Journal of Mechanical Science and Technology, Vol. 19, No. 1, ⟨Special Edition⟩ pp. 403~410, 2005 **403**

Simulation and Experimental Methods for Media Transport System : Part II, Effect of Normal Force on Slippage of Paper

Jae-Kwan Ryu, Soon-Geul Lee, Sung-Soo Rhim*, Jin-Hwan Choi
School of Mechanical and Industrial Systems Engineering, Kyung Hee University, Yongin 449-791, Korea
In-Ho Song
FunctionBay, 601 6F, Seo-Won B/D, 1515-4, Seocho-Dong, Seocho-Gu, Seoul, 131-871, Korea

Many daily appliances for examples copiers, printers and ATMs contain the media transport system (MTS) and the slippage between the medium in the MTS deteriorates the performance quality of the whole system. The slippage of the medium in the MTS is affected by many parameters including the friction coefficient between the feeding rollers and the medium, the velocity of the feeding rollers, and the normal force exerted on the medium by feeding rollers. This paper focuses on the effect of the normal force on the slippage while the medium is being fed. For this purpose, we developed a two-dimensional simulation model for a paper feeding system. Using the simulation model, we calculated the slippage of the paper for different normal forces. We have also constructed a testbed of the paper feeding system to verify the simulation results. Experimental results are compared with the simulation results.

Key Words : Media Transport System, Slippage, Normal Force, Friction Coefficients, Paper Modeling

1. Introduction

The media-transport (or media feeding) system (MTS) is a key sub-system in many daily appliances for examples printers, copiers, film-developing machines, and ATMs. In those machines, the medium (e.g. papers, films, and bills) is usually fed into the main processing unit by a pair or a consecutive series of pairs of rollers. The crucial role of the MTS is to feed the medium to the main process in a uniform and repeatable manner. A small slippage between the medium and the feeding rollers causes irregular feeding and significantly degrades the performance of the entire system. Thus the study on the slippage of the medium in the MTS is essential for the improvement of the performance of those daily appliances fore-mentioned. The slippage in the MTS is affected by many parameters including the friction coefficient between the feeding rollers and the medium material, the angular velocity of the feeding rollers, and the normal force exerted by the pair of feeding rollers on the medium material. The effect of the roller speed and other parameters on the slippage have been studied and reported by some researchers but the effect of the normal force has not been fully investigated yet. This paper focuses on the effect of the normal force on the slippage between the medium and the feeding rollers.

For the evaluation and development of the

* Corresponding Author,
E-mail : ssrhim@khu.ac.kr
TEL : +82-31-201-3248; **FAX** : +82-31-202-8106
School of Mechanical and Industrial Systems Engineering, Kyung Hee University, Yongin 449-791, Korea.
(Manuscript **Received** November 29, 2004; **Revised** December 15, 2004)

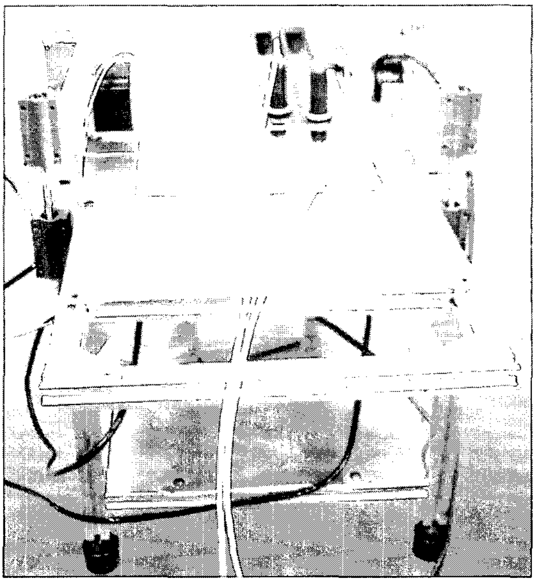
MTS, it is the experimental trial-and-error (TE) approach that has been adopted up to date. However, the experimental TE method is not very efficient and not an accurate way of developing and evaluating new media transport systems. The general state of the medium being passed through the complex process experiences semi-static and dynamic deformation and it cannot be well analyzed by TE approach. As an alternative, computer simulation using multi-body dynamic models is recently developed and suggested for the analysis and the design of the media feeding and separation processes. In the current paper we developed a novel two-dimensional simulation model for a paper feeding system consists of a sheet of paper and a pair of feeding rollers (the driving and the driven) and the feeding tray. In the simulation a sheet of paper is modeled as multiple rigid bodies interconnected by revolute joints and rotational springs and dampers. Using the simulation model, we calculated the slippage of the paper being fed through the rollers for different normal forces on the feeding rollers. The modeling and the computation are done using a multi-body dynamic analysis tool called **RecurDyn®**. To verify the effectiveness of the simulation model we have constructed a testbed of the paper-feeding system and performed experiments. The system parameters used for simulation were matched with those of the testbed. Both simulation results and experimental results are included in the paper.

