Computer modeling of the process of shape deviations parameters control and analysis*

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Abstract
Calculation and mathematical representation of the measurement of shape deviations for cylindrical surfaces are presented in this paper. The measurement data taken by the inductance sensor from flour milling rollers are analyzed and they are compared them with the ideal profile. In this paper coefficients for taper, saddle, barrel, and other deviations and shape defects are found by applying mathematical approach to the analysis of the cross-sectional profile of the cylinder at different sample lengths using the data obtained from the calculations.

Keywords
device, shape deviation, mathematical modeling, model.

1. Introduction

Precise analysis and measurement of the shape deviations are of fundamental importance in precision manufacturing, metrology and quality control. Ensuring that the dimensions, shapes and geometric characteristics of manufactured components meet their design specifications requires both precise measurement technologies and reliable mathematical modeling methods. Over the past few decades, researchers have made significant progress in understanding and quantifying shape deviations, driven by the increasing demands of high-precision industries such as aerospace, automotive, optical, and medical.

Mathematical modeling for the shape deviation analysis has its roots in classical metrology, and the first works were focused on defining mathematical standards for the evaluation of geometric tolerances. The pioneering works by G.-J. Berger and G. Kunzmann laid the foundation for the use of the least squares methods to fit measured data to idealized geometric primitives such as planes, spheres and cylinders. These efforts significantly influenced early computational methods for describing deviations and optimizing the alignment of measured points [1].

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In the field of computational metrology, P. Bourdet and his colleagues have advanced the development of methodologies for shape errors analysis based on numerical optimization of fitting. Their papers provided an early framework for measurement datasets association with canonical shapes and residual deviations minimization, establishing critical baseline for modern shape error analysis. Similarly, W.T. Estler contributed to the statistical processing of shape deviation data, promoting uncertainty analysis for better understanding and interpretation of measurement results [2].

The development of coordinate measuring machines (CMMs) in the second half of the 20th century stimulated further development of mathematical processing of shape measurement results. Such researchers as R.K. Hardwick and R. Shrinivasan have achieved significant success in CMM data processing algorithms, converting tactile measurements into geometric models that can be compared to design specifications. Their contribution clarified mathematical problems related to sampling strategies, error propagation, and efficient data processing [3].

As non-contact measurement methods such as laser scanning, optical profilometry, and structured light systems have become more widely used, researchers, including L. De Schiffer and Y. Villasis, have studied the integration of surface scanning data with shape deviation modeling. Their efforts demonstrated the need for reliable algorithms capable to process dense point clouds, noisy measurements, and arbitrary-shaped surfaces [4]. The paper by T. Varady and R. Martin became particularly important for reengineering and geometric reconstruction, where large data sets from scanning systems required mathematical methods of smoothing, fitting, and interpolation in order to model surfaces with submicrometer accuracy [5].

Recent research trends are focused on combining optimization techniques, advanced computational geometry, machine learning, and probabilistic modeling to improve accuracy and solve real-world manufacturing problems. For example, B. Denken and B. Zhang investigated the role of adaptive algorithms in modeling complex arbitrary shapes with increased computational efficiency [6]. Furthermore, the quantification of uncertainty, as investigated by A. Forbes and colleagues, at present plays a crucial role in determining not only the accuracy of measured data but also the reliability of shape deviation estimates [7].

In this paper, we try to contribute to this growing number of works by presenting new approach to mathematical modeling adapted to the device specially designed to measure shape deviations. We are focused on optimizing measurement accuracy, reducing computational complexity, and solving problems specific for modern manufacturing environments, thus based on the fundamental efforts of previous researchers while introducing new methodologies uniquely suited to modern needs.

The device is designed to measure the shape deviations of cylindrical surfaces. Flour mill rollers were chosen as the object of the investigation. The shape deviations of cylindrical surfaces were standardized according to State Standard (DSTU) 2.308:2013. The following listed below elements and concepts are used as the basis for quantitative assessment of shape deviations (Fig. 1). Nominal surface is an ideal surface whose dimensions and shape correspond to the specified nominal dimensions and nominal shape. Real surface is a surface that limits the body and separates it from the environment. Similarly, the nominal and real surface profile. Surface profile is a line of intersection of the surface with the plane or given surface [8].

