Traveling Wave Transport of Conductive Toner Particles

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Abstract

Recent experiments by the author revealed that the transport of conductive, magnetic toner on a traveling wave device significantly differs from that of insulating toner. The major difference results from a critical frequency at which the direction of particle transport reverses.

In this paper the traveling wave transport of conductive toner is studied in detail. Toner conveyors with a grid ranging from 10 lpi to 83.3 lpi are used for the experiments. Three toners of different conductivity and particle size are examined. It is shown that the motion of highly conductive toner particles can be affected by higher harmonics of the applied voltages. Thereby, the toner might travel faster than the fundamental of the electrostatic wave. This effect appears at low velocities only.

Introduction

A number of experimental studies on the transport of charged toner particles utilizing traveling electrostatic waves has been reported.[1-5] Insulating monocomponent toner was used in all these publications. Experiments by the author revealed that the traveling wave transport of conductive toner particles differs from that of insulating toner. The major differences are:

1. Insulating toner must be charged by a charging device like a charge roller or a magnetic brush before it can be transported with a traveling wave device. Such a charging device is not needed for conductive toner. The conductive toner particles are charged on the conveyor through induction.
2. With conductive toner a critical frequency is found, at which the direction of particle motion reverses. This backward transport has never been reported in other publications of experimental toner transport so far.[1-5]
3. Charged insulating toner particles can be transported even when the grid is upside down without loosing significant amounts of toner.[4] This is impossible with conductive toner particles. They fall down when the gravitational force is pointing away from the conveyor surface.

Experimental Setup

The toner transport was studied with 11 different 3-phase toner conveyors each consisting of a printed circuit board with parallel electrodes. These were covered with an insulating polypropylene tape of 58 µm thickness (Fig. 1). The electrode dimensions of all tested toner conveyors are summarized in Table 1.

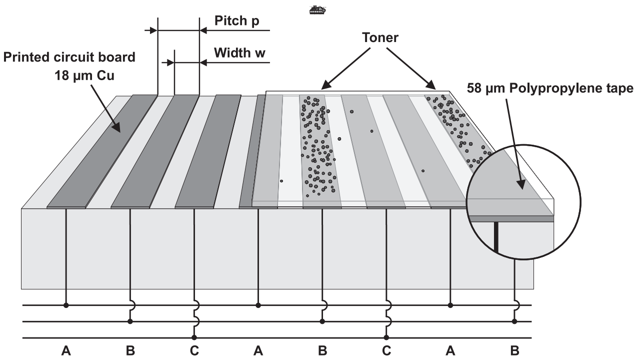

Figure 1. Three phase toner conveyor covered with insulating polypropylene tape

Table 1. Tested Toner Conveyors

Grid	Pitch p (µm)	Width w (µm)	Ratio w/p
10 lpi	2540	1970	0.78
		1470	0.58
		995	0.39
20 lpi	1270	950	0.75
		660	0.52
		300	0.24
40 lpi	635	375	0.59
		230	0.36
		145	0.23
62.5 lpi	406	140	0.34
83.3 lpi	305	125	0.41

Initially uncharged conductive and magnetic toner was placed on the conveyor were it was charged and transported after the driving voltages were applied. The velocity of the traveling toner clouds was measured using a high speed camera. For the experiments, three different types of toners were used. Their specifications are shown in Table 2. Note that in all cases the toner with higher conductivity is composed from particles of smaller size.

Table 2. Toner Specifications

Toner	Particle size distribution (90 Vol.% in this range)	Specific Resistivity
A	9 – 19 µm	10^6 Ωm
B	7.1 – 13.7 µm	9.4 x 10^4 Ωm
C	5.9 – 11.9 µm	6.7 x 10^2 Ωm

The traveling electrostatic waves were generated by a high voltage wave form generator which has been described previously.[6] With this generator, three phase-shifted voltages with an amplitude V_0 up to 750 V were applied to the conveyor electrodes.

In order to study the influence of the higher harmonics of the applied voltages two different wave forms were used. These wave forms, which have been referred to as wave form 1 and 3 previously[6], are sketched in Fig. 2.

