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High Frequency Recording with Electrostatically Deflected Ink Jets*

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A high speed oscillograph, using ordinary ink and paper, has been developed that provides a new approach to the old problem of producing instantly visible, high frequency records with inexpensive writing materials. A high speed jet of ordinary fountain-pen ink is divided into a uniform procession of drops, each of which is independently charged in proportion to an input-signal voltage. After projection through a constant transverse-deflecting field, the charged drops are collected on a moving chart to form an instantly visible, permanent record of the input signal. Drops are typically formed at a rate of 100 000/sec; each has an independent trajectory and makes an individual mark representing an independent sample of the input waveform. The ink stream may be switched on or off at high speed by providing, between the drop-launching point and the record surface, a collector that intercepts drops having a specific trajectory. Besides oscillography, which is discussed in detail, the technique has applications in other fields requiring marking at high speed or marking without pressure or physical contact.

INTRODUCTION

CURRENTLY used pen or stylus oscillographs are limited to input signals having frequency components below a few hundred cps, while recorders useful in the kilocycle range generally capture the signal information on a relatively expensive and inconvenient light-sensitive medium. This paper describes a high speed oscillograph, using ordinary ink and paper, that provides a new approach to this old problem of producing instantly visible, high frequency records with inexpensive writing materials.

The system writes with a jet of ink that is electrostatically charged and deflected in accordance with the input signal potential. The technique differs from methods used in previous jet-writing systems in that the ink stream is divided into a regular procession of uniform drops, and the drop charge, rather than the deflecting field, is controlled by the input signal. Each ink drop leaves on the record surface a mark that represents an independent sample of the input-signal amplitude, taken at the instant the drop was charged. In a typical oscillograph, drops are charged and launched at a repetition frequency of 100 000/sec, and although about 200 drops are simultaneously in flight, each has an independent trajectory. The high frequency detail that can be recorded is determined only by the rate at which drops are formed, and not by the transit time required for them to traverse the constant-deflection field.

BACKGROUND

The recording system writes with fluid drops having precise uniformity in size, repetition frequency, and initial velocity. The drops are generated by the division of a regularly disturbed cylindrical jet, a process first described in 1833 by Felix Savart,[1] and later treated analytically by Raleigh,[2] Weber,[3] and Goren.[4] As they form, the drops are charged by electrostatic induction, using essentially the same configuration employed by Kelvin[5] in 1867 for charging the water drops in his electrostatic generator. Magnus[6] showed in 1859 that the drops in a regular procession of uniform fluid drops, formed in a constant electric field, follow identical curved trajectories, and this principle has been employed by Waage[7] in a cathode-ray-tube demonstration model that uses water drops to represent electrons. Recently, Magarvey and Blackford,[8] Mason and Brown-

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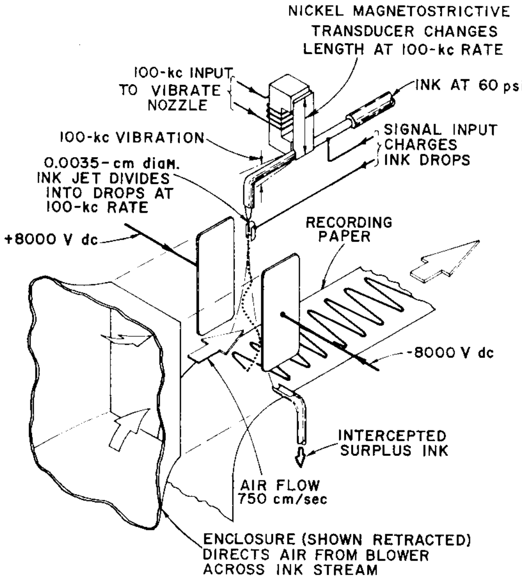

FIG. 1. Ink-jet oscillograph.

scombe,[9] and Schneider[10] have reported on techniques for forming, charging, and deflecting water drops, using methods similar to those described here.

