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Keur et al.

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[54] **METHOD AND APPARATUS FOR CONTROL OF INK DROP FORMATION**

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[52] **U.S. Cl.** **346/1**, 346/75, 346/140
[51] **Int. Cl.** **G01d 15/18**
[58] **Field of Search** 346/75, 140

[56] **References Cited**

UNITED STATES PATENTS

3,512,172 5/1970 Colecchi 346/75

OTHER PUBLICATIONS

Sweet, Richard G.; High-Frequency Oscillography With Electrostatically Deflected Ink Jets; SEL-64-004; SEL-TR-1722-1; Standford Electronics Labs, Stanford Univ, Calif.; March 1964; pp. 52- 62 and 83- 90.

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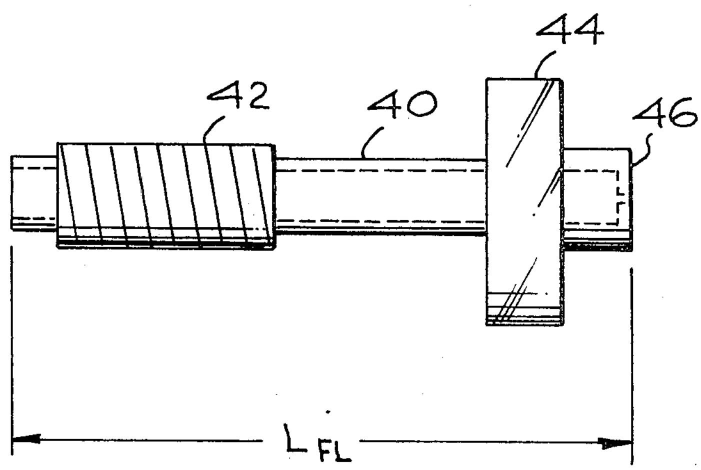
[57] **ABSTRACT**

In an ink drop writing system it was found that the drops formed by vibrating a nozzle would be accompanied by smaller satellite drops which could be detrimental to printing. This condition was considerably improved by designing the nozzle so that it would have a mechanical resonance at the frequency at which it formed drops. In order to insure a most efficient transfer of power from the driving source into the drop forming mechanism, the nozzle had to be designed to provide a fluid resonance condition. If the nozzle be considered as a closed pipe, then the frequency of vibration of the fluid in the pipe at which its length is an odd multiple of a quarter wavelength of sound through the fluid in the pipe, results in the highest power transfer.

7 Claims, 4 Drawing Figures



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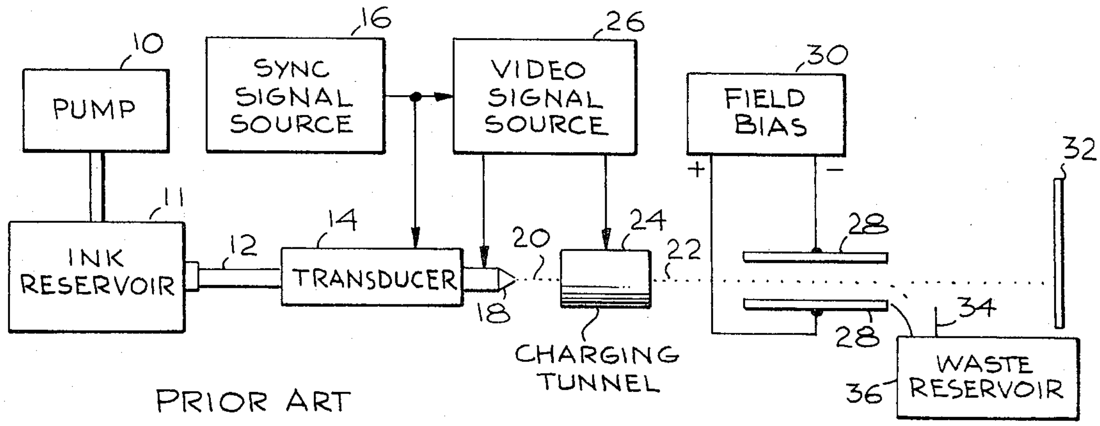

