TRACTION FORCE BETWEEN ROTATING ROLL AND MOVING WEB CONSIDERING THE EFFECT OF AIR-ENTRAINMENT AND FRICTION

by

M. Sasaki, K. Tanimoto, K. Kohno, S. Takahashi and S. Suzuki
Mitsubishi Heavy Industries, Ltd.
JAPAN

ABSTRACT

High-speed transportation of paper web sometimes leads the web handling system into unstable state because of increase in the air-entrainment into the gap between a rotating roll and moving web or the nip region of winding system.

In this paper, the property of the traction change with increase in the air-entrainment into the gap between a paper roll and web or the nip region of winding system was investigated experimentally and theoretically. The critical speed to avoid slippage between a roll and web was found to be estimable by applying and extending the concept of "effective" frictional coefficient with the consideration of air-entrainment, which is proposed by Good [1], Hashimoto [2] and so on, to the estimation of the traction force defined as the frictional force on a paper roll or at the nip region. Consequently, the web handling stability at high-speed was found to be predictable.

NOMENCLATURES

b	Nip contact half width
B	Web rap half angle on the roll
h	Air film thickness
N	Nip load
p	Air pressure
R	Radius of roll
R_q	RMS surface roughness
T	Web tension
Tr	Traction capacity
U	$V_{roll}+V_{web}$
V_{roll}, V_{web}	Roll rotating speed, web running speed
W	Web width
α	Speed-differential ratio
β	Coefficient of permeance of a paper web per unit period and unit pressure difference

μ	Viscosity of air
μ_{eff}	Effective frictional coefficient
μ_{st}	Static frictional coefficient
θ	Rap angular position on the roll

INTRODUCTION

With the increasing demands for high productivity in paper machine mills, it is required to transport paper web stably at high-speed in dry-end section. However, high-speed transportation of paper web sometimes leads the web handling system into unstable states, lateral slide motion of web line and interlayer slippage of wound roll and so on, due to the excessive air-entrainment between a roll and web. These phenomena are frequently observed in handling coated paper or plastic film comparing with newspaper, because the former allows little permeation of air and their surface roughness is small. Therefore, it is of vital importance to clarify the property of the traction between various types of roll and moving web considering the effect of air-entrainment.

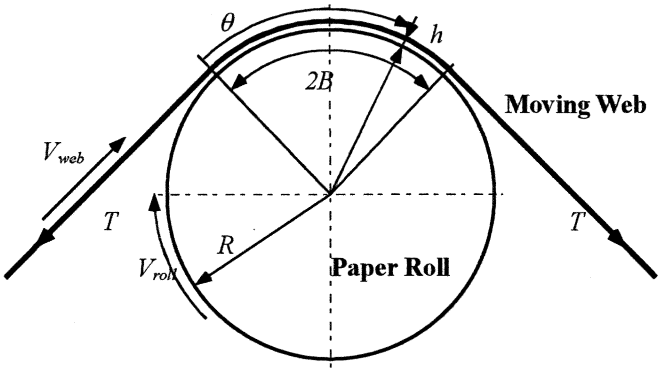
So far, the frictional properties of the web on a rotating roll has been investigated by Good [1], Hashimoto [2] and so on, and has become to be able to explain the frictional property at the contact region with introduction of the "effective" coefficient of friction. For evaluating the stability of practical web handling system, however, it is indispensable to clarify the traction force between a rotating roll and moving web considering the frictional property that changes with increase in the air-entrainment into the contact region, but there is no research that investigates the problem above mentioned, as far as I know.

In this paper, the air film thickness between a rotating roll and moving web and the traction change with increase in the air-entrainment were investigated experimentally and theoretically, where the concept of "effective" frictional coefficient with the consideration of air-entrainment was applied and extended to estimate the traction force defined as the frictional force between a roll and web.

