FSI(Fluid-Structure Interaction) Analysis for Harmonious Operation of High-Speed Printing Machine

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Abstract

Proper amount of entrained air and nip force should be also considered to minimize ballooning phenomenon since tight contact between a roller and web is required. In this paper, various web materials, PET(Polyester) and OPP(Oriented Poly Propylene) have been selected and investigated to satisfy high-speed printing requirement. Several web speeds, web tensions, and temperature conditions are imposed on each web materials and the pressure and gap profiles as well as nip force have been calculated. Increase of both the winding roller radius and the incoming wrap angle is considered under proper taper tension at 500 m/min of rewinding roller. By solving coupled Reynolds equation and web deflection equation simultaneously, the fluid-structure interaction process has been developed and is applied to the rewinding roller to investigate the ballooning phenomenon which causes guiding problems in high-speed printing performance conditions. By adjusting the linear taper tension, stress distribution between rewinding webs can be remarkably reduced and stable pressure and gap profile with ignorable ballooning phenomenon have been found.

Key Word : Air Entrainment, Ballooning Phenomenon, Fluid-Structure Interaction, Incoming Wrap Angle, Nip Force, Taper Tension, Web

Nomenclature

Alphabet

h_0	:	gap between winding roller and nip roller at the nip center (m)
h_1	:	gap between web and winding roller (m)
h_2	:	gap between web and nip roller (m)
h_c	:	amount of air entrainment (m)
h^*	:	nominal clearance (m)
p_1	:	pressure between web and winding roller (N/m^2)
p_2	:	pressure between web and nip roller (N/m^2)
p_a	:	ambient pressure (N/m^2), 101315N/m^2
$\overline{p_w}$	:	contact pressure (N/m^2)
s	:	circumferential coordinate (m)

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t	:	web thickness (m)
u	:	web speed (m/s)
w	:	web deflection (m)
B	:	compressibility
D	:	dimensionless stiffness parameter
E	:	Young's Modulus (N/m^2)
F	:	nip force (N)
L_{in}	:	length of incoming web span (m)
L_{out}	:	length of outgoing web span (m)
R_1	:	radius of winding roller (m)
R_2	:	radius of nip roller (m)
T	:	tension (N/m)

Greek

ϵ	:	foil bearing number
θ_{in}	:	incoming wrap angle of winding roller (degrees)
θ_{out}	:	outgoing wrap angle of winding roller (degrees)
λ_a	:	mean-free-path of the air molecules (m), 6.731E-8m
μ	:	dynamic viscosity (N/m^2 • s), 1.81133E-5N/m^2 • s(for 20°C)
ν	:	Poisson's ratio

Superscript

$\bar{\ }$	:	previous value

Introduction

There are no clear definitions of high operation speed, but generally above 300 m/min is called high speed. A smooth operation of web in high-speed printing machines requires tight contact between a roller and web. To do this, it needs nip force and should also consider possible ballooning phenomenon by the force[1]. In addition, when web is moving at constant speed by a winding roller, in order to get precise copying, printing machines have to prevent obstructions like slippage, floating, telescoping, and buckling of web caused by air entrainment. It is required to find some conditions of maintaining the same speed of a roller and web and minimizing air entrainment[2].

A nip roller is used for a close contact between a process roller and web, but it has a ballooning phenomenon by nip force that generates wrinkling. The effects of the nip roller on the amount of entrained air and ballooning phenomenon should be understood to solve this problem. In particular, in case of high-speed operation required, air entrainment is one of very essential considerations so that analysis and design for the air entrainment are performed[1].

Remarkably convenient and stable way of web production is to use the winding roller, which is used widely in the high-speed printing fields. However, between each web, i.e. in the winding roller, stress occurs as the winding roller radius increases cumulatively due to web thickness. The stress of inner winding roller may result in the damage of the web material according to stress distribution and magnitude, and printing ink may be spread between the webs during the printing process. This phenomenon results in a decrease of the production rate and quality deterioration of web. Therefore, the winding mode with improved tension control than existing facilities is required to increase the production rate of web and to guarantee high quality printing[4].

