Investigation of the Behavior of Optical Based Toner-Level Sensing

Hong Ren and Larry Stauffer, Department of Mechanical Engineering, University of Idaho, Boise, Idaho, USA
Santiago Rodriguez and Thom Ives, LaserJet Supply R&D, Hewlett-Packard Company, Boise, Idaho, USA

Abstract

The optical based toner-level sensor (TLS) is extensively used in color LaserJet printers to monitor the remaining toner in a cartridge, which helps users know when to change and reorder replacement cartridges. Our recent study found that the optical based TLS signals exhibit large variation. In order to have a better understanding of the optical based TLS technology, statistically designed experiments were used to identify the factors that most significantly impact variation of the signal. Six major factors were investigated in this study. It was found that different toner colors with different toner levels have different significant factors. The governing equation of translational motion for particulate materials is used to qualitatively explain the observed phenomena.

Introduction

"A typical image-forming apparatus, such as a printer or a copier, involves the development of powder toner onto a latent electrostatic image formed on the surface of a photoconductor."[1] For electrophotographic printing, the supply of powder toner is usually stored in a replaceable toner cartridge. By more accurately sensing available toner level inside cartridges, users will know when to order and replace cartridges. One of the most extensively used technologies in color LaserJet printers to monitor toner levels is optical based toner level sensing (TLS) technology.

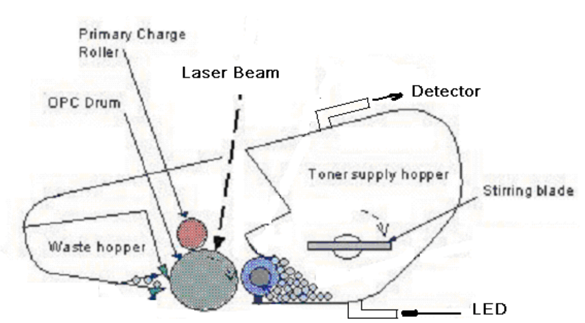

Figure 1. Toner Cartridge Cross Section

As shown in Figure 1, optical based TLS technology involves the use of an emitter and detector pair to sense the presence of toner within a toner cartridge. This technique requires the use of a viewing window and a wiper, or stirring blade, inside a cartridge. A typical detector voltage waveform is plotted in the Figure 2. When the wiper rotates, the window will be cleaned (toner is moved off the window surface) allowing light from an emitter to shine into the window and be detected, which results in a voltage drop. After this wiper passes the window, some toner will flow back to cover the window, resulting in a voltage rise. A threshold value distinguishes between a covered window and a clear window. The time interval between high voltages is proportional to toner level.

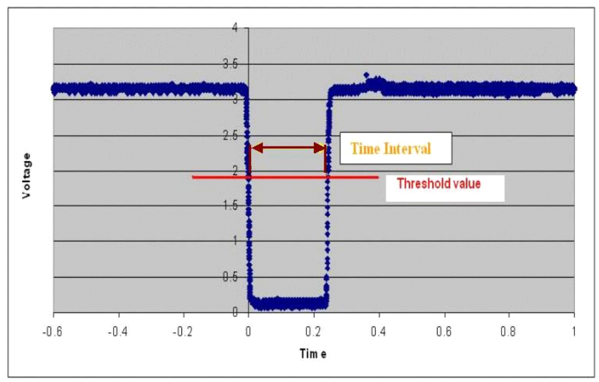

Figure 2. Typical Detector Voltage Waveform

Although this technology is extensively used, there is no in-depth research on its behavior. Our preliminary study revealed that the TLS time interval signals are very noisy, that is, they exhibit a high degree of variability (Fig. 3).

In this study, we conducted statistically designed experiments to identify the factors that most significantly impact TLS signal variations.

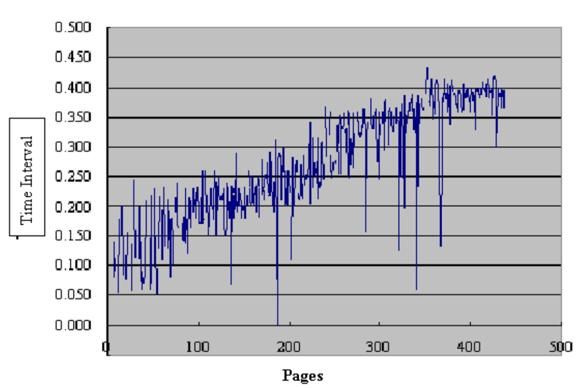

Figure 3. TLS Time Intervals vs. Printed Pages

Experimental Design

Selection of Design Factors

In our preliminary study, toner flow inside a cartridge was observed using a high-speed video camera. Through the high-speed videos, it was found qualitatively that the shape of the wiper has a very significant impact on the toner flow, which is the basis of optical based TLS. Four factors associated with the shape and geometry of the wiper were chosen as well as rotational speed and emitter light intensity. Although some other factors, such as geometry of a toner cartridge, may significantly impact TLS variation, it is hard to modify that because of limited resources. They were not studied in this project.

