ON-LINE CONTINUOUS MEASUREMENT OF ROLLS' COEFFICIENT OF RESTITUTION

by

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ABSTRACT

This paper reports on the development of a novel technique to measure on-line rolls' coefficient of restitution or "springiness". The ratio of speed of separation to speed of approach in an elastic collision is termed the coefficient of restitution (Cr). The Cr sensor is based on the concept of an elastic collision of a steel object being freely dropped onto the web, as a roll is being wound, from a known height in the direction normal to the contact surfaces and rebound to a measured elevation. An important feature of this is the relationship between the rebound height and the in-roll stresses. The sensor returns the value of Cr as a function of roll radius. The latter can accurately be calculated from the data acquired via the sensor. The results indicate that the Cr values are complex and produce dramatic changes near the roll core. Further investigations are underway to verify the results and their interpolation in terms of the direct relationship with the in-roll stress and other parameters that may contribute to changing the roll springiness.

INTRODUCTION

A profitable procedure for reducing paper waste and improving process reproducibility is to ensure that shipping rolls supplied by the roll producers are of the highest quality. To warrant this, a paper roll producer may want to test the roll structure before shipping. The Cameron Strain test (1), 'J' line testing (2), Beloit Rhometer (3), Schmidt Hammer (4) and Smith Needle (5) are all available methods to check the integrity of the final product before shipping. However, some of these test methods are labor intensive and destructive in nature and others can take a long time to undertake. Furthermore, some are suited for testing profiles from the core to the outside diameter but are not effective in cross winder direction. Conversely, others are effective in the cross winder direction but not suitable for diameter profiling.

Several attempts were instigated in the past to continuously monitor hardness profiles of paper rolls as they are being wound (6-8). The most appreciated method was the "Backtender's Friend" which was first reported in the late seventies. It was an automated roll hardness control system and was demonstrated to reduce substantially roll defects (9). In this paper a similar stand-alone system is described, but in this case to determine on-line springiness profile of paper rolls from the core to the outside diameter and also can be easily adapted across the winder direction. The outcome profile obtained by this method may directly be related to the web structure, residual stresses, interlayer slippage, drum vibration and moisture content. The principal advantage of this system is the ability to check the gradual change in springiness of a roll during winding. The instantaneous analysis of the hardness data provided by this method can further be used as an aid to establishing the winding criteria of an existing winder or a newly installed one. Moreover, it will be shown in an another paper "Dynamic Model of a Winding Process for Monitoring and Control" refer to Kabore et al. (10), that this testing methodology can be used as dynamic input to control the winding parameters and to understand and optimise the winding conditions so as to reduce roll irregularities and produce rolls of the highest quality.

COEFFICIENT OF RESTITUTION (Cr)

The phenomenon of elastic impact of spheres on plates was first described by Raman 1920 and was theoretically investigated by Zener in 1941 on the basis of the quasi-static Hertzian impact theory and the classic bending theory of thin plates (11). Although, Zener was able to predict the height of rebound for all values of the spheres' diameter to height ratio, his analysis did not include an examination of shear effects in thick plates. For very thick plates, elastic waves do not have time during the impact process to propagate back and forth several times in the direction of thickness of the plate (12). As a consequence, the concept of bending loses its physical justification and separate reflections of spatial waves must be investigated. This alone indicates that simple collisions are rather complex events. Forces of interaction of the colliding bodies are certainly not constant; they vary in complicated ways. A variety of things can happen, depending on the masses, material properties, environment and the different initial motions of the colliding bodies. Furthermore, collisions can occur at various angles and might involve simultaneous interaction of more than two bodies. Yet, as a consequence of the systematic regularity of the results of simple collisions experiments performed with steel spheres, it begins to seem that, regardless of the complexity of the detailed interaction, there exists a simple connection among the motions before and after collision. Prior to Newton, the determination of this connection was the foremost goal for physicists. They saw in collisions the beginning of a science of dynamics. In 1668, Wallis, Wren and Huygens (13) proposed descriptions of rectilinear collisions that remain, from modern point of view, essentially correct, although they confused concepts such as mass with weight. It is possible to distinguish three different classes of simple rectilinear collisions:

(i) The colliding bodies stick together and move as a unit after collision; this type is called "perfectly inelastic;"
(ii) The colliding bodies reverse the direction but not magnitude of their relative velocity (frictional forces here are completely absent, which is an idealisation of the collisions of glass and steel objects); this type is called "perfectly elastic;"
(iii) The colliding bodies reverse the direction of their relative velocity but the magnitude is smaller than the relative velocity (this case, in general, represents actual collisions); this type is called "partly elastic."