Table 1. Parameters essential for analysis[3]

Parameters	
R_1	T
R_2	u
θ_{in}	t
θ_{out}	E
μ	ν
B	λ_a

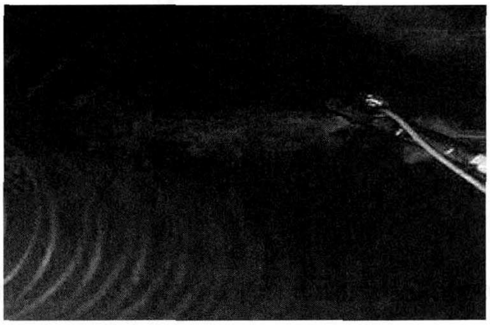

Fig. 1. The aspect of behavior of air entrained between a roller and web[3]

In this study, to obtain appropriate design guidelines for high-speed printing machines, several web speeds, tensions and temperatures are investigated for the web materials like PET(Polyester) and OPP(Oriented Poly Propylene), which are currently used for the high-speed printing. Based on this condition and by using fluid-structure interaction method, where mutually coupled Reynolds equation and web deflection equation are applied, not only pressure profile and gap profile generated from both between the nip roller and web, and a winding roller and web by the change of nip force but also a proper nip force and the amount of entrained air will be obtained.

In addition, because the winding roller radius and incoming wrap angle increase while OPP continuously in rewinder zone, linear taper tension which maintains the web tension and prevents abnormally high stress between the webs is applied. The amount of entrained air and proper nip force are calculated at the same condition. Attention has been paid mainly to the analysis of the amount of entrained air and nip force for elements shown on Table 1 and the elastic deformation of the roller is not considered as constraints of analysis. It is assumed that web and the surface of the roller are smooth and also the effect of asperity contact is ignored[5].

Theoretical Approach

Following the foil bearing theory for the amount of entrained air at a winding roller can be used to guess the initial amount of entrained air. When the nip force is zero, the web is waving to the degree of about 71.6% of nominal clearance(h*) at the outlet zone. That is called the minimum clearance[1, 5]:

$$\frac{h^*}{R} = 0.643\left(\frac{12\mu u}{T}\right)^{2/3} \tag{1}$$

$$H^* = \frac{h^*}{R}\varepsilon^{-2/3} = 0.643 \tag{2}$$

Reynolds Equation

Reynolds equation is used to include the effects of important fluid compressibility and slip boundary assuming that the gap is not much larger than λ_a. Reynolds equation becomes an equation combining continuity equation with Navier-Stokes equation, provided that a lubricant is compressible Newton flow, air flow is laminar flow, and web is infinitely wide[6, 7].

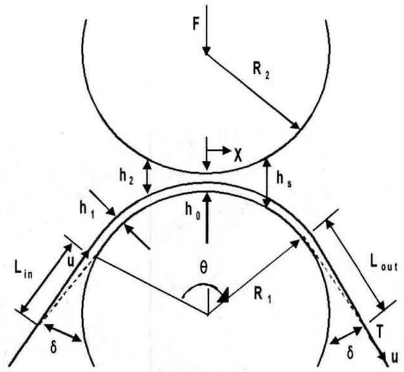

Fig. 2. A model for applying fluid-structure interaction analysis[1]

The air compressibility is an important element at the nip center because a local pressure could increase large. The air-film thickness at the nip center is very small, so that no-slip boundary condition is not adequate to that range. λ_a is very smaller than the gap at the range; therefore fluid flow cannot be treated as a continuum. So modified Reynolds equation that contains slip boundary condition is used. Slip boundary condition is important in the range of '$0.01 \le \lambda_a/h \le 15$' and '$\lambda_a/h$' is called Knudsen number[8, 9].

$$\frac{d}{ds}\left(ph^3\frac{dp}{ds}+6\lambda_a p_a h^2\frac{dp}{ds}\right)=12\mu u\frac{d}{ds}(ph) \tag{3}$$

p means an absolute pressure and the pressure at the two points is the same with the atmospheric pressure since the start and end points of paper web are far from the wrapped zone. p_1 is calculated by using Reynolds equation at the given h_1[5, 7].

