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Method for *in situ* runout measurement of large rolls

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Abstract. This work presents a method for *in situ* runout measurement of large cylindrical rotors, such as paper machine rolls. The method is based on an acceleration sensor attached to a sliding probe which is held against the rotating surface. Measured acceleration signal is averaged and double-integrated using a computer to get radial surface displacement, i.e., runout. Laboratory tests showed that, with this method, it is possible to measure runout with accuracy in the scale of a few micrometers. Measurements showed that, by using this method, it is possible to detect and measure phenomena like thermal bending or so-called polygon effect in running thermo rolls. These phenomena have not been reported to have been measured *in situ* before.

Key words: paper machine, roll geometry, deformation, roundness, displacement.

1. INTRODUCTION

In a paper machine there are dozens of rolls for various tasks. In the calender the paper web is pressed between a pair or multiple pairs of rolls under heavy load and high temperature to give the paper desired structure and finish. Geometrical and rotational errors of the rolls will be copied on the paper web and may cause several different calendering problems like profile problems in gloss, caliper or moisture and barring. Errors may also weaken the runnability of the paper machine. At high machine speeds and with wide paper webs, high demands exist on the dynamic properties of rolls.

Errors in the roll geometry and rotation appear as a runout. The runout is a very practical and directly measurable parameter, which is defined as the movement of the surface of a rotating object in relation to a fixed datum. Traditional displacement measurement methods, such as dial gauge or optical, capacitive and eddy current sensor, can be used to detect runout [1–3]. The runout of a paper machine roll is caused, for example, by the roundness error, eccentricity, unbalance, initial curvature, uneven thermal expansion and errors in the bearing [4].

However, the measurements of the rolls are usually made in workshop conditions during the normal maintenance operations. The roundness measurement of the roll, for example, is typically made in the grinding machine at a low speed. Only with special workshop test equipment the dynamic behaviour of a roll can be measured also at higher speeds [5]. High temperatures can not be reproduced in the workshop and the rolls are usually mounted on the support of the machine tool. To find out the true dynamic behaviour of the rolls requires that the measurements should be made in the real operating conditions during the papermaking process. Current approach to measure the roll vibration through the bearing houses does not provide enough information about the behaviour of the roll body during the operation and about the causes for the vibration.

In the *in situ* measurements the main difficulties arise from the support and the fixture of the sensors. The sensor must be located close to the surface of the roll and yet the support of the sensor must be rigid. Some sensors also require on-site calibration to the measured surface. The vibrations conducting through the sensor support may distort the signal, which calls for actions to compensate the own movement of the sensor from the signal. High surface velocities restrict the usage of traditional contact sensors and combined with the shiny roll surface makes also the laser optic methods practically unusable.

In this study, a device and a method for the *in situ* measurement of a roll shell runout, based on the radial acceleration measurement of the surface, is described. The objective of this research is to confirm experimentally that with the developed device and method it would be possible to measure the runout of the paper machine rolls in the process conditions with an adequate accuracy. A number of measurements were done to demonstrate the applicability of the method. This paper is based on the doctoral thesis of P. Kiviluoma [6].

2. METHODS

2.1. Device

The device (Fig. 1) consists of a polymer-based slide pad, which is in contact with the moving surface, an accelerometer, attached to the slide pad and an extension handle for the user to hold the device on the target surface. During the measurement, the operator positions the slide pad on the surface of the target (Fig. 2) and keeps the probe in contact with the target for the duration of the measurement. The slide pad self-aligns itself on the target surface. The acceleration signal, along with a trigger signal, is collected using a PC-based data acquisition system (Fig. 3).

There are only few references to slider-type measurement of runout in the literature [7,8]. No results of these measurements have been presented. Neither the structure nor operational principles of the devices were described in detail.

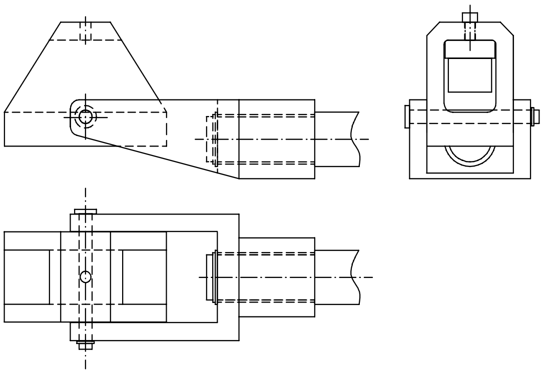

Fig. 1. The structure of the measurement device.

