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EFFECT OF WALL THICKNESS VARIATION ON DYNAMIC GEOMETRY OF ROTATING CYLINDER

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Abstract: *The dynamic behavior of typical paper machine roll is often characterized by unbalance and bending stiffness variation. Relatively thin walled cylindrical structure brings up different dynamic phenomena such as geometry change as a function of rotating speed. The geometry change, which is typically caused by the manufacturing inaccuracy and material inhomogeneity, is often misinterpreted as either unbalance or half-critical vibration, and it is more prominent in rolls with large diameter relative to the shell thickness. The wall thickness of a roll was measured using an ultrasonic device. A FE model was built to analyze the effect of thickness variation on the dynamic geometry changes. Measured wall thickness showed significant variation, and the FE analysis pointed out that the thickness variation can be the cause for the dynamic geometry change.*

Key words: paper machine, roll geometry, roll dynamics, deformation, dynamic roundness.

1. INTRODUCTION

This research is based on observations on quality issues of light weight coated magazine paper (LWC) [1,2]. The wave length of harmonic coating grammage variation was found to be in synchronization with half of the perimeter of a backing roll in a blade coating station as shown in Figure 1. The coating grammage and gloss variation exceeded acceptable values. This measured variation occurs at whole running speed range of the paper machine. In addition, the variation seemed to increase as a function of running speed.

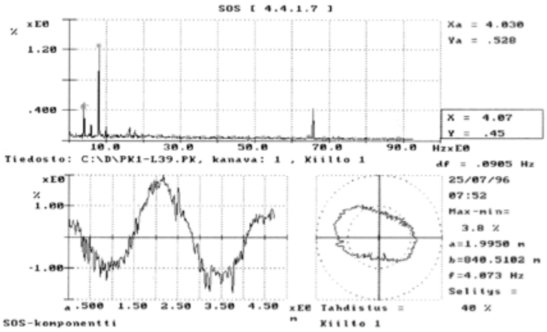

Fig. 1. A backing roll of a coating station is analyzed to be the most significant source for quality variation of light weight coated LWC paper in machine direction. [3]

The dynamic behavior of a typical rotating shaft is often characterized by unbalance [4,5] and bending stiffness variation [6,7]. Unbalance can be observed as a vibration component at rotating frequency. Unbalance causes bending of a flexible rotor as a function of rotating speed and it excites excessive vibration when rotation frequency and natural frequency coincide.
Asymmetry of paper machine rolls, i.e. asymmetry of inertia moments I_x and I_y is causing bending stiffness variation of the roll. Bending stiffness variation is found to be one cause for half-critical vibrations. At half critical speed i.e. the rotating frequency which is only 0.5 times the natural frequency the harmonic excitations twice per rotation cause excitation at the resonance frequency. This frequency corresponds the wavelength of the discovered grammage variation. In typical

cases resonance vibration occurs on a relatively narrow frequency band; therefore this resonance vibration phenomenon does not explain the observed behavior in paper quality variation. In most cases, this vibration problem has been tackled with improved manufacturing technology.

In the studied case, run-out measurements carried out by one displacement sensor show increasing of the 2nd harmonic component of the run-out as a function of running speed to the power of two. The measured behavior is somewhat similar to the deflection of a flexible roll as a function of running speed caused by unbalance.

A typical balancing machine with a run-out measurement system cannot be used to analyze the cause of the run-out behavior. Run-out consists of two components, i.e. run-out is a sum of a geometry error profile and rotational error motion of the rotor axis. These basic components cannot be distinguished from each other with a simple measurement setup using only one measurement sensor. From earlier studies [1,2,3] it was shown that the geometry of a roll is not perfect after grinding, but a varying amount of irregularities exists in the roundness profile of a roll. The original hypothesis was that the geometry of a rotating cylinder is not constant, but changes as a function of i) running speed, ii) mechanical and iii) thermal loading conditions. In this study, the focus is on the effect of running speed though the technology may as well be adapted to studying mechanical and thermal loads.