Writing techniques employing fine jets of ink have a history extending back to at least 1873. One version of Kelvin's[11] "siphon recorder," and the Elmqvist[12,13] system now used in commercial oscillographs in Europe, use an ink jet issuing from a nozzle that is aimed by the moving coil of a galvanometer. Jet writers patented by Hansell,[14] Schroter,[15] Richards,[16] and Winston[17] deflect ink jets with electrostatic or magnetic fields; however, the transient-response time of these systems is limited by the time required for the ink to traverse the deflection field.

SYSTEM CONFIGURATION

Figure 1 shows the configuration of an experimental oscillograph and gives an example of typical parameter values. Ordinary fountain-pen ink (Schaeffer's "Scrip"), having fluid properties similar to those of water, is supplied at a pressure of 4.2 kg/cm^2 to a nozzle having an exit diameter of 0.0035 cm. The resulting cylindrical jet of ink emerges with an initial velocity of 2100 cm/sec and a volume flow rate of 0.02 cc/sec. Most of the 3.5-cm flight from nozzle to paper takes place in a constant transverse electric field of 16 kV/cm.

Figure 2 is an exploded view showing the principal components of the assembly that launches and charges the ink. The tiny glass nozzle, cemented into the end of the metal supply tube, points to the left. The ferrite core and coil magnetize the strip of nickel brazed to the nozzle supply tube at a frequency of 100 kc, and magnetostriction of the nickel results in vibration of the nozzle along its axis at the excitation frequency. The ink-drop-charging electrode, just to the left of the nozzle, has a U-shaped cross section where it surrounds the jet. The jet passes between the sides of the U, spaced 0.050 cm apart, entering as a continuous stream and emerging as a series of discrete drops. The electrode is pivoted so that it can be swung away from the jet to facilitate observation of the drop-formation process.

DROP FORMATION

Surface tension acts to decompose the unstable cylindrical jet issuing from the nozzle into drops having a smaller total surface area and lower surface energy. The nozzle vibration modulates the velocity of the ink jet and establishes an axially symmetric disturbance in the jet profile that initiates the breakup process. Once established, the disturbance envelope grows exponentially, finally severing the jet at regularly spaced intervals. Drops form in exact synchronism with the 100-kc nozzle vibration—the distance from the nozzle at which the drops separate, and their size and spacing, are determined, within limits, by the vibration amplitude and frequency. Surface-tension forces are opposed mostly by fluid inertia in the breakup process. Jet surface charge induced by the signal input causes electrostatic forces that oppose surface tension; the effect on disturbance growth is small for the maximum input potentials used. Viscous forces are negligible[3] if the square of the ink viscosity is small compared with the product of ink density, ink surface tension, and jet diameter—this is the case for the ink actually used.

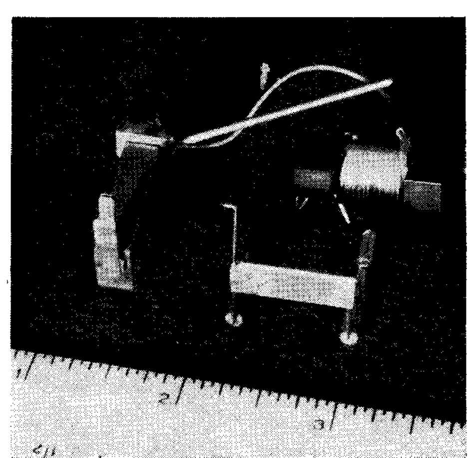

FIG. 2. Ink-drop gun, exploded view.

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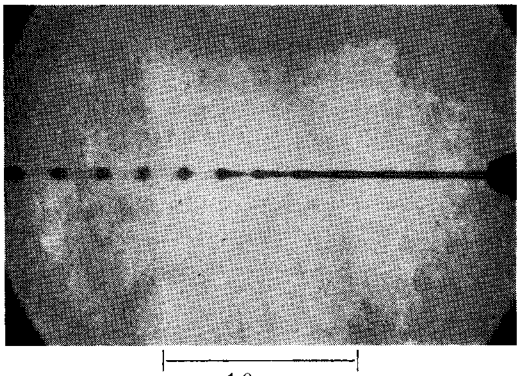

FIG. 3. Ink-drop formation.