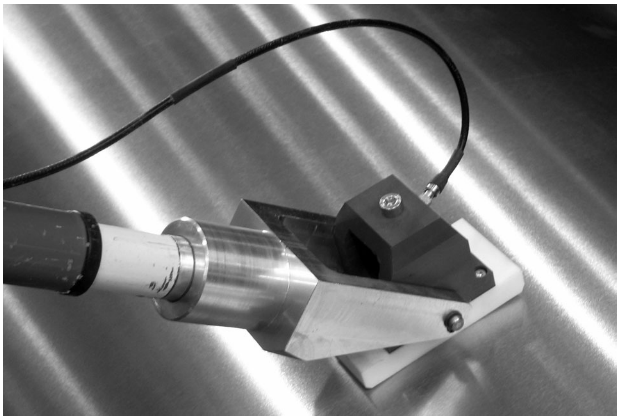

Fig. 2. The device on the roll surface.

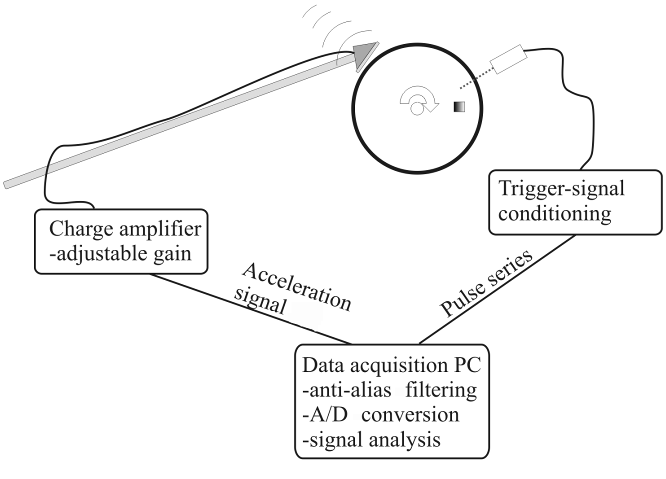

Fig. 3. Components of the measurement system.

2.2. Signal processing

The accelerometer used with the device is a piezoelectric acceleration sensor Brüel & Kjaer type 4381 with Nexus 2692 OI4 charge amplifier. The data are acquired using a 14-bit analogue-to-digital board, located in a personal computer with a sampling rate of 10 kHz. An analogue 2.5 kHz low-pass filter is used before sampling to avoid aliasing. The measurement is triggered using a laser-type photoelectric sensor (Omron E3C-LD11) with reflective tape glued on the roll axis or surface. The duration of one measurement is typically 10 s. After each measurement the data are saved to a file.

The analysis of the measured data is based on the synchronized averaging of the displacement (Fig. 4). As a result of the trigger analysis, the rotation frequency of the target and an average number of measured points per revolution are found out. The acceleration data are divided to sequences of one revolution using the trigger signal. The data are resampled and a certain number of equally spaced points are interpolated for each revolution. Finally, the averaged data are integrated twice using Fast Fourier Transform (FFT) to get the displacement signal. FFT is also used to analyse the harmonic content of the runout.

Sinusoidal linear movement can be described as

$$x(t) = A \sin \omega t, \tag{1}$$

$$v(t) = \dot{x}(t) = \omega A \cos \omega t, \tag{2}$$

$$a(t) = \ddot{x}(t) = -\omega^2 A \sin \omega t, \tag{3}$$

where x is displacement, A is the displacement amplitude, ω is angular velocity ($2\pi f$) and t is time. From Eqs. (1) and (3) it is easy to see that it is

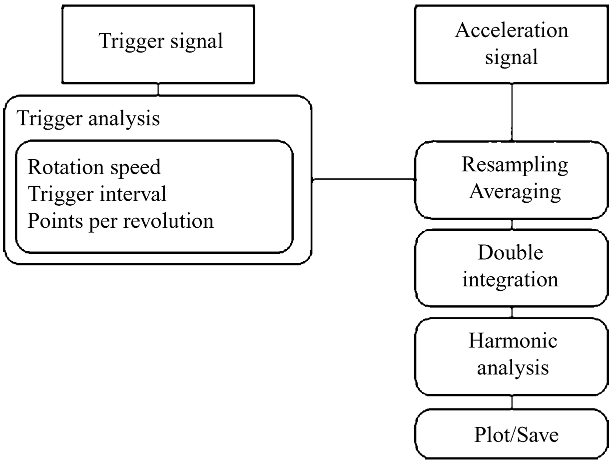

Fig. 4. Signal flows in the measurement.

