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Two-lead-wire Drive for Multi-micro Actuators

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Abstract

We have proposed a new concept for an active endoscope with hyper redundancy. This medical tool called "Hyper Endoscope" for minimally invasive surgery is driven by miniature cybernetic actuators. A dynamic model of the cybernetic actuator, taking into account its piezoelectric effect, is proposed and its detailed performance analyzed. Based on the result, a new technique to minimize the number of lead wires is proposed and verified experimentally. FMVC (Frequency Modulation Velocity Control) with two lead wires as an analog control method has been perfected.

1 Introduction

Typical abdominal operations inflict a great deal of physical and mental damage on a patient, so recovery takes a long time. Furthermore, problems with infection cannot be bypassed. This demands attention to children and the elderly, too. On the other hand, demand for minimum or noninvasive surgery is on the increase. In particular, minimum invasive surgery in the abdominal cavity has been developed dramatically.

Fig.1 shows a schematic diagram of laparoscopic surgery today. The abdominal cavity is expanded by air pressure from an air compressor to maintain a certain working space for surgery. Several forceps are inserted from small dissections. The surgeons perform an operation with the visual information obtained by a laparoscope. This new method of clinical surgery enables us to minimize damage to the patient dramatically. However, new types of medical skill and tools are lacking. It is necessary to develop new tools such as surgical robots, an active endoscope and an active catheter.

The authors have already developed a laparoscopic surgical robot, the "Hyper Redundant Active Endoscope (Hyper Endoscope)", as shown in **Fig.2** [1] [2]. The outer diameter of the segment is 10 [mm] and the length is 50 [mm]. Each miniature active universal joint has two degrees of freedom and can be bent by a pair of miniature cybernetic actuators sliding along the segment. Total length of the present prototype is 250 [mm] and it has ten degrees of freedom. But any such mechanism, which is distributed with several micro actuators, increases in the number of lead wires as actuators are increased. This makes not only miniaturization but also any bending motion difficult.

In this paper, a new method for the minimum wire drive of multi micro actuators is proposed and verified.

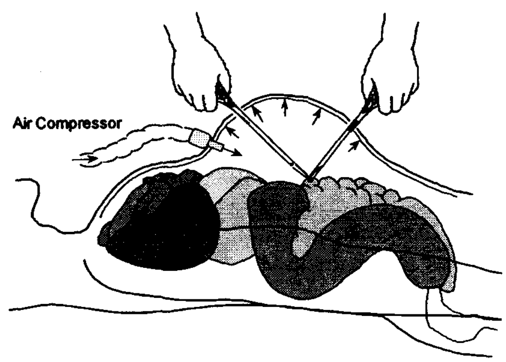

Fig.1 Minimally invasive surgery

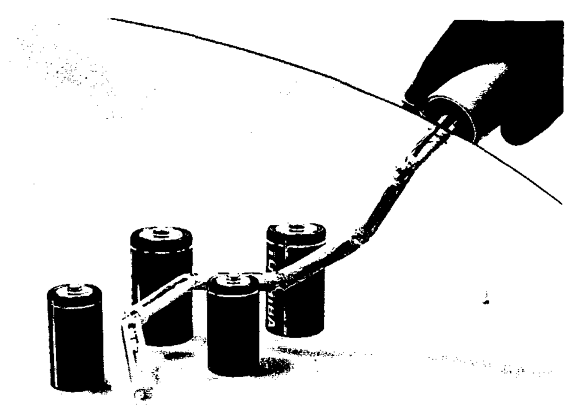

Fig.2 Prototype of Hyper Endoscope

2 Proposal of minimum wire drive by analog control method

It has been considered that both the digital control method and an analog one will be appropriate to the minimum wire drive of a multi-micro actuator system. The digital control method (**Fig.3**) proposed by K.Park, K.Minami and M.Esashi has three lead wires such as power supply line, ground line and control line [3]. This method has the advantage of easily increasing the number of actuators. But many decoder circuits must be put into the equipment, which makes the system weak. This is not always suitable for medical robots which demand reliability.