In the fast time scale of the impact, several events happen in close succession. To clarify this Figure 1 shows a simple sketch of the events taking place in one stroke.

The contact event occurs when the tip of the Cr sensor makes a contact with the roll. This contact is followed by a period of compression, in which it converts its vertical kinetic energy at the collision point into potential energy by deforming the roll surface layers slightly. When all of the vertical kinetic energy is converted and the velocity of the wheel in the vertical direction is zero, maximum compression occurs. Maximum compression is followed by a period of restitution, in which the stored energy is converted back into vertical kinetic energy as the deformed part returns to its original shape. When the Cr tool has regained enough vertical velocity to lose contact with the roll, termination occurs and the collision is considered over.

In an impact, vertical kinetic energy is lost for several reasons. Noise created during impact removes some energy. Internal atomic friction of the part during compression and restitution removes some energy as heat. It is possible for some materials to achieve termination before all the internal potential energy is completely converted to vertical kinetic energy. The modeling factor that accounts for all of the losses in vertical kinetic energy is the coefficient of restitution.

The coefficient of restitution (Cr) is a measure of the elasticity of the collision, which is the ratio of speed of separation to speed of approach in a collision. So for example, if the velocities of two bodies, A and B, before and after collisions are v_{A1}, v_{B1}, v_{A2} and v_{B2} respectively, a perfectly elastic collision is defined as

$$v_{B1} - v_{A1} = -(v_{B2} - v_{A2}) \qquad \{1\}$$

The negative sign indicates the reverse in the movement direction after collision. While Cr a number less than unity, is defined by

$$Cr = (v_{B2} - v_{A2}) / (v_{B1} - v_{A1}) \qquad \{2\}$$

In this investigation one of the two colliding bodies, the roll, is stationary and therefore Cr becomes

$$Cr = v_l/v_o \qquad \{3\}$$

Where v_o is the speed of the Cr sensor at impact and v_l is the speed of separation. At the surface of a roll if (m) is the mass of the colliding object and (h) is the rebound height then the kinetic energy equals the potential energy

$$\tfrac{1}{2} mv^2 = mgh \qquad \{4\}$$

$$v = \sqrt{2gh} \qquad \{5\}$$

The coefficient of restitution can hence be written as

$$Cr = \sqrt{h_l/h_o} \qquad \{6\}$$

EXPERIMENTAL

In Figure 2 the complete Cr sensor arrangement is shown. The design consists of a 100 mm long stroke displacement transducer or LVDT held by a 'U' shape frame. The frame is accurately mounted on top of a roll by the stand arrangement shown in the same Figure. This to ensure that the LVDT's shaft can fall freely and vertically on a roll being wound in the same location at each cycle. The movement of the shaft was automated using an electrical motor to repeat the impact cycles. To support the frame with the movement of the roll as it is being wound, two wheels support the frame. Another wheel is located on the tip of the LVDT to minimise friction upon impact. The LVDT was linked to a computer via a data acquisition card to acquire data at the rate of 1 kHz using LabView (5.1) software for data manipulation.

The current investigation, including the designing, improving and building of the Cr arrangement, is highly involved as may be appreciated. Due to time limitations, we will report herein results pertaining to only one tested roll. (Further results will be forthcoming in subsequent publications). The roll specimen used in this study was 750 mm wide with a 275 mm outside radius. The roll comprises Cigarette paper, 40 □ in thickness, the history of which is unknown. The roll has a cardboard, hollow core with a 51 mm radius and a wall thickness of 10 mm. The Cr testing was carried out on a centre winder, and data were collected during unwinding.