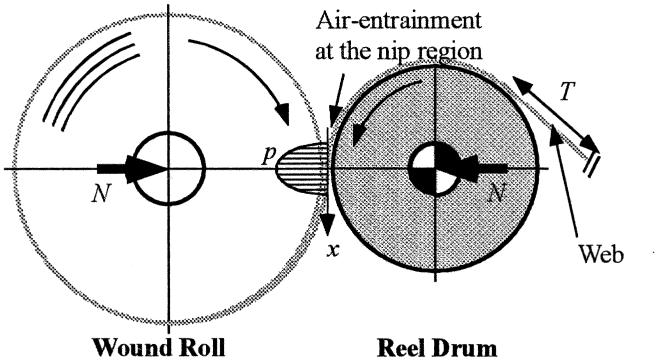
THEORY

Background and outline

Figure 1 shows the typical web transporting and winding system. The traction force between a roll and web is defined as the frictional force with a roll and web. The frictional force at that region is derived with consideration of "effective" frictional coefficient proposed by Good [1] and Hashimoto [2]. Air film pressure p on a paper roll is obtained from the relationship with radius R of roll and web tension T, and nip pressure p is obtained by using the extended theory with the consideration of equivalent elastic modulus of wound roll including air-layer and the effect of elastic deformation of wound roll into Chang's [3] theory, which estimates the air-entrainment into two cylinders being pressed each other.



(a) Web transporting system



(b) Winding system

Figure 1 - Web handling system

Effective frictional coefficient

With the assumption of Gaussian distribution of asperity heights on the roller and web surface, the "effective frictional coefficient μ_{eff} is defined using air film thickness h as follows [1];

$$\mu_{eff} = \begin{cases} \mu_{st} & for \quad h \leq R_q \\ \mu_{st} \dfrac{1}{2R_q}\left(3R_q - h\right) & for \quad R_q < h \leq 3R_q \\ 0 & for \quad h > 3R_q \end{cases} \qquad \{1\}$$

Where R_q indicate RMS surface roughness of roll and web.

Air film thickness

Between a rotating roll and moving web. Air film thickness between a roll and web shown in Figure 1(a) is calculated by solving Reynolds equation and web elastic equation simultaneously. Good [4] and Hashimoto [2] proposed the concise and simple formula to estimate the air film thickness in a sufficient accuracy by applying the curve fitting technique to the numerical results of the air film thickness for wide range of parameters, which is shown in the following [4];

$$h = 0.643R\left(\frac{6\mu U}{T}\right)^{\frac{2}{3}} - 2\left(\frac{\beta T}{U}\right)\theta \qquad \{2\}$$

Where, β is a coefficient of web permeance per unit period and unit pressure and decided by Gurley method, and the first term of right hand indicates the initial air film thickness, and the second indicates the decrease in the air film thickness due to web permeability. In eq. {2}, it is assumed that web has infinite width.

At the nip region. Air film thickness and nip pressure at the nip region is calculated by solving Reynolds equation with the consideration of elastic deformation of wound roll. Reynolds equation taking account of the compressibility of air, and the equilibrium equation with the nip load is shown in eq. {3} and {4}, respectively.

$$\nabla \cdot (ph^3 \nabla p) - 6\mu V \frac{\partial (ph)}{\partial x} = 0 \qquad \{3\}$$

$$\int_A p dA - N = 0 \qquad \{4\}$$

Air film thickness h is the sum of air film thickness at the nip center h_n, geometric clearance h_g and elastic deformation of wound roll δ_p as follows;

$$h = h_n + h_g + \delta_p \qquad \{5\}$$

In eq. {5}, elastic deformation δ_p is obtained using equivalent elastic modulus of wound roll surface layers and nip pressure p, of which values are calculated using the wound roll stress analysis method proposed by the authors [5, 6].

Nip pressure $p(x)$ and air film thickness $h(x)$ is obtained numerically with applying Newton-Raphson technique to solve eq. {3}, {4} and EHL equation with consideration of elasticity of wound roll.

Traction force

Between a rotating roll and moving web. The traction capacity Tr between a paper roll and moving web is defined as the cumulative frictional force between a roll and web.

$$Tr = WR\int_0^{2B} \mu_{eff}\, pRd\theta \qquad \{6\}$$

Where, μ_{eff} is "effective" frictional coefficient defined by eq. {1} using the air film thickness derived by eq. {2}. And p is air film pressure derived with use of the relationship of radius R of roll and web tension T.

At the nip region. The traction capacity Tr at the nip region is also defined as the cumulative frictional force at the nip region. The traction force at the web-lapping zone of reel drum is neglected here, because it is sufficiently small compared with that of nip region.

$$Tr = WR\int_{-b}^{b} \mu_{eff}\, p\, dx \qquad \{7\}$$

Where, μ_{eff} is "effective" frictional coefficient defined by eq. {1} with use of air film thickness derived by eq. {3}, {4}. And p is pressure profile in the nip region derived by eq. {3}, {4}.