We propose the "analog control method for two lead wires" as shown in **Fig.4**. Multi-actuators, which have a different proper oscillation, are connected in parallel and controlled separately by tuning the frequency of the driving wave. This produces two-lead-wire drive control without a control line. In this method, there is a limit to a frequency band, so it is difficult to increase the number of actuators relative to the digital method. But with decoder circuits and many components unnecessary, this improves the reliability of the whole system dramatically.

The characteristics of the digital and analog methods are integrated as follows:

<u>Digital method</u>

three lead wires, many actuators, many components, complicated system

<u>Analog method</u>

two lead wires, a limit to the number of actuators, fewer components, simple system

There were some researches for wireless methods that use of analog vibration. One or several parts on the plate can be moved by vibrating a base plate horizontally or vertically (e.g. T.Yasuda et al. [4], D.Reznik et al. [5]). This method cannot help vibrating the whole area which the parts move. The vibration is transmitted by the mechanical contact between plate and parts, so it produces a loss of energy and it is difficult to achieve precise operation of independent part. It is not suitable to drive miniature actuators for medical use.

A new requirement for the analog control method is an actuator which can have speed controlled by frequency modulation. The authors have already designed and developed a safe, small, lightweight and silent actuator called the "Cybernetic Actuator".

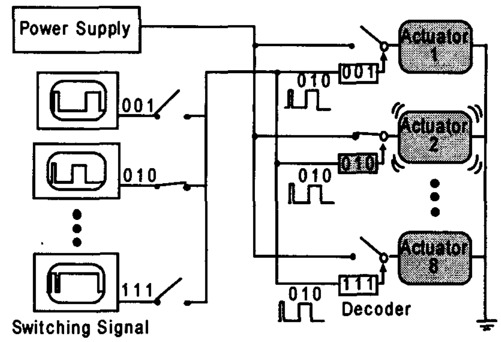

Fig.3 A digital method for reducing the number of wires

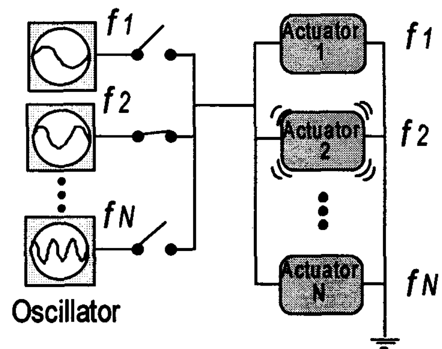

Fig.4 An analog method for reducing the number of wires

The basic concept of the Cybernetic Actuator was proposed by Tomovic and McGee in 1966 [6]. It is based on consideration of the human muscle system. It has four drive states, namely free, decreasing, increasing and locked. **Fig.5** shows the world's first Cybernetic Actuator we designed [7] [8]. Its dimension is 4x4x12[mm] and weight is only 1[g]. The miniature electromagnetic coil produces "clamping force" magnetically to control friction between the actuator and a guide rail made of steel. A miniature piezoelectric element (1x2x5[mm]) is used to produce "high frequency impact" for motion.

The motion characteristic of the actuator is determined by the inertial weight and the proper oscillation, one which is dependent on the field-effect of the piezoelectric element. As a result, the cybernetic actuator is the most suitable for the analog control method in order to realize a minimum wire drive.

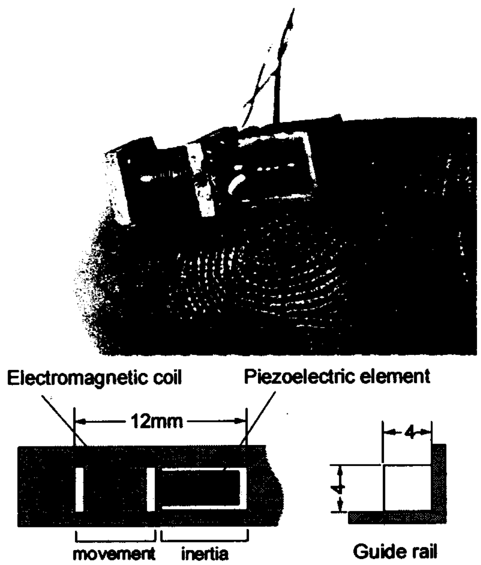

Fig.5 The Cybernetic actuator

So we studied the method of speed control by using frequency modulation. First, we tried to investigate the movement characteristic theoretically.

