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Device for roundness measurement of continuously changing diameter objects

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Abstract
This paper presents a device designed to measure the roundness of objects whose diameters change continuously, such as rolls of paper, plastic film, or thin metal sheets. The device is equipped with four probes to implement a redundant multi-point roundness method. This approach is necessary to accommodate the object's changing conditions, specifically the motion of the center point caused by variations in mass. The device can measure objects with diameters ranging from 100 mm to 750 mm. Validation was conducted using a steel reference disk, which was measured with both the presented device and a Mitutoyo RA-2200 roundness tester. Additionally, measurements of a paper roll with approximately 2500 layers are presented to demonstrate the capability to detect roundness changes during reeling. The device was found to be able to measure the test steel roundness profile within micrometer accuracy which is adequate for the intended application of the device.

Roundness measurement, Multi-probe method, Changing diameter

1. Introduction

Measuring roundness is one of the routine operations in precision metrology. Current devices face significant limitations when applied to large-scale objects or those with variable diameters. Objects such as paper rolls, thin-film plastic rolls, and metal strip coils cannot be accommodated by standard instruments due to their size and dynamic geometry. Consequently, accurate in-process roundness measurement for these materials remains a partially unresolved challenge in the industry.

Previous methods and devices for measuring large objects, such as paper machine rolls employ the multi-probe roundness measurement method. The use of more than one measurement probe is necessary when the object cannot be assumed rigid and rotate around a fixed center point [1]. To separate the center point motion from the object surface at least three probes are needed [2]. Alternative methods exist, which include rearranging the object and/or measurement probe to different angles to achieve the same outcome [3,4].

Typical large scale roundness measurement devices widely used in roll servicing industries use an arch with one, two, three or four radially spaced probes [5]. These applications typically employ sensors such as contacting length gauges, eddy current sensors or lasers. On the other hand, smaller work pieces in laboratory conditions can be measured with roundness testers which often only use single probe but are equipped with a precision spindle to eliminate center point motion. Also, coordinate measurement machines can be used to measure roundness to a certain extent.

This paper describes a device and method to measure objects such as paper roll during reeling which have a constantly increasing diameter. The presented device uses the multi-probe roundness measurement scheme.

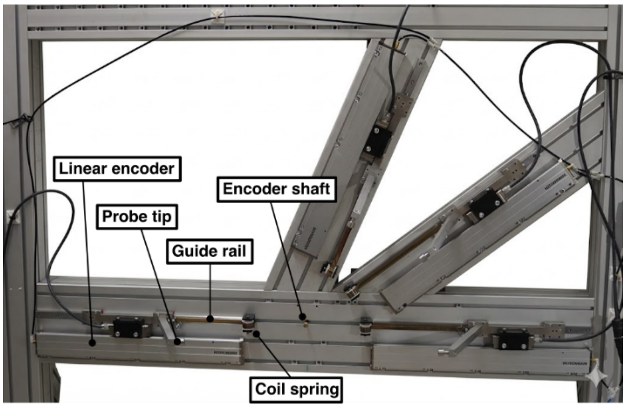

Figure 1. Image of the presented roundness measuring device. The device consists of the four measurement probes attached to linear encoders via linear guide rails. The probes are constantly tensioned against the work piece using constant force springs.

2. Methods

The structure of the device is shown in Figure 1. The device is assembled on aluminum frame with four radially placed guide rails (Hiwin MGNR). Each guide rail has a probe tip riding on a block, which is also attached to linear encoder (Heidenhain LF185C) to detect the block position. A rotary encoder (Heidenhain ROD 480-5000) is used to capture the angular position of the work piece. The blocks are additionally spring loaded with small 20N brass constant force coil springs. The encoder data was captured using Heidenhain EIB741 data acquisition device.

Four measurement probes are used, each attached to the linear guide rail with an angled beam. The four probes are arranged radially around the work piece with nominal angles [0, 38, 67, 180]. These angles provide were adoped as they are a known reliable configuration suggested by Kato [7]. Movement of the probes is recorded by the linear encoders, and the rotary encoder is used to trigger the measurement at equally spaced intervals 5000 times per revolution. Thus, the angular sampling interval between measurement points was 0.072 degrees. Schematic indicating the probe angles and movement of the linear encoders is shown in Figure 2. The device is designed to measure the roundness of objects with diameters ranging from 100 mm to 750 mm.

