wave amplitude [mm]	0,004	0,004	0,004
Maximum sensor diameter (VDI) [mm]	7,0	1,5	2,9
Maximum sensor diameter (morphological filtering) [mm]	-	1,5	2,5

Table 4. Specifications of the multi-wave standard Kombi-MWN 1. Adapted from[42].

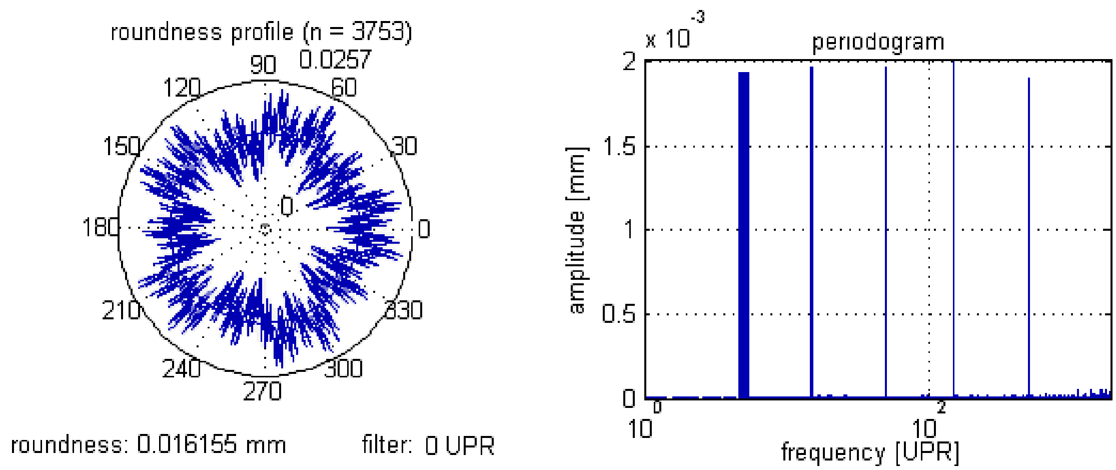

Figure 34. The multi-wave standard used at this research, non-filtered profile(left) and the frequency spectrum (right).

3.2 EVALUATION OF METHODS OF OUTLIER ELIMINATION

The easiest and most efficient way to compare the methods of outlier elimination is to perform a graphical analysis of the resulting signal, verifying the successful cut of the outlier and the distortion in the region close to the outlier. For this purpose a Matlab^{TM} evaluation environment was created [46], that will be presented in the following section.

3.2.1 Evaluation Methodology

After the implementation of all methods, it was necessary to define how to compare the methods. At first, some mathematical parameters were defined, such as the maximum difference between the signals before and after the outlier elimination. However, the best method is not necessarily the one that produces the greatest difference between the signals before and after removal, but one that behaves more smoothly, leaving the signal in the outlier region as similar as possible to the rest of the signal.

Another point that is very important here is the distortion caused by each method in the region close to the outlier, what is also not easy to be evaluated by mathematical results. Hence, the best way to perform the comparison of the methods is to analyse the graphical results of each method and discuss about them, in a objective way.

Thus, a Matlab script was made for the evaluation of the methods, where the outputs are the graphics of the outlier elimination of all methods, with a zoom at the outlier region. Furthermore, in the same software is possible to use more than one filter parameter for each method, being possible to do a comparison between different input parameters for the same method. The input for the Brick-wall is the bandwidth, for the Morphological is the radius increment, while for the Wavelet and the Moving Average is the cut-off frequency.

Finally, the processing time of each method is evaluated, since it is an important variable in the step of signal processing.

3.2.2 Outlier Characterization

From the parts used in this work, it was possible to perceive 4 different essential kinds of outliers. Depending on the measuring environment, a particular feature describes the outlier, showing that the causes of this error are directly related to the measuring environment and can be caused, for example, by mechanical vibration or electrical noises. Briefly, the different kind of outliers, with the respective examples that will be used to the result analysis, can be defined as:

Asymmetric-spike outlier: It has a very narrow width at the space domain and is present in just one side of the signal. Figure 35 shows the signal acquired during the calibration setting of a ring at CERTI Foundation, which contains at least one asymmetric-spike outlier.

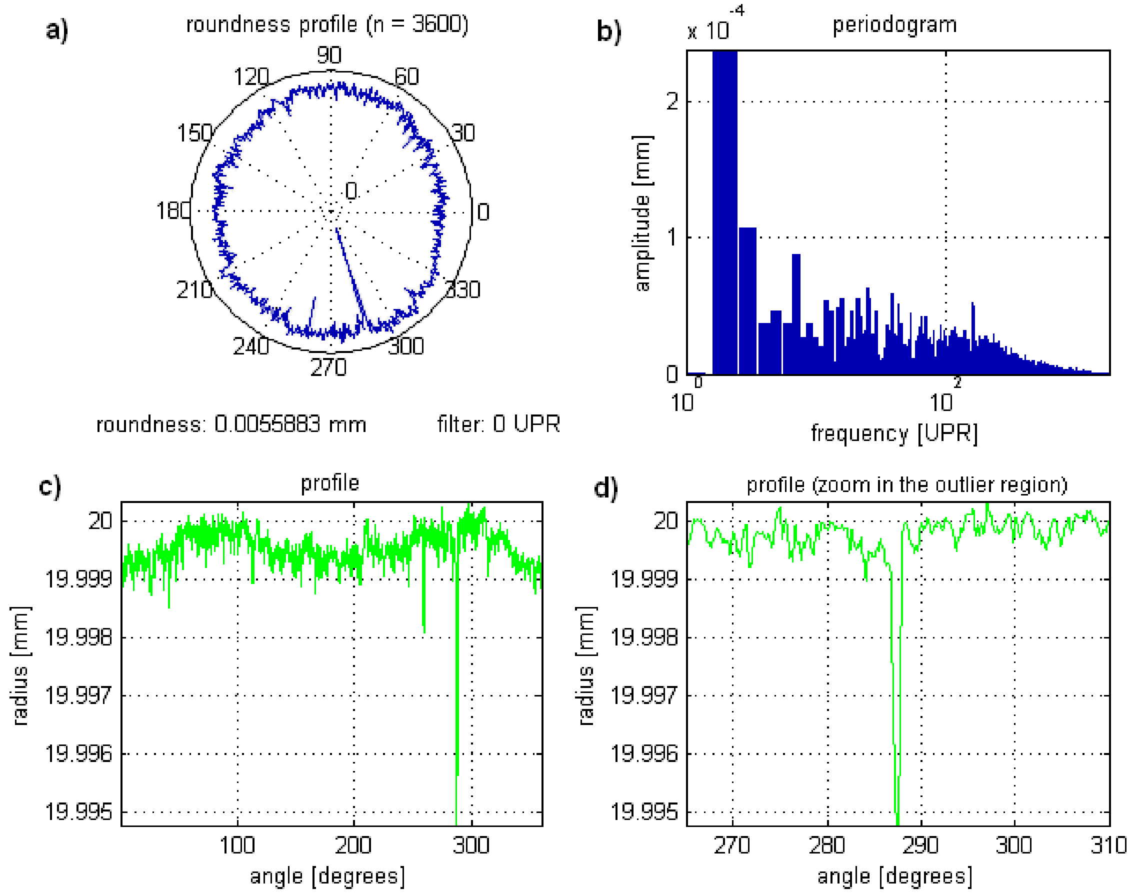

Figure 35. Experimental signal with an asymmetric-spike outlier. a) Polar graphic. b) Frequency spectrum. c) Linear graphic. d) Zoom in the outlier region.

Symmetric-spike outlier: It has a very narrow width in the space domain and has components for both sides of the profile. Figure 36 presents the signal from a measurement of a brake drum at Tupy, which contains an asymmetric-spike outlier.

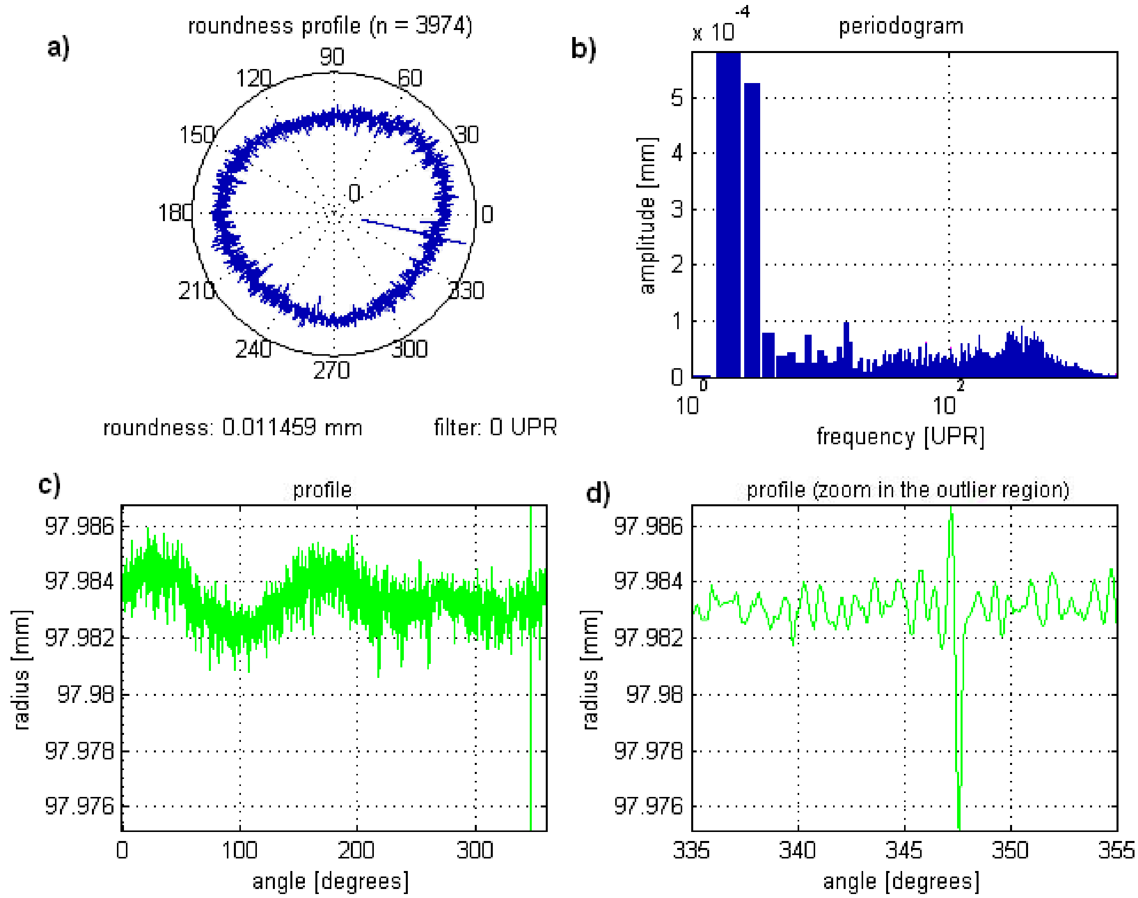

Figure 36. Experimental signal with a symmetric-spike outlier. a) Polar graphic. b) Frequency spectrum. c) Linear graphic. d) Zoom in the outlier region.

Damped-oscillatory outlier: It presents the same high frequencies contained in the profile, with an increase in the amplitude and consequent damping until the signal return to its regular form. It has components in both positive and negative sides of the profile. Figure 37 shows the signal acquired from the measurement of an axle hub at Schulz, that contains a damped-oscillatory outlier.

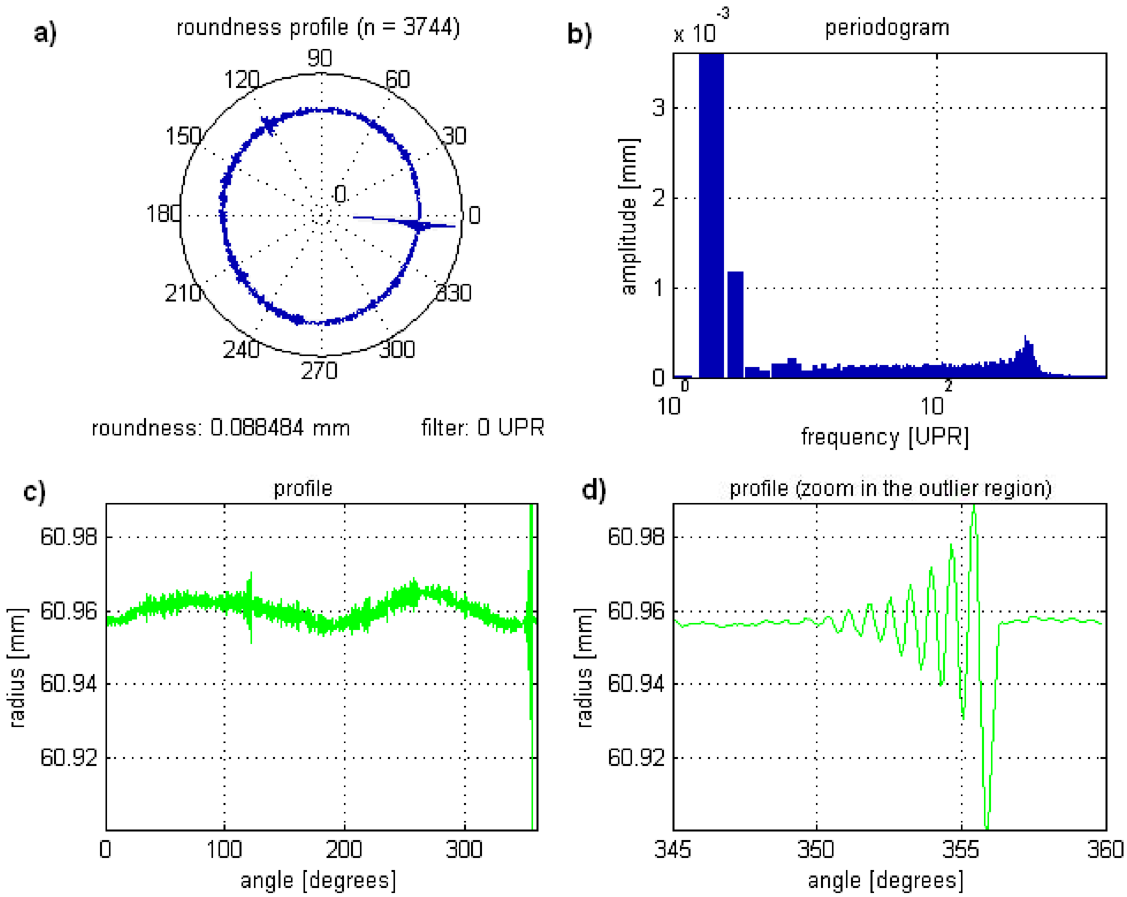

Figure 37. Experimental signal with a damped-oscillatory outlier. a) Polar graphic. b) Frequency spectrum. c) Linear graphic. d) Zoom in the outlier region.