3 Characteristic analysis at high frequency

3.1 Proposal of a dynamic model

A piezoelectric impact drive such as that of a cybernetic actuator used to be analyzed by a "static model" with the law of conservation of momentum [9]. This model is used for positional adjustment equipment which has a weight from 200[g] to 1000[g] with a low-frequency impact drive, so it can deal only with heavy actuators. Our cybernetic actuator is small and lightweight, so it is difficult to resolve its detailed performance in a high-frequency band by using the static model.

We proposed a linear approximate dynamic model of the cybernetic actuator shown as **Fig.6**. This model consists of three components, namely movement, piezoelectric element and inertia. The parts in movement and inertia are deemed a material particles. The piezoelectric element is deemed an aspect of viscoelasticity. Frictional force is always produced against the direction of the moving part.

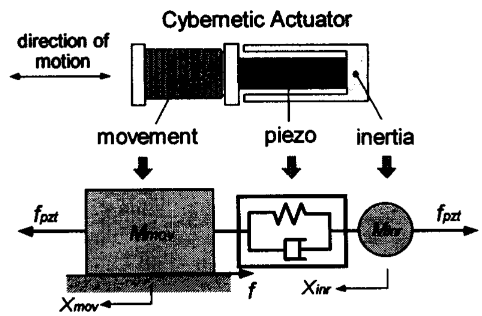

Fig.6 Dynamic model of cybernetic actuator

3.2 Introduction of piezoelectric effect

The merit of this model is that it takes into account the piezoelectric effect for detailed analysis. A piezoelectric effect means the phenomenon in which a dielectric polarization causes stress or strain by inputting voltage. This phenomenon can be expressed as a piezoelectric equation, eq.(1).

$$\epsilon_i = s_{ij}{}^E \sigma_j + d_{mi} E_m \tag{1}$$

ϵ_i : *strain*
E_m : *Electric field intensity* $[V/m]$
σ_j : *Stress* $[N/m^2]$
$s_{ij}{}^E$: *Inverse of Young modulus* $[m^2/N]$
d_{mi} : *Piezoelectric modulus* $[m/V]$

The attached symbols in eq.(1) are used for the expression of the multi-dimensional tensor with the piezoelectric phenomenon. The upper attached symbol is a parameter kept constant during the phase transition and the lower attached symbol is a piezoelectric axis of cause and result. Each axis of i, j, m(i, j=1,2,$\cdots$,6; m=1,2,3) shows the direction of strain, stress and the electrode surface. It takes into account the piezoelectric effect in the producible force of the piezoelectric element (f_{pzt} in Fig.6) .

This actuator uses a piezoelectric element that is layered only toward the direction of motion, so it produces the mode of a vertical vibration. As a result, it can be replaced eq.(1) with a simple equation, and the upper and lower attached symbols can be omitted. This equation also expresses a piezoelectric response against a force impinging from outside. In this paper, in order to deal with an inner force, the sign of the first member of a right side equation is used. From the above premises, eq.(1) simplified is shown as eq. (2).

$$\epsilon = -s\sigma + dE \quad (2)$$

Consequently, a producible stress by the piezoelectric effect is shown as follows.

$$\sigma = \frac{dE - \epsilon}{s} \quad (3)$$

A piezoelectric element has a high response (response speed: 0.1[msec]), so it is possible to consider that the target stress is produced at $\epsilon = 0$, with electric field intensity when $E = V/L$ (input voltage is V, distance between electrode plates is L). When the cross section of a piezoelectric element is A, the producible force of both of its edges is calculated as eq.(4) from eq.(3).

$$f_{pzt} = A\sigma = \frac{AdV/L}{s} \quad (4)$$

The motion equations of the inertial and moving parts can be expressed as eq.(5)(6). We can verify the dynamic performance of an actuator by solving these simultaneous equations.

