Morphological filters for functional assessment of roundness profiles

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Abstract. Filtration techniques are useful tools of analysing roundness profiles. The 2RC filter and Gaussian filter are commonly used to assess peripheral undulations of the roundness data. However they cannot do every aspect of functional prediction. Morphological filters are employed to characterise roundness profiles for functional assessment. Traditional computation methods for morphological filters are limited to planar surfaces and unable to be extended to roundness measurement. A novel method based on alpha shape theory is developed to break up the confinement. The morphological closing and opening envelopes are obtained by rolling a disk upon the roundness profile from the air and material side of the component respectively. They can be used to identify significant peaks and valleys on the profile respectively, which are vital to the functional performance of component, especially contact phenomenon. A case study is presented that various options of morphological filters and reference circles are applied to a roundness profile, delivering different functional meanings. An in-depth comparison of morphological filters and the Gaussian filter is followed to derive their pros and cons.

1. Introduction

Round components are the most popular elements in products. From power stations to power tools, from the smallest watch to largest car, all contains round component. It was reported that around 70% of all engineering components have an axis of rotational symmetry. A component is described as round if all points of a cross section are equidistant to a common centre (Whitehouse 2002). However, the component will never be truly round because of the imperfect manufacturing process. The radial deviation of the actual profile from the ideal roundness is called as out-of-roundness. Roundness and size both play significant roles in the way components fit together. Roundness also contributes to in-service performances in many aspects, not least of which is maintaining a lubricating film between mating components in rotation operations.

A couple of international or national standards were published along with the development of roundness instruments, such as ISO 6318 (1985) (identical to BS 3730-1 (1987)), ISO 4291 (1985) (equivalent to BS 6740 (1987)) and ASME B89.3.1 (1972). ISO 12181 (2011) was then produced in 1994 and replaced its predecessors. It defines an ideal operator, which was not rigorously defined in the old standards, for instance, probe tip radius, filter transmitting and minimum number of sample points etc (Nielsen and Malburg 1996).

In practice filtering is often applied to measured profiles before evaluating roundness departures. Filtration techniques are used in the analysis of roundness data for several intents. Roundness is often coupled with roughness. If the point of interest is the geometry of the component or of the machine that made it, the geometry generally being characterised by a relatively small number of peripheral undulations, it is likely that the most meaningful assessment will be made by excluding the roughness, which could be sometimes large enough to mask departure from roundness (BS 3730-2 1982). As a result, the roundness data is often filtered to exclude roughness. The most commonly used filtration techniques are the 2RC filter (Whitehouse and Reason 1965; Whitehouse 1967) and the Gaussian filter (ISO 11562 1994). The 2RC filter was first recommended for use in roundness evaluation and is still in use in many older roundness instruments. Afterwards the Gaussian filter was standardized for surface texture analysis and roundness evaluation. There are even other variations with additional capabilities, such as the spline filter (Krystek 1996) and the robust Gaussian regression filter (Zeng *et al.* 2011). Because most of roundness instruments only capture deviations in the radial direction and they are insensitive to the actual diameter of the part, the cut-off of filtering of roundness profiles is specified by the undulation per revolution (UPR), rather than the wavelength as is in the case of planar surface filtration. By doing so, the filtration only concerns about the frequency contents of roundness waves and is blind to the actual radius of the part (Muralikrishnan and Raja 2009). The use of these filters is also motivated by the need of analysing the harmonic contents of roundness profiles and controlling manufacturing process. Various harmonic contents are responsible for different defect sources (Whitehouse 2002; Graham 2002). The first harmonic content is caused by the setting-error on the instrument, which equals to the eccentricity; the second harmonic content represents the ovality; the harmonic content with 3-5 UPR could be caused by the distortion of the workpiece by clamping or manufacturing forces, while the harmonic content with 6-20 UPR may attribute to the chatter raised by lack of rigidity of the machine tool.

Although roundness filtering is not a major problem in practice, there is still demand for enhancement, especially in a functional evaluation's point of view. The 2RC filter and the Gaussian filter, good in analysing the frequency content of roundness profiles, may not be applicable for all functional aspects in that they tend to smooth the profile and suppress functionally significant geometrical features on the surface topography. In contact phenomenon, peak features on the surface determine the position of first contact and indicate those surface portions easy to be worn at the initial stage of contact operation. In the meanwhile, valley features serve as reservoirs for oil lubrication and pockets to capture wear particles, therefore to reduce the wear of components (Bruzzone *et al.* 2008). Figure 1 presents a prime example, where a shaft is rotating in its mating plain bearing (Graham 2002). The shaft will run smoothly provided that both the shaft and bearing are round and their fit is neither too tight nor too loose, and if particularly the lubrication is present. However the magnified inset figure shows that the shaft profile is far from "true round" and that those lobes at points A will carry most of the load of the shaft and the lubricating film thickness at positions B will considerably greater than that of positions A. In a similar manner, the bearing's bore may not be circular, creating variable lubricating effects to the complete assembly which were not as the designer intended.

Therefore functional orientated methods are desired to evaluate and predict the performance of round rotating components. In contrast to the 2RC filter and the Gaussian filter, morphological filters are closely related to geometrical properties of surface topography and can simulate the contact interface of two mating surfaces (Lou *et al.* 2013a). However, morphological filters were mainly used to evaluate textures of planar surfaces (Groger et al. 2011; Lou et al. 2013b). There are few literatures showing that they can be applied to roundness filtration. In this paper, morphological filters are employed as a means of characterising round components. A novel supporting computational method for morphological filtering on roundness profiles is developed. A case study is also followed to demonstrate the feasibility of the proposed method. Morphological filters are compared to the Gaussian filter in details to reveal their advantages and disadvantages.