The instant of drop separation is defined by the breaking of the fine fluid ligament connecting a drop in the final stage of formation to the parent jet. Under some conditions, the ligament breaks at more than one point, forming a tiny secondary or satellite drop ("Plateau's spherule"). The tendency for this secondary drop formation is increased when the jet is charged. Surface charge also enhances a tendency for the main drops to subdivide if the sections into which the jet is resolved are too long.

To minimize electrostatic and aerodynamic interaction between neighboring drops in flight, the initial drop-to-drop spacing, equal to the disturbance wavelength on the undivided jet, should be as large as possible. Subdivision of the main drops limits the ratio of disturbance wavelength to jet diameter that can be used. Vibration amplitudes that favor secondary-drop formation must be avoided. In our example, which is typical, the disturbance wavelength (jet velocity/vibration frequency) is 0.021 cm, or 6 jet diameters. The peak jet-velocity modulation at the nozzle is about 70 cm/sec and results in drop separation at a point 0.13 cm downstream from the nozzle exit. Each drop has a diameter of 0.0073 cm and a mass of 0.2×10^{-6} g. Figure 3 is a photograph showing the drop-formation process.

DROP CHARGING

The drop-charging signal is applied between the metal ink-supply tubing, which contacts the ink flowing to the nozzle, and an electrode that surrounds, but does not touch, the jet at the drop-separation point. The signal potential establishes an axially symmetric electric field and corresponding charge at the surface of the unbroken column of conducting fluid extending from the nozzle. Neglecting the influence of charges on nearby free drops, the charge on a separating drop is equal to the product of the capacitance between drop and charging electrode and the charging potential at the instant of drop separation. Axial-velocity modulation of the drops by forces due to the charging field is small, because the charging potential is low compared with that establishing the deflection field. In our example, the computed capacitance between charging electrode and separating drop is 0.004 pF. A 1-cm drop deflection at the record surface requires a drop charge of 0.6×10^{-12} C and an input charging potential of 150 V. The input impedance equals the reactance of the capacitance—a few picofarads—of the charging electrode to the ink jet and ground.

A separating drop is also capacitively coupled to nearby drops just previously launched, and its charge is influenced to some extent by the charges on these neighboring drops. This drop-to-drop coupling modifies the high frequency response and results in an overshoot for a step change in input voltage. Typically, the overshoot has a magnitude of 20% and a decay time constant of 15 μsec. The frequency response may be equalized, and the overshoot may be eliminated, by preceding the input terminals with a simple RC network.

The foregoing discussion of drop charging assumes a perfectly conducting fluid and thus an equi-potential jet surface between nozzle and drop-separation point. For a fluid having finite conductivity, the "beam" current (0.06 μA for a drop charge of 0.6×10^{-12} C) causes a potential drop along the undivided jet between nozzle and drop separation point that must be subtracted from the input potential to obtain the effective drop-charging voltage. For transient inputs, the current that charges the capacitance distributed along the undivided jet must also be considered. The potential drop along the jet should be small compared with the input charging voltage, and the charge redistribution time on the jet, following a transient input, should be small compared with the drop repetition period. In a typical system, this requires that the ink resistivity not exceed several thousand Ω-cm. The ink actually used in our systems (Schaeffer's "Scrip") has a resistivity of 130 Ω-cm and the resulting potential variation along the jet is negligible.

ELECTROSTATIC FORCES

The deflection field traversed by the drops should be everywhere parallel to the record surface, so that drops having different charges will have the same transit time. If the only force on the drops in flight were exerted by such a field, each drop would follow a parabolic trajectory, and the impact point on the record surface would be displaced from the jet axis by an amount accurately proportional to drop charge. The magnitude of the deflection field is limited by the dielectric strength of air. It is made as high as possible, over as much of the drop flight path as possible, in order to minimize the drop charge required for a given drop deflection. However, the field cannot be maintained at the record surface, because the ink forming the record trace is a conductor. The deflection plates therefore do not extend all the way to the record surface, and edge effects result in fringing and nonuniformity of the field in the region adjacent to the record surface. The result is nonlinearity in the deflection characteristic and an increase in drop transit time for large deflections.