Low-frequency outlier: It has a large width in the space domain and is caused, for example, by a dust grain. It appears only in one side of the profile, the negative for internal surface measurements and positive for external. Figure 38 shows another calibration signal of the same part presented at Figure 35. In this case, a low-frequency outlier appears.

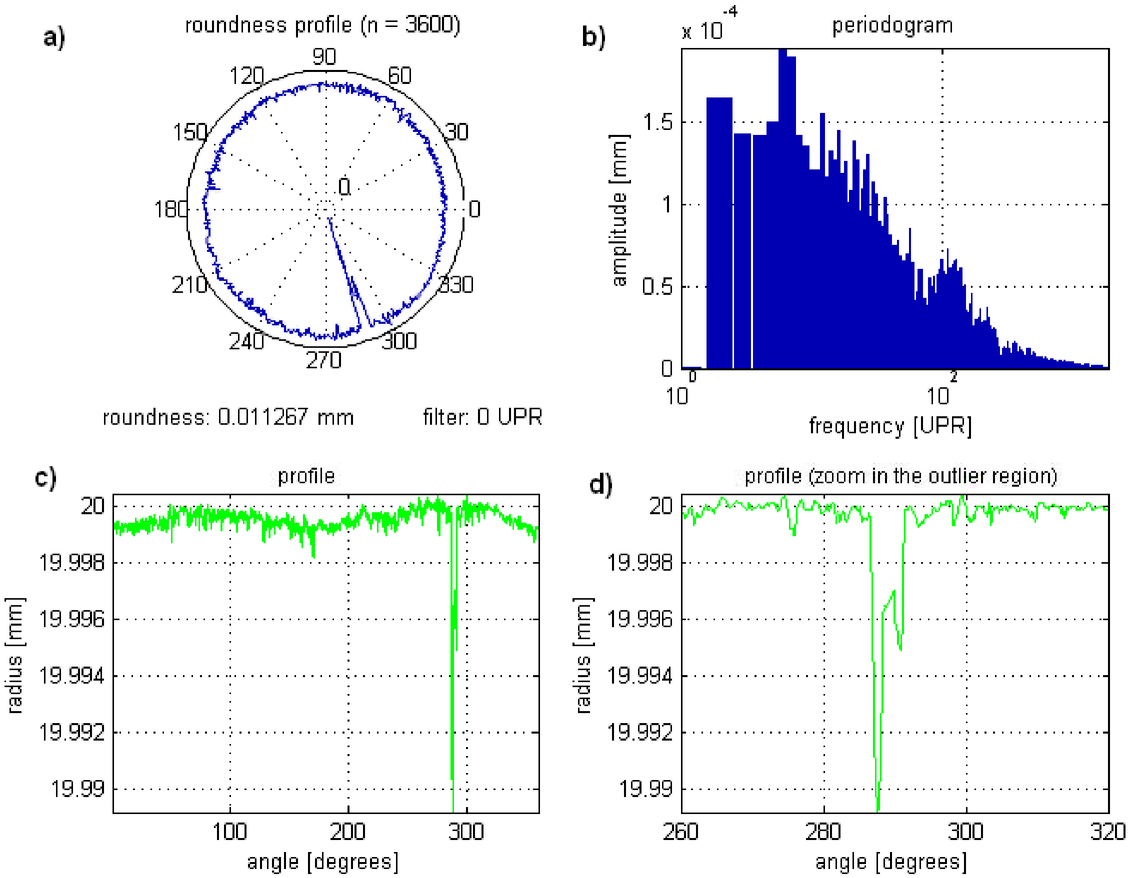

Figure 38. Experimental signal with a low-frequency outlier. a) Polar graphic. b) Frequency spectrum. c) Linear graphic. d) Zoom in the outlier region.

Thereby, the performance of the methods will be evaluated for each kind of outlier described and the results will be presented in the chapter 4.

3.3 EVALUATION OF METHODS OF SIGNAL FILTERING

Comparing the filtering methods directly by the roundness deviation is not the best way, mainly because some of the evaluated methods have different principles of operation. For example, while the Gaussian and the Spline can be directly analysed at frequency domain, the Wavelet uses the multi-scale analysis to perform the filtering and the Morphological is dependent of both frequency and amplitude of the input signal.

Therefore, some important criterions were established, aiming to verify the performance of each filter:

- Behaviour for uneven spacing signals;

- Distortions at the extremes of open profiles;
- Behaviour in presence of outliers;
- Computational efficiency and complexity of implementation.

Each criterion was addressed by an specific methodology and implemented in Matlab scripts.

3.3.1 Behaviour for Uneven Spacing Signals

The evaluation of the behaviour of the filters for uneven spacing signals is very important because, with a good result, the interpolation is not required. To do this analysis, it was used the signal whose spectrum are shown in the Figure 28.

First, the signal is created by 360000 points to simulate a real multi-wave standard. Thereafter this signal is sampled obtaining approximately 3600 points with an even and uneven sampling distribution. At this point both even and uneven spacing signals are filtered by all implemented methods, with three different cut-off parameters, and the relative bias in the form error is taken, from (Eq. 17),

$$\text{Form error bias} = \frac{\text{form error (ufs) - form error (efs)}}{\text{form error (efs)}} \qquad \text{(Eq. 17)}$$

where ufs is the uneven spacing filtered signal and efs is the even spacing filtered signal.

For a good estimation of this values, this algorithm runs 1000 iterations, where for each iteration the uneven spacing signal is different, being sampled by a spacing described by a multimodal Normal distribution, as presented in Figure 39, simulating the behaviour of a CMM at high sampling rates. Finally, the mean of the output values is computed and a graphical analysis supports the conclusions.

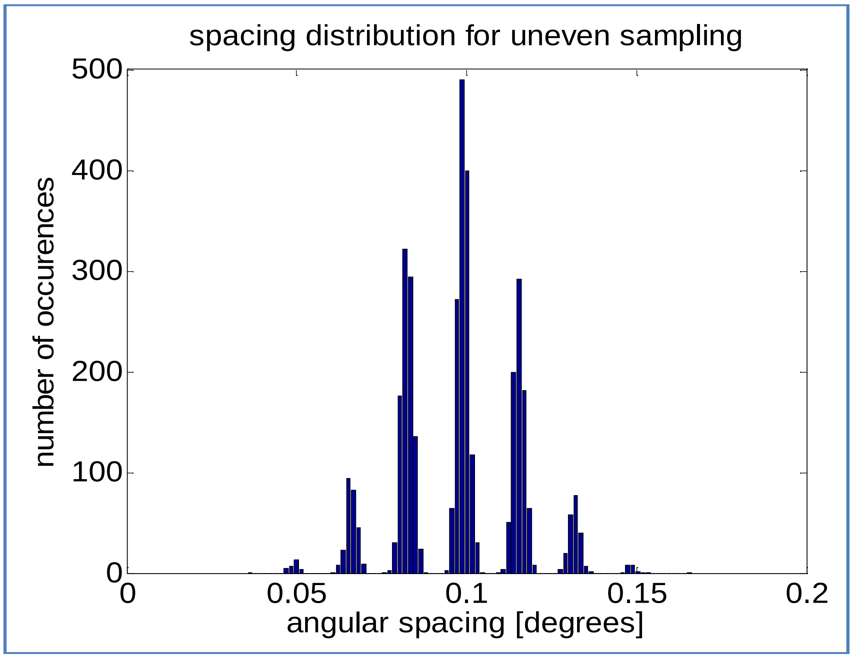

Figure 39. Multimodal distribution of a simulated sampling pattern.

3.3.2 Distortion at the Extremes of Open Profiles

As described in the Chapter 2, some filters have problems when filtering open profiles, causing distortion at the extremes. This trouble is called edge distortion and it is very known as one of the negative characteristics of the Gaussian filter, mainly for profiles with high form deviation.

For the evaluation of this behaviour, a closed profile is firstly filtered, being the reference signal. Then, the input signal is transformed in an open profile, by cutting a specific length at the end, and this signal is filtered again. Therefore, it is possible to compare the filtered open profile with the reference signal. This comparison is made for each filtering method and a graphical analysis is performed.

The signal used for this evaluation is a real measurement of an axle hub with a large form deviation, shown at the Figure 40, that is after cut to 340^{o}.

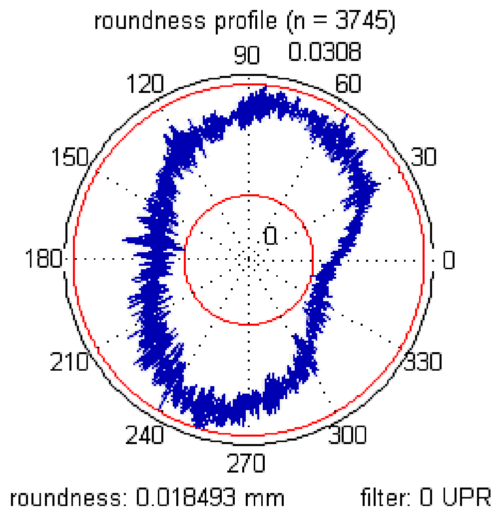

Figure 40. Original measured signal used for the evaluation of open profiles.

3.3.3 Behaviour in Presence of Outliers

The evaluation of the methods for signals with outlier is made by the graphical analysis, where all filtered signals are plotted in the same graphic, and the behaviour for each filter is analysed. It is performed for the same signals exposed in section 3.2.2, that exemplifies the kind of outlier found at this research.

3.3.4 Computational Efficiency and Complexity of Implementation

Finally, the signals are evaluated comparing the computational efficiency or, in other terms, the capability to have a good result at the shortest time as possible. Some facts about the complexity of implementation are also discussed at this point.

3.4 EVALUATION WITH CASE STUDIES

Aiming to analyse some specific characteristics explained before, some case studies are shown in chapter 5. First, an evaluation about the aliasing is performed to verify if the CMMs have anti-aliasing filter and if this problem is significant in the acquired signal. For this evaluation, it is used two different acquisitions from the MWN, changing the number of points.

Furthermore, it is evaluated the influence of mechanical distortion caused by the tip radius in the acquired profile, comparing the signals before and after the tip radius correction at space and frequency domain. The MWN is also used for this evaluation.

Afterwards, the filtering methods are compared regarding the transfer characteristic and the results on roundness deviation for a profile without outliers. Finally, an evaluation about functional filtering is performed, relating the selection of filter and filtering parameters to the function of the work-piece, specially for a ground profile.

4 RESULTS

This chapter presents the results obtained in the context of recognition and elimination of outlier, besides the evaluation of the filtering methods.

4.1 RESULTS ON OUTLIER ELIMINATION

As explained in the chapter 3, the methods of outlier elimination are analysed according the kind of outlier and the input parameters were empirically selected based on the evaluated profiles. For the Brick-wall, bandwidth of 100 and 150 UPR are used. The Coif4 and Bior6.8 are the evaluated functions for the Wavelet method, by the reasons explained in the section 2.2.8. For the moving average, 20 and 50 UPR are used as cut-off frequency, while an increment of 0.5 and 0.8 radians is applied to the Morphological method. It is important to perceive that the radius of the Morphological filter is specified in radians because the signal is described in polar coordinates, with the amplitude in mm and the angle in radians.

4.1.1 Elimination of Asymmetric-spike Outlier

Performing the outlier elimination for the signal of the Figure 35, the results are presented in the Figure 41. As said before, beyond the comparison between the methods of outlier elimination, a comparison of the same method with different parameters is also realized.

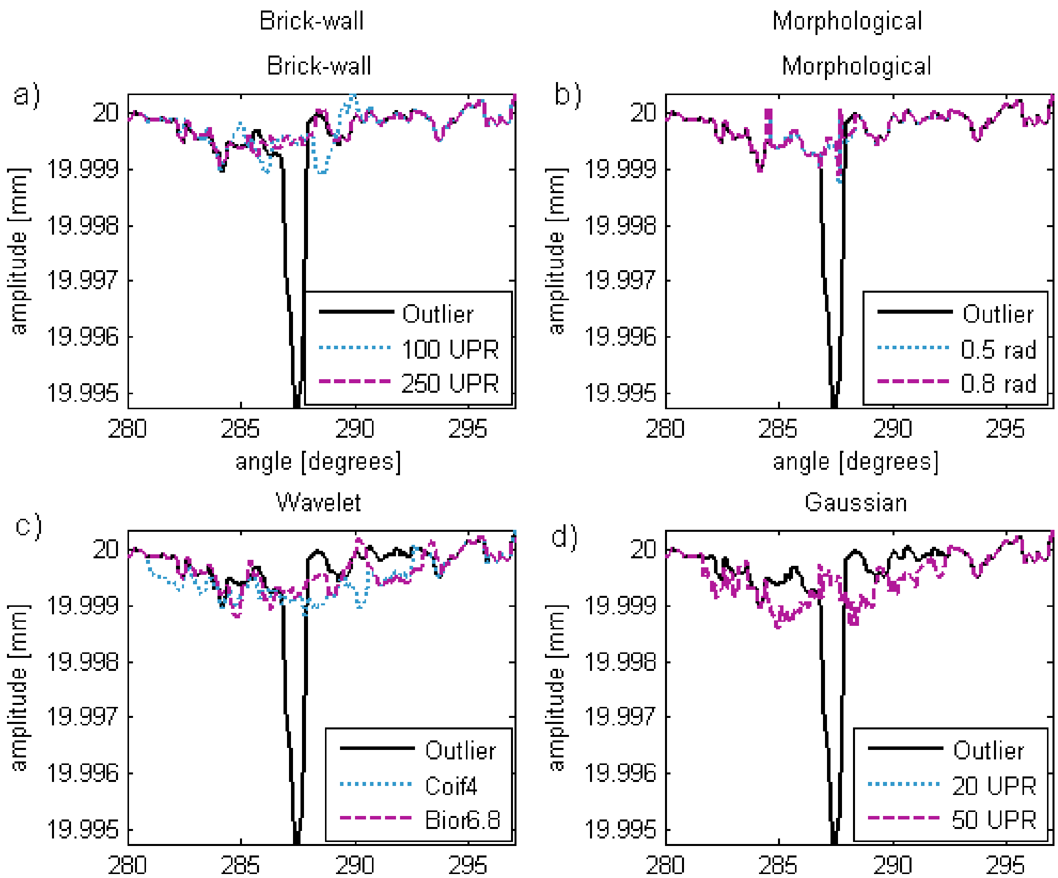

Figure 41. Outlier elimination applied to a signal with an asymmetric-spike outlier. a) Outlier elimination with the Brick-wall method. b) Outlier elimination with the Morphological method. c) Outlier elimination with the Wavelet method. d) Outlier elimination with the Gaussian method.

