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PIEZOELECTRIC IMPACT PRINTER DEVELOPMENT IN THE 1980's

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Abstract:

This paper describes basic technologies on which the author experienced during development of piezoelectric impact printer heads in 1980's. By this development, impact printers that introduced piezoelectric stiffened effect to printer head were successfully commercialised as the world's first product. The printer head also broke through printing speed limit of electromagnetic type. Stacked piezoelectric actuator, mechanical amplifier and electrical driver circuits were newly developed for this purpose. The technologies described here are "maximum available energy of an actuator", "energy transfer efficiency and amplification ratio", "mechanical amplifier configuration", "electrical driver circuit employing an inductor". Finally performances of the printer head are summarized in "performances of the developed printer head".

Keywords: maximum available energy, energy transfer efficiency, amplification ratio, mechanical amplifier, electrical driver circuit, printer head performances

Introduction

In 1988, the author, in cooperation with other members who belonged to NEC, succeeded in development of impact printer head utilizing stiffened piezoelectric effect. This was the world's first product that introduced piezoelectric stiffened effect to impact printer heads, which broke through printing speed limit of electromagnetic type(6). For this purpose, stacked piezoelectric actuators(1), mechanical amplifiers(3) and electrical driver circuits(4) were newly developed. In this paper, "maximum available energy of an actuator(2)(3)", "energy transfer efficiency and amplification ratio(2)(3)", "mechanical amplifier configurations(3)", "electrical driver circuits(4)(5)", and "performances of the developed printer head(7)" are described.

Maximum Available Energy of an Actuator(2)(3)

In this section, the energy which can be extracted from an actuator is discussed in both statically and dynamically driven cases. Fig.1 shows stroke-force relationship of an actuator when maximum applicable voltage V is applied to the electrical terminals. Zero-force-stroke and zero-stroke-force are expressed by ξ and F, respectively. Stiffness k is given by eq.(1).

$$k = \frac{F}{\xi} \qquad (1)$$

The energy of the actuator E is shown by the hatched triangle area in Fig.1 and given by eq.(2).

$$E = \frac{1}{2} F \cdot \xi = \frac{1}{2} k \xi^2 \qquad (2)$$

We call E "reserved energy" here.

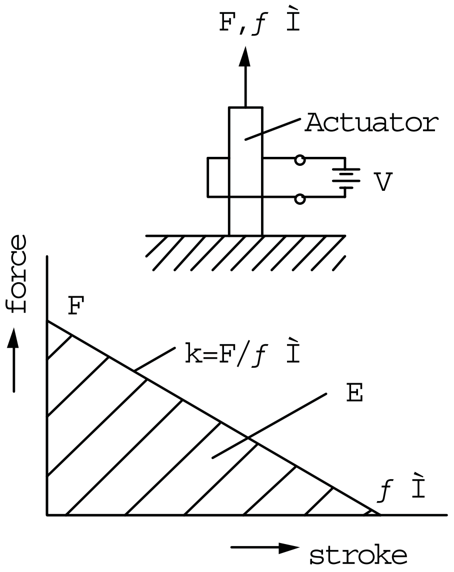

Fig. 1: *Stroke-Force relationship of an actuator*

1) Statically driven case

When a static load, for instance a coil spring with stiffness k_x, is connected to the actuator as shown in Fig.2, the energy E_x, which is stored in the coil spring, is given by eq.(3).

$$E_x = \frac{k \cdot k_x^{\ 2}}{2(k + k_x)^2} \xi^2 \qquad (3)$$

In order to calculate maximum condition for eq.(3), k_x derivative of eq.(3) is set to zero. Then we get eq.(4).

$$k_x = k \qquad (4)$$

If we set k_x=k in eq.(3), then we get maximum value of E_x. The maximum value $E_{x\max}$ is given by eq.(5).