Distortion caused by field fringing and by mutual electrostatic forces between drops is minimized by a long, flat trajectory and low drop charge. For a deflecting field of 16 kV/cm, the deflecting force (proportional to drop charge) on a drop with the typical charge (for a 1-cm deflection) of 0.6×10^{-12} C is 0.10 dyn. The corresponding mutual force (proportional to charge squared) between two drops with minimum spacing (0.021 cm) is 0.007 dyn. Gravity exerts the negligible force of 0.0002 dyn. In general, distortion caused by mutual forces determines the practical limit for drop charge rather than corona or deformation of the jet surface by electrostatic forces during drop formation and charging.

AERODYNAMIC DRAG

Although increasing the distance from nozzle to record decreases the charge required for a given deflection and hence the relative importance of mutual forces, it increases the distortion caused by aerodynamic drag. Associated with each drop in transit is a turbulent wake of disturbed air extending back along the line of flight, and a drop immediately following another experiences substantially less aerodynamic drag than does a drop traveling in still air. The decelerating force on a particular drop thus depends on the waveform being recorded and the position of the drop in that waveform. The resulting uncertainty in transit time increases with jet length and causes both time and amplitude errors in the record.

The maximum nozzle-to-paper spacing that may be used without serious aerodynamic effects is increased substantially by directing a stream of air across the space traversed by the drops, as shown in Fig. 1. The air flows in a direction perpendicular to the jet axis, and displaces the wake behind each drop so that it extends at an angle to the line of flight. Interference with following drops is reduced and, except for a constant displacement down the air-stream axis, each drop behaves as if it were traveling in still air. The air typically has a velocity of 750 cm/sec (about $\frac{1}{3}$ of the jet velocity), and is carefully smoothed to minimize turbulence. In our example, the initial axial decelerating force due to air resistance is 0.11 dyn—about the same magnitude as the transverse electrostatic deflecting force. Air drag decreases the axial component of drop velocity from the initial value of 2100 cm/sec to about 1300 cm/sec at impact. The corresponding transit time for the 3.5-cm journey is 2.1 msec.

DISTORTION

System fidelity is determined by: (1) uniformity and short-term stability of the mass, initial velocity, and charging geometry of the ink drops; and (2) variations from the ideal drop trajectories during flight resulting from deflection-field fringing, aerodynamic forces, and mutual electrostatic forces. It turns out that system distortion is dominated by the defects listed in (2), which are associated with forces acting on the ink drops during flight, and not by defects in the launching and charging processes. Recording fidelity is thus principally determined by the geometry of the flight path and deflection system, the aerodynamic Reynolds number, and the relative magnitudes of the aerodynamic forces, mutual electrostatic forces, and deflection forces that act on the drops during flight.

The typical parameter values given are appropriate for a system having a 100-kc drop-repetition rate and a maximum peak-to-peak deflection, without serious distortion, of 2 cm. To obtain a greater undistorted deflection, a larger system is necessary, having a lower drop-repetition rate. Conversely, to increase the drop-repetition frequency, the dimensions of the system, including the maximum deflection, must be reduced. For systems not differing too much from the one described, the product of drop-repetition frequency and maximum deflection amplitude is approximately constant.

FREQUENCY RESPONSE

The full-scale transient-response time of the oscillograph equals the drop-repetition period—10 μsec in our example. The corresponding frequency response is not so easily defined. The oscillograph constitutes a sampled-data system, with a sampling rate equal to the drop-repetition frequency—typically 100 kc. According to Shannon's[18] sampling theorem, the frequency response extends to one-half the sampling frequency (i.e., to 50 kc), provided the input-signal frequency is band-limited to that value. However, the discontinuous sampling process and presentation make the interpretation of high frequency records difficult, and result in a usable frequency response that may be much less than theory indicates, depending on the particular application.

INTENSITY MODULATION

A collector is interposed between nozzle and paper, as shown in Fig. 1, to intercept ink drops having a deflection just exceeding that produced by the maximum signal. The quantity of ink forming the recorded trace may then be reduced by charging the ink drops with a pulse train that is amplitude-modulated by the signal to be recorded. The width of each pulse is made just sufficient to charge one ink drop, and the pulse-repetition frequency is made equal to the desired ink-drop delivery rate. The charging signal

[18] B. M. Oliver, J. R. Pierce, and C. E. Shannon, Proc. IRE **36**, 1324 (1948).

is biased so that drops charged by the pulse peaks form the record trace, while drops having a charge corresponding to the pulse baseline voltage are intercepted by the collector.

