

Advances in Traveling Wave Toner Transport

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Abstract

Characterization of the different modes of Traveling Wave Toner Transport (TWTT) is advanced through the use of improved measurement techniques, including a direct time-of-flight determination of particle speeds. Using these techniques, the attractive speed characteristics of the recently predicted "Hunching Mode" (HM) of transport is confirmed. Space charge, however, appears to severely limit the mass flows attainable in the HM. Mass flows in the "Surfing Mode" (SM), on the other hand, have been extended to exciting new levels, exceeding 25 mg/(cm-sec) - enough to develop or print more than 50 ppm. New approaches to powder cloud development and direct printing based on the SM of TWTT are indicated and referenced.

Introduction

Traveling Wave Toner Transport (TWTT) is uniquely capable of becoming the ultimate powder handling process for imaging applications. It transports unipolar, dry powder in "electrostatic capsules" with no moving parts or static adhesion to a carrier device (beads or donor roll). Therefore, it has the potential of extending the operating latitude, stability and quality of toner based imaging systems, while reducing cost.

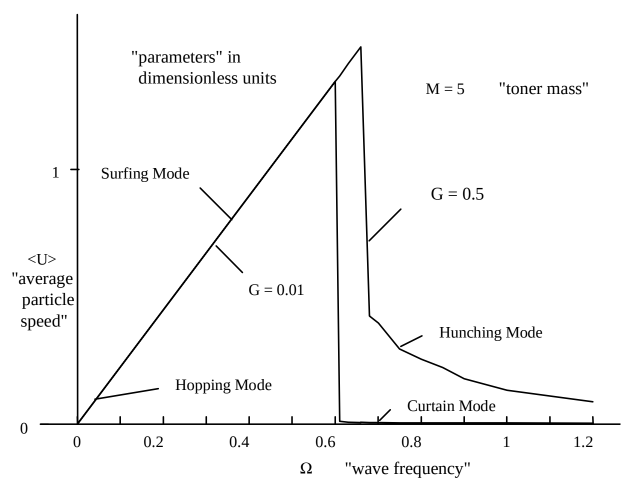

Figure 1. Particle speed vs. wave frequency of TWTT Modes in dimensionless units as defined in Ref. 1.

The efficacy of TWTT in imaging applications was discussed at the Eleventh NIP Conference.[1] Means of optimizing particle speeds for image development or printing was identified as an important issue. A newly discovered mode of TWTT, called the Hunching Mode (HM), was identified as a possible means of providing speed control in the desired range. Experimental techniques developed to investigate the feasibility of producing the HM and utilizing it for imaging purposes are now described. The results confirm the predicted speed characteristics of the HM but toner flow rates so far achieved are severely limited. However, new high levels of toner flow in the well-established Surfing Mode (SM) have inspired the invention of alternative methods of utilizing the SM in xerographic development[2] and powder priniting.[3]

Overview of the Modes of Traveling Wave Toner Transport

Fig. 1 shows the predicted particle speed characteristics of the modes of TWTT based on single particle analysis, reconstructed from Reference 1. Average particle speed is plotted vs. frequency in dimensionless units for selected bias conditions. The synchronous modes of transport, SM or "Hopping", fall along the straight line segment through the origin whose slope is consistent with the wave speed. The hopping mode, first identified by Melcher,[4] occurs at very low frequencies where a particle has sufficient time to hop ahead of the wave and come to rest on the conveyor until the wave catches up. When a particle stops, an adhesive bond to the conveyor forms that must be broken by the wave to launch the next hop. At higher frequencies, the SM occurs where the particle remains in motion while seeking out its equilibrium position on the wave where the wave force balances viscous drag. The toner actually move in a cloud- like state that is sustained by particle scattering. At sufficiently high frequencies the particles are unable to catch a wave, whence the passing wave generates a "levitation" force that pushes the particle away from the conveyor surface until it becomes balanced by a "gravitational" force. This is the "Curtain Mode" (CM) first identified by Masuda.[5] Applicability of this mode to imaging is precluded by the extremely slow speed of the particles in the direction of transport. But when the "gravity"[1] parameter is increased by application of a uniform electrostatic force normal to the conveyor, the average particle speed in the wave propagation direction greatly increases. This is called the "Hunching Mode" (HM) because the wave action appears to hunch the particle forward along the conveyor surface. The attractive feature of this mode is the predicted particle speed range that is tunable for specific applications.

Experimental Test Setup

The test arrangement utilized to investigate the HM and extend the TWTT database is shown schematically in Fig. 2.