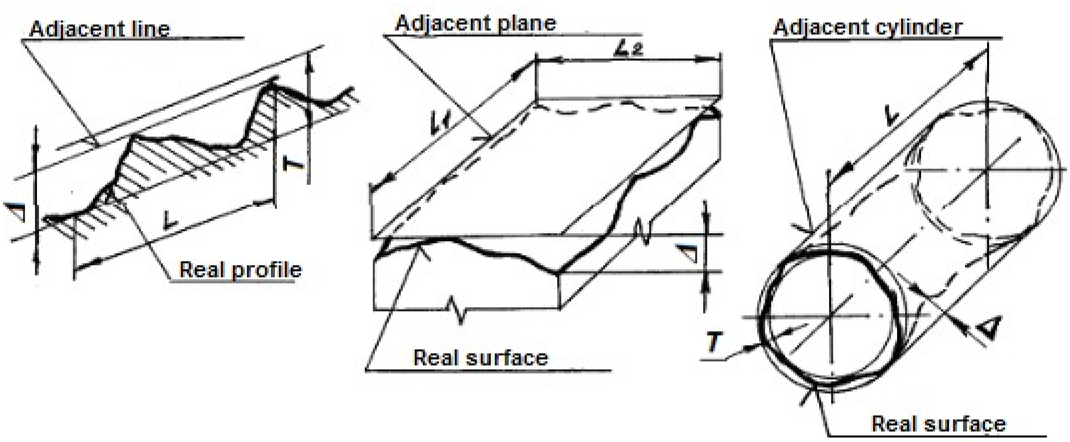

Figure 1: The principle of adjacent surfaces: L, L1, L2 - dimensions of the normalised areas; Δ- deviation or the greatest distance from the real surface (straight line) to the adjacent surface (straight line).

The principle of adjacent surfaces, straight lines and profiles is used to standardise deviations in shape and location.

Adjacent line is the line that touches the real profile and is located outside the material of the part so that the deviation from it of the farthest point of the real profile within the normalized section has minimal value.

Adjacent surface is the surface that has the shape of nominal surface, is in contact with the real surface and is located outside the material of the part so that the deviation of the farthest point of the real surface from it within the normalized area has minimal value.

Particular case:

Adjacent cylinder is the cylinder with minimum diameter circumscribed around the real outer surface or with maximum diameter inscribed in the real inner surface.

Adjacent profile is the profile that has the shape of the nominal profile, is in contact with the real profile and is located outside the material of the part so that the deviation of the farthest point of the real profile from it within the normalized section has minimal value.

Particular case:

Adjacent circle is the circle of minimum diameter circumscribed around the real profile of the outer surface of rotation, or the circle of maximum diameter inscribed in the real profile of the inner surface of rotation.

The tolerance field of the shape is the area in space or on the plane, inside which all points of the real given element within the normalized area should be located. The width or diameter of the tolerance field is determined by the tolerance value, and its location is determined by the adjacent element.

As the result of measuring the part, the deviation (error) values obtained during the manufacture of the part are determined and compared to the shape tolerance specified in the drawing. If the error does not exceed the tolerance, the part is of good quality.

2. Modelling and predicting the roller profile by means of MatLab

Mathematical modelling is the method of studying processes or phenomena by creating and investigating their mathematical models. Mathematical modelling is a powerful tool for investigating complex systems, enabling researchers to provide deeper understanding of processes and phenomena by creating and analyzing their mathematical models Nowadays, this method is becoming an integral part of numerous scientific and engineering investigations making it possible to find solutions that are often impossible to obtain in any other way.

The method is based on the principles of identical forms of equations and unambiguous correlation between variables in models and originals making it possible to reflect important aspects of the investigated systems with maximum accuracy. Due to the application of analogue machines, digital computing devices and powerful computers, modelling becomes a real bridge between theoretical knowledge and its practical application [10].

