ABSTRACT

A character generator is connected to the charging electrode of an ink jet printer nozzle through a compensating circuit which modulates the charging voltage applied to each individual ink drop in accordance with the charges on one or more preceding drops in order to compensate for the capacitance effect of the preceding drops on said one individual drop.

10 Claims, 21 Drawing Figures
where \( V(t) = \alpha \left[ f(t) + \beta_1 f(t-\Delta t) + \beta_2 f(t-2\Delta t) \right] \) and \( \alpha = 1 \), \( \beta_1 = .2 \), and \( \beta_2 = .01 \).
<table>
<thead>
<tr>
<th>STAIRCASE LEVEL</th>
<th>REQUIRED W</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>ACTUALLY OBTAINED W</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>MAX ERROR</th>
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</table>

WHERE

\[
W = \alpha \left[ f(t) + \beta_1 f(t-\delta t) + \beta_2 f(t-2\delta t) \right] \\
X = \alpha \left[ f(t) + \beta_1 f(t-\delta t) \right] \\
Y = \alpha \left[ f(t) + \beta_2 f(t-\delta t) \right] \\
Z = \alpha f(t) \\
\]

\[\beta_1 = .15\]  
\[\beta_2 = .05\]  
\[\alpha = 1.\]

**FIG. 10**

![Staircase Diagram](image)

**FIG. 11**

![Staircase Diagram](image)

**FIG. 12**

![Staircase Diagram](image)
1

INK DROP COUPLING CAPACITANCE COMPENSATION

FIELD OF THE INVENTION

The invention relates to ink drop printing and it has reference in particular to the generation of the proper charging voltage such that accurate compensation for the drop coupling capacitance distortion is achieved.

DESCRIPTION OF THE PRIOR ART

Richard G. Sweet, in Technical Report No. 1722-1, dated March 1964, of Stanford Electronics Laboratories, Stanford University, prepared under Signal Corps Contracts, DA36 (039) SC87300 and DA36 (039) AMC-03761E, entitled "High Frequency Oscillography with Electrostatically Deflected Ink Jets," on page 64, at FIG. 36(c), shows a normalized equalizing network comprising a simple RC circuit for preventing transient overshoot, and U. S. Pat. No. 3,631,511, entitled "Drop Charge Compensated Ink Drop Video Printer," which issued on Dec. 28, 1971, to Robert I. Keur and Vincent E. Bischoff, discloses a printer in which the adverse affects of the charge on a just-formed ink drop upon the charge of a following ink drop being formed are compensated for by utilizing an amplifier to amplify a video signal whenever a previous drop was charged.

OBJECTS AND SUMMARY OF THE INVENTION

Generally stated, it is an object of the invention to provide an improved quality of ink drop printing.

More specifically, it is an object of this invention to provide for modifying the charge applied to one ink drop in an ink drop printer in accordance with the value of the charges on the preceding one or more ink drops.

Another object of this invention is to provide for using storage means to provide for modifying the charge on an ink drop being formed in an ink drop printer in accordance with the charges on one or more ink drops which have just previously been charged.

Yet another object of the invention is to provide for modifying the charge on an ink drop being formed in accordance with a voltage defined by the equation

\[ V(t) = \sum_{i=0}^{K} \beta_i f(t - i\delta t) \]

where K is the number of drops having a non-negligible coupling capacitance with the drop being charged.

Still another object of the invention is to provide for detecting if one or more previously formed drops of ink in an ink jet printer have been charged and for modifying the charge on a drop currently being formed in accordance with the greater of two or more modifying voltages dependent on the charges on said previously charged drops.

Another important object of the invention is to provide in an ink drop printer for modifying the charge on a drop just being formed so as to substantially neutralize the capacitance effects on said drop of drops previously charged and thereby insure accurate positioning of said drop being formed.

Yet another object of the invention is to provide for connecting a character generator charging electrode signal source to the charging electrode in an ink drop printer through a plurality of circuits each of which apply different functions of the charging electrode signal to the charging electrode.

It is also an object of the invention to provide for connecting a charging signal source to the charging electrode in an ink drop printer by a plurality of delay means having different delay characteristics for modifying the charging signal at any instant in accordance with previous values of the charging signal.

Still another important object of the invention is to provide in an ink drop printer for utilizing a plurality of delay means having different characteristics to modify the charging signal at the instant of forming one drop in accordance with the charging signals at the instance of forming one or more previously formed drops.

The foregoing and other objects, features and advantages of the invention will be apparent from the following more particular descriptions of preferred embodiments of the invention, as illustrated in the accompanying drawing.