ROLL RADIUS (R) CALCULATION

An added bonus with the Cr sensor is that the roll radius can be calculated from a simple calculation. With reference to Figure 3, $\sin\alpha = h / r$ and $\cos\alpha = (r - rw - d)$, where (rw) is the radius of the small wheels, (r) is the roll radius (R) plus the rw and (d) is the curvature shift measured by the LVDT. From a simple geometric relationship, the role radius can be found as follows:

$$\sin^2\alpha + \mathrm{con}^2\alpha = 1 = (h/r)^2 + ((r - rw - d)/r)^2 \qquad \{7\}$$

$$h^2 + (r - rw - d)^2 = r^2 \qquad \{8\}$$

$$h^2 + r^2 + 2(d + rw)\, r + (rw + d)^2 = r^2 \qquad \{9\}$$

$$r = (h^2 + (rw + d)^2)/\,(2(d + rw)) \qquad \{10\}$$

$$R = r - rw \qquad \{11\}$$

$$R = ((h^2 + (rw + d)^2)/\,(2(d + rw))) - rw \qquad \{12\}$$

The actual roll radius was measured during the experiment and when compared with the calculated radius using the Cr tool, good agreement was found as shown in Figure 4. In future reports the calculated radius from the Cr sensor will be quoted.

RESULT AND DISCUSSION

Figure 5 shows the end result obtained from the Cr sensor. Each datum point in the same Figure represents the mean value of seven points acquired while unwinding the roll. It has to be mentioned that at this stage of the project one roll sample was tested, thus it is very difficult, at this stage, to safeguard a comprehensive discussion regarding the full meaning of the results obtained. However, it is very clear from Figure 5 that with the addition of more layers to the core, the springiness of the paper roll increases. This is indicated by the sharp rise in the Cr values up to 100 mm. The Cr value for the hollow core alone (51 mm radius) is 0.47. This low Cr value indicates that the energy of impact was quickly dissipated through the core cardboard wall, which is expected as the core material including the hollow centre is a very poor medium for the elastic waves generated by the impact to travel. So the rebound height was reduced due to the energy absorbed in the wall, thus resulting in a low value of Cr. Moreover, a close examination of the results indicates that after 100 mm there is a slight drop in the Cr value that can be associated with a phenomenon known as the core effect (14). The non-linear behaviour in the curve may reflect the visco-elastic nature of the paper roll when considering it as one entity. For instance, if there are gaps and incomplete contact between layers, this is because materials such as paper are by nature rough and porous and relatively few fibres of adjacent layers are in initial contact. As the pressure increases more fibres become involved in the contact and can contribute to additional stiffness. This behaviour will lead to a non-linearity in the results, which is also evident in both the exponential curve fit proposed by Pfeiffer (15) and the polynomial curve fit proposed by Hakiel (16). So as interlayer pressure increases, the proportion of area in contact increases, allowing more material to contribute to the radial stiffness. Thus, if the coefficient of restitution is representing the springiness of a roll and the roll can be regarded as a spring-like system, then it is possible to assume that there is a direct link in the relation with the radial modulus.

CONCLUSIONS AND FUTURE WORK

This study is a preliminary investigation and there are a number of unclarified points concerning the rebound height and what the actual Cr values means in terms of the fundamental physics. Obviously, the accuracy of the sensor also needs to be addressed before any assumption can be made. However, when using the Cr sensor on a paper roll a clear trend emerged near the core. There is a dramatic reduction in the Cr value as the measurement is taken closer to roll core. It is therefore essential for this study to include in future work the core effect. For example, how a hollow or solid core influences the Cr value and also what effect the core radius has on Cr including the type of material it is made from.

As the speed of papermaking is rocketing, more than 2000 m/min (17), new challenges exist to adapt the Cr sensor with the high speed of winding and to take in to account other parameters associated with ultra fast winding processes.

