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(54) Droplet ejectors.

(57) A nozzleless droplet ejector for ejecting droplets from a free surface (16) of a pool of liquid (17), such as a pool of ink, comprises a selectively-energizable droplet-emission controller (21) for generating a freely-propagating capillary wave on the surface of the pool to provide on/off timing control and/or ejection trajectory angle control for the ejector. The controller comprises a conductor (22) and a counter-electrode (23). The conductor is immersed in the pool, whereby a capillary surface wave is generated when a periodic voltage is applied across the conductor and the counter-electrode. In one embodiment, a ultrasonic pressure wave is focused on the free surface of the pool, and the capillary wave supplied by the controller coherently interacts with that pressure wave to provide the desired control.

Separate controllers may be provided for independently controlling the ejectors of multiple ejector arrays.

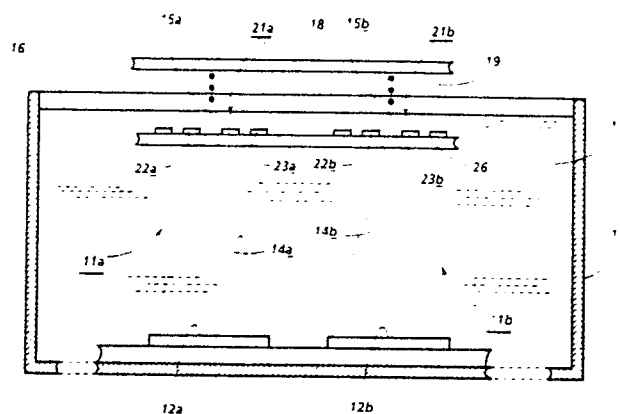


FIG. 1

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DROPLET EJECTORS

This invention relates to nozzleless droplet ejectors and, more particularly, to emission controllers (e.g., on/off switches and directional controllers) for such ejectors. Droplet ejectors having emission controllers embodying this invention are useful for liquid ink printing and similar applications.

Ink jet printing has the inherent advantage of being a plain paper compatible, direct-marking technology. "Continuous stream" and "drop on demand" ink jet print heads have been developed to exploit that advantage. Unfortunately, however, the nozzles which are used in conventional ink jet print heads are expensive to manufacture and are a significant source of maintenance problems.

Others have proposed nozzleless droplet ejectors for liquid ink printing. For example, US-A-4,308, 547 describes a print head in which a piezoelectric transducer having a hemispherically shaped focusing lens is submerged in a reservoir of ink to generate a spherically focused ultrasonic pressure wave for exciting the ink near the surface of the reservoir sufficiently to eject individual droplets of ink.

As a general rule, liquid ink printing requires substantial control over the timing of the drop ejection process. The transducers of nozzleless print heads of the above-described type may be driven by amplitude-modulated r.f. signals to provide the necessary timing control, but the electronics needed to modulate a rf signal are expensive. Thus the preferred approach is to provide timing controllers which operate independently of the transducers. Under those circumstances, the transducer or transducers may be driven by a relatively-inexpensive r.f. signal generator to excite the ink to a sub-threshold, incipient energy level for droplet emission, thereby enabling the timing controller or controllers to destabilize the excited ink selectively so that individual droplets are ejected on command.

Some liquid ink printing processes, such as matrix printing, are easier and less costly to implement if there also is provision for directionally steering the ink droplets. In recognition of that, some transducers are configured to generate focused acoustic waves having a directionally-controlled asymmetry.

In accordance with the present invention, a nozzleless droplet ejector for ejecting droplets from a free surface of a pool of liquid, such as a pool of ink, comprises a selectively energizable droplet emission controller for generating a freely propagating capillary wave on the surface of the pool to provide on/off timing control and/or ejection trajectory angle control for the ejector. The controller

comprises a conductor and a counter electrode which are immersed in the reservoir, whereby a capillary surface wave is generated when a periodic voltage is applied across the conductor and the counter electrode. In one embodiment, a focused ultrasonic pressure wave or the like periodically perturbs the pressure acting on the free surface of the pool, and the capillary wave supplied by the controller coherently interacts with that pressure wave to provide the desired control.