DESCRIPTION OF THE DRAWING

In the drawings:

FIG. 1 is a schematic diagram showing the relations between an ink stream drop formation and a charging electrode in an ink jet printer;

FIG. 2 is a schematic circuit diagram of a compensated ink jet printer charging circuit embodying the invention in one form;

FIG. 3 is a schematic circuit diagram of a compensated charging circuit embodying the invention in a different form;

FIGS. 4a - 4d show curves illustrating the voltage relations in FIG. 3;

FIG. 5 is a schematic circuit diagram of a compensated charging circuit diagram embodying the invention in another form;

FIG. 6 is a schematic circuit diagram of a compensated charging circuit embodying the invention in yet another form;

FIG. 7a is a circuit diagram of a R-C compensating network;

FIG. 7b is a waveform of a typical input signal;

FIG. 7c is a waveform of the resulting output signal from the R-C compensating network;

FIG. 8 is a schematic block diagram of a compensating circuit embodying the R-C network of FIG. 6a;

FIGS. 9a - 9d show waveforms for the circuit of FIG. 7;

FIG. 10 is a table of compensated charging amplitude voltage values for first and second order compensation according to the formulas of the invention;

FIG. 11 is a typical uncompensated staircase waveform of a charge amplitude control used with the circuit of FIG. 5 to provide the compensated values of the table in FIG. 9; and

FIG. 12 is a schematic showing of the WXYZ voltage divider of FIG. 6 showing the calculated values of resistance to give the voltage values of the table in FIG. 9.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIG. 1, the reference numeral 1 designates a stream of ink issuing from a nozzle N, the numeral 2 designates a drop just about to break off from the Stream 1 and the numerals 3 and 4 designate drops which have previously broken off. The numeral 5 desig-
nates a charging electrode for placing a charge on the drops as they are formed for deflecting them in accordance with a predetermined pattern onto a record or the like. The reference numeral 6 designates generally a source of voltage for the charging electrode 5. The following is a generalized derivation for the modified voltage pulse to be applied to a drop being formed in order to accurately position it on the document.

In the following analysis the symbols \( \Phi_i(t) \) and \( q_i(t) \) shall mean the voltage potential and charge respectively at time \( t \) on the \( i \)th conducting body in FIG. 1. From elementary electrostatics theory, there is a simple expression relating the charges to the voltage potentials which for the configuration of FIG. 1 is:

\[
q_i(t) = \sum_{j=1}^{5} C_{ij} \Phi_j(t); \quad i = 1, 2, \ldots, 5 \tag{1}
\]

where the \( C_{ij} \)'s are the coefficients of capacitance and \( C_{ij} \)'s, \( i \neq j \), are the coefficients of electrostatic induction. Alternatively, the above expression may also be rewritten in the form

\[
q_i(t) = \sum_{j=1}^{5} C_{ij} [\Phi_j(t) - \Phi_i(t)] \tag{2}
\]

The \( C_{ij} \)'s are called direct capacitances and in particular, \( C_{ii} \)'s are self-capacitances. It is known also from electrostatics theory that \( C_{ii} \geq 0, C_{ij} = 0 \) for \( i \neq j \), and \( C_{ii} \geq 0 \).

Without loss of generality, \( \Phi_i(t) \) and \( q_i(t) \) may be set to zero or at ground level since Equation (2) clearly implies that the charges only depend on the relative voltage potentials of the conductors. With \( \Phi_i(t) = q_i(t) = 0 \), Equation (1) simplifies to

\[
q_i(t) = \sum_{j=1}^{5} C_{ij} \Phi_j(t); \quad i = 1, 2, \ldots, 5 \tag{3}
\]

Conductor 5 in FIG. 1 represents the charging electrode hence

\[
\Phi_5(t) = f(t) \tag{4}
\]

where \( f(t) \) is a voltage pulse proportional to a curve which traces through the sequence of intended droplet deflections. Combining Equation (3) into Equation (5) and solve for \( \Phi_5(t) \) and \( q_5(t) \) explicitly

\[
C_{25} q_2(t) + C_{45} q_4(t) = q_5(t) - C_{25} f(t) \tag{5}
\]

\[
C_{35} q_3(t) + C_{45} q_4(t) = q_5(t) - C_{35} f(t) \tag{6}
\]

or

\[
\Phi_5(t) = \frac{[1/C_{25}C_{45} - C_{25}C_{45}]}{[C_{45}q_4(t) - C_{45}f(t)]} \tag{7}
\]

