An Experimental Setup for Bucket Brigade Toner Transport

Ralph Kober and Bernhard Hill
Technical Electronics Institute, Aachen University of Technology, Germany

Abstract

Traveling electrostatic waves rather than mechanical systems can be used to transport charged toner particles as a controlled aerosol. Extensive theoretical and experimental work on this subject has been done by Masuda, Schmidlin and Melcher et al. These authors used experimental setups with electrodes arranged in a grid structure. Multiple phase shifted sinusoidal voltages were applied to the groups of these electrodes to generate a traveling electrostatic wave.

As an alternative to using sinusoidal voltages, we propose a new method. Charged toner particles are transported utilizing the bucket brigade principle as it is used in charged-coupled devices (CCD).

For experimental work, a programmable 4-channel high voltage multiplexer has been developed which is able to switch voltages up to 1500 V. A traveling electrostatic wave suitable for toner transport is generated by multiplexing the voltages applied to groups of electrodes in an appropriate manner.

In first promising experiments using a Masuda panel, particle transport was achieved with conductive, magnetic monocomponent toner. At low switching frequencies, the charged toner particles moved synchronously in the direction of the traveling wave. A critical frequency was found at which propagation in both directions appeared and above this frequency backwards transport was observed.

Introduction

The idea to transport particulate material with traveling electrostatic waves was first conceived by Masuda.[1] Afterwards, this method has been studied in-depth for toner applications by Schmidlin[2,3,4,5], Melcher et al.[6,7,8] Utilizing a traveling wave conveyor for toner transport has the advantage that particle transport can be controlled through electrical parameters instead of mechanical means. Commonly, multiple phase shifted sinusoidal voltages are applied to the electrodes of the conveyor to generate a traveling electrostatic wave. In this paper an alternative method is presented.

The Bucket Brigade Principle

Charged particles can be transported using the bucket brigade principle. This method is well known from charged-coupled devices (CCD). Fig. 1 illustrates the way how particles of positive polarity are captured in potential wells. The electrostatic potential is generated by three groups of electrodes (A, B, C). Propagation is achieved by switching the applied voltages in the sketched way (wave form 1), causing the particles to move one pitch at each clock. The three phase shifted voltages have a period T of three clock pulses.

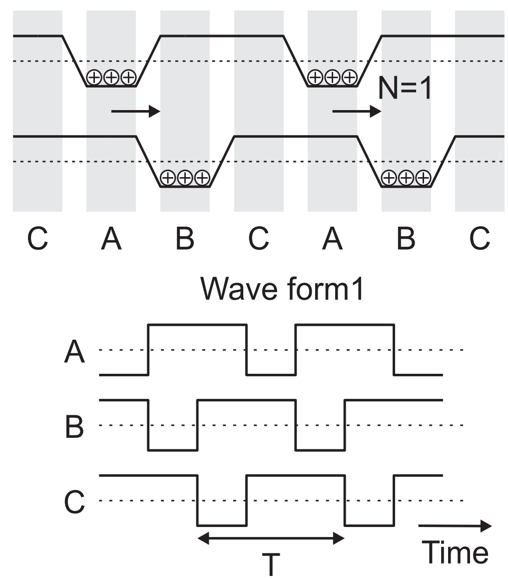

Figure 1. Charged particle transport

Salmon[9] and Yoshiki et al.[10] proposed this method for toner transport in their US Patents. Both inventors suggested to transport charged toner on a conveyor consisting of electrodes of appromimately the same width as the diameter of the particles (≈10 μm). Schmidlin refers to this invention as a digital packet conveyor.[5] Yet it is clear, that toner transport on a conveyor with much wider electrodes like a Masuda panel[11] or Schmidlin's charged toner conveyor (CTC)[2] will be possible as well. Furthermore, the bucket brigade principle will not be constrained to the wave form mode described in Fig. 1. A large variety of other wave forms can be used as well.

For example, in the first generation of CCDs, wave form 2 (Fig. 2) was commonly used for charge transport purposes. It differs from the first method in that transport from one electrode to an adjacent one takes place within N=2 steps. To achieve the same transport velocity as in the mode of Fig. 1, the clock frequency must be twice as high. In addition a third voltage level is used.

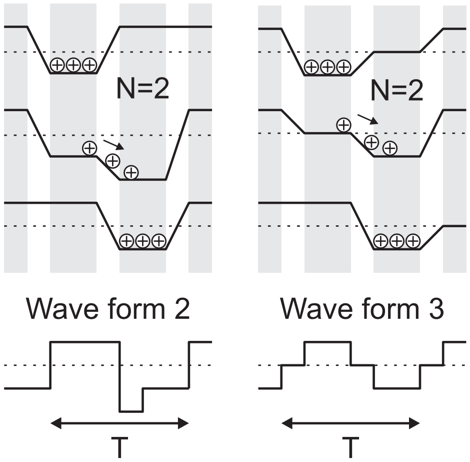

Figure 2. Bucket brigade transport with N=2

In a general approach toner particles could be transported from one electrode to an adjacent one within N steps (clock pulses) by applying M phase shifted voltages with K different voltage levels to M groups of electrodes.