To avoid deflections corresponding to the raising and falling portions of the pulses, signal sampling (drop separation) must not occur during the transition intervals. The pulses are therefore synchronized with the drop-forming signal (nozzle-vibration-transducer input) and phased so that drop separation occurs at the center of each pulse and not during the transitions between pulse peak and baseline. Proper operation requires appropriate stability for all the parameters that influence the phase relationship between the drop-forming signal and the drop-separation time.

PERFORMANCE

For a system having a 100-kc drop rate and a maximum peak-to-peak record amplitude of 2 cm, the maximum deviation from a linear deflection characteristic is about $\pm 5\%$ of this full-scale amplitude. Accuracy along the time axis is limited by variations in ink transit time to about ± 25 μsec.

Performance of typical experimental systems is illustrated by the oscillograms reproduced full size in Fig. 4. The 10-cps square-wave record of Fig. 4(a) was written with 2000 ink drops per sec. The good resolution at the low (17-cm/sec) chart speed results from interception in transit of 98% of the 100 000 drops launched per second. Figure 4(b) shows a 1-kc damped-sine-wave record for which drop interception was determined automatically by circuits controlled by the signal derivative. The drop-repetition rate at the record surface varies from a minimum of 4 kc at zero signal to a maximum of 50 kc at maximum signal slope. This derivative-control technique permits high frequency signals to be recorded at low chart speeds without blurring the trace with surplus ink when the signal fluctuations are small.

Figures 4(c) through 4(e) show records of equal-amplitude sine waves, having different frequencies, taken at the same chart speed and a drop-repetition frequency of 80 kc. No ink was intercepted. The high frequency capabilities and shortcomings of the system, resulting from the discrete sampling process, are evident. Figure 4(f) shows a 10-kc sine-wave record taken with a smaller, higher frequency system having a drop-repetition frequency of 174 kc.

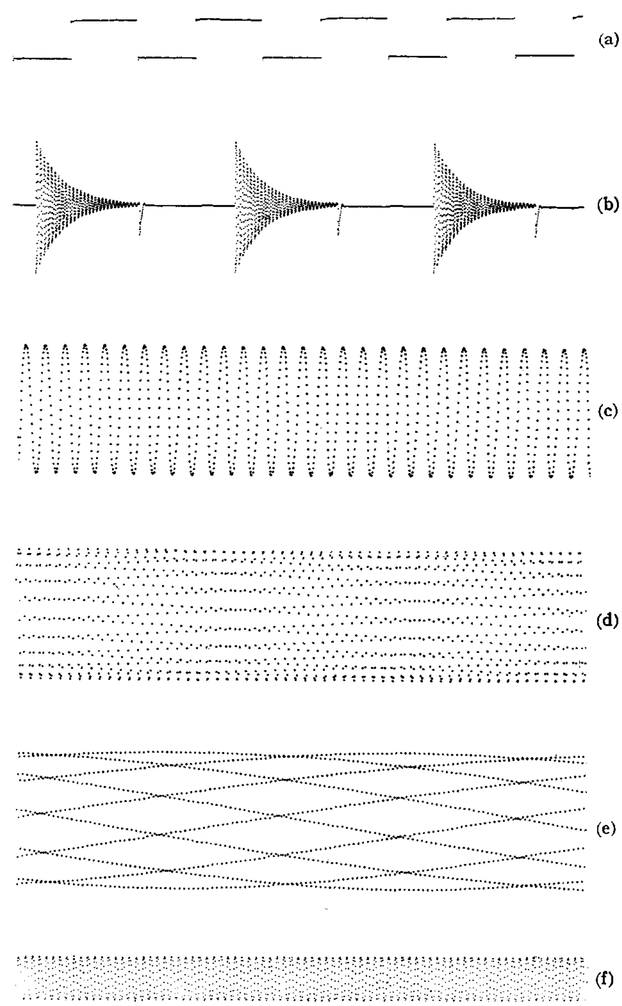

FIG. 4. Representative oscillograms, (a) 10-cps square wave, (b) 1-kc damped sine wave, (c) 2-kc sine wave, (d) 4-kc sine wave, (e) 8-kc sine wave, (f) 10-kc sine wave.