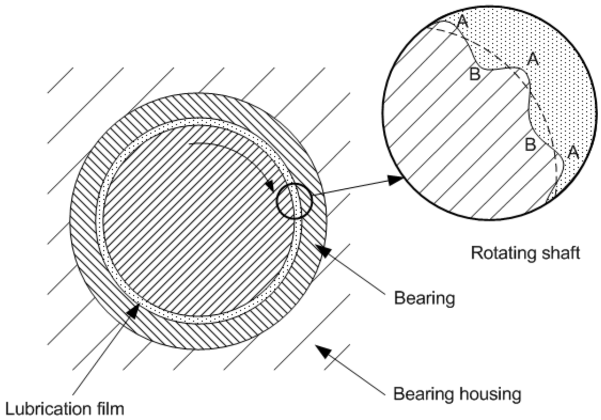

Figure 1. Roundness of a bearing affects its performance.

2. Morphological filters for surface texture analysis

Morphological filters origin from the traditional envelope method, which mechanically simulates the contact of a converse surface, e.g. a shaft, with the face of the anvil of a micrometer gauge. It appeared as a large ball rolling across over the surface from above (Von Weingraber 1956). The locus of the centre of the rolling ball with a following offset towards the surface by the ball radius is treated as the reference line. The advantages of the E-system were claimed to be that it is more physically significant in that many engineering properties of a surface are determined by its peaks (Thomas 1999).

By introducing morphological operations, morphological filters emerged as the superset of the early envelope filter, but offering more tools and capabilities (Srinviasan 1998). Morphological operations are applied on the input set by a pattern, called the structuring element, to extract the geometrical structure of the input set. There are four basic morphological operations, namely dilation, erosion, closing and opening (Serra 1982). Figure 2 and Figure 3 illustrate two examples of applying these morphological operations on an open profile with a disk structuring element. In Figure 2, an infinite number of identical disks are placed in contact with the profile from above along all the profile, the locus of the centre of the disks is the dilation envelope (Scott 2000). Conversely, in Figure 3, the erosion envelope is generated by placing an infinite number of identical disks in contact with the profile from below along all the profile and then taking the locus of the centre of the disks. Applying dilation followed by erosion leads to the closing envelope. A reverse combination yields the opening envelope. In fact, the opening and closing envelope are the upper and lower boundary of the disks respectively, as shown in Figure 2 and Figure 3.

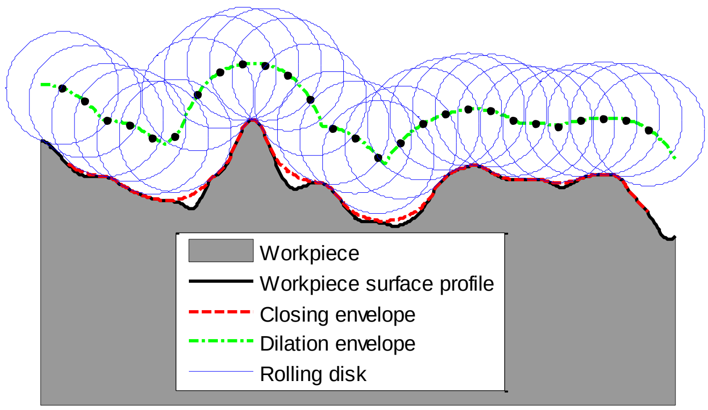

Figure 2. Dilation and closing envelope of an open profile by a disk.

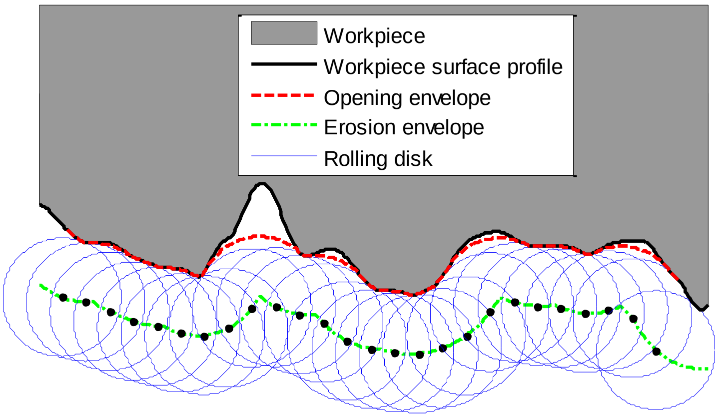

Figure 3. Erosion and opening envelope of an open profile by a disk.

It can be easily recognized that the closing filter suppresses the valleys on the profile whose radius curvature are smaller than the disk radius, meanwhile it remains the peaks unchanged. On the contrary, the opening filter suppresses the peaks and retains the valleys. The alternating symmetrical filter (ASF), the combined effect of closing and opening, suppresses both peaks and valleys.

Morphological filters behave quite differently from the Gaussian filter. The former is mainly determined by topographical features on the surface, such as peaks and valleys, meanwhile the latter tends to produce a smoothing effect based on the frequency spectrum. Morphological filters can give better results in functional characterisation of surface textures, which attribute to two factors. For one thing, morphological filters are closely related to functional requirements of workpieces, such as sliding, adhering, sealing, contact, assembly. To take one of these, morphological methods can help with the characterisation of contact phenomenon, wherein the contact of two mating surfaces is simulated by rolling a ball with the given radius, which is sized to simulate the largest reasonable radius at a contact e.g. peak curvature, upon the underlying surface (Lou *et al.* 2013a). For another, morphological envelopes can offer a common reference system to associate all geometrical elements, including dimension, orientation, form, waviness and roughness (Dietzsch *et al.* 1998).