2. Experimental Setup and Material

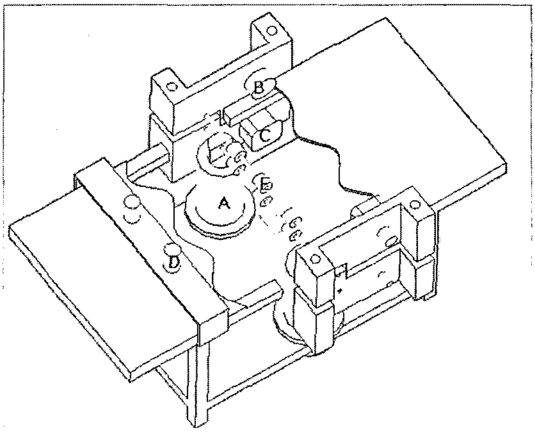
To compare the simulation results with actual experimental results we have designed and constructed a testbed of a paper feeding system. The paper feeding system consists of feeding rollers and various sensors to measure the movement of the rollers and the paper and the normal force between the feeding rollers. In the following sub-sections details of the testbed is explained.

2.1 Experimental setup

Fig. 1 shows a picture and a 3D drawing of the testbed designed and built by the Media Transport System Research Group at Kyung Hee University. The main component in the testbed is a pair of rolling shafts, a driving and a driven. Two shafts make contacts at the three pairs of rollers and roll against each other through three pairs of rollers. The rollers affixed on the shafts are coated with urethane for high friction. In Fig. 1 the upper shaft is the driving and the lower one is the driven. The normal force exerted on the three pairs of the rollers is adjusted by moving up and down the lower (driven) shaft. At each end of the riven shaft is installed a cylindrical height



(a) Picture of testbed



(b) 3D view of CAD drawing of testbed

Fig. 1 Picture and 3D drawing of testbed adjustor (marked A in Fig. 1(b)). Using the height adjustor we can change the height of the driven shaft and eventually the normal force exerted on the feeding rollers. The normal force being exerted on both shafts is measured by a pair of load cells (SBA-50L, CAS) installed inside the two cylindrical height adjustors. The angular velocities (V_r) of both shafts are measured by rotary optical encoders (marked B in Fig. 1(b)). In order to measure the transfer velocity of the paper (V_p) and the spin of the paper, two optical non-contact sensors (S50-PA, DATASENSOR) are installed at the points marked D in Fig. 1(b). A step motor of step size 1.8° mounted at point C is used to drive the upper shaft. Signals from the encoders of the two shafts and the contract sensors are acquired by a multi-function DAQ board (MF614, HUMUSOFT) installed in a PC.

2.2 Property of medium

High quality papers are used as transfer medium in this paper. A conventional measure of the quality of the paper is mass per one square meter (W). The W value of the paper that we used in our research is 80 g/m^2 (Double A grade). Another conventional measure of the paper quality is the degree of paper's curving (EI, Nm^2). EI value of the paper, which is introduced by (Kenji OKUNA et al., 1994), is related with mass per unit area and calculated as following equations,

$$EI_V = 2.27 \times 10^{-10} W^{2.93} \quad (1)$$

$$EI_H = 1.92 \times 10^{-10} W^{2.93} \quad (2)$$

The subscript V represents the vertical direction of the paper and the subscript H represents the horizontal direction of the paper. The width and the height of the paper used in the research are 210 mm and 294 mm, respectively. The thickness of the paper is 0.1 mm.