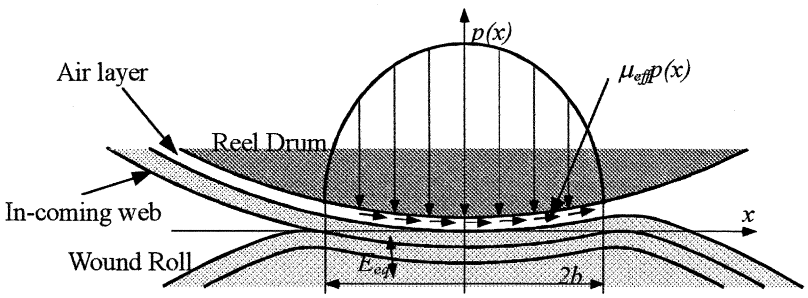


Figure 2 - Frictional force at the nip region

EXPERIMENTAL VERIFICATIONS

Experimental procedure

Web handling tests were conducted by usage of the dry-end section of MHI papermaking pilot machine to assure the applicability of the proposed method. Figure 3 shows the schematic figure of the testing machine. New wound roll is placed at the wound-off part and the web is drawn out under the preset speed by drag roll. Winding tension is applied by the traction force at the nip region which consists of a reel drum and wound roll. The web-running stability is evaluated by measuring the air film thickness on the paper roll (a) and reel drum, rotating speed of rolls and web tension at each rolls.

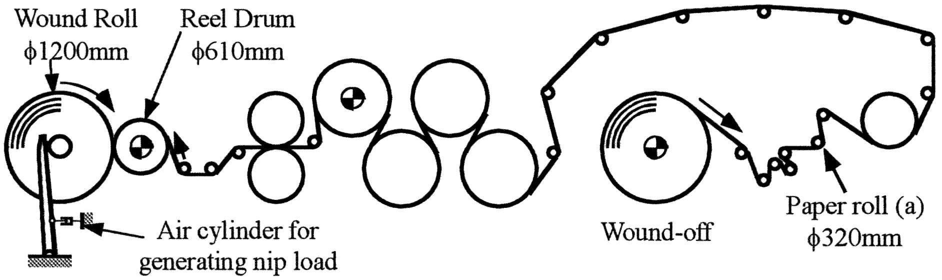


Figure 3 - Testing machine

Test conditions

Material properties of webs, specifications of rolls and winding parameters are listed on the Table 1, 2 and 3, respectively. Coated paper and newspaper were tested to evaluate the effect of surface roughness and web permeability. The maximum winding speed in experiments is 2100m/min for coated paper and 2800m/min for newspaper, paper width is 765mm and maximum diameter of the wound roll is 1200mm. The winding torque is applied by reel drum.

Table 1 - Material properties of paper webs

Item		Value	
Paper Grade		Coated paper	Newspaper
Thickness t (mm)		0.0605	0.0683
Coefficient of air permeance β (m/sec/Pa) (Permeability (sec))		1.75×10^{-8} (10,400)	2.48×10^{-6} (48.3)
Frictional coefficient μ_{st} (-)	Paper / Idle Roll	0.47	0.43
	Paper / Reel Drum	0.38	0.36
Surface Roughness $R_{q,web}$ (μm)		0.67	2.9

Table 2 - Specifications of rolls

Item	Value	
Roll	Paper Roll	Reel Drum
Radius R (mm)	160	305
Surface Roughness $R_{q,roll}$ (μm)	4.12	0.675