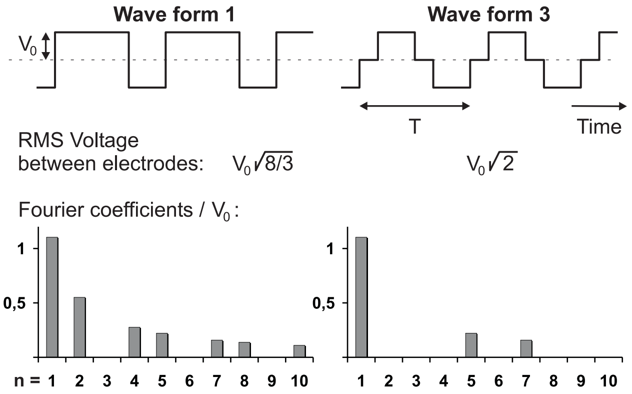

Figure 2. Wave forms 1 and 3 with their fourier spectrum

Both periodic signals can be expanded in a fourier series, revealing that wave form 3 contains significantly less higher harmonics than wave form 1. All even harmonics (n=2,4,6,...) vanish due to the symmetry of wave form 3.

Results and Discussion

With a signal frequency $f=1/T$ and a wavelength $\lambda=3p$ of the conveyor, the velocity of the fundamental traveling electro-static wave is $v_{fund}=\lambda f$.

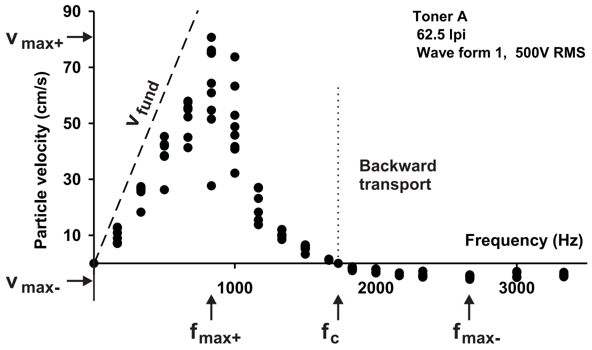

Figure 3. Particle velocity vs. wave frequency

Fig. 3 shows that the average toner velocity is usually slightly lower than the speed of the fundamental wave up to a frequency fmax+ where the particle velocity reaches a maximum of vmax+. At a critical frequency fc, the direction of particle transport reverses and the toner moves backward. The frequency fmax- marks the point of the maximum backward velocity vmax-. At very high frequencies, the backward motion finally stalls. Typical values of the mentioned characteristic frequencies and velocities are displayed in Table 3.

Table 3. Characteristic Parameter

Transport Direction	Typically
Forward	$1.7 \le f_c / f_{max+} \le 2.6$
	v_{max+} = 50 .. 100 cm/s
Backward	$f_{max-} / f_c \approx 1.5$
	v_{min-} = -3 .. -10 cm/s

A general observation is that the particle velocity depends on the particle density. Toner clouds which appear darker travel faster. For this reason, a range of velocities is measured for each frequency with the largest variations near the frequency f_{max+}.

When higher voltages are applied to the conveyor the maximum particle velocity and the critical frequency increase approximately linearly. It was found that the critical frequency is independent of the wave form, as long as the same RMS voltage is applied between adjacent electrodes of the conveyor (Fig. 4).

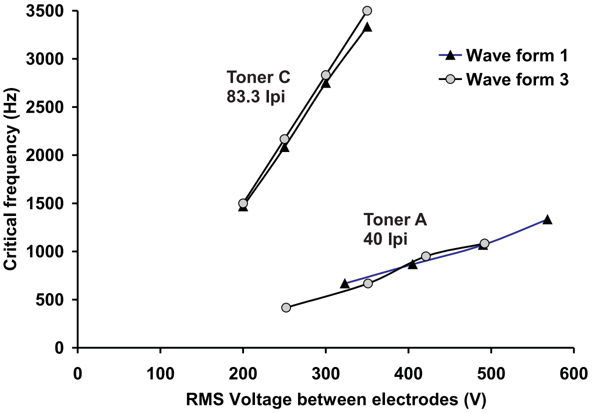

Figure 4. Critical frequency as a function of the RMS voltage applied between adjacent electrodes

Electrode Dimensions

As can be seen in Fig. 5, the critical frequency increases as the pitch of the electrodes becomes smaller. A similar result is achieved by using wider electrodes (larger ratio w/p). Of course, in both cases the electric field strength is larger if the same voltages are applied.