2.3 Measurement of friction coefficients

In the paper feeding system, the paper is transferred by the friction force occurring between the paper and the feeding rollers. Thus the accurate measurement of friction coefficients between the roller and the paper is essential for the study of the paper feeding mechanism. To measure both static friction coefficient and dynamic friction coefficient we devised a measuring system shown in Fig. 2. As shown in the Figure a paper is placed and attached on a plastic plate and the pair of shafts from the paper feeding system is placed on the top of the paper. The shafts are bound to each other to prevent them from rolling.

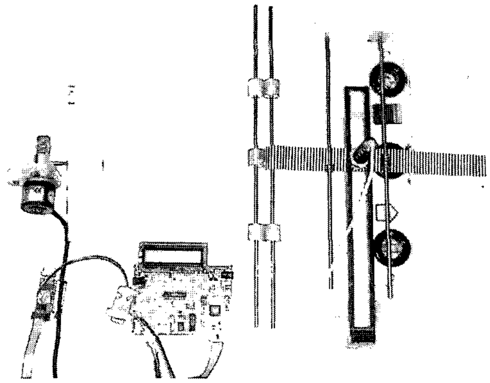


Fig. 2 Experimental setup to measure friction coefficients

2.3.1 Maximum static friction coefficient

Beginning with the bundle of two shafts on the paper and the plastic plate set parallel to the ground, we tilt up one end of the plate at a very small speed until the shaft bundle starts to slide down on the paper. From the angle between the ground and the plate where the shaft bundle begins to move down the plate we calculate the static friction coefficient between the rollers and the paper. When the bundle of the two shafts starts to slide down the plate as we tilt the plate up, we measure the tilt angle (θ) between the ground and the plate. The measured angles in repeated experiments are shown in Fig. 3. The average of the measurements is 44.61°. Taking the average value we calculate the maximum static friction coefficient between the roller coated with urethane and the paper to be 0.987.

2.3.2 Kinetic friction coefficient

Beginning with the plate at about 50° with the ground we let the bundle of the shafts slide down the plate. Then, we tilt down the plate until the bundle of shafts moves at a uniform speed. The angle between the plate and the ground where the uniform movement begins gives us the dynamic friction coefficients between the roller and the paper. From one hundred times of the same test we get the average tilt angle of 23.94°. From the average value of the measured tilt angle, the kinetic friction coefficient is calculated 0.444.

In the experiments the initiation of the motion and the uniform slip-down motion of the shafts are detected by an optical non-contract sensor attached at the plate. The angle between the ground and the plate was measured by a rotational optical encoder (4000 pulse per rotation). A level is used to level the plate initially.