Fig. 1

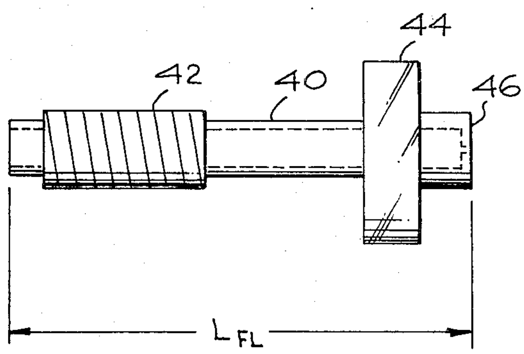

Fig. 2

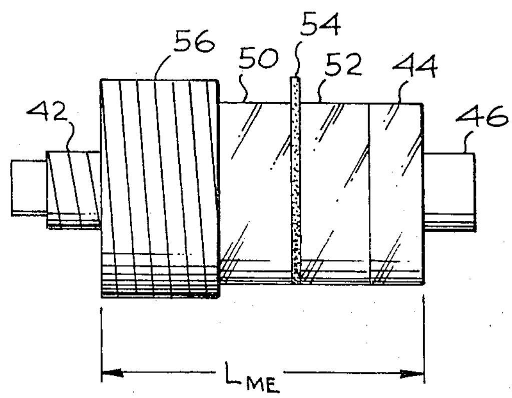

Fig. 3

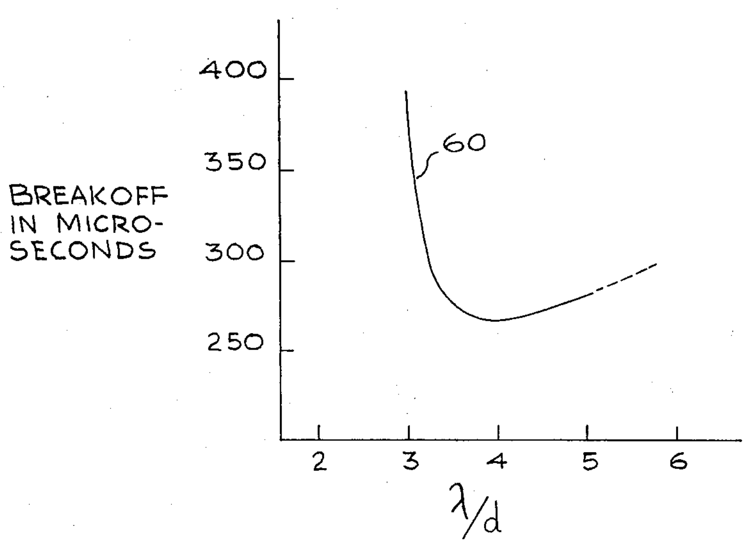

Fig. 4

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METHOD AND APPARATUS FOR CONTROL OF INK DROP FORMATION

BACKGROUND OF THE INVENTION

This invention relates to ink drop printing systems and more particularly to improvements therein.

Briefly and simply described, an ink jet printing system of the type with which this invention is concerned, comprises a nozzle which is coupled by suitable means to a reservoir of ink, so that ink is discharged in a stream from the nozzle under a pressure determined by the reservoir. The nozzle is either vibrated or periodically constricted so that a short distance from the nozzle opening the ink stream breaks off into drops. At or about the break off point, a conductive ring is placed so that the stream passes through it. A succession of voltages are applied to the ring at a frequency synchronous with the formation of the drops.

Each of the drops receives a charge which is determined by the voltage applied to the ring at the time the drop is formed. The drop thereafter passes between two plate electrodes to which a fixed potential is applied. In its passage through these electrodes, the drop is deflected from the straight line path an amount determined by the amplitude of the charge upon it. The drop thereafter falls upon paper, which is moved to provide a new surface for receiving the drops.

From the foregoing brief description it will be appreciated that the voltages which are applied to the drops can cause the drops to be deposited on the paper in a pattern which can form alphanumeric characters, symbols or waveforms. It should be appreciated that in order for the system to perform satisfactorily, the charge on each drop should not be altered once it is established, otherwise, the drop will not be deflected to the proper location to form the desired alphanumeric character or symbol.

