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(54) **Method of operating an ink jet to achieve high print quality and high print rate.**

(57) A drop-on-demand ink jet print head has an ink chamber coupled to a source of ink, and an ink drop orifice with an outlet. An acoustic driver produces a pressure wave in the ink and causes the ink to pass outwardly through the ink drop orifice and outlet. The driver is driven with bipolar drive pulses having a refill pulse component and an eject pulse component of a polarity which is opposite to the refill pulse component. The refill and eject pulse components are separated by a wait period. The drive pulses may be adjusted to minimize their energy content at a frequency corresponding to the dominant acoustic resonance frequency of the ink jet print head. This will accelerate drop breakoff, optimize drop shape and minimize drop speed variations over the range of drop printing rates. The size of the ink drops may be varied, such as by driving the acoustic driver with varying drive signals, preferably utilizing individual or combinations of a plurality of bipolar drive pulses. The ink jet printer of the present invention may be used to print with a wide variety of inks, including phase change (hot melt) inks to achieve high print quality at high print rates.

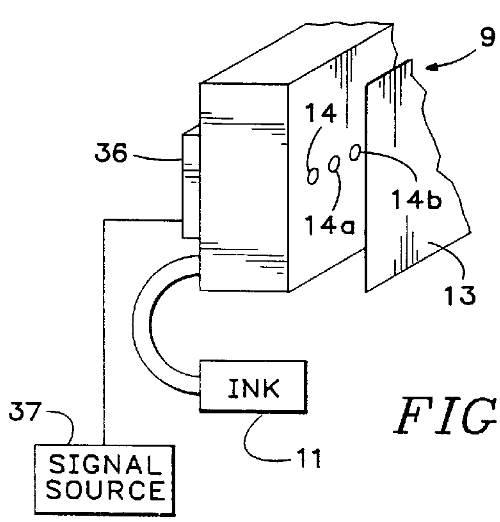

FIG. 1

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The present invention relates to printing with a drop-on-demand ink jet print head, and, more specifically, primarily to various configurational and operational aspects of such printing which improves print quality and provides long periods of stable operation.

Ink jet printers, in particular drop-on-demand ("DOD") ink jet printers having ink jet print heads with acoustic drivers for ink drop formation, are well known in the art. The principle behind an ink jet print head of this type is the generation of a pressure wave in an ink chamber and the resultant subsequent emission of ink droplets from an ink pressure chamber through a nozzle orifice as a result of the pressure wave. A wide variety of acoustic drivers is employed in ink jet print heads of this type. For example, the drivers may consist of a pressure transducer formed by a piezoelectric ceramic material bonded to a thin diaphragm. In response to an applied voltage, the piezoelectric ceramic material deforms and causes the diaphragm to displace ink in the ink pressure chamber, which displacement results in a pressure wave and the flow of ink through one or more nozzles.

Piezoelectric drivers may be of any suitable shape such as circular, polygonal, cylindrical, and annular-cylindrical. In addition, piezoelectric drivers may be operated in various modes of deflection, such as in the bending mode, shear mode, and longitudinal mode. Other types of acoustic drivers for generating pressure waves in ink include heater-bubble source drivers (so-called bubble or thermal ink jet print heads) and electromagnet-solenoid drivers. In general, it is desirable in an ink jet print head to employ a geometry that permits multiple nozzles to be positioned in a densely packed array, with each nozzle being independently driven by an associated acoustic driver.

U.S. Patent No. 4,523,200 to Howkins describes one approach to operating an ink jet print head with the purpose of achieving high velocity ink drops free of satellites and orifice puddling and providing stabilized ink jet print head operation. In this approach, an electromechanical transducer is coupled to an ink chamber and is driven by a composite signal including independent successive first and second electrical pulses of opposite polarity in one case and sometimes separated by a time delay. The first electrical pulse is an ejection pulse with a pulse width which is substantially greater than that of the second pulse. The illustrated second pulse in the case where the pulses are of opposite polarity has an exponentially decaying trailing edge. The application of the first pulse causes a rapid contraction of the ink chamber of the ink jet print head and initiates the ejection of an ink drop from the associated orifice. The application of the second pulse causes rapid volume expansion of the ink chamber and produces early break-off of an ink drop from the orifice. There is no suggestion in this reference of controlling the position of an ink meniscus before drop ejection; therefore, problems in printing uniformly at high drop repetition rates would be expected.

The prior art has also recognized that advantages may arise from printing with ink drops of selectively varying volume. For example, drop volume can be selected to provide optimum spot size to effectively produce high resolution printing. Also, by using only larger drops, a draft-mode print quality can be chosen. Such printers are also useful in applications requiring half-tone images, such as involving the control of color saturation, hue and lightness.

U.S. Patent No. 4,513,299 of Lee, et al. describes one approach for achieving variations in ink drop size. In this approach, an electromechanical transducer is coupled to an ink chamber and is driven by one or more electrical drive signals of the same polarity which are each separated by a fixed time delay. This time delay is short with respect to the drop-on-demand drop production rate. Each electrical drive signal ejects a predetermined volume of ink with the ejected volumes of ink merging to form a single drop. An increase in the number of electrical drive signals between the formation and ejection of a drop causes an increase in the drop volume. This patent mentions that the various sized drops travel at a constant velocity to the print medium. This patent also recognizes that, because the print head is moving at a constant velocity during printing, any variation in drop velocity would cause displacement of the drops on the print medium from their desired position, and would degrade the print quality. However, inasmuch as all of the energy for drop formation and ejection results from the drive pulse supplied to the transducer, the variation in drop size is somewhat limited, the velocity of individual drops is limited, and some variation in the travel time to paper would tend to occur. In addition, the capacity of the ink jet to produce large ink drops using a large number of successive pulses limits the maximum rate of drop ejection. U.S. Patent No. 4,491,851 of Mizuno, et al. illustrates another approach in which successive drive pulses are used to generate ink drops of varying sizes.

U.S. Patent No. 4,561,025 of Tsuzuki describes another printer for printing half-tone images with ink drops or dots of varying sizes. The diameter of each dot is controlled by controlling the energy content of the driving pulse which causes the dot, for example, by varying the amplitude or pulse width of the driving pulse.

U.S. Patent No. 4,563,689 to Murakami, et al. discloses an approach for operating an ink jet print head with the purpose of achieving different size drops on print media, such as desired for achieving half-tone printing. In this approach, a preceding pulse is applied to an electromechanical transducer prior to a main pulse. The preceding pulse is described as a voltage pulse that is applied to a piezoelectric transducer in order to oscillate ink in the nozzle. The energy contained in the voltage pulse is below the threshold necessary to eject a drop. The preceding pulse controls the position of the ink meniscus in the nozzle and thereby the ink drop size. In Figures 4 and 8 of Murakami et al., the preceding and main pulses are of the same polarity, but in Figures 9 and 11, of this patent, these pulses are of opposite polarity. Murakami et al. also mentions that the typical delay time between the start of the preceding pulse to the start of the main pulse is on the order of 500 microseconds. Consequently, in this approach, drop ejection would be limited to relatively low-repetition rates. Moreover, there is no teaching or suggestion in Murakami et al. that a bipolar wave form with a wait period has a minimum energy content at the dominant acoustic resonant frequency of the ink jet.

U.S. Patent No. 4,403,223 of Tsuzuki, et al. describes a drop-on-demand type ink jet printer in which a driving pulse is applied to a piezoelectric transducer to cause the ejection of a drop of ink from a nozzle. The drop size is varied by controlling the energy content of the applied driving pulse for purposes of achieving half-tone printing. The ejected ink drops pass between charging electrodes and are charged by a voltage which is applied as the drops are ejected from the nozzle. This charging voltage varies as a function of the energy content of the driving pulses. In the embodiment of FIG. 10 of this patent, the charged ink drops pass between deflection plates which generate a field oriented transversely to the direction of drop travel for purposes of altering the flight path of the drops. In the FIG. 1 form of the apparatus, the charged drops pass between a pair of plates 40 and a pair of plates 60, with the deflection plates positioned between plates 60 and plates 40. The plates 40 and 60 establish an electric field oriented in the direction of travel of the ink drops for purposes of accelerating the drops.

The Tsuzuki, et al. patent requires relatively complex driving circuits inasmuch as the charging voltage is varied with variations in the driving pulse. In addition, the use of deflection voltages also adds to the complexities of this device.

Although these prior art devices are known, a need exists for an improved ink jet printer which is capable of effectively achieving uniform high quality printing, at high print rates. Therefore, it is a primary object to provide such an ink jet printer and method of operating it.

It is another object of the present invention to provide an ink jet print head which is capable of reliably and efficiently printing media with ink, including hot melt ink.

It is a further object of the present invention to provide an ink jet printer and method of operating it which reliably and efficiently operates to provide half-tone or grey scale printing without requiring complex field switching or time delay circuitry.

Another object of the present invention is to provide an improved ink jet print head which is capable of selectively producing ink drops of varying sizes.

A drop-on-demand ink jet is described of the type having an ink chamber coupled to a source of ink, an ink drop forming orifice with an outlet, and in which the ink drop orifice is coupled to the ink chamber. An acoustic driver is used to produce a pressure wave in the ink to cause the ink to pass outwardly through the ink drop orifice and the outlet. The driver is operated to expand and contract the ink chamber to eject a drop of ink from the ink drop ejecting orifice outlet with the volume of the ink chamber first being expanded to refill the chamber with ink from a source of ink. During this expansion, ink is also withdrawn within the orifice toward the ink chamber and away from the ink drop ejection orifice outlet. A wait period is then established during which time the ink chamber is returning back to its original volume and the ink in the orifice to advance within the orifice away from the ink chamber and toward the ink drop ejection orifice outlet. In addition, the driver is then operated to contract the volume of the ink chamber to eject a drop of ink. Thus, a sequence of ink chamber expansion, a wait period, and ink chamber contraction is followed during the ejection of ink drops.

In accordance with another aspect of the invention, these drop ejection steps are repeated, for example, at a high rate to achieve rapid printing. In addition, each of the waiting steps comprises the step of waiting until the ink in the orifice advances to substantially the same position within the orifice to which the ink advances during the other waiting steps before the ink chamber is contracted to eject an ink drop.

As yet another aspect of the present invention, the waiting step comprises the step of waiting until the ink advances to a position substantially at the ink drop ejection orifice outlet, but not beyond such orifice outlet, before contracting the volume of the ink chamber to eject a drop of ink.

As still another aspect of the present invention, the contracting step occurs at a time when the ink is advancing toward that is, has a forward component of motion toward, the ink drop ejection orifice outlet.

As a still further aspect of the present invention, the driver may comprise a piezoelectric driver which is driven by a drive pulse including first and second pulse components separated by a wait period, the first and second pulse components being of an opposite polarity. These pulse components or electric drive pulses may be of a square wave or trapezoidal wave form.