$$E_{x\max} = \frac{1}{8} k \xi^2 \qquad (5)$$

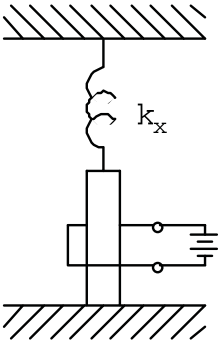

Fig. 2: *Statically Driven Case*

If we compare eq.(1) and eq.(5), we can see that $E_{x\max}$ is 1/4 of the reserved energy. When a stiffness k_x is connected to an actuator as a load, maximum available energy given to stiffness k_x from the actuator is 1/4 of the reserved energy, and the condition for this is that the stiffness of the load is equal to the actuator stiffness .

2) Dynamically driven case

Now we will study dynamically driven case shown in Fig.3, in which a mass m is connected to an actuator instead of coil spring.

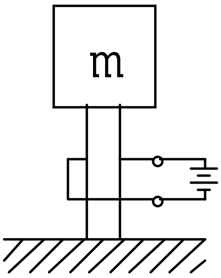

Fig. 3: *Dynamically Driven Case*

Motion of the mass ξ(t) after step voltage V is applied to the actuator is expressed by the following differential equation.

$$m\ddot{\xi}(t) + k\xi(t) = k\xi \cdot 1(t) \qquad (6)$$

Where ξ(t) and ξ are different notations and 1(t) shows a step function of Laplace transformation. Solution of eq.(6) is given by eq.(7).

$$\xi(t) = \xi(1 - \cos \omega t) \qquad (7)$$

$$\text{where} \quad \omega = \sqrt{k / m} \qquad (8)$$

Eq.7 shows that the peak stroke of the dynamically driven case reaches two times of the actuator static stroke. Velocity is obtained as shown in eq.(9), by differentiating eq.(7) by t.

$$\ddot{\xi}(t) = \omega\xi \sin(\omega t) \qquad (9)$$

In eq.(9), maximum velocity is given by ωξ. Therefore, maximum kinetic energy E_k which is given to mass m becomes like eq.(10).

$$E_k = \frac{1}{2} m \ddot{\xi}(t)^2 = \frac{1}{2} m \xi^2 \omega^2 = \frac{1}{2} k \xi^2 \qquad (10)$$

In this case, E_k is equal to reserved energy E regardless of mass m value. In dynamically driven case, kinetic energy available in a mass connected to the actuator is equal to the reserved energy of the actuator, regardless of mass m value.

Energy Transfer Efficiency and Amplification Ratio(2)(3)

In the preceding section, it was cleared that the maximum available energy given to load is decided by the “reserved energy” of the actuator both in statically and dynamically driven cases. Therefore, it is natural to define energy transfer efficiency η of the mechanical amplifier by reserved energy ratio of piezoelectric actuator and the mechanical amplifier output. Then we get eq.(11).

$$\eta = \frac{E_s}{E_0} = \frac{k_s \cdot \xi_s^2}{k_0 \cdot \xi_0^2} \qquad (11)$$

Where suffix notation o and s means piezoelectric actuator and the mechanical amplifier, respectively. The amplification ratio n is defined by eq.(12).

$$n = \frac{\xi_s}{\xi_0} \qquad (12)$$

In this definition, both the actuator stroke and the mechanical amplifier stroke are defined under “free” condition.

The ideas of “energy transfer efficiency” and “amplification ratio” came from “operating loss” and “voltage transfer function” of the circuit theory, respectively.

Mechanical Amplifier Configurations(3)

The first trial of the mechanical amplifier was done by simple one-staged lever mechanism shown in Fig.4. The mechanism, however, showed no capability of printing, although it had enough stroke. The necessity to define energy transfer efficiency described in the preceding section arose from this experimental result. By calculating the energy transfer efficiency, it was found that the arm stiffness is not enough. The arm length is decided by the necessary wire stroke. On the other hand, in order to attain high-speed printing, the mass of the arm must be reduced, which limited cross sectional area of the arm. And this made the arm stiffness weak. By the author’s modelling, the energy transfer efficiency of one-staged mechanical amplifier did not exceed 10%.