Now substitute the above values for \( \Phi_5(t) \) and \( q_5(t) \) into the expression for \( q_5(t) \) in Equation (3) \( q_5(t) = C_{25} \Phi_2(t) + C_{45} \Phi_4(t) + C_{35} \Phi_3(t) \)

\[
q(t) = \sum_{i=1}^{5} C_{ij} \Phi_j(t); \quad i = 1, 2, \ldots, 5 \tag{1}
\]
The difference between \(q^{(a)}\) and \(D_\phi^{(a)}\) is a measure of the charge distortion which according to Equation (16) is

\[
|q^{(a)} - D_\phi^{(a)}| = |D_1(D_1^2 + 2D_2)| |q^{(a)} - D_\phi^{(a)}| + |D_2(D_1^2 + D_2)||q^{(a)} - D_\phi^{(a)}|
\]

(17)

In view of the smallness of the numerical values of \(D_1\) and \(D_2\), one concludes simply that \(|q^{(a)} - D_\phi^{(a)}| \to 0\) very rapidly as \(n\) increases. That is, one essentially has the desired result of achieving droplet charges in direct proportion to the intended droplet deflections. This is achieved by using the modified charge voltage pulse \(V(t)\) in place of \(f(t)\).

An immediate generalization of the above analysis is as follows: Let \(f(t)\) be a voltage pulse such that \(f(n+1)\) is proportional to the intended deflection of the \(n\)th droplet formed, where the proportionality constant must be common for all integers \(n\). Then in order that the charge trapped on the \(n\)th droplet be proportional to \(f(n+1)\), one should apply the following modified charging voltage pulse to the charging electrode:

\[
V(t) = \alpha \sum_{i=0}^{K} \beta_i f(t - i \eta t)
\]

(18)

where \(\alpha\) is an overall amplitude factor; \(K\) is the number of preceding droplets having non-negligible coupling capacitance with the droplet just being formed; \(\beta_i\)'s are constants depending on the coupling capacitance values. The case with \(K=2\) and \(\alpha\beta_0 = 1\) reduces to that which was considered in detail. Also the value of the parameters \(\beta_i\) may be determined by electrically tuning or adjusting the resistors in the circuit of FIG. 2 for the best droplet deflections.

Referring to FIG. 2, the reference numeral 10 denotes a stored character generator circuit for applying a deflection signal to a Charging Electrode 5. In order to accurately position the drops a Compensating Circuit 14 is connected between the stored Character Generator 10 and the Charging Electrodes 5. The compensating circuit 14 may comprise a Resistor 16 connecting the stored Character Generator 10 to the Charging Electrode 5 for applying a voltage to the Charging Electrode 5 without time delay in accordance with the actual signal from the stored Character Generator 10. In addition to the Resistor 16, compensation storage means such as a shift register or a Delay Circuit 18 may be connected in parallel with the Resistor 16. The Delay Circuit 18 has a delay equal to \(\eta t\) which is the time interval between the drops. Connected in series with the Delay Circuit 18 is a Resistor 20 having a value equal to \(R_\beta / \beta_0\) where \(R_\beta\) is the value of Resistor 16. This provides a compensating voltage which is dependent on the charging voltage applied to the previous drop which occurred \(\eta t\) ahead of the drop just being formed. Additional compensation may be supplied by one or more additional delay circuits such as the Delay Circuit 22 having a delay equal to \(2\eta t\) and which is connected to the charging electrode 5 through a resistor having a value \(R_\beta / \beta_0\). This circuit provides compensation in accordance with the second drop ahead of the drop currently being formed. The Resistor 16, Delay Circuit 18 and Delay Circuit 22 may be connected to a Summing Circuit 24 for applying the resulting voltage to the Charging Electrode 5 through an operational Amplifier 26 having a feedback circuit comprising a Resistor 28 having a value equal to \(\alpha R_\beta\).

Referring to FIG. 3, a different embodiment is shown of a compensating circuit embodying the invention. As shown, a Compensating Circuit 30 connects the Character Generator 10 to the Charging Electrode 5. The Compensating Circuit 30 comprises Delay Circuits 32 and 34, each having a delay equal to \(\eta t\) and connected in series circuit relation. An adjustable Rheostat 36 connects a point between the two delay circuits to the Charging Electrode 5 through an Amplifier and Adder Circuit 38. A second Rheostat 40 connects the Delay Circuit 34 to the charging electrode through the Amplifier and Adder 38. Additional delay circuit may be added on when needed. A Conductor 42 provides a direct connection from the character generator to the Charging Electrode 5 through the Amplifier and Adder 38. Accordingly, each time a signal is applied from the Character Generator 10 to the Charging Electrode 5, at the same time delayed signals will be applied to the Charging Electrode 5 from the Delay Circuits 32 and 34, which are representative of the charges on previously charged drops which were generated \(\eta t\) and \(2\eta t\) ahead of the drop currently being charged. The curves in FIGS. 4a through 4d show the resulting compensated charging signal in FIG. 4d generated from an original charging signal shown in FIG. 4a.