Upon application of a first voltage pulse, called the "refill pulse component," the acoustic driver operates to increase the volume of the ink pressure chamber through chamber expansion to refill the chamber with ink from the ink source. During ink pressure chamber expansion, ink is also drawn back within the orifice toward the ink pressure chamber and away from the orifice outlet. When the refill pulse component is no longer applied, a wait period state is then established during which time the ink pressure chamber returns to its original volume and the ink in the orifice advances within the orifice away from the ink pressure chamber and toward the orifice outlet. Upon application of a second voltage pulse of opposite relative polarity, called the "ejection pulse component," the acoustic driver then operates to reduce the volume of the ink pressure chamber through chamber contraction to eject a drop of ink. Thus, by applying these voltage pulses to the acoustic driver, a sequence of ink pressure chamber expansion, a wait period, and ink pressure chamber contraction accomplishes the ejection of ink drops.

In accordance with the invention, these steps are repeated at a high rate to achieve rapid printing. The refill pulse component, followed by the wait period state and the ejection pulse component comprise the drive signal. The refill pulse component and the ejection pulse component may be of square wave or trapezoidal wave form.

A preferred embodiment of the drive signal comprises a bipolar electrical signal with refill and ejection pulse components varying about a zero amplitude reference voltage maintained during the wait period state; however, skilled persons would appreciate that the reference voltage need not have zero voltage amplitude. The drive signal may comprise pulse components of opposite relative polarity varying about a positive or negative reference voltage amplitude maintained during the wait period state.

In accordance with still another aspect of the present invention, the drive signal is also tuned to the characteristics of the ink jet print head to avoid the presence of high energy components at the dominant acoustic resonant frequency of the ink jet print head, which may be determined in a known manner. Typically, the most significant factor affecting the dominant acoustic resonant frequency of the ink jet is the resonant frequency of the ink meniscus. Another significant factor affecting the print head dominant acoustic resonant frequency is the length of ink passage from the outlet of the ink pressure chamber to the orifice outlet of the ink jet, called the "offset channel". The energy content of the complete electric drive pulse at various frequencies is also determined.

The complete electric drive pulse in this case includes the refill pulse components, the drive pulse components, and wait periods utilized in ejecting a drop of ink. The drive pulse is then adjusted such that a minimum energy content of the drive pulse exists at the dominant acoustic resonance frequency of the ink jet. If an ink jet of the type having an offset channel between the ink chamber and the ink drop ejection orifice outlet is used, the dominant acoustic resonance frequency corresponds to the standing wave resonance frequency through liquid ink in the offset channel of the ink jet. With this approach, the drive signal is tuned to the characteristics of the ink jet to avoid high energy components at the dominant resonance frequency of the ink jet.

The drive signal is preferably tuned to the characteristics of the ink jet print head by adjusting the time duration of the wait period state and the time duration of the first or refill pulse component, including the rise time and fall time of the refill pulse component. The rise time and fall time for the refill pulse component is the transition time from zero voltage to the voltage amplitude of the refill pulse component and from the voltage amplitude of the refill pulse component to zero voltage, respectively. A standard spectrum analyzer may be used to determine the energy content of the drive signal at various frequencies. After a tuning adjustment, a minimum energy content of the drive signal coincides with the dominant acoustic resonant frequency of the ink jet print head.

As yet another aspect of the present invention, the drive pulse may be adjusted, if necessary, such that the minimum energy content of the drive pulse at a frequency which substantially corresponds to the dominant acoustic frequency of the ink jet is at least about 20 db below the maximum energy content of the drive pulse at frequencies other than the frequency which substantially corresponds to the dominant acoustic resonance frequency. In addition, the drive pulse may be adjusted, such that the maximum energy content of the drive pulse does not occur at a frequency which is sufficiently close (for example, less than 10 KHz) to any of the major resonance frequencies of the ink jet print head. These major resonance frequencies include the meniscus resonance frequency, Helmholtz resonance frequency, piezoelectric drive resonance frequency and various acoustic resonance frequencies of the different channels and passageways forming the ink jet print head.

As a further aspect of the present invention, the drive pulse may have refill and ejection pulse components of a trapezoidal shape in which the pulse components have a different rate of rise to their maximum amplitude than the rate of fall from the maximum amplitude. More specifically, the first electric drive pulse or refill pulse component may have a rise time from about 1 to about 4 microseconds, be at a maximum amplitude for from about 2 to about 7 microseconds, and may have a fall time from about 1 to about 7 microseconds. In addition, the wait period may be greater than about 8 microseconds. Furthermore, the second electric drive or eject pulse component may be within the same range of rise time, time at a maximum amplitude and fall time as the first electric drive pulse, but of opposite polarity. More specifically, the rise time of the first and second electric drive pulse component may more preferably be from about 1 to about 2 microseconds, the first and second electric drive pulse component may be at its maximum amplitude for from about 4 to about 5 microseconds, and the first and second electric drive pulse may have a fall time of from about 2 to about 4 microseconds, with the wait period being from about 15 to about 22 microseconds.

A significant advantage of the present invention is that the improved ink jet print head is capable of producing ink drops requiring a substantially uniform travel time to reach print media over a wide range of drop repetition or ejection rates. This directly affects the quality of the resulting printing. An adverse effect of variations in the velocity of ink drops ejected from a single outlet over time, or among several outlets operating simultaneously, is a distortion in the resulting print. This is because ink jet print heads typically scan the print medium, and thus are moving, or the print medium is moved, during printing. A drop-on-demand ink jet printer incorporating the various aspects of the present invention may comprise an array of ink jets, each with an orifice or nozzle outlet.

Another primary aspect of the present invention provides a technique of controlling the drive electrical pulse applied to the acoustic driver in order to selectively vary the volume of ink in the ink drops ejected through the individual ink jets.

As another aspect of the present invention, the volume of the ink drop is controlled by controlling one or more characteristics of at least one bipolar electric pulse applied to acoustic drivers of the ink jet printer, with refill and ejection pulse components having voltages of opposite polarity that are separated by a wait period. The volume of the ink in the ink drops is varied by selectively varying the duration of the wait period, varying the duration or pulse width of the ejection pulse component, varying the amplitude of the ejection pulse component, varying the ratio of the pulse width of the ejection pulse component to the pulse width of the refill pulse component, varying the ratio of the amplitude of the ejection pulse component to the amplitude of the refill pulse component, and by combinations of the above techniques.

In another approach for varying the volume of ink in the ink drops, a plurality of bipolar pulses are used to form the drops, with the number of pulses used to form an individual drop controlling the volume of ink in the drop. Each of these bipolar electric pulses are separated from one another by a time period which is insufficient to permit the breaking off of an ink drop at the orifice outlet until a selected number of the bipolar drive pulses have been applied. In one specific approach, these bipolar electric pulses are separated from one another by a time period of at least about two times the duration of an individual bipolar electric pulse. More specifically, the bipolar electric pulses which are applied to form a single drop may be separated from one another by a time period of from about 40 microseconds to about 100 microseconds.

Alternatively, the acoustic drivers may be driven by unipolar electric pulses with the amplitude and pulse width of the unipolar pulses being varied to vary the volume of ink in the ink drops. In addition, strings or packets of successive drive pulses may be used to vary the volume of ink in the ink drops.

In addition to the foregoing factors that affect the nature of the driving signal, the driving pulses are also configured to limit the maximum negative pressure within the ink jet chambers to a value that is less than a predetermined threshold limit in order to avoid adverse effects of rectified diffusion. Excessive, repeated negative pressure pulses can cause air bubbles within the ink to grow to the point of affecting print quality and the eventual failure of operation of an ink jet. This is not described in detail in this application but rather the disclosure of the aforementioned copending application Serial No. 07/665,615 (EPA 91 306471.3) is to be referenced for a description of driving signal pulse shapes that avoids problems of rectified diffusion. This disclosure also appears in corresponding European patent application publication no. 467,656 dated January 22, 1992, which is incorporated herein by this reference.

The present invention relates to a method including the above aspects individually and in combination with one another. Portions of this are disclosed in European patent application publication no. 437,106, dated July 17, 1991, corresponding to the aforementioned parent United States application Serial No. 461,860. This published European application is incorporated herein by this reference.

Additional objects, features and advantages of the present invention will become more apparent with reference to the following description and drawings.

FIG. 1 is a schematic illustration of one form of an ink jet print head in accordance with the present invention with print media shown spaced from the ink jet print head.

FIG. 2 illustrates a form of drive signal for an acoustic driver of an ink jet print head in accordance with the present invention.

FIG. 3 is a schematic illustration, in section, of one type of ink jet print head which is capable of being operated in accordance with the method of the present invention.

FIGS. 4a, 4b and 4c illustrate a simulation of the change in shape of an ejected ink column at a point near breakoff of an ink drop from the column when an ink jet print head of the FIG. 3 form is actuated by a single drive pulse of the type shown in FIG. 2 and with the wait period for such pulse being varied.

FIG. 5 is a plot of drop flight time versus drop ejection rate for the continuous operation of an ink jet print head of the type illustrated in FIG. 3 when actuated by the drive wave form of FIG. 2, where the eject pulse width has been optimized.

FIG. 6 is a plot of the drop flight time as a function of drop ejection rate for the continuous operation of an ink jet of the type illustrated in FIG. 3 actuated by a drive pulse having only the eject pulse component "C" of the wave form of FIG. 2 and in which the eject pulse has been optimized for a specific ink jet print head.

FIG. 7 illustrates another drive signal for an acoustic driver of an ink jet printer in accordance with the present invention.

FIG. 8 is an electronic block diagram of a signal source that generates the bipolar drive signal shown in FIG. 7.

FIG. 9 shows yet another drive signal for an acoustic driver of an ink jet printer.

With reference to FIG. 1, a drop-on-demand ink jet print head 9 is illustrated with an internal ink pressure chamber (not shown in this figure) coupled to a source of ink 11. The ink jet print head 9 has one or more orifice outlets 14, 14a, 14b, etc. coupled to or in communication with the ink chamber by way of an ink orifice. Ink passes through the orifice outlets during ink drop formation. The ink drops travel in a first direction along a path from the orifice outlets toward print medium 13, which is spaced from the orifice outlets. A typical ink jet printer includes a plurality of ink chambers each coupled to one or more of the respective orifices and orifice outlets.

An acoustic drive mechanism 36 is utilized for generating a pressure wave or pulse, which is applied to the ink residing within the ink pressure chamber to cause ink to pass outwardly through the orifice and associated outlet 14. The acoustic driver 36 operates in response to signals from a signal source 37 to cause the pressure waves to be applied to the ink.

