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To impose an electric field on the piezoelectric unit 5, an electric voltage is applied from an outside power source via driving line 7 to an electrode 6 which is disposed on the piezoelectric unit 5. This applied voltage causes a distortion in the piezoelectric unit 5, and this distorting force causes the vibrating plate 4 to exert an abrupt pressing force on the ink chamber 2, thereby jetting forth ink droplets 3 out of very small holes present in the ink chamber frame 1. A plurality of actuators such as this are disposed in the an ink jet recording head.

The piezoelectric unit 5 can be represented in electrical terms as a capacitor, as shown in Fig. 1(b). Accordingly, electric current in proportion to the time differential of the waveform of the applied voltage flows as a charging current and a discharging current when the electric field is applied and removed, respectively.

As the voltage is applied to and removed from the piezoelectric unit 5 at a higher frequency, the charging current and the discharging current increases. Hence, when a large number of driving elements are present in the piezoelectric unit 5, for example, when 24 elements are driven, the charging or discharging current will have a peak value of 50A. Consequently, a large drop in the voltage on the driving line 7 occurs. This results in a considerable change in the jetting characteristics effected by the driving elements in the



piezoelectric unit 5, and also a breakdown of electronic components in the piezoelectric unit 5.

Therefore, in an attempt to eliminate these problems, a method for driving a piezoelectric unit exists in which the charging and discharging currents are limited by current limiting resistors. This method is described in United States Patents Nos. 4,459,599, 4,126,867, and 4,282,535.

In this method, however, the resistance values of the current limiting resistors are readily susceptible to change. As a result, the charging and discharging times for the individual piezoelectric units vary, which affects the ink jetting characteristics considerably. This problem also exists in integrated circuit (IC) including such current limiting resistors.

Moreover, the charging and discharging times of the piezoelectric units will eventually become different due to inherent changes in capacitance of the individual piezoelectric units. Hence, because of this, the ink jetting characteristics will deteriorate even if current limiting resistors having identical resistances could be formed in an IC with a high degree of accuracy.

As an alternative, United States Patent No. 4,284,996 describes a method for driving one piezoelectric unit with constant current sources, one of which being a flow type and the other being a synchronizing type. However, in this method, it is difficult to maintain uniform driving characteristics



when driving a plurality of piezoelectric units due to the differences in the capacitances of the piezoelectric units and the differences in the current values of the constant current sources.

5 In an attempt to eliminate the problems associated with the conventional apparatuses, such as those described above, applicant has previously developed a driving device which is capable of suppressing the peak values of the charging and discharging currents without being influenced by the
10 differences in the capacitance of the piezoelectric units, and without using any current limiting resistors. In particular, in the driving device, a plurality of piezoelectric units are directly coupled to a driving power source whose output voltage is fluctuated at a prescribed gradient in a single driving
15 period for the piezoelectric units. This device is described in Japanese Laid Open Patent Application Nos. 274554-1990 (Heisei 2), 36036-1991 (Heisei 3), 133647-1991 (Heisei 3), 164544-1990 (Heisei 2), 369543-1992 (Heisei 4).

20 Figs. 2(a) and 2(b) of the present application illustrate this driving device. A high voltage V_p of approximately 20V is input to the driving voltage generator 10 and 20, while a V_d of approximately 5V is input to power the logic circuit. The driving voltage generators 10 and 20 are grounded at GND, and output a driving voltage V_s for driving
25 the piezoelectric units 14. In subsequent figures, identical parts are identified by the same numbers or characters.



The driving circuit of Fig. 2(a) is employed in an ink jet recording head which uses d31 type piezoelectric units and has pressure chambers which expand upon application of a voltage to the piezoelectric units, thereby sucking ink out of the reservoir and the pressure chamber upon removal of the voltage and thus jetting out ink droplets. In this driving circuit, the individual piezoelectric units 14 of the piezoelectric unit array 13 are connected, via bi-directional transfer gates 12 acting as selecting switches in a block of selecting switches 11, to the output of a driving voltage generator 10, which generates the driving voltage V_s that changes at a desired gradient. Because the electric power is applied selectively to these transfer gates 12 to charge and discharge the piezoelectric units 14 which are made of the same base material, the driving voltage V_s at the prescribed voltage gradient is applied selectively to the piezoelectric units 14 without being influenced by any dispersion in their capacitance.

Fig. 2(b) illustrates a driving circuit which is employed in an ink jet recording head which uses d33 type piezoelectric units and has pressure chambers which expand upon application of a voltage to the piezoelectric units, thereby sucking ink out of the reservoir and the pressure chamber upon removal of the voltage and thus jetting out ink droplets. The driving voltage generator 20 generates a negative driving voltage $-V_s$ which changes at a desired gradient.



In this driving circuit, a common terminal of the piezoelectric units 14 of the piezoelectric unit array 13 is connected to the output of driving voltage generator 20 which generates the driving voltage $-V_s$ that changes at the desired gradient. The other ends of the piezoelectric units 14 are connected to ground GND via a group of selecting switches 21 comprising mono-directional transistors 22, each having a parasitic diode 23 coupled in parallel. These selecting switches can be formed in an IC, such as those presently sold on the market.

When the driving voltage $-V_s$ grows larger at a constant gradient in the negative direction, all the piezoelectric units 14 are charged via the parasitic diodes 23, and the pressure chamber is thereby expanded. Then, as the driving voltage V_s becomes smaller (i.e., is reduced toward zero) at a prescribed gradient, electric power is conducted through only transistors 22, which have a signal being applied to their bases sufficient to turn on the transistors. Hence, the piezoelectric units 14 corresponding to those transistors 22 are discharged, which causes the corresponding pressure chambers to contract, thereby jetting out the ink. Moreover, the transistors 22 having an "off" signal (i.e. a voltage not large enough to turn on the transistor) applied to their bases remain non-conductive, and thus, the piezoelectric units 14 coupled to these transistors maintain their charged state, and do not jet out any ink.