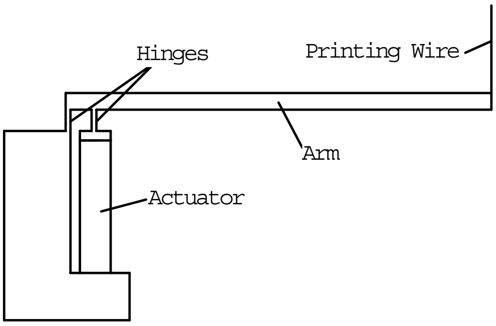

Fig. 4: One-staged mechanical Amplifier

Under the pressure of above inconsistencies, two-staged mechanical amplifier shown in Fig. 5 was developed, in which two levers are connected in tandem. In this case, it was easy to take required amplification ratio by short arm lengths, because the total amplification ratio was decided by the product of 1st and 2nd-stages.

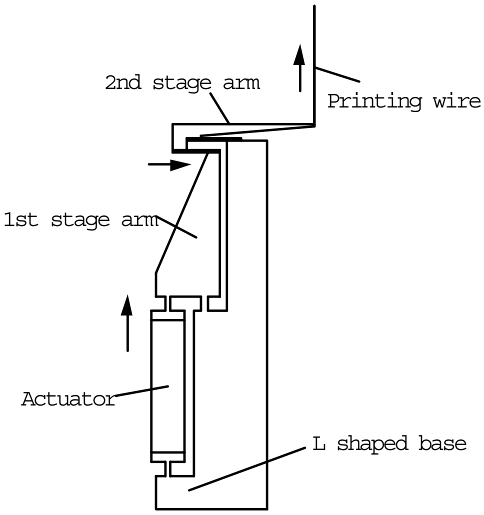

Fig. 5: Two-staged mechanical Amplifier

By using the two-staged mechanical amplifier, weak dot marks were printed on paper. The printing force, however, was not improved in spite of various trials on the lever parameter. Problem of the mechanism was finally found in another place. The L shaped base portion, which supports the piezoelectric actuator, was found to have not enough stiffness. In order to avoid this problem, the base portion must be U shaped, instead of L. By combining two two-staged mechanical amplifiers back-to-back, two-staged differential motion mechanical amplifier shown in Fig.6 was finally developed. The energy transfer efficiency of Fig.5 was 25%, while that of Fig.6 reached 60%.

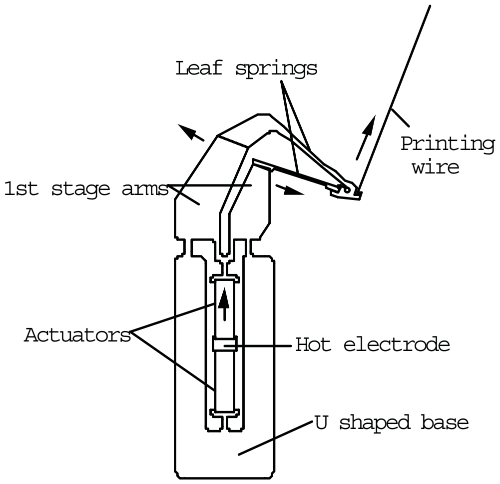

Fig. 6: Two-staged Differential Motion Mechanical Amplifier

Electrical Driver Circuit Employing an Inductor(4)

Basically, electrical driver circuit induces transient phenomena to mechanical resonance system. The printing wire of the impact printer head is required to move and stop intermittently, corresponding to black and white dot printing. The wire movement must be immediately stopped after movement, because the residual movement after a dot printing deteriorates printing quality. If mass and stiffness of a mechanical amplifier are expressed by m and k, resonance frequency F_{rm} is given by eq.(13).