The model, as a substitute object, reproduces critically important properties of the original, making it possible to study its behavior under different conditions. It can be represented physically (e.g., a scaled copy of an object) or in the form of mathematical descriptions that can be easily integrated into computer programs, which makes it possible to carry out complex calculations quickly and efficiently.

The main task of modelling is not only to display, but also to obtain, process and present information about the interaction of system components with each other and with the environment. This enables us to reveal new properties and patterns of object behaviour that can be critical for optimizing and managing complex systems. It is evident that modelling can be used to predict the system's response to various control influences, which is especially important in control tasks where the speed and accuracy of responses are critical.

In this paper, the main tool used is MatLab, which has become the standard for mathematical modelling due to its numerous capabilities and wide range of functions. MatLab offers convenient tools for working with matrices, graphical construction of functions, development and debugging of algorithms, and integration with other programming languages. This provides researchers with the opportunity to create comprehensive models that includes all aspects of the systems under study.

Special attention in the model is paid to the analysis of data recorded by inductance sensors from the surface of flour mill rollers. The measured data are compared with the ideal profile, which makes it possible to identify and analyze the main shape deviations. This enables us to detect shape deviations that can affect overall performance and the quality of the final product.

The results of such modelling approach makes it possible not only to understand the technological process better, but also to develop strategies for the improvement of the efficiency and reliability of the system as a whole. The measurement data recorded by the inductance sensor from the flour mill rollers are analyzed and compared with the ideal profile. The main elementary shape deviations are also shown.

3. Control and analysis of the shape deviation parameters

The main elementary shape deviations include: cone shape, barrel shape, saddle shape, and deviation of the longitudinal cross-section profile.

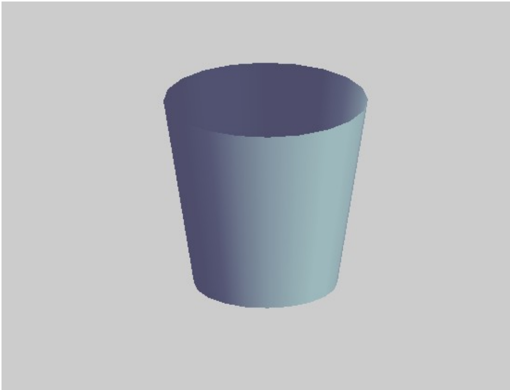

Figure 2: Cone shape**.**

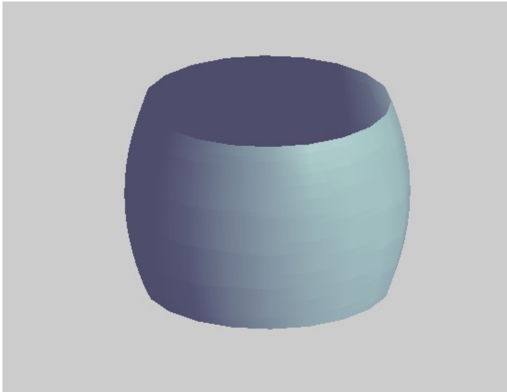

Figure 3: Barrel shape.

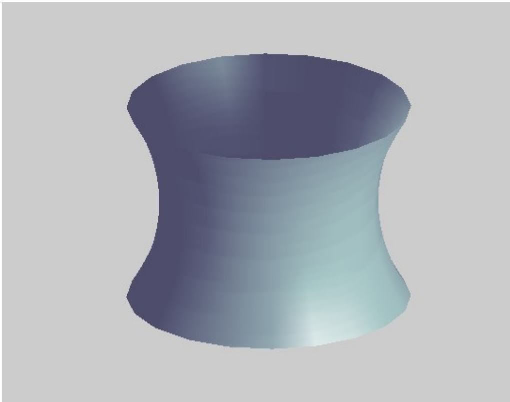

Figure 4: Saddle shape.