Separate controllers may be provided for independently controlling the ejectors of multiple ejector arrays. The functionality of these emission controllers is dependent on the geometry of their conductors, so a few exemplary geometries are disclosed with the understanding that there are others which may be used.

The present invention will now be described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a partially sectioned and fragmentary, schematic elevational view of a nozzleless liquid droplet ejector array having emission controllers constructed in accordance with the present invention;

Figure 2 is an enlarged simplified plan view of one of the capillary wave control switches shown in Fig. 1, and

Figure 3 is an enlarged simplified plan view of a capillary controller which is similar to the switch shown in Fig. 2, except that it has a segmented conductor to provide angular trajectory control in addition to on/off control.

Turning now to the drawings, and at this point especially to Fig. 1, there is an array of liquid droplet ejectors 11a and 11b comprising a plurality of acoustic transducers 12a and 12b which are submerged in a liquid-filled reservoir 13. The transducers 12a and 12b are laterally displaced from each other and are driven by an r.f. power supply - (not shown) to launch ultrasonic pressure waves 14a and 14b into the reservoir 13, so that the pressure waves come to generally-circular foci on laterally-offset centers 15a and 15b, respectively, at or near the surface 16 (i.e., the liquid/air interface) of the reservoir 13. Known transducers may be employed periodically to perturb the pressure acting on the free surface 16 of the reservoir or pool 13, so the transducers 12a and 12b are illustrated schematically. Indeed, there are mechanical, electrical, thermal, pneumatic and other alternatives to the transducers 12a and 12b which may be employed to provide a focused (e.g., circularly-focused or linearly-focused) periodic pressure perturbation, on the free surface 16 of the reservoir 13.

Furthermore, while only two ejectors 11a and 11b are shown, it will be understood that the number of transducers may be increased to form larger arrays. The ejector packing density is limited primarily by the transducer center-to-transducer center spacing that is required to prevent objectionable levels of "crosstalk" between adjacent ejectors, such as between the ejectors 11a and 11b.

In a printer, of course, the reservoir 13 is filled with liquid ink 17. Moreover, a suitable record medium 18, such as plain paper, is located above the reservoir 13, with just a narrow air gap 19 separating it from the ink/air interface or surface 16. Typically, the ejectors 11a and 11b are assembled in a linear array, so the record medium 18 is advanced in an orthogonal cross-line direction (into or out of the plane of Fig. 1) relative to the ejectors 11a and 11b while a two-dimensional image is being printed. As will be appreciated, the individual picture elements or "pixels" of such an image are determined by (1) the time dependent on/off switching of the individual ejectors, such as the ejectors 11a and 11b, and (2) in some cases, by the time dependent steering of the individual droplets of ink.

In accordance with the present invention, relatively inexpensive and easily fabricated capillary wave control devices 21a and 21b are provided for controlling the on/off timing of the ejectors 11a and 11b, respectively, and/or for steering the droplets of ink emitted thereby. The control devices 21a and 21b comprise electrical conductors 22a and 22b and counter-electrodes 23a and 23b, respectively, which are immersed in the liquid 17. The conductors 22a and 22b are located near (for example, within about 10 mm of) the focal centers 15a and 15b of the pressure waves 14a and 14b, respectively. The counter-electrodes 23a and 23b should be nearby and preferably are concentric with the electrodes 22a and 22b, respectively. Typically, the counter-electrodes 23a and 23b are returned to a suitable reference potential - (hereinafter, "ground potential"). Furthermore, a switched power supply 25 (Fig. 2), which is also referenced to the ground potential, has electrically independent outputs coupled to the conductors 22a and 22b for applying appropriately and independently timed voltage pulses thereto. Alternatively, the controllers 21a and 22b could be driven by an a.c. power supply having appropriate control circuitry.