Web Deflection Equation

The force balance equation of web could be used as a form of inclusion of bending stiffness and contact pressure. Web might become a model as a cylindrical shell, which is easily affected by air pressure, wrapped-zone pressure and contact pressure. Provided that the surfaces of web and the roller are completely tender and p_c is ignored, an equation could be formulated as below[5, 10].

$$\bar{d}\frac{d^4w}{ds^4}-T\frac{d^2w}{ds^2}=p_1-p_2-\bar{p}_w \tag{4}$$

$$\bar{p}_w=\begin{cases}0 & : \textit{inlet region}\\ T/R & : \textit{wrapped region}\\ 0 & : \textit{outlet region}\end{cases}$$

$$\bar{d}=\frac{Et^3}{12(1-\nu^2)}$$

At this time, the relation of h, the gap between the roller and web and w, web displacement is shown as the following[6].

$$h = w + \delta \tag{5}$$

And, the boundary condition for the analysis of the fourth order differential equation is given below.

$$\left. w \right|_{s=0} = 0, \quad \left. \frac{d^2 w}{ds^2} \right|_{s=0} = 0$$
$$\left. w \right|_{s=L} = 0, \quad \left. \frac{d^2 w}{ds^2} \right|_{s=L} = 0 \tag{6}$$

Provided paper web is completely flexible (EI = 0), then web deflection equation becomes a membrane equation. The air gap of three zones (inlet zone, wrapped zone and outlet zone) works differently. Three compositions of Figure 2, winding roller, nip roller and web have the same speed[2].

Non-Dimensionalized Governing Equation

The governing equations are non-dimensionalized as follows:

$$\varepsilon = \frac{12\mu u}{T}, \quad S = \frac{s}{R_1}\varepsilon^{-1/3},$$
$$H = \frac{h}{R_1}\varepsilon^{-2/3}, \quad P = \frac{p}{p_a},$$
$$W = \frac{w}{R_1}\varepsilon^{-2/3}, \quad D = \frac{d}{TR_1^2}\varepsilon^{-2/3} \tag{7}$$

In particular, at the nip center film thickness(h) is so small that foil bearing number(ε) is used to control the size of film thickness[5, 11]. In case ϵ is very small, then round-off error should be considered carefully.

$$\frac{d}{dS}\left[H^3\left(P\frac{d\overline{P}}{dS} - \overline{P}\frac{d\overline{P}}{dS} + \overline{P}\frac{dP}{dS}\right) + \Lambda_a H^2 \frac{dP}{dS}\right] = \frac{1}{B}\frac{d}{dS}(PH)$$
$$\Lambda_a = \frac{6\lambda_a}{R_1}\varepsilon^{-2/3}, \quad B = \frac{R_1 p_a}{T} \tag{8}$$

Equation (5) shows a linear form of the non-dimensionalized form of modified Reynolds equation[5, 7].

$$D\frac{d^4 W}{dS^4} - \frac{d^2 W}{dS^2} = B(P_1 - P_2) - P_w \tag{9}$$

Equation (6) is a non-dimensionalized form of force balance equation of web and the pressure at each zone is written in non-dimensional form like this[5, 7]:

$$P_w = \begin{cases} 0 & : \ inlet \quad region \\ 1 & : \ wrapped \quad region \\ 0 & : \ outlet \quad region \end{cases} \tag{10}$$

FSI(Fluid-Structure Interaction) Analysis Method

The amount of entrained air and a nip force of the responsible operation conditions are calculated from pressure and gap profiles at the three zones by using fluid-structure interaction method.

Figure 3 is the algorithm of fluid-structure interaction analysis method. Once the initial pressure and gap profile are entered, then P_1, new pressure profile, is acquired by Reynolds equation and P_2, another pressure profile, is also calculated by the same equation. H_1, new gap profile, based on P_1 and P_2 is calculated by web deflection equation and H_2, another gap profile, is acquired by '$h_2 \approx h_s - h_1$'(simple geometric relation)[3]. P_1, P_2, H_1, and H_2 become the initial values of the next iteration. Such a series of iterative process is continuously accomplished until convergence is achieved.