The invention has particular applicability and benefits when piezoelectric ceramic drivers are used in ink drop formation. One preferred form of an ink jet print head using this type of acoustic driver is described in detail in US patent no. 5,087,930, incorporated herein by this reference. However, it is also possible to use other forms of ink jet printers and acoustic drivers in conjunction with the present invention. For example, electromagnet-solenoid drivers, as well as other shapes of piezoelectric drivers (e.g., circular, polygonal, cylindrical, annular-cylindrical, etc.) may be used. In addition, various modes of deflection of piezoelectric drivers may also be used, such as bending mode, shear mode, and longitudinal mode.

With reference to FIG. 3, one form of ink jet print head 9 in accordance with the disclosure of the above-identified patent no. 5,087,930 has a body 10 which defines an ink inlet 12 through which ink is delivered to the ink jet print head. The body also defines an ink drop forming orifice outlet or nozzle 14 together with an ink flow path from the ink inlet 12 to the nozzle 14. In general, an ink jet print head of this type would preferably include an array of nozzles 14 which are proximately disposed, that is closely spaced from one another, for use in printing drops of ink onto a print medium.

Ink entering the ink inlet 12, e.g. from ink supply 11 as shown in FIG. 1, passes to an ink supply manifold 16. A typical color ink jet print head has at least four such manifolds for receiving, respectively, black, cyan, magenta, and yellow ink for use in black plus three color subtraction printing. However, the number of such ink supply manifolds may be varied depending upon whether a printer is designed to print solely in black ink or with less than a full range of color. From ink supply manifold 16, ink flows through an ink inlet channel 18, through an ink inlet 20 and into an ink pressure chamber 22. Ink leaves the ink pressure chamber 22 by way of an ink pressure chamber outlet 24 and flows through an ink passage 26 to the nozzle 14 from whicn ink drops are ejected. Arrows 28 diagram this ink flow path.

The ink pressure chamber 22 is bounded on one side by a flexible diaphragm 34. The pressure transducer, in this case a piezoelectric ceramic disc 36 secured to the diaphragm 34, as by epoxy, overlays the ink pressure chamber 22. In a conventional manner, the piezoelectric ceramic disc 36 has metal film layers 38 to which an electronic circuit driver, not shown in FIG. 3, but indicated at 37 in FIG. 1, is electrically connected. Although other forms of pressure transducers may be used, the illustrated transducer is operated in its bending mode. That is, when a voltage is applied across the piezoelectric disc, the disc attempts to change its dimensions. However, because it is securely and rigidly attached to the diaphragm 34, bending occurs. This bending displaces ink in the ink pressure chamber 22, causing the outward flow of ink through the passage 26 and to the nozzle. Refill of the ink chamber 22 following the ejection of an ink drop can be augmented by reverse bending of the pressure transducer 36.

In addition to the ink flow path 28 described above, an optional ink outlet or purging channel 42 is also defined by the body 10 of the ink jet print head 9. The purging channel 42 is coupled to the ink passage 26 at a location adjacent to, but interior to, the nozzle 14. The purging channel 42 communicates from ink passage 26 to an outlet or purging manifold 44 which is connected by a purging outlet passage 46 to a purging outlet port 48. The purging manifold 44 is typically connected by similar purging channels 42 to similar ink passages 26 associated with multiple nozzles 14. During a purging operation, ink flows in a direction indicated by arrows

50, through purging channel 42, purging manifold 44, purging outlet passage 46 and to the purging outlet port 48.

To facilitate manufacture of the ink jet print head of FIG. 3, the body 10 is preferably formed of plural laminated plates or sheets, such as of stainless steel. These sheets are stacked in a superposed relationship. In the illustrated FIG. 3 form of ink jet print head, these sheets or plates include a diaphragm plate 60, which forms the diaphragm and also defines the ink inlet 12 and purging outlet 48; an ink pressure chamber plate 62, which defines the ink pressure chamber 22, a portion of the ink supply manifold, and a portion of the purging passage 48; a separator plate 64, which defines a portion of the ink passage 26, bounds one side of the ink pressure chamber 22, defines the inlet 20 and outlet 24 to the ink pressure chamber, defines a portion of the ink supply manifold 16 and also defines a portion of the purging passage 46; an ink inlet plate 66, which defines a portion of the passage 26, the inlet channel 18, and a portion of the purging passage 46; another separator plate 68 which defines portions of the passages 26 and 46; an offset channel plate 70, which defines a major or offset portion 71 of the passage 26 and a portion of the purging manifold 44; a separator plate 72 which defines portions of the passage 26 and purging manifold 44; an outlet plate 74 which defines the purging channel 42 and a portion of the purging manifold; a nozzle plate 76 which defines the nozzles 14 of the array; and an optional guard plate 78 which reinforces the nozzle plate and minimizes the possibility of scratching or other damage to the nozzle plate.

More or fewer plates than illustrated may be used to define the various ink flow passageways, manifolds and pressure chambers. For example, multiple plates may be used to define an ink pressure chamber instead of a single plate as illustrated in FIG. 3. Also, not all of the various features need be in separate sheets or layers of metal.

Exemplary dimensions for elements of the ink jet print head of FIG. 3 are set forth in Table 1 below.

TABLE 1

Representative Dimensions and Resonant Characteristics For Figure 3 Ink Jet Print Heads			
Feature	Cross Section	Length	Frequency of Resonance
Ink Supply Channel 18	0.008”x0.010”	0.268”	60-70KHz
Diaphragm Plate 60	0.110”dia.	0.004”	160-180KHz
Body Chamber 22	0.110”dia.	0.018”	
Separator Plate 64	0.040”x0.036”	0.022”	
Offset Channel 71	0.020”x0.036”	0.116”	65-85KHz
Purging Channel 42	0.004”x0.010”	0.350”	50-55KHz
Orifice Outlet 14	50-70μm	60-76μm	13-18KHz

The various layers forming the ink jet print head may be aligned and bonded in any suitable manner, including by the use of suitable mechanical fasteners. However, one approach for bonding the metal layers is described in U.S. Patent No. 4,883,219 to Anderson, et al., and entitled "Manufacture of Ink Jet Print Heads by Diffusion Bonding and Brazing."

In accordance with the present invention, an advantageous drive signal for driving ink jets utilizing acoustic drivers is illustrated in FIG. 2. This particular drive signal is a bipolar electrical pulse 100 with a refill pulse component 102 and an ejection pulse component 104. The components 102 and 104 are voltages of opposite relative polarity of possibly different voltage amplitudes. These electrical pulses or pulse components 102, 104 are also separated by a wait period state indicated at 106. The time duration of the wait period 106 is indicated as "B" in FIG. 2. The relative polarities of the pulse components 102, 104 may be reversed from that shown in FIG. 2, depending upon the polarization of the piezoelectric ceramic driver mechanism 36 (FIG. 1).

FIG. 2 demonstrates the representative shape of the drive signal, but does not provide representative values for the various attributes of the signal or its pulse components, such as voltage amplitudes, time durations or rise times and fall times. Furthermore, although the pulse components of the drive signal shown in FIG. 2 have trapezoidal or square wave form, in actual operation these pulse components may exhibit exponentially rising leading edges and exponentially decaying trailing edges.

A preferred embodiment of the drive signal comprises a bipolar electrical signal with refill and ejection pulse components varying about a zero voltage amplitude maintained during the wait period 106; however, the invention is not limited to this particular embodiment. The drive signal may comprise pulse components of opposite relative polarity varying about a positive or negative reference voltage amplitude maintained during the wait period state.

In the operation of an ink jet print head, utilizing the drive signal described above, the ink pressure chamber 22 expands upon the application of the refill pulse component 102 and draws ink into the ink pressure chamber 22 from the ink source 11 to refill the ink pressure chamber 22 following the ejection of a drop. As the voltage falls toward zero at the end of the refill pulse component 102, the ink pressure chamber 22 begins to contract and moves the ink meniscus forward in the ink orifice 103 (FIG. 3) toward the orifice outlet 14. During the wait period "B", the ink meniscus continues toward the orifice outlet 14. Upon the application of the ejection pulse component 104, the ink pressure chamber 22 is rapidly constricted to cause the ejection of a drop of ink. After the ejection of the drop of ink, the ink meniscus is once again drawn back into the ink orifice 103 away from the orifice outlet 14 as a result of the application of the refill pulse component 102. The time duration of the refill pulse component, including rise and fall times, is less than the time required for the ink meniscus to return to a position adjacent to the orifice outlet 14 for ejection of a drop of ink.

Typically, the time duration of the refill pulse component 102, including rise time and fall time, is less than one-half of the time period associated with the resonant frequency of the ink meniscus. More preferably, this duration is less than about one-fifth of the time period associated with the resonant frequency of the ink meniscus. The resonant frequency of an ink meniscus in an orifice of an ink jet print head can be easily calculated from the properties of the ink, including the volume of the ink inside the ink jet print head, and the dimensions of the orifice in a known manner.

As the time duration of the wait period "B" increases, the ink meniscus moves closer to the orifice outlet 14 at the time the ejection pulse component 104 is applied. In general, the time duration of the wait period 106 and of the ejection pulse component 104, including the rise time and fall time of the ejection pulse component, is less than about one-half of the time period associated with the resonant frequency of the ink meniscus. For controlling the operation of an ink jet print head to achieve high print quality and high printing rates by the drive signal described, typical time periods associated with the resonant frequency of the ink meniscus range from about 50 microseconds to about 160 microseconds, depending upon the configuration of the specific ink jet print head and the particular ink.

The pulse components 102 and 104 of the drive signal controlling the operation of the ink jet print head to achieve high print quality and high printing rates are shown in FIG. 2 as being generally trapezoidal and of 5 opposite polarity. Square wave pulse components may also be used. A conventional signal source 37 may be used to generate pulses of this shape. Other pulse shapes may also be used. In general, a suitable refill pulse component 102 is one which results in increasing the volume of the ink pressure chamber 22 through the expansion of the chamber to refill the chamber with ink from the ink source 11 while withdrawing the ink in the ink orifice 103 back toward the ink pressure chamber 22 and away from the orifice outlet 14. The wait period 106 is a period during which essentially zero voltage is applied to the acoustic driver. It comprises a period during which the ink pressure chamber 22 is allowed to return back to its original volume due to contraction of the chamber so as to allow the ink meniscus in the ink orifice 103 to advance within the orifice away from the ink pressure chamber 22 and toward the orifice outlet 14. The ejection pulse component 104 is of a shape which causes a rapid contraction of the ink pressure chamber 22 following the wait period 106 to reduce the volume of the chamber and eject a drop of ink.