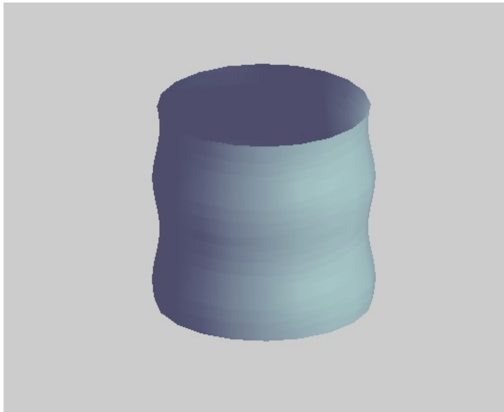

Figure 5: Deviation of the longitudinal cross-section profile.

The cone shape coefficient (Fig. 2) is defined as half the sum of the largest and smallest diameters measured in two cross-sections along the edges of the part or at a given length.

$$K = \frac{D + d}{2} \tag{1}$$

The barrel shape coefficient (Fig. 3) is defined as half the difference between the largest and smallest diameters measured at the edges and in the middle or at a given length.

$$K = \frac{D - d}{2} \tag{2}$$

The saddle shape coefficient, as well as the barrel shape coefficient (Figures 4, 5) is defined as half the difference between the largest and smallest diameters measured at the edges and in the middle or at a given length.

$$K = \frac{(D_1 - d) + (D_2 - d)}{2} \tag{3}$$

The deviation of the longitudinal cross-section profile is the complex indicator for the longitudinal cross-section of the cylinder, which is determined by the set of the shape deviations of the whole section from the shape formed by two parallel straight lines [12].

The deviation of the longitudinal section profile is taken as the largest deviation of the actual profile from the adjacent parallel straight lines, maximally enlarged (for a shaft) and maximally distant from each other (for a hole).

4. Analysis of the device designed for shape deviations measurement

If the assembly technology and manufacturing technology are followed during the roller production of the, perfect profile can be achieved.

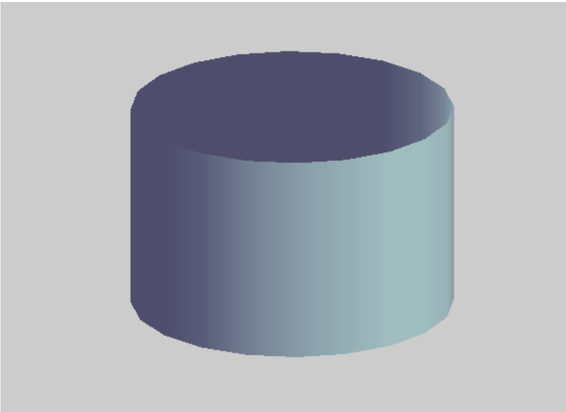

Figure 6: Ideal profile.

The main elementary deviations can be evaluated by examining the cross-sectional profile taken at given lengths of the controlled sample.

The cross-sectional profile was evaluated by analyzing its roundograms by means of MatLab software [13]:

```
clear all
t(1:30)=2;
[X,Y,Z]=cylinder(t);
%mesh(X,Y,Z)
surfl(X,Y,Z)
colormap bone
shading interp
axis off
t=[2 2.05 2.1 2.15 2.2 2.25 2.3 2.35 2.4 2.45 2.5 2.55 2.6 2.65 2.7 2.75 2.8 2.85];
[X,Y,Z]=cylinder(t);
%mesh(X,Y,Z)
figure,surfl(X,Y,Z)
colormap bone
shading interp
axis off
```

```
l=[pi/3:.01:2*pi/3];
t=.1*sin(l);
[X,Y,Z]=cylinder(t);
%figure,mesh(X,Y,Z)
figure,surfl(X,Y,Z)
colormap bone
shading interp
axis off
l=[-3:.1:3];
t=1.5+.05*l.^2;
[X,Y,Z]=cylinder(t);
%mesh(X,Y,Z)
figure,surfl(X,Y,Z)
colormap bone
shading interp
axis off
l=[-3:.1:3];
t=3+.1*sin(2*l);
[X,Y,Z]=cylinder(t);
%mesh(X,Y,Z)
figure,surfl(X,Y,Z)
colormap bone
shading interp
axis off
```

Let us analyse the measurement data taken by the inductance sensor from the flour milling rollers and compare them with the ideal profile.