Fig. 5 shows the magnitude of voltages which have to be applied to achieve the toner transport.

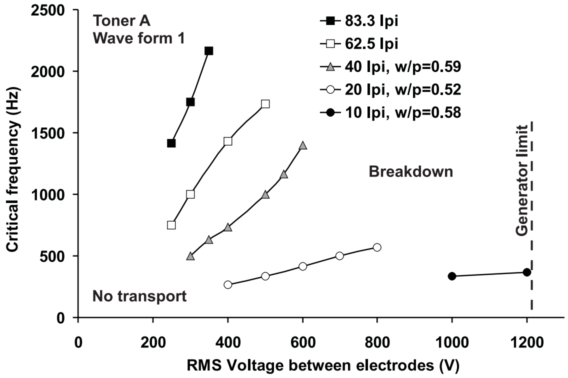

Figure 5. Critical frequency of conveyors with different grid

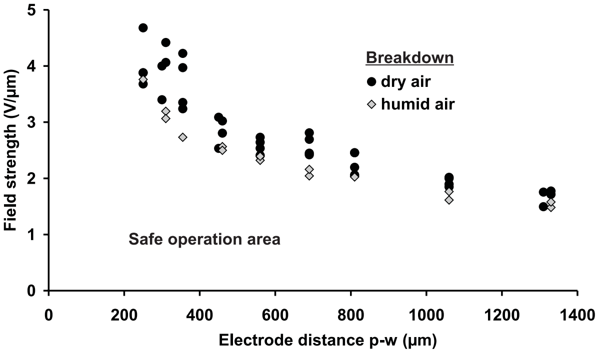

Figure 6. Breakdown field strength vs. electrode distance w-p

The useable range of each toner conveyor is limited by a minimum field strength being necessary for sufficient toner charging and a maximum field strength at which the conveyor can be damaged through electric breakdown.

The breakdown voltage is a nonlinear function of the distance p-w of the electrodes (Fig. 6)

For conveyors with a smaller grid, a higher electric field strength can be applied between the electrodes. On the other hand, the thickness of the insulating dielectric layer is larger in proportion to the wavelength λ, reducing the electric field strength at the conveyor surface. Both effects compensate each other and it was found that the achievable maximum particle speed for all conveyors is nearly the same.

For toner transport applications a conveyor with a small grid size is preferable for two reasons:

1. Lower driving voltages.
2. Fewer toner loss (dust), because the toner travels in closer distance above the conveyor surface.

Toner Conductivity and Particle Size

An increase of the toner conductivity has a similar effect as an increase of the applied electric field strength. As shown in Fig. 7 the critical frequency is significantly higher for a given applied RMS voltage between the electrodes. This effect can be explained by a forced charging of the toner particles.

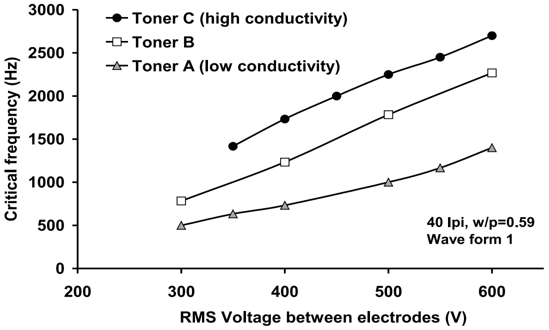

Figure 7. Critical frequency of toners with different conductivity

In accordance with this result, the characteristic velocities v_{max+} and v_{max-} increase as well. Their absolute maximum values are summarized in Table 3.

Table 3. Maximum Particle Velocities

Toner	Forward (cm/s)	Backward (cm/s)
A	81	-7.5
B	98	-11
C	105	-14

Nevertheless, it should be remarked that the particle size of the more conductive toner is smaller, too. Therefore, it cannot be distinguished clearly whether the particles travel faster due to a higher charge or because they are smaller in size. A combination of both effects might be possible as well. Further experiments with other toners would be useful.