2. MATERIAL AND METHODS

2.1 Ultrasonic measurement

The ultrasonic measurement can be used for different purposes to analyze material structure. Ultrasound is characterized as sound with frequency over 20 kHz. Precision ultrasonic thickness gages usually operate at frequency range of 0,5…100 MHz. Typically, lower frequencies are used to optimize penetration when measuring thick, highly attenuating, or highly scattering materials. For measuring the thickness of a paper machine roll made of steel the applicable frequency range is about 1…10 MHz, which optimizes the resolution and penetration. [8]

A pulse-echo ultrasonic thickness gage determines the thickness of a part or structure by accurately measuring the time required for a short ultrasonic pulse generated by a transducer to travel through the thickness of the material, reflect from the back or the inside surface, and be returned to the transducer (Figure 2). The measured two-way transit time is divided by two to account for the down-and-back travel path, and then multiplied by the velocity of sound in the test material. The result is expressed as:

$$s = \frac{v \cdot t}{2},$$

where s is the thickness of the work piece, v is the velocity of sound waves in the material and t is the measured round-trip transit time.

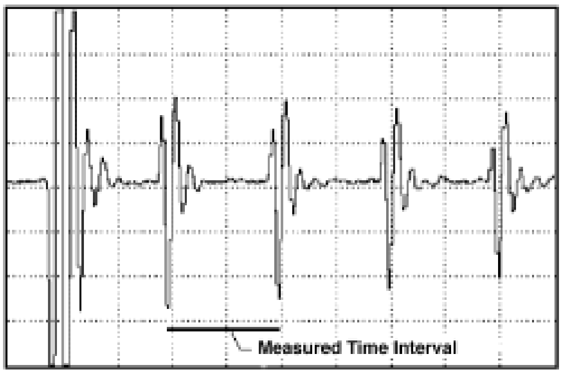

Fig. 2. Typical echoes from an ultrasonic measurement with little damping in the material. The 1st echo is the sensor surface, the 2nd echo is the outer surface and the 3rd echo comes from the backside wall of the measured object.

Continuous on-line ultrasonic thickness gaging is done by coupling the sound energy into the test piece through a water column generated by a squirter.

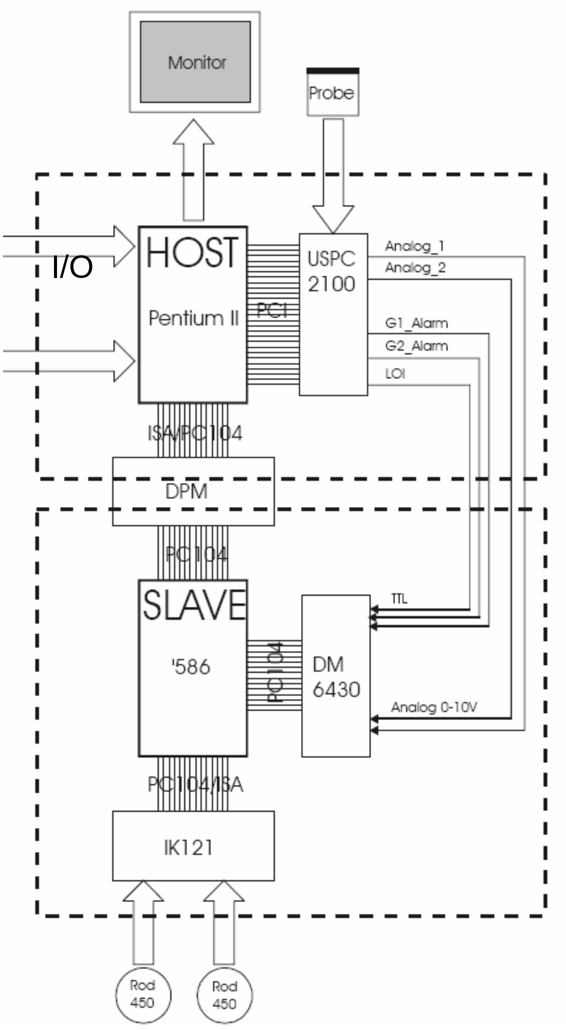

Fig. 3. Ultrasonic measurement system consists of two computers which share information through dual port RAM (DPM). The host computer is used for setting up the measurement and the ultrasonic measurement unit USPC2100 while the slave computer is saving the measurement data from USPC2100 and two ROD450 position sensors to map the data. [9]