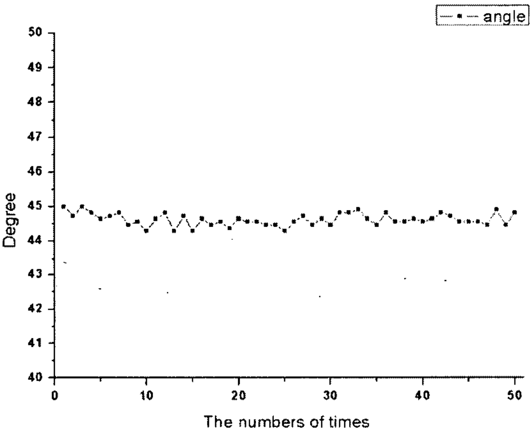


Fig. 3 Measured tilt angle in static friction coefficient measurement

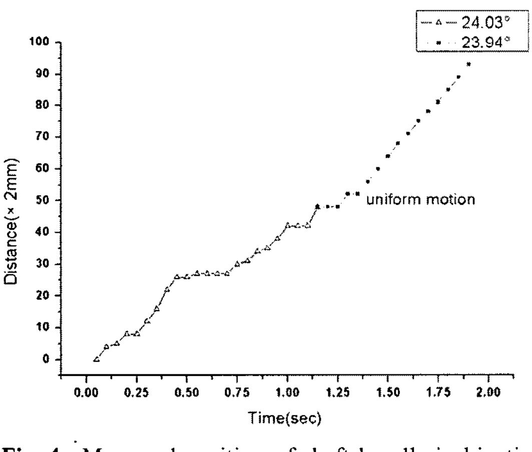


Fig. 4 Measured position of shaft bundle in kinetic friction coefficient measurement

3. Simulations

To simulate the dynamic behavior of the paper during the feeding process, we modeled a sheet of paper and the feeding system illustrated in the previous section. The system parameters used in the simulation including friction coefficients are matched with those obtained from the testbed.

3.1 Modeling of paper feeding system

For the simulation of the paper feeding process, we modeled a sheet of paper as a two dimensional multi-body dynamic system. In this research we adopt the two dimensional multi-body dynamic model of the flexible paper initially introduced by (Cho et al., 2001), which is shown in Fig. 5. Several research results show that the most efficient model of the two-dimensional approximation of the a sheet of paper is a series of rigid bars connected with revolute joints and rotational spring-dampers (Cho, 2001 ; Ashida, 2002). The multi-body model of a sheet of paper we used consists of 99 homogeneous rigid body segments. The length of each segment is 3 mm. The density of the paper is 8×10^{-6} g/mm^3 and the Young's modulus is 2250. For the simulation we used a commercial general-purpose multi-body dynamic

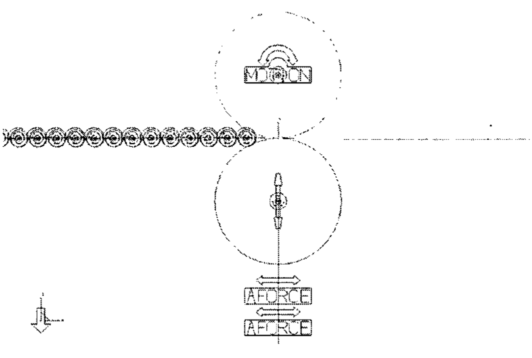
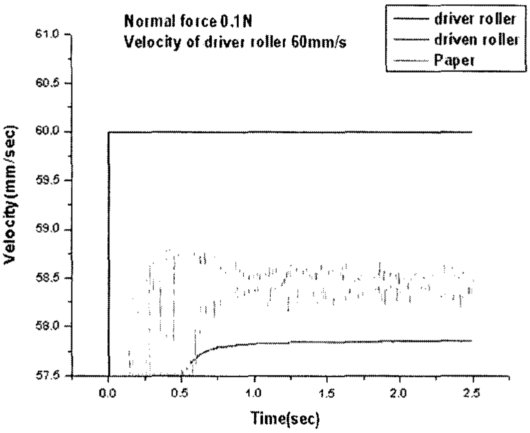


Fig. 5 2D multi-body dynamic model of paper in **RecurDyn®**

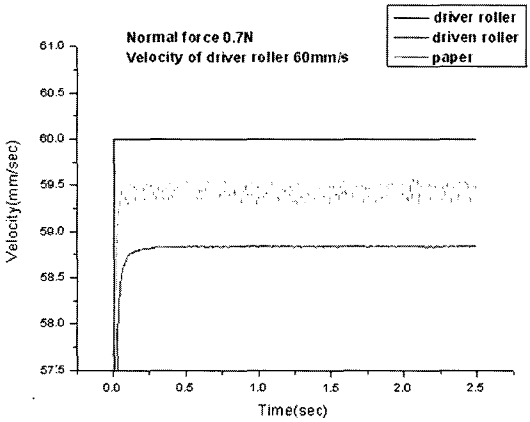
analysis program called **RecurDyn**. As shown in Fig. 5, also two feeding rollers, a driving and a driven, are modeled and included in the system model. The friction coefficients between the rollers and the paper are modeled following the experimental results shown in the previous section.