Comparison with Sinusoidal Voltages

Both methods use multiple phase shifted alternating voltages to generate traveling waves. The bucket brigade principle is more or less a different view of the same idea. But it has the advantage that the traveling wave is generated in a digital manner, which is easier to control. At least, if only two or three different voltage levels are needed, a wave form generator suitable for toner conveyance can be built at low expense.

Nevertheless, there is a remarkable difference due to the different wave forms both methods use: the digitally switched voltages contain higher harmonics. So far, it is unknown if this affects traveling wave transport of toner particles. It might be a useful feature or be of disadvantage. Anyway, the amount of higher harmonics can be controlled through the use of different wave forms. For example, if a sine wave is aspired to, wave form 3 (Fig. 2) will be a useful approximation. If necessary, the remaining higher harmonics (n=5,7,11,...) can be attenuated through low pass filtering.

High Voltage Wave Form Generator

For experimental bucket brigade toner transport a high voltage wave form generator has been developed. Because of practical reasons the number of voltage levels K, steps N and phases M each have been limited to a maximum of four. The phase shifted output voltages are generated by a programmable 4-channel multiplexer. It consists of an array of 16 bilateral electronic switches (Fig. 3), through which each of the four outputs A,..,D can be connected to any of the four input voltages V1,..,V4 individually.

Thus, each of the four channels, indicated by the dashed boxes in Fig. 3, comprises four switches, forming a 4-to-1 multiplexer. A decoder being part of the programmable control unit ensures only one switch of every channel to be closed at a time.

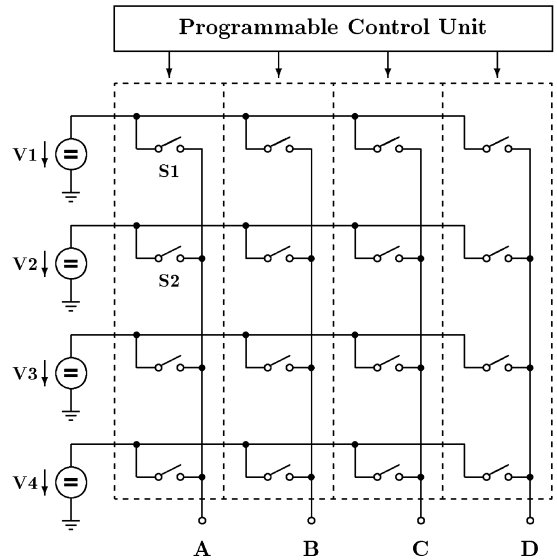

Figure 3. 4-channel multiplexer consisting of 16 switches

Each bilateral switch consists of a pair of high voltage power MOSFETs with a breakdown voltage of 1500 V. As an example, Fig. 4 shows a schematic of the electronic switch S1 that connects the output of channel A with the input voltage V1. Both N-channel MOSFETs Q1, Q2 are of enhancement type (normally OFF). The diodes D1, D2 represent the built-in reverse diodes of the transistors.

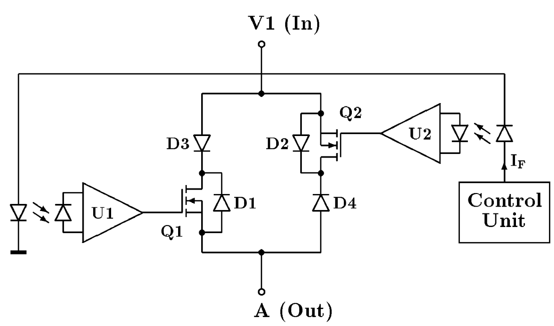

Figure 4. Schematic of a switch (Example: S1)

Normally, the switches are closed. They are turned on through optocouplers (U1, U2) which drive the gates of both MOSFETs simultaneously. For clarity of presentation, built-in protection devices are not shown.

The current rating of each switch should be preferably high, because it limits the slew rate of the output voltage. Nevertheless, even with relatively large capacitive load of 10 nF, a slew rate of 500 V/µs was achieved. The output voltages settle within 0.5 µs typically during the experiments.