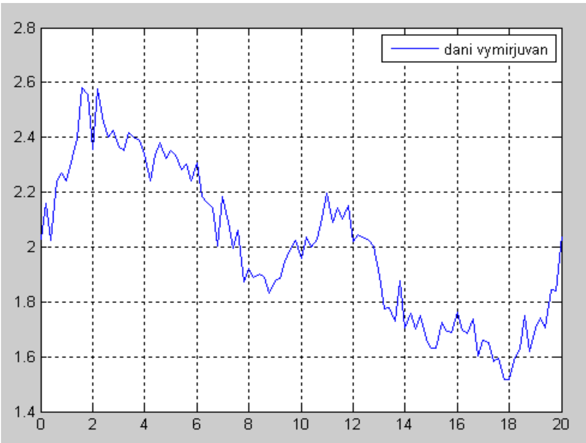

Figure 7: Measurement data.

In Fig. 7 we can see the graph of the measurement of shape deviations (μm) for the flour milling roller recorded by inductance sensor during one roller rotation. Based on the obtained data, the deviation from the roller cross-section roundness can be estimated using the Fourier series expansion of the curve.

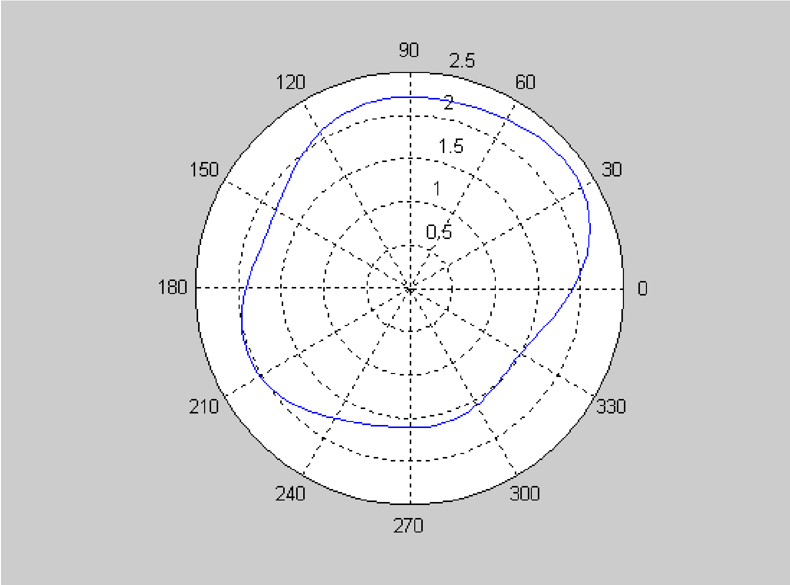

Figure 8: Real cylinder cross-section.

The cross-section of the cylinder obtained as the result of the measurement. Is shown in Fig. 8 Its deviation from roundness is affected by both assembly technology and manufacturing technology. The deviation from roundness is a complex indicator for the cylinder cross-section, which is determined by the set of shape deviations of the actual cross-section from the regular circle shape [14].

The value of non-circularity is taken to be the largest deviation of the actual profile from the adjacent regular circle, which has (for a shaft) the smallest possible diameter and is described around the actual cross-section of the shaft; which has (for a hole) the largest possible diameter and is inscribed in the actual cross-section of the hole [15].

