The Role of Traveling Wave Toner Transport in Powder Printing

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Abstract

Results of recent analytical studies indicate that traveling electrostatic waves have the potential for becoming the ultimate powder handling technology for imaging applications. Prior traveling wave art has focused on the modes of toner transport known as the “curtain” and “surfing” modes of toner motion invented respectively by Masuda and Schmidlin. These modes of toner transport have the inherent ability to deliver unipolar toner to latent images as a controlled aerosol - providing potential for the formation of powder images with zero background density and particle size limited noise. However, the range of mass transport rates, toner speed and degree of aerosol confinement best suited for electrostatic image development are not fully accessible with any of the previously known modes of toner motion alone. The physical nature and limitations of the prior art are discussed, together with the nature and potential of new ideas for overcoming their limitations. Illustrative examples suitable for direct toner printing and xerographic development, or laser printing, are included.

Introduction

Traveling electrostatic waves provide the opportunity to convey a thin layer of unipolar, charged toner past a xerographic latent image in close proximity, but without contact, and with no moving parts. However, several problems must still be solved before this attractive, if not the ultimate, form of xerographic development can be realized. The objective of this paper is to review the physical nature of the previously known “curtain”[1] and “surfing”[2,3] modes of toner motion produced by traveling waves and show how they fail to transport toner with the speed and spatial distribution required for quality development. A newly discovered “hunching” mode of transport is then described which overcomes the limitations in the prior art and shows promise of conveying toner past latent images in an optimal manner. This new “hunching” mode was discovered via analysis and still requires experimental verification. It should be pointed out that its discovery was motivated by the desire to achieve a toner delivery process that will enable advanced forms of XeroJet[4] (XI-Tech’s trademark for dry-ink jets similar to DEP[5] and TonerJet[6]). But it will be evident that the same process is also suitable as a new form of n̲on-interactive u̲nipolar xerographic development system, referred to as NU-Development.

Background Theory

Following Melcher, Warren and Kotwal[7] (MWK), the possible modes of toner motion produced by a traveling electrostatic wave are found among the steady state solutions to the equations of motion. Simplified versions of these equations are:

$$M\frac{d^2\theta}{dt^2}+\frac{d\theta}{dt}+\Omega=-e^{-z}\sin(\theta) \tag{1}$$

$$M\frac{d^2z}{dt^2}+\frac{dz}{dt}=-e^{-z}\cos(\theta)-G \tag{2}$$

These equations are written in dimensionless terms and involve only three lumped parameters (M, Ω, G). By virtue of their position in the equations, these parameters play the role of “mass”, “frequency” and “gravity” respectively, but should not be confused with the physical quantities from which they are derived. The dimensionless quantities are defined in Table 1 in terms of the physical quantities listed in Table 2.

Equations 1 and 2 are further based on a simple periodic boundary wave as illustrated in Figure 1. This is the potential function at the boundary (z = 0) where the conveyor surface resides. It should be kept in mind however that the potential function continues throughout the half space (z > 0), but with a wave amplitude that decreases exponentially ($\sim e^{-z}$) with distance from the boundary. Except for this important caveat, the force on a charged particle appears somewhat similar to force on a floating object on a water wave. The particle is forced toward a potential trough with a tangential force proportional to the slope of the wave. But in addition, it will “feel” a vertical force proportional to the amplitude of the wave.

Table 1. Definition of Dimensionless Quantities

Quantity	Definition
$(x, z,) = (kx', kz')$	coordinates
$(t, U) = (bEokt', bEov')$	time, toner speed
$\theta \equiv x - \Omega t$	phase angle of wave
$M = 2\pi bE_o\tau/\lambda$	"mass"
$G = (mg + QE_b)/QE_o$	"gravity"
$\Omega = f\lambda/bE_o$	"frequency"

Table 2. Relevant Physical Quantities

Quantity	Definition
(x’, z’, t’, v’)	coordinates, time and particle speed
f, λ	frequency, wavelength of wave
$k = 2\pi/\lambda$	propagator of wave
Q, m, a	charge, mass, radius of a toner particle
η, g	viscosity of air, acceleration of gravity
$b = Q/6\pi\eta a$	particle mobility
$\tau = m/6\pi\eta a$	viscous relaxation time
E_o, V_o	field and voltage amplitudes of wave
E_b	bias field normal to wave