Discharge Circuit

If more than only one positive and/or negative voltage shall be applied to the electrodes the following problem might occur. Depending on the desired wave form it might be that the capacitance of each electrode group must be discharged from a higher absolute voltage to a lower absolute voltage periodically. If both voltages have the same polarity, a reverse current for discharge must flow. Commercial power supplies usually don't deliver a reverse current, therefore the lower voltage level cannot be reached. To solve this problem, the power supply with the lower absolute voltage must be replaced by an expensive high voltage amplifier with a push-pull output stage. Alternatively a special discharge circuit (Fig. 5) as described in the following has been developed.

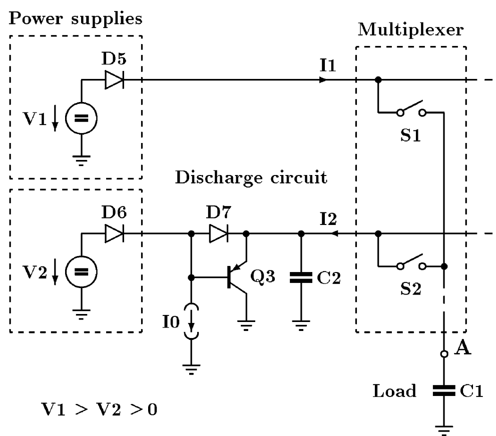

Figure 5. Schematic of the discharge circuit (positive voltages)

In Fig. 5 two power supplies are connected to the multiplexer, assuming V1>V2>0. Both power supplies deliver a forward current only, illustrated by the diodes D5 and D6. Capacitor C1, representing load of channel A, is charged to voltage V1 (current I1) and discharged to voltage V2 periodically. The discharge current I2 is short-circuited to ground via the transistor Q3. The current source I_0 provides the base current for Q3. Switching performance is improved by a bypass capacitor C2, C2>>C1 preferably.

Some technical limitations arise from bipolar transistors available on the market. If voltage V2 shall exceed 500 V, it is suggested to connect several power supplies in series, each equipped with a separate discharge circuit in parallel. To generate a wave form with only three different voltage levels these can be chosen +V, -V and GND. Then no discharge circuit is required at all.

Experimental

Experiments were carried out with a Masuda panel consisting of parallel electrodes 0.37 mm wide and 0.635 mm apart (40-lpi grid) on a printed circuit board. The electrodes were covered with a thin dielectric layer to provide electrical insulation and to give the conveyor a smooth surface. Particle transport was studied with a three-phase conveyor (wavelength $\lambda \approx 1{,}9$mm) using a conductive, magnetic monocomponent toner (Océ F10). A conductive toner was used for experimentation, because no tribo-electrical charging device like a charge roller or a magnetic brush is required. The initially neutral toner is charged through induction. Yet, the efficiency of the toner conveyor strongly depends on the properties of the dielectric layer. Best results were achieved with a 58 µm thick scotch tape made of polypropylene (35 µm foil + adhesive).

Observation of Particle Motions

When the voltages are switched at sufficiently low frequencies the toner particles move from one electrode to the adjacent within N clock pulses as it is expected from the bucket brigade principle. Being N=1, the particles jump over a distance of one pitch at each clock pulse. But, with N≥2, the particles are shifted from one side of the electrodes to the other before they hop to an adjacent electrode. The particles gather at the edges of the electrodes before they finally hop. In this hopping mode the particles move in a band-like structure where toner of the same polarity is displaced by one wavelength.

When the frequency increases the bands disappear and the toner moves in a cloud like manner. This mode was expected to be the "curtain mode", but surprisingly the transport velocity was observed to increase further as the frequency rises. This is inconsistent with the known "curtain mode". Efforts were made to measure the mean transport velocity of this mode with a light barrier. The results pointed to an asynchronous transport, but some doubt remains because of large scattering of the results.

An interesting effect is observed when a critical frequency is reached at which the velocity of the toner cloud steeply falls off and propagation in both directions appears. Above this frequency all particles are propelled backwards, in the direction opposite to the fundamental traveling electrostatic wave. The particles fly in a "curtain mode". The transport velocity and flying altitude are significantly smaller than during forward propagation. Both decrease further as the frequency rises until particle motion becomes imperceptible. Microscopic analysis revealed that most particles settle on the dielectric layer on top of the electrodes. The rest of them oscillate between the electrodes. Small particles cross the electrodes in backward direction occasionally. Finally, at very high frequencies motion stalls.

Discussion

The observed particle motions are very similar to those reported by Masuda et al.[12] They studied a traveling wave transport of lycopodium particles in silicone oil. It shall be noted that they reported a synchronous transport up to the frequency we labeled as critical. This would explain why the transport velocity seems to increase continuously. But the velocity could also increase in the case of an asynchronous transport. Hence, an open question remains.