In all, six factors were selected for study. These factors and their levels for study are listed in Table 1. To protect the company, the names are not listed here.

Table 1: Factors and Levels Selected

Factors	Description	Type	Low	High
A	Rotation Speed	Numeric	-1	+1
B	Wiper Shape Related	Categorical	-1	+1
C		Numeric	-1	+1
D		Numeric	-1	+1
E		Numeric	-1	+1
F	Light Intensity	Numeric	-1	+1

Response Variable

For each experimental run, 15 to 30 TLS signals were captured. Since the rotation speed is one of the design factors, the average TLS signals were very different. Lower rotation speeds yield larger averages. Thus, coefficient of variation (ratio of standard deviation to TLS signal average) was chosen as the response variable.

Experiment Selection

A half fractional two-level factorial design was applied in this study. Standard data analysis techniques are used to determine effects of factors and relationships between them. This process is commonly referred to as Design of Experiments.[3] There are two reasons to chose a half fractional design: 1) cost, a full factorial experiment needs 64 runs and 32 modified cartridges; and 2) the alias structure (see Ref. [2] for details) of this design shows that: a) both main effects and two-factor interactions are not confounded with any other effects, and b) all three-factor interactions are confounded with another three-factor interaction. Generally, three-factor interactions are not very probable. Also results confirmed that no significant three-factor interactions exist. The 2^{6-1} (32) experiments are divided into 2 blocks: 1) normal office temperature and humidity, 2) high temperature and humidity.

In all, a half fraction two-level factorial design in 2 blocks was used to study six factors and their interaction effects.

Experimental Setup

The experiments were run outside printers, so a rotating mechanism, called as an idler, was designed to hold cartridges and rotate their wipers. An emitter-detector pair was fixed on the idler to simulate TLS. Voltage waveforms were documented and used to calculate the time interval. Sixteen modified cartridges were used in this study. Sixteen runs were conducted with cartridges normalized to normal office conditions and the high conditions, respectively.

Three toner levels (25%, 10%, and 0%) and two toner colors (Yellow and Black) were investigated in this study.

Results

The coefficient of variation was calculated and analyzed for every experimental run corresponding to different colors.

Results for Yellow Toner

The results for yellow are plotted in Figure 4. These results are based on square root transformed scales to validate the independently and normally distributed constant error term assumption.

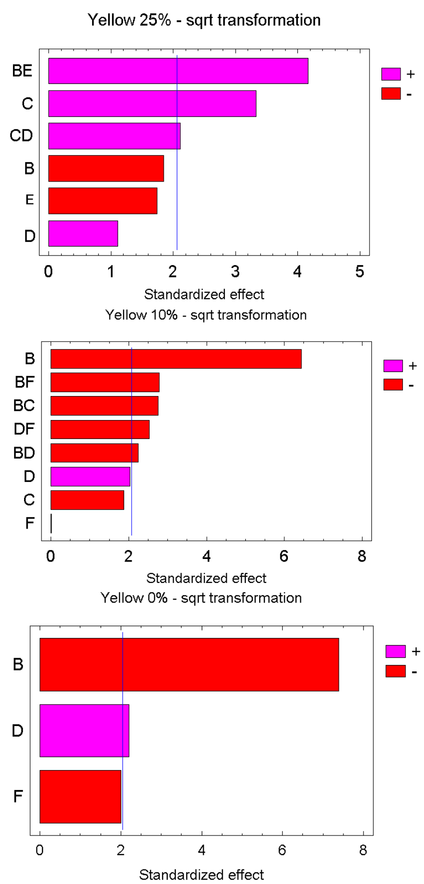

Figure 4. Results for Yellow (25% - 10% - 0%)

The vertical lines in these graphs indicate a decision value. Any effects exceeding this line will be treated as significant factors. Based on the hierarchy principal,[3] a factor will be kept if interactions between it and other factors were significant.

At 25% toner level, BE interaction is most significant followed by C, and CD. At 10%, B is 43.4% of the total variation and it interacts with F, C, and D. DF and D are significant too. BE and C is no longer significant. At 0%, the system is simple again with only 3 significant factors: B, D, and F. The system transition was simple-complex-simple with yellow toner and dominant factors changed at different levels. Thus, TLS optimization would be very difficult.