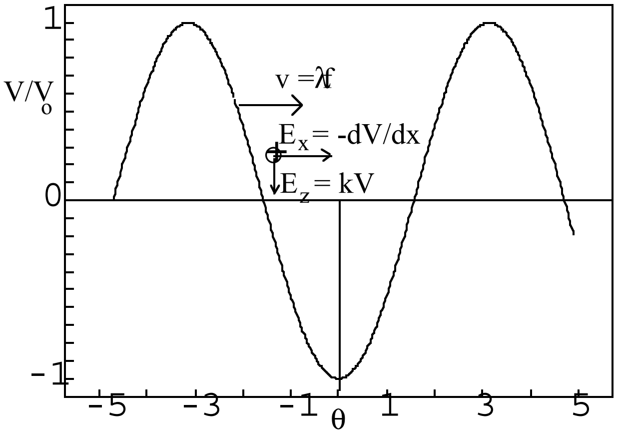

Figure 1. Sinusoidal boundary wave vs. phase angle

Numerical details and extensive discussion of the previously known modes of transport can be found in References 2,3,7. Here it is possible to simply highlight examples of the modes of interest.

The Modes of Traveling Wave Transport

The Curtain and Surfing Modes

The earliest known form of traveling wave particle transport is the “curtain mode” (CM) of Masuda.[1] Masuda first focused on ways to exploit the levitation force produced by an oscillating charge (dipole) in a field gradient. The inducement of a translational motion with a traveling wave came later. Examples of the CM for two different frequencies are shown in Figure 2. Note that the higher frequency produces a tighter cycloid. To achieve the same lift to balance gravity, the particle moves into a stronger field gradient closer to the conveyor surface. Note also that the higher frequency results in a slower average speed in the direction of the wave, given in dimensionless terms by $\langle U\rangle$. For typical conditions, $\langle U\rangle = 1$ translates to approximately 1 m/sec. Therefore, the average toner speed in the CM is much too low to be of practical interest in imaging applications.

Circa 1980, I independently foresaw the possible uses of moving toner with traveling waves, and invented the Charged Toner Conveyor.[2] The idea was suggested by the way people ride water waves. Though for an electrostatic wave, I envisioned the charged toner being held against the surface of the conveyor by the normal field of the wave, while the tangential field pushed it along. To distinguish this mode of motion from the CM, I called it the “surfing mode” (SM) - after the water surfing analog. An example of the SM is shown in Figure 3. Note that after one “hop”, the particle catches the wave and starts sliding along the conveyor surface at the wave speed ($f\lambda$), which in dimensionless terms, is U = 1.34. The particle, in this case, was started at rest on the surface of the conveyor, at z = a = 0.07, the toner radius. Not surprisingly, the speed change of a toner after catching the wave is dramatic - it increases by more than two orders of magnitude.