As the ink stream emitted by the nozzle breaks up into drops, it is noted that each drop is accompanied by a small drop known as a satellite. The satellite has a velocity which is often different from that of the drop. It was found initially that this velocity could be varied by either varying the frequency driving the piezoelectric device which constricted or vibrated the nozzle, or by varying the voltage applied to the piezoelectric device, or by varying the pressures applied to the fluid whereby the velocity of the fluid stream could be varied.

Customarily, an electric field is applied to the stream to establish a charge on a drop or satellite when separation occurs. Describing the separation in more detail, when a drop is formed, there is a fine filament of the fluid that connects the drop to the stream just before separation. This filament forms a satellite. If the drop separates from the filament before the filament separates from the stream, the filament will form into a satellite whose speed will be less than that of the drop resulting in a slow satellite condition. If the filament separates from the stream before it separates from the drop, the filament will form into a satellite whose speed is greater than that of the drop resulting in a fast satellite condition. There is an intermediate satellite condition which occurs when the drop and filament separate simultaneously resulting in the satellite speed being the same as that of the drop. As a consequence the satellite

does not collide with any droplets, but rather travels at substantially the same speed as the droplets through the flight. In the fast satellite condition, only one charge establishing separation occurs for each satellite drop pair, whereas in the slow satellite condition, two charges establishing separations occur for each satellite drop pair.

It will be appreciated that the synchronism of the charge inducing voltages is much less difficult with the fast satellite condition than with the flow satellite condition because the voltage need only be synchronous with one separation per drop period instead of two separations; i.e., that of the drop and also that of the satellite. Thus, a system can operate with slow satellites, however, it is greatly preferred to operate with fast satellites. The third satellite condition, that of intermediate satellites is completely unsatisfactory because once the satellites obtain a charge, they easily deflect into the high voltage deflection plates due to their low mass. The result is an undesirable accumulation of ink on the plates which tends to short out the deflection voltage.

It was found that excessive values of the parameters described were needed for obtaining a fast satellite condition with early nozzle designs. It wasn't until the nozzle was designed to be mechanically resonant near the operation frequency, that fast satellites could be formed at more reasonable values of the parameters.

At the same time that it is desirable to design a nozzle so that it is mechanically resonant near its frequency of operation, it is also desirable to transfer energy as efficiently as possible to the fluid stream. This is advantageous first, for the obvious reason that it provides a saving in power consumption and component costs, but additionally, lower power usage reduces heat dissipation at the nozzle and thereby prevents extreme temperature excursions of the fluid stream, whereby a much more stable operating system is provided. The condition at which the system operates most efficiently, as far as operating parameters are concerned is one in which the nozzle is also designed to produce "fluid resonance." This is advantageous also because it provides a method of compensation for ambient temperature changes. The design of the nozzle to achieve fluid resonance could affect the design of the nozzle to achieve mechanical resonance, and thus it is important to reconcile the two.

OBJECTS AND SUMMARY OF THE INVENTION

An object of this invention is to provide an ink jet nozzle design which is "fluid resonant" near the desired operation frequency.

Another object of this invention is to provide a nozzle design having fluid resonance which enhances the formation of fast satellites.

Still another object of the present invention is the provision of a novel and useful ink jet nozzle construction.

The foregoing and other objects of the invention are achieved by designing the nozzle so that its internal length is determined by the formula $F=(n/4)\cdot(V_f/L_f)$ where $N=1, 3, 5$, etc., V_f= speed of sound through the fluid in the nozzle. L_f is the length of the nozzle, and F is the desired frequency of resonance.

It has been found that the nozzle cavity holding the fluid acts like a closed pipe. Closed pipes are resonant when their lengths match odd multiples of quarter wavelengths of sound in the cavity. The formula indicated in the foregoing paragraph is the one which expresses the relationship in a closed pipe between frequency of resonance and pipe length for a given odd multiple of the sound wavelength.

After on has designed for fluid resonance, then the nozzle design proceeds for mechanical resonance which essentially has the same formula, $F=N/2\cdot V_M/L$ where F equals the desired operating frequency of resonance, $N=1, 2, 3$, etc., V_M is the speed of sound through the structure of the nozzle, and L_M is a distance over which resonance occurs. The significant length is one which includes the major masses combined that are associated with the nozzle. In designing a nozzle it is convenient to have the mechanical resonant length shorter than the fluid resonant length.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block schematic diagram of an ink jet printing system shown to assist in an understanding of the invention.