3. Morphological filters for roundness profiles

Similar to the planar profile situation where disks are traversed from above and below the profile, morphological filtration can be extended to roundness profiles by rolling disks over the profile from inside or outside. However, the rolling side cannot settle the type of morphological envelope, because a roundness profile can not by itself discriminate whether it is measured from a shaft or a bore and morphological filtering of these two situations will have converse results. To reduce the confusion, the interface function of the surface to separate the component from surrounding media should be employed. If the disk is rolled upon the roundness profile from the air/media side of the component (the side from which the component is interacting with its mate), then the resulted disk boundary is the closing envelope. On the contrary, if roll from the material side of the component, then the disk boundary is the opening envelope.

Morphological filtering is common practice in geometrical measurement. If only unconsciously, the traversing process of the stylus tip in tactile roundness measurement is a morphological filtering operation. The roundness profile as the data under the operation is filtered by the circular structuring element, the stylus tip, to generate the morphological output, the measured profile. In industry, it is standard practice to employ a relative large stylus to reduce the affection of surface textures. Figure 4 shows diagrammatically how styli of small and large radii react to the tool marks on a turned cylinder which is not part of component shape but contribute to the surface texture. It is obvious that if using a sharp stylus the tip will sink into the process tool marks while a "hatchet" style stylus with a deliberately large radius will not. This is intentionally made because the hatchet stylus actually acts as a mechanical filter and bridges the gaps in the closely spaced surface texture marks (ISO 6318 1985). This fact is consistent with morphological filtering in that a circular structuring element with relative large radius will suppress (filter out) tiny peaks or valleys on the surface topography. More impacts of tip geometry on roundness measurement were found in term of both spatial and harmonic components, causing spatial and frequency distortion (Thalmann et al 2012). Attempts have been made to reduce these effects, either by deconvoluting the measured roundness profile with the 'Kilroy's cat' function (Nielson and Malburg 1996), or using the traditional morphological reconstruction method (Morel 2006).

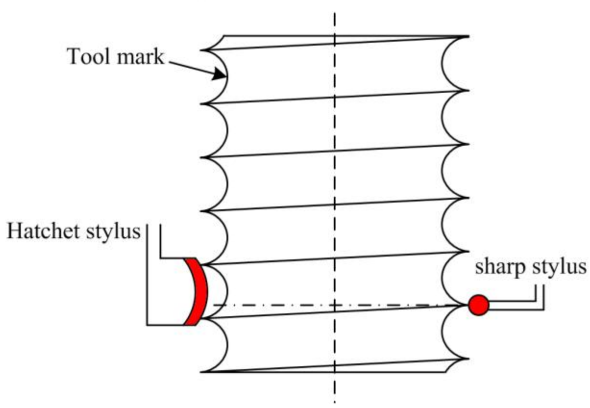

Figure 4. Effect of stylus radius when in contact with surface.

A notable issue of using morphological filters is that they must work on the "unsuppressed" roundness profiles, i.e. the radius deviations is compounded with the radius value of the component. Conventionally, the data measured by roundness instruments is radius suppressed, i.e. the data only reflects the radial deviation and is insensitive to the radius itself. In such a situation, the 2RC filer or the Gaussian filter is applied to analyze the undulation in radial deviations. Morphological filters, by their nature, should be based on the real profile data without any suppression. Both state-of-the-art roundness instruments and Coordinate Measurement Machines (CMMs) can provide such kind of data.

4. Computational method for morphological roundness filters

4.1. Image processing based method for planar surfaces

The traditional computation of morphological filters acts in a similar manner to image processing, where the sampled surface points are treated as image pixels. ISO 16610-41 (2010) presents a basic method to compute discrete morphological filters. It puts the origin of the structuring element at every point of the input profile, as illustrated for a few positions of a circular structuring element for dilation in Figure 5. Extreme value at each position is collected and they form the output envelope. The extreme heights for input points are the results of adding the ordinates of input profile points with the ordinates of sample points on the disk, as marked by the top-most stars at vertical lines in the figure. The erosion envelope can be easily obtained by first flipping the original profile followed by flipping its dilation envelope. The closing and opening envelopes are achieved by combining dilation and erosion in sequence. Using this method, the measured data are regarded as height variations over the sampling plane. Therefore it is limited to planar data and unable to extend to roundness profiles.

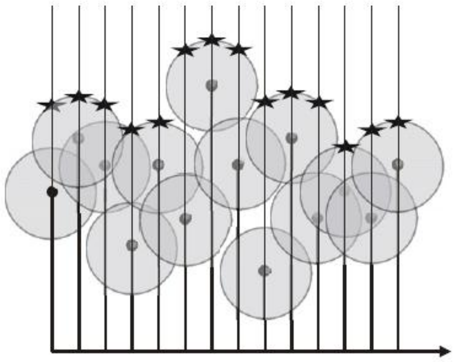

Figure 5. Dilation of the profile with a circular structuring element.