$$M_{inr}\ddot{x}_{inr} + C(\dot{x}_{inr} - \dot{x}_{mov}) + K(x_{inr} - x_{mov}) = -f_{pzt} \quad (5)$$

$$M_{mov}\ddot{x}_{mov} + C(\dot{x}_{mov} - \dot{x}_{inr}) + K(x_{mov} - x_{inr}) = f_{pzt} - sgn(\dot{x}_{mov})f \quad (6)$$

$$sgn(x) = \begin{cases} +1 : x \geq 0 \\ -1 : x < 0 \end{cases} \quad (7)$$

x_k : **Displacement** f_{pzt} : **Force(piezo)**
C : **Coefficient of viscosity** M_k : **Mass**
K : **Modulus of elasticity** f : **Friction**
($k = inr, mov$)

Table 1 Parameters of actuator

Young's modulus[N/m²]	$1/s$	27×10^9
Mass(movement)[g]	M_{mov}	0.503
Mass(inertia)[g]	M_{inr}	0.353
Modulus of elasticity[N/m]	K	10.8×10^6
Cross section[mm²]	A	2.0
Piezoelectric modulus[m/V]	d	66.7×10^{-9}
Piezo length[mm]	L	5.0
Friction[N]	f	1.2

3.3 Simulation result of a dynamic model

This simulation has solved the discrete eq.(5)(6). The viscosity is small, so it can be neglected. **Fig.7** shows the wave pattern input to the piezoelectric element and electromagnetic coil. In the voltage wave, the hysteresis of piezoelectric element has not been taken into account because the input electric field intensity is not high. Simulation parameters are shown in **Table 1**. The value of friction was measured by a load cell (KYOWA Electronic Instruments Co. LTD., LVS-1kA). It was used Young's and piezoelectric modulus provided from the manufacturer.

The simulation results of the displacement in which driving frequency is 20[kHz] are shown in **Fig.8**(4 cycles) and **Fig.9**(10 cycles). The results obtained show that high-frequency vibration increases inside the actuator by inputting the driving waves. It shows that the actuator oscillates at a high frequency and moves at a constant speed. As a result, it is clear that the cybernetic actuator is driven by mixing low vibration with the input wave pattern.

3.4 Comparison between measured values and simulation results

We verified the dynamic model by experimentation using the cybernetic actuator(**Fig.5**). The experimental equipment is shown in **Fig.10**. Driving wave patterns produced by a function generator (YOKOGAWA, AG2100A) were inputted and amplified by a voltage amplifier (NF ElECTRONIC INSTRUMENT, 4010) or a current amplifier (TAKASAGO LTD., BPS120-5). These waves were inputted to the piezoelectric element (NEC, size: $1 \times 2 \times 5$[mm]) and electromagnetic coil (ϕ 0.15, 30 turns). Measurements

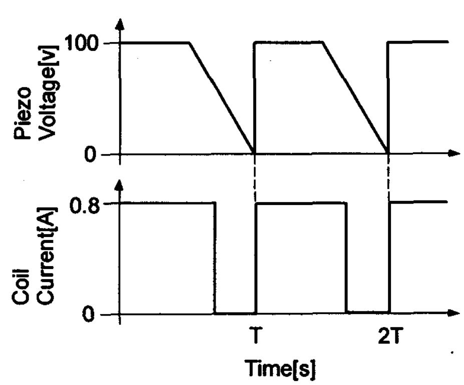

Fig.7 Input voltage and current pattern

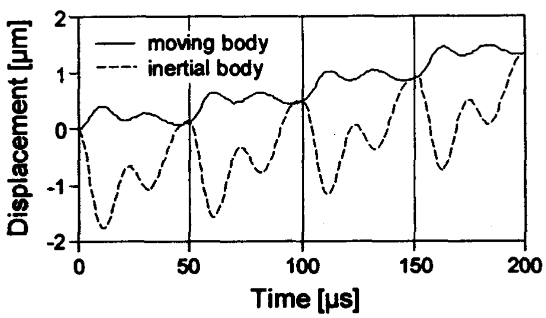

Fig.8 Result of simulation (4 cycles)