possible to obtain displacement simply by dividing the acceleration by the negative angular velocity squared

$$x(t)=\frac{a(t)}{-\omega^2}. \tag{4}$$

In the frequency domain, the integration can be done by diving each spectral line by corresponding angular velocity squared

$$x(\omega)=\frac{a(\omega)}{-\omega^2}. \tag{5}$$

2.3. Measurements

A series of laboratory and *in situ* measurements were made to study the performance of the method in measuring the runout of cylindrical and rotationally symmetrical objects. First, a series of laboratory measurements for a workpiece with a known geometry were made to study the accuracy and functionality of the method. A test disk was measured, in addition to the slide pad device, with a Taylor Hobson Talyrond 31C roundness geometry measurement system, a LVDT probe and an eddy current sensor. Secondly, a series of *in situ* measurements in paper mills were made to study the usability of the method in actual cases in the measurement of the calender thermo rolls. There were two main effects to look for in the roll behaviour: thermal bending [9] and possible undulations on the roll surface in the locations where the heating bores exist (so-called polygon effect) [10].

3. RESULTS

3.1. Laboratory measurements

The test disk was rotated in a lathe at a slow rotation speed (0.3 Hz) and the runout was measured with a contact-based LVDT sensor and a non-contact eddy current sensor. The lowest 10 harmonics of the runout, are compared with the lowest 10 harmonics of the roundness in Fig. 5.

In Fig. 6 the first 10 harmonic components of the runout, measured with the eddy current sensor at four different rotation frequencies, are depicted. The result of the slide pad measurement is shown in Fig. 7.

In Fig. 8 the runout is depicted as a displacement around the circumference of the disk.

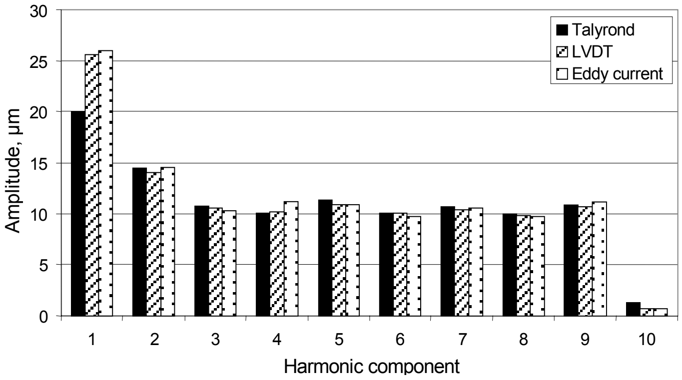

Fig. 5. Roundness measurement (Talyrond) compared with LVDT and eddy current runout measurements.

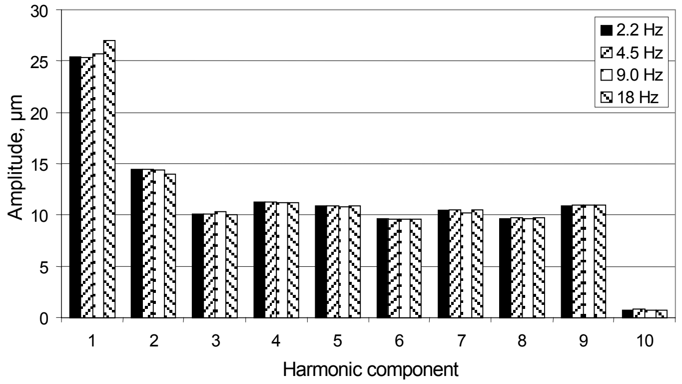

Fig. 6. Eddy current runout measurements at different rotation frequencies.

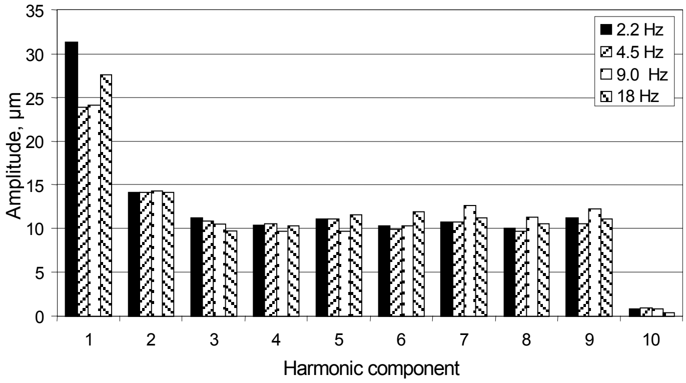

Fig. 7. Slide pad runout measurements at different rotation frequencies.