Results for Black Toner

Figure 5 shows the significant factors for black toner. As before, analysis is based on the sqrt transformation scales.

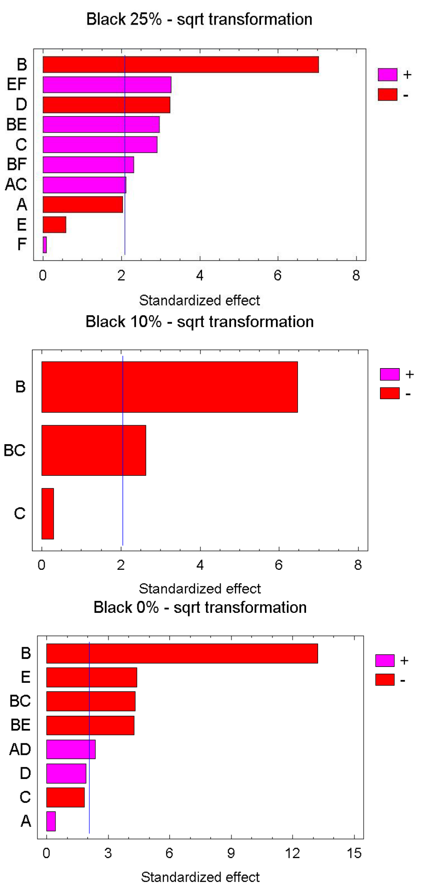

Figure 5. Results for Black (25% - 10% - 0%)

At 25%, there are many significant factors to TLS variation. B contributes the most followed by EF, D, BE, C, BF, AC and A. At 10%, there are only two significant factors: B and BC. At 0%, the system returns to complex. B continues to be the most significant followed by E, BC, BE, and AD.

The results were summarized in Table 2. A plus or minus sign indicates that when this effect changes from low level to high level, the coefficient of variations will increase or decrease respectively.

Comparing results for yellow and black, it was found that the TLS system transition for black was complex-simple-complex and yellow toner transition was simple-complex-simple. For the same color at different levels, the significant factors are different.

Table 2: Results

TL (%)	Significant Factors	
	Yellow	Black
25	BE, C, CD + + +	B, EF, D, BE, C, BF, AC, A -- + -- + + + + +
10	B, BF, BC, DF, BD, D -- -- -- -- -- +	B, BC -- --
0	B, D, F -- + --	B, E, BC, BE, AD -- -- -- -- +

Discussion

The results show that TLS behaves differently for different colors at different levels. The results also validate that the wiper's shape has a great impact on the variation of the TLS.

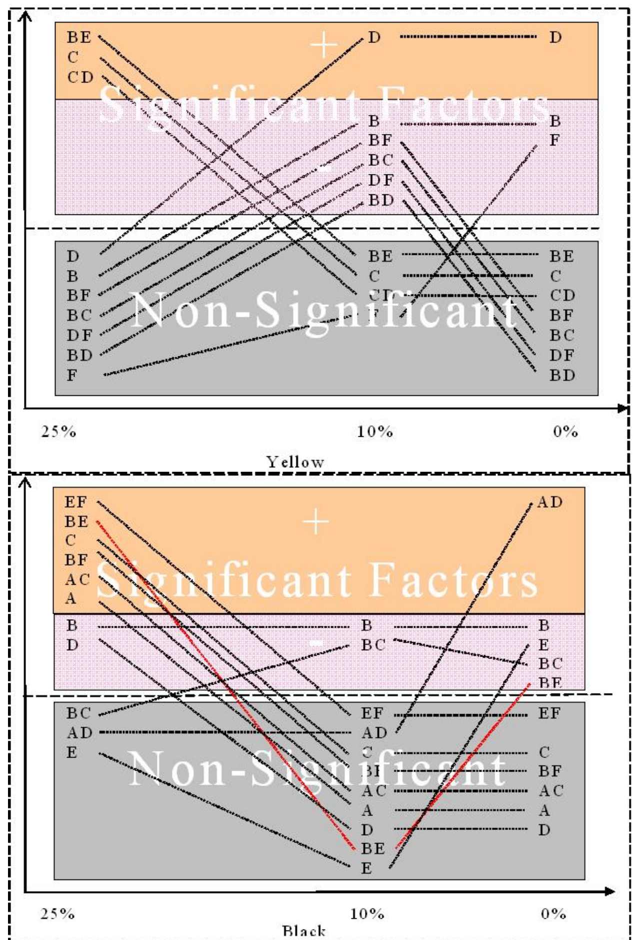

Figure 6. Results for Yellow & Black at Different Levels

Discussion on Factors

The results are plotted in Figure 6 to show the trends in significance between different levels. From these figures, we can see that there is no consistency for the significance of the factors as level and color changes. Besides, some significant factors even have different effect on TLS variations. For example, as shown in Figure 6 b), setting BE to low helps to reduce the variation at 25%

for black, which will increase variations at 0% for black. This makes it very difficult to optimize TLS system.