4.2. Alpha shape based method for roundness profiles

In this paper, we propose a geometrical computation method for morphological roundness filtering as an extension of the our previous work reported in Jiang *et al.* (2012), which was based on alpha shape theory and built for open surface filtering. The alpha shape is a geometrical structure aiming to describe the specific "shape" of a finite point set with a real parameter α controlling the desired level of details (Edelsbrunner and Muche 1994). As Figure 5 illustrates, the alpha hull is the boundary formed by rolling a disk with the given radius α over the point set. Straightening the round faces (arcs) of alpha hull by line segments yields the alpha shape. It was proved that the alpha hull is equivalent to the closing of the point set X with a generalized ball of radius $-1/\alpha$ and that from the duality of closing and opening the alpha hull is the complement of the opening of X^c (complement of X) with the same ball as the structuring element (Worring and Smelders 1994). Thus by examining boundary facets of the alpha shape of the measured profile, morphological closing and opening envelopes can be derived.

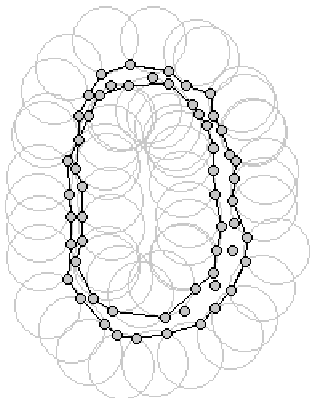

Figure 6. Alpha hull and alpha shape of the planar point set.

Figure 6 apparently reveals that the alpha shape method is naturally suitable for morphological roundness filtration. To apply alpha shape theory, the Delaunay triangulation is first applied to generate a series of triangular mesh, from which boundary facets of alpha shape can be extracted. Due to the link between the alpha hull and morphological envelopes, each boundary facet of the alpha shape will determine a portion of morphological envelope. The procedures of using the alpha shape method to compute morphological envelopes for roundness profiles are detailed as follows.

(a) Delaunay triangulation

The Delaunay triangulation contains all the information of extracting the whole family of alpha shapes, from the point set itself ($\alpha \to 0$) to the convex hull of the point set ($\alpha \to \infty$). To extract the alpha shape facets that belongs to the given radius α, the initial step is performing the 2D Delaunay triangulation on the roundness profile data. Figure 7 illustrates such an example roundness profile (about 2 mm in radius) and the triangular mesh resulted from the Delaunay triangulation.

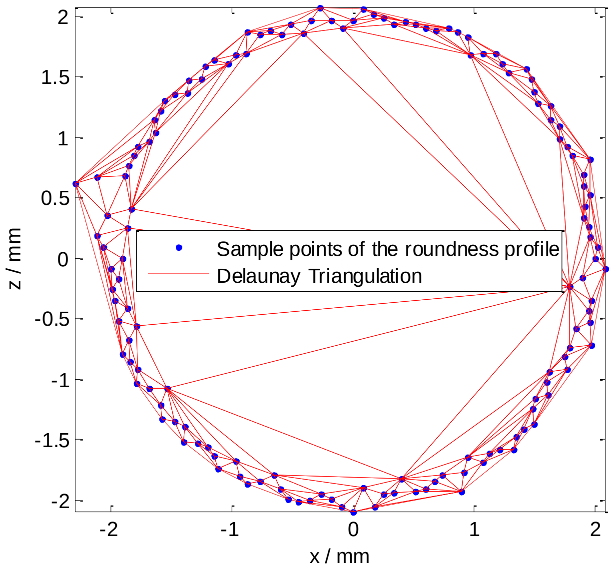

Figure 7. Delaunay triangulation of a roundness profile.

(b) Boundary alpha shape facets extraction

The Delaunay triangulation results in a number of 2-simplices, i.e. the triangular mesh. These simplices can be categorized into two groups: one having the circumscribed circle radii larger than α and the other one having the circumscribed circle radii smaller than α. For the first group, each edge of the 2-simplex can hold an empty disk with radius α. The edges (1-simplices) which bounds the joint 2-simplices, not the common shared edges, are regarded as the boundary facets of the alpha shape. These edges are called the regular facets. For the second group, each edge of the 2-simplex needs further separate examination: an edge is a boundary alpha shape facet if the radius of smallest circumscribed circle of the edge is smaller than α and also that circle has to be empty. Such kind of edges is named the singular facets. The regular and singular facets comprise the whole boundary facets of the alpha shape corresponding to the given radius α. A functionally significant fact is that the vertices of the boundary alpha shape facets are those points on the roundness profile that will be in contact with the rolling disk. Figure 8 presents the boundary facets of the alpha shape of the example roundness profile with disk radius 1 mm.

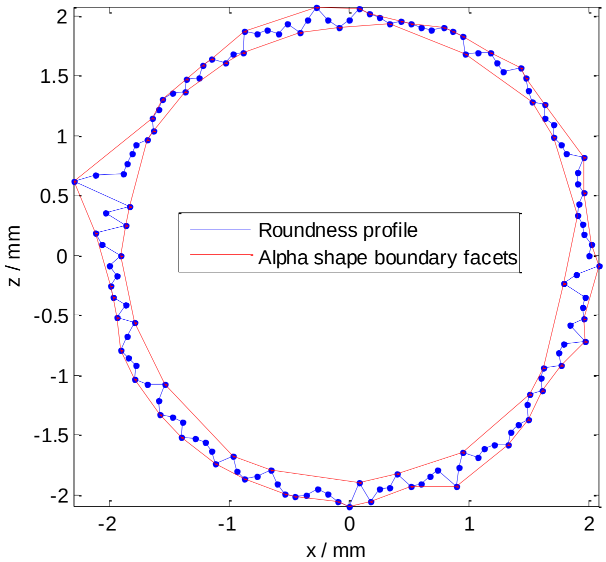

Figure 8. Extraction of boundary facets of the alpha shape of a roundness profile.