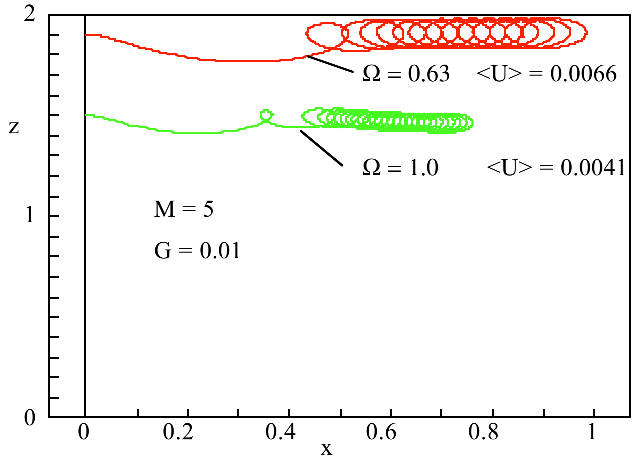

Figure 2. Examples of curtain mode at two frequencies

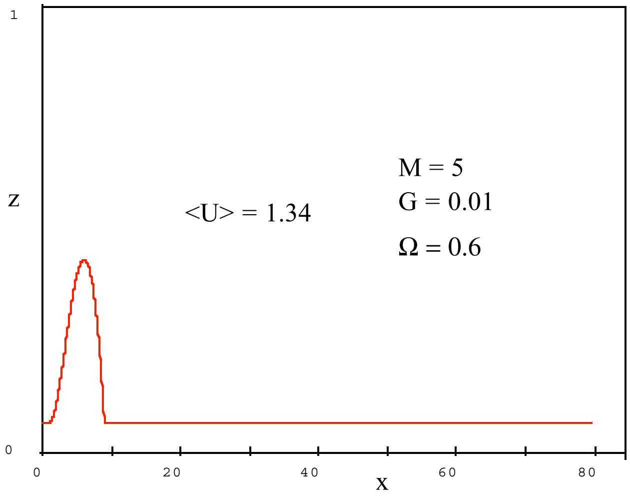

Figure 3. Example of surfing mode

A plot of average toner speed vs. frequency for normal gravity conditions, G = 0.01, is included in Figure 4. Note that the surfing and curtain ranges are sharply separated at a critical frequency, $\Omega_c \cong 0.61$. For $\Omega < \Omega_c$, the toner moves with the wave speed, but for $\Omega > \Omega_c$, the inertial response time of the toner becomes too long for it to catch the wave. At this point the toner launches into the CM, and its speed becomes extremely small, imperceptible on the scale in Figure 4.

Finding a toner speed suitable for imaging applications using these prior art modes of transport proves to be a problem. Toner speeds in the CM are much too slow. In the SM, on the other hand, toner speeds are too high at mass transport rates useful for imaging. At toner mass flow rates of practical interest, ~ 10 to 30 (mg/sec)/cm, the toner speed proves to be in the m/sec range - too fast for quality development - unwanted lead edge deletions appear. There is limited freedom to adjust the toner speed in the SM at constant mass flow. This limitation is inherent in the nature of the SM because stable toner motion is possible on a wave only for the 1/4 wavelength following the potential minimum (cf. Figure 1). Experimentally, toner covers only about 1/8 of the conveyor surface in the SM. Thus the speed for useful mass flow is about 10x too high.

Reflecting on the nature of the SM and CM, it was realized that the most plausible approach to solving the above dilemma is to look for a way to modify the CM. Since gravity plays a first order role in the CM, it occurred to me that some means of enhancing the gravitational force, or rather replacing it by a uniform electrostatic force normal to the conveyor, would force the toner into the high field region of the wave (close to the conveyor surface), and the toner might speed up. This idea worked. However, the toner action became dramatically different which called for a new descriptive name. For a reason soon to become evident, I called it the "hunching mode."

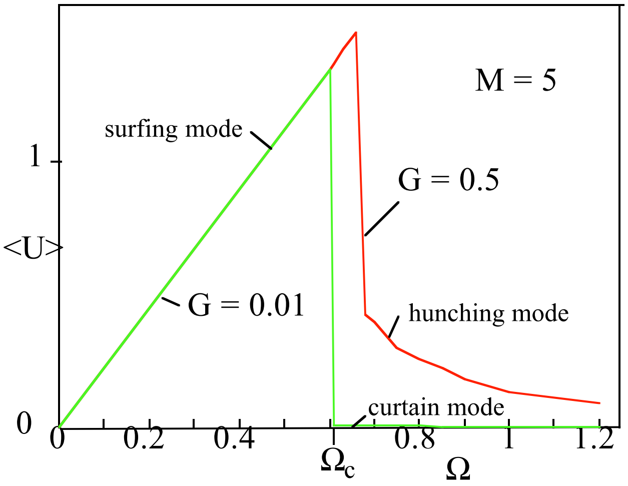

Figure 4. Average toner speed vs. frequency

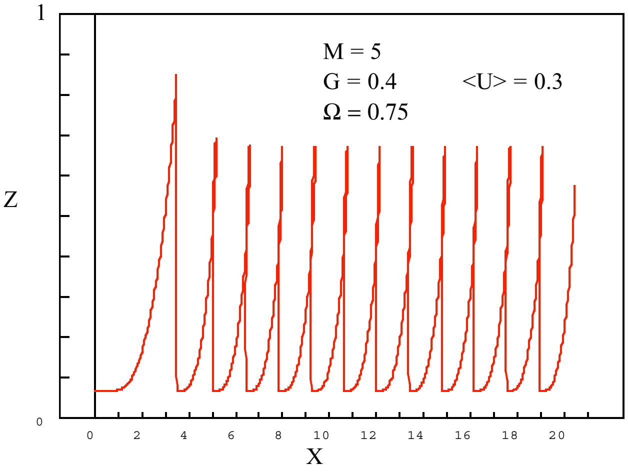

Figure 5. Example of the hunching mode

The Hunching Mode

Numerical experiments with anomalous parameters are easy to perform. Thus increasing G by a factor of 10 to 100 would provide an immediate test to the above idea. An example of the effect produced is shown if Figure 5. Note that the toner now slides part of the time on the conveyor surface, but each passing wave also lifts the toner off the conveyor surface and hunches it forward. Inertia prevents the toner from catching the wave (as in the normal gravity CM limit), so the toner slips backward until it is hunched forward again by the next wave. A plot of the average forward speed vs. frequency for G = 0.5 is compared to the former case (for G = 0.01) in Figure 4. In a nutshell, the toner speed is greatly increased and in the desired range. Additional plots, at constant frequencies, showing the average speed and average distance from the conveyor surface as a function of G are shown in Figures 6 and 7.