The measurement system (Figure 3) comprises position sensing devices. The rotational angle of the roll and the axial position of the ultrasonic sensor were measured by an incremental rotary encoder Heidenhain ROD450. Wall thickness measurements were carried out by Krautkrämer USPC2100 ultrasonic PC-board, which is attached to a bus of the PC. The used squirter probe Krautkrämer H5KF operates at 5 MHz. [9]

Ultrasonic gage was calibrated by setting the sound velocity with respect to the material being measured. A calibration block with known thicknesses was used. measurement uncertainty was estimated to be less than ±0.1 mm.

In this study, the measurement is carried out in a grinding machine and the transducer is fixed on the tool carriage. The transducer is aligned perpendicular to the measured surface and the setup is steady during the measurement. The welding seam of the roll shell might give false readings, because the inner surface is not machined after welding.

2.2 FE-analysis

In order to find out the significance of roundness errors due to normal tolerances in wall thickness a roll is FE modeled.

The FE model used in this study does neither take into account the measured wall thickness distribution nor the end plate support. The wall thickness variation is simplified by the allowed tolerances of the inner wall roundness. FE analysis is done only for the cross-sections, only. The FE model is not end supported and the inner surface profile is assumed to be the same for the whole cylinder.

The cross-section of the outer surface of a cylinder is an ideal circle (D=2188 mm), nominal wall thickness, t=30 mm. The material of the cylinder is cast iron (E=150 GPa, v=0.33, ρ=7000 kg/m^3). The analysis is performed by variation of web speed (0, 1200, 1500 and 1700 m/min) and inner surface profile errors for harmonics 2, 3 and 4 one at a time (A_2=0.5, 1.0 or 2.0 mm, A_3 and A_4=0.25, 0.5 or 1.0 mm). In the model the cross-section rotates around the geometric center of the outer surface. The centrifugal forces are distributed according to the mass distribution and corresponding rotation radius. Each analysis consists of one harmonic of the inner surface profile, only (A_2, A_3 or A_4). The run-out profile of the outer surface is therefore the roundness error.

The FE analysis is performed using conventional 24 degrees of freedom 8-node brick elements. Mesh consists of 64 elements in hoop and 3 elements radially in the cross-section resulting in 512 nodes, 192 elements and 1536 degrees of freedom. The FE model is constrained on the plane of the cross-section. The analysis is performed in Matlab 6.1 using code based on linear structural FEM-FEA. [10]

3. RESULTS

3.1 Wall thickness

Wall thickness variation was measured as a spiral measurement on a grinding machine. With a pitch of 10 mm/rev the measured matrix was 1024 x 690 points, hence a total of 720 000 measured points were acquired. The slightly low-pass filtered measurement result is shown in Figure 4.

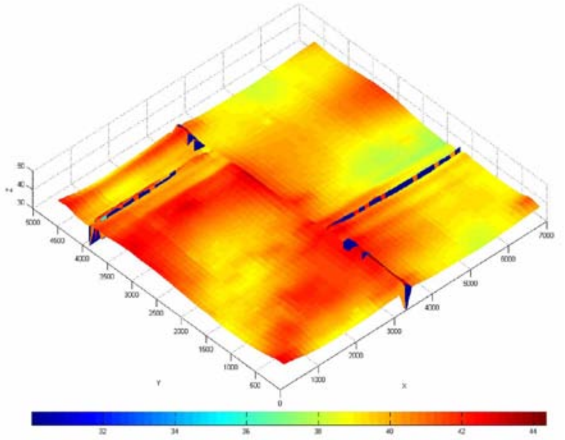

Fig. 4. Wall thickness of a measured roll varies in the range of 37...43 mm without welding seams.