(c) Inner and outer facets separation

Suppose the presented example roundness profile is measured from a shaft component. The outer facets will determine the closing envelope as the disk is rolled from the outside; similarly the inner facets determine the opening envelope. Hence the outer and inter facets have to be separated from each other in order to compute the desired morphological envelope. This is discriminated by the normal vector of the facet, which is defined to be normal to the facet and pointing from the interior of alpha shape towards its outside for the outer facets and vice versa for the inner facets. The vertex opposite to the evaluating facet (1-simplex) in their super 2-simplex can help determine the normal in computation: it is supposed to be in the direction opposite to that vertex. Figure 9 illustrates the normals of the boundary facets. Apparently the normals of outer facets point to outside of the roundness profile and those of inner facets point to inside.

To further the separation, a justification vector is established, which is oriented from one of the vertices of the facet towards an interior point of the roundness profile, e.g. the centre of the least square circle of the roundness profile. The boundary facets whose normals are consistent with their justification vectors are considered as the inner facets, and vice versa for the outer facets. In this example, since the profile is supposed to be extracted from a shaft and the closing envelope is desired, the outer facets are retained. See Figure 10.

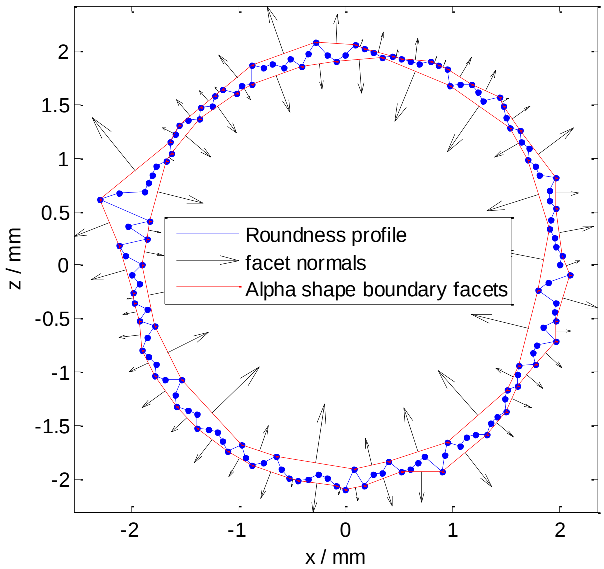

Figure 9. Justification of the normals of boundary facets.

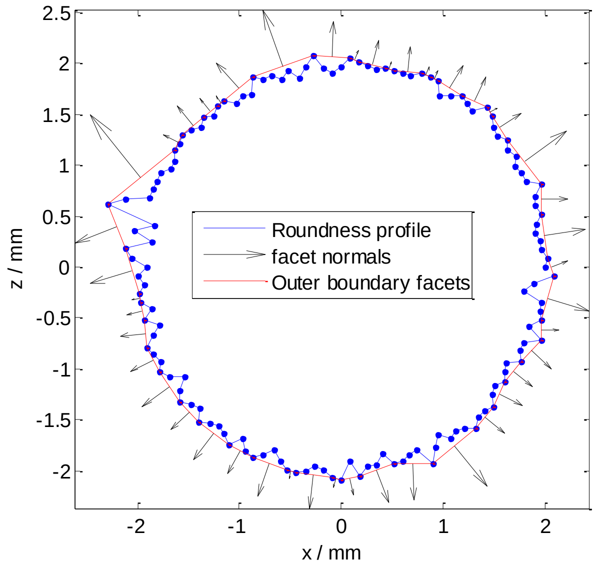

Figure 10. Extraction of the outer facets for morphological closing envelope.

(d) Envelope calculation

With the separated boundary facets of the alpha shape, a specific morphological envelope can be solved. For each sample point on the profile, there is a one-to-one corresponding point on the envelope. These points form a discrete representation of the envelope. Due to the fact that the target envelope is equal to the alpha hull related with the separated boundary alpha shape facets, the envelope coordinates are achieved by interpolating points on the arcs of alpha hull. Figure 11 illustrates the resulted closing envelope of the example roundness profile using a 1 mm disk.

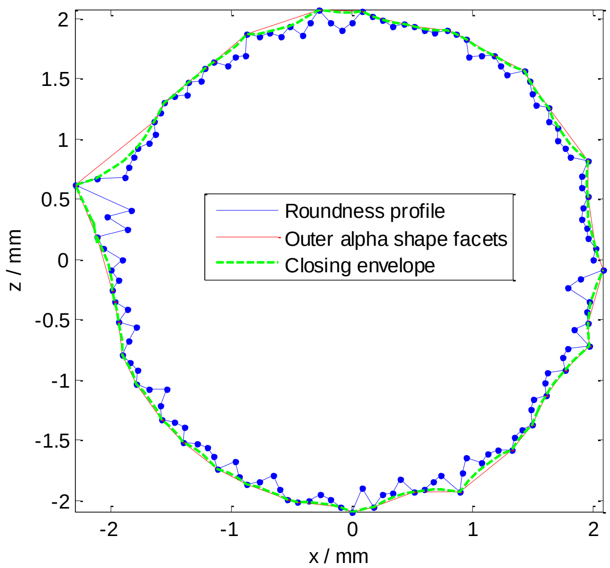

Figure 11. Morphological closing envelope of the roundness profile with disk radius 1 mm.