$$F_{rm} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \tag{13}$$

In this case, if we choose pulse voltage with pulse width $t=1/F_{rm}$ for the driving voltage, we can cancel out the transient after one-shot movement, by compensation of transients induced by rise step voltage and fall step voltage. When step voltage is applied to the actuator, however, peak of rush current becomes infinite, if there's no resistance in the driver circuit, because the piezoelectric actuator has parallel capacitance between the electrical terminals. One method to reduce peak current was to use series resistance between the driver circuit and the actuator. By transient analysis, however, it was cleared that even a small resistance seriously affects impact force. Therefore, the author introduced series inductor between the driver circuit and the actuator. By introducing the inductor, the peak current reduced by about 1/20, while, the impact force became even stronger than the one without inductance. Another effect of the inductor was increase of the damping performance, because the capacitive reactance of the actuator was compensated by the inductor. The first impression of test operation after introduction of the inductance was silence in printing. This silence was a result of high frequency component cut off effect of the inductor. The inductance value was so selected that the tuning frequencies of mechanical portion and the electrical portion are equal. Therefore, the suitable inductance value can be calculated by eq.(14).

$$L = \frac{1}{4\pi^2 \cdot C_d \cdot F_{rm}^{\ 2}} \qquad (14)$$

Where C_d is parallel capacitance of the actuator.

Performances of the Developed Printer Head

Performances and used materials of the developed impact printer head are summarized in Table 1.

Table 1 Performances of the Developed Printer Head

Category	Items	Performances
Piezoelectric actuator	Size	1.4Tx3Wx9Lx2pieces
	Layer thickness	115μm
	Numbers of layers	64 layers/piece
	Free stroke	11.1μm/85V/2 pieces
	Capacitance	188nF/piece
Mechanical amplifier base	Material	Precipitation hardening invar
	Thickness	1.4mm
Leaf springs	Material	Martensite aging steel
	Size	0.3Tx1.3-.85Wx8L (Lower one) 0.65-1.2Tx0.3Wx13L (Upper one)
Mechanical amplifier	Wire free Stroke	390μm (Dynamic peak stroke)
Printer head	Numbers of printing wire	24
	Wire diameter	0.2mm
	Operating frequency	3051Hz
	Life guarantee	>1x10^9 dots
Electrical driver circuit	DC pulse voltage	85V
	Inductor inductance	8mH

Conclusion

The printer head was commercialised from NEC in 1988, as an impact printer NM5020. The author doesn't know about the present situation whether the technologies described here are already known or not. But the author will be very happy if some of them are useful for people who are conducting now in piezoelectric actuator applications.

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References

[1] S.Takahashi, A.Ochi, M.Yonezawa, T.Yano, T.Hamatsuki and I.Fukui: "Internal Electrode Piezoelectric Ceramic Actuator", Ferroelectrics, vol.50, pp.181-190, 1983

[2] T.Yano and S.Takahashi: "Utilization of Piezoelectric Stiffened Effects on Impact Printer Heads", Trans.IECE of Japan, vol. J71-C,no.11, pp.1576-1586, Nov.1988(in Japanese)

[3] T.Yano and I.Fukui: "An Amplitude Mangifying Mechanism of Piezoelectric Impact Printer Heads", Report of Technical Group IECE of Japan, EMC87-63, May 1988(in Japanese)

[4] T.Yano, S.Hori and E.Sato: "An Electrical Driving Circuit of Piezoelectric Impact Printer Heads", Report of Technical Group IECE of Japan, EMC88-4, April, 1988(in Japanese)

[5] T.Yano and E.Sato: "Time Domain Simulation of Piezoelectric Impact Printer Heads", Report of Technical Group IECE of Japan, EMC88-58, March, 1989(in Japanese)

[6] T.Yano and S.Komuro: "High-Speed Printer Features Piezolectric Printhead",OEP(published from Dempa Shinbun-sha), may,1987,p.52-53

[7] T.Yano: Doctoral Thesis Tokyo University "Research into an Impact Printer Utilizing Piezoelectric Longitudinal Effect", Nov. 1988