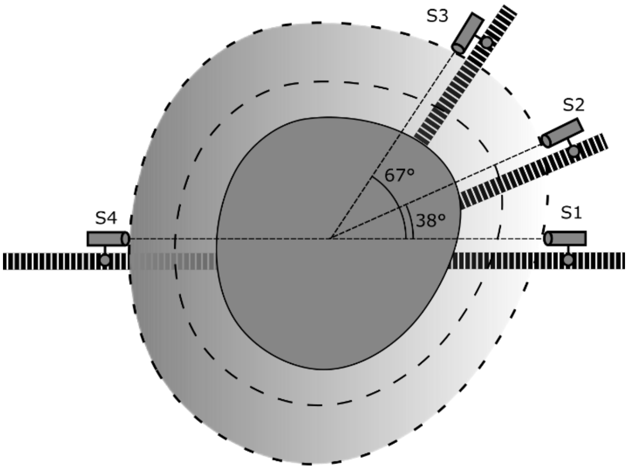

Figure 2. Schematic of the probe arrangement. The probes have maximum moving distance 340mm radially with respect to the measured object. This movement allows the object diameter to increase while the measurement is being conducted, useful for example if the object is a paper roll being reeled.

The regular and hybrid multi-probe measurement processes are relatively straightforward for an object with constant geometry, and the theory has been well-documented in previous studies. Let the displacement of the rotational center in the x- and y-axis and the roundness deviation be denoted by $x(\phi)$, $y(\phi)$, and $r(\phi)$, respectively. The measurement signals can be modelled as:

$$s_{k(\phi)}(\phi) = x(\phi)\cos(\phi_k) + y(\phi)\sin(\phi_k) + r(\phi - \phi_k), \quad (1)$$

where ϕ is the rotated angle of the object, k is the probe index, and ϕ_k is the position of the probe. Jansen et. al. [6] showed that the nth complex Fourier coefficients S_{kn}, x_n , y_n , and r_n of the parameters are related:

$$S_{kn} = x_n \cos(\phi_k) + y_n \sin(\phi_k) + r_n \exp(-in\phi_k), \quad (2)$$

With all the probes, a matrix form equation can be constructed:

$$\mathbf{S}_n = \mathbf{H}_n \mathbf{x}_n \quad (3)$$

$$\begin{bmatrix} S_{1n} \\ S_{2n} \\ \vdots \end{bmatrix} = \begin{bmatrix} \cos(\phi_1) & \sin(\phi_1) & \exp(in\phi_2) \\ \cos(\phi_2) & \sin(\phi_2) & \exp(in\phi_2) \\ \vdots & \vdots & \vdots \end{bmatrix} \quad (4)$$

To solve for $\mathbf{x}_n$, at least three probes are needed. For more probes, $\mathbf{x}_n$ can be solved with the least square method:

$$\hat{\mathbf{x}}_n = (\mathbf{H}_n^T \mathbf{H}_n)^{-1} \mathbf{H}_n^T \mathbf{S}_n \quad (5)$$

For $\hat{\mathbf{x}}_n$ to not be sensitive to relatively small changes in $\mathbf{H}_n$ and for reducing harmonic suppression, $\mathbf{H}_n$ should be well-conditioned [6]. This depends on the angles ϕ_k. These can be chosen so that suppression is reduced for harmonics of interest. For example, [7] suggested a reliable combination of angles for four-probe method being [0, 38, 67, 180], which is used in our device.

The zeroth and first coefficients of r can be set to 0, since they are the average offset and the eccentricity, respectively. These properties are not of interest in roundness measurement.

An alternative approach to extract roundness measurement from the probe signals is the hybrid method, where subsets of the harmonics are solved from different combinations of the probes, before the individual harmonics are assembled to obtain the full range [8]. For example, from four probes with the angle combination above, the even harmonics can be calculated from two opposing probes, and the odd harmonics can be calculated from three non-opposing probes.

For an object with increasing diameter, e.g., a winding paper roll, the probe signals are the sum of the roundness profile for each revolution and the change in radius (or diameter). For the case of the winding paper roll, this change in radius is approximately linear as layers of paper are approximately the same thickness. This linear increase in radius seen in the probe signals is then easily removed by detrending the signals for example by subtracting a least-squares fitted line function.

A precision-manufactured steel disk (240mm diameter, 10mm thick) was used to validate the accuracy of the measurement device. The setup of the disk in the roundness measuring device is depicted in Figure 3. The disk was mounted on the evaluated roundness tester in an overhung-rotor configuration, supported by two ball bearings on one side. Measurements were taken while slowly rotating the disk using a small DC motor and a belt-pulley drive. To minimize friction and suppress chatter, the disk surface was lightly coated with synthetic lubricant. The same disk was then mounted, centered, and measured on a Mitutoyo RA-2200 roundness tester to give comparison. Measurement repeatability of the proposed device was evaluated by calculating the standard deviations over all angular positions over 40 rotation cycles.

Figure 3. Reference steel disk mounted on the presented roundness measuring device. The disk was rotated with small electric motor and supported by two ball bearings. Encoder is directly attached to the steel disk.