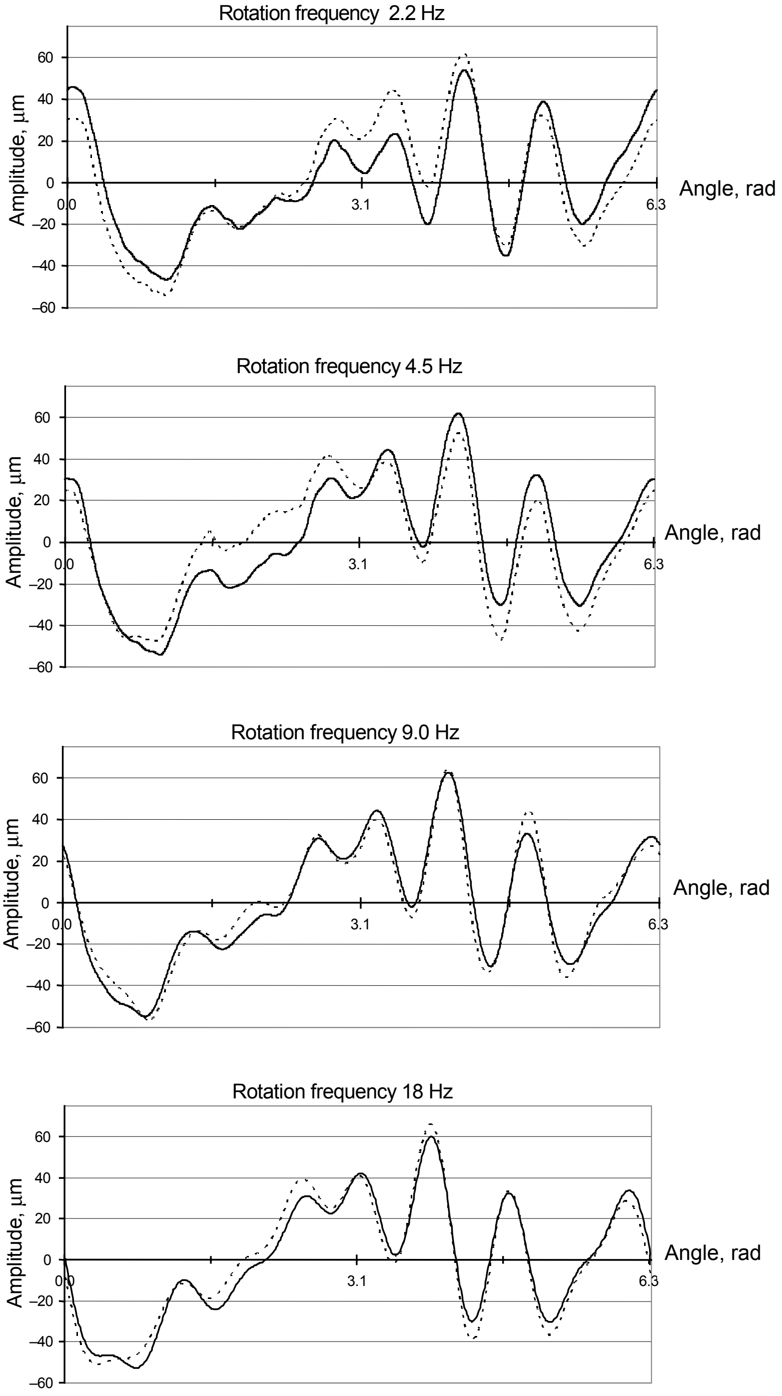

Fig. 8. Runout measured with slide pad (continuous line) and eddy current (dashed line) methods at rotation frequencies of 2.2, 4.5, 9.0 and 18 Hz.

3.2. *In situ* measurements

The runout of a cast iron thermo roll at different temperatures of the heating oil is represented in Fig. 9. The runout was measured at nine cross-sections. The rotation frequency of the thermo roll was 5.8 Hz.

Figure 10 shows vibrations up to 50 Hz, measured at a calender thermo roll support using acceleration sensors. The roll rotation frequency of 5.8 Hz and especially its 2nd (11.6 Hz) and 7th (40.6 Hz) multiples can be detected. For comparison, the vibration spectrum of the slide pad measurement at the middle of the roll is shown in Fig. 11.