A drive signal composed of pulses of the form shown in FIG. 2 is repeatedly applied to cause the ejection of ink drops. One or more such pulses may be applied to cause the formation of each drop, but, in a preferred embodiment, at least one such composite drive signal is used to form each of the drops. In addition, the time duration of the wait period 106 is typically set to allow the ink meniscus in the ink orifice 103 to advance to substantially the same position within the orifice during each wait period before contraction of the ink pressure chamber 22 to eject a drop. During the wait period 106, the ink which was retracted during the refill pulse component is allowed to return to a location adjacent to the orifice outlet 14 prior to the arrival of the drop ejection pressure pulse as a result of pulse component 104. By positioning the meniscus at substantially the same position prior to the drop ejection pressure pulse component, uniformity of drop flight time to the print medium is enhanced over a wide range of drop ejection rates. In addition, the duration of the wait period is preferably established to allow the ink meniscus to advance within orifice 103 to a position substantially at the ink drop ejection orifice outlet 14, but not beyond such orifice outlet, before the ink chamber 22 is contracted to eject a drop of ink. If ink is allowed to project beyond the orifice outlet 14 for a substantial period of time before the ejection pulse 104 is applied, it may wet the surface surrounding the orifice outlet. This wetting may cause an asymmetric deflection of ink drops and non-uniform drop formation as the various drops are formed and ejected. By positioning the ink meniscus at substantially the same position prior to the pressure pulse, uniformity of drop flight time to the print medium is enhanced over a wide range of drop ejection rates.

In addition, it is preferable that the ink meniscus have a remnant of forward velocity within the orifice 103 toward orifice outlet 14 at the time of arrival of the pressure pulse in response to the ejection pulse component 104 of FIG. 2. Under these conditions, the fluid column propelled out of the ink jet print head properly coalesces into a drop to thereby minimize the formation of satellite drops. The eject pulse component 104 causes the diaphragm 34 of the pressure transducer to rapidly move inwardly toward the ink chamber 22 and results in a sudden pressure wave. This pressure wave ejects the drop of ink presented at the orifice outlet at the end of the wait period. Following the termination of the eject pulse component 104, diaphragm returns toward its original position and, in so doing, initiates a negative pressure wave which assists in breaking off an ink drop.

Exemplary durations of the various pulse components for achieving high print quality and high printing rates are 5 microseconds for the "A" portion of the refill pulse component 102, with rise and fall times of respectively 1 microsecond and 3 microseconds; a wait period "B" of 15 microseconds; and an ejection pulse component 104 with a "C" portion of 5 microseconds and with rise and fall times like those of the refill pulse component 102. As stated earlier, FIG. 2 demonstrates the representative shape of the drive signal, but does not provide representative values for its various attributes. To achieve high print quality and high printing rates, it may sometimes be advantageous to reduce the duration of these time periods so that the fluidic system may be reinitialized as quickly as possible, thereby making faster printing rates possible. An alternative method to increase the drop repetition rate for the drive signal comprises reducing the time duration from the trailing edge of the ejection pulse component to the leading edge of the refill pulse component. This method has the advantage that it does not affect the time durations of the pulse components, including rise and fall times.

FIG. 4 illustrates a simulation of the change in shape of an ejected ink column when an ink jet print head of the type illustrated in FIG. 3 is actuated by a drive signal composed of the exemplary durations above. FIGS. 4a, 4b, and 4c demonstrate the effect of varying the wait period 106. As shown in FIG. 4a, with the time duration of the wait period "B" at 18 microseconds, the main volume of ink 120 forms a spherical head which is connected to a long tapering tail 122 with drop breakoff occurring at a location 124 between the tail of this filament and the orifice outlet 14. After drop breakoff, the tail 122 starts to coalesce into the head 120 and does not form a spherical drop by the time it reaches the print medium. However, due to the relatively high speed of the ink column with respect to the print medium the resulting spot on the print medium is nearly spherical.

As shown in FIG 4b, with a wait period 106 of 8 microseconds, the drop breakoff point 124 is adjacent to the main volume of ink 120 and results in a cleanly formed drop. In this case, the tail 122 of the drop breaks off subsequently to the orifice outlet 14 and forms a satellite drop which moves at a relatively smaller velocity than that of the main drop. Consequently, the main drop 120 and satellite drop 122 form two separate spots on the print medium.

With reference to FIG. 4c, and with a wait period 106 of zero microseconds, the drop breakoff point 124 occurs adjacent to the main drop volume 120. However, the remaining ink filament 122 has weak points, indicated at 126 and 128, corresponding to potential locations at which the filament may break off and form satellite drops.

The FIG. 4 illustrations are the result of a theoretical model of the operation of the ink jet print head of FIG. 3 using the form of the drive signal shown in FIG. 2. The FIG. 4 illustrations show only the upper half of the formed drop above the center line of the ink orifice 103 in each of these figures.

Neither a pull back or refill pulse, such as pulse component 102 alone, nor an ejection pulse, such as component 104 alone, results in satisfactory print performance, even though drop ejection may be accomplished by either of the pulse components 104, 106 alone. In practice, using just a refill pulse component 104 would tend to severely limit the drop ejection speed, such as to about 3.5 meters per seconds or less. In addition, increasing the magnitude or duration of the refill pulse component 104, in an attempt to increase drop speed, would result in pulling the meniscus so far into the upstream edge of the ink orifice 103 that ingestion of air bubbles may result. High drop speeds are desirable, such as on the order of 6 meters per second or more, to increase the capacity of an ink jet printer to operate at high drop ejection rates.

The use of an eject pulse component 104 only, without the refill pulse and wait period components, results in a rhythmical variation in drop speed with changing drop ejection rates. The frequency of the rhythmical variations may be verified from the information in Table 1 above to be the same as that of the reverberation resonance in the channel sections forming the ink flow path between the ink chamber 22 and the ink orifice outlet 14. As shown in FIG. 6, an eject pulse component only drive signal may be designed which smoothes the speed or flight time variations by using a drive pulse with a frequency spectrum which deliberately removes energy from the reverberations. However, in this case, the ink volume per drop declines as the ejection rate increases. In other words, the ink chamber does not adequately refill between drop ejections at all drop ejection rates. A further disadvantage is that, since the same amount of energy is imparted by the piezoelectric element to every drop ejected regardless of refilling, the smaller drops tend to travel at faster speeds. Thus, as shown in FIG.

6, the drop speed generally increases (corresponding to a decrease in flight drop time) as the drop ejection rate increases, although the rhythmical drop speed variations are absent.

The deficiencies of the eject only pulse component drive approach, are overcome by actuating a refill pulse component 104 first to actively refill the ink chamber 22. In addition, the offset channel 71 in FIG. 3 is also refilled if the ink jet print head is of a design having such a channel. The ink chamber may be passively refilled fully by enlarging the ink inlet 18, 20 from the ink supply reservoir (11 in FIG. 1), without using an active refill pulse component 104. However, in this case upon movement of the diaphragm inwardly to cause a drop to issue from the drop ejection orifice 14, the pressure pulse set up in the ink chamber 22 would flow into the conduit leading to the orifice 26 and also into the ink inlet 18, 20 itself. The portion of the pressure wave traveling into the ink inlet would then represent energy unavailable for the ink drop formation. The use of an active refill pulse component permits a smaller inlet opening 20 which reduces this potential loss of energy available for drop formation and also isolates the body chamber 22 and passageway 26 from pressure pulse disturbances originating in the ink reservoir or manifold 16 if the jet is a member of an array. This isolation is progressively reduced as the inlet opening 20 is enlarged. A balance is thus struck among the size of the ink inlet 20, the strength of the refill pulse component 102 (FIG. 2) and the strength of the eject pulse component 104. A strong refill pulse component 102 will pull ink through the inlet opening 20 into the pressure chamber 22. Too strong of a refill pulse component will cause the ingestion of a bubble through the orifice outlet. Likewise, too strong of an eject pulse component 104 will eject more ink in a single drop than the refill pulse component may be able to draw through the ink inlet 20. One preferred interrelationship of these parameters is described in Table 1 above and in the exemplary pulse component durations mentioned above.

The inclusion of a refill pulse component 102 in the drive signal tends to draw ink back from the external surface surrounding the ink orifice outlet 14. This action minimizes the possibility of ink wetting the surface surrounding the outlet and distorting the travel or breakoff of ink drops at the orifice outlet.

The preferred time duration of the wait period "B" is a combined function of the time for the retracted ink meniscus in ink orifice 103 to reach the orifice outlet 14 and the velocity of the ink at the instant of arrival of the pressure pulse initiated by the ejection pulse component 104. It is desired that the retracted ink meniscus reach the orifice outlet 14 with waning velocity just before the pressure pulse from the ejection pulse component 104 is applied.

As shown in FIG. 5, and which should be contrasted with FIG. 6, a plot of the flight time for an ink jet print head of the type shown in FIG. 3 versus drop ejection rate and is substantially constant over a range of drop ejection rates through and including ten thousand drops per second. FIG. 5 depicts the situation in which the ink jet print head is operated in the manner described to achieve high print quality and high printing rates. In this FIG. 5 example, the print medium was 1 mm. from the ink jet print head orifice outlet 14, and drop speeds in excess of 6 meters per second were achieved. As also shown in FIG. 5, a maximum deviation of 30 microseconds was observed over an ink jet drop ejection rate ranging from 1,000 drops per second to 10,000 drops per second. In addition, at below 8,500 drops per second, this deviation was much less pronounced. Thus, by suitably selecting a drive signal having a refill pulse component 102, a wait period 106, and an ejection pulse component 104, substantially constant drop flight times can be achieved over a wide range of drop ejection rates. Substantially constant drop flight times result in high print quality.

In addition, the drop speeds are relatively fast with uniform drop sizes being available. The drop trajectories are substantially perpendicular to the orifice face plate for all drop ejection rates, inasmuch as the refill pulse component 102 of the drive pulse assists in reducing wetting of the external surface surrounding the orifice outlet 14 which may cause a deflection of the ejected drops from a desired trajectory. Moreover, satellite drop formation is minimized because this drive signal allows high viscosity ink, such as hot melt ink, within the conduit of the ink orifice 103 to behave as an intracavity acoustic absorber of pressure pulses reverberating in the offset channel 71 of an ink jet print head of the type shown in FIG. 3. The relatively simple drive signal of the type illustrated in FIG. 2 may be achieved with conventional off-the-shelf digital electronic drive signal sources.

Referring again to FIG. 2, a preferred relationship between the drive pulse components 102, 104 and 106 have been experimentally determined. In particular, for an ink jet print head, such as of the type shown in FIG. 3, by establishing a wait time period of at least about and preferably greater than about 8 microseconds, uniform and consistent ink drop formation has been achieved. Shorter wait periods have been observed in some cases to increase the probability of formation of satellite drops than with the wait period established at or above this 8 microsecond level. In addition, preferably the refill or expanding pulse component 102 is no more than about 16 to 20 microseconds. A greater refill pulse component duration increases the possibility of ingesting bubbles into the ink orifice outlet. In addition, the refill pulse component duration need be no longer than necessary to replace the ink ejected during ink drop formation. In general, shorter refill periods increase the drop repetition rate which may be achieved. In general, the refill pulse component 102 has a duration in a preferred form of no less than about 7 microseconds. In addition, the duration of the ejection pulse component 104 is typically no more than about 16 to 20 microseconds and no less than about 6 microseconds. Again, pulse components within these ranges enhances the uniformity of drop formation and drop travel speed over a wide variation in drop ejection rates.