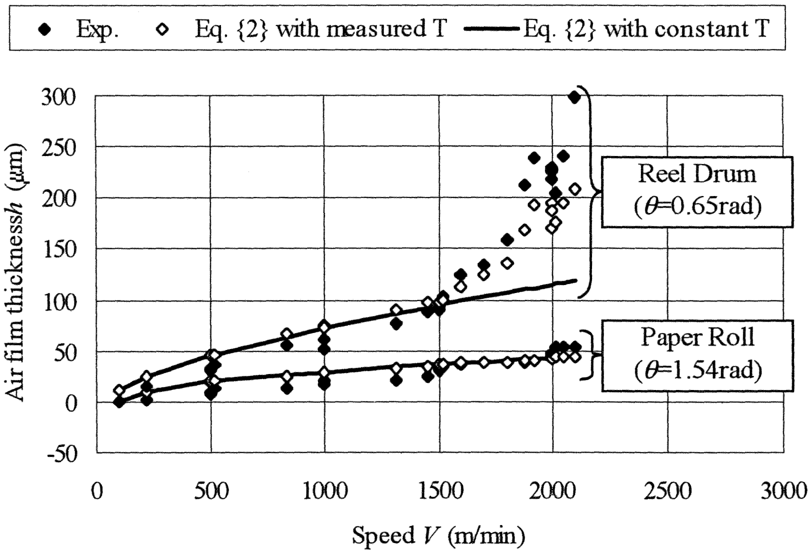
Table 3 - Winding Parameters

Paper Grade	Speed V (m/min)	Nip Load N (kN/m)	Tension T (kN/m)
Coated paper	~2100	2.4	0.52
Newspaper	~2800	2.7	0.43

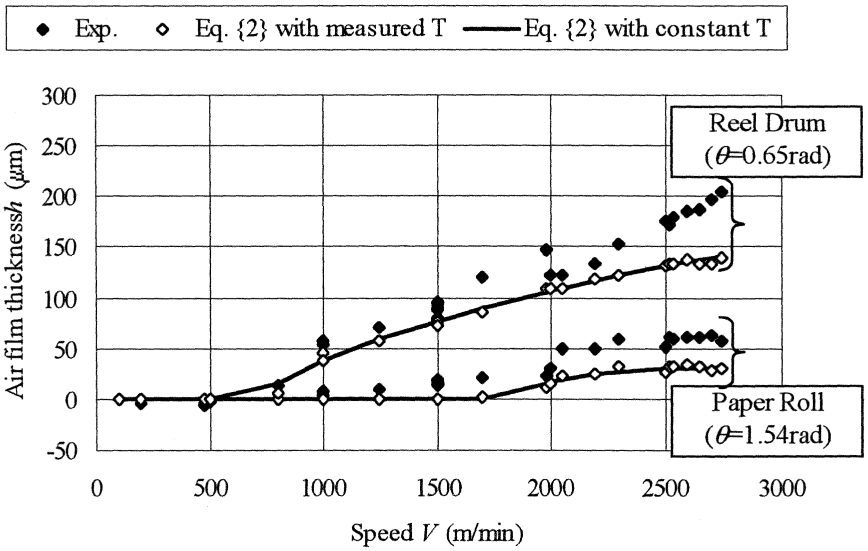
Experimental Results

Traction force between a roll and web. Figure 4 shows the comparison of the experimental results of air film thickness on a paper roll and reel drum with the theoretical results from eq. {2}. Two kinds of theoretical results are shown in Figure 4, the calculated value by using measured web tension and by using constant preset tension Table 3. In the case of coated paper, the air film thickness on a reel drum from eq. {2} using measured tension is estimated to be thick compared with the results using constant tension over 1500m/min. Therefore, it seems that web tension near the reel drum becomes lower than preset value over 1500m/min.

Figure 4 shows that theoretical values of air film thickness with consideration of web permeability are predicted to increase with web speed for both of coated paper and newspaper. Especially in the case of newspaper, it is predicted that the effect of web permeability is remarkable and air film thickness is small compared with the case of coated paper. In addition, for both of coated paper and newspaper, there are good agreement with experimental results and theoretical results from eq. {2}. It is found that the air film thickness between a rotating roll and moving web is estimable in a fairly good accuracy using eq. {2} proposed by Good [4] such a high-speed listed on Table 3.