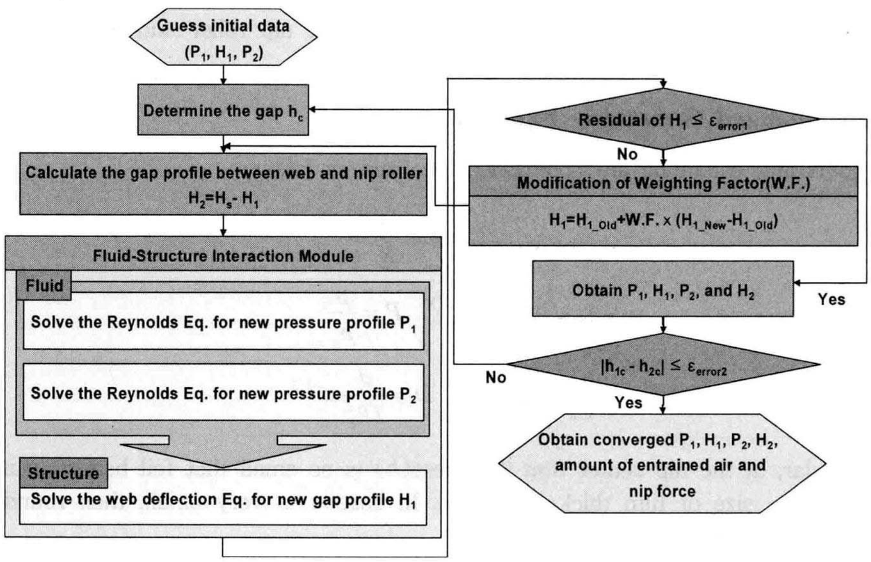

Fig. 3. Fluid-structure interaction analysis procedure[3, 5]

Result

According to the fluid-structure interaction analysis procedure, Calculated is the amount of entrained air and a proper nip force of the responsible operation conditions with converged pressure and gap profiles of the three zones. The iterative computation is performed to fulfill the two convergence criteria below by using Newton method through making the constant values of P_1, H_1, and P_2 as initial ones.

Convergence 1 : Pressure and gap profile

$$\frac{h_{residual}}{h_{residual,initial}} \leq 10^{-4} \tag{11}$$

Convergence 2 : Nip force and the amount of entrained air at operation conditions

$$|h_{1c} - h_{2c}| \leq 10^{-3}\,\text{mm} \tag{12}$$

Table 2. The amount of entrained air through case studies of PET

cases	5 N/m	10 N/m
200 m/min	h=0.1060553 mm	-
350 m/min	h=0.1537434 mm	h=0.09701658 mm
500 m/min	h=0.1946680 mm	h=0.12299260 mm
cases	15 N/m	20 N/m
200 m/min	-	-
350 m/min	h=0.07405614 mm	-
500 m/min	h=0.09392849 mm	h=0.07756816 mm

Table 3. Nip force through case studies of PET

cases	5 N/m	10 N/m
200 m/min	F=0.010513723 N	-
350 m/min	F=0.011896595 N	F=0.020749012 N
500 m/min	F=0.012136342 N	F=0.022109414 N
cases	15 N/m	20 N/m
200 m/min	-	-
350 m/min	F=0.025641700 N	-
500 m/min	F=0.028985494 N	F=0.035359211 N

Table 4. The amount of entrained air through case studies of OPP

cases	Radius Ratio=1	Radius Ratio=3
500 m/min	h=0.02273966 mm	h=0.02883151 mm

Table 5. Nip force through case studies of OPP

cases	Radius Ratio=1	Radius Ratio=3
500 m/min	F=0	F=0.033247822 N

In this study, actual model data is applied as input value for the present fluid-structure interaction method. In case of PET, the total number of nodes are 3999 and the roller has radius of $R_1 = R_2 = 0.06\,m$. The wrap angle of the winding roller is all fixed at 45° and calculations are performed for the tension of 5, 10, and 15 N/m and web speed of 350 and 500 m/min. In case of OPP, the total number of nodes are 7999 and the nip roller has radius of $R_1 = 0.05m$; however, the winding roller radius starts at 0.046 m initially and the web winds winding roller at 0.138 m in all(where, the "radius ratio=1,"denotes the initial winding roller and the "radius ratio=3." is for the final winding roller state). The incoming wrap angle of the winding roller is from 170° to 180°and there is no the outgoing wrap angle of the winding roller. Analysis has been performed for web speed of 500 m/min and the tension decreases linearly from 96.78 N/m to 67.64 N/m.