Within these drive signal parameters that control the operation of an ink jet print head to achieve high print quality and high printing rates, ink jet print heads of the type shown in FIG. 3 have been operated at drop ejection rates through and including 10,000 drops per second, and higher, and at drop ejection speeds in excess of 6 meters per second. The drop speed nonuniformity has been observed at less than 15 percent over continuous and intermittent drop ejection conditions. As a result, the drop position error is much less than one-third of a pixel at 11.81 drops per mm. (300 dots per in.) printing with an 8 kilohertz maximum printing rate. In addition, a measured drop volume of 170 picoliters of ink per drop ± 15 picoliters (over the entire operating range of 1,000 to 10,000 drops per second) has been observed and is suitable for printing at 11.81 drops per mm addressability when using hot melt inks. Additionally, minimal or no satellite droplets occur under these conditions.

As shown in FIG. 2, the first pulse component, refill component 102, reaches a voltage amplitude and is maintained at this amplitude for a period of time prior to termination of the first or refill pulse component. In addition, the second or ejection pulse component 104 reaches a negative voltage amplitude and is maintained at this amplitude for a period of time prior to termination of the second pulse. Although this may be varied, in the illustrated form to achieve high print quality and high printing rates, these drive pulse components are trapezoidal in shape and have a different rise time to their respective voltage amplitudes from the fall time from their respective voltage amplitudes. In a drive signal to achieve high print quality and high printing rates, the two pulse components 102, 104 have rise times from about one microsecond to about 4 microseconds, maintain their respective voltage amplitudes from about 2 microseconds to about 7 microseconds, with the wait period 106 being greater than about 8 microseconds. In an alternative drive signal to achieve high print quality and high printing rates, the rise time of the first pulse is about 2 microseconds, the first pulse achieves its voltage amplitude from about 3 microseconds to about 7 microseconds, the first pulse has a fall time from about 2 microseconds to about 4 microseconds, and the wait period 106 is from about 15 microseconds to about 22 microseconds. In addition, in this case the ejection pulse component 104 is like the refill pulse component 102, except of opposite relative polarity.

It should be noted that to achieve high print quality at high printing rates these time durations may be varied for different ink jet print head designs and different inks. Again, it is desirable for the ink meniscus to be traveling forward and to be at a common location at the occurrence of each pressure wave resulting from the application of the ejection pulse component 104. The parameters of the drive signal may be varied to achieve these conditions.

It has also been discovered that optimal print quality and printing rate performance is achieved when the drive signal is shaped so as to provide a minimum energy content at the dominant acoustic resonant frequency of the ink jet print head. That is, the dominant acoustic resonant frequency of the ink jet print head can be determined in a well-known manner. The dominant resonant frequency of the ink jet print head typically corresponds to the resonant frequency of the ink meniscus. When an ink jet print head of the type shown in FIG. 3 is used with an offset channel 71, the dominant acoustic resonant frequency in general corresponds to the standing wave resonant frequency through the liquid ink in the offset channel. By using a drive signal with an energy content which is at a minimum at the dominant acoustic resonant frequency of the ink jet print head, reverberations at this dominant acoustic resonant frequency are minimized, such reverberations otherwise potentially interfering with the uniformity of flight time of drops from the ink jet print head to the print medium.

In general, to assist in adjusting the drive signal to achieve high print quality and high printing rates, a Fourier transform or spectral analysis is performed of the complete drive signal. The complete drive signal is an entire set of pulses used in the formation of a single ink drop. In the case of a drive signal of the type shown in FIG. 2, the complete signal includes the refill pulse component 102, the wait period 106, and the election pulse component 104. A conventional spectrum analyzer may be used in determining the energy content of the drive signal at various frequencies. This energy content will vary with frequency from highs, or peaks, to valleys, or low points. A minimum energy content portion of the drive signal at certain frequencies is substantially less than the peak energy content at other frequencies. For example, a minimum energy content may be at least about 20 dB below the maximum energy content of the drive signal at other frequencies.

The drive signal may be adjusted to shift the frequency of this minimum energy content to be substantially equal to the dominant acoustic resonant frequency of the ink jet print head. With the drive signal adjusted in this manner, the energy of the drive signal at the dominant acoustic resonant frequency is minimized. As a result, the effect of resonant frequencies of the ink jet print head on ink drop formation is minimized. Although not limited to any specific approach, a preferred method of adjusting the drive signal to achieve high print quality and high printing rates comprises the step of adjusting the time duration of the first pulse, or refill pulse component 102, including rise time and fall time, and of the wait period 106. These pulse components are adjusted in duration until there is a minimum energy content of the drive signal at the frequency which is substantially equal to the dominant acoustic resonant frequency of the ink jet print head.

Although these advantages exist, another principal advantage of the present invention relates to the effective achievement of half-tone or grey scale printing in a drop-on-demand ink jet printer. The phrase grey scale printing is synonymous with drop volume modulation or variation. FIGS. 7 and 8 show a wave form and circuit for generating the wave form, respectively, that provides for such drop volume control.

In general, the volume of ink contained in an individual ink drop is controlled by the diameter of the ink jet orifice and by controlling the wave form used in driving the acoustic driver. By adjusting the wave form to increase the volume of ink, larger ink drops can be achieved. Conversely, by adjusting the drive wave form to reduce the volume of ink, smaller ink drops result.

In accordance with the present invention, an advantageous drive signal for achieving grey scale printing is illustrated in FIG. 7. This particular drive signal is a bipolar electric pulse 160 with a refill pulse component 162 and an ejection pulse component 164. The components 162 and 164 are of voltages of opposite polarity. The pulse components 162, 164 are also separated by a wait time period X. The polarities of the components 162, 164 may be reversed from that shown in FIG. 7 depending upon the polarization of the piezoelectric driver mechanism 36 (FIGS. 1 and 3). In operation, upon the application of the refill pulse component 162, the ink chamber 22 expands and draws ink into the chamber for refilling the chamber following the ejection of a drop. As the voltage falls toward 0 at the end of the refill pulse, the ink chamber begins to contract and moves the ink meniscus forwardly in the orifice 103 toward the orifice outlet 14. Upon the application of the ejection pulse component 164, the ink chamber is rapidly constricted to cause the ejection of a drop of ink. In this approach for forming a drop the duration of the refill pulse component is less than the time required for the meniscus, which has been withdrawn further into the orifice 103 as a result of the refill pulse, to return to an initial position adjacent to the orifice outlet 14. The duration of the refill pulse component is less than one-half of the time period of the natural or resonance frequency of the meniscus. More preferably, this duration is less than about one-fifth of the time period of the meniscus' natural resonance frequency. The resonance frequency of an ink meniscus in as orifice of an ink jet can be easily calculated from the properties of the ink and dimensions of the ink orifice in known manner. As the duration of the wait period increases, the ink meniscus moves closer to the orifice outlet 14 at the time the ejection pulse component 164 is applied. Smaller drop volumes of ejected drops are obtained by establishing a wait period which is short enough such that the eject pulse component is applied at a time that the meniscus is moving forward within the orifice and prior to the time that the meniscus reaches the orifice outlet. Conversely, larger volumes of ejected drops are obtained by extending the duration of the wait period sufficiently to allow the ink to reach the orifice outlet before the eject pulse component is applied. At this later time, the orifice is completely filled with ink. The duration of the desired wait period and the eject pulse width for a given drop volume depends upon the characteristics of the particular ink jet being utilized and can be observed by monitoring the performance of the ink jet. In general, the wait period and eject pulse component period are less than about one-half of the time period of the natural or resonance frequency of the meniscus. Typical meniscus resonance time periods range from 50 microseconds to 160 microseconds, depending upon the ink jet configuration and the ink being used. In addition, by increasing the duration of the eject pulse component 64, or by increasing the amplitude of the eject pulse component, the volume of the ink drops can be increased.

As a specific example, assume that an ink jet print head of the type disclosed in the previously mentioned United States patent no. 5,087,930, is to be operated at a 4 kilohertz drop repetition rate. In this case, various levels or volumes of ink in individual ink drops would result from altering the drive wave form of FIG. 7. The spots or dots, if printed with hot melt ink on mylar print medium and before fusing, are expected to range in size from about 2.2 mils. to about 3.9 mils. If the ink is hot melt ink, following fusing of the ink spots on the print medium, by the application of pressure, this variation in spot size is even greater, for example, from about 2.6 mils to about 5.5 mils. To achieve the smallest dot size, for example, the wait period X would be set at 9 microseconds and the duration Y of the eject pulse component 64 would be set at 3 microseconds. To achieve a next level of dot size, for example, X would be set at 11 microseconds and Y would be set at 5 microseconds. To achieve a still higher or greater dot size level, for example, X would be set at 11 microseconds and Y would be set at 9 microseconds. To achieve a fourth level dot size, for example, X would be set at 12 microseconds and Y would be set at 11 microseconds. To achieve a level 5 dot size, for example, X would be set at 12 microseconds and Y would be set at 15 microseconds. Finally, to achieve the largest dot size, for example, X would be set at 12 microseconds and Y would be set at 20 microseconds. In each of these cases, the amplitude and pulse width of the refill pulse component would be, for example, respectively forty volts and five microseconds. Also, the amplitude of the eject pulse component would be, for example, forty volts. By adjusting these component values of the bipolar drive pulses, the ink drop volumes and ink dot sizes would be correspondingly adjusted. Similarly, by increasing the amplitude of the eject pulse component, either alone or in combination with an adjustment of the duration of the wait period and of the pulse width of the eject pulse component, variation in ink drop volume would also be achieved. As the amplitude of the eject pulse component 64 increases, the ratio of the amplitude of the eject pulse component to the refill pulse component would increase as would the volume of ink included in the drops Similarly, as the pulse width of the eject pulse component increases, the ratio of the pulse width of the eject pulse component to the pulse width of the refill pulse component would also increase, as would the ink drop volume.

In addition, plural bipolar pulses of the type shown in FIG. 7 may be utilized to produce an individual ink drop. In general, by increasing the number of such bipolar pulses used in forming an ink drop, the volume of ink in the ink drop is increased. In effect, each bipolar pulse causes an additional amount of ink to be added to the ink drop and thus increases the volume of ink included in an ink drop before the ink drop separates from the orifice outlet. To cause separation of an individual ink drop formed in this manner, the time period between the bipolar pulses is increased. Alternatively, it is also expected that drop break off can also be accomplished by applying a pulse of higher energy after the desired number of bipolar pulses have been used to generate the drop of the desired size.