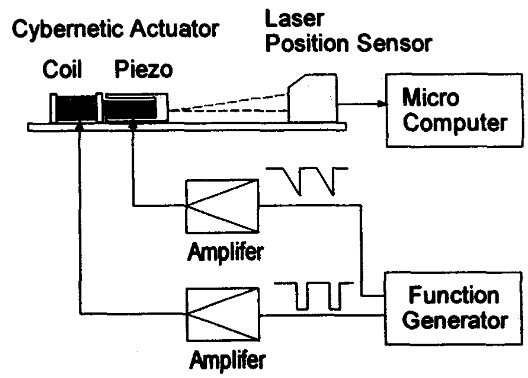

Fig.10 Experimental systems of driving cybernetic actuator

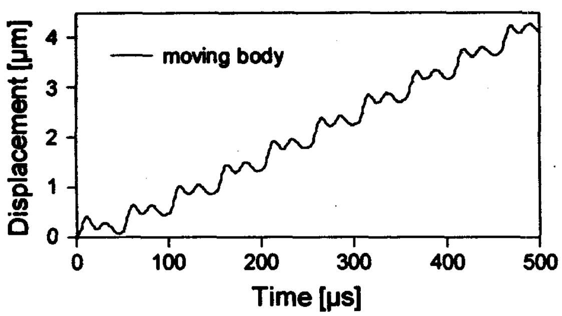

Fig.9 Result of simulation (movement part,10 cycles)

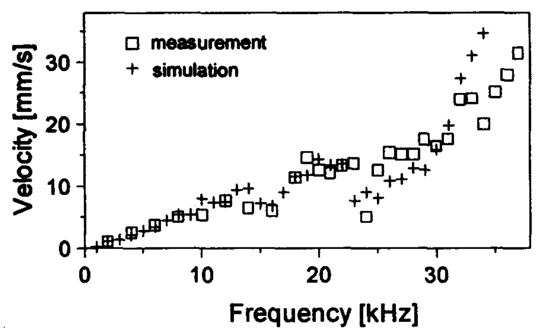

Fig.11 Comparison between measurement and simulation of moving part

of the actuator's displacement were made using a laser sensor(KEYENCE,LB − 02, LB − 62). The same equipment was used for the following experimentation. **Fig.11** shows the comparison between the experimental values and the simulation results of actuator speed against various frequencies when the same wave is inputted. There is a little disagreement between each of the speed values. It is considered that the effect of the frequency dependence appeared to be sensitive because the cybernetic actuator is driven by mixing the input wave pattern with low vibration caused by the proper oscillation of the actuator, friction of the rail, and so on. This is clear from the behavior of the moving and inertial parts. In a low-frequency range from 0 to 10[kHz], the simulation results of the dynamic model agree quite well with the experimental values of the static model. In the upper-frequency range, we can see the same tendency of speed as in the simulation results, so the validity of this model was verified. It will be useful for design and control of a cybernetic actuator.

From these results, our dynamic model made it clear that the performance of the actuator in motion is driven by piezoelectric impact in a wide-frequency band.

4 Frequency Modulation Velocity Control (FMVC)

4.1 Proposal for FMVC

The authors propose a new technique in order to minimize the number of lead wires for multi-micro actuators called the "Frequency Modulation Velocity Control (FMVC) ", which makes full use of frequency dependence on speed. The following experiment was conducted to verify the feasibility of this control method.

First, we tried to direct the inputting wave pattern to control not only speed but also the moving direction of the actuator by FMVC. **Fig.12**(broken line), which is a symmetrical wave used against **Fig.7**, was chosen as a driving wave. The magnetic clamp at 0.8[A] is kept in place in order to supply constant friction between the rail and actuator.

Fig.13 shows the relationship between the speed and driving frequency. Although other waves such as square, triangle and so on were examined, the authors selected the trapezoid wave (broken line in **Fig.12**) for the following reasons: (1)This wave produces high-impact force; (2)there is little rapid change and less load on the piezoelectric element; and (3)the self-vibration of the actuator is retained on part of the flat voltage wave. We consider this wave to be the most suitable one for FMVC.

4.2 Results of experiment for FMVC

The experiments were made by inputting the driving wave (broken line in **Fig.12**) to the cybernetic actuator. The actuator weight was 0.422[g](including the mass of the piezoelectric element). The same parameters as those in **Table 1** were used, too.

The measured speed values of the cybernetic actuator were shown on the simulation results of **Fig.13**. As a result, it was verified that speed could be controlled by tuning the driving frequency. In particular, it is possible to control the speed linearly in a frequency band from 6 to 10[kHz]. In addition, the negative speed, namely reverse motion, was confirmed at around 16[kHz]. The conventional method of changing the motion direction requires two types of driving waves for forward and reverse. It was ensured that the motion direction could be changed by FMVC, with the validity of the proposal method verified experimentally.