FIG. 2 illustrates an ink jet nozzle construction without a piezoelectric driver unit mounted on it.

FIG. 3 illustrates an ink jet nozzle construction with the piezoelectric driver thereon.

FIG. 4 is a Rayleigh curve.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. 1 is a schematic drawing of the presently known arrangement which is shown to afford a better understanding of the invention. A pump **10** applies pressure to an ink reservoir **11** so that it can provide ink under pressure to tubing **12** which is flexible. An electromechanical transducer **14** is usually placed adjacent to or around the tubing. The transducer is driven in response to signals from a source **16**. The transducer serves to vibrate and/or compress the tubing **12** in the region of the nozzle **18**. This results in an ink jet **20** being emitted which at a short distance downstream breaks up into drops **22** which are formed at a rate determined by the frequency of the vibration. In the region where the stream **20** breaks down into drops, a charging tunnel **24** is provided. This comprises a conductive cylinder to which video signals from a video signal source **26** are applied. The video signals establish a field within the charging tunnel so that the ink drops which are formed therein assume a charge determined by the amplitude of the video signal present at the time the drop separates from the ink jet **20**.

Downstream of the charging tunnel there are usually placed a pair of electrodes **28** which are connected to a field bias source **20**. As a result, there is established between the electrodes a constant electric field. The ink drops, which bear charges in accordance with the video signal, enter this field and are deflected by an amount which is proportional to the amplitude of the charge. This enables intelligent writing to occur on a writing medium **32**, which is moved at some synchronous rate past the electrodes. Drops which do not bear a video charge are captured by a tube or trough **34** which is judiciously placed at one side so as to capture these drops. It leads to a waste reservoir **36**. The paper **32** moves into the plane of the drawing whereby its motion, together with the deflection of the drops, may be used for forming intelligible characters.

Referring now to FIG. **2**, there may be seen a nozzle without its piezoelectric driver unit. It consists of a tube **40** having a threaded portion **42** near its rear, and an enlarged region **44** near its front end. As indicated by the dotted lines, the center of the tube is hollow and the opening therethrough at the front or emitting end **46**, is reduced to a diameter which is very much smaller than the diameter of the opening through the remainder of the tube.

FIG. **3** is a drawing of the appearance of the nozzle with the piezoelectric driving unit mounted thereon. This consists of two piezoelectric crystals respectively **50** and **52**, which are separated by a conductive electrode **54**. The tubes are pressed against the enlarged region **44** by means of a retaining mass **56**, which is mounted upon the threaded portion **42**. The piezoelectric crystals are polarized so that they expand and contract axially in response to the application of potential thereto. This serves to push against the retaining mass and the enlarged section **44** whereby the nozzle is caused to elongate and contract which in turn results in constrictions being applied to the fluid flowing through the nozzle.

Referring again to FIG. 2, the length to be considered in designing the nozzle for fluid resonance is represented by L_{fluid} on the drawing and extends from one end of the nozzle to the other. In the FIG. 3, the length to be considered for mechanical resonance is the length $L_{mechanical}$ which extends from one end of the retaining mass to the other end of the enlarged section. Effectively, it includes the section of the nozzle covered by the two masses retaining the piezoelectric crystals together with the length of the two crystals.

It should be noted that the back end of the nozzle, which is adjacent the threaded portion **42**, is usually connected to a fluid reservoir by means of other tubing not shown.

An efficient transfer of energy to the fluid stream is indicated by the time required for an element of fluid to pass from the end of the nozzle to the point where the continuity of the stream ends and thereafter becomes drops. This is known as a break-off time. A shorter break-off time indicates a more efficient transfer of energy. Lord Rayleigh determined that there was a relationship between the break-off time and a ratio expressed as λ/d. λ comprises v/f where V is the velocity of the stream of the fluid being used, f is the frequency of the disturbance applied to the fluid, and d is the diameter of the issuing fluid.

FIG. 4 represents a curve **60** which is derived when the relationship is plotted, at a particular driving voltage applied to the piezo-electric crystal. It is known as a Rayleigh curve. The curve **60** has the breakoff in microseconds plotted as the ordinate, and the abscissa has the value of λ/d. The voltage applied to drive the crystals for the purposes of this curve was 25 volts. Decreasing the driving voltage would cause a substantial duplication of this curve to occur but is placed higher on the graph. Increasing the voltage would cause a substantial duplication of this curve to occur but is placed lower on the graph.