As shown in Table 2 and 3, the amount of entrained air and nip force are additionally calculated at 200 m/min of 5 N/m, fixed tension, for more accurate graph comparison of pressure and gap profile and, so does at 20 N/m of 500 m/min, fixed web speed. It is found from Table 2 and 3 that the amount of entrained air is proportional to the increase of web speed at a fixed tension and is inversely proportional to the increase of tension at a fixed web speed, while nip force becomes bigger as web speed increases at a fixed tension but its change is small and also increases rapidly with the increase of tension at a fixed web speed.

As shown in Table 4 and 5, in the case of "radius ratio=1," web starts winding and the amount of entrained air increases gradually according to the decrease of pressure profile and proper nip force is increasing by degree.

When looking into the nip force of "radius ratio=3,"operating in same web speed, 500 m/min for both OPP with tension of 67.64 N/m and PET with tension 20 N/m, the nip force of the former is lower than the latter, although the tension of the former is higher than the latter. The reason is that high tension of the former acts as a nip force with the gradually increasing radius, while the radius of the latter is fixed.

Figure 4 shows the pressure profile of the winding roller with the various tensions at a fixed web speed. Here, the position of s = 0 means the nip center. The pressure increases from the start point of web and nearly maintains constant except for the nip center and outlet zone. Pressure fluctuation generates at the nip center and the pressure is sharply decreasing at the outlet zone, but the pressure goes back to the ambient pressure starting with the end point of web. As the tension increases at the same speed, the means of pressure fluctuation increases and the sharp drop at the outlet zone goes to extreme.

Figure 5 shows the gap profile of the winding roller according to the various tension changes at a fixed web speed. Air film thickness starts to decrease at the start point of web, at the nip center, a weak ballooning phenomenon appears, and at the outlet zone, air film thickness becomes suddenly increasing because of drastic falling of pressure at the outlet zone and then returns to ambient pressure as heading for the end point of web, therefore it is going back to the same air film thickness of the start point of web. As tension increases at the same speed, ballooning phenomenon becomes weak, and air film thickness decreases and the starting point of ballooning gradually loses its speed. The air film thickness at the start and end points of web has the same conditions of ambient pressure.

Figure 6 displays the pressure profile of the winding roller with the various web speeds at a fixed tension and Figure 7 shows the gap profile of the winding roller according to the various speed changes at a fixed tension. Under the condition of the same tension, an ignorable change shows up at the pressure of the nip center as web speed increases. On the other hand, at the same tension, ballooning phenomenon gets stronger and air film thickness becomes extensive largely. What is noticeable is that air film thickness is proportional to the web speed but pressure distribution gets little influences from that at the constant tension.

Figures 8 and 9 show the pressure profile and the gap profile of the winding roller with increasing winding roller radius and linear taper tension. The pressure and gap profile shows similar and relatively stable aspects. From starting winding the roller, the pressure is decreasing and the gap distribution is increasing step by step.

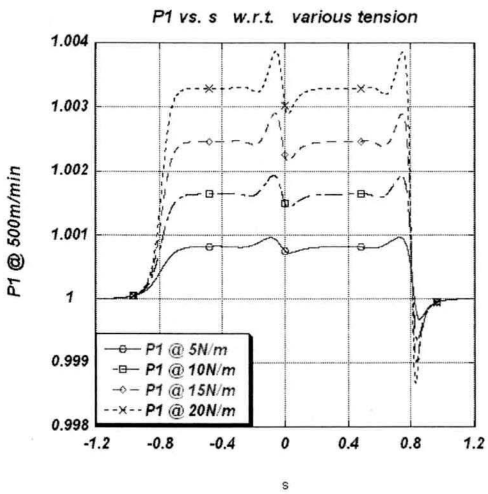

Fig. 4. P_1 vs. s with respect to fixed web speed (i.e. 500 m/min) and various tension

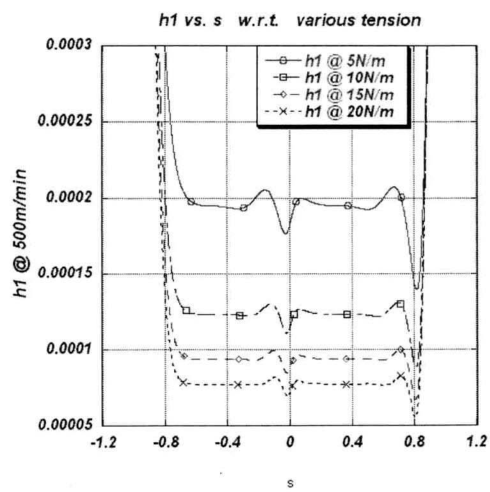

Fig. 5. h_1 vs. s with respect to fixed web speed (i.e. 500 m/min) and various tension