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REFERENCES

1. TAPPI Routine "Control Method RC317. Cameron Test for Determining Residual Strain in Paper," TAPPI Journal, Vol. 46, No 12, 1963, pp 123A.
2. Adams, R. J., Baum, S.A., Roisum, D.R., Oliver, W.K., "Method and Apparatus for Quantitatively Evaluating Roll Hardness," US Patent 5079728, Beloit Corporation, Beloit, WI, Jan. 7, 1992 / Jan. 31, 1990.
3. Lucas, R.G., "Internal Gearing in Roll of Paper," TAPPI Paper Finishing and Converting Conference Proceeding, October 1974.
4. Hurst, F., "Hardness of Paper Rolls using Schmidt Concrete Test Hammer," TAPPI JOURNAL, Vol. 54, No 7, 1971, pp. 1177.
5. Roisum, D., The Mechanics of Winding, TAPPI Press, Atlanta, 1994, pp.25.
6. Duff, I. L., "Unique Tester Improves Paper Quality," Can. Chem. Processing, Vol. 61, 1977, pp. 30-31.
7. Banazza, L., "Automatic Reel Hardness Control with the 'Backtender's Friend'," Pulp Can., Vol. 80, No. 7, 1979, pp. 33.
8. Crotogino, R. H., "State of the Art in CD Calendar Control", Proceeding of Eucepa Symposium Control Systems in the Pulp and Paper Industry, held 11-14 May 1982 in Stockholm, pp. 220-228.
9. Bonazza, L., "Automatic Reel Hardness Control With the 'Backtender's Friend'," Pulp & Paper Canada, Vol. 80, 1979, pp. 33.
10. Kabore P., Wang, H., Jaafar, H and Hamad, W., "Dynamic Model of a Winding Process for Monitoring and Control," Proceedings of 5th International on Web Handling, Oklahoma, USA, 1999.
11. Koller, M.G. and Busenhart, M., "Elastic Impact of Spheres on Thin Shallow Spherical Shells," International Journal of Impact Engineering, Vol.4, No.1, 1986, pp.11-21.

12. Koller_MG, Kolsky_H, "Waves Produced by the Elastic Impact of Spheres on Thick Plates," International Journal of Solids and Structures, Vol.23, No.10, 1987, pp.1387-1400.

13. Goldsmith, W., "Impact: The Theory and Physical Behaviour of Colliding Solids," Edward Arnold (Publishers) Ltd., London, 1960, pp. 4.

14. Hamad, W., "Winding Mechanics of Anisotropic Materials," Pira International, UK, 1998, pp.27.

15. Pfeiffer, J. D., "Measurements of K2 Factor of Paper," Tappi Journal, Vol. 64, No. 4, 1981, pp. 105.

16. Hakiel, Z., "Nonlinear Model for Wound Roll Stress," Proceeding of Tappi Paper Finishing and Converting Conference, 1986, pp. 9.

17. Pulp and Paper Canada Special Report, "New World Speed Record," Pulp & Paper Canada, Vol. 98:9, 1997, pp. 11.

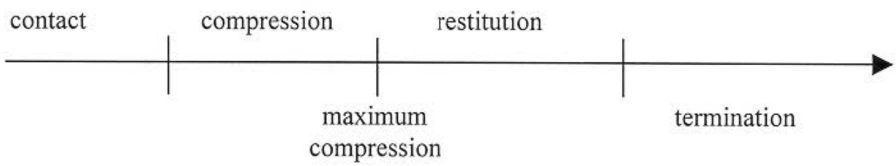

Figure 1. Timeline of impact events.