It was found, for each one of these curves, that when the value λ/d increased beyond a certain value, that conditions favorable for fast satellites would occur. For the curve shown, this took place at the point indicated at a value of λ/d of approximately 4.8. For each curve the same point beyond which fast satellites would occur was found to occur. As the driving voltage increased the required value of λ/d decreased. Thus, values of λ/d greater than a minimum value for a particular operating voltage assists in obtaining the desirable fast satellite operation.

To insure an efficient transfer of energy while at the same time obtaining fast satellites, it was necessary to design the nozzle so that fluid resonance was obtained. In observing the behavior of the nozzle over a range of frequencies it was found that the nozzle cavity holding the fluid acted like a closed pipe. Closed pipes are resonant when their lengths match odd multiples of quarter wavelengths of sound in the cavity. As previously indicated this phenomenon is represented by the equation $F=N/4 \cdot V_{fluid}/L_{fluid}$.

It was further found that operation of a nozzle in a non-resonant condition may involve either great waste of energy or even a poor drop formation. Accordingly it was realized that because of fluid resonances, the first step in design is to build a nozzle wherein the fluid resonance should be near or close to the frequency at which it is desired to form droplets.

It was found that the velocity of sound varies quite differently for various fluids. Also, when the ink jet printing apparatus is employed, a temperature rise occurs within the fluid as a result of ambient conditions. Within the temperature range involved, it was found that some fluids, for example, water, have a positive coefficient of the velocity of sound which increase in temperature, that is the velocity of sound goes up with temperature, and for a number of other fluids including oil base fluids, the speed of sound decreases with a rise in temperature. The temperature coefficient is negative.

Therefore, in accordance with this invention it was discovered that by displacing the frequency to be employed in the formula for fluid resonance, to one side or the other of the actual desired frequency of drop formation which side depending upon whether the fluid to be used has a positive coefficient or a negative coefficient, the change in efficiency with change in temperature could be compensated for. With increasing temperature we see an increase in the resonant frequency for water based solutions. Simultaneously, the inherent increase in λ/d with increasing temperature makes the system easier to drive. As a consequence, when the resonance is higher than the operating frequency, the frequency shift makes it harder to drive and the λ/d change makes it easier to drive.

Lowering temperature causes the role of each to be the opposite. When the resonance is lower than the operating frequency, the two changes act in the same way causing overdriving to occur sooner. Obviously for practical purposes, the former case above is preferable as a wider temperature range is tolerated. In one practical example an aqueous solution of polyethyleneglyco was used in a system set to separate at a frequency of 66 KHz. A fluid resonant frequency of 68 KHz, 2 KHz above the operating point, was used in the design formula for determining the required cavity length. The foregoing allows for ambient temperature drift of the ink jet printing system.

Techniques for measuring the speed of sound at a given temperature or over a temperature range for a particular fluid are well known and thus, from the information given one can design a nozzle to have a desired fluid resonance whereby most efficient transfer of power and temperature compensation within the nozzle is made to occur.

While the determination of mechanical resonance is not a part of this invention, at the time of designing the nozzle for fluid resonance, consideration must be given to the mechanical resonance design to insure that the length of the mechanical masses which are mounted on the nozzle are not incompatible with the required length for fluid resonance. It is convenient to have mechanical resonance length slightly shorter than the fluid resonance length and the length should be realistic in defining a nozzle.

To summarize the foregoing, in accordance with this invention, one can operate the ink jet producing structure of an ink jet printing system in a λ/d range which gives fast satellites and also which operates at or near a resonance point where energy is most efficiently transmitted to the fluid stream and temperature compensation is obtained. Initially, a desired droplet formation rate is selected, and that indicates the frequency to be applied to the nozzle to cause perturbations in the fluid stream. For example, assume that it is desired to obtain 66,000 drops from the first nozzle and 16,500 from a second nozzle. This indicates frequencies (F) of 66 KHz and 16.5 KHz respectively.

A second step in the design is to determine the velocity of sound for the particular fluid in the particular cavity at a temperature determined as the operating temperature. The velocity of sound (V_f) in the inks to be used with the two nozzles is 1,575 meters per second. Assume now that N is 3 for the first nozzle and N is 1 for the second nozzle.