The 1st harmonic components of the runout of five identical forged steel thermo rolls of a multinip calender at nine cross-sections are represented in Fig. 12. Figure 13 shows the 24th harmonic component of the runout. The rotation frequencies of the thermo rolls were 5.3 Hz.

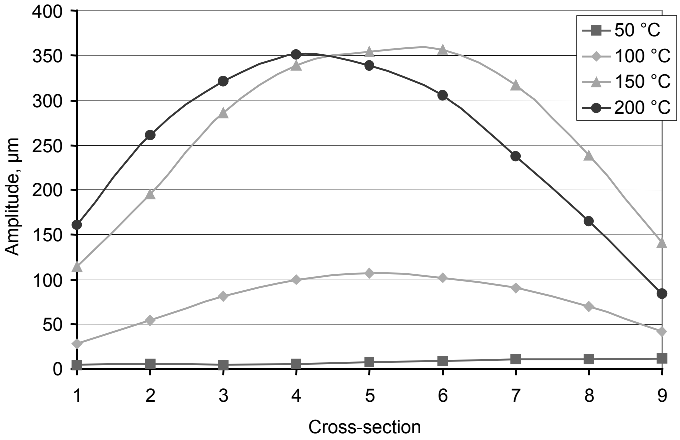

Fig. 9. Thermo roll runout at different temperatures.

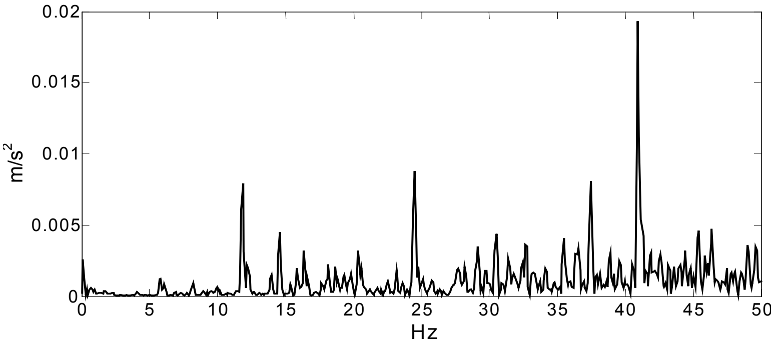

Fig. 10. Vibration spectrum measured at the roll support.

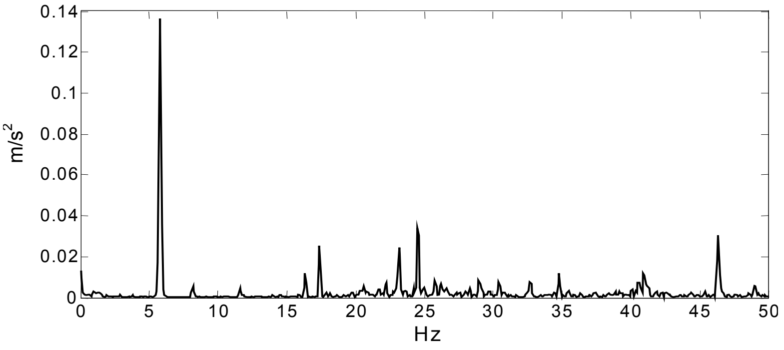

Fig. 11. Vibration spectrum measured at the middle of the roll.

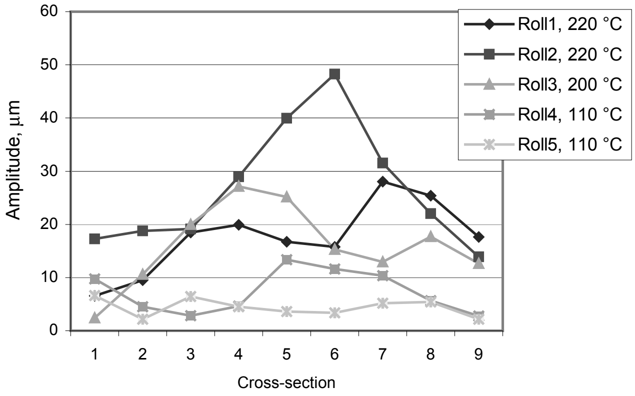

Fig. 12. The 1st harmonic components of the runout of multinip calender thermo rolls.