All the methods eliminate the outliers, but the Wavelet and Moving Average methods cause a distortion in the region of the outlier. The Morphological has a regular result, because it eliminates the outlier but keeps some undesired peaks, which can be relevant on the form evaluation, if they are not cut in the filtering process. However, the Brick-wall (specially with a bandwidth of 250 UPR) presents a very good result. It is important to say that the Brick-wall with the parameters of 100 UPR also caused a distortion in the region close to the outlier.

4.1.2 Elimination of Symmetric-spike Outlier

The signal present in the Figure 36 is used for this analysis and the results are presented in the Figure 42.

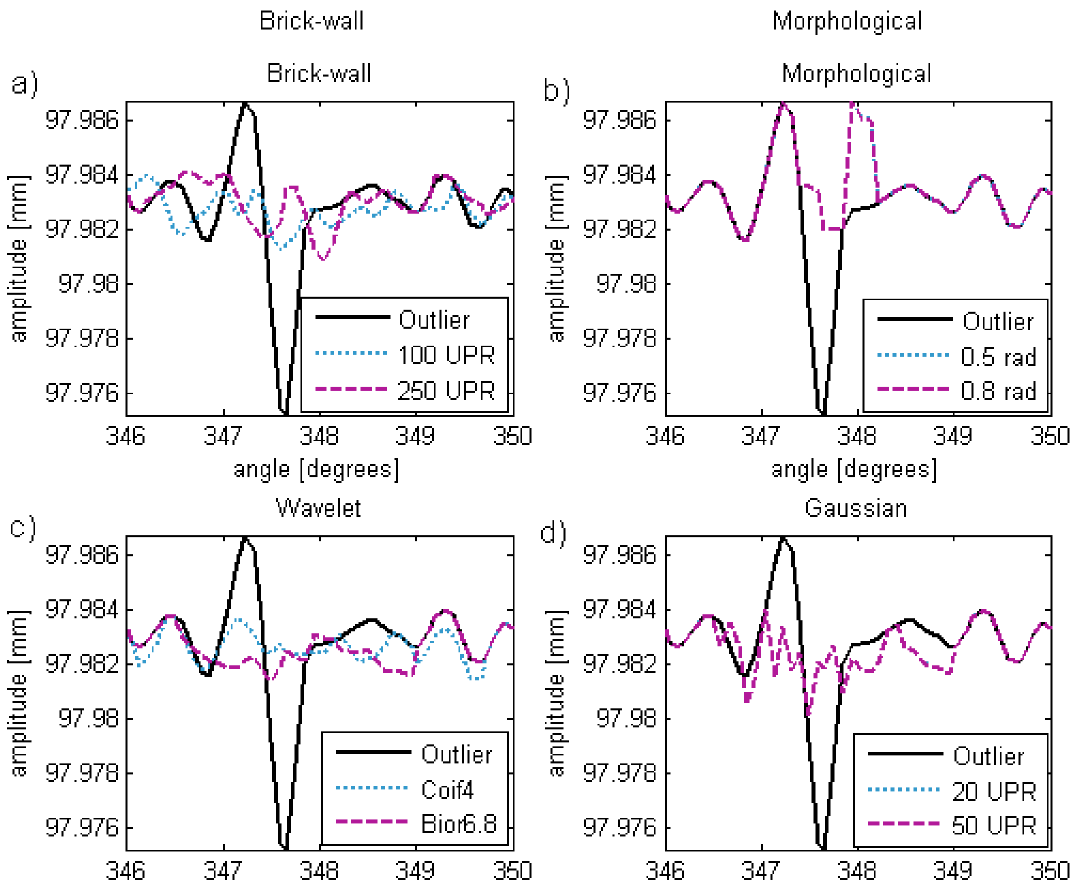

Figure 42. Outlier elimination applied to a signal with a symmetric-spike outlier. a) Outlier elimination with the Brick-wall method. b) Outlier elimination with the Morphological method. c) Outlier elimination with the Wavelet method. d) Outlier elimination with the Gaussian method.

The results here are not so clear because every method cause a distortion in the region close to the outlier. However, the methods Brick-wall and Wavelet seem to have a smoother elimination, cutting the main part of the peak and the valley. The Moving average also cuts the outlier, but the result has also some tips that can influence the roundness evaluation. Finally, the Morphological presents a very poor result, cutting partially the outlier, but creating another peak.

4.1.3 Elimination of Damped-oscillatory Outlier

To check the performance of the studied methods for damped-oscillatory outlier, the signal presented in the Figure 37 was used. The results are presented in the Figure 43.

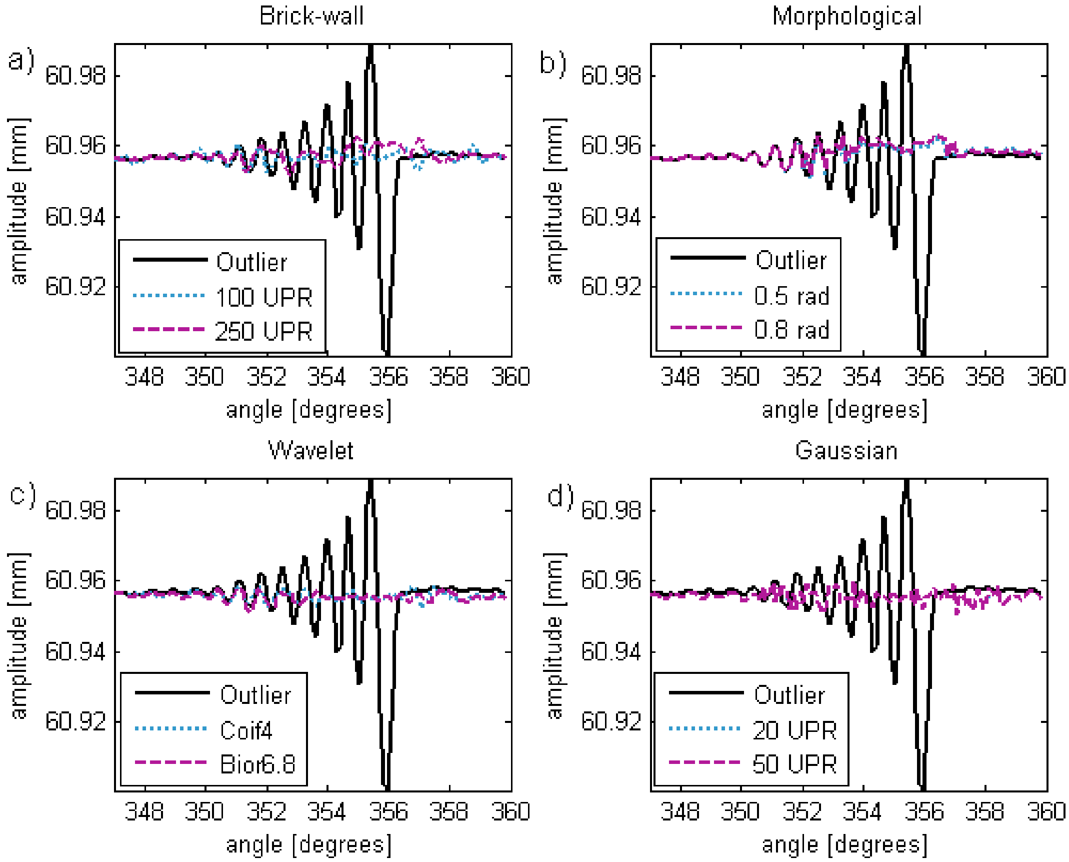

Figure 43. Outlier elimination applied to a signal with a damped-oscillatory outlier. a) Outlier elimination with the Brick-wall method. b) Outlier elimination with the Morphological method. c) Outlier elimination with the Wavelet method. d) Outlier elimination with the Gaussian method.

For this kind of outlier, all methods can be considered successful in the outlier elimination, but some observations can be made about each one. The Brick-wall has a very good result, for any parameter. The Morphological can also cut the outlier, but the result is not so smooth and some peaks and valleys are not eliminated. The Wavelet has a result very similar to the Brick-wall, presenting just a small distortion in the part after the outlier. Furthermore, the Moving Average presents also a small distortion after the outlier. In general, it is possible to say that the Brick-wall and Wavelet can be considered the best methods for damped oscillatory outliers.

4.1.4 Elimination of Low-Frequency Outlier

To evaluate the outlier elimination for a signal with a low-frequency outlier, the signal of the Figure 38 was used and the results are shown in the Figure 44.

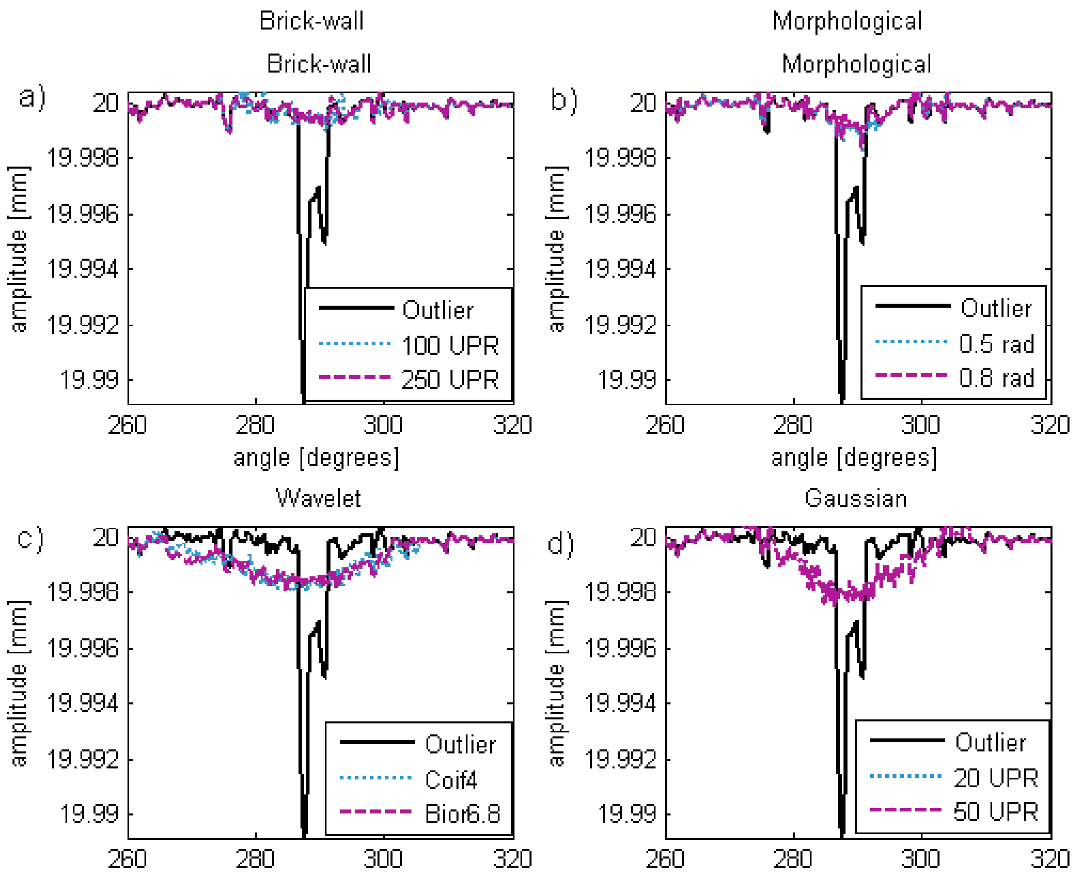

Figure 44. Outlier elimination applied to a signal with a low-frequency outlier. a) Outlier elimination with the Brick-wall method. b) Outlier elimination with the Morphological method. c) Outlier elimination with the Wavelet method. d) Outlier elimination with the Gaussian method.

The results for this case are easy to be analysed. At first, the Wavelet and Moving Average methods present a very poor result, because they cause a big distortion in the outlier region. The Morphological and the Brick-wall have a good result, but it is possible to perceive that the Brick-wall has a more stable result, practically eliminating the anomaly without changing the signal in the region out of the outlier.

4.1.5 Complexity of Implementation and Processing Time

The methods of outlier elimination Brick-wall and Gaussian are simple to implement, since they use directly a function implemented at frequency domain. The Wavelet is more complex but, as the Matlab has already implemented the used Wavelet functions, the implementation is not so difficult. However, the Morphological method is complex to implement, because it is necessary to create the structuring element of different size and roll it over the signal on each iteration.

Regarding the processing time, the methods were evaluated performing 10 times the outlier elimination for the Low-frequency outlier presented in Figure 38, getting the mean of the processing time of each method. The parameters used were: band of 250 UPR for the Brick-wall, band of 0.5 radians for the Morphological, the function Bior6.8 for the Wavelet and a cut-off of 50 UPR for the Gaussian method. The results are shown in Table 5.

Processing time for outlier elimination (seconds)			
Brick-wall	**Wavelet**	**Gaussian**	**Morphological**
0,1947	0,9928	1,0043	17,8350

Table 5. Processing time for the methods of outlier elimination.

Analysing the table above, it is possible to see that the Brick wall is the quickest method, while the Wavelet and Gaussian have also a short processing time. However, the Morphological is very slow, having a processing time about 100 times bigger than the Brick-wall, for example. As said before, the time is very important and if the Morphological is used, it is necessary to use a quick filtering method, to compensate the spent time at this step.

4.1.6 Summary of the Analysis on Outlier Elimination

After the analysis exposed above, a matrix can summarises the conclusions about the performance of each evaluated method, regarding the kind of outlier. Table 6 presents these results, classifying the behaviour of the methods in three levels: poor, regular and good.

Analysis of outlier elimination methods regarding the kind of outlier				
Outlier \ Method	Brick-wall	Morphological	Wavelet	Gaussian
Asymmetric-spike	**Good**	**Regular**	**Poor**	**Poor**
Symmetric-spike	**Regular**	**Poor**	**Regular**	**Poor**
Damped-oscillatory	**Good**	**Regular**	**Good**	**Regular**
Low-frequency	**Good**	**Regular**	**Poor**	**Poor**

Table 6. Compilation of the results of the outlier elimination.

The Brick-wall method had better result for the evaluated outliers, comparing to the others methods and, therefore, it can be considered the best method at this work. The following section presents a case, which shows the importance of the outlier elimination in the roundness evaluation, using the Brick-wall as the outlier elimination method.

4.2 RESULTS ON SIGNAL FILTERING

This section presents the results obtained in the evaluation of the filtering methods, following the methodology described in the chapter 3.