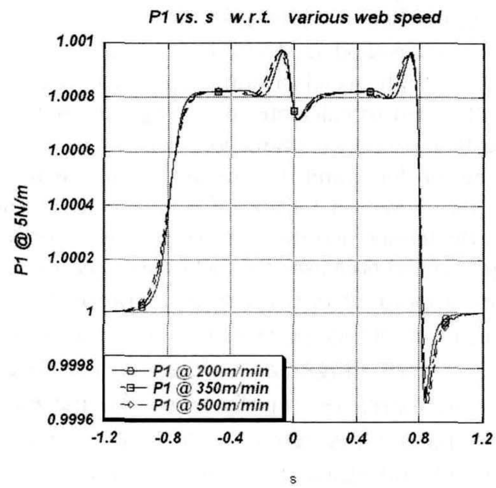

Fig. 6. P_1 vs. s with respect to fixed tension (i.e. 5 N/m) and various web speed

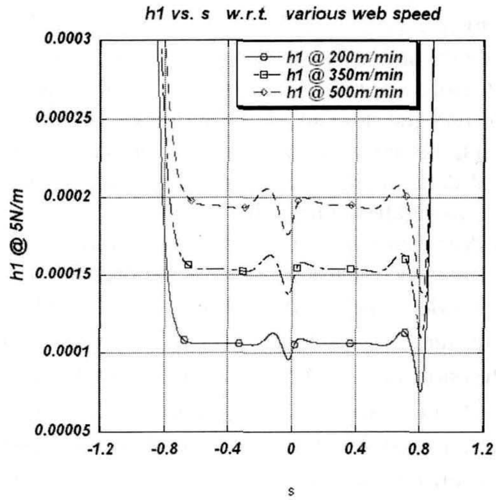

Fig. 7. h_1 vs. s with respect to fixed tension (i.e. 5 N/m) and various web speed

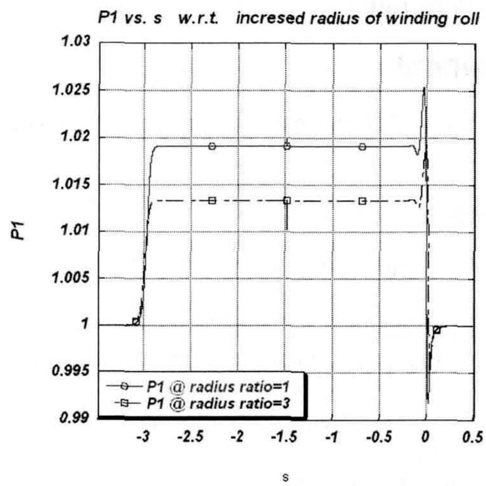

Fig. 8. P_1 vs. s with respect to increased winding roller radius

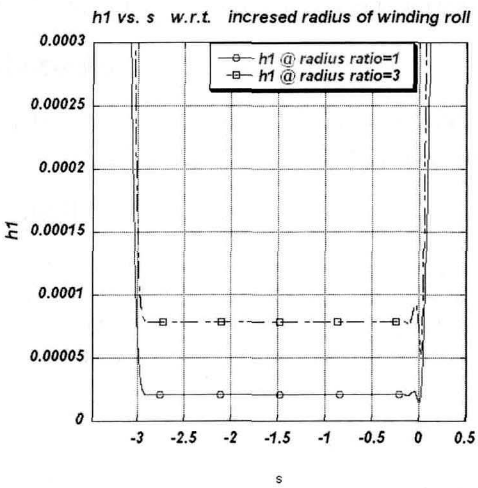

Fig. 9. h_1 vs. s with respect to increased winding roller radius

Unlike the case of early occasions, the ballooning phenomenon occurs between the inlet zone and nip center but shows only temporarily.

As shown in Table 2, at the constant tension, the amount of entrained air increases as web speed increases. As a result, air film thickness grows big but there is little change in nip force. The increased tension makes the gap smaller but the web speed rather increases the gap due to the increased amount of the entrained air. This can lead to a conclusion that you need a proper combination of tension and supply-speed to design a highly efficient high-speed printing machine.