The measured thickness values were in the range 37...43 mm welding seams excluded. It was hard to determine the material thickness accurately at welding seams, because the back wall echo was scattered.

The roll was welded from two rolled cylinders with one radial welding seam close to the lengthwise center of the roll. Also, there were two axial welding seams on the opposite sides of the roll shell.

The most prominent component in wall thickness variation was the second harmonic component, i.e. oval geometry. The roundness error of the outer surface is typically less than ±20 µm, hence the wall thickness variation comes from inner surface geometry. The FFT analysis showed the average value of 2nd harmonic (ovality) component of wall thickness variation was about 2 mm. The other shorter wavelength components were negligible.

In this study, only the mean value of the error component was used to find proper initial values for FE analysis. The welding seam is not modeled and therefore the effect of the welding seam is not analyzed. Because of the manufacturing technology the welding seam and the geometry of the roll are related so that the basic harmonic components are typically "phase locked" with the seam.

3.2 FE-Analysis

The cylinder tube was analyzed using shell thickness variation component values derived from the thickness measurement data and web speeds of operating speed range up to 1700 m/min. The results are shown in Figure 5. Each graph consists of the simulated data from three analyzed amplitudes of error for the harmonic components of thickness variation.

For example, 1 mm of systematic thickness variation component at 2nd harmonic (oval inner geometry) results in dynamic geometry change of about 2 mm. The dynamic geometry changes with 3rd and 4th harmonic variation components were 0.3 mm and 0.09 mm, respectively. The dynamic variation component increase as a function of speed to the power of two.

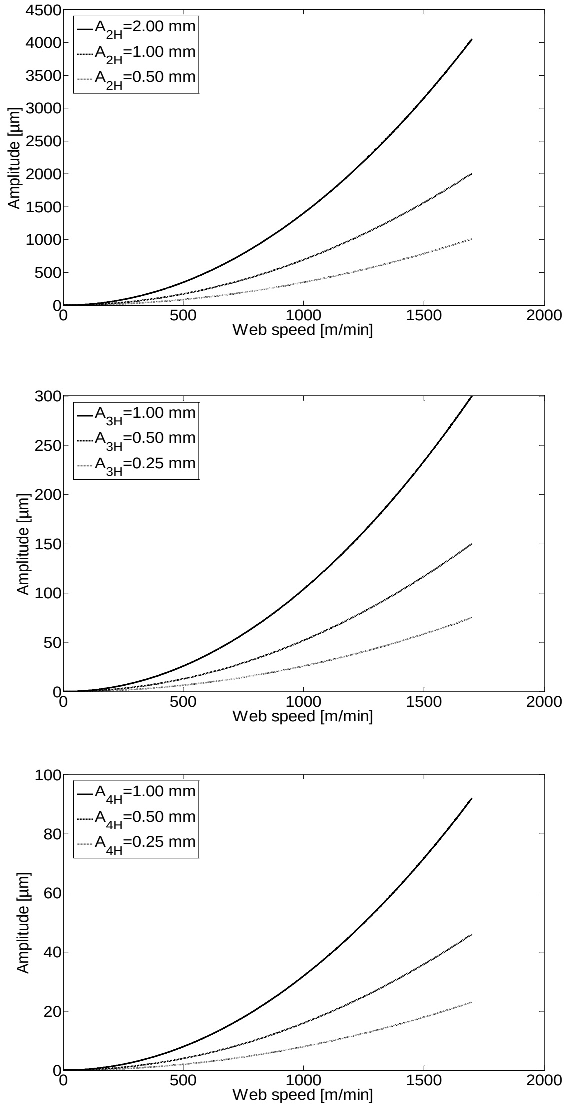

Fig. 5. The effect of the wall thickness variation on the dynamic roundness of a paper machine roll. The 2nd (top), 3rd and 4th (bottom) harmonic components of the wall thickness variation and matching run-out harmonics of the outer surface.