Referring to FIG. 5, the reference numeral 44 designates a nozzle having a Transducer 46 for vibrating the nozzle to cause a stream of Ink 1 issuing from the nozzle to break up into drops which are charged by a Charging Electrode 5 and deflected by Deflection Electrodes 48 either into a Gutter 50 or onto a Document 52 for printing thereon. Instead of applying signals from a Charge Amplitude Control Circuit 54, which may, for example, produce a staircase type signal, as shown, to the Charging Electrode 5 in conjunction with character generating signals from a Character Generator System 56, which provides a pulse output characteristic of predetermined characters, the Charge Amplitude Control Circuit 54 may be connected to a Charging Electrode Driver 58 through AND gate 60 and a maximum priority OR circuit 62. A Voltage Divider 64 comprising Resistors 66 and 68 is connected between the Charge Amplitude Control Circuit 54 and ground at a point X. Point Y between the Resistors 66 and 68 is connected to the OR circuit 62 through AND gate 72. A two-position Shift Register 74 is connected to the Character Generator Circuit 56 and is connected to be advanced by a Droplet Generation Frequency Source 76, which is also connected to the Transducer 46 for producing the ink drops. Stage A of the Shift Register 74 is connected to the AND 72, as well as the AND 60, while Stage B is connected to the AND 60 only. The Resistors 66 and 68 are so proportioned that the output at X equals \(f(t) + \beta f(t-\eta t)\) and the output Y equals \(f(t)\). The output Y corresponds to the signal normally applied to the charging electrode 5 as an uncompensated signal, while the signal at X corresponds to the signal to be applied to the Charging Electrode 5 compensated in accordance with the charge on a previous drop, which can be readily determined with a uniform staircase signal of the type being used. Accordingly, the charge on each drop being formed is compensated in accordance with the value of the charge on a previous drop, if the previous drop was charged. The Shift Register 74 determines whether or not the previ-
ous drop was charged. If the previous drop was charged, the Shift Register 74 gates the signal from the X junction through AND 60 and the maximum priority OR 62 to provide a compensated charging signal. If the previous drop was not charged, the output of the B stage would be 0 and the signal from the X junction will not be gated through the AND 60 so that an uncompensated signal voltage will be gated through the AND 72 and OR 62 for application to the Charging Electrode 5.

Referring to FIG. 6, it will be seen that a 3-position Shift Register 80 is utilized in conjunction with AND circuits 82, 84, 86, and 88 and a maximum priority OR circuit 90 for applying compensated charging signals to a Charging Electrode 5 through a Driver 58 under the control of a Character Generation Circuit 56 and a Droplet Generation Frequency Source 76. The Charge Amplitude Control Circuit 54 is connected directly to the AND 82 and to a Voltage Divider 92 comprising Resistors 93, 94, 95, and 96 providing voltages at the WXYZ points in accordance with the equations

\[ W = f(t) + \beta_1 f(t-\sigma) + \beta_2 f(t-2\sigma) \]
\[ X = f(t) + \beta_1 f(t-\sigma) \]
\[ Y = f(t) + \beta_2 f(t-2\sigma) \]
\[ Z = f(t) \]

The 3-position Shift Register 80 gates signals from the W, X, Y, and Z points of the Voltage Divider 92 through AND circuits 82, 84, 86, and 88, depending on whether the first or second previous drop was charged or not.

Referring to FIG. 7a, a Compensating Network 100 is shown similar to that described in the article by R. G. Sweet, hereinafter referred to. As shown, the network comprises a capacitor C connected with a resistor R2 in a T network having a resistor R connected between the input and output terminals of one leg. This network, when provided with input waveform, such as shown in FIG. 7b modifies the waveform to provide the output shown in FIG. 7c. The disadvantage of such a network is that exact compensation occurs only at one instant of the clock cycle, whereas the droplet may separate at any time during this cycle.