From the foregoing, one can determined, by using the resonant pipe formula, $F=N/4 \cdot V_f/L_f$ the required length of the fluid cavity. Thus, for the first nozzle, $L_f=$ .0240 meters.

Finally, one determines the length of the nozzle required for achieving mechanical resonance. Using the formula $F=N/2 \cdot V_{M/L_M}$ for the first nozzle, $L_M=$ 0.0150 and for the second nozzle, $L_M=0.0200$ meters. If it is desired to compensate for temperature effects in the first nozzle, for example, then, on the assumption that the ink has a positive temperature coefficient, assume the frequency F at 68 KHz, instead of 66 KHz (i.e., 2,000 KHz more). Then the fluid length L_f calculates as 0.0174 meters.

After building the nozzle, it is operated at a desirable λ/d ratio and the applied voltage is adjusted until operation is definitely in the fast satellite region. This can be determined by observing the behavior of the satellites after they pass through the charging ring. The foregoing design technique assures a most efficient usage and a desirable fluid stream configuration for good printing.

Should a nozzle which is being employed not have a smooth fluid cavity but have a step configuration along its length with different diameters, the speed of sound through the fluid in that cavity may not be precisely predictable. By varying the frequency applied to that nozzle while observing the break-off time, one can determine where the resonant point is. From this and a knowledge of the length of the nozzle, the closed pipe formula may be employed to give the effective velocity of sound. Once the effective velocity of sound is obtained, the formula may be again used with the desired resonant frequency, and the length of the nozzle may be calculated. The nozzle may then be shortened or lengthened until this calculated length is reached.

In the foregoing, there has been described a novel and unique method and means for designing a nozzle.

What is claimed is:

1. In an ink drop printing system of the type wherein ink under pressure is applied to flow through a nozzle and an electromechanical transducer is employed for applying perturbations to the ink, as it flows through said nozzle, at a predetermined frequency, a method of improving the operation of said nozzle comprising:

making the length of the internal cavity in said nozzle that length which produces fluid resonance at the desired frequency of operation of the printing system.

2. In an ink drop printing system as recited in claim **1** wherein the internal cavity of said nozzle has a length which produces fluid resonance at a frequency which is displaced from said desired frequency of operation by the change in fluid resonance frequency caused by a change in the ink temperature during operation of the ink jet printing system.

3. In an ink jet printing system of the type wherein ink is applied under pressure to a nozzle to flow therethrough and mechanical perturbations are applied to the ink flowing through said nozzle by means of an electromechanical transducer operated at a predetermined frequency, the improvement comprising a nozzle having an internal length for establishing fluid resonance during operation at said predetermined frequency to provide the most efficient power transfer between said electromagnetic transducer and said fluid at said predetermined frequency of operation.

4. Apparatus as recited in claim **3** wherein there is included means for establishing the pressure of the ink applied to said nozzle at a value whereby fast satellites will occur.

5. Apparatus as recited in claim **4** wherein the internal length L_f of said nozzle equals $N/4 \cdot V_f/E$ where F equals the operating frequency, N equals a desired odd harmonic of operation at said frequency, and V_f equals the speed of sound through the ink to be used with said nozzle.

6. In an ink jet printing system of the type wherein ink is applied under pressure to a nozzle to flow therethrough and mechanical perturbations are applied to the ink flowing through said nozzle by an electromechanical transducer operated at a predetermined frequency, the improvement comprising:

a nozzle having an internal length to establish fluid resonance at a frequency displaced from said predetermined frequency by the change in said fluid resonance frequency caused by a change in the ink temperature during operation of the ink jet printing system.

7. In an ink jet apparatus wherein ink is applied at pressure to a selected nozzle to flow therethrough, and perturbations are applied to the ink flowing through said nozzle by means of an electromechanical transducer mounted on said nozzle in order to cause the ink stream to break up into drops after leaving said nozzle, the improved method of determining the frequency of fluid resonance of said nozzle comprising:

varying the frequency applied to said electromechanical transducer until the observed breakoff time of said ink jet from the tip of said nozzle is a minimum, and

detecting the frequency at which said breakoff time is a minimum, which is the fluid resonance frequency.

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