4. DISCUSSION

The wall thickness measurement of a paper machine roll showed significant systematic variation. The roll structure was determined easily from the results. The most important result was that the wall thickness measurement is harmonic with one main component. The measured ovality of the inner surface geometry is in the range of millimeters instead of tens of micrometers that is the tolerance for outer geometry.

In the analyzed finite element cases, the outer surface deformation consists mainly of the harmonics of the inner surface profile. Centrifugal forces tend to rapidly increase the dynamic geometry error on the lowest harmonics of the inner surface profile. The higher harmonics of the inner surface profile have a small effect on the dynamic geometry under centrifugal forces.

As the inner profile does not change without machining, the worst case is low inner surface harmonics with high amplitudes and a small wall thickness with increasing web speed. As the effect of centrifugal force on roundness is dependent on the web speed to the power of two, the outer surface run-out harmonics may appear quite high at a normal production speed of a paper machine.

The normal engineering tolerance of the inner surface is total run-out, which is not suitable solution for this kind of dynamic problem as it neither takes into account the harmonic content of the surface profiles nor the rotating speed.

5. CONCLUSIONS

The measurement showed significant wall thickness variation on the studied roll due to manufacturing inaccuracy. The main variation component was used in finite element analysis, to find out if manufacturing inaccuracy can be the cause for dynamic geometry change, and furthermore, could explain the quality variation of LWC paper. The study showed that the measured wall thickness variation is in the magnitude that can be the cause for the dynamic geometry change.

In the future, the FE modeling should be based on the measured thickness of the roll shell and modeling of the whole roll having realistic degrees of freedom at the bearings only. This model together with an ultrasonic wall thickness measurement system could be used in advanced manufacturing process to minimize dynamic deformations.

REFERENCES

1. Juhanko, J. & Kuosmanen, P. *New method for proactive maintenance of paper machine rolls*. The 2nd World Congress on Engineering Asset management (EAM) and The 4th International Conference on Condition monitoring, Harrogate UK, 11-14th of June 2007. pp. 812-921.

2. Kuosmanen, P. *Predictive 3D roll Grinding method for reducing paper quality variations in coating machines*. Dissertation, Helsinki University of Technology, Publications in Machine Design 2/2004, Espoo 2004. 91 p.

3. Juhanko, J. *Dynamic behavior of a paper machine roll*. Licentiate Thesis, (in Finnish). Helsinki University of Technology, Laboratory of Machine Design. Espoo 1999. 82 p.

4. ISO 11342 *Mechanical vibration - Methods and criteria for the mechanical balancing of flexible rotors*, 1994.

5. Keskiniva, M. & Lauste, L. *Dynamic balancing of flexible rolls of paper machines subjected to distributed unbalance loads*. Ninth World Congress on the Theory of Machines and Mechanisms. August 30-31/September 1-2 1995, Milano, Italy. 6 p.

6. Jei, Y.-G. & Lee, C.-W. *Modal analysis of continuous asymmetrical rotor-bearing systems*. Journal of Sound and Vibration, 152(2):245-262, 1992.

7. Kang, Y., Shih, Y.-P. & Lee, A.-C. Investigation of the steady state responses of asymmetric rotors. Journal of Vibration and Acoustics. Transactions of ASME, 114(2):194-208, April 1992.

8. Fowler, K. A., Elfbaum, G. M., Smith, K. A. and Nelligan, T. J. *Theory and application of precision ultrasonic thickness gaging*. NDTnet - October 1997, Vol.2 No.10 The Journal of the British Institute of Non-Destructive Testing, www.ndt.net/article/wt1097/ panam/panam.htm.

9. Uski, T. *Ultrasonic inspection of coatings of paper machine rolls*, Master's Thesis (in Finnish), Helsinki University of Technology, Laboratory of Machine Design. Espoo 1999. 53 p.

10. Bathe, K.J. & Wilson, E.L., *Numerical methods in finite element analysis.* Prentice-Hall, Englewood Cliffs, 1976, 528 p.

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