In order to provide an improved compensating circuit, the arrangement, as shown in FIG. 8, may be used. As shown, a typical Compensating Network 100 is connected between a Source 102 of clock signals and a non-sequential Scan Character Generation Circuit 104 and a Charging Electrode Driver 58 for applying a charging signal to a Charging Electrode 5. A Sample and Hold circuit 106 is connected between the Sweet Network 100 and the Charging Electrode Driver 58. This circuit is controlled by a Sample Gate 108 and a Delay Circuit 110 so that the Sweet Network 100 output is gated to the Charging Electrode 5 at the exact instant of correct compensation. Thus, the correct charge amplitude is presented to the droplet regardless of when it separates during the cycle. The Delay Circuit 110 is provided to insure the Sample Gate 108 occurs at the correct time relative to the Character Generator output. Timing relations are shown by the typical waveforms of FIGS. 9a through 9c.

FIG. 10 shows a table of charging voltage values obtained at the junctions W, X, Y, and Z in the circuit of FIG. 6, when utilizing an uncompensated staircase signal such as shown in FIG. 11. The values of the Resistors 93 through 96 are shown in FIG. 12 for obtaining the values in the table of FIG. 10. A typical value for R is 1000 ohms.

From the above description and the accompanying drawing it will be apparent that we have provided in a simple and effective manner for accurately compensating the charging electrode voltage in an ink jet printer for interdrop capacitance effects. By utilizing storage means such as the delay devices for providing compensation to the charging electrode voltage for a drop currently being formed in accordance with values of the voltages applied to previous drops, greatly improved print quality is obtainable. The delay circuit technique is applicable to non-uniform voltage signals as well as uniform, while the voltage divider technique provides excellent results when used with a uniform or staircase type generator in which the differences between voltages on successive drops may be readily calculated.

While the invention has been particularly shown and described with reference to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

What is claimed is:

1. In an ink jet printer wherein a stream of ink drops is directed from a nozzle toward a recording medium, electrode means adjacent said nozzle and the path of said stream, circuit means connecting video means to said electrode means to apply signals thereto to selectively charge different ones of said ink drops to deflect said ink drops in accordance with predetermined video signals to position selected ones of said drops on said recording medium in a predetermined pattern, and compensation means including storage means connected between said circuit means and said electrode means for detecting the charges on previous drops and modifying the video signal from said circuit means for charging a particular drop in accordance with the equation \( V(t) = a(f(t) + \beta_1 f(t-\sigma) + \beta_2 f(t-2\sigma) - \alpha) \) where \( V(t) \) is the compensated charging voltage function; \( \sigma \) is the drop generation period; and \( a \) is a scaling or amplitude constant; to minimize the effects of said previous drop charges on said particular drop.

2. The invention as defined in claim 1 characterized by said storage means comprising a delay network.

3. The invention as defined in claim 1 characterized by said storage means comprising a plurality of delay networks connected to said charging electrode through a summing network.

4. The invention as defined in claim 3 characterized by said delay networks having different values which are integral multiples and being connected in parallel circuit relation between said circuit means and said charging electrode.

5. The invention as defined in claim 3 characterized by said delay networks comprising similar elements connected in cascade between said circuit means and said charging electrode.

6. The invention as defined in claim 1 characterized by said compensation means including a voltage divider having sections proportioned according to the terms of the equation \( V(t) = f(t) + \beta_1 f(t-\sigma) + \beta_2 f(t-2\sigma) - \alpha \) —connected between said circuit means and ground, and gate means controlled in accordance
with the charge condition of previous drops connecting different sections of said voltage divider to said charging electrode.

7. The invention as defined in claim 6 characterized by a shift register connected to respond in accordance with said video signals and connected to said gate means to control said gate means in response to charge condition of said preceding drops.

8. The invention as defined in claim 7 characterized by said gate means being connected to said charging electrode by a maximum priority gate means which passes only the maximum of a plurality of signals.

9. The invention as defined in claim 8 characterized by said shift register being advanced in accordance with the frequency of formation of said ink drops.

10. In an ink jet printer wherein a stream of ink drops is directed from a nozzle toward a recording medium, electrode means adjacent said nozzle and the path of said stream, circuit means connecting video means to said electrode means to apply signals thereto to selectively charge different ones of said ink drops to deflect said ink drops in accordance with predetermined video signals to position selected ones of said drops on said recording medium in a predetermined pattern, and compensation means including a RC network and a sample and hold gate with circuit means for delaying the gating operation thereof connected between said circuit means and said electrode means for detecting the charge on a previous drop and modifying the video signal from said circuit means for charging a particular drop in accordance with the value of said previous drop charge to minimize the effects of said previous drop charge on said particular drop.

* * * * *