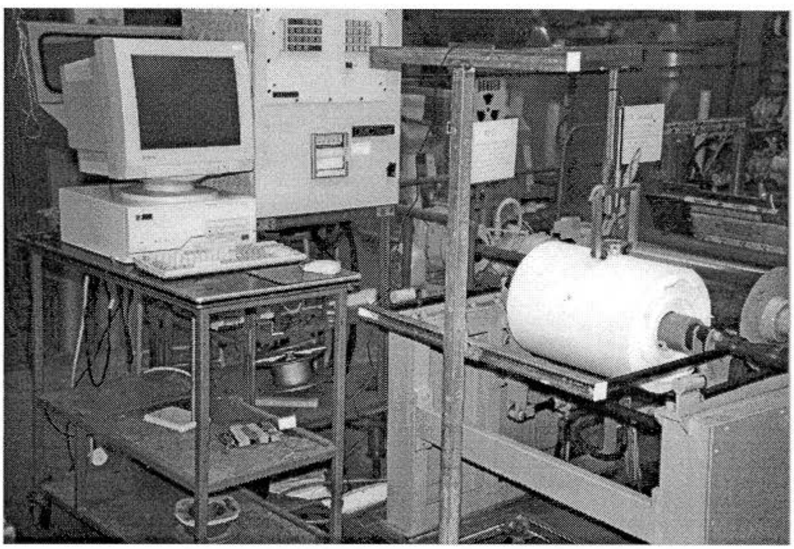

Figure 2. Photograph of the Cr sensor positioned on the winding end of the paper pilot plant in the Department of Paper Science, UMIST.

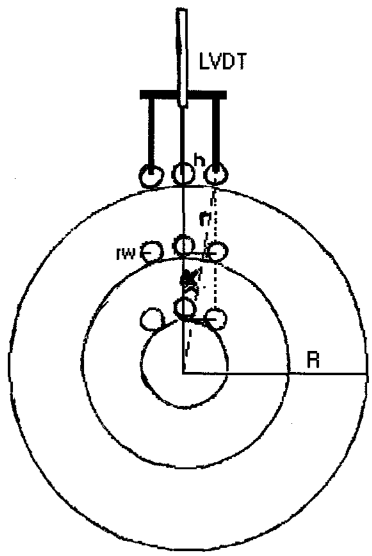

Figure 3 . Illustration depicting the change in the outer layer curvature with the roll radius, which can be detected by the Cr sensor.

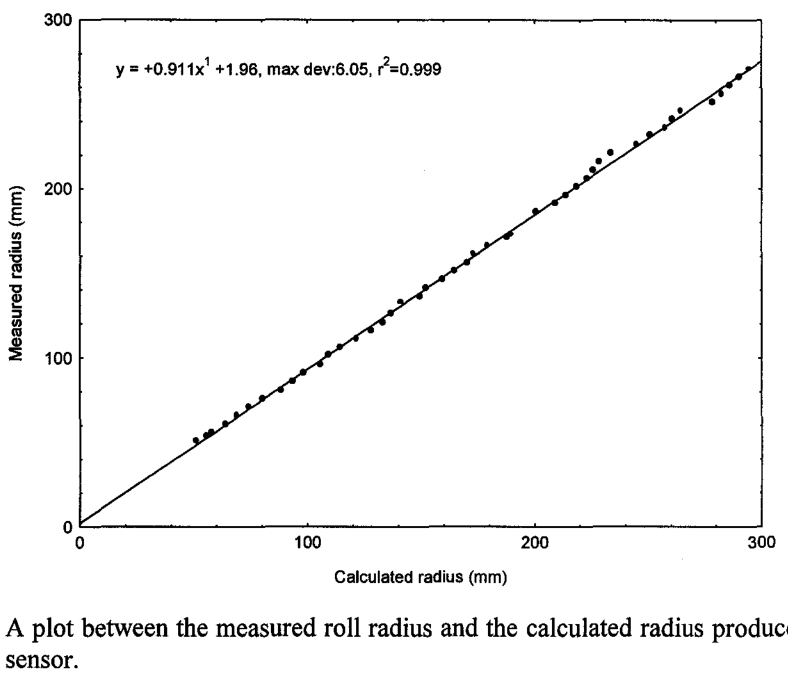

Figure 4. A plot between the measured roll radius and the calculated radius produced by the Cr sensor.