5. Case study

5.1. Morphological filtering on experimental roundness profile

Case study is carried out to demonstrate the capability and usability of morphological filtration on roundness profiles. A number of roundness profiles were measured from the round interlocking taper of a total hip replacement using CMM. Figure 12 presents such a profile, which has the radius approximately 5.74 mm and contains 3,631 sample points. The morphological closing filter is applied on this profile using disk radius 5 mm. Figure 12 also illustrates the generated closing envelope and the corresponding contact points (some of them are clearly presented in the magnified inset figure). For the convenience of better visualization, both the roundness profile and the resulted closing envelope are radially suppressed by 5.7 mm based on the centre of the reference circle. The contact points are functionally important in that they can serve as an indication that the surface portions in neighborhood of these points are possibly active in contact phenomenon.

If the disk is rolled over from inside, it results the opening envelope, which is physically identical to the closing filtering on the same profile but facing inward as if the profile is measured from the ideal mating bore counterpart. Evidently the radius of the disk used to roll upon the profile has to be smaller than the part's radius. In this experiment, a 5 mm disk is applied to generate the opening envelope and the corresponding contact points, see Figure 13.

Figure 14 presents the combined effect of applying the closing filter followed by the opening filter, i.e. the alternating symmetrical filter. The measured profile is filtered from both outside and inside, indicating both peaks and valleys are suppressed. The filtered roundness profile passes through the measured profile from the middle, which resembles the one produced by the Gaussian filter (cutoff 50 UPR). However, if carefully examine the generated ASF roundness profile, this profile is found to run a bit towards the air side of the unfiltered profile. This is due to the fact that the closing operation is first applied, by which its envelope will cover the air side of profile, and then the following opening operation partially cuts off the peak features on the basis of this closing envelope. If the opening filtering is applied prior to the closing filtering, then a result towards to the material side will be obtained.

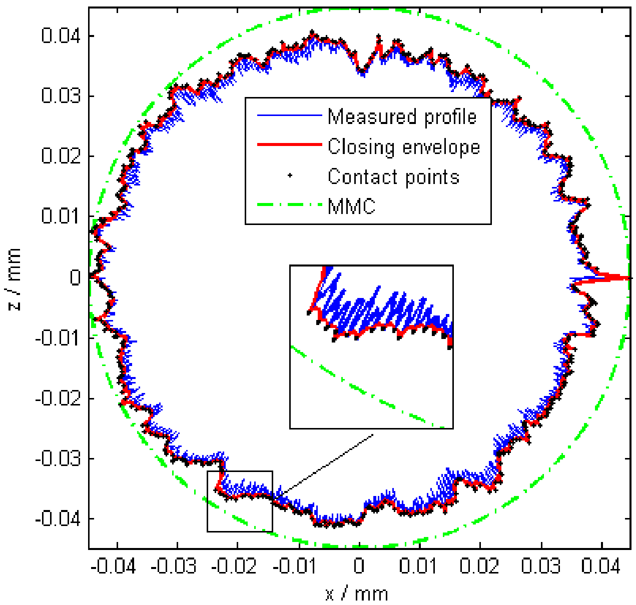

Figure 12. Closing envelope and contact points of the roundness profile with disk radius 5 mm.

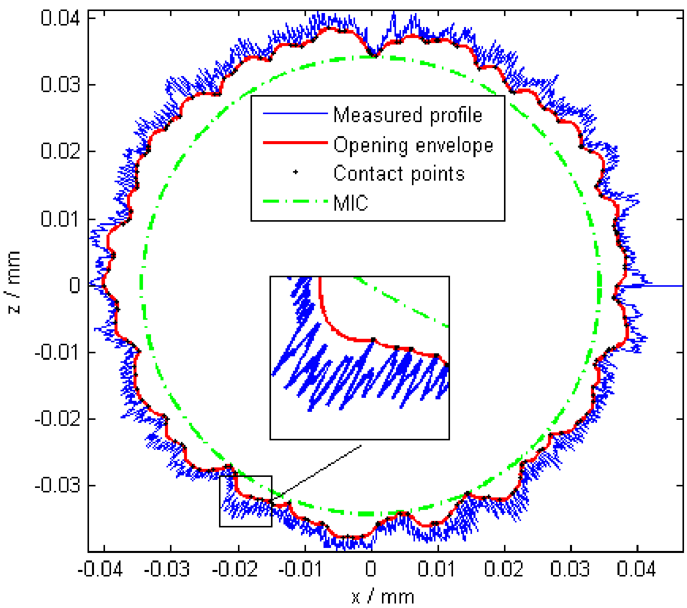

Figure 13. Opening envelope and contact points of the roundness profile with disk radius 5 mm.

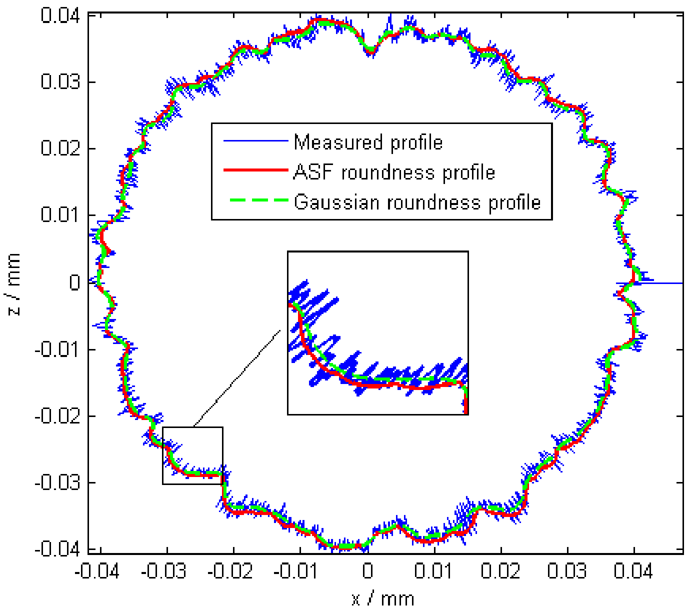

Figure 14. Roundness profiles filtered by the alternating symmetrical filter (closing followed by opening) with radius 5 mm and the Gaussian filter with cutoff 50 UPR.