A small paper-roll sample was used to demonstrate the variable-diameter operation of the roundness-measuring device. The paper was wound onto a cardboard core with an initial diameter of approximately 100 mm using a Tapio laboratory paper analyzer. Winding was performed at a slow speed. The measurement probes tracked the paper surface and moved radially outward from the center as the roll diameter increased. Final diameter of the paper roll was around 600 mm.

3. Results

Figure 4 illustrates the displacement signals obtained via TSA. To characterize measurement repeatability, uncertainty intervals are included, representing the standard deviation over 40 cycles for each angular position. The actual standard deviations are also shown as function of rotation angle below each displacement figure in Figure 4. The average and maximum values of these standard deviations are shown in Table 1.

The roundness profile of the steel disk is presented in Figure 5. The depicted profiles were calculated with the filter level set to 1024 undulations per revolution. The profile measured with the presented device is overlaid with a profile measured with the Mitutoyo RA-2200. The first 50 harmonics of both the RA-2200 and presented device are shown in Figure 6.

The roundness profile for different layers of the sample paper roll measured with the device is depicted in Figure 7 as a heatmap for each layer separately.

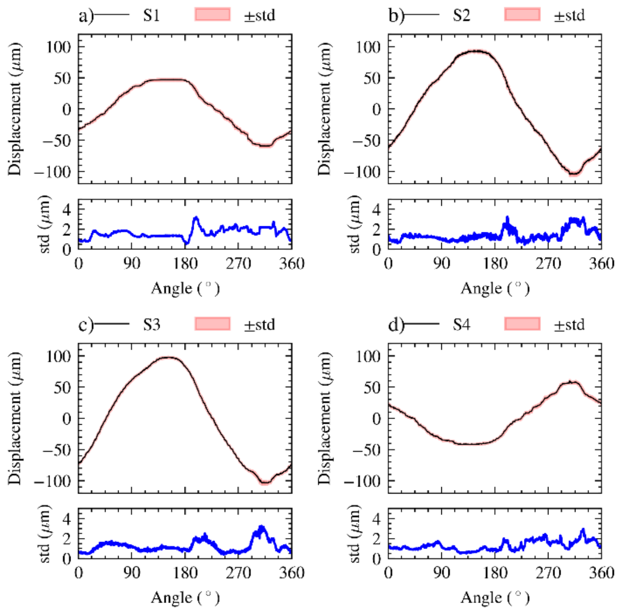

Figure 4. Displacement readings for the four probes averaged over 40 revolutions. Red highlight depicts the standard deviation limits around the mean and small figures below each figure indicates the exact standard deviation as function of rotation angle.

Table 1 Average and maximum values for standard deviation of displacement measurements from the steel disk over 40 revolutions.

Probe	Average std (μm)	Max std (μm)
1	1.6	3.2
2	1.4	3.3
3	1.2	3.3
4	1.3	3.0

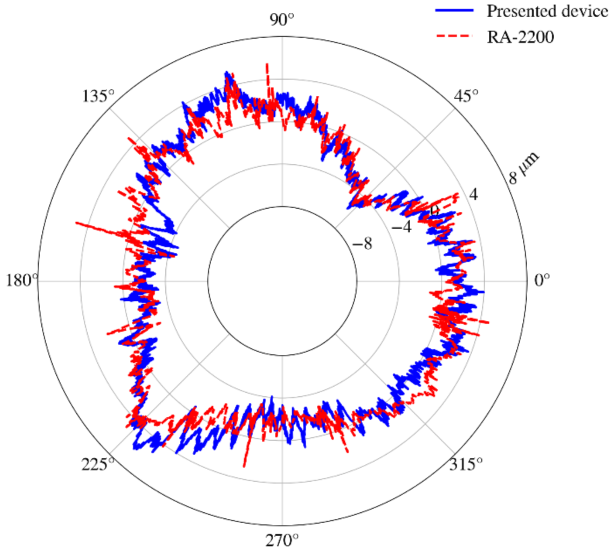

Figure 5. Roundness profiles of the test disk measured with the presented device and the RA-2200 roundness tester.

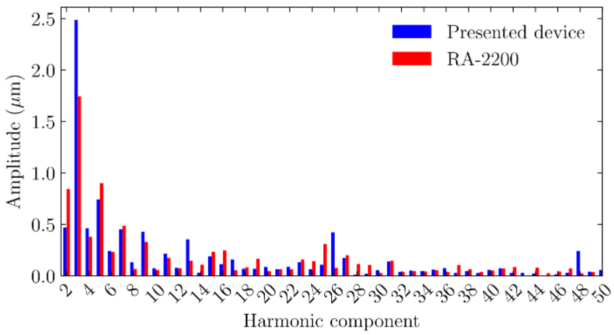

Figure 6. Amplitudes for different harmonics of the roundness profiles measured from the steel disk with the presented device and the RA-2200. Only the first 50 harmonics are depicted in this figure.