Fig. 3(a) illustrates an arrangement of the circuit of the driving voltage generator 10, which generates a driving voltage V_s , as shown in Fig. 2(a). This driving voltage generator 10 charges a capacitor C via a transistor TR1 at a time constant determined by the capacitance of capacitor C and the resistance of resistor Rt1, and thereafter discharges the capacitor C via a transistor TR2 at a time constant determined by the capacitance of capacitor C and the resistance of resistor Rt2, thereby obtaining a reference fluctuating voltage. The driving voltage V_s is generated by amplifying this fluctuating voltage of the capacitor C by a power amplifier 30. This power amplifier 30 comprises a pair of mutually complementary transistors.

This circuit illustrated in Fig. 3(a) is simple and low cost. However, since the waveform has the characteristics of an exponential function, the waveform tapers near the end of operation of the actuator. Hence, this driving device cannot attain favorable ink jetting characteristics. Moreover, the charging and discharging currents of the piezoelectric unit, respectively, have the characteristics of an exponential function and thus do not provide constant current. Accordingly, in this circuit, large current flows in the initial phases of the charging period and discharging period, which is not favorable.

Fig. 3(b) illustrates a driving voltage generator which overcomes the defects of the conventional driving devices



described above. This driving device attains a reference fluctuating voltage by charging and discharging the capacitor C with constant current sources 31 and 32. The reference fluctuating voltage is amplified by the power amplifier 30, and the driving voltage V_s is thereby obtained.

The piezoelectric units are thus driven with constant charging and discharging currents at the driving voltage V_s . When this process is used, the voltage V_c of the capacitor C will be $V_c = (i_1/C) \times t$ or $V_c = V_p - (i_2/C) \times t$ (wherein, t : time). The voltage V_c , therefore, undergoes a linear change, and thus, this voltage generator overcomes the problems found with the conventional driving voltage generators.

Figs. 4(a) through 4(c) illustrate the wave-forms provided by the driving voltage generator, which attains a linear change in the generated voltage, as shown in Fig. 3(b). In particular, Figs. 4(a) and 4(b) show the wave-form of the driving voltage V_s that is provided, and Fig. 4(c) shows the wave-form of the driving current I_s that is provided. Actually, Figs. 4(a) and 4(b) show the driving voltage V_s that it is used for the d31 type piezoelectric units and the d33 type piezoelectric units, respectively.

Differences in the base material of which a piezoelectric unit is made, such as a difference in the thickness of the base material, will result in a difference in the amount of expansion or contraction of the piezoelectric unit, so that there will be differences in the quantity of the



jettted ink, the velocity of the jettted ink, and so forth. Accordingly, it is necessary to adjust the value of the wave height of the driving voltage V_s in order to compensate for such differences.

5 Furthermore, it is necessary to adjust the value of the wave height of the driving voltage when there is a sharp change in the characteristics (e.g. viscosity) of the ink in relation to the temperature in the environment. Such a correction can be made by adjusting the charging and discharging times of the
10 piezoelectric unit, as shown by a single dot chain line in Figs. 4(a) and 4(b). However, such an adjustment increases the time in which the ink chamber is maintained in its state of its maximum expansion from t_0 to t_0' . As a result, a deviation occurs in the position of the meniscus of the ink at the point
15 in time when the ink is jettted out, and thus, a change eventually occurs in the ink jetting characteristics.

Also, with the driving voltage generator shown in Fig. 3(b), the charging current i_1 , which is fed from the constant current source 31 to the capacitor C, and the discharging
20 current i_2 , fed from the constant current source 32, will assume the values determined by the following equations:

$$i_1 = E_{be} / R_{s2}$$

$$i_2 = E_{be} / R_{s4}$$

where the voltage between the base and emitter in transistors
25 TR3 and TR6 is expressed as E_{be} .



However, the voltage between the base and emitter of a transistor depends on the temperature in the environment and changes considerably from 0.7 V to 0.35 V in the range from 0 to 40° C. Hence, the circuit shown in Fig. 3(b) suffers from problems related to the temperature characteristics.

It is the object of the present invention to provide a method and apparatus for driving an ink jet recording head which avoids the above mentioned drawbacks. This object is solved by an apparatus according to independent claims 1 and 5 and by a method according to independent claims 9 and 12. Further advantageous features, aspects and details of the invention are evident from the dependent claims, the description and the drawings. The claims are to be understood as a first nonlimiting approach to define the invention in general terms.

The invention provides an ink jet recording head having piezoelectric units and, in particular, a method and apparatus for driving an ink jet recording head to provide uniform ink jetting characteristics of the ink jet recording head without being influenced by fluctuations in temperature of the surrounding environment.

According to one aspect of the present invention there is provided a driving device for use with an ink jet recording head that is capable of maintaining consistent ink jetting characteristics by adjusting the value of the wave height of the driving voltage wave-form while controlling the rise and fall times of the driving voltage wave-form to fluctuate consistently at a desired voltage gradient. In a specific aspect of the present invention there is provided a driving device which is not influenced by temperature.

According to another aspect the present invention further provides

a driving voltage generator which generates a driving voltage waveform rising and/or falling in a prescribed driving period to drive a plurality of piezoelectric units. The force generated by the piezoelectric units when driven enlarges or reduces the volumetric capacity of an ink chamber of the ink



jet recording head, thereby jetting out ink droplets through nozzle holes formed in the recording head.

5 The driving voltage generator such as this comprises a constant voltage source, which is capable of varying the output voltage in accordance with a correcting voltage signal, and a first constant current source, which generates a first constant voltage in proportion to the output voltage through the use of the constant voltage source.

10 The driving voltage generator further preferably includes a capacitor, which is charged approximately up to the output voltage by the first constant current, and a second constant current source, which provides a second constant current, in proportion to the output voltage, for discharging the charged capacitor. Finally, the driving voltage generator preferably comprises a power amplifier, which inputs the voltage of the capacitor and
15 outputs the driving voltage wave-form approximately equal to the terminal voltage of the capacitor. Accordingly, the driving device of the present invention keeps the rise and fall times of the driving voltage wave-form constant, regardless of
20 the correcting voltage signal.

In another aspect of the present invention the driving device is also capable of varying the wave height of the driving voltage waveform by adjusting the correcting voltage signal in accordance with the temperature of the environment. Further,
25 the constant current sources which generate the first and second constant currents each comprise a pre-transistor, which



acts as an emitter or source follower to receive a voltage in proportion to the output voltage, an output transistor, connected at its base or gate to the emitter or source of the pre-transistor, and a resistor for setting a value of the electric current at the emitter of the output transistor.