Electric field gradients associated with the applied potential between the conductors 22a and 22b and the counter-electrodes 23a and 23b exert a dielectric body force on the liquid 17. This results in a disturbance at the liquid surface 16 which subsequently propagates as a free capillary wave on the surface 16. Generation of capillary waves is accomplished with moderately high voltage (e.g.,

300 volts or so) pulses of brief duration (e.g., on the order of 500 μ secs) being periodically applied across the conductors 22a and 22b and the counter-electrodes 23a and 23b. The voltage and time limits, if any, of this wave generation process have not been determined, so it is noted in the interest of completeness that the foregoing examples are based on data from experiments conducted in water. However, the experimental data indicate that the emission control is most effective if the conductors 22a and 22b are located just below the free surface 16 of the liquid 17. For example, as shown, the conductors 22a and 22b may be supported on an electrical insulator 26, such as a 'Mylar' sheet, so that they are covered by a thin film of liquid 17. A sufficiently thin sheet 26 will allow essentially unimpeded passage of the pressure waves 14a and 14b.

As will be understood, the capillary waves propagate radially with respect to the conductors 22a and 22b at the capillary surface wave velocity, v , in the liquid 17, and they are damped as a function of time because of the viscosity of the liquid 17. Their wavelength, λ , is dependent on the dominant Fourier transform component(s) of the voltage pulses applied to the conductors and is given to a first approximation by $\lambda \approx v/\Delta t$, where Δt equals the width of the pulses applied to the conductors 22a and 22b. The damping of the capillary waves is an important consideration for determining the maximum permissible radial displacement of the conductors 22a and 22b from the pressure wave focal centers 15a and 15b, respectively. The radial propagation of the capillary waves and the pulse width dependency of their wavelengths, on the other hand, are relevant to optimizing the configuration of the conductors 22a and 22b and to selecting the phase and the width of the pulses applied thereto for the specific emission control tasks which the control devices 21a and 21b are intended to perform.

More particularly, as best shown in Fig. 2, the conductor 22a and its associated counter-electrode 23a have constant radius, ring-like configurations and are generally circularly symmetric with respect to the focused pressure wave 14a (i.e., concentric with its focal center 15a). Thus, a capillary wave launched by them converges, as indicated by the arrows, to a symmetrical focus at approximately the focal center 15a of the pressure wave 14a, thereby enabling the controller 21a to provide axial on/off switching control for the ejector 11a (Fig. 1). The relative phase relationship of the focused capillary and pressure waves determines whether they interact constructively (additively) or destructively (subtractively). For example, the controller 21a may be employed to "turn on" the ejector 11a if the amplitude of the pressure wave

14a is selected to excite the liquid 17 upon which it is focused (i.e., the liquid within the waist of the pressure wave 14a) to be near but below the threshold of incipient droplet formation. In this case, the ejector 11a would be operated in a "normally-off" mode. While the circular symmetry of the conductor 22a is well suited to the switching function of the controller 21a, other symmetrical geometries could be employed, including equilateral polygon-shaped conductors. The symmetrical focus of the capillary wave is the key to providing axial on/off control for the ejector 11a.