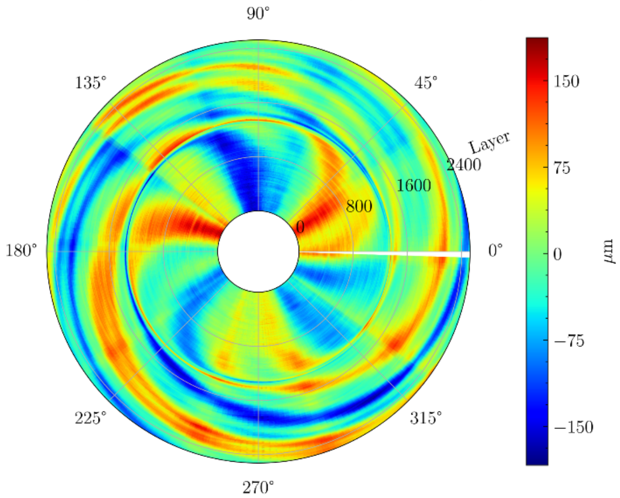

Figure 7. Heatmap of roundness profiles for a reeled small paper roll. The radial axis is the layers of paper, and the color illustrates the roundness profile of each layer. The first harmonic component has been filtered out.

4. Discussion

A device for measuring roundness of variable diameter objects was shown in this paper. The applicability of the device concept was studied and a preliminary validations and tests are presented.

The device showed good repeatability with the test disk. The maximum standard deviation among all probes was only 3.3 µm, with the best being 3.0 µm. Figure 4 shows that the test disk had eccentricity, most likely due to lack of alignment. The eccentricity was well compensated away using the multiprobe method. Some variability in the measurement standard deviation at different angles was detected. All sensors showed increased variability at around 200° and 330°. These angles appear to have some slope in runout, which could lead to a change in contact force and affecting friction. A change in friction force due to probe kinematics might explain the increased uncertainty. Nevertheless, the standard deviations are quite small. Validation measurement performed on a steel disk showed good agreement between commercial RA-2200 instrument and the presented device. Deviations in the roundness profile presented in Figure 5 are minor and within few micrometers from each other. The manufacturer indicated that the accuracy of the linear encoders is 2 µm, which can explain at least some of the deviation to the reference profile. Other error source in the measurement device can be attributed to Abbe error which is result from bending of the probe supporting beam and slack between linear rails and the sliding blocks. Additionally, the test disk was likely measured from slightly different axial position leading to small surface imperfections being different thus causing differences in the roundness profiles.

Observing the harmonic components of the roundness profiles in Figure 6, a deviation between reference measurement can be noticed at components 3, 13, 26 and 48. Possible reasons for the differences can be error in probe angles, radial alignment of lack of stiffness of the probe beams [9], or any of the above detailed error sources. Most of the harmonic components are relatively similar, establishing that the presented device is indeed capable of estimating the roundness harmonics with good accuracy.

A key contribution of this paper is handling the continuous change in diameter without interrupting the measurement. By using a rotary encoder for angular synchronization and four probes for center-motion separation, the device isolates roundness from center displacement and monotonic radius growth. Advantage of the design presented is that it allows harmonic content of true roundness to be tracked across successive layers.

The paper roll experiment captured roundness profile across approximately 2500 layers of paper shown in Figure 7. Unlike the steel test disk, the roll exhibits significantly larger geometric variation, which relaxes the need for sub-micrometer accuracy in this application while still requiring robust separation of center motion.

Each layer could be measured only once, causing more noisy estimates for the roundness as synchronous averaging could not be used. Since paper is compressible, local compaction under probe contact can possibly affect the measurement readings. Surface slip or slight creep during reeling can change the phase of the roundness features between layers.

Overall, the device produced stable, interpretable roundness profiles over thousands of layers, allowing visualization of how the geometry of the roll changes as it is reeled. This capability is directly relevant for diagnosing winding errors, such as out-of-roundness build-up.

5. Conclusions

A four-probe, encoder-synchronized roundness device was developed for large objects with continuously changing diameters (100–750 mm). By applying multi-probe roundness algorithms and suppressing mean radius drift, the system separates roundness from center-point motion during reeling.

Validation on a steel disk confirming the device's capability to recover roundness harmonics accurately. Observed deviations at specific harmonic orders are consistent with prototype mechanical and alignment limitations and can be reduced by improved calibration and stiffness. Measurements over ~2500 paper layers demonstrated the device's ability to track roundness evolution. Despite material compressibility and occasional phase changes due to surface slip, the system revealed meaningful harmonic trends and layer-wise deviations that are substantially larger than those of the test disk. The device is suitable for analyzing paper roll winding errors, providing a practical pathway to correlate harmonic content with process conditions. Future work will focus on improving probe stiffness, reducing rail friction and investigation roundness of paper rolls. More thorough investigation of the measurement device errors should still be done to quantify device limitations.

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