4.2.1 Filtering of Uneven Spacing Signals

After running the simulation explained in the section 3.3.1, the obtained results are presented in the Figure 45. The variable *radius* represents the cut-off radius for the Morphological filter, while *n_levels* is the number of levels for the Wavelet filter. It is important to remember that, given that the Morphological filter is dependent of both amplitude and frequency of the signal, the relationship between the cut-off frequency and the cut-off radius is valid only for this signal, that simulates the external cylinder from a multi-wave standard.

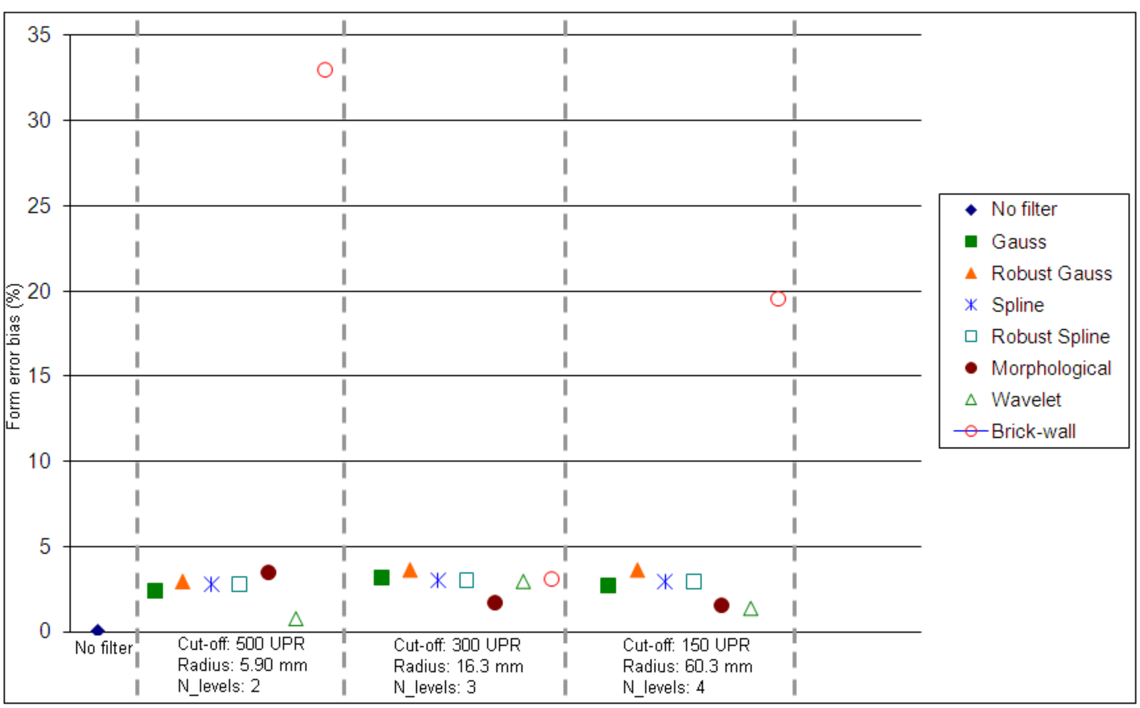

Figure 45. Form error bias for three different cut-off.

From this graphic, the first observation is that the Brick-wall method has a very discrepant behaviour, for 150 and 500 UPR, and a comparable result for 300UPR. The cause of this big difference is that, as shown in the Figure 28, the uneven spacing induces a spreading of the frequency spectrum of the signal and then, instead all the 150 or 500 UPR be cut, some frequencies near them remain in the signal, influencing completely the value of the form deviation. As the frequency of 300 is between the frequencies from the signal, this effect does not occurs and form deviation is less influenced. This phenomenon does not happen to the other filters because they do not have a so sharp cut-off as the Brick-wall.

Making a zoom between 0 and 5 percent, it is possible to do a better analysis for the other methods, as shows the Figure 46.

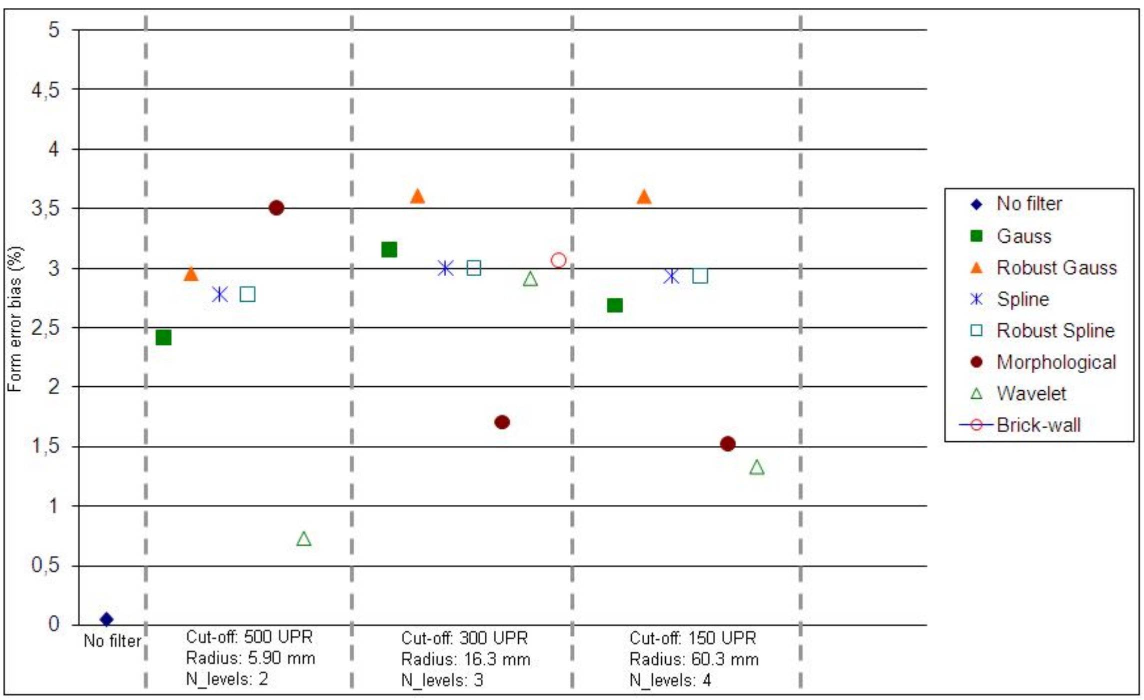

Figure 46. Form error bias for three different cut-off (zoom from 0 to 5 %).

At this graphic, it is possible to verify that every method reaches a form error bias about 3 %, which is a representative value on roundness evaluation. Therefore, no method can be considered good on overcoming the problem of uneven spacing and the interpolation should be made in a previous step.

4.2.2 Filtering of Open Profiles

As said in the section 3.3.2, the profile of the Figure 40 is cut at 340° for the evaluation of the methods for open profiles. This signal is presented in the Figure 47.

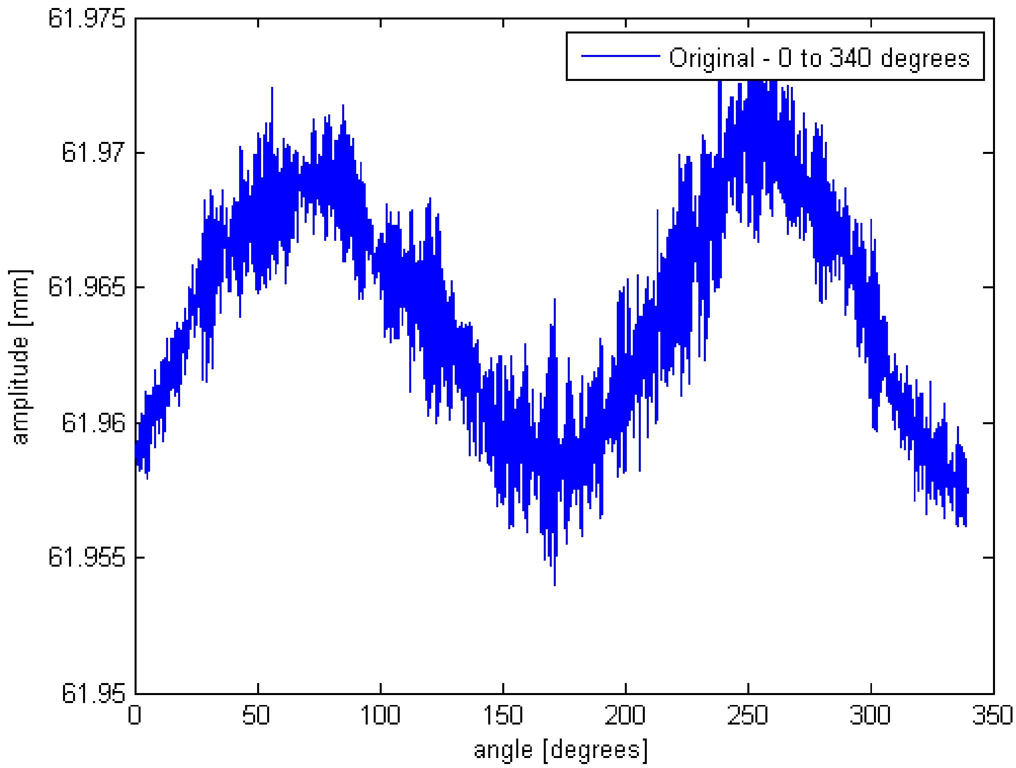

Figure 47. Real profile cut at 340° for the evaluation of open profiles.

The results of the filtering for each filter are presented in Figure 48 to Figure 54, with a zoom at the right extreme.

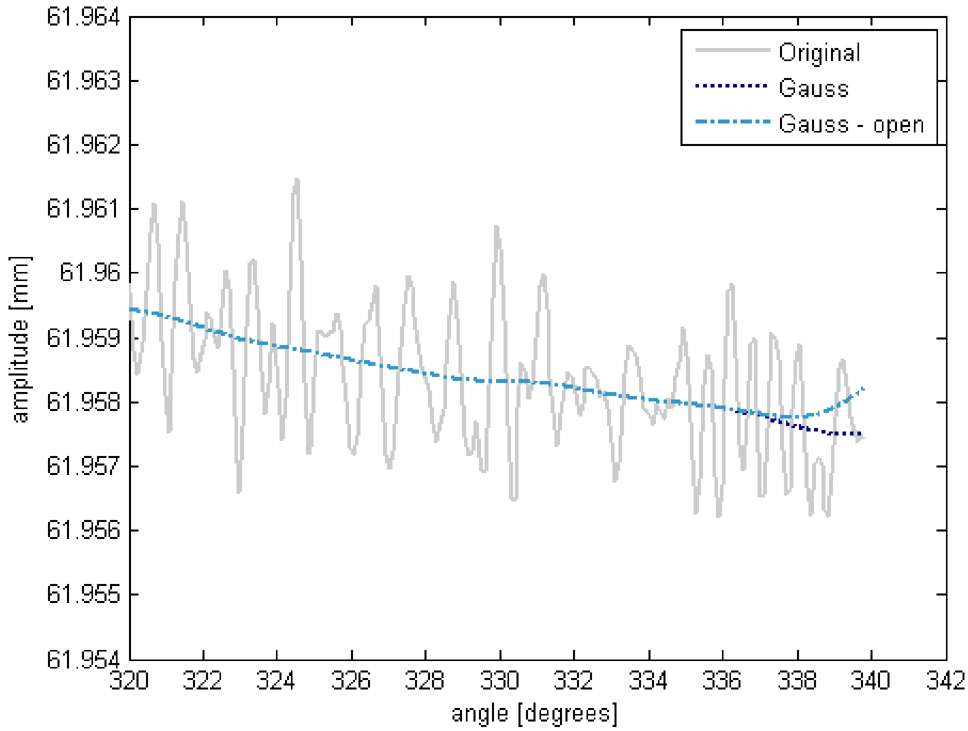

Figure 48. Filtering of an open profile by the Gaussian filter.

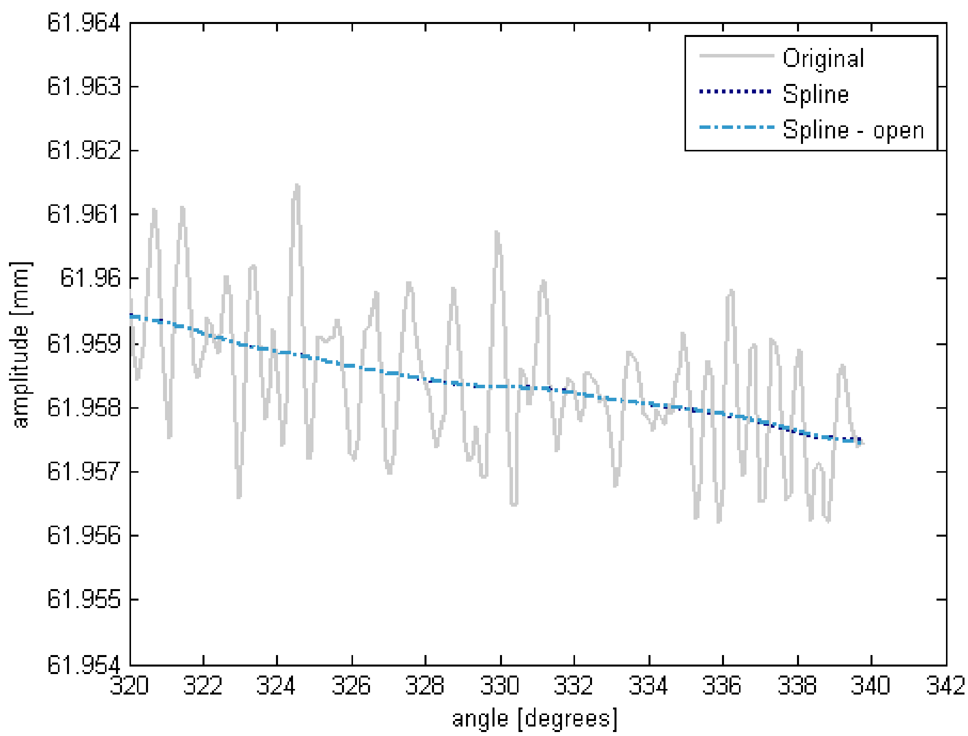

Figure 49. Filtering of an open profile by the Spline filter.