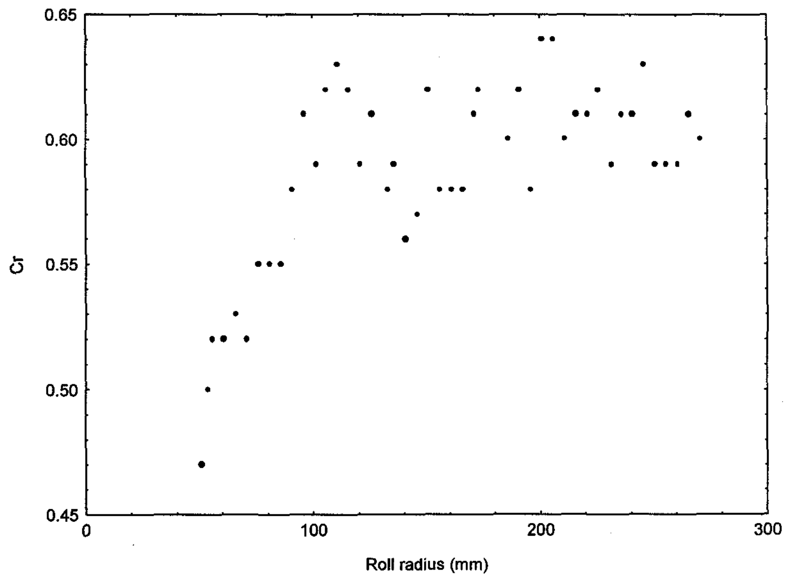

Figure 5. A plot represents the coefficient of restitution as a function of roll radius.

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On-line Continuous Measurement of Roll's Coefficient of Resitution
6/8/99 Keynote - Session 3 9:25 - 9:50 a.m.

Question – David Pfeiffer, JDP Innovations
Your diagram of the plunger that strikes the rolls is not too clear. Figure 3 shows an LVDT with 3 balls on it. So, could you explain that a little more carefully and is it a free falling object or is it driven against the roll?

Answer – W. Hamad, International Paper
It is a free falling object, but the roll is rotating so that you need to eliminate the friction on contact, and that is why we have that wheel in contact. And incidentally, shown in that same figure, we managed to calculate the radius because the curvature of the surface is changing. The curvature changes, so we can relate that to the radius. So we have direct measurement of the radius and CR. So this was an added bonus.

Question – David Pfeiffer, JDP Innovations
As a designer of the roll meter I would like to point out that you can also get coefficient of restitution signals from the roll meter and its not being currently employed, but it is a possibility. Also you have to watch out as an observation for the effect of the rolls speed, as an ability to impart energy to your falling object. Because if you hit it just right, the roll might kick the object up with more speed than it came down with. So you have to watch that in your design.

Answer – W. Hamad, International Paper
Yes, I agree.

Question – Keith Good, Oklahoma State University
The Figure 5, with the data on it, was that a roll running, or at a standstill?

Answer – W. Hamad, International Paper
The roll was running.

Question – Keith Good, Oklahoma State University
Okay. And so maybe part of the scatter that we see at the higher roll radius might be some of the effects that David Pfeiffer just mentioned. You may have been exciting your transducer with eccentricities that often develop at larger wound roll radii.

Answer – W. Hamad, International Paper
Well, even though it was in static, I mean its not moving. You will see that in different points you will get different results within the roll itself. The structure is different. And hence, the accuracy of the technique, whether it is something we are measuring or it is the technique itself; we still need to look at these things.

Question – Keith Good, Oklahoma State University
I'm just saying that I think the device might as well be a measure of the concentricity of the roll. How perfect it is.

Answer – W. Hamad, International Paper
Yes

Question -- Pete Towns, Mobile Chemical
What is the material that you were hitting that is actually making contact with the roll. I know that we have a lot of material that are sensitive to contact like that.

Answer – W. Hamad, International Paper
The falling object is falling on a plate that we can change. So we are experimenting with different plates. But, the idea is to really minimize contact and not to force it. So we aren't banging very hard on the surface. We are in a way just tapping on it. It is not intended to damage the web. We intend to use this with paper and polymeric films, it is a new technique and we are trying to find out whether it will work here or there.