In yet another aspect the present invention also provides

a device for detecting the point in time when the driving voltage waveform attains its maximum voltage or minimum voltage, and a phase difference detecting device which detects a deviation in phase between the output from the detecting device and a reference signal indicating the point in time. In

another aspect the driving device further provides a device for making fine adjustments of the first constant current or the second constant current in accordance with the output from the phase difference detecting device regardless of the output voltage from the constant voltage source. The driving device therefor automatically adjusts the rise or fall times of the driving voltage waveform to a set value.

Accordingly, in one aspect of the present invention the capacitor is charged up to the output voltage value of a variable constant voltage source by using a constant current source. In the constant current source, the current value is controlled by a voltage dividing signal for the output from the variable constant voltage source, and then the capacitor is discharged until it attains a zero voltage potential. Hence, the capacitor thereby



produces a reference voltage and the driving voltage generator generates a driving voltage V_s on the basis of this reference voltage. Thus, simply by adjusting the output from the variable constant voltage source in accordance with the temperature in the environment in such a manner as to correct characteristics of the ink such as viscosity or the like, it is possible to vary the value of the wave height of the driving voltage V_s while maintaining the rise and fall times of the driving voltage V_s constant.

Furthermore, the constant current source formed of mutually complementary transistors, namely, a pair of a PNP transistor and an NPN transistor in a cascade connection, cancels the respective base-emitter voltage components, so that the constant current source itself does not depend on temperature.

In a specific aspect the present invention also provides another driving device, for driving an ink jet recording head, which includes a driving voltage generator for generating a driving voltage waveform rising and/or falling in a prescribed driving period to drive a plurality of piezoelectric units disposed in the ink jet recording head. The force generated by the piezoelectric units being driven enlarges or reduces the volumetric capacity of an ink chamber, thereby jetting out ink droplets through nozzle holes in the recording head.

The driving voltage generator comprises in another aspect of the invention a device for generating a variable frequency clock signal, a counter which



counts the clock signal, and a control device which outputs an adding signal, a counting stop signal, and a deducting signal in repetition at prescribed time intervals to the counter. The driving voltage generator further includes a digital-analog (D/A) converter, which converts the digital output from the counter into an analog voltage, a voltage amplifier for amplifying the analog voltage, and a power amplifier which inputs the output voltage from the voltage amplifier and outputs the driving voltage waveform approximately equal to the output voltage from the voltage amplifier. Hence, this driving device of the present invention keeps the rise and fall times of the driving voltage waveform constant, regardless of the frequency of the clock signal.

This driving device also is capable of varying the wave height of the driving voltage waveform by adjusting the frequency of the clock signal in accordance with the temperature of the environment.

According to another aspect, in the second driving device provided by the present invention, the count output from a counter which counts the clock signals at prescribed time intervals is converted by a digital-to-analog (D/A) converter into analog voltage signals which rise or fall in stages. These analog voltage signals are amplified to produce a reference voltage, and a driving voltage V_s for the piezoelectric unit is generated on the basis of this reference voltage. Therefore, no capacitor, whose capacitance may change due to a change in



temperature or a secular change, is necessary. Hence, a more stable driving voltage V_s can be obtained.

Further, the second driving device is capable of varying the wave height value of the driving voltage waveform, while keeping the rise and fall times of the driving voltage V_s constant simply by adjusting the frequency of the clock signal in accordance with the temperature in the environment, so as to correct the viscosity characteristics, etc., of the ink.

The power amplifier of both driving devices described above provide in a specific aspect a front stage comprising a first transistor and a second transistor whose bases and emitters are connected to each other, and which are mutually complementary and perform a push-pull operation on the voltage at their base terminals. An output stage of the power amplifier comprises a third transistor circuit, which is substantially complementary with the first transistor, and a fourth transistor circuit, which is substantially complementary with the second transistor. The collector and emitter of the first transistor is connected to the base and emitter of the third output transistor circuit, so that the collector current generated by the first transistor is applied as the base current of the third transistor circuit. Further, the collector and emitter of the second transistor is connected to the base and emitter of the fourth output transistor circuit, so that the collector current generated by the second transistor is applied as the base current of the fourth transistor circuit.



Both of the driving devices described above comprise according to a further aspect of the invention a

current limiting circuit which inhibits base current flowing to the third transistor circuit and the fourth transistor circuit, respectively, when an output current flowing through the third transistor circuit and the fourth transistor circuit, respectively, flows in excess of a predetermined value.

These and other objects and advantages of the invention will become more apparent and more readily appreciated from the following detailed description of the presently preferred exemplary embodiments of the invention taken in conjunction with the accompanying drawings, of which:

Fig. 1(a) illustrates a conventional ink jet recording head employing a piezoelectric unit;

Fig. 1(b) shows an equivalent electronic circuit for the ink jet recording head shown in Fig. 1(a);

Figs. 2(a) and 2(b) are circuit diagrams of conventional driving devices for an ink jet recording head shown in Fig. 1(a);

Figs. 3(a) and 3(b) each illustrate circuit diagrams of typical driving voltage generators employed in the driving devices shown in Figs. 2(a) and 2(b);

Figs. 4(a) and 4(b) are graphs illustrating the voltage waveform of a driving voltage V_s generated by the conventional driving voltage generators shown in Figs. 3(a) and 3(b);



Fig. 4(c) is a graph illustrating the current waveform
Is generated by the conventional driving voltage generators
shown in Figs. 3(a) and 3(b);

5 Fig. 5 shows a circuit diagram of an embodiment of a
driving device of the present invention for use in an ink jet
recording head;

Fig. 6 is a graph illustrating the temperature
characteristics of the output voltage of the variable constant
voltage source of the circuit shown in Fig. 5;

10 Fig. 7 is a circuit diagram of an embodiment of a
variable constant voltage source used in a driving device of
the embodiment of the present invention shown in Fig. 5;

Figs. 8(a) and 8(b) illustrate waveforms of control
signals generated by the circuit shown in Fig. 5;