3.2 Simulation results

Simulations of the paper transfer process were performed for four different normal forces of 0.1 N, 0.3 N, 0.7 N and 1 N. In each simulation the linear speed of the driving roller is set to 60 mm/sec. Detail simulation results for normal forces of 0.1 N and 0.7 N are included in this paper and they are shown in Fig. 6. Plot (a) in Fig. 6 shows calculated speeds of the driving rollers, the driven rollers and the paper transfer when the normal force between the driving rollers and the driven rollers is set to 0.1 N, the linear speed of the driven rollers calculated to be about 62 mm/sec. The speed of the paper being fed through the feeding rollers calculated to be oscillating around the speed of the driven roller speed and the range of the speed is between 57 and 65 mm/sec. Plot (b) in Fig. 6 shows simulation results for the normal force of 0.7 N. In the plot the speed of the driven rollers is calculated to be about 67 mm/sec. Similarly to the case of 0.1 N the speed of the paper oscillates around the speed of the driven rollers and the amplitude of the oscillation is about ± 1 mm/sec. Comparison of plot (a) and (b) in Fig. 6 shows that, as expected, the speed of the driven rollers follows better the speed of the driving rollers with the increased normal force and the amplitude of the oscillation of the paper transfer speed is apparently diminished with the higher normal force. Fig. 7 shows the calculated slippage of the paper for four normal forces (0.1 N, 0.3 N, 0.7 N and 1 N) and four different driving speeds (30, 60, 120 and 150 mm/sec). In Fig. 7 we observe the amount of the slippage of the paper diminishes as the normal force between the rollers increases and it increases as the driving roller speed increases.



(a) Normal force=0.1 N



(b) Normal force=0.7 N

Fig. 6 Simulation results of paper feeding process for two different normal forces

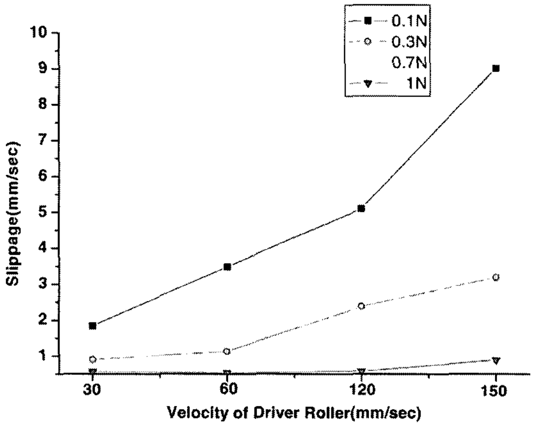


Fig. 7 Slippage of paper for four different normal forces and four different driving roller speeds (Simulations)

4. Experiments

4.1 Experimental configuration

Using the test-bed illustrated in section 2, we performed a series of paper feeding experiments to measure the slippage of the paper for different normal forces. Two optical photo sensors were used to measure the movement of the paper. The photo sensors measures the speed of the paper movement by detecting the evenly spaced lines marked on the paper being fed through. To improve the resolution of the photo sensor, we have aligned two photo sensors with 90 degree phase offset and the signals from the two sensors are fed into an encoder device. The resultant resolution of the photo sensor unit is 0.75 mm. The pulse signal generated by a function generator is sent to the driving step motor to regulate the speed of the driving roller at 60 mm/sec. The linear speed of the driving rollers and the driven rollers are measured with the two encoders attached at the driving axis and the driven axis. The sampling times for the encoder signals and the optical photo sensors are set to 0.2 sec. The height of the driven axis was adjusted using the cylindrical adjusting mechanism at the each end of the driven axis to produce a desired normal force at contacting points of the driving rollers and the driven rollers. Fig. 8 shows the diagram of the entire experimental setup including the data acquisition units.