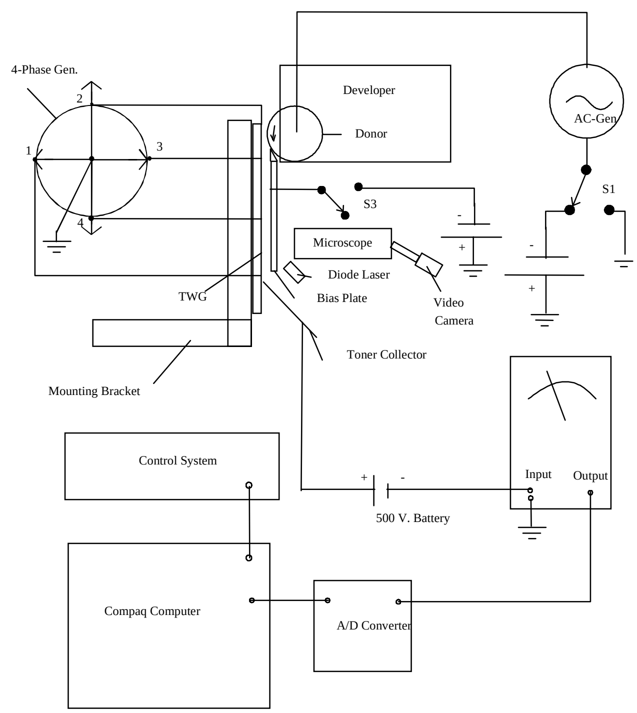

Figure 2. Schematic of Experimental Setup

The 4-phase Traveling Wave Conveyor (TWC) and 4-phase generator utilized in this work are similar to those described previously.[6] A bias plate, comprised of NESA glass joined to an aluminum wedge is spaced above the conveyor surface to produce a uniform bias field normal to the conveyor. The aluminum wedge is shaped to facilitate placement of the bias plate in close proximity to the donor roll of a Cannon jumping development system. The NESA glass in the bias plate enables inspection of the conveyor surface via a microscope fitted with a video attachment. Toner flow is monitored by recording its charge accumulation on a “collector” - a strip of aluminized Mylar biased to attract the arriving toner. The accumulated charge is measured with an electrometer whose output is passed through an A/D converter to a computer control system. In this way the time history of charge accumulation on the collector subsequent to the onset of toner loading is accurately recorded. The toner loading time and length of “run” are judiciously set to obtain a conveniently measurable quantity of toner accumulated on the collector. The latter is weighed before and after a transport recording to determine the average tribo (q/m) of the collected toner. A 0.5 mm wavelength conveyor 10 cm wide and 10 cm long from the loading nip to the collector is used throughout the work reported herein.

Transport Measurements

A typical family of charge accumulation traces for different wave frequencies is shown in Fig. 3. Toner loading is initiated at t = 0. An initial offset due to a residual electrometer drift is often evident. The important features of each trace are the sharp increase in negative slope (caused by toner arriving at the collector) and the time delay after which it starts.

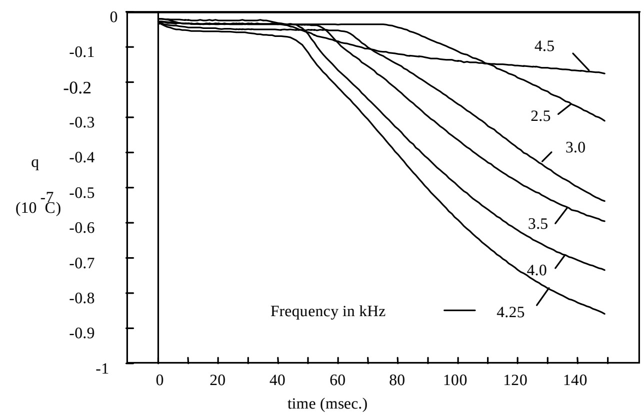

Figure 3. Toner Charge Accumulation on Collector subsequent to the onset of toner loading at t = 0 for different wave frequencies and the operating conditions for Case C in Table I.

The initial negative slope provides a measure of toner flow before significant space charge develops on the collector. The total travel time (tt) prior to the onset of charge collection represents the transit time down the conveyor plus a fixed loading delay. Plotting tt vs. wave period (not shown due to limited space) separates the two times. A linear segment whose slope agrees with the wave speed readily identifies synchronous transport. The tt intercept corresponds to the toner loading time. The transit times for all traces in Fig. 3 signify synchronous transport, including the trace for 4.5 kHz where the initial toner collection rate has fallen off dramatically.