15 Fig. 8(c) illustrates waveforms of the charging and
discharging currents applied to the capacitor in the circuit of
Fig. 5;

Fig. 8(d) illustrates the voltage of the capacitor C in
the circuit shown in Fig. 5;

20 Figs. 9(a) and 9(b) are other illustrations of
waveforms of the control signals generated by the circuit in
Fig. 5;

Fig. 9(c) is another illustration of waveforms of
charging and discharging currents applied to the capacitor in
25 the circuit of Fig. 5;



Fig. 9(d) is another illustration of the voltage of the capacitor C in the circuit shown in Fig. 5;

Figs. 10(a) and 10(b) are circuit diagrams of an embodiment of the constant current source unit used in the present invention;

Fig. 11 is a circuit diagram of an embodiment of a driving device similar to the embodiment of the embodiment of the present invention shown in Fig. 5 and realizes a more accurate rise time for the driving voltage;

Fig. 12(a) is a graph showing the waveform of the driving voltage V_s provided by the circuit shown in Fig. 11;

Fig. 12(b) is a graph illustrating the signal T_s which indicates the starting point in time for the rise-up of the driving voltage shown in Fig. 12(a);

Fig. 12(c) is a graph of the reference signal T_d which indicates the target point in time for the termination of the rise-up of the driving voltage shown in Fig. 12(a);

Fig. 12(d) is a graph of an output signal from a peak detector of the circuit shown in Fig. 11;

Figs. 12(e) is a graph illustrating an advance phase signal provided by a phase detector in the circuit shown in Fig. 11;

Fig. 12(f) is a graph showing a delay phase signal provided by the phase detector in the circuit shown in Fig. 11;



Fig. 13(a) is a circuit diagram illustrating an embodiment of a driving voltage generator used in the driving device of the present invention;

Fig. 13(b) is a graph illustrating a waveform of the driving voltage generated by the circuit shown in Fig. 13(a);

Fig. 14 is a circuit diagram of another embodiment of a driving device of the present invention for use in an ink jet recording head;

Fig. 15 is a graph showing the waveform of the output voltage from a digital-analog converter of the circuit shown in Fig. 14;

Figs. 16(a) and 16(b) are circuit diagrams for a power amplifier circuit; and

Figs. 17(a) through 17(d) are circuit diagrams for embodiments of a power amplifier circuit used in the embodiments of the driving devices of the present invention.

Fig. 5 is a circuit diagram showing an embodiment of a driving device, for use with an ink jet recording head, provided by the present invention. As shown, a driving voltage generator 10a includes a variable constant voltage source 40 for outputting a voltage V_k , which is dependent on the temperature of the environment.

The variable constant voltage source 40 comprises a reference voltage generating unit 41, which generates a



reference voltage V_r achieved by superposing a correcting voltage V_x , which will be described later, on a Zener voltage of a Zener diode Z_d . A feedback unit 43 generates a voltage V_f which is obtained by dividing the output voltage V_k by resistors R_{f1} and R_{f2} . Further, a controller 42 compares the voltage V_r from the reference voltage generating unit 42 to the voltage V_f from the feedback unit 43 to control the output voltage V_k so that V_r is equal to V_f .

A voltage divider 44 of the driving voltage generator 10a produces voltage V_{in1} and voltage V_{in2} by dividing the output voltage V_k from the variable constant voltage source 40 by the resistors R_{d1} , R_{d2} , and R_{d3} . These voltages V_{in1} and V_{in2} control constant current sources 45 and 46, respectively, to each generate a constant current.

Constant current source 45 generates a constant current in proportion to the voltage V_{in1} , and a current from this constant current source 45 charges the capacitor C . The rise which occurs in the voltage at the terminal of the capacitor C at such a time is linear, and the charging voltage V_c attains a peak value approximately equal to the output voltage V_k .

Constant current source 46 generates a constant current in proportion to the voltage V_{in2} , and the capacitor C is discharged by this constant current source 46. The voltage at the terminal of the capacitor C during discharge decreases linearly from the peak voltage V_k to zero. These constant current sources 45 and 46 are operated in accordance with



control signals S1 and S2 output alternately in a prescribed operating cycle from a system controller 60.

The voltage V_c at the terminal of the capacitor C is amplified by a power amplifier 30, and a driving voltage V_s for a piezoelectric unit is thereby generated.

Recording head 51 includes an actuator formed of piezoelectric units, a selecting switch unit shown in Fig. 2(a) or Fig. 2(b), and a temperature sensing element 52 for detecting the temperature of the environment. The temperature information, which is obtained based on changes in the resistance value of the temperature sensing element 52, is input to the system controller 60 via a signal line 52a, and the system controller 60 outputs a printing data signal, via a signal line group 60a, which controls the selecting switch unit.

The temperature information input to the system controller 60 is converted into a digital value by an analog-digital (A/D) converter 61. The digital value is input to a data processing device 62 comprising a look-up table, and the data processing device 62 outputs compensating data for changing the peak value of the driving voltage V_s in order to compensate for the fluctuations which the temperature causes in the elements of the actuator. This compensating data is converted into analog values by a digital-analog (D/A) converter 63, and the analog values are output to the reference voltage generating unit 41 to cause the reference voltage



generating unit 41 to set the reference voltage V_r at a higher level as the temperature decreases. In particular, as described above, the reference voltage V_r is changed by superposing a correcting voltage V_x , which is obtained by
5 dividing the voltage of the analog output from the digital-analog (D/A) converter 53 by resistors R_{c1} and R_{c2} , on a Zener voltage of the Zener diode 2D via transistor TR7.

The reference voltage V_r which is thus generated at resistor R_{b2} is expressed by the following equation:

10
$$V_r = V_x + E_{be7} + V_z - E_{be8}$$

where the saturated voltage between the base and emitter of the PNP type transistor TR7, and that between the base and emitter of the NPN type transistor TR8, are expressed as E_{be7} and E_{be8} , respectively, and the Zener voltage of the Zener diode 2D is
15 expressed as V_z .