As a specific example, a typical bipolar pulse of a string of such pulses, including the refill component, wait period component and eject component, may have a duration of from about 20 microseconds to 40 microseconds. In addition, the typical time delay between individual bipolar pulses may range from about 30 to about 100 microseconds. For an ink jet print head of the type shown in FIGS. 1 and 3, if the time delay between individual pulses becomes greater than about 100 microseconds, the drops break off. Assuming a 20 microsecond duration bipolar pulse, then one exemplary separation between the bipolar pulses is about 40 microseconds. In this case the separation is about two times the duration of an individual bipolar pulse. If the time period between bipolar pulses is less than about 100 microseconds, or such other time at which drop break-off occurs, a successive bipolar pulse would add ink to the volume of an individual ink drop instead of generating a separate drop.

The compounding of one or more bipolar pulses to produce an individual drop does reduce the maximum drop repetition rate at which an ink jet printer can be operated. However, high drop repetition rates are still possible. For example, assuming the case above where up to three bipolar pulses are combined to produce the largest drop sizes, repetition rates of up to eight kilohertz have been achieved.

Finally, it should be noted that the present invention is applicable to ink jet printers using a wide variety of inks. Inks that are liquid at room temperature, as well as inks of the phase change type which are solid at room temperature, may be used. One suitable phase change ink is disclosed in U.S. Patent 4,889,560. Again, however, the present invention is not limited to particular types of ink.

FIG. 8 illustrates an example of circuitry inside the signal source 37 that can be used to produce the bipolar electric pulse 160, which is applied to the piezoelectric ceramic material 36. Referring to FIG. 8, a central-processing unit ("CPU") 200 outputs a trigger pulse to refill a pulse timer 202 to initiate the pulse component 162. In response to the trigger pulse, the refill pulse timer 202 outputs a refill pulse drive signal at its output 206 to the negative input of a transducer driver 204, causing the transducer driver 204 to output the pulse component 162 of FIG. 7. The duration of the component 162 is controlled by a count that is loaded from the CPU 200 through a counter preset line 208.

When the refill pulse timer 202 counts to zero, the signal at the output 206 goes to a zero value which (1) causes the negative input of the transducer driver 204 to return to a zero value and (2) initiates the wait period timer 210. As the input of the transducer driver 204 returns to zero, the pulse component 162 ends and the wait period begins. The wait period has a duration X which is controlled by a count that is loaded from the CPU 200 through a counter preset line 212.

When the wait period timer 210 counts to zero, the signal at its output 214 goes to a zero value which initiates an eject pulse timer 218. The output of the eject pulse timer 218 in a line 222 causes a positive input of the transducer driver 204 to go high and the pulse component 164 of FIG. 7 to begin. The component 164 has a duration Y which is controlled by a count that is loaded from the CPU 200 through a counter preset line 216. When the eject pulse timer 218 counts to zero, the signal at its output 222 goes to a zero value, thereby ending the pulse component 164.

With reference to FIG. 9, a unipolar drive pulse is illustrated. As described above, the bipolar pulse drive signal of FIG.2 is preferred but some situations exist where a unipolar pulse is useable. Such a unipolar drive pulse can be generated in a conventional manner by the signal generator 37 and applied to the acoustic drive mechanism 36. In a first approach for varying the volume of ink drops, an amplitude modulation approach, the amplitude of the pulse shown in FIG. 9 may be increased from V_0 to V_1. This results in an increase in the volume of ink included in ink drop. Conversely, if the voltage is reduced from V_0 to a lower level, the volume of ink in the ink drop is reduced. A pulse width modulation technique may also be used. For example, by increasing the duration or pulse width of the pulse illustrated in FIG. 9 from t_1 to t_2 to t_1 to t_3, the volume of ink included in an ink drop is increased. In contrast, by decreasing the pulse width of the illustrated pulse, the volume of ink included in an ink drop is reduced. Combinations of amplitude and pulse width modulation approaches may also be used and different wave forms may be applied other than those shown in FIG. 9. For example, strings of pulses may be used with the number of pulses applied to the driver 30 between initial drop formation and break-off of the drop determining the volume of the ink drop.

In addition to the foregoing, control of the volume and travel of the ink drop from the print head orifice to the print medium can be assisted by providing a controllable electric field in the space therebetween. This is not described herein but rather the disclosure of aforementioned copending application Serial No. 07/892,494, (EP 00 437 062) a continuation of applications Serial Nos. 07/698,172 and 07/451,080, is to be referenced. This disclosure also appears in corresponding European patent application publication no. 437,062 dated July 17, 1991, which is incorporated herein by this reference.

Having illustrated and described the principles of the invention with reference to several preferred embodiments, it will be apparent to those of ordinary skill in the art that the invention may be modified in arrangement and in detail without departing from such principles. We claim as our invention all such modifications.

Included within the scope of the invention is a method of operating an ink jet of the type having an ink chamber coupled to a source of ink, an ink drop ejecting orifice with an ink drop ejection orifice outlet, the ink drop ejecting orifice being coupled to the ink chamber, driver means for expanding and contracting the ink-chamber to eject a drop of ink from the ink drop ejecting orifice outlet, the method comprising:

expanding the volume of the ink chamber to fill the chamber with ink from the source of ink and to draw the ink in the orifice toward the ink chamber and away from the ink drop ejection orifice outlet;

waiting for a wait time period during which the ink chamber is returning back to is original volume so as to allow the ink the orifice to advance within the orifice away from the ink chamber and toward the ink drop ejection orifice outlet; and

contracting the volume of the ink chamber following the wait period to eject a drop of ink.

Claims

1. A method of operating an ink jet printer of a type that accepts ink in solid form into a reservoir where it is melted to supply a plurality of print head chambers with molten ink for selective simultaneous ejection of molten ink droplets through individual chamber orifices onto a media a distance from the orifices and with relative motion therebetween, said ink droplets solidifying shortly after striking the media, comprising the steps of:

   providing a maximum operable repetition rate of droplet ejection from said chambers to be that which ejects a droplet of ink onto designated pixel locations across the media in at least one direction of said relative motion between the print head and the media, and

   applying a pressure function to ink within the chambers to eject through respective of said orifices individual droplets (a) with velocities within a range of about fifteen percent of each other over a range of repetition rates from intermittent droplet ejection up to said maximum operable repetition rate, and (b) with a shape when striking the media that is substantially round and free of satellite droplets.

2. A method as claimed in Claim 1 wherein the step of providing a maximum operable repetition rate of droplet ejection includes setting said rate at substantially 8000 droplets per second or more.

3. A method as claimed in Claim 2 wherein the step of providing a maximum operable repetition rate of droplet ejection includes setting said maximum repetition rate at substantially 10000 droplets per second or less.

4. A method as claimed in any one of Claims 1 to 3 wherein the step of applying a pressure function includes the step of ejecting said droplets with said velocities lying substantially within a range of 3.5 to 8 meters per second.

5. A method as claimed in any preceding claim wherein the step of applying a pressure function includes the step of ejecting said droplets with a velocity of about 6 meters per second or more.

6. A method as claimed in any preceding claim wherein the step of applying a pressure function includes applying two pressure pulses per droplet with a delay between them.

7. A method as claimed in Claim 6 wherein the step of applying a pressure function additionally includes reducing the pressure within the ink chamber by the first of said two pressure pulses and increasing the pressure within the ink chamber by the second pressure pulse with respect to an ambient pressure.

8. A method as claimed in any preceding claim wherein the step of providing a maximum operable repetition rate of droplet ejection includes matching the relative motion of the media and the print head to the maximum operable repetition rate.

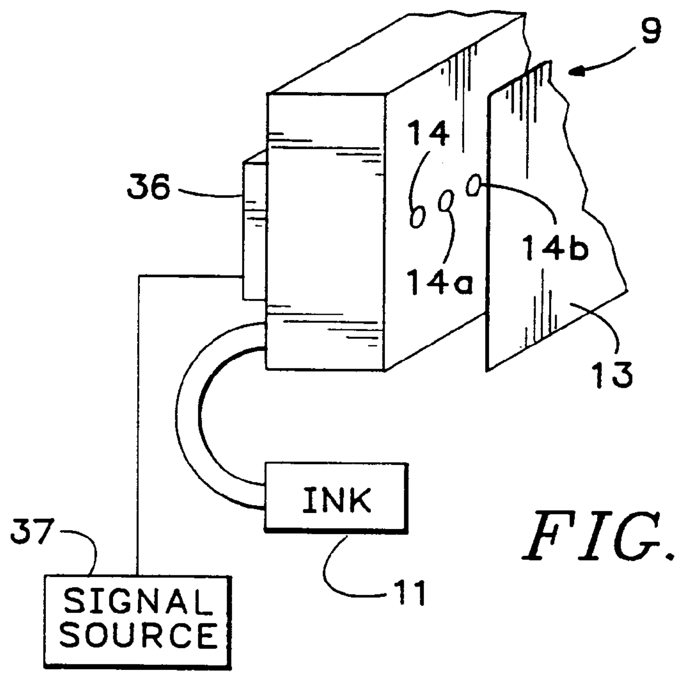
9
14
36
14b
14a
13
INK
37
11
SIGNAL SOURCE