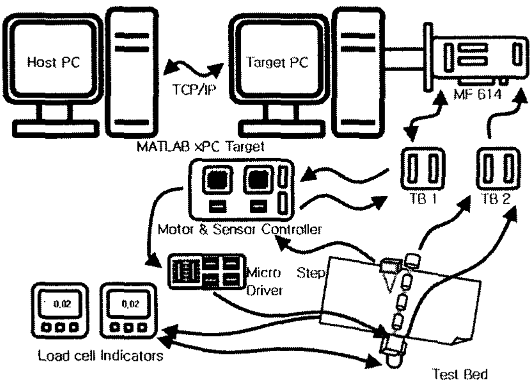
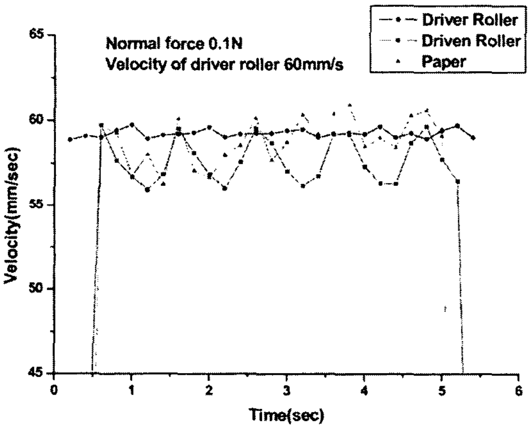


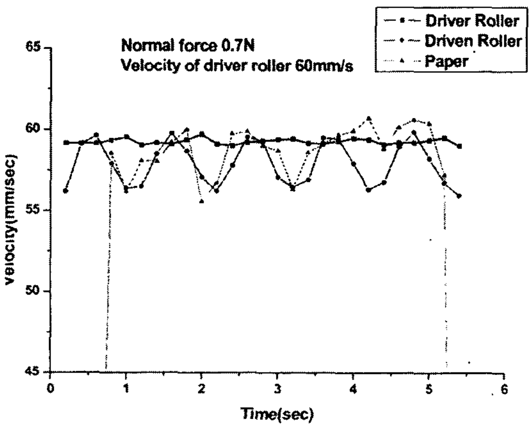
Fig. 8 Diagram of entire experimental setup for paper feeding experiments

4.2 Experimental results

Experiments of the paper feeding process are performed for normal forces of 0.1 N, 0.3 N, 0.7 N and 1 N. In this paper are included only two sets of detail experimental results obtained for the normal forces of 0.1 N and 0.7 N. Plot (a) in Fig. 9 shows the measured linear speed of the driving rollers, which is regulated around 60 mm/sec, the measured linear speed of the driven rollers and the measured paper transfer speed. Overall the measured speed of the driven rollers is slightly smaller than that of the driving roller. The measured speeds of both the driving and the driven rollers fluctuate around their nominal value. The speed of the paper is measured to fluctuate around its nominal value of 67 mm/sec.



(a) Normal force=0.1 N



(b) Normal force=0.7 N

Fig. 9 Experimental results of paper feeding process for two different normal forces

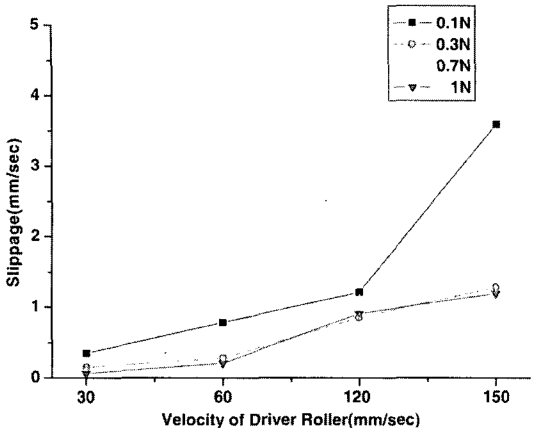


Fig. 10 Slippage of paper for four different normal forces and four different driving roller speeds (Experiments)

At the initial ramping-up period, the speed of the paper momentarily exceeds the driving roller speed and remains lower for the rest of the feeding process. Plot (b) in Fig. 9 where the normal force is 0.7 N shows similar trend to what is shown in Plot (a) but the overall slippage of the paper has decreased. The decreasing trend of the slippage of the paper with the increasing normal force can be observed better in Fig. 10, which shows the amount of slippage of the paper calculated from the experimental results for four different normal forces and for four different driving roller speeds. The trend of the variation of the slippage amount in experiments is very similar to the result obtained in simulations as shown in Fig. 7.