However, since E_{be7} and E_{be8} are almost equal, though they change under the influence of the temperature, the terms E_{be7} and E_{be8} cancel each other, and the following equation is obtained:

20
$$V_r = V_x + V_z$$

Thus, the temperature characteristics of the base-emitter voltages of the transistors do not appear in the reference voltage V_r . That is, the output voltage V_k from the variable-constant voltage source 40 can be expressed by the
25 following equation:

$$V_k = V_r \cdot (1 + R_{f1} / R_{f2})$$



$$= (V_x + V_z) \cdot (1 + R_{f1} / R_{f2})$$

Hence, the output voltage V_k depends only on a correcting voltage V_x according to the temperature and is therefore adjusted, at a high degree of accuracy, to the voltage value shown in Fig. 6. In this regard, the value of resistor R_{b1} is determined to be a value to allow ample electric current to flow so that an adequate Zener voltage V_z can be generated.

It is conceivable that in a temperature correcting method, temperature sensing element 52 can control directly the reference voltage generating unit 41 or the feedback unit 43. However, it is sometimes difficult to select a temperature sensing element 52 that matches the temperature characteristics of the actuator or those of the recording head. In particular, a temperature correcting process in which a temperature sensing element directly operates to correct a driving voltage applied to a piezoelectric unit is disclosed in Laid Open Japanese Patent Application No. 65566-1980 (Showa 55). However, that process is completely different from the present invention, in particular, with regard to circuit construction and the driving system.

When correction needs to be made for the thickness, etc., of the piezoelectric unit, it is necessary to change the value of the wave height in the driving voltage even if the temperature remains the same. To accomplish this, a driving voltage generating unit should be constructed so that the ratio



of the resistors R_{f1} and R_{f2} in the feedback unit 43 can be varied to adjust the feedback voltage V_f .

In the circuit construction shown in Fig. 5, the output which can be obtained from the digital-analog (D/A) converter 63 will be a maximum of approximately 3.33V, which corresponds to $5V \times 2/3$ (the details of calculating this value are omitted here for convenience), provided that the voltage supplied to the digital-analog (D/A) converter 63 is 5V.

However, during actual application, sometimes the variable ratio of the reference voltage V_r needs to be increased. In such a case, the Zener voltage V_z can be reduced. Nevertheless, in this case, in order to obtain a prescribed output voltage V_k , it is necessary to make the magnifying ratio of $(1 + R_{f1}/R_{f2})$ larger. Hence, it may not be possible to obtain a favorable output voltage V_k .

To overcome this dilemma, a variable constant voltage source, such as that shown in Fig. 7, is used. The variable constant voltage source maintains the relationship $V_r < V_k$, but does not increase the magnifying ratio of $(1 + R_{f1}/R_{f2})$, and enlarges the ratio of change in the reference voltage V_r even if it increases the Zener voltage V_z .

In particular, in the circuit shown in Fig. 7, the resistors R_{e12} and R_{e13} ($R_{e12} = R_{e13}$) and the transistors TR_{28} and TR_{29} form a current mirror circuit, wherein collector currents i_c (V_x/R_{e11}) having equal values flow to the



transistors TR28 and TR29. The reference voltage V_r will therefore be as expressed by the following equation:

$$\begin{aligned} V_r &= i_c \times R_{c3} + V_z \\ &= (R_{c3} / R_{e11}) \times V_x + V_z \end{aligned}$$

5 Accordingly, the fluctuating range of the reference voltage V_r can be made larger by arbitrarily amplifying the correcting voltage V_x by appropriately selecting the respective resistance values of the resistors R_{c3} and R_{e11} .

10 Next, the operation of the circuit shown in Fig. 5 is described with reference to Fig. 8(a) through Fig. 8(d).

Figs. 8(a) and 8(b), respectively, illustrate the control signals S_1 and S_2 . These control signals are output by the system controller 60 so that the constant current sources 45 and 46 are operated alternately. In response to these control signals S_1 and S_2 , as shown in Fig. 8(c), the constant current source 45 generates a charging current i_1 which charges capacitor C, and constant current source 46 generates a discharging current i_2 which discharges capacitor C. Fig. 8(d) illustrates the wave-form of the voltage V_c at the terminal of the capacitor C, which is charged and discharged, respectively, by charging current i_1 and discharging current i_2 .

20 Moreover, a waveform is shown in Fig. 8(d) for a case when the output voltage from the variable constant voltage source 40 is reduced from V_{k1} to V_{k2} . In this case, the charging current value i_1 and the discharging current value i_2 will be smaller in proportion to the decline of the output



voltage, and the rising and falling gradients of the voltage V_c at the terminal of the capacitor C being thereby adjusted. However, the charging time τ_1 , the peak voltage holding time τ_2 , and the discharging time τ_3 will not change. In other words, this circuit is capable of performing stable control over the discharging operation since it does not cause any deviation in the position of the meniscus of the ink at the point in time of jetting the ink even if the output voltage is changed.

Figs. 9(a) through 9(d) illustrate another driving timing chart, which is an improvement from the driving timing chart shown in Figs. 8(a) through 8(d), and which can suppress the residual vibrations of the meniscus to the maximum extent possible after the ink droplets are discharged. As shown, the discharge of the capacitor C is temporarily stopped after the ink is jetted out. Then, the discharge is resumed at the point in time when the meniscus is considerably drawn in, thus canceling the further drawing in of the meniscus.

Even with a driving system like this, it is possible to perform stable control over the jetting of ink droplets because only the rising and falling gradients of the voltage at the terminal of the capacitor C are adjusted as in the timing shown in Figs. 8(a) through 8(d). Again, no change is made to the charging time τ_1 , the peak voltage holding time τ_2 , and the discharging time τ_4 through τ_6 .



If the driving system operating as shown in Figs. 9(a) through 9(d) is employed, it is possible to improve the ink jetting period. Further, when the discharge of the capacitor C is stopped halfway in the operation, the waveform of the driving signal can be kept flat because the input impedance of the current amplifier 30 is very high.

In addition, the meniscus will be set in a still state almost without any vibration if the charging operation is stopped temporarily, with the control signal S1 being turned OFF halfway through the charging operation. If the charging operation is then resumed, with the control signal S1 being turned ON at the point in time when the meniscus returns, it is possible to keep the peak voltage holding time τ_2 a very short period.

An embodiment of a constant current source used in the present invention will be described. Fig. 10(a) illustrates flow type constant current sources 45, and sink type constant voltage source 46, which include mutually complementary transistors in emitter-follower connections.