Discussion on Colors and Levels

Results reveal that toner behaves differently at different levels. Newton's second law helps to explain this phenomenon. Since this topic is complicated, only qualitative explanations are given here. Further research is being conducted to quantify these explanations. The governing equation for the translational motion of toner particle i can be written as

$$m_i \frac{d\vec{V}_i}{dt} = m_i \vec{g} + \sum_{j=1}^{k_i} (\vec{F}_{c,ij} + \vec{F}_{d,ij}) + \vec{f}_v + \vec{f}_e \tag{1}$$

The forces included in this equation are: 1) gravitational force $m_i \vec{g}$, 2) inter-particle collision forces, which are summed over all particles that come in contact with particle i, 3) electrostatic forces, and 4) Van der Waals forces.

As the particle populations varies, the number of particles contacting each other changes causing inter-particle collision forces to change. Subsequently, this will cause the electrostatic forces and Van der Waals forces to vary. How these forces change at various toner levels is a subject of future research.

Different colored toner particles have different ratios of component concentrations, which will result in different physical properties (e.g. friction coefficients). These properties directly impact inter-particle forces, electrostatic forces and Van der Waals forces. This has been confirmed by direct observations of toner flow using the videos, which revealed that yellow toner flows more easily, and black toner particles are more likely to adhere to one another.

Conclusions

Based on all above discussions, the followings may be concluded:

- Yellow and black toner colors have different flow patterns, since they have different physical properties.
- Different toner levels of the same color have different flow patterns, since the number of interacting particles varies.
- Yellow and black TLS transition oppositely.
- Factors associated wiper shape and geometry are the most significant factors to impact TLS variation.

The ongoing research of this work is aimed at give quantitative explanations for the above conclusions.

Future Work

Optical based TLS is based on toner flow in a cartridge. To understand toner flow in a typical cartridge environment is the goal for our future work, which can:

- Provide quantitative explanations for TLS;
- Explore some other factors that may be significant;
- Help to improve cartridge design.

Acknowledgments

The authors would like to thank Daniel Bates and Pat Dougherty for helping with experimental setup; all other engineers in HP LaserJet Supplies R&D group for their advice on factor selecting; Marcos Esterman and Darius Boockholdt for reviewing this paper. The authors would also like to thank HP LaserJet Supplies R&D for funding this work.

References

1. Darius Boockholdt, Hooper Howard G, Accurate toner level feedback via active artificial intelligence, EP877300, (1998).
2. D.C. Mongomery, Design and analysis of experiments, 5th Edition, ISBN 0-471-31649-0, Wiley, (2000).

Author Biographies

Hong Ren received her MS degree in Mechanical Engineering from Southwest Jiaotong University (1999). She is currently a Mechanical Engineering PhD student at the University of Idaho, doing research on LaserJet supplies. She is currently performing numerical simulation of cartridge toner flow.

Larry Stauffer is a professor of mechanical engineering at the University of Idaho in the field of design and manufacture. He has over 60 technical publications and supports a variety of industrial-sponsored research. He has B.S. and M.S. degrees from Virginia Polytechnic Institute and a Ph.D. from Oregon State.

Santiago Rodriguez has worked at HP for 18 years in many different areas of product generation such as manufacturing of circuit boards, development of "Surface Mount processes", design of circuit boards, ASIC packaging design, and LaserJet product development management. The last seven years he has worked as an Electro-photographic engineer responsible for Laser Jet development of monochrome and color consumables. He received his M.S. in 1987 from SDSU, and B.S. from the University of Puerto Rico.

Thom Ives, Ph.D., has worked at HP for 7 years and has performed a variety of research, development and engineering tasks. He has 16 U.S. patents. He teaches occasionally at local universities. He received his Ph.D. in 1997 from Texas A&M University where he modeled and researched hybrid-electric-vehicle power plants. His 1995 M.S. was also from Texas A&M with research in robotics. His B.S. was received from The University of Texas in 1984. All these degrees are in Mechanical Engineering.