PIEZOELECTRIC IMPACT PRINTER DEVELOPMENT IN THE 1980's

Takeshi Yano EM Precision Technologies Ltd. Shinagawa-ku, Japan

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).

$$k = \frac{F}{\xi} \tag{1}$$

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

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

$$E_{x} = \frac{k \cdot k_{x}^{2}}{2(k + k_{x})^{2}} \xi^{2}$$
(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).

$$k_x = k \tag{4}$$

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



Fig. 2: Statically Driven Case

If we compare eq.(1) and eq.(5), we can see that E_{xmax} 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 $\xi(t)$ after step voltage V is applied to the actuator is expressed by the following differential equation.

$$m\xi(t) + k\xi(t) = k\xi \cdot \mathbf{l}(t) \tag{6}$$

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

$$\xi(t) = \xi(1 - \cos \omega t)$$
(7)
where $\omega = \sqrt{k / m}$ (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.

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

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

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

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 $\operatorname{Ratio}^{(2)(3)}$

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).

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

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

$$n = \frac{\xi_s}{\xi_0} \tag{12}$$

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 The mechanism, however, showed no Fig.4. 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, twostaged 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 1^{st} and 2^{nd} -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 twostaged mechanical amplifiers back-to-back, twostaged 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_m is given by eq.(13).

$$F_{rm} = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$$
(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).

$$L = \frac{1}{4\pi^2 \cdot C_d \cdot F_{rm}^2}$$
(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	Size	1.4Tx3Wx9Lx2pieces	
actuator	Layer	115µm	
	thickness		
	Numbers	64 layers/piece	
	of layers		
	Free stroke	11.1µm/85V/2 pieces	
	Capacitance	188nF/piece	
Mechanical	Material	Precipitation hardening	
amplifier		invar	
base	Thickness	1.4mm	
Leaf springs	Material	Martensite aging steel	
	Size	0.3Tx1.385Wx8L	
		(Lower one)	
		0.65-1.2Tx0.3Wx13L	
		(Upper one)	
Mechanical	Wire free	390µm	
amplifier	Stroke	(Dynamic peak stroke)	
Printer head	Numbers	24	
	of printing		
	wire		
	Wire	0.2mm	
	diameter		
	Operating	3051Hz	
	frequency	0	
	Life	$>1 \times 10^9$ dots	
-	guarantee		
Electrical	DC pulse	85V	
driver circuit	voltage		
	Inductor	8mH	
	inductance		

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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