The constant current source 45 uses voltage V_{in1} as its input voltage, and comprises an NPN type transistor TR9 and a PNP type transistor TR10 provided with an emitter resistor R_{e2} . This constant voltage current source 45 also includes a transistor TR11 that is activated by the control signal S1 from the system controller 60.



The constant current source 46 uses voltage V_{in2} as its input voltage, and comprises a PNP type transistor TR12 and an NPN type transistor TR13 provided with an emitter resistor R_{e4} . This constant current source 46 further includes transistor TR14 that is activated by the control signal 52 from the system control means 60.

The voltages generated in the resistors R_{e2} and R_{e4} , respectively, are expressed by the following equations:

$$V_{out1} = V_{in1} - E_{be9} + E_{be10}$$

$$V_{out2} = V_{in2} + E_{be12} - E_{be13}$$

where the saturated voltages between the base and the emitter of each of the transistors TR9, TR10, TR12, and TR13 are expressed by E_{be9} , E_{be10} , E_{be12} , and E_{be13} , respectively.

However, since the saturated voltages between the base and emitter of the individual transistors are almost equal in their temperature characteristics, regardless of the polarity, the equations given above can respectively be restated, regardless of the temperature, as follows:

$$V_{out1} \approx V_{in1}$$

$$V_{out2} \approx V_{in2}$$

Therefore, the flow current i_1 from the constant current source 45 is $i_1 = V_{in1} / R_{e2}$, and the sink current i_2 from the constant current source 46 is $i_2 = V_{in2} / R_{e4}$. Accordingly, these current can be determined based only on the



consistency of the resistance values, without dependence on the temperature.

Since resistors having a tolerance of about 0.5 % are available at low cost, this circuit provides a constant current source at low cost and with a high level of performance. In addition, since the constant current source 45 operates at a high degree of accuracy when voltage V_{in1} and voltage V_{in2} are 0.3 V or higher, it is possible to set the final charging voltage of the capacitor C almost to the output voltage V_k from the variable constant voltage source 40, and to set the final discharging voltage almost to GND.

Fig. 10(b) is a diagram illustrating another embodiment of a constant current source, which obtains a constant current by maintaining the voltages generated in the emitter resistors R_{e5} and R_{e6} of the transistors TR15 and TR17, respectively, at the voltages V_{in1} and V_{in2} , by using operating amplifiers 82 and 83. However, this circuit becomes unstable in its operation if V_{in1} is set approximately equal to the output voltage, or if V_{in2} is set approximately equal to GND, when the voltage being supplied to the operating amplifiers 82 and 83 is to be supplied from the output voltage V_k from the variable constant voltage source 40.

In addition, it is possible to form a constant current source by using a current mirror circuit. Although such a constant current source can maintain a very small voltage drop



in the constant current source, a pair of transistors having well-balanced characteristics must be used to achieve this.

During actual application of the above circuits, in some circumstances, the peak voltage holding time τ_2 must be made very small. However, such a small peak voltage holding time τ_2 may not be easily obtained due to a dispersion in the accuracy of the constant current source 45 in the circuit shown in Fig. 5.

Accordingly, a circuit which provides an accurate driving voltage V_s will be described with reference to Fig. 11. In this circuit, resistors R_{e2} or R_{e5} (shown in Fig. 10(a)) for determining the flow current value for the constant current source 45 are replaced with a variable impedance 120, and automatic control is performed on the value of the variable impedance 120 in accordance with a dispersion in the accuracy of the constant current source 45.

In particular, the difference in phase between the point in time when the driving voltage V_s , detected by a peak detector 121, attains the maximum voltage and the reference signal T_d , which indicates the control point in time, is detected by a phase detecting circuit 122. The detected difference in phase is converted into an analog voltage signal by a charge pump 123 and an integrating circuit 124, and the analog voltage signal is applied as the base current of the transistor TR31 to adjust the impedance between the collector and the emitter of the transistor TR31.



Fig. 12(a) through 12(d) are graphs illustrating the operations of the circuit shown in Fig. 11. In particular, Fig. 12(a) shows the voltage wave-form of the driving voltage V_s , Fig. 12(b) shows the rise-up point in time T_s for the driving voltage V_s , Fig. 12(c) shows the reference signal T_d output with a lag by the time τ_1 from the occurrence of the rise time T_s , and Fig. 12(d) shows the output from the peak detector 121. Figs. 12(e) and 12(f) show a phase advance signal (UP) and a delay signal (DN) output from the phase detector 122. In this regard, a similar circuit can be used also for controlling the fall time τ_3 of the driving voltage V_s .

The embodiments described above relate to the operation of an ink jet recording head which, using a d31 type piezoelectric unit, sucks up ink from a reservoir by expanding a pressure chamber in accordance with a voltage applied to a piezoelectric unit, and jets out ink droplets by contracting the pressure chamber by removing the voltage. An embodiment for use with an ink jet recording head using having d33 type piezoelectric units, which operate in reverse to the operation of the d31 type piezoelectric units, is illustrated in Fig. 10.

Fig. 13(a) is a circuit diagram of a driving voltage generator 20a, which is used for an ink jet recording head having d33 type piezoelectric units. A logic power source V_d provides a voltage of 5V to a level converter 93. This level converter 93 performs a level converting process on the control



signals S1 and S2 output from the system controller 60 and the correcting voltage V_x based on the temperature information, provides control signals S1' and S2' to control constant current sources 91 and 92, and provides correcting voltage V_x' to control the voltage ($-V_k$) output by a variable constant voltage source 90, thereby causing the driving voltage generator 20a to generate a driving voltage V_s in a negative voltage shown in Fig. 13(b). This driving voltage generator 20a also can be employed in the circuit shown in Fig. 5.

This embodiment is advantageous over the first embodiment of the present invention. That is, as described above, the first embodiment of the present invention generates a driving voltage V_s on the basis of a charging voltage and a discharging voltage of capacitor C. However, the capacitor C can have a large change in its capacitance due to the temperature of the environment, or due to a change in comparison with a resistor. In view of this, the second embodiment of the present invention generates a driving voltage V_s without using any capacitor C.