Conversion of the initial slopes in Fig. 3 to mass flow per unit width of the conveyor, using the measured tribo of the accumulated toner, yields the mass transport characteristic identified as Curve C in Fig. 4.

Note the relatively strong wave amplitude and presence of a bias field for this characteristic. The peak mass-flow is outstanding for the high magnitude achieved, > 25 mg/(cm-sec). Comparison to Case B shows the expected advantage of using wave amplitudes approaching breakdown strength. Case A corresponds to the conventional base case with no bias plate present.

Table I – Operating Conditions for the Results in Fig. 4

Case	A	B	C
wave amplitude (volts)	350	350	490
donor speed (cm/sec)	18.8	18.8	18.8
$E_o = 2\pi V_o/\lambda$ (V/μ)	4.6	4.6	6.2
developer bias (volts)	210	230	230
donor-TWG gap (mm)	0.25	0.33	0.33
field plate bias (volts)	--	740	740
field gap (mm)	--	0.68	0.68
normal bias field, E_b (V/μ)	0	1.09	1.09
G (E_b/E_o)	0	0.24	0.18

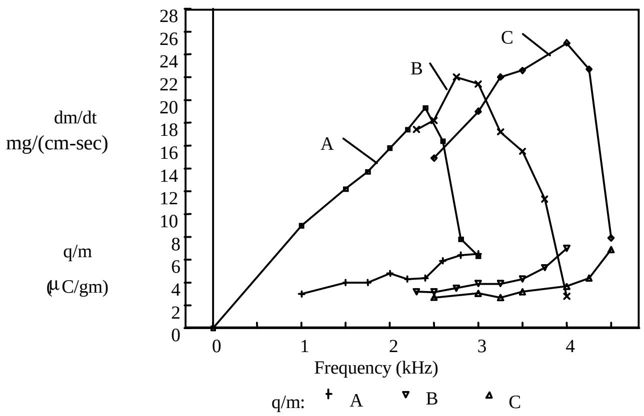

Figure 4. Toner mass flow per cm of wavefront and q/m vs. wave frequency, for the parameters listed in Table I.

Note that the mass transport characteristics for Cases A & B show a striking similarity to the theoretical toner speed characteristics shown in Fig. 1. This is the first known achievement of this similarity. It implies constant mass flow per unit area and signifies wave limited transport. Previous characteristics[6] involving magnetic brush toner loading have been consistently much flatter, indicating a loading limitation attributable to carrier beads interfering with toner successfully surfing out of the nip.

In accordance with analysis[1], evidence for the HM might be expected at the high frequency end of the flow characteristic. The measured transit time, however, at 4.5 kHz confirms the presence of the SM. The fall-off in mass flow at this frequency is therefore most plausibly explained by the onset of lower charged toner stalling in the nip. Its accumulated charge then chokes down the loading process. Further support for this hypothesis is evident in the plots of q/m in Fig. 4 for the three cases. Note the rapid rise in tribo of the collected toner coincides with the rapid decline in mass flow. More definitive evidence is found by repeating the 4.5 kHz measurement with the wave and toner loading voltages being switched off simultaneously. Disassembly and inspection of the conveyor surface revealed heavy toner deposits in the nip area under the donor roll. No significant deposits on the conveyor downstream were evident, as might be expected if slow moving toner had progressed down the conveyor.

Search for the Hunching Mode

In anticipation of possible difficulty in getting toner started in the HM due to congested and poorly defined field conditions in the loading nip, the TWC was constructed at the outset in isolated segments to enable operation of tandem sections of the conveyor at different frequencies. This makes it possible to start toner down the conveyor in the SM and then transfer it to an adjoining section operated at a frequency sufficient to support only the HM. Momentum of the toner particles should carry them across the interface between the two sections. An important advantage of this approach is that toner with measured properties and flow rate can be “smoothly” injected into the high frequency conveyor section. The transition can also be monitored with a video camera.

The lengths of the first and second conveyor sections are 5.1 and 4.9 cm respectively for the test conditions listed in Table II.