Higher Harmonics

It was found that the front of the toner cloud can move faster than the fundamental of the traveling electrostatic wave. This is observed when the driving voltages contain higher harmonics of sufficient strength. The effect is stronger for toner with higher conductivity and appears at moderately low velocities of the traveling wave only.

In Fig. 8, the particle velocity relative to the velocity of the fundamental wave is shown for both wave forms 1 and 3. Although wave form 1 contains additional higher harmonics no significant difference can be seen with Toner A (low conductivity). The same experiment with the highly conductive Toner C (Fig. 9) reveals that at low velocities a certain amount of toner particles is transported by the faster traveling waves of the higher harmonics. The experimental data strongly suggest that the 2. harmonic is dominant.

In some cases, two wave fronts can be observed running at different speed: a small amount of faster traveling particles being transported by the 2. harmonic and the rest traveling with the speed of the fundamental.

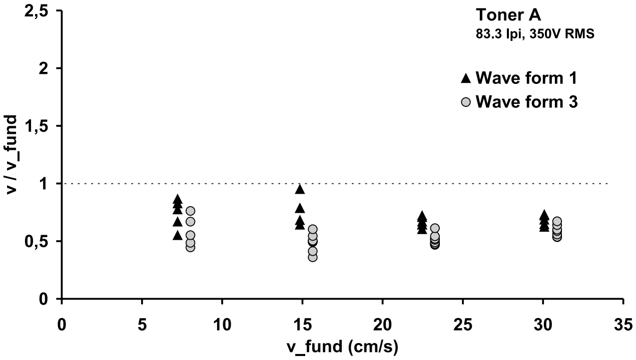

Figure 8. Particle velocity relative to the speed of the fundamental wave for different wave forms, Toner A (low conductivity)

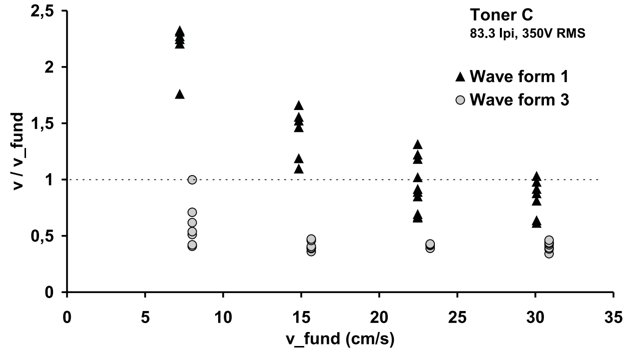

Figure 9. Particle velocity relative to the speed of the fundamental wave for different wave forms, Toner C (high conductivity)

It shall be remarked that the experiments with the different wave forms (Fig. 8 + Fig. 9) were carried out with the same RMS voltage being applied between the electrodes. Thereby, the amplitude V0 and the amplitude of the fundamental were larger by a factor $2/\sqrt{3} \approx 1.15$ in the case of wave form 3 (Fig. 3). The maximum particle velocity vmax was found to be larger by approximately the same factor when wave form 3 was applied. This is in good agreement with the observation that the particle motion is affected by the higher harmonics only at low speed.

Conclusions

1. The toner charging and the particle velocity of traveling conductive toner primarily depend on the strength of the applied electric field. The maximum velocity is determined by the strength of the fundamental of the traveling wave.
2. Smaller toner particles with a higher conductivity travel faster and the critical frequency is higher.
3. Highly conductive toner can be affected by higher harmonics of the applied voltages. Thereby the front of the toner cloud can travel faster than the fundamental wave. This effect appears at low velocities only.

References

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Biography

Ralph Kober was born in 1969 in West Germany. He studied at the Aachen University of Technology and received his diploma in electrical engineering in 1995. His diploma thesis dealt with the experimental study of an electrostatic printing process with dry toner using an electronic printing plate. At present he is with the Technical Electronics Institute at the Aachen University of Technology. He is engaged in electrostatic printing technologies and traveling wave toner transport.