FIG.1

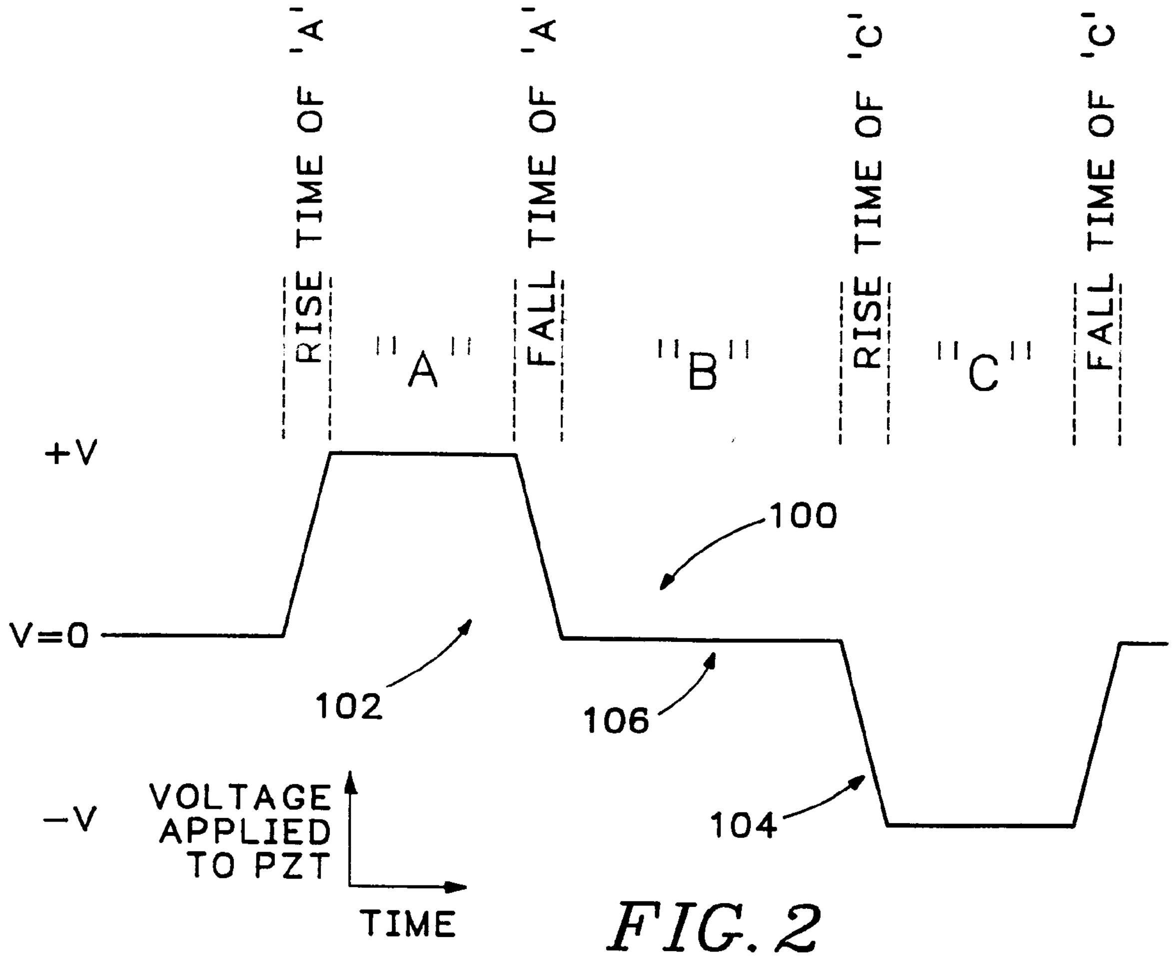
RISE TIME OF 'A'
FALL TIME OF 'A'
RISE TIME OF 'C'
FALL TIME OF 'C'
"A"
"B"
"C"
+V
100
V=0
102
106
104
−V
VOLTAGE APPLIED TO PZT
TIME

FIG. 2

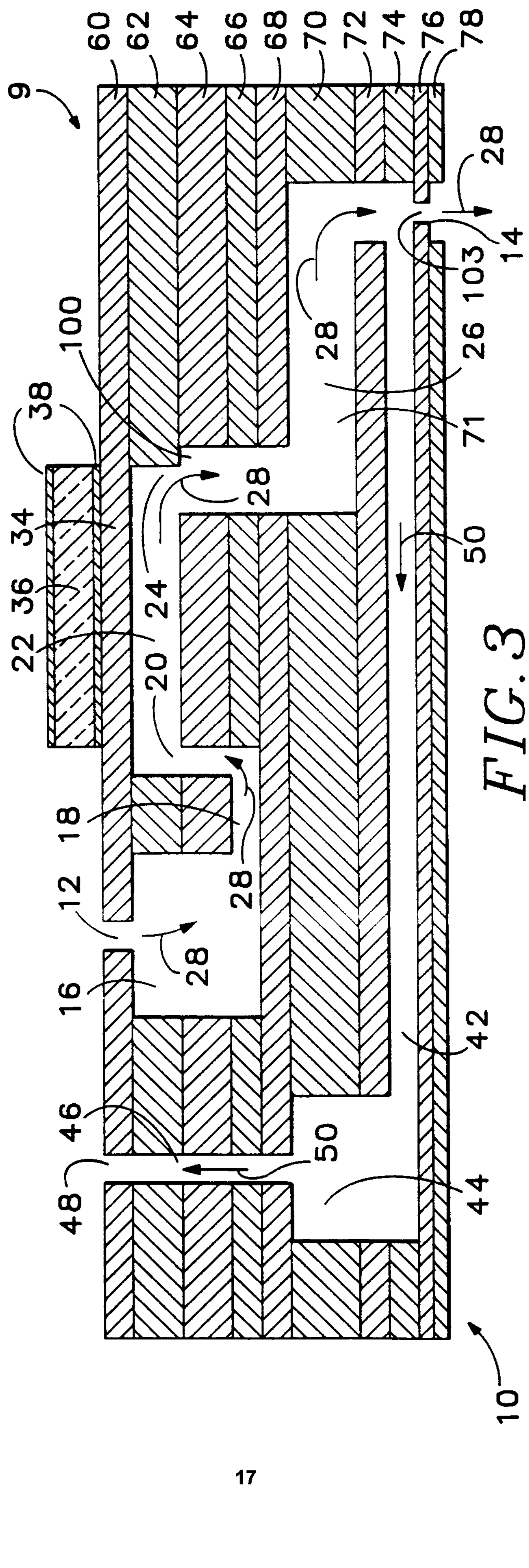
9
60
62
64
66
68
70
72
74
76
78
28
14
103
28
26
71
100
38
34
36
22
24
28
20
50
18
12
28
28
16
42
46
50
48
44
10

FIG. 3

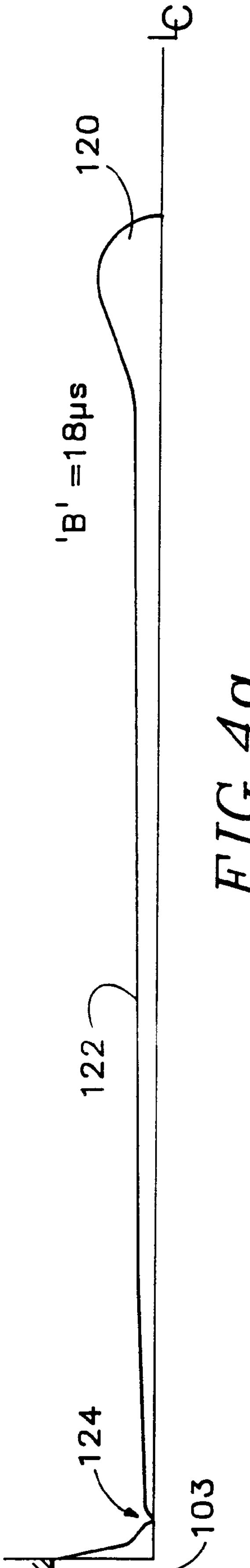

FIG. 4a

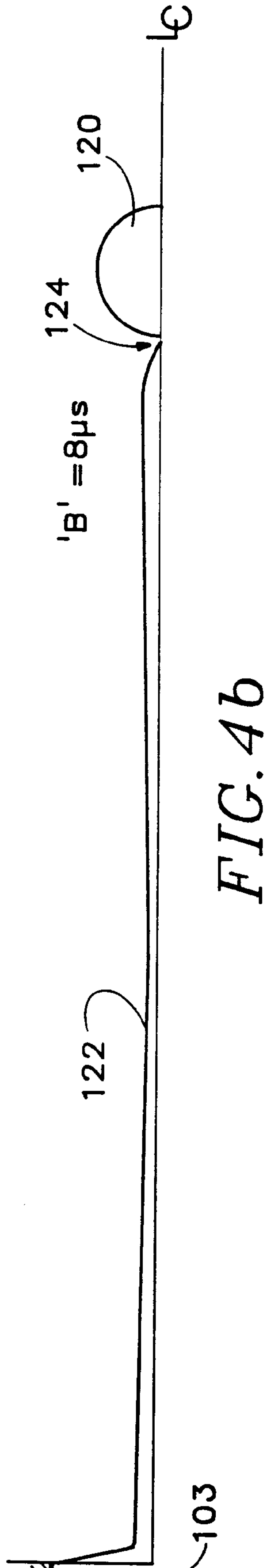

FIG. 4b

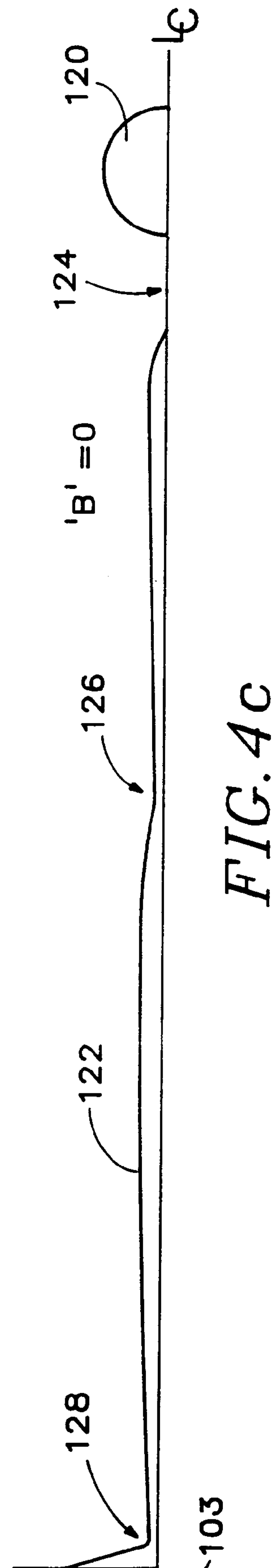

FIG. 4c

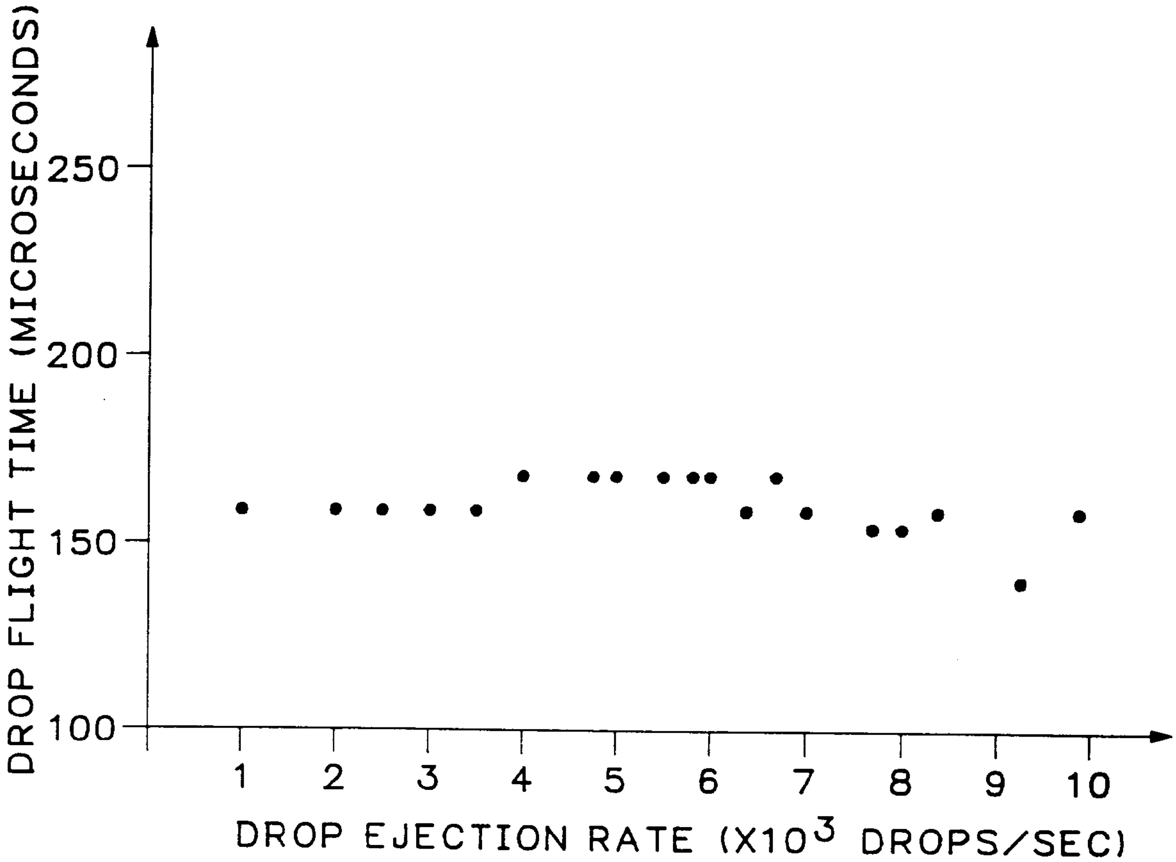
DROP FLIGHT TIME (MICROSECONDS)
250
200
150
100
1
2
3
4
5
6
7
8
9
10
DROP EJECTION RATE (X10³ DROPS/SEC)