5.2. Roundness deviation characterisation

According to ISO 12181 (2011), four reference circle options are available for fulfilling different roundness evaluation requirements, i.e. the least square circle (LSC), the maximum inscribed circle (MIC), the minimum circumscribed circle (MCC) and the minimum zone circles (MZC). They provide the datums to which the deviations from roundness and roundness parameters are referred. The general roundness parameters consist of RONp (peak-to-reference deviation), RONv (reference-to-valley deviation), RONt (peak-to-valley deviation) and RONq (root mean square deviation). Only RONt is valid for all the reference circle options.

Table 1 lists the calculated RONt values based on various combinations of morphological filters and reference circles. The calculation results from the raw data are also presented for comparison. The closing filter is intentionally coupled with MCC because they are both sensitive to the external extreme points on the measured profile. Similarly the opening filter is combined with MIC since they are sensitive to the internal extreme points. In employment of morphological closing and opening filtering, it is observed that the radii of reference circles (MCC or MIC) are consistent for each group. For example, the raw measured profile, the closing filtered profile and the contact points obtained from closing filtering all lead to the same MCC. This indicates the fact that the closing operation retains the external extreme points on the measured profile, which definitely contain the three key points for establishing the MCC. The RONt value calculated based on the closing roundness profile is smaller than that of the raw profile. The result from the closing contact points is even a bit smaller. It is reasonable because it means that only the significant peaks are taken into the calculation despite of other profile portions which might not be active in functional service. Similar results can be found for the opening group.

In comparison, Table 2 presents the results by applying the Gaussian filter and the alternating symmetrical filter with the LSC reference. They are used together because both of them have averaging properties, which can be evidenced by their LSC radii. The RONt value of the ASF filter is close to that of the Gaussian filter. This verifies the previous statement described in Section 5.1 that by suppressing both peaks and valleys the ASF achieves a similar effect to the Gaussian filter by which peripheral undulations of the roundness profile are suppressed.

Table 3 illustrates RONt values of the closing roundness profile and contact points subject of increasing of the disk radius. The decreasing of RONt values is exhibited as the disk radius increases. Two issues can be further recognized. On one hand, as the disk radius used by the closing filter gets smaller, the RONt value is approaching to that of the raw data (0.0117 mm), indicating the filter is becoming less effective. On the other hand, as the disk radius increases to 100 mm or even bigger, the resulted RONt value does not change any more, being a fixed value (0.0106 mm). In this case, the strongest filtering effect is achieved. Similar pattern also applies to the opening filter. The only difference is that the growing of disk radius is limited to the MIC radius.

Table 1. RONt values regarding to various combinations of different morphological filters with MCC and MIC references.

Options	Raw + MCC	Closing + MCC	Closing contact points + MCC	Raw + MIC	Opening + MIC	Opening contact points + MIC
RONt (mm)	0.0117	0.0108	0.0106	0.0124	0.0059	0.0058
RC radius (mm)	5.7447	5.7447	5.7447	5.7343	5.7343	5.7343

Table 2. RONt values regarding to combinations of the Gaussian filter and the alternating symmetrical filter with the LSC reference.

Options	Raw + LSC	Gaussian + LSC	ASF + LSC
RONt (mm)	0.0137	0.0063	0.0068
LSC radius (mm)	5.7389	5.7389	5.7392

Table 3. RONt values regarding to increasing disk radius of closing filtering subject of MCC.

Disk radius (mm)	0.1	0.2	0.5	1	2	5	10	100
RONt (closing) (mm)	0.0117	0.0117	0.0114	0.0112	0.0111	0.0108	0.0107	0.0106
RONt (closing contact point) (mm)	0.0117	0.0117	0.0112	0.0112	0.0107	0.0106	0.0106	0.0106

The experiment results reveal that morphological filters and the Gaussian filter yield different parameter results, delivering different physical meanings. When evaluating geometry related functional performance, the results from morphological filters could be more instructive. For example, the contact phenomena in bearing industry, the interaction of two round surfaces is influenced by the factors such as the combined effects of the contact form, the number of contacts, the typical contact radius and the typical lateral extension. In this situation, morphological filters are more suitable and the using of Gaussian filter is limited due to two reasons. For one thing, because of the averaging effect of the Gaussian filter, it tends to smooth the peaks and valleys which are critically important for functional services. For another, the Gaussian filter is operated to analyze harmonic components of the roundness profile. It endeavors to accurately evaluate the roundness form by suppressing the affection of the diameter and surface texture. However, all these geometries should be unified as a whole and taken into consideration in a perspective of functional evaluation. Morphological method behaviors differently in these two aspects. It works on an integrated data set including form, size and surface texture. It can also extract functionally important geometrical features and corresponding contact points by simulating the interaction of two mating surfaces. The determination of these significant features is based on the selection of the disk radius. The radius should be carefully decided according to the requirements of a specific application. For instance, in the scenario of the interaction of ball and roller bearing, the disk radius can be chosen same as that of the steel ball and thus those contact points will represent the real contact points of the bearing race and steel balls, which could be helpful to further tribological analysis.