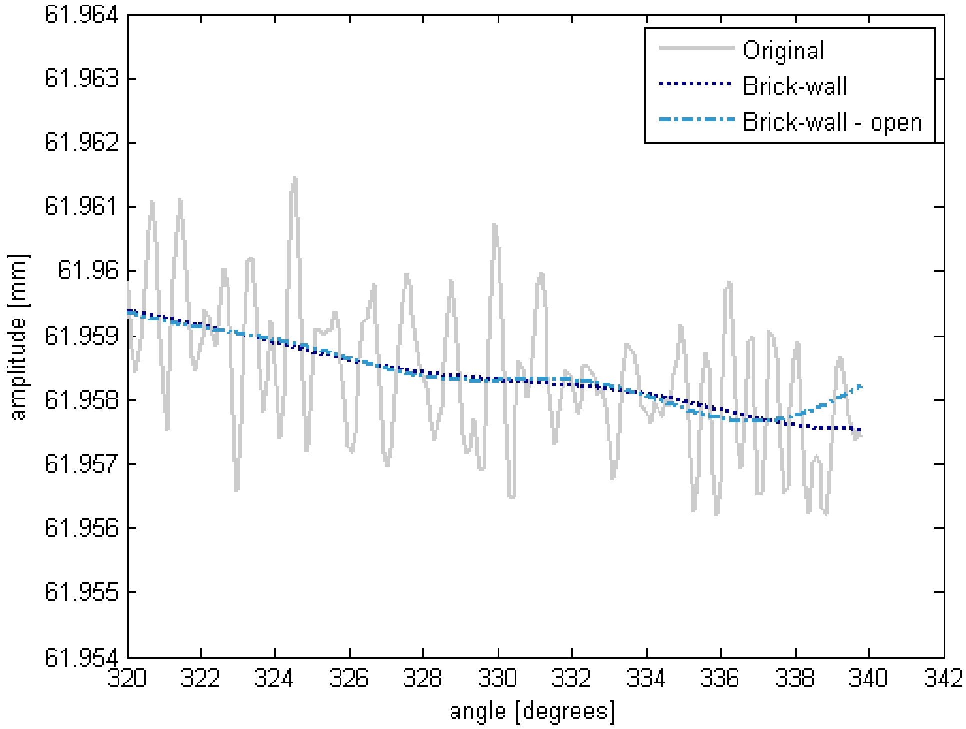

Figure 50. Filtering of an open profile by the Brick-wall filter.

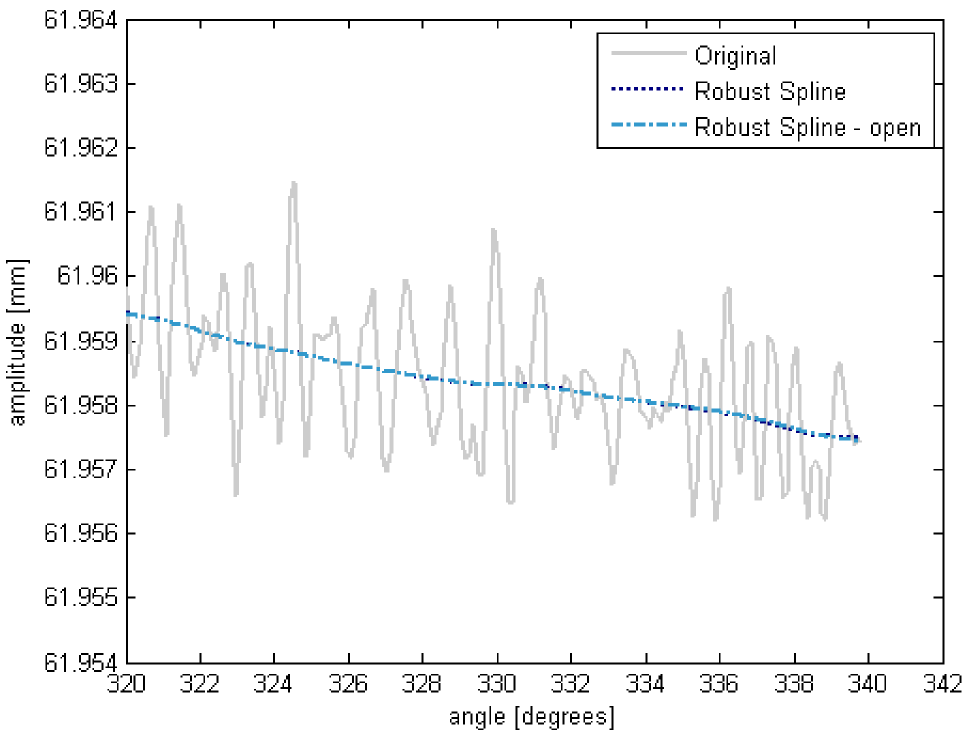

Figure 51. Filtering of an open profile by the Robust Spline filter.

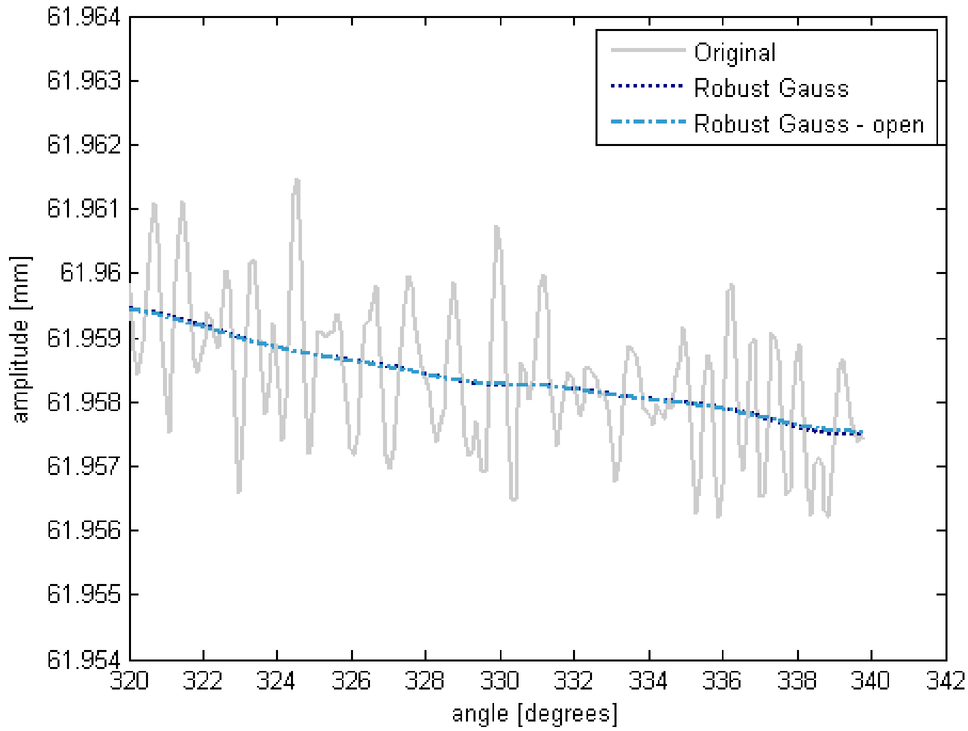

Figure 52. Filtering of an open profile by the Robust Gaussian filter.

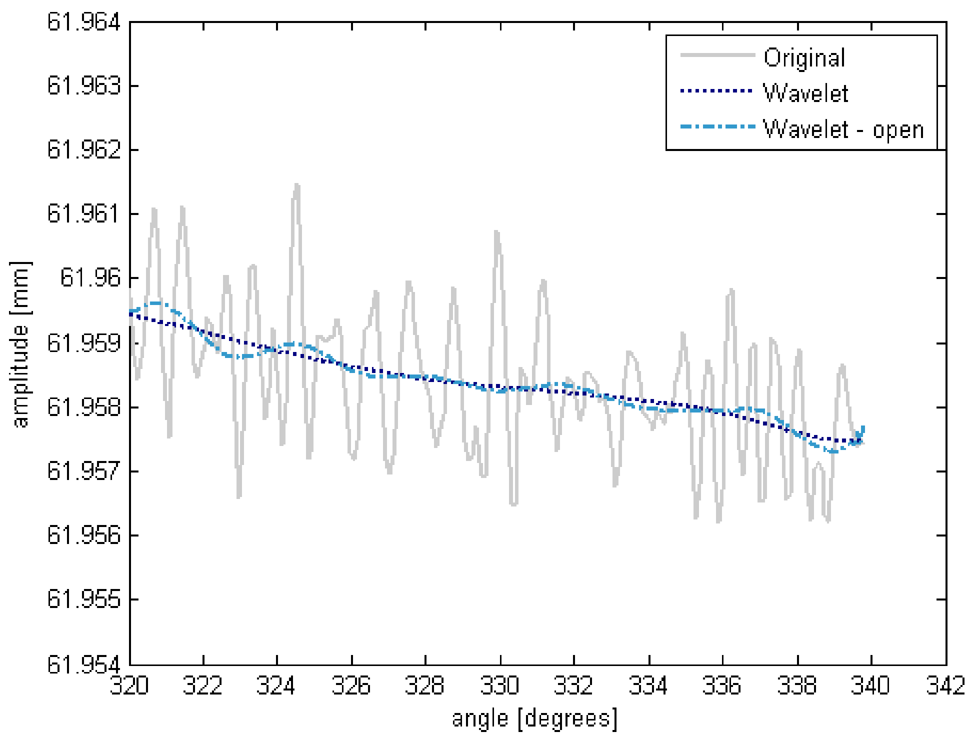

Figure 53. Filtering of an open profile by the Wavelet filter.

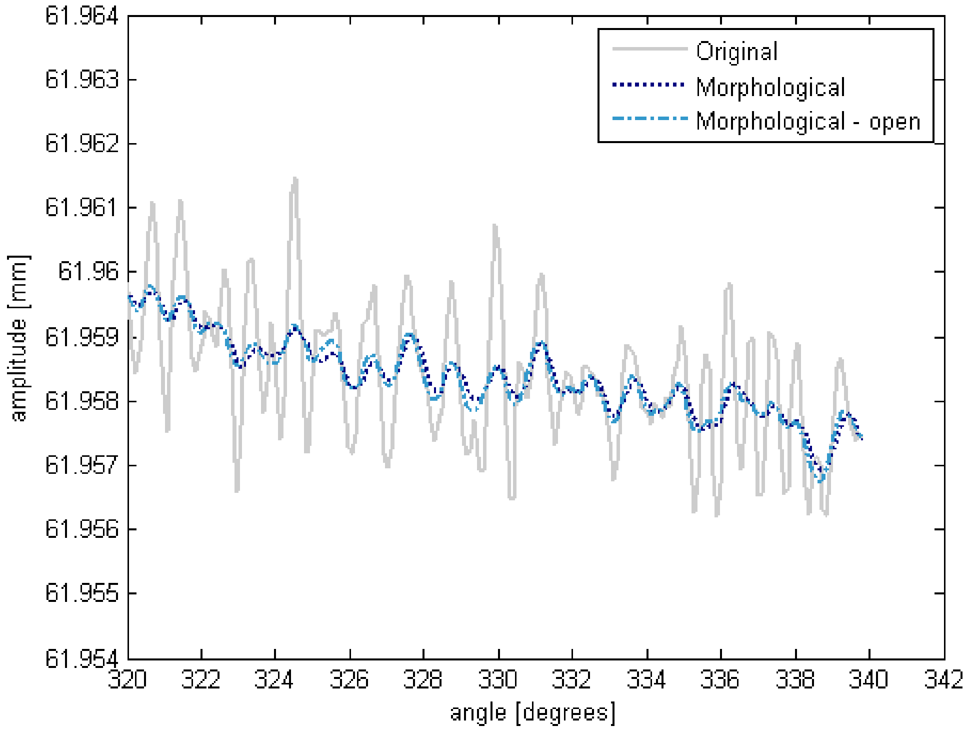

Figure 54. Filtering of an open profile by the Morphological filter.

Analysing the graphics, it is possible to have clear conclusions. At first, the Gaussian filter, as expected, causes a considerable distortion at the extreme of the profile. Furthermore, the Brick-wall and Wavelet have also a poor behaviour at extremes, performing the worst filtering for this example. Only the Robust Gaussian, Spline, Robust Spline and Morphological have a good filtering performance for open profiles.

4.2.3 Filtering of Profiles with Outliers

As said before, the behaviour of the filters in presence of outliers is another characteristic to be evaluated in this work. Therefore, the same signals used for the evaluation of the methods of outlier elimination were filtered with a cut-off of 150 UPR (with a correspondent radius for the Morphological and number of levels for the Wavelet) and the results are presented in the sequence.

At first, the signal presented in the Figure 35 (signal with an asymmetric-spike outlier) was filtered and the result is presented in the Figure 55.

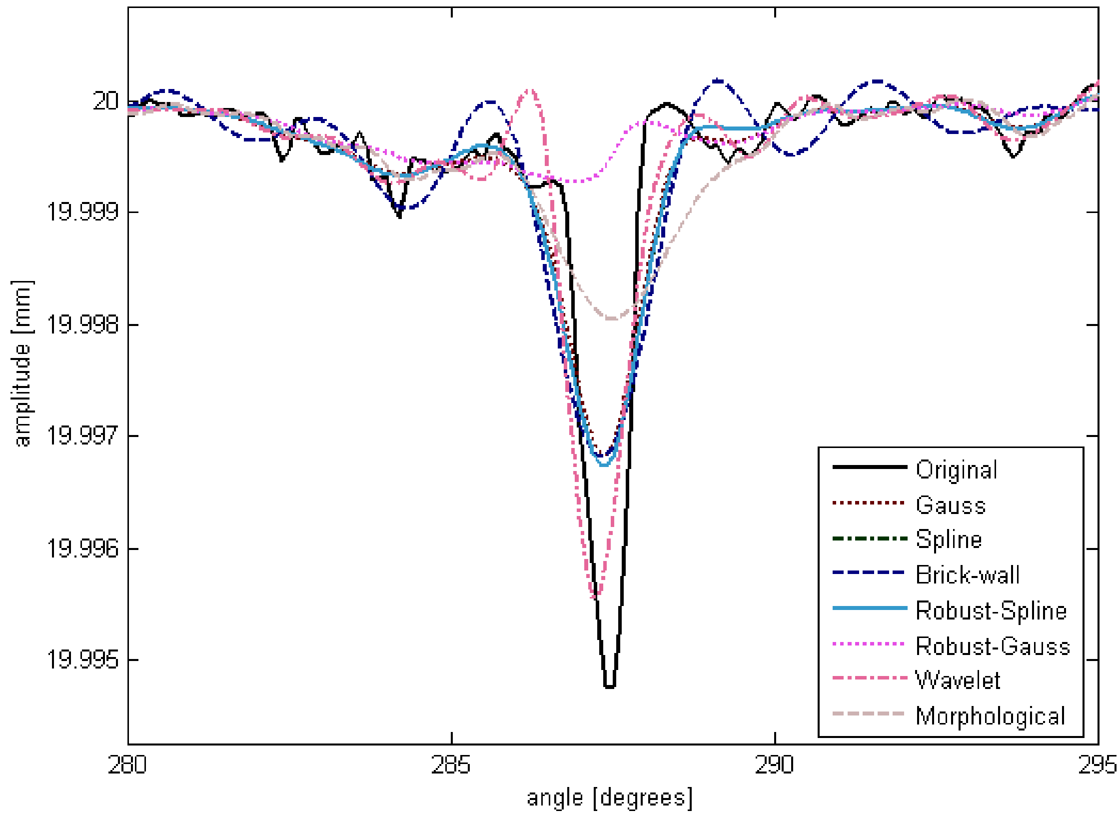

Figure 55. Filtering of a signal with an asymmetric-spike outlier (zoom at the outlier region).