FIG. 5

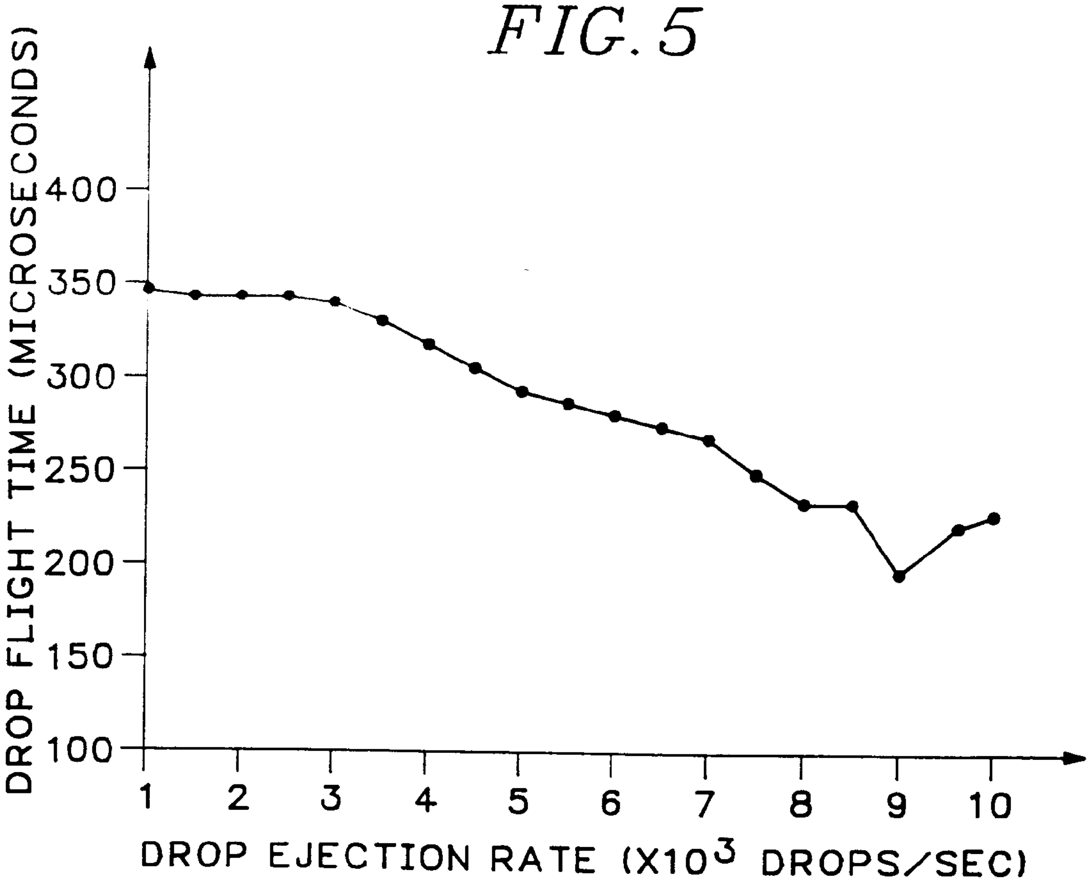
DROP FLIGHT TIME (MICROSECONDS)
400
350
300
250
200
150
100
1
2
3
4
5
6
7
8
9
10
DROP EJECTION RATE (X10³ DROPS/SEC)

FIG. 6

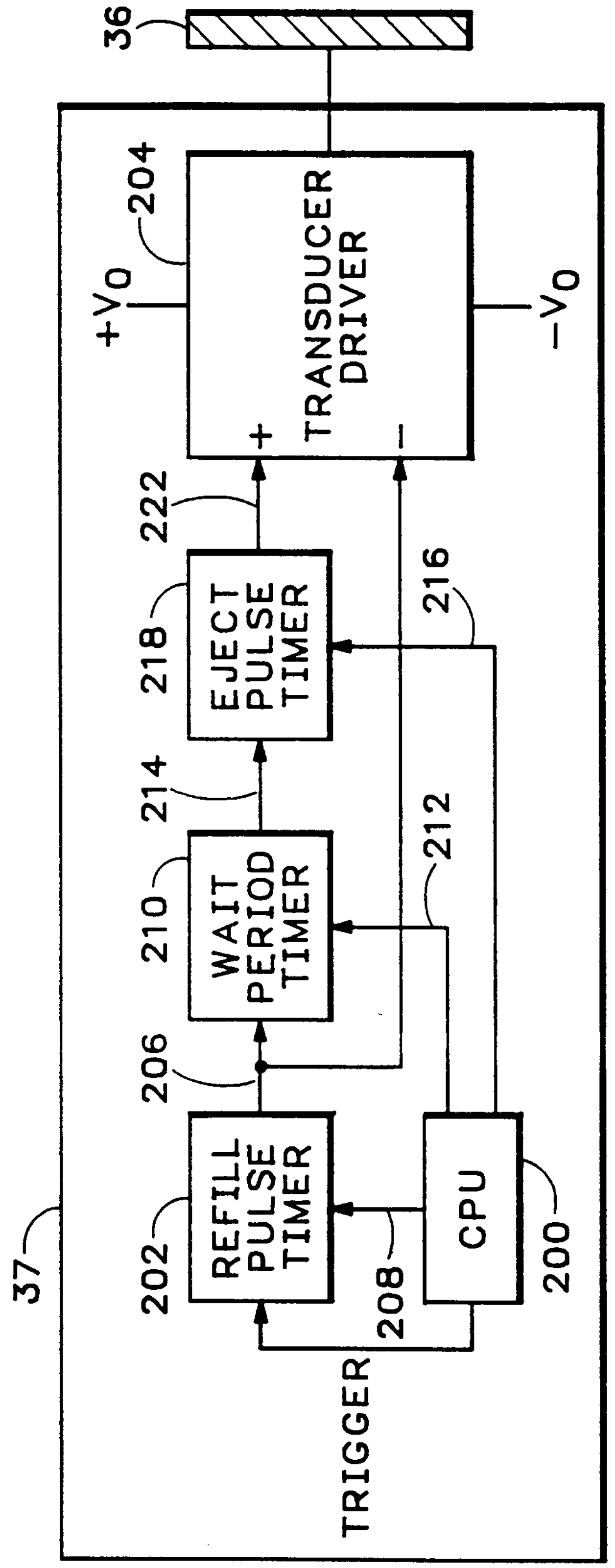
36
37
204
$+V_0$
$-V_0$
TRANSDUCER DRIVER
+
−
222
218
EJECT PULSE TIMER
216
214
212
210
WAIT PERIOD TIMER
206
202
REFILL PULSE TIMER
208
CPU
200
TRIGGER

FIG. 8

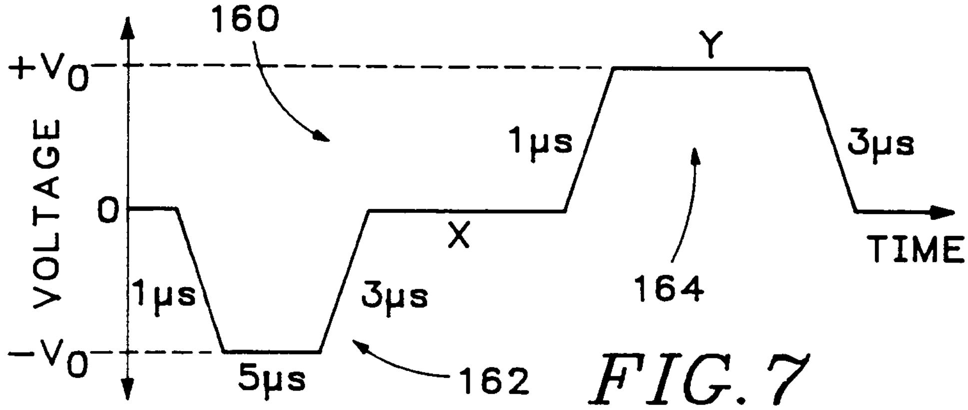
160
+V0
Y
VOLTAGE
1μs
3μs
0
X
TIME
1μs
3μs
164
-V0
5μs
162

FIG. 7

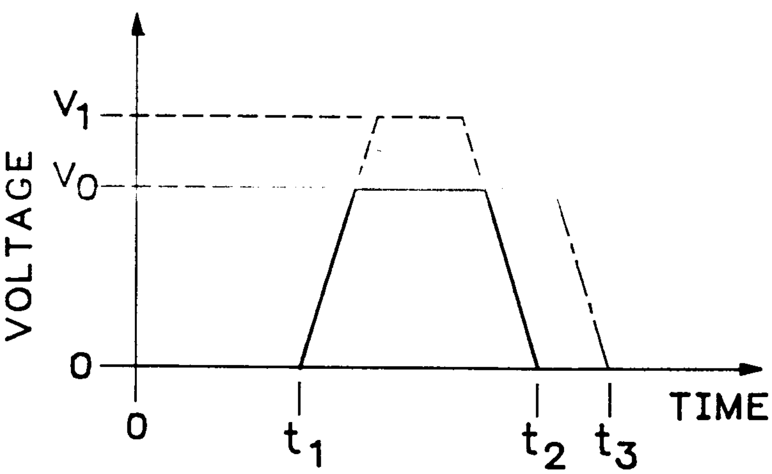
V1
VOLTAGE
V0
0
TIME
0
t1
t2
t3

FIG. 9