Referring to Fig. 3, there is another controller 31 which is constructed in accordance with this invention to provide on/off switching and angular trajectory control for a nozzleless droplet ejector, such as the representative ejector 11a (Fig. 1). As will be seen, the controller 31 is similar to the controller 21a (Fig. 2), except that its ring-like conductor 32 comprises a plurality of electrically independent segments 33 and 34 which are selectively addressable by a switched power supply 35. When the power supply simultaneously applies equal amplitude voltage pulses to all of the conductor segments 33 and 34, the capillary waves launched by them converge to a generally symmetrical focus at or near the focal center 15a of the pressure wave 14a (Fig. 1), thereby causing the controller 31 to perform essentially the same axial on/off switching function as the controller 21a. When, however, the conductor segments 33 and 34 are differentially driven, such as if voltage pulses are applied to one of them but not the other, the capillary wave or waves come to an asymmetrical focus, thereby altering the angular trajectory of any droplets which are then being emitted by the ejector 11a. The phase of the asymmetrically focused capillary wave may be selected to switch the ejector 11a on, or the on/off control for the ejector 11a may be provided by means not shown. Dividing the conductor 32 into two diametrically opposed, independently addressable segments 33 and 34, such as shown, allows the angular trajectory of the ejected droplets to be controlled along an axis parallel to the center line of the segments 33 and 34 over a range on the order of $\pm 30^\circ$ (at a droplet diameter of about $100\mu\text{m}$) with respect to longitudinal axis of the ejector or, in other words, with respect to an axis normal to the plane of the recording medium 18. Smaller diameter droplets are capable of being steered over even wider angles. If multi-axial trajectory control is desired, the conductor 32 may be divided into a larger number of individually-addressable segments. Furthermore, it will be understood that the conductor 32 may be composed of individually-addressable, polygonally-arranged segments, without materially altering its performance.

In view of the foregoing, it will be seen that the present invention provides relatively reliable and inexpensive ejection controllers for nozzleless droplet ejectors of various types. These controllers may be design optimized to perform a variety of different control functions. For example, they can be employed not only as on/off switches and/or angular trajectory controllers as described herein, but also as droplet ejection velocity controllers. Thus, while the controllers may be used to substantial advantage in nozzleless liquid ink printers of the above-described type, it will be understood that the broader aspects of the invention are not limited to printing,

Claims

1. A nozzleless droplet ejector having a pool (17) of liquid with a free surface, and means (12) for launching a pressure wave into the pool such that the pressure wave comes to a focus approximately at the free surface, including a capillary wave emission controller (21) for the ejector, including

a conductor (22) and a counter-electrode (23), the conductor being near the surface of the liquid and proximate to the focus of a pressure wave, and means (25) coupled across the conductor and the counter-electrode for applying a periodic voltage thereacross on command, to cause a freely-propagating capillary surface wave to radiate from the conductor, whereby the capillary wave interacts with the pressure wave to control at least one emission characteristic of the ejector.

2. The ejector of Claim 1, wherein the pressure wave excites the liquid upon which it is focused to an energy level which is offset from a threshold energy level for destabilizing the liquid, and

the capillary wave causes the energy level of the excited liquid to cross over the threshold level, whereby the emission controller provides on/off control for the ejector.

3. The ejector of Claim 1 or 2, wherein the conductor is symmetrical with respect to the focus of the pressure wave and is electrically continuous, whereby the emission controller provides axial on/off timing control for the ejector.

4. The ejector of Claim 1 or 2, wherein the conductor is asymmetrical with respect to the focus of the pressure wave, whereby the controller provides angular ejection trajectory control for the ejector.

5. The ejector of Claim 4 wherein the conductor has two or more electrically-independent segments, and the means for applying the periodic voltage include means for selectively addressing the seg-

ments, whereby the voltage is selectively applied to the segments to control the angular ejection trajectory of the ejector.

6. The ejector of Claim 1 or 2, wherein

the conductor has two or more electrically-independent segments which are symmetrical with respect to the focus of the pressure wave, whereby an axial ejection trajectory is provided when the pulses are applied simultaneously to all of the segments.

7. The improvement of Claim 6, wherein the conductor is circularly symmetrical with respect to the focus of the pressure wave.

8. A printer having a nozzleless droplet ejector including a pool of liquid ink having a free surface defined by an ink/air interface, and means for launching an acoustic pressure wave into the pool such that the acoustic wave comes to a generally-spherical focus approximately at the free surface, and a droplet-emission controller for the ejector comprising

a conductor and a counter-electrode, the conductor being shallowly immersed in the pool and being proximate to the focus of the pressure wave, and

means coupled across the conductor and the counter-electrode for applying a periodic voltage thereacross on command to launch a freely-propagating capillary surface wave from the conductor, whereby the capillary wave interacts with the pressure wave to control at least one emission characteristic of the ejector.