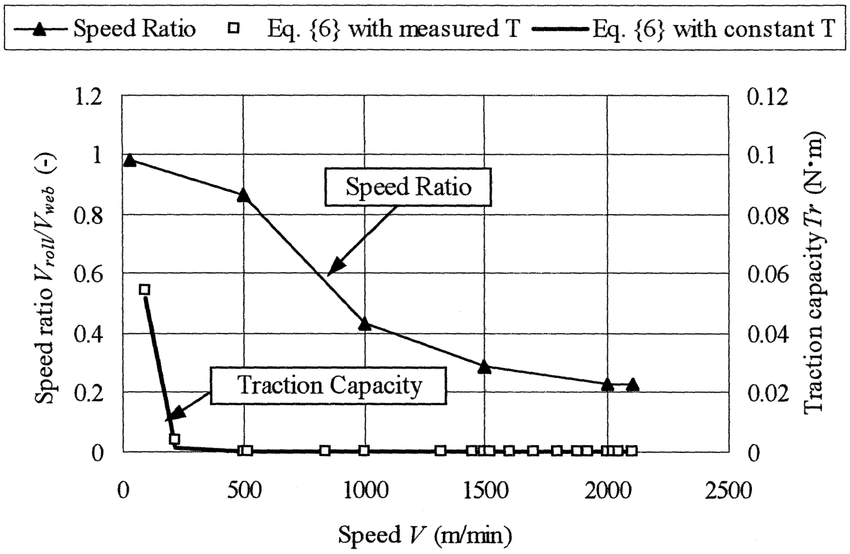
(a) Coated paper



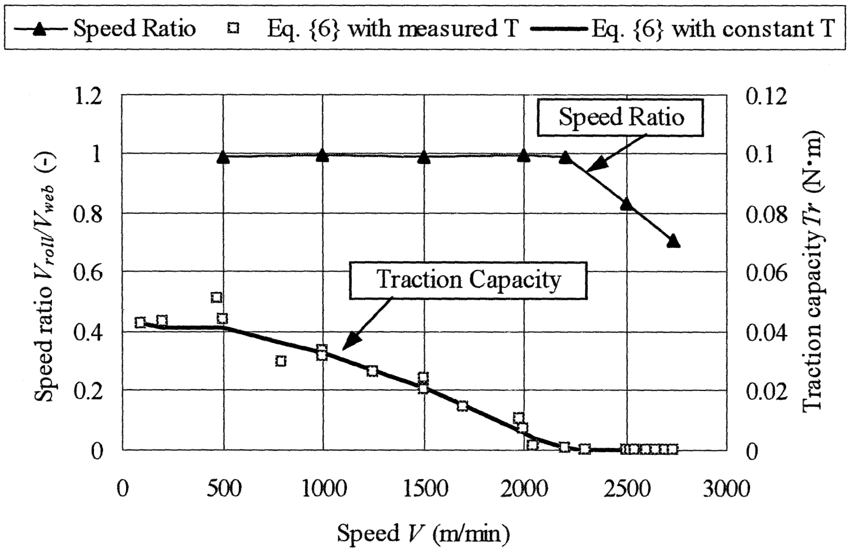
(b) Newspaper

Figure 4 - Air film thickness between a rotating roll and moving web

Figure 5 shows the traction capacity defined in eq. {6} and speed ratio between a paper roll and web. In Figure 5, there are also two theoretical results obtained with measured tension and constant tension in Table 3.



(a) Coated paper
Figure 5 - Traction capacity on the idle roll



(b) Newspaper
Figure 5 - Traction capacity on the idle roll

Figure 5 shows that, in the case of coated paper, the speed ratio decreases with increase in web speed and rotating speed of paper roll falls below web speed at 500m/min. This means that slippage between a paper roll and web has occurred over 500m/min. As is the same with the speed ratio, the traction capacity in eq. {6} falls to 0N·m at 500m/min.

On the other hand, in the case of newspaper, the speed ratio is maintained almost 1 under 2200m/min and starts to decreases at 2200m/min. This means that slippage between a paper roll and web has occurred over 2200m/min. As is the same with the speed ratio, the traction capacity in eq. {6} decreases with increase in web speed and finally falls to 0N·m at 2200m/min.

So, it is found that it is able to evaluate the critical speed to avoid slippage between a paper roll and web with use of the traction capacity defined in eq. {6}. When the traction capacity falls to 0N·m and slippage has occur, web-running stability easily get worse due to a slight change in web tension or miss-arraignment of paper rolls.

Traction force at the nip region. Figure 6 shows the traction capacity defined in eq. {7}. In Figure 6, solid line is the minimum traction force to keep web tension listed in Table 3. Figure 7 shows the web tension T and speed-difference ratio α between a reel drum and web.