Analysing the signal above, it is possible to see that the Robust Gaussian filter has a very good result on filtering this kind of outlier. Furthermore, the Wavelet present the worst result. The Morphological filtering can be considered a regular result, because the others are almost as poor as the Wavelet.

In sequence, the result of the filtering of the signal shown in the Figure 36, that contain a symmetric-spike outlier, is presented in the Figure 56.

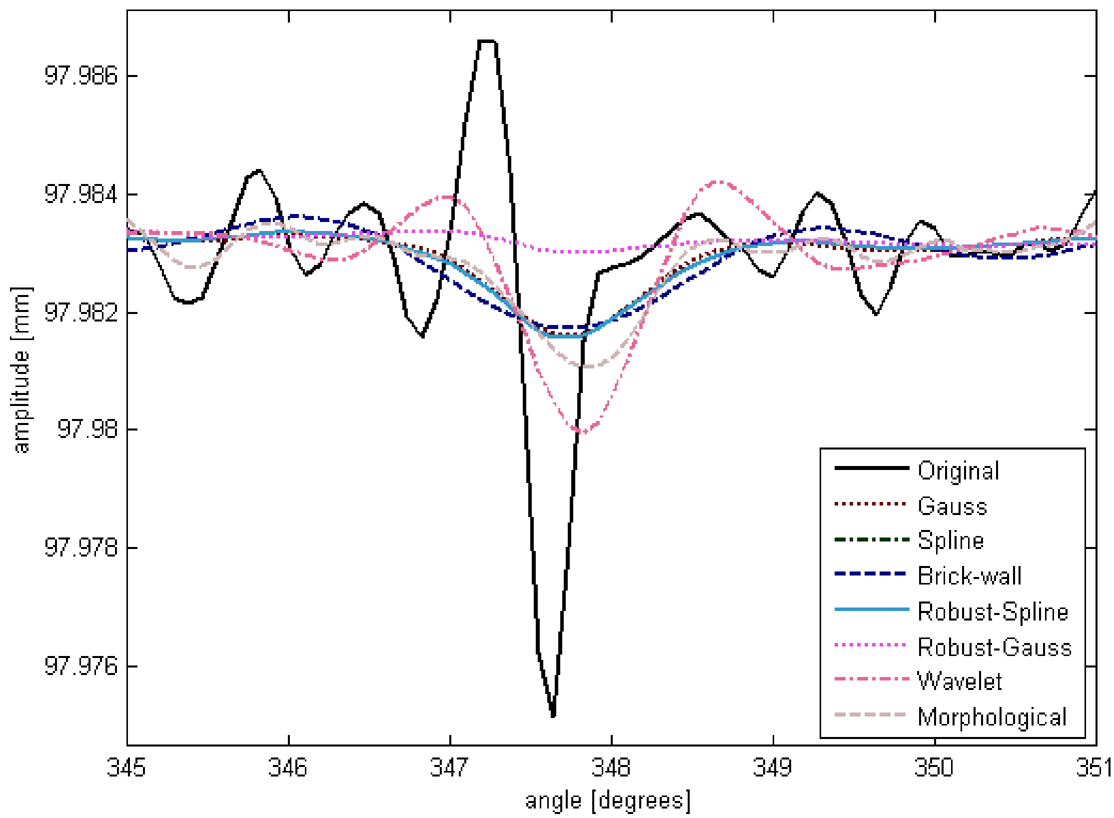

Figure 56. Filtering of a signal with a symmetric-spike outlier (zoom at the outlier region).

The result for this kind of outlier is similar to the previously analysed, where the Robust Gaussian presents a very good result, while the Wavelet is the worst again. The other methods can be considered just regulars on eliminating the outlier.

The third one to be analysed is the signal presented in the Figure 37, which has a damped-oscillatory outlier. The Figure 57 presents the result.

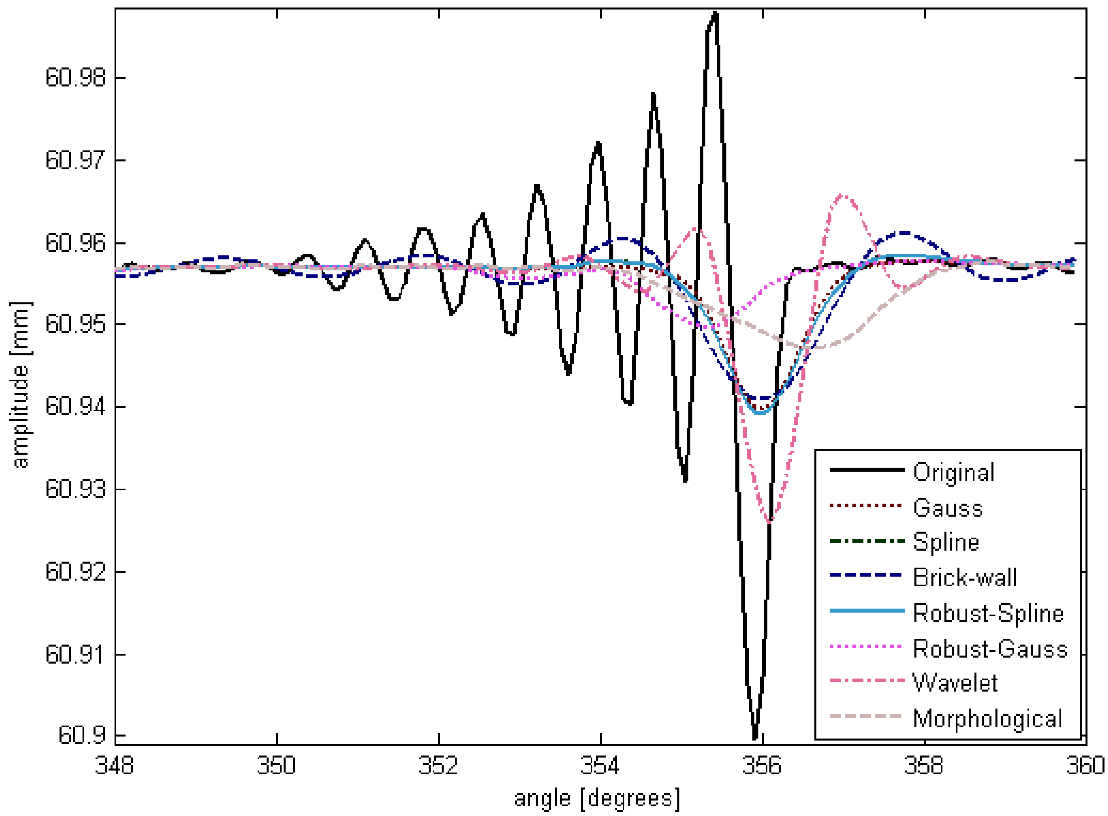

Figure 57. Filtering of a signal with a damped-oscillatory outlier (zoom at the outlier region).

The result here is also similar to the previous and the Robust Gauss seems to be a very stable method against outliers. The Morphological presented again a regular result, while the others can be considered poor against this kind of outlier.

Finally, the signal presented in the Figure 38, which has a low-frequency outlier, is filtered and the result is shown in the Figure 58.

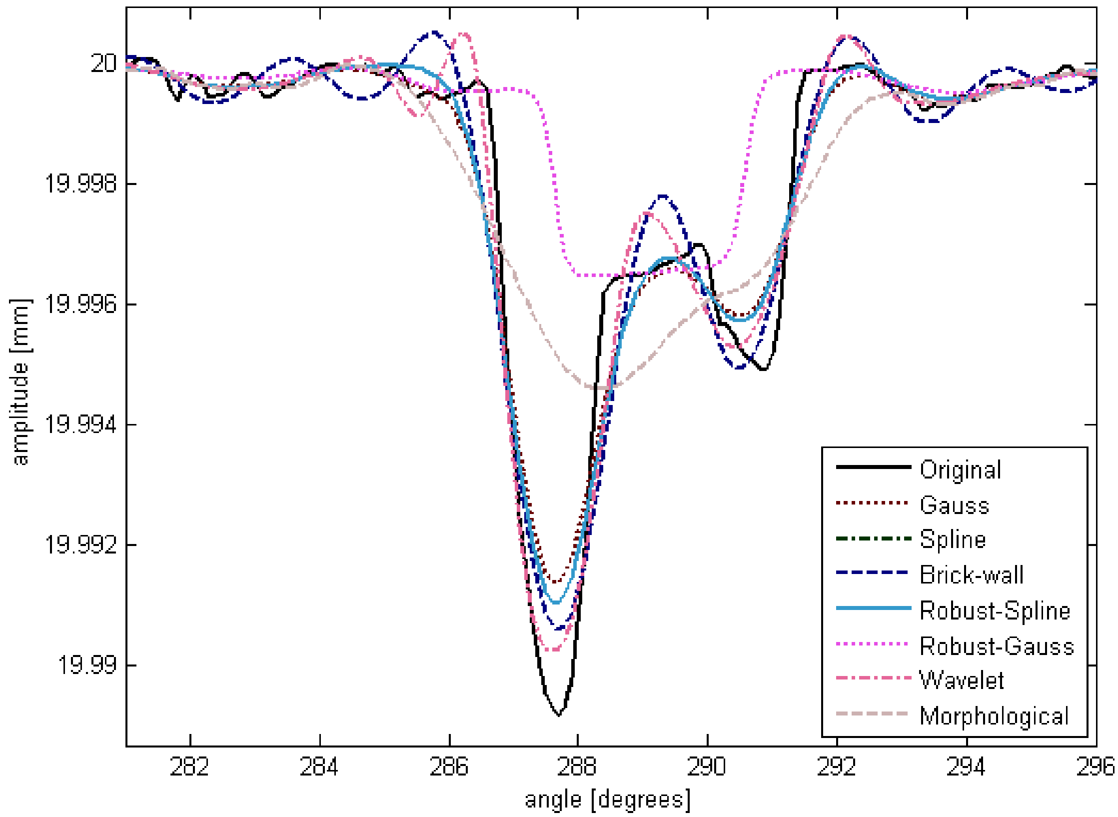

Figure 58. Filtering of a signal with a low-frequency outlier (zoom at the outlier region).

The sequence repeats again, the Robust Gaussian has the best result, the Morphological the second best and the others a very poor result. However, in this case the Robust Gaussian does not have a very good result as presented for other cases and its performance here can be considered just intermediate.

After the analysis of every kind of outlier here evaluated, it is possible to say that the Robust Gaussian has, in general, a good performance against outliers, the Morphological has a regular efficiency, while the others have a poor result on filtering signals with outlier. The most surprising negative result is the bad behaviour of the Robust Spline filter, since the main purpose of it is to be robust against outlier.

4.2.4 Computational Efficiency and Complexity of Implementation

In terms of complexity of implementation, the Gaussian, Spline and the Brick-wall filters are very easy to implement, since they use directly a function described in the frequency domain and, therefore, only a multiplication by the DFT of the signal and the respective IDFT are necessary to do the filtering. The Wavelet has a not so difficult implementation, because the Matlab has already implemented the Wavelet functions. However, the Robust Spline and the Robust Gauss have a more complex algorithm, because they are iterative methods. Furthermore, the Morphological has also a difficult implementation, because a comparison point by point between the structuring element and the signal must be performed.

Aiming to compare the computational efficiency, a simulated multi-wave standard was filtered 10 times with a cut-off of 150 UPR, radius of 60 mm for the Morphological filter and 4 levels for the Wavelet, selected by an empirical analysis of the transfer characteristics of the filters. Thereafter, the mean of the processing time of each filter was taken and is presented in the

Table 7.

Processing time for the filtering of a simulated multi-wave standard (seconds)						
Brick-wall	**Gaussian**	**Spline**	**Wavelet**	**Robust Spline**	**Morphological**	**Robust Gaussian**
0,0025	0,0036	0,0076	0,0558	0,6731	5,0454	8,4158

Table 7. Processing time for the filtering of a simulated multi-wave standard.

In general, the computational efficiency is directly related to the complexity of implementation. It is clear for the Gaussian, Spline and Brick-wall methods, that have a very short processing time, and also for the Robust Gaussian and the Morphological, that are very slow. The Robust Spline is the only case that has a difficult implementation but is very good computationally, because it uses storage techniques for sparse matrices.

4.3 Summary of the Analysis on Signal Filtering

After the results exposed above, the evaluation of the filtering methods can be summarized by the Table 8, where each filter has a classification between three levels, according to the stipulated parameters.

Further the parameters previously analysed, the comparability to the Gaussian filter was also evaluated, because some filters, as explained before, are not directly comparable using the same cut-off parameter or have a very different transfer characteristic.

Analysis of filtering methods regarding some important characteristics							
Characteristic \ Filter	Gaussian	Spline	Brick-wall	Robust Spline	Robust Gaussian	Wavelet	Morphological
Behaviour for uneven spacing signal	**Regular**	**Regular**	**Poor**	**Regular**	**Regular**	**Regular**	**Regular**
Distortion at extremes of open profiles	**Poor**	**Good**	**Poor**	**Good**	**Good**	**Poor**	**Good**
Behaviour against outlier	**Poor**	**Poor**	**Poor**	**Poor**	**Good**	**Poor**	**Regular**
Complexity of implementation	**Good**	**Good**	**Good**	**Poor**	**Poor**	**Regular**	**Poor**
Computational efficiency	**Good**	**Good**	**Good**	**Regular**	**Poor**	**Good**	**Poor**
Comparability with classical Gaussian filter	**------**	**Good**	**Regular**	**Regular**	**Regular**	**Poor**	**Poor**

Table 8. Compilation of the results of the filtering methods evaluation.

5 CASE STUDIES

In this chapter, it is presented some case studies that, as explained in the section 3.4, evaluate some problems of signal processing and compare the filtering methods according special conditions.