APPLICATIONS

This technique should be capable of development into a practical oscillograph having advantages found in no other currently available system. Recorders with a multiplicity of channels are easily arranged, with several channels sharing a common deflection system. Traces may cross without interference, and channel identification can be facilitated by the use of colored inks. With respect to deflection amplitude and accuracy, the system performance is inferior to that achievable with optical oscillographs—the technique is, therefore, most useful in high frequency applications requiring only moderate precision, but where convenience and operating economy are important.

Extensions of the technique should be applicable to high speed printing and facsimile systems. In systems requiring only on-off control, and not analog deflection, the drop flight path need be shifted very little to transfer between marking and intercepted trajectories. Very small jets with drop-formation rates substantially higher than those appropriate for oscillographs might then be practical. Jets arranged in closely spaced arrays, using a common deflection field, could be independently controlled to provide information-recording rates well into the megacycle range.

The absence of physical contact or critical spacing between the ink-launching mechanism and the record surface suggests applications in marking or labeling of rough or curved surfaces, or surfaces sensitive to pressure. More general applications include the precise high speed control of any kind of low volume fluid flow. The technique could be used to accurately dispense or deposit any solid substance that is soluble in a conducting-fluid vehicle, or that is sufficiently fluid and conductive when molten.

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High Efficiency Source for Metal Ions

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An ion source is described which produces beams of ions of both high and low vapor pressure materials. The source has the following characteristics which make it suitable for accelerator applications or laboratory ion beam experiments where the large size and complexity of isotope separator ion sources would be a disadvantage: (1) small size, (2) simplicity of construction and operation, (3) long filament life, (4) high charge utilization efficiency, (5) wide operating temperature range, (6) relatively modest power requirement, (7) ability to operate efficiently on either gas or solids. The source operates by electron bombardment ionization of the vapor of the charge material. The vapor is obtained by heating the charge to a sufficiently high temperature to achieve the proper source operating pressure. A unique feature of this source is the combination of the discharge chamber and charge container into one chamber. The operating temperature range of the source is from approximately 300 to about 1600°C. Beams of Zn^+, Al^+, Cu^+, Ag^+, Au^+, and Fe^+ ions have been produced which contain but a small percentage of impurity ions. The charge material in all these cases has been the pure metal.

I. INTRODUCTION

THE ion source reported in this paper was designed and constructed to produce ions of both high and low vapor pressure materials. It was designed for use on a 3.0-MeV accelerator to investigate high energy particle-particle and surface-particle interactions using various metal ions.

Previously reported metal ion sources have been designed principally for use in electromagnetic isotope separators, and are usually of the oven-ionizer type.[1–3] In the oven-ionizer source the charge material is contained in an oven or furnace which is separate from the discharge chamber. The vapor of the solid charge material is then introduced to the discharge chamber where ionization of the material takes place and ions extracted from the plasma. Freeman[4] has recently reported a new type oven-ionization source where the vapor issuing from the oven is ionized as it passes an electron-emitting filament located in a longitudinal magnetic field. The charge utilization efficiency for the type of source in Ref. 4 is generally very low (of the order of one ion for 500 neutrals effusing from the source).

Other types of sources for the production of metal ions have been the sputtering source[5–7] and the surface ionization source.[8,9] However, these are usually limited in their application, output current, and operating lifetime.

Certain features of the usual oven-ionizer sources designed for isotope separator applications are objectionable when these sources are to be used in accelerators or in laboratory ion beam experiments. These disadvantages arise mainly from the large size and relative complexity of design of these sources. Thus the ion source reported here was designed to have the following characteristics: (1) small size and low power requirements, these are important considerations since space and power are usually limited at the high voltage terminal of an accelerator; (2) simplicity of construction and operation; (3) long

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