6. Comparison of morphological filters and the Gaussian filters

Morphological filters differ from the Gaussian filter in many aspects. The following presents a detailed comparison of these two types of filtration techniques in term of roundness measurement.

(1) Morphological filters and the Gaussian filter operate on different types of roundness measurement data. Traditional roundness measurement instruments measure the peripheral “skin” of the workpiece, not the whole part (Whitehouse 2002). It aims to capture and evaluate the variations in part’s radius instead of the radius itself. Thus the radius is ignored and the data “suppressed” to only reflect the radial variations. In this aspect, morphological filters are only valid when applied to the whole extracted circumferential profile, in other words, the intersection of the real surface and the roundness plane. Therefore morphological method takes into consideration the holistic geometry of the part, including size, form and surface texture.

(2) It follows that the Gaussian filter only cares about the amplitude information while the lateral distribution on the circumference is ignored. Oppositely, morphological filters, by their nature, have to tackle with both amplitude and lateral information as integrity.

(3) The Gaussian filter is essentially the convolution operation of the roundness signal and the Gaussian weighting function. The linear theory and Fourier transform help build efficient algorithms and explain the physical function of frequency component filtering. In comparison, mathematical morphology lays the foundation for morphological filters. The operations of morphological filters are nonlinear. Morphological filters also gain its basis from the common practices of tactile measurement that stylus scanning and mechanical filtering are both morphological operations (Lou et al. 2013c).

(4) The filtering effect of morphological filters and the Gaussian filter are determined by the disk radius and the cut-off UPR respectively. They have different physical meanings. For the Gaussian filter, the harmonic components larger than the cut-off UPR are suppressed. The cutoff with 1 UPR has the strongest effect while using an infinitely great cut-off value it might not filter anything. In contrast, the suppression effect of morphological filters is based on the disk radius. The peaks or valleys having radius curvature smaller than the disk radius are suppressed. Thus in the case that the disk radius goes for infinitesimal, the disk will be small enough to sink into any surface cusps, indicating nothing is filtered at all. In the opposite case that the radius goes for infinity (only valid for the outside roundness profiles), the morphological closing filter achieves the strongest effect and the morphological envelope is unlimitedly approaching to the convex hull of the roundness profile, reaching the strongest filtering effect that the closing filter can obtain.

(5) It is usually in real practice to randomly put the cut-off value of the Gaussian filter at 1-50 UPR or 1-150 UPR. It is agreed that for normal workpieces the differences are relatively small, as the major deviation comes from first harmonic components. In terms of morphological filters, an appropriate disk radius is selected on a trial basis, by which the filter is supposed to fulfill the requirements of a functional evaluation. Roughly estimating the physical size of geometrical features on the roundness profile may help with choosing a good candidate radius (Decenciere and Jeulin 2001).

(6) The Gaussian filter does not distinguish whether the measurement is taken from inside or outside for it processes with the frequency components of roundness signals. However, as already stated in Section 3, these two situations are totally different for morphological filters. For outside measurement, the disk radius can go to infinity, while it is limited to MIC radius for inside measurement.

(7) Morphological closing and opening filters are sensitive to significant peaks on the roundness profile, by which the geometrical behaviors of round workpieces are clearer. It could be arguable that some extreme points are not true surface features but caused by measurement noises. If that risk can be neglected, it is the proper way of filtering. In contrast, the Gaussian filter tends to produce an averaging effect and is closely related to the analysis of harmonic components of the roundness profile. The alternating symmetrical filter can yield a similar result to the Gaussian filter, by suppressing both peaks and valleys (See Figure 14 as an example). However they are totally different tools and the effect of alternating symmetrical filter on harmonic components is unclear.
(8) The Gaussian filter can help analyze harmonic behaviors related to either the component manufacturing process or its measurement. Whereas, morphological filters can contribute to the prediction of functional performances of workpieces, especially those closely related to the geometrical properties of workpieces, e.g. tribology. Instead of competing to each other, morphological filters and the Gaussian filter are complementary to each other, contributing a better analysis of roundness measurement.

7. Conclusion

Filtration techniques are necessary for the evaluation of roundness profiles. The Gaussian filter although good in analysing peripheral undulations of roundness deviation, it can not work for all aspects of functional evaluation. This paper proposes to use morphological filtration techniques for functional assessment of roundness profiles, especially contact phenomenon. The morphological closing and opening filtering on roundness profiles are obtained by rolling a disk from the air and material side of the component respectively. They can identify significant peaks and valleys on the roundness profile, which are functionally important to the tribology related performance of the component.

A feasible supporting algorithm for morphological filtration of roundness data is developed to break up the confinement of the traditional method to planar surfaces. The method is built on the basis of alpha shape theory and its computation procedures are detailed. A case study is illustrated wherein various options of morphological filters and reference circles are applied, delivering different functional meanings. A further detailed comparison of morphological filters and the Gaussian filter is conducted to reveal their advantages and disadvantages. Rather than competing with each other, morphological filters and the Gaussian filter are complementary to each other, contributing for a better solution for practices.

In this work, morphological filters are in principle proposed for the functional assessment of roundness profiles. Future work will include a quantitative assessment of the functional performance of morphological filters via functional tests.

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