5.1 ALIASING

Aliasing is a critic problem that occurs in the acquisition step and, as seen before, it is necessary to limit artificially the band of the profile to avoid it. Therefore, two different acquisition of the MWN was obtained, aiming to analyse if the CMMs have an anti-aliasing filter. The MWN has frequencies of 5, 15, 50, 150 and 500 UPR and, hence, at least 1000 points must be acquired to avoid the aliasing or, if less points are acquired, an anti-aliasing filter is required.

First, the profile was sampled with 3368 points and all frequencies are acquired correctly, as shown Figure 59.

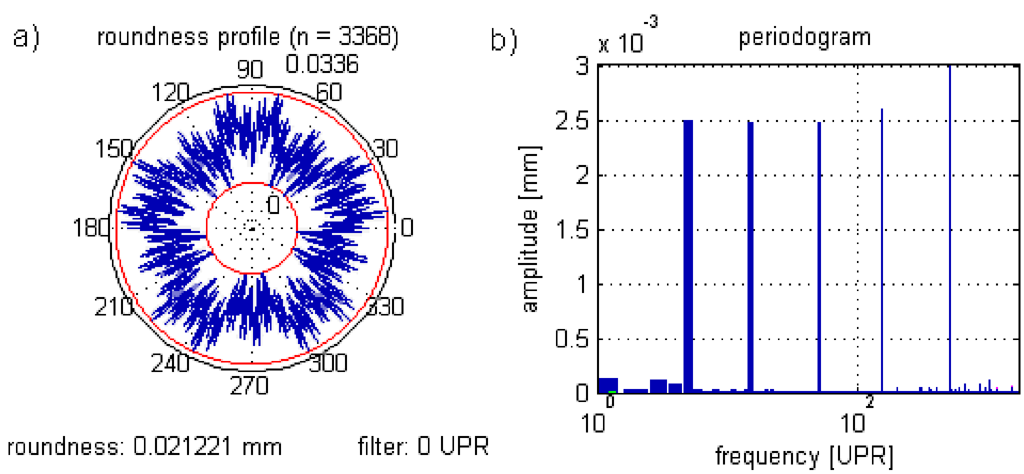

Figure 59. Profile without aliasing, sampled with 3368 points. a) Polar graphic. b) Periodogram.

In sequence, the same profile was sampled with 458 points and, the aliasing is clearly perceived, where the frequency of 500 UPR does not appear but it is reflected about 42 UPR, proving that the evaluated CMM does not have an anti-aliasing filter. The Figure 60 shows this problem.

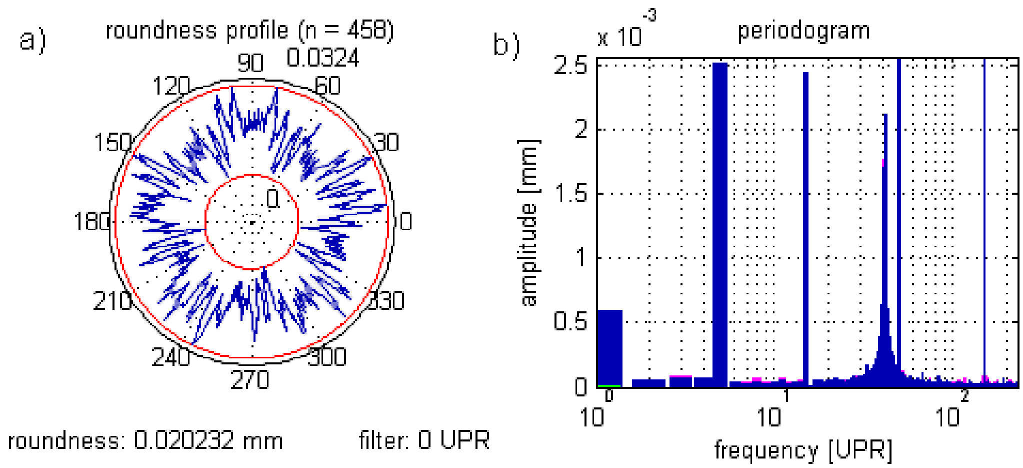

Figure 60. Profile with aliasing, sampled with 458 points. a) Polar graphic. b) Periodogram.

The aliasing changes considerably the acquired signal and should be avoid for a correct form evaluation. On surface metrology, some standards define that the number of points to be acquired must be at least seven times the cut-off frequency, based on the transmission characteristic of the Gaussian Filter.

However, what occurs is that, if the signal has a white noise, for example, that includes components on the whole spectrum, the high frequencies are reflected in the spectrum of the acquired signal and can lead to a wrong evaluation of the profile. Thereupon, an analog anti-aliasing filter should be included in the CMMs, where the cut-off frequency is selected according the number of acquired points.

5.2 TIP RADIUS DISTORTION

As said in section 2.5, the CMM acquire the coordinates of the point that represents the centre of the sphere that performs the measurement. Aiming to analyse the distortion caused by this characteristic, a multi-wave standard was measured and corrected by an erosion operation and the results are compared at space and frequency domain. Figure 61shows the polar graphic and the periodogram of the MWN before tip radius correction.

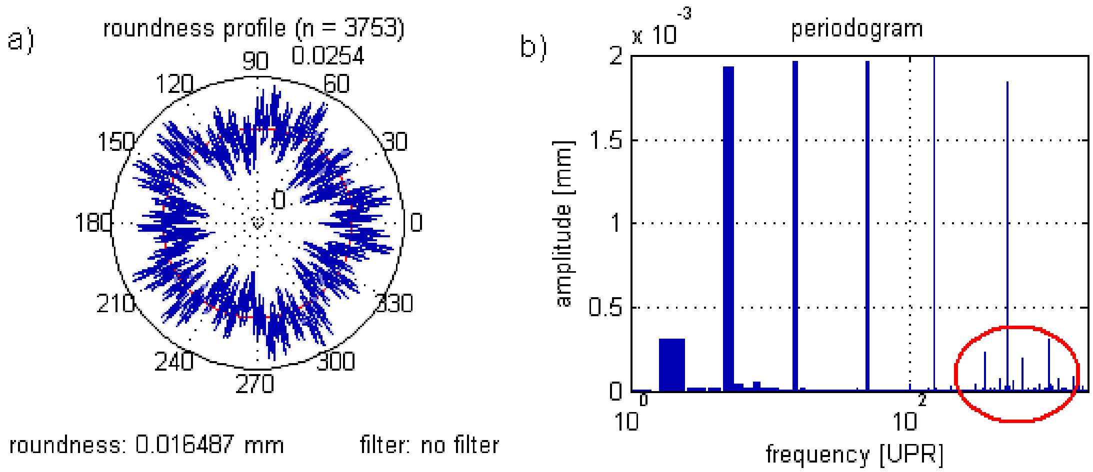

Figure 61. Measurement of a multi-wave standard without tip radius correction. a) Polar graphic. b) Periodogram.

It is possible to see some high frequencies close to 500 UPR that do not are from the real profile. In fact, what occurs is that the distortion caused by the stylus tip in the acquiring process changes the frequencies of the profile. Figure 62 shows the same signal after the tip radius correction.

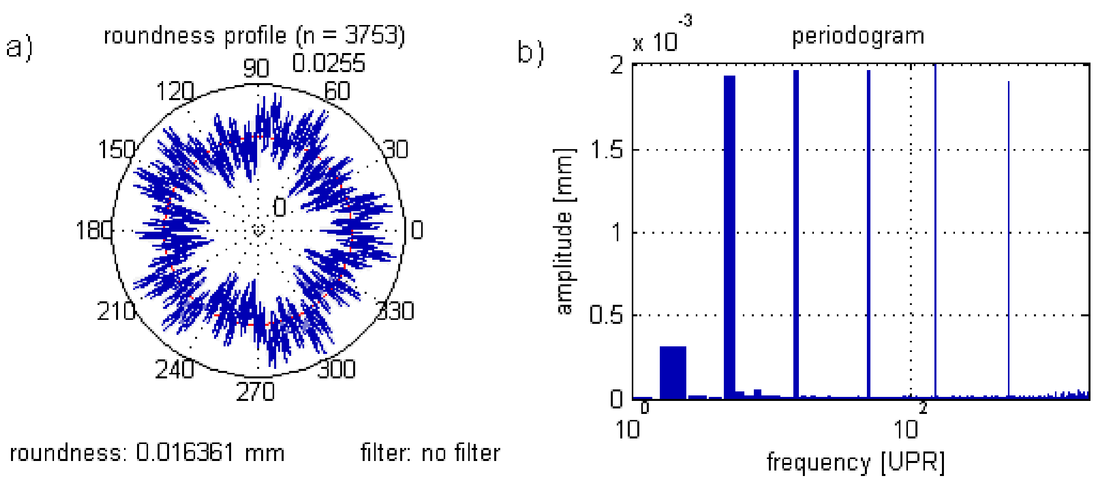

Figure 62. Measurement of a multi-wave standard with tip radius correction. a) Polar graphic. b) Periodogram.

After the Erosion, the frequencies show in Figure 61 are eliminated and the amplitude of 500 UPR is increased. The roundness evaluation is also influenced by this problem. In this case, it is possible to perceive that the roundness after the tip radius correction is about 0,2 µm. However, it is important to know that if the signal is filtered with a low cut-off frequency, this problem can become irrelevant.

5.3 ROUNDNESS EVALUATION OF A GROUND PROFILE

Although the comparison of the filtering methods directly on the roundness deviation does not give a clear result, the behaviour of them for a specific profile can be compared, extracting some important observations. For this evaluation, it was chosen a ground profile without outlier, presented in Figure 63.

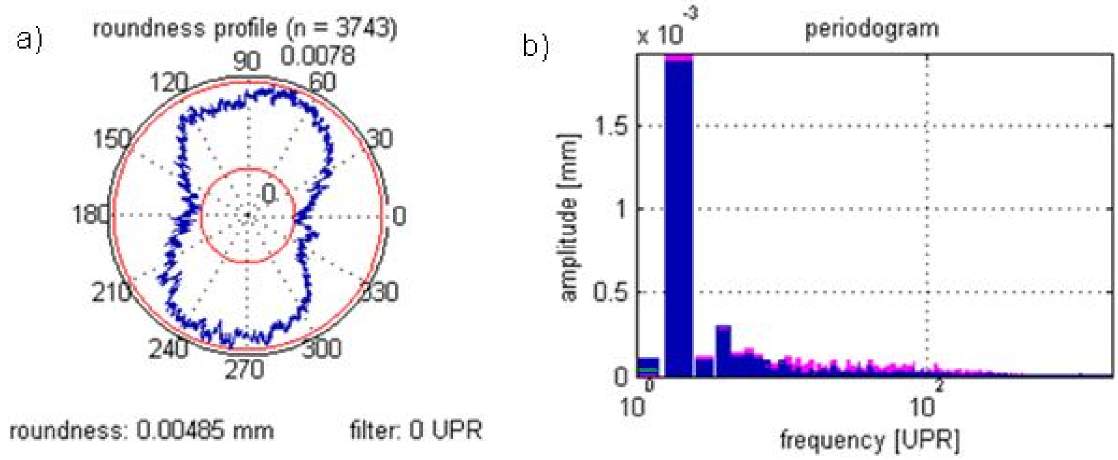

Figure 63. Ground profile without outlier. a) Polar graphic. b) Periodogram.

As this profile does not present any problem related in the chapter 4, it was filtered by the evaluated filtering methods with three different cut-off parameters (empirically defined) to compare the behavior of the filters on roundness evaluation. The result of the roundness deviation is shown in Figure 64.

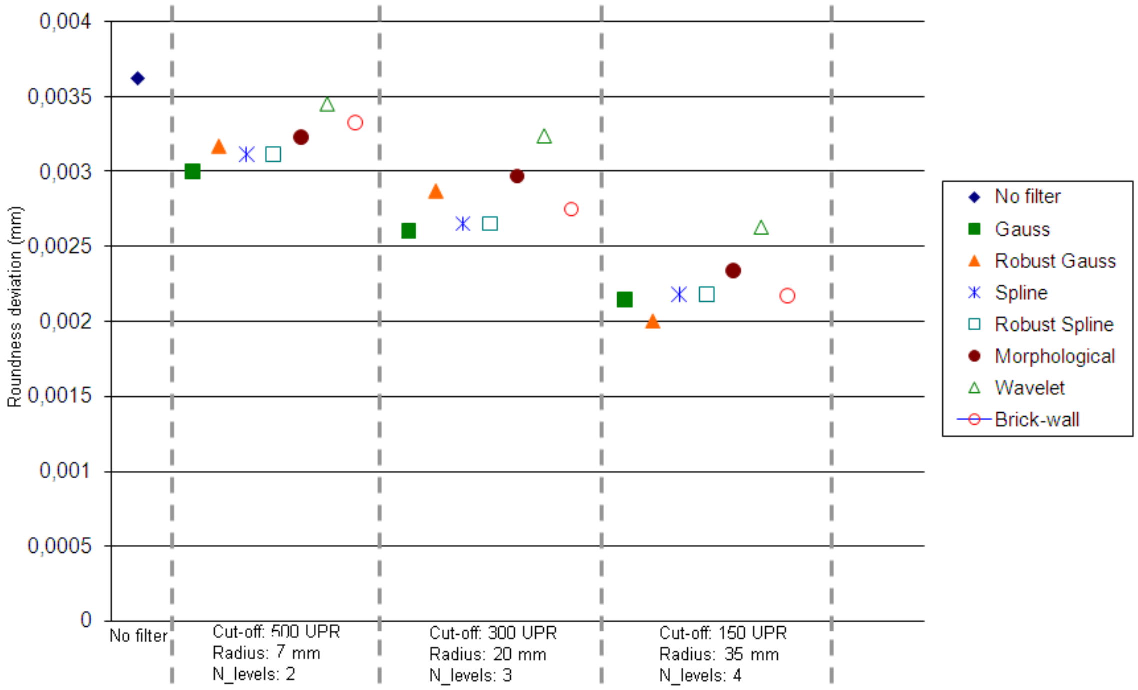

Figure 64. Roundness deviation of a ground profile filtered with different filters and filtering parameters.

From this picture, some conclusions can be obtained. As said before, it is not possible to say if a filter is better than others, because it is not known the real value of the roundness deviation of the evaluated profile and, so, every filter can be considered successful on filtering. The difference on the roundness deviation occurs because they have different transmission characteristics.

Furthermore, it is possible to see that the Spline and Robust Spline present the same result, showing that, such as for signals with outlier, the Robust Spline did not represent a good advance on signal filtering at this work.

5.4 FUNCTIONAL FILTERING

As related in section 2.2.11, the selection of the filtering method and filtering parameters should consider some additional information about the work-piece, such as manufacturing process and its function. Therefore, it was evaluated a profile with many outliers that can be part of the real profile. Considering that these valleys are effectively present in the work-piece, some considerations about the function of the work-piece can be discussed. The evaluated profile is presented in Figure 65.