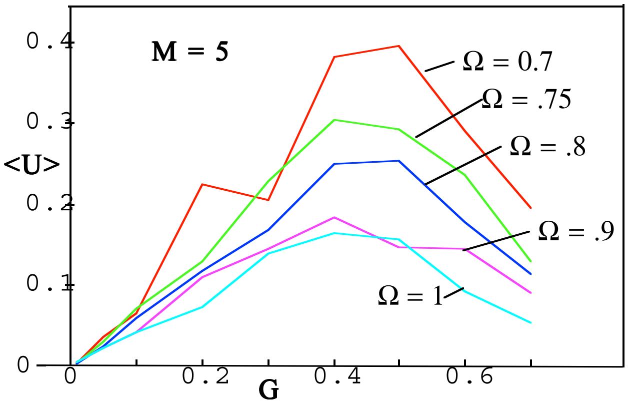

Figure 6. Toner speed vs. bias (G) for different Ω

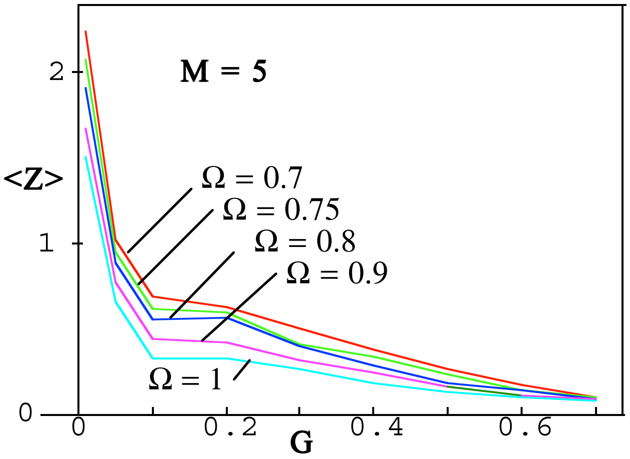

Figure 7. Distance from conveyor vs. bias (G) for different Ω

The range of physical speeds desired is v' = 0.1 to 0.5 m/sec. This will enable a wide range of applications, from direct printing and low volume xerographic engines, to mid and high volume xerographic engines. Further assuming typical xerographic toner will be used, 10 microns in diameter, Q/m = 5 to 10 micro Coulombs/gm, with a 0.4 mm wavelength conveyor, the working range of M is found to be 5 to 100. Using this information, the above range of v' converts to U = 0.1 to 0.4, for M = 5, and U = 0.005 to .02, for M = 100. Space limitations preclude showing data for different M, but numerical results show that the desired speed range is just as easily obtained for higher M. Figure 7 shows that z ~ 0.5 is easily attainable, which translates to a physical height of 35 microns. Allowing for dispersion, the physical depth of the mobile toner layer is thus estimated to be 50 to 75 microns. Therefore, the hunching mode opens the possibility of moving unipolar toner as a thin aerosol layer at speeds comparable to that of an image receiver - a condition that is ideally suited for advanced forms of scavengeless development, as well as practical forms of direct powder printing. It should be pointed out that the bias field will remove wrong sign toner before it is delivered to the latent image. The mass flow rate attainable with the hunching mode remains an unknown. It will have to be determined experimentally.

It should be remembered, of course, that these results have been obtained by solving the equations of motion for single particles. Certainly collective effects, especially the self field of the moving toner, scattering and air drag, will produce modifications, but these may well prove to be of second order importance.

Conclusion

Traveling wave toner transport has not been suitable for use in either direct powder printing or xerography prior to this time. This is attributed to the inability of the curtain and surfing modes of transport to deliver toner to a latent image with the speed and distribution required for quality development. The newly discovered hunching mode, however, provides a solution to this problem, at least in theory. The predicted toner motions and the applications they enable clearly justify continued ursuit of this promising technology.

References

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