The deviations were evaluated on the basis of spectral analysis by means of MatLab software:

```
dt=.2;
tm=20;
t=[0:dt:tm];
y=2+.3*sin((2*pi/tm)*t)+.2*sin((4*pi/tm)*t)+.1*sin((8*pi/tm)*t);
k=length(t);
for i=1:k
   y(i)=y(i)+.05*randn(1);
end
%y=[1.1 1 1.03 ]
plot(t,y)
grid
legend('dani vymirjuvan')
figure
phi=[0:pi/50:2*pi];
lphi=length(phi)
```

```
r=2+.3*sin(phi)+.2*sin(2*phi)+.1*sin(4*phi)+.1*randn(1);
polar(phi,r);
figure
fmax=1/dt;
df=1/tm;
f=0:df:fmax;
x=fft(y);
%stem(f,abs(x))
f1=-fmax/2:df:fmax/2;
xp=fftshift(x);
l=length(x)
xp1(1:10)=xp(51:60);
amp(1:10)=abs(xp(51:60))
amp=2*amp/l;
amp(1)=amp(1)/2;
subplot(2,1,1)
stem(amp);grid
%axis([0,10,0,1])
dixp=real(xp1);
uxp=imag(xp1);
phxp=atan(xp1);
%stem(f1,dixp);grid
subplot(2,1,2)
stem(phxp);grid
%axis([0,10,-1,2])
r=2+.3*sin(phi)+.2*sin(2*phi)+.1*sin(4*phi)+.1*randn(1);
figure,polar(phi,r);
hold on
r0(1:length(phi))=amp(1);
r1=amp(1)+amp(2)*sin(phi);
polar(phi,r0,'r')
hold on
polar(phi,r1,'g')
```

The result of spectral analysis of the measurement data is shown in Fig. 9.

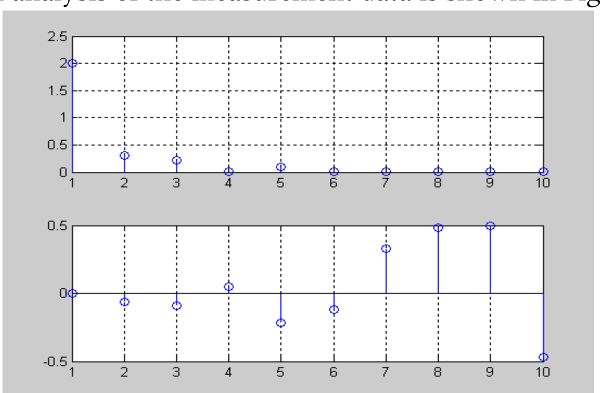

Figure 9: The result of spectral analysis of the measurement data.

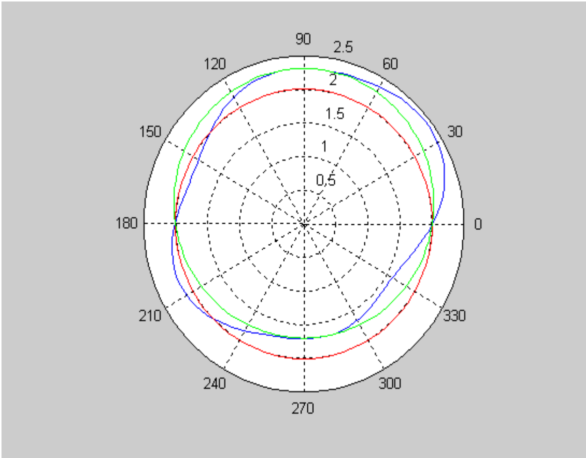

Figure 10: Deviation from the given shape.

In Fig. 10 we can see three main lines that together form the real profile (blue line): the ideal profile is highlighted in red, the displacement caused by misalignmet is represented in green, and the displacement caused by shape deviation is shown in blue. The obtained results and future research in this direction are related to the research given in [16-20].

Conclusion

Applying the demonstrated approach for the analysis of the cylinder cross-sectional profile at different sample lengths, using the data obtained from the above mentioned formulas (1, 2, 3), we can find the coefficients for cone-shaped, saddle-shaped, barrel-shaped and other shape deviations and defects. The versatility of the approach provides prospects for the application of the developed model both in laboratory research and in industrial standardized processes.

Declaration on Generative AI

The authors have not employed any Generative AI tools.

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