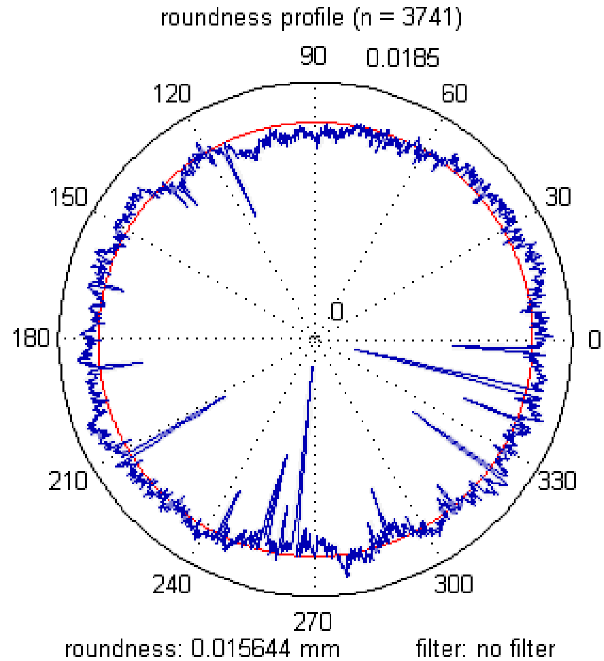

Figure 65. Roundness profile for the evaluation of functional filtering.

For a piece used on assembling or sliding for example, this valleys are not important on form evaluation, because only the external surface has contact with other surface. In this case, it is possible to evaluate the profile in two different ways. First, the valleys can be eliminated with an outlier elimination method and, afterward, the profile is filtered by the Gaussian or other mean line filter. Figure 66 shows the result of the processing of the evaluated signal by the sequence: Morphological method for outlier elimination and Gaussian for signal filtering.

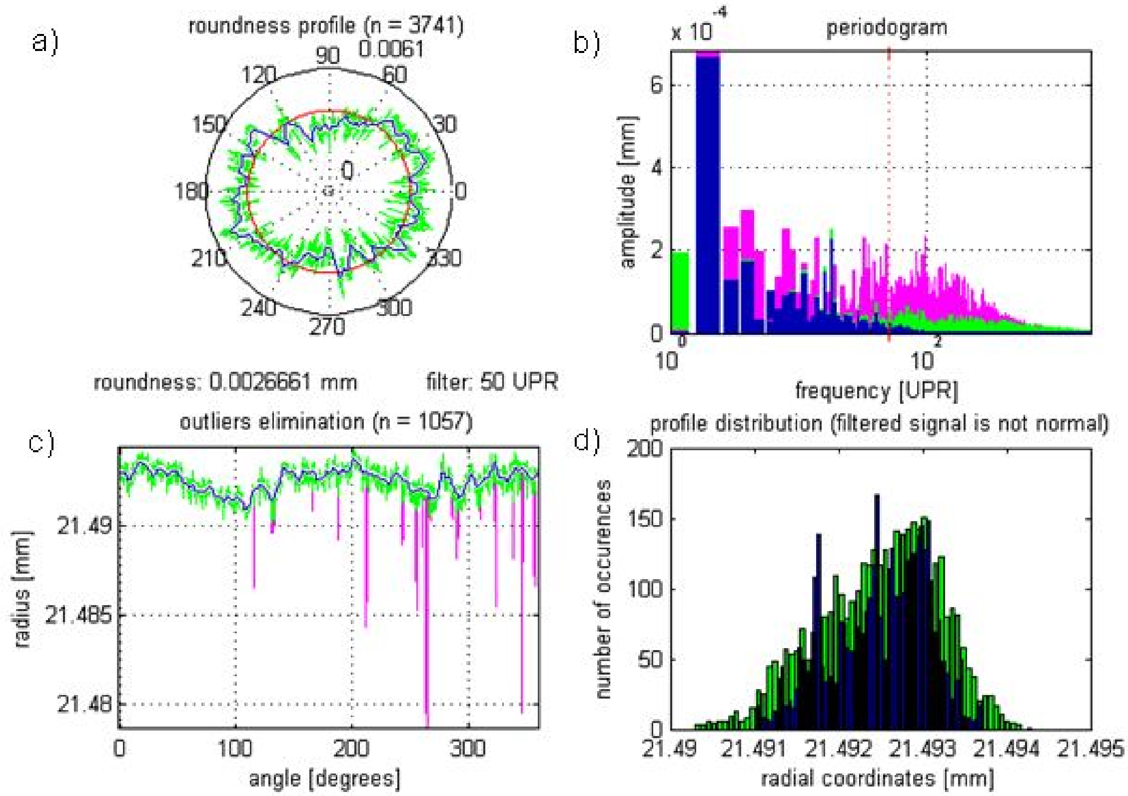

Figure 66. Roundness profile processed by the Morphological method for outlier elimination and Gaussian filter. a) Polar graphic. b) Periodogram. c) Linear graphic. d) Profile distribution.

From this figure, it is possible to observe that the valleys are completely eliminated and the filtered signal represents an external contour of the real profile. The same result is proposed by the Robust Gaussian, that eliminates itself the valleys and provides an external approximation of the profile. Figure 67 presents the result of the filtering with the Robust Gaussian filter.

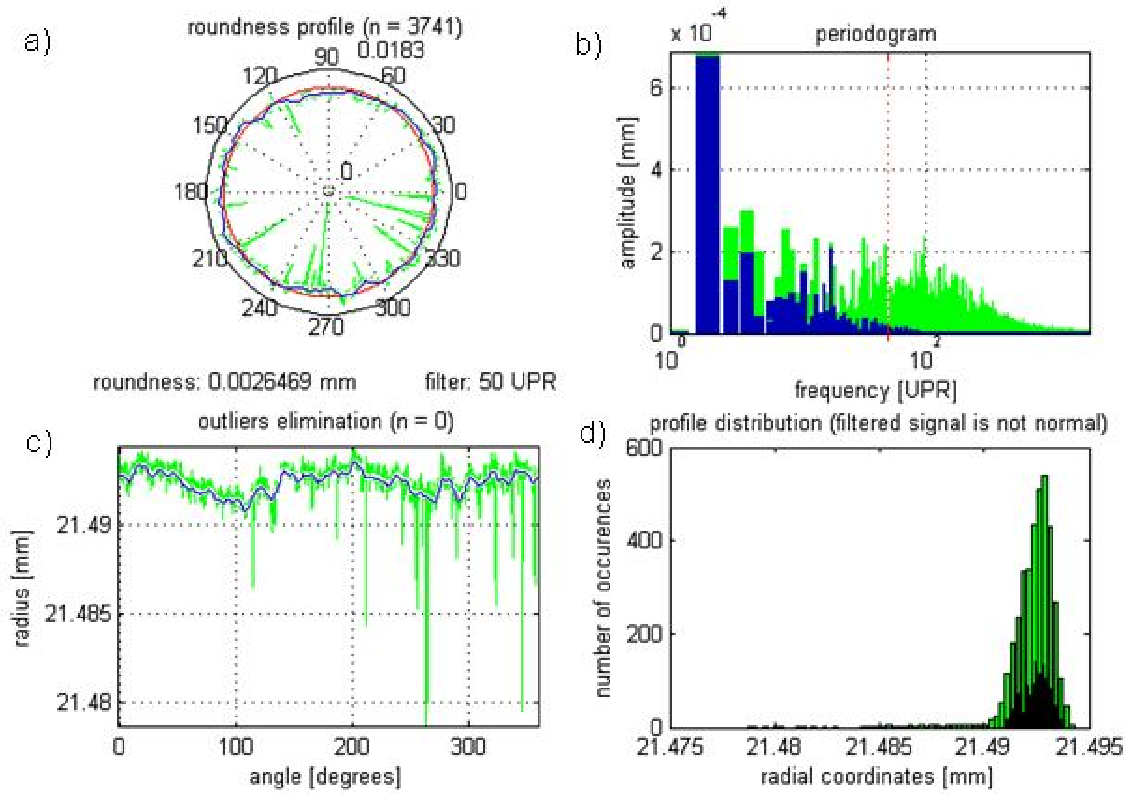

Figure 67. Roundness profile processed only by the Robust Gaussian filter. a) Polar graphic. b) Periodogram. c) Linear graphic. d) Profile distribution.

As expected, all valleys are eliminated and the filtering result is very similar to the presented in Figure 66 (clearly observed in the linear graphic). Comparing the roundness, the difference is just about 0.02 µm and both can be considered very good on processing this profile if the function of the work-piece is not influenced by the valleys present in the profile.

However, if the same profile is a sealing surface from a duct for example, these valleys can allow leakages of the fluid if a wrong evaluation is done. Therefore, it is necessary to consider the valleys on roundness evaluation and the process of outlier elimination or robust filtering methods should not be used. The Figure 68 shows the same profile filtered by the Gaussian filter.

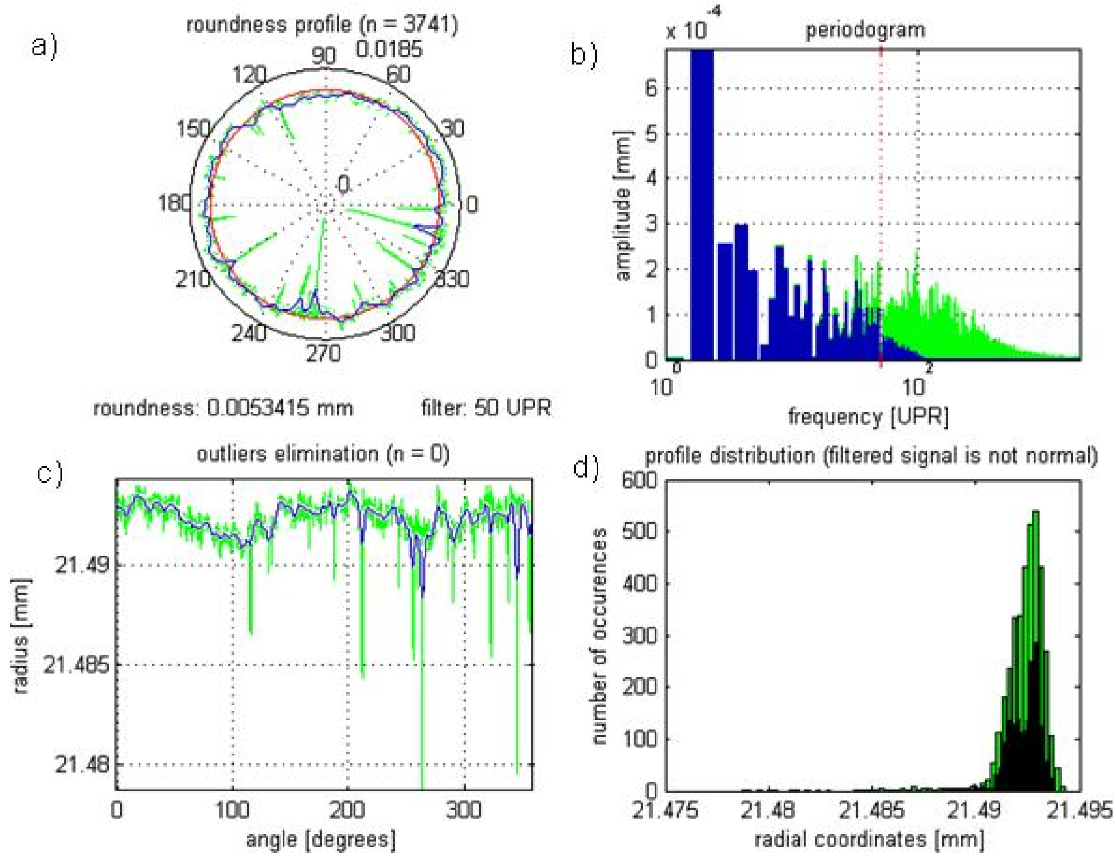

Figure 68. Roundness profile processed only by the Gaussian filter. a) Polar graphic. b) Periodogram. c) Linear graphic. d) Profile distribution.

In this case, the narrowest valleys are eliminated, but those that can be determinant for any problem remain in the filtered profile and are considered on roundness evaluation. Comparing the roundness, the obtained value is about 2 times bigger than the values obtained before.

Finally, this case study shows the importance of the previous knowledge about the work-piece before the roundness evaluation and it is important to reinforce that it is very important that the metrologist receives some additional information, such as manufacturing process and function of the piece.

6 FINAL CONSIDERATIONS

This research work presented an evaluation of the signal processing techniques applied to roundness measurement performed by scanning in CMMs. The results show the importance of the signal processing for this theme, specially because of the undesired consequences that appear in the acquisition step, like outliers, uneven spacing or non-closed profiles. Some relevant conclusion were obtained and will be exposed in sequence.

About the outlier elimination, the Brick-wall filter presented a very stable behaviour for the evaluated outliers and, hereupon, can be considered the best method. The Wavelet has a good behaviour when the outlier is present in both sides of the profile, however it is very poor for asymmetrical outliers.

Furthermore, the Morphological has the opposite behaviour, presenting a good result when the outlier occurs in just one side of the profile. This characteristic allows it to be used specially in the evaluation of profiles that have some spikes in the real surface that should not be considered in the form evaluation, for example, the plateau honed profiles.

The Robust Gaussian and Morphological filters have a good behaviour against spikes and can be used for the same case explained in the previous paragraph. However, for outliers with a bigger width, they are not able to overcome this problem and a specific method of outlier elimination is required.

The Robust Gaussian also changes the cut-off frequency, because its iterative algorithm that cut 50% of the profile on each iteration. This characteristic influences the direct comparison with the linear filters.

Using the techniques of outlier elimination, it is possible to perform an intermediate evaluation of the frequency spectrum of the profile, before the filtering, while the Robust filters do not allow this evaluation.

None filtering method overcomes the problem of uneven sampling, presenting a considerable deviation in the filtering result, therefore the interpolation is always necessary.

For open profiles, the methods Gaussian, Brick-wall and Wavelet should be avoid. The last one has also a problem with closed profile, does not presenting a good closing, even with the use of an overlapping technique.

The time processing of the Robust Gaussian and Morphological filters are extremely high compared to the other methods, what must be considered a big problem when many profiles are evaluated in sequence or when the signal has a high points density.

Although some of the evaluated filtering methods overcome the related problems in roundness measurement by scanning, compare them directly for roundness deviation is not simple. As they have different behaviour, the selection of the method and filtering parameters must be done carefully, regarding some secondary characteristics of the evaluated surface. Therefore, it is very important that the designer specify some additional information about the surfaces, as the manufacturing process, the frequencies of interest and the function of the work-piece.

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