As shown in Table 4 and Figure 8 and 9, linear taper tension control has been appropriately applied enough to prevent the stress distribution between each web, hence results in stable pressure and gap profile which leads ignorable ballooning phenomenon.

Conclusions

Tight contact between a roller and web is required to achieve a harmonious operation of a web handling process line. Nip force is applied to help and maintain this close contact, but proper amount of entrained air and nip force should be also considered to minimize ballooning phenomenon. Parameters necessary for analysis of high-speed printing machine are arranged based on governing equations and a loosely coupled fluid-structure interaction method is devised. A loosely coupled fluid-structure interaction method is presented to analyze high-speed printing machines. The nip force and the amount of the entrained air are repeatedly used to calculate the change of pressure and gap between the winding and the nip rollers. Using fluid-structure interaction method and actual model data, changes of pressure and gap as well as the nip force and the amount of entrained air are investigated. Through this study, it is found that the increased tension affects directly to the load distribution of web and there is a trade-off between the tension and the web speed. It is confirmed that linear taper tension stabilizes the pressure and gap profile and decreases the ballooning phenomenon in rewinder zone. In this study, it is found that the amount of entrained air is proportional to the increase of web speed at a fixed tension and is inversely proportional to the increase of tension at a fixed web speed, while nip force becomes bigger as web speed increases at a fixed tension but its change is small and also increases rapidly with the increase of tension at a fixed web speed. By adjusting the linear taper tension, stress distribution between rewinding webs can be remarkably reduced and stable pressure and gap profile with ignorable ballooning phenomenon have been found. For the study to maximize the efficiency of high-speed printing machine, we need to study design optimization for combination between tension, web speed, and radius ratio.

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References

1. Chang, Y. B., Chambers, F. W., and Shelton, J. J., "Air Entrainment with a Force-Loaded Nip Roller", Web Handling Research Center, Oklahoma State University, 1994.

2. Ducotey, K. S., and Good, J. K., "A Numerical Algorithm for Determining the Traction between a Web and Circumferentially Grooved Roller", Journal of Tribology, Transaction of the ASME, Vol. 122, 2000, pp. 578~584.

3. Jin-Ho Kim, Jae-Woo Lee, Soo Hyung Park, Do-Young Byun, Yung-Hwan Byun, Chang Jin Lee, Hee Soo Kang and Goo-Pil Jeong, "Fluid-Structure Interaction Analysis of High Speed Printing Machine", Proceedings of the KSME 2006 Spring Annual Meeting, 2006, pp. 585~590.

4. Chang Woo Lee, Jang Won Lee, Kee Hyun Shin and Soon Oh Kwon, "Hybrid Taper Tension Logic in a Rewinding System", Proceedings of the KSME 2006 Spring Annual Meeting, 2006, pp. 526~531.

5. Lee, J. Y., "A Computational Analysis of Air Entrainment with a Nip Roller", Oklahoma State University, 1999, pp. 1~23.

6. Sinan, M., and John, J. J., "Traction between a Web and a Smooth Roller,"Journal of Tribology, Transaction of the ASME, Vol.126, 2004, pp. 177~184.

7. Barlow, E. J., "Derivative of Governing Equations for Self-Acting Foil Bearings", Journal of Lubrication Technology, Transaction of the ASME, 1967, pp. 334~340.

8. Eshel, A., "Compressibility Effects on the Infinitely Wide, Perfectly Flexible Foil Bearing", Journal of Lubrication Technology, Transaction of the ASME, 1968, pp. 221~225.

9. Burgdorfer, A., "The Influence of Molecular Mean Free Path on the Performance of Hydrodynamic Gas Lubricated Bearings", Journal of Basic Engineering, Transaction of the ASME, 1959, pp. 94~100.

10. Eshel, A., "Stiffness Effects on the Infinitely Wide Foil Bearing", Journal of Lubrication Technology, Transaction of the ASME, Vol. 89, 1967, pp. 92~97.

11. Eshel, A., "Reduction of Air Film in Magnetic Recording by External Air Pressure", Journal of Lubrication Technology, Transaction of the ASME, 1974, pp. 247~249.