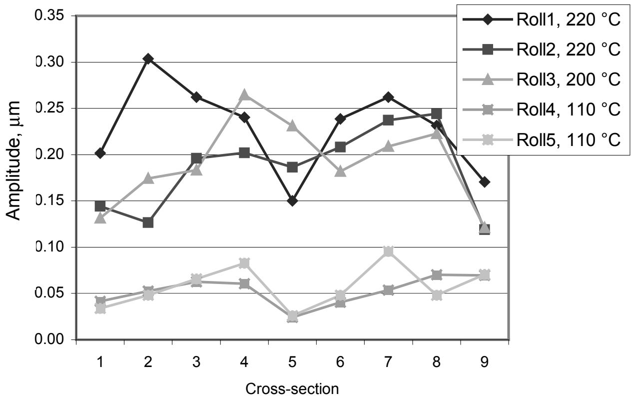

Fig. 13. The 24th harmonic components of the runout of multinip calender thermo rolls.

3.3. Measurement uncertainty

The measurement method is based on the principle that the operator holds the device by hands during the measurement. This will naturally add uncertainty to the measurement. The uncertainty of the method is, to some extent, dependent on the frequency. At low frequencies, that is, at low rotation frequencies and lower harmonic components up to 2 Hz, the uncertainty of the method is more than 10%. This is mostly affected by the weak response of the accelerometer at low frequencies, detected by the sensor calibration. Possible movement of the operator will as well be seen at low frequencies. It is not advisable to use the method at frequencies this low. Other significant factors, affecting the measurement uncertainty, are the ambient temperature, possible tilting of the measurement head and factors related to the measurement instruments and signal processing. The estimates for these uncertainties are found out experimentally by a series of laboratory measurements and from the instrument specifications in accordance with the ISO Guide to the Expression of Uncertainty in Measurement [11]. The combined standard uncertainty of the method for the frequencies from 2 to 5 Hz is 4.5% ($k = 2$) and for the higher frequencies 3% ($k = 2$).

4. DISCUSSION

The slide pad measurement of the test disk gave reproducible results at different speeds. The deviation was largest at lower frequencies, especially at the 1st harmonic component. The comparison between the slide pad and eddy current measurements showed that the differences between the methods were small, within a few micrometers, for the most of the harmonic components. The shape of the displacement curve as a function of the circumferential angle showed that the phase of the runout was also measured correctly.

The measurements in the paper machines clearly verified the phenomena that have been described in the literature. The tests proved that the slide pad method has many advantages compared with the traditional displacement measurement methods. The device is easy and fast to take into operation, no calibration for a specific target is needed and the manoeuvrability of the device is good. In some cases, it is possible to replace multiple conventional sensors with a single device, assuming that the measurement conditions between the measurements remain unchanged.

The tests indicated that the accuracy of the method is in the micrometer scale. The accuracy is adequate for the purposes the method is designed for. Notably, at the rotation frequencies of the rolls typical in the paper industry, i.e., from 5 to 10 Hz, the accuracy is good.

The slide pad method makes it possible to measure the movement of the whole roll body instead of the roll support alone. This opens up new possibilities to study the behaviour of the rolls during the process. The *in situ* runout measurement makes it possible to detect and understand the dynamic behaviour of the rolls and the causes of it. The method can be used, for example, for applications related to problem solving in the paper quality and runnability issues, for online geometry measurement and shape correction, for balancing and for validation and verification of theoretical models. Information about the run-time geometry and behaviour can be used for the planning of the future maintenance operations.

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Suurte rullide viskumiste kohapealne mõõtmismeetod

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On esitatud kohapealne mõõtmismeetod suurte silindriliste rootorite, näiteks paberimasina rullide jaoks. Meetod põhineb libiseva sondi külge kinnitatud ja vastu pöörlevat pinda toetuva kiirendusanduri kasutamisel. Mõõdetud kiirenduse signaal on keskmistatud ja kaks korda integreeritud, et arvutada radiaalpinna siire ehk viskumine. Antud meetodiga laboris läbi viidud katsed on näidanud, et mõõtmisi on võimalik teostada mõnemikromeetrise täpsusega. Mõõtmised näitavad, et antud meetodi rakendamine võimaldab kindlaks määrata selliseid nähtuseid, nagu soojusvõnkumine või nn polügooniefekt termorullide kasutamisel. Uurimusi nende nähtuste mõõtmiste kohta pole autoritele teadaolevalt eelnevalt avaldatud.