Table II – Operating Conditions for Two-Frequency Transport Measurements

Cases	A	B	C
Frequency (kHz) 1st Section	2.25	2.25	2.25
Frequency (kHz) 2nd Section	2.25	4.4	4.4
HF wave amplitude (volts)	460	460	350
Donor speed (cm/sec)	8.4	8.4	8.4
$E_o = 2\pi V_o/\lambda$ (V/μ)	5.8	5.8	4.4
Donor bias (volts)	230	230	230
Donor ac (volts amp @ 1.8 kHz)	600	600	600
Donor – TWC gap (mm)	0.3	0.3	0.3
Bias on field plate (volts)	200	740	740
Field gap (mm)	0.68	0.68	0.68
Normal bias field, E_b (V/μ)	0.29	1.09	1.09
G (E_b/E_o)	0.05	0.19	0.25

To establish a base case and quantify the toner flow to be transferred to the high frequency conveyor, both sections of the conveyor are first driven with the same 4-phase generator. This is designated as Case A in Table II and the result is Trace A in Fig. 5. For these tests, the toner loading-rate is reduced to approximately 4 mg/(cm-sec). This results in supply limited transport conditions (separately verified) and minimizes possible space charge effects. Trace A shows the onset of toner collection at 100 msec, which is divisable into 89 msec transit time and 11 msec loading time.

For Case B, the second conveyor section is connected to a separate 4-phase generator operated at 4.4 kHz. Note that the corresponding charge accumulation record, Trace B, shows the onset of toner collection delayed to 165 msec. Since the toner must arrive at the second section in 56 msec, as determined from Case A, 109 msec is left for the toner to transit the second conveyor, giving an average transport speed of .45 m/sec on the high frequency section of the conveyor. This is about 5 times slower than the wave speed, in good agreement with the speed anticipated for the HM.

Case C is the same experiment repeated with the wave amplitude reduced. Similar analysis of observed time delay, 175 msec for Trace C, now yields an average transport speed over the high frequency section of .40 m/sec - once again in good agreement with the anticipated speed of the HM.

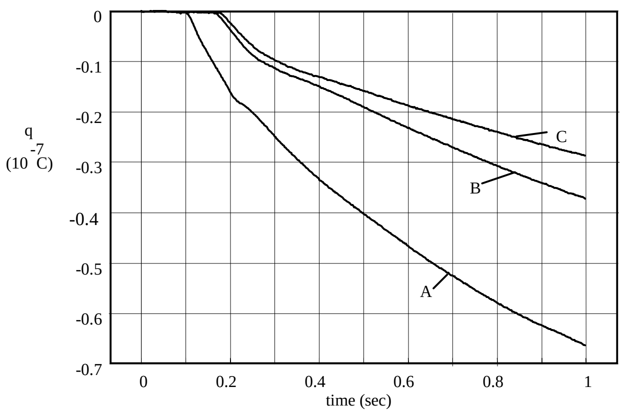

Figure 5. Charge collection traces for the experimental conditions in Table II.

Further inspection of the charge accumulation traces in Fig. 5, however, reveals a problem. The initial charge collection rates for Cases B and C are both smaller than that for case A. In addition, the measured average tribo of the toner collected for Cases B and C (6 and 7 μC/gm respectively) is found to be more than twice that for Case A (3 μC/gm). This implies that more than half the toner is not making it across the high frequency section of the conveyor. A video camera focused on the conveyor surface near the junction of the two frequency sections reveals that the missing toner stalls (piles up) on the conveyor just inside the high frequency section.

Extensive testing showed that still lower loading rates resulted in less toner stalling at the interface, and that sufficiently small accumulations would self-clear in time without assistance. Techniques for improving the efficiency of getting toner started in the HM are not yet apparent, but it is conceivable that sharper toner charge distributions in the supply might be helpful.

New Applications

The high mass-flow rates in the SM have inspired new techniques for dealing with the high particle speeds that naturally accompany the SM. An electrostatic path deflection method[2] for reducing the gap between the developer aerosol and a latent image has been found effective as an alternative solution to the previously noted edge deletion problem associated with traveling cloud development[1]. A new direct powder printing process[3] forms images off the end of a TWC without changing the particle direction. It utilizes means of dividing the linear toner clouds on a TWC into pixel wide segments, with the quantity of toner transported in each segment being continuously modulated independently. Simple continuous-tone printers capable of making photographic quality prints are possible.

Conclusion

The attractive particle speed control of the HM as a means of solving the edge deletion problem with traveling cloud development[1] appears limited to extremely low mass-flow applications. However, the means of using the high-flow SM indicated above provide exciting new opportunities.

References

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Biography

Fred Schmidlin obtained his Ph.D. in theoretical solid state physics from Cornell in 1956. After seven years in the aerospace industry, he joined the Xerox Research Laboratory in Webster, NY where his primary focus was on the fundamental processes of electrophotography, transport phenomena, and the signal/noise limitations of particulate imaging systems. In 1993 he retired from Xerox to start his own company and conduct independent research in powder imaging. He has over 50 publications, 50 patents and won two SBIR Phase I Grants. He is a member of the American Physical Society, IEEE and IS&T.