5. Discussions

The overall trends of the paper speed in both the experiment and simulation match well, but the quite significant fluctuations in the speed of the driven rollers and the paper transfer are observed in experimental results. From the careful comparison of the period of the oscillations and the driven roller rotation angles, there exists a very strong correlation between the period of the oscillation and the period of the rotation of the driven axis. Thus the oscillation in the speeds of driven rollers and the paper transfer speeds could be explained with the fluctuation in the normal force at the feeding rollers caused by two major manufacturing flaws in the experimental setup. The first one is in the circularity of the rollers and the second is in the straightness of the driving shaft and the driven shaft. The irregular radius of the roller around the perimeter could result in fluctuation of the normal force while the rollers are spinning. Also the manufacturing error in the shafts could result in similar fluctuation in the normal force during operation.

Compared to the driving roller speeds of our interest the optical sensor unit used to measure the paper movement in experiments has a relatively coarse resolution. Although we have used a large sampling time to avoid quantization noise in the velocity calculation, there is much more to desire in terms of improving the resolution of the paper position measurement. A new sensory system is being developed and to be implemented in the future works for a better measurement.

6. Conclusions

The slippage of the medium in the media transport system (MTS) degrades the performance of the whole system that includes the MTS as its sub-system. The understanding of the dynamics of the slippage in the media feeding system is essential to improve the performance of the MTS. This paper focuses on the effect of normal force on the slippage of the medium, particularly paper. As a fundamental feeding mechanism, we took a pair of shafts that have three pairs of rollers coated with high friction material. In the feeding system, the paper is transferred by the friction force between the paper and the rollers spinning with the driving shaft and the driven shaft. To study normal force the effect we have performed a series of simulations using a commercial multi-body dynamic analysis tool called **RecurDyn®**. In the simulation the paper is modeled as a multi-body dynamic system which consists of 99 rigid body segments connected by rotational springs and dampers. The feeding rollers were also modeled in the simulation. We calculated the slippage of the paper being fed into the feeding system for the different normal forces exerted between the two feeding shafts. To verify the simulation results, we have designed and constructed a test-bed of a paper feeding system. The system parameters of the testbed were experimentally estimated and the parameters are used in the simulations. The slippage of the paper for different normal forces was experimentally measured and compared to the simulation results. Both the simulation results and the experimental results show that the slippage of the paper increases as the speed of the driving roller increases and it decreases as the normal force increases. Using the developed simulation model and the testbed, active control of the paper transfer behavior is to be studied in the near future.

Acknowledgment

We would like to thank S. H. Lee and S. E. Kim, members of Intelligent Robotics and Mechatronic Systems Laboratory at Kyung Hee University, for their helpful assistance in experiments.

References

Ashida, T., 2002, *Technical Meeting*, Miyanodai Technology Development Center, Fuji Film Inc. Japan.

Cho, H., Choi, J., 2001, *2DMTT Development Specification*, Technical Report, FunctionBay Inc.

Diehl, T., 1995, "Two dimensional and Three Dimensional Analysis of Nonlinear Nip Mechanics with Hyperelastic Material Formulation," *Ph. D. Thesis, University of Rochester*, Fuji Film Inc. Japan.

Nishigaito, T., Okuna, K. and Ishii, H., 1994, "A Method for Analyzing Paper Behavior to Prevent Slippage of Transferred Image in Laser Printers," *JSME*, Vol. 60, No. 557, pp. 272~278.

Okuna, K., Nishigaito, T. and Shina, Y., 1994, "Analysis of Paper Deformation Considering Guide Friction," *JSME*, Vol. 60, No. 575, pp. 75~80.