9. A droplet-emission controller for a nozzleless droplet ejector having means for applying a periodic pressure perturbation to a free surface of pool of liquid, the controller comprising

means for generating a capillary wave on the surface on command to affect the ejector operationally.

10. The droplet-emission controller of Claim 9, wherein the pressure perturbation is focused approximately on the surface of the pool, the controller is located to generate the capillary wave in close proximity to the focus of the pressure perturbation, and the capillary wave has a wavelength selected to interact coherently with the pressure perturbation.

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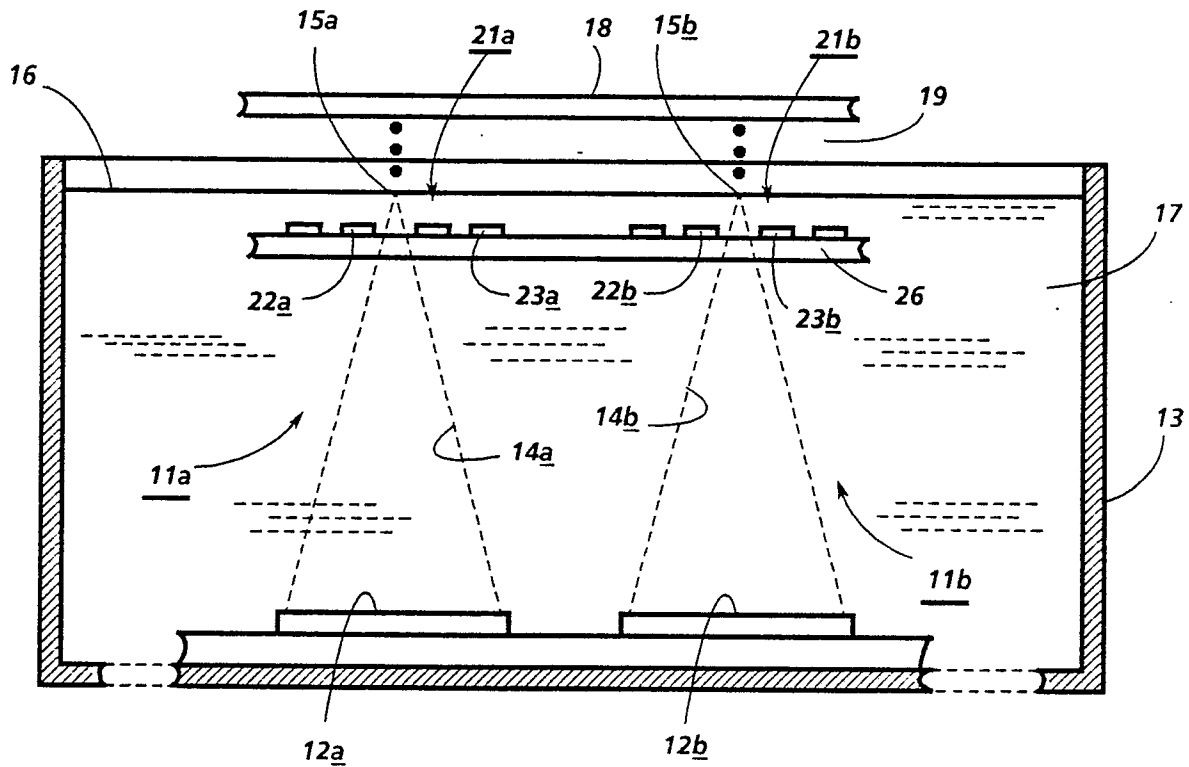
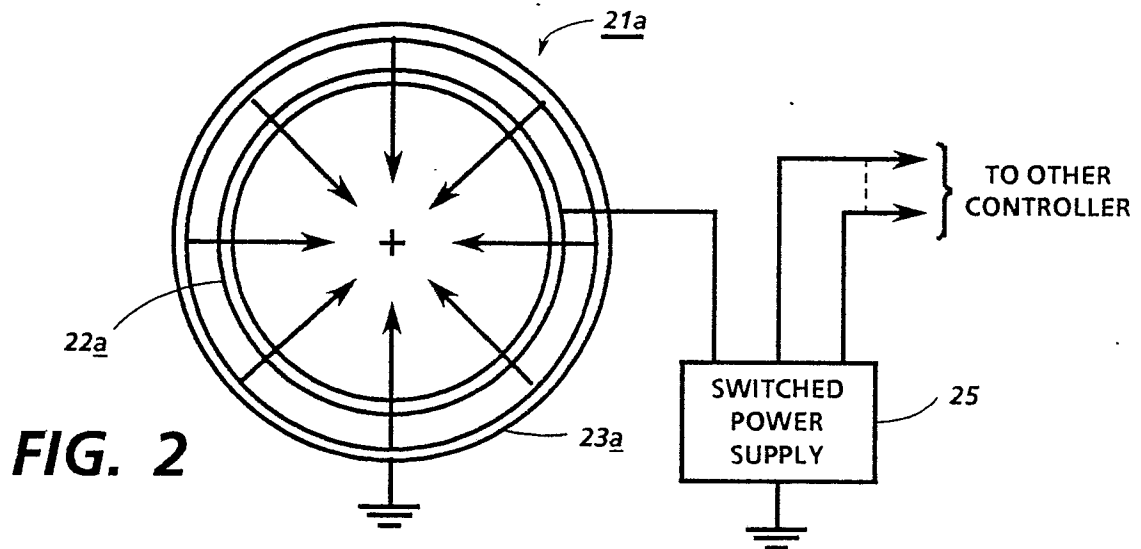
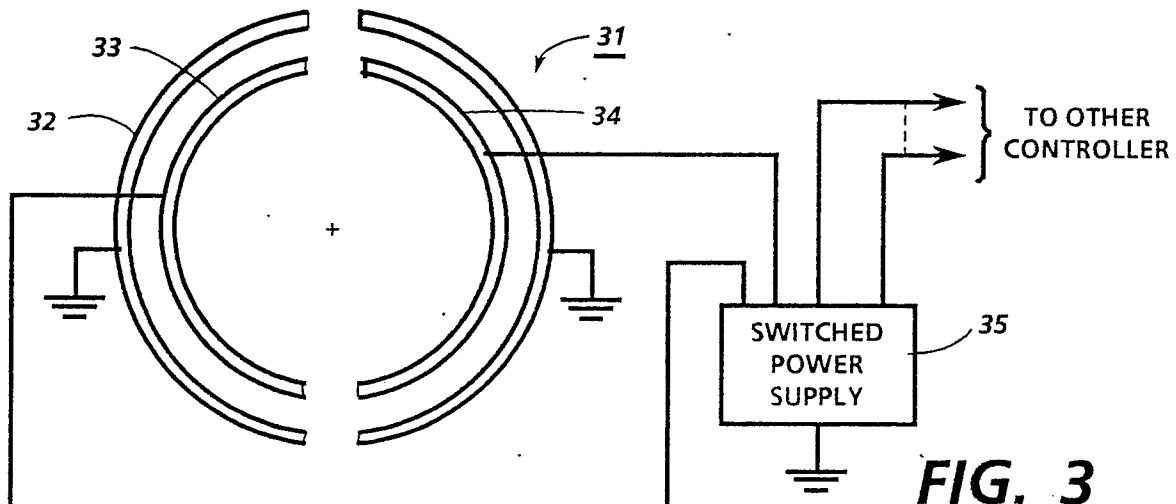
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**FIG. 1****FIG. 2****FIG. 3**