Backwards transport was observed in the mentioned experiments with lycopodium particles[12] and it has also been reported from experiments with agricultural products.[13] But to the knowledge of the authors, it has never been reported from experimental work with toner particles so far.[2,8] Although perturbation theory predicts that the particles start drifting backwards at sufficiently high frequencies, the normal "curtain mode" was always observed instead. It shall be stated that all these experiments were carried out with insulating monocomponent toner.

Schmidlin searched for backward modes among the numerical solutions of particle motions. His conclusion was, that a countermoving harmonic of normal strength cannot account for backwards transport.[3] This condition of normal strength was true for our experiments.

Because of these contradictions we looked at the conditions for backwards transport. We found an approximately linear relationship between the critical frequency (fundamental) and the RMS voltage which is applied between adjacent electrodes of the conveyor (Fig. 6).

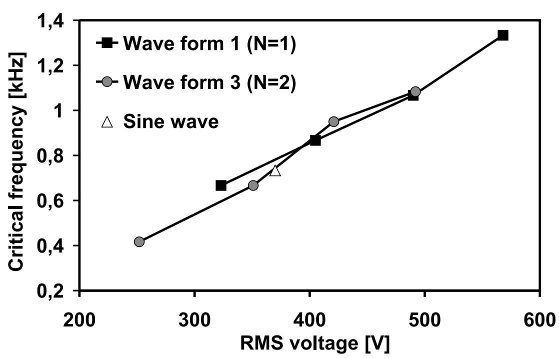

Figure 6. Critical frequency as a function of the RMS voltage applied between adjacent electrodes

In accordance with perturbation theory[12] the explanation seems to be that charging of the conductive toner becomes inferior at higher frequencies. The particles fly in closer proximity to the conveyor surface due to lower repulsion forces. There, the propulsion force of the countermoving harmonic wave is dominant and causes the particles to drift backwards. An increase of the electric field strength can compensate for this effect through forced toner charging. This is consistent with the observation of a higher transport rate in the low frequency hopping mode when the electric field is increased. Although the details of backwards transport still remain unknown it can be stated that space charge effects and the complex inductive charging mechanism seem to play a major role.

Conclusion

The charging and thereby the transport rate of conductive toner on a traveling wave conveyor primarily depend on the RMS voltage applied between adjacent electrodes. In technical applications, normally the peak-to-peak voltage between adjacent electrodes is limited. In this case digitally switched voltages can be of advantage. For example, wave form 1 provides a 15% higher RMS voltage than with sinusoidal voltages.

References

1. S. Masuda, US Patent #3,778,678, Dec. 11, 1973.
2. F. W. Schmidlin, *IEEE Trans. Indust. Appl.*, **27** (3), 480–487 (1991).
3. F. W. Schmidlin, *J. Electrostatics*, **34**, 225-244 (1995).
4. F. W. Schmidlin, The Role of Traveling Wave Toner Transport in Powder Printing, *Proc. 11th NIP*, pg. 515 (1995).
5. F. W. Schmidlin, US Patent #5,850,587, Dec. 15, 1998.
6. J. R. Melcher, E. P. Warren and R. H. Kotwal, *Particulate Sci. Technol.*, **7** (1), 1-21 (1989).
7. J. R. Melcher, E. P. Warren and R. H. Kotwal, *IEEE Trans. Indust. Appl.*, **25** (5), 949-955 (1989).
8. J. R. Melcher, E. P. Warren and R. H. Kotwal, *IEEE Trans. Indust. Appl.*, **25** (5), 956-961 (1989).
9. P. C. Salmon, US Patent #5,153,617, Oct. 6, 1992.
10. S. Yoshiki et al., US Patent #5,416,568, May 16, 1995.
11. S. Masuda, US Patent #3,801,869, Apr. 2, 1974.
12. S. Masuda, M. Washizu and M. Iwadare, Separation of small particles suspended in liquid by non-uniform travelling field produced by three phase electric curtain device, *IEEE-IAS Annual Meeting*, Toronto, ON, Canada, pp. 1418-1423 (1985).
13. J. M. Hemstreet, *J. Electrostatics*, **17**, 245-254 (1985).

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 on an electrostatic printing process with dry toner using an electronic print plate. Presently 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.

Bernhard Hill was born in 1938 in West Germany. He studied at the Aachen University of Technology and received his diploma in electrical engineering in 1964 and his Dr.-degree in 1968. From 1969 to 1984, he did industrial research with Philips GmbH in Hamburg, Germany. He developed new systems and components for laser deflection, holographic storage and erasable magnetooptic recording, magnetooptic displays and image bars for electro-photographic printing. In 1984, he became Professor at the Aachen University of Technology and head of the Technical Electronics Institute. He is now engaged in electronic imaging, printing and color reproduction.