Figure 6 shows that, in the case of newspaper, the traction capacity in eq. {7} is maintained almost constant and sufficiently higher than the minimum traction. On the other hand, in the case of coated paper, the traction capacity in eq. {7} decreases at 1000m/min due to the increase in air-entrainment and finally falls below the minimum traction at 2000m/min. It means that it is unable to wind coated paper stably over 2000m/min

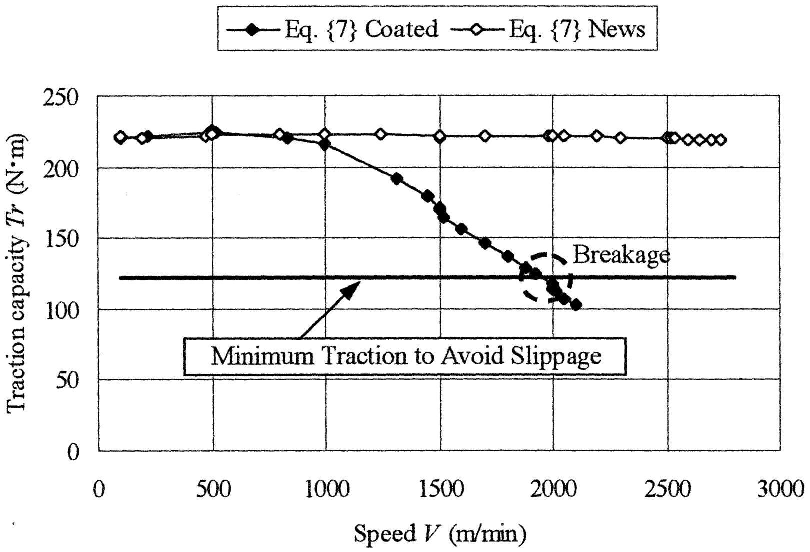


Figure 6 - Tracition capacity at the nip region

Figure 7 shows that, in the case of newspaper, tension and speed-difference ratio is maintained almost constant. On the other hand, in the case of coated paper, tension decreases and speed-difference ratio increases suddenly at around 1500m/min, which means that slippage occurs at the nip region and rotating speed of reel drum is higher than web speed. In the experiments for coated paper, paper breakage occurred at 2100m/min, which can be explained with the relationship between the traction capacity and the minimum traction as the above mentioned.

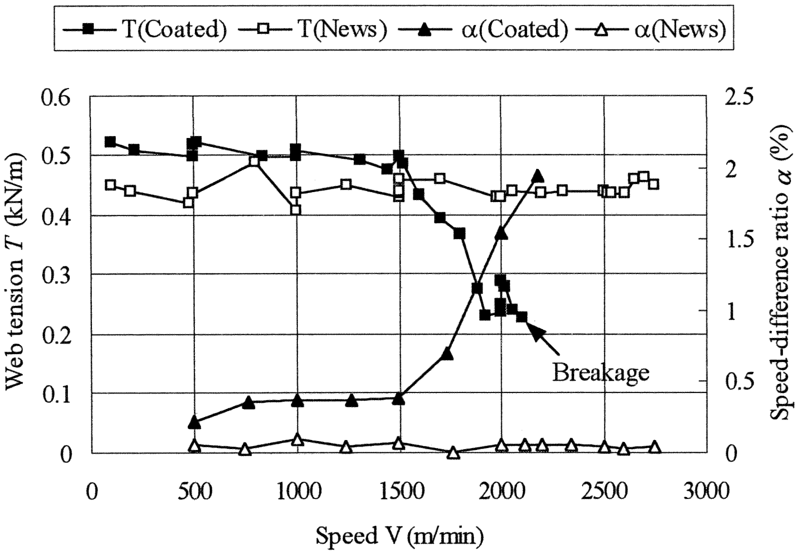


Figure 7 - Web tension and speed differential ratio

So, it is found that it is able to evaluate the critical speed to avoid the slippage at the nip region with use of the traction capacity defined in eq. {7} and the minimum traction to maintain the web tension.

CONCLUSIONS

The authors found that it is able to evaluate the critical speed of slippage between a rotating roll and moving web by applying and extending the concept of "effective" frictional coefficient to estimate the traction force with the consideration of air-entrainment. Consequently, the web handling stability on a paper roll and the winding stability at high-speed becomes predictable with use of the traction capacity considering "effective" frictional coefficient and the air film thickness.

ACKNOWLEDGEMENTS

The authors would like to express sincere appreciations to Prof. Hashimoto at Tokai University in evaluating the "effective" frictional coefficient between a roll and paper web.

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