Fig. 14 is a diagram illustrating a circuit of the driving device of the second embodiment of the present invention, which employs an analog-digital (A/D) converter 111 in a system controller 110 to convert the temperature information provided by temperature sensing element 52 into digital values. A data processing unit 112 increases the frequency of a clock generator 113 as the temperature becomes



lower, depending on whether it is in a charging period or in a discharging period.

The data processing unit 112 also outputs an adding signal, a counting stop signal, and a subtracting signal in repetition at prescribed time intervals to the counter 114, which counts the clock signals generated from a clock generator 113, to control the counting operation of the counter 114. The digital count output from the counter 114 is converted into an analog value by a digital-analog (D/A) converter 115, which outputs voltage waveforms in stages as shown in Fig. 15. In particular, the right-hand side of Fig. 15 shows the output waveform in a low temperature state in which the viscosity of the ink is increased, and the left-hand side of Fig. 15 shows the output waveform in the normal temperature state.

A constant current source 101 receives the voltage V_{in3} from the digital-analog (D/A) converter 115, and in accordance with this voltage, synchronizes the constant current $i3$ so that $i3 = V_{in3}/R_{e7}$. Moreover, constant current source 102 inputs a voltage V_h and controls the constant current $i4$ so that $i4 = V_h/R_{e8}$ with the voltage $V_h = R_{c1} \times i3$. Therefore, a voltage $V_{out3} = i4 \times R_{c2}$ is generated at resistor R_{c2} .

Assuming that $R_{e7} = R_{c1} = R_{e8} = (R_{e0})$, then the equation $V_{out3} = V_{in3} \times (R_{c2} / R_{e0})$ is valid, and the voltage V_{out3} at an amplification ratio determined by the values of the resistors R_{c2} and R_{e0} is obtained. This voltage V_{out3} is further amplified by a power amplifier 30 to become the driving



voltage V_s . Hence, in this second embodiment of the present invention, the smoothness of the driving voltage V_s depends on the number of bits of the counter 112, but any number of bits not less than five bits will suffice for practical purposes.

5 Furthermore, the driving device of the second embodiment of the present invention may be arranged so that if the frequency of the clock generator 113 is set to a fixed value, the output bits of the counter 114 depend on the temperature information and are shifted appropriately and
10 output to the digital-analog converter 115.

An embodiment of the power amplifier 30, which is employed in the driving devices of both embodiments of the present invention, will now be described.

15 Figs. 16(a) and 16(b) illustrate a power amplifier arranged as an emitter-follower comprising mutually complementary transistors coupled in a Darlington connection and, for example, having the same polarity. Although the power amplifying circuits shown in Figs. 16(a) and 16(b) can be used
20 if the output has fallen into a nearly short-circuited state, in this case, the base current of transistors TR20 and TR21 or transistors TR22 and TR23 at the final output stage will flow without being limited, so the transistors will break down. Also, with the circuit shown in Fig. 16(b), a decrease in the
25 voltage between the input and output can be as great as two times the saturated voltage between the base and the emitter of the transistors.



Therefore, to avoid these problems, the present invention employs a power amplifying circuit as shown in Fig. 17(a) through Fig. 17(d).

Fig. 17(a) illustrates a basic circuit which detects the output current flowing to the final output transistors TR23 and TR22 by using current detecting resistors Rp1 and Rp2. Also, transistors TR24 and TR25 prevents the base current from flowing without being limited. The transistors are also coupled as shown to resistors Rb3 and Rb4.

Fig. 17(b), on the other hand, illustrates a circuit for increasing the capacity of the sink current, and includes additional transistors TR26 and TR27. Fig. 17(c) shows a circuit for increasing the capacity of the flow current. Finally, Fig. 17(d) shows a circuit for increasing both the capacity of the sink current and the capacity of the flow current.

In any of the circuits shown in Figs. 17(a) through 17(d), the voltage drop between the input and output is such that one unit portion of the saturated voltage between the base and the emitter of the transistor is sufficient. Further, the resistors Rb4 and Rb5 are used for preventing an open state from forming between the base and the emitter. Whether the circuit shown in Fig. 17(a), Fig. 17(b), Fig. 17(c) or Fig. 17(d) is used in the driving circuit of either embodiment depends on the desired maximum output current value, the



charging time for the piezoelectric unit, and the length of the discharging time desired.

Moreover, in either embodiment of the driving circuit, the output V_k from the variable constant voltage sources 40 or 90 may be supplied to the power amplifier. However, in these cases, it is necessary to sufficiently increase of the electric power capacity of the variable constant voltage sources 40 and 90. Further, although the transistors employed in the power amplifier and the constant current sources and are illustrated as bipolar transistors, such transistors can be field effect transistors or the like.

As described above, the first embodiment of the present invention provides a driving device having a capacitor that is discharged by a constant current source in which the current value is controlled with a voltage dividing signal output from a variable constant voltage source. The voltage of the capacitor is amplified by a power amplifier to provide a driving voltage V_s for the piezoelectric unit. Hence, the value of the wave height of the driving voltage V_s can be adjusted, while the rise and fall times of the driving voltage V_s are maintained constant simply by controlling the output from the variable constant voltage source in accordance with the temperature in the environment to compensate for viscosity characteristics of the ink. Therefore, it is possible to maintain constant ink jetting characteristics without any influence by the temperature in the environment. Further, by



employing in the device a constant current source comprising a pair of mutually complementary transistors, that is, a PNP type transistor and an NPN type transistor, the voltage components between the base and the emitter in these transistors are mutually canceled, so that the constant current source also is not influenced by the temperature.

The second embodiment of the present invention provides a driving device which converts the output from a counter that performs adding, count stopping, and subtracting operations of clock signals at prescribed time intervals, into an analog voltage signal which rises or falls in stages. The analog voltage signal is amplified through a power amplifier to provide a driving voltage V_s for a piezoelectric unit. Hence, a capacitor, whose capacitance may change due to changes in the temperature and a secular change, is not needed. Accordingly, the driving device can generate a more stable driving voltage and can adjust the value of the wave height of the driving voltage V_s , while keeping the rise and fall times of the driving voltage V_s constant, simply by controlling the frequency of the clock signal in accordance with the temperature in the environment to compensate for the viscosity characteristics, etc., of the ink. Thus, the driving device maintains uniform ink jetting characteristics without being influenced by the temperature in the environment.

Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in



the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. Accordingly, all such modifications are intended to
5 be included within the scope of this invention as defined in the following claims.





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CLAIMS

1. An apparatus for generating a driving voltage for driving
5 at least one piezoelectric unit of an ink jet recording
head (51) which, when driven, changes the volumetric
capacity of an ink chamber of the recording head (51) to
jet out ink droplets through a nozzle hole in the
recording head (51), said apparatus comprising:
10
a constant voltage source (40) for providing an output
voltage (V_k) which varies in accordance with a correcting
voltage signal (V_x);
15
a first constant current source (45) for generating a
first constant current in proportion to the output
voltage (V_k);
a capacitor (C) for being charged by the first constant
20 current to a voltage approximately equal to the output
voltage;
a second constant current source (46) for providing a
second constant current, in proportion to the output
25 voltage (V_k), to discharge the capacitor (C); and
a power amplifier (30) for amplifying the voltage of the
capacitor to provide said driving voltage (V_s), said
driving voltage having a constant rise time and fall time
30 independent of a value of the correcting voltage signal
(V_x).
2. An apparatus as claimed in claim 1, further comprising a
35 circuit (60) for adjusting the correcting voltage signal

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(V_x) in accordance with a temperature in the environment to vary an amplitude of the driving voltage (V_s).

- 5 3. An apparatus as claimed in claim 1 or 2, wherein the first and second constant current sources (45, 46) each comprise:

10 an input transistor which receives a voltage in proportion to the output voltage;

an output transistor coupled to the input transistor; and

15 a resistor for setting a level of current inserted to the output transistor.

- 20 4. An apparatus as claimed in any of the preceding claims, further comprising:

a detector (121) which detects a point in time when the driving voltage attains one of a maximum voltage and minimum voltage;

25 a phase difference detector (122) which detects a deviation in phase between an output from the detector (121) and a reference signal (T_d) indicating the point in time; and

30 an adjusting circuit (124) which adjusts one of the first constant current and the second constant current in accordance with an output from the phase difference detector regardless of the output voltage from the constant voltage source (40); and

35

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wherein the driving device automatically adjusts one of the rise time and the fall time of the driving voltage (V_s) to a set value.

5 5. An apparatus for generating a driving voltage for driving at least one piezoelectric unit of an ink jet recording head (51) which, when driven, changes the volumetric capacity of an ink chamber of the recording head (51) to jet out ink droplets through a nozzle hole in the
10 recording head (51), said apparatus comprising:

a clock (113) which generates a clock signal having a variable frequency;

15 a counter (114) which counts the clock signal;

a controller (112) which outputs an adding signal, a counting stop signal, and a deducting signal in repetition at prescribed time intervals to the counter
20 (114);

a digital-analogue (D/A) (115) converter for converting the digital output from the counter (114) into an analogue voltage; and
25

an amplifier (30) which amplifies the analogue voltage to provide the driving voltage, the rise time and fall time of the driving voltage being constant regardless of the frequency of the clock signal.
30

6. An apparatus as claimed in claim 5, further comprising a circuit which adjusts the frequency of the clock signal in accordance with the temperature of the environment to vary an amplitude of the driving voltage.
35





7. An apparatus as claimed in any of the preceding claims, wherein the power amplifier comprises:

a front stage comprising a first transistor and a second transistor, which are mutually complementary and perform a push-pull operation at the voltage of their base terminals; and

an output stage comprising a third transistor circuit, which is substantially complementary with the first transistor, and a fourth transistor circuit, which is substantially complementary with the second transistor, collector current generated by the first transistor being applied as base current to the third transistor circuit and collector current generated by the second transistor being applied as base current to the fourth transistor circuit.

8. An apparatus as claimed in claim 7, further comprising:

a current limiting circuit, which inhibits the base current flowing to one of the third transistor circuit and the fourth transistor circuit when an output current flowing through one of the third transistor circuit and the fourth transistor circuit, respectively, is in excess of a predetermined value.

9. A method for generating a driving voltage for driving at least one piezoelectric unit of an ink jet recording head which, when driven, changes the volumetric capacity of an ink chamber of the recording head to jet out ink droplets through a nozzle hole in the recording head, said method comprising the steps of:





providing a variable voltage which varies in accordance with a correcting voltage signal;

5 generating a first constant current in proportion to the variable voltage;

charging a capacitor by the first constant current to a voltage approximately equal to the variable voltage;

10 generating a second constant current in proportion to the variable voltage to discharge the capacitor in accordance therewith; and

15 amplifying the voltage of the capacitor to provide said driving voltage, said driving voltage having a constant rise time and fall time independent of a value of the correcting voltage signal.

20 10. A method as claimed in claim 9, further comprising the step of adjusting the correcting voltage signal in accordance with a temperature in the environment to vary an amplitude of the driving voltage.

25 11. A method as claimed in claim 9 or 10, further comprising the step of:

30 detecting the point in time when the driving voltage waveform attains one of a maximum voltage and minimum voltage and outputting a detection signal;

35 detecting a deviation in phase between the detection signal and a reference signal indicating the point in time and outputting a deviation signal; and





adjusting one of the first constant current and the second constant current in accordance with the deviation signal regardless of variable voltage so that one of the rise time and fall time of the driving voltage are automatically adjusted to a set value.

12. A method for generating a driving voltage for driving at least one piezoelectric unit of an ink jet recording head which, when driven, changes the volumetric capacity of an ink chamber of the recording head to jet out ink droplets through a nozzle hole in the recording head, said method comprising the steps of:

generating a digital clock signal having a variable frequency;

counting the clock signal;

outputting an adding signal, a counting stop signal, and a deducting signal in repetition at prescribed time intervals to the counter;

converting the digital clock signal into an analog signal; and

amplifying the analog signal to provide the driving voltage, the rise time and fall time of the driving voltage being constant regardless of the frequency of the clock signal.

13. A method as claimed in claim 12, further comprising the step of adjusting the frequency of the clock signal in accordance with the temperature in the environment to vary an amplitude of the driving voltage.