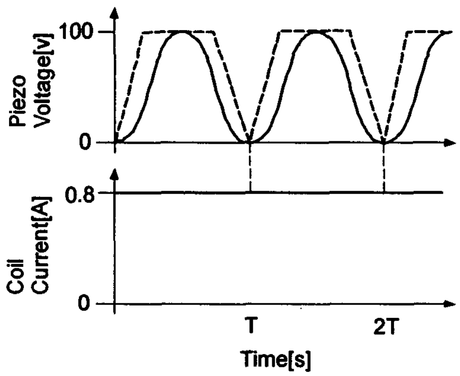

Fig.12 Input voltage and current pattern for FMVC

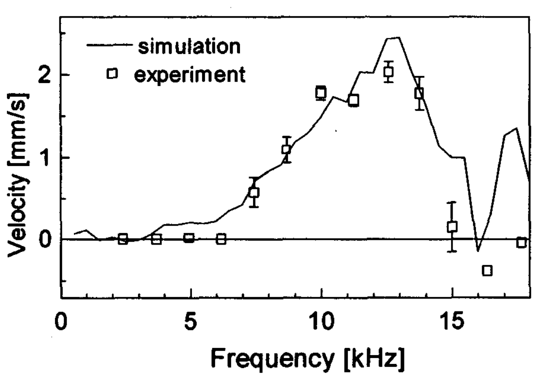

Fig.13 Comparison of simulation and experiment for frequency dependence of velocity

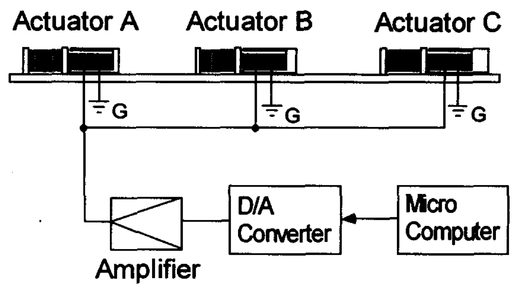

Fig.14 Experimental system of two-wire drive of multi-actuators

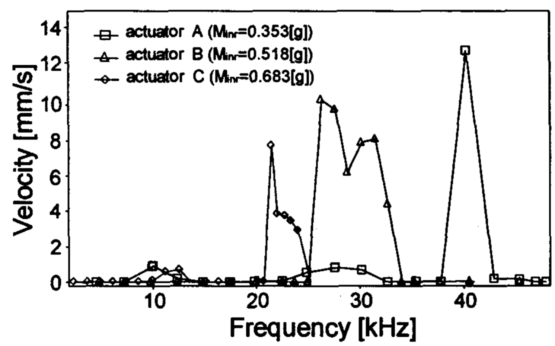

Fig.15 Experiment on minimum wire drive of multi-micro actuators(Analog method, moving part)

As a result, it was confirmed that the trapezoid wave pattern was a suitable wave for precisely controlling the speed of one cybernetic actuator. But when multi-actuators are driven on only two wires, there is a slight tendency that the high-frequency aspect, which is produced by the folding part of the trapezoid wave, will affect other actuators on the same wires.

So we chose a sine wave as shown in **Fig.12** (solid line) for the FMVC of multi-actuators, because there is no high-frequency aspect and the voltage power as the same as the trapezoid wave in the sine wave. Impact force is a little smaller, but the speed of the attracting inertial part is almost the same, so the same producible force can be expected.

5 Experiment on minimizing lead wires

In this section, we describe the experiment of minimizing lead wires for multi-actuators using a sine wave **Fig.12** (solid line) as a driving wave. Three cybernetic actuators with masses of were 0.353[g], 0.518[g], 0.683[g] (named actuators A,B,C), were wired in parallel as shown in **Fig.14**. When driving waves with frequencies from 0 to 50[kHz] were inputted, speed of the moving part was measured.

The experimental values of the actuator's speed are shown in **Fig.15**. The results revealed the appearance of each speed peak in the frequency band of 38$\sim$42[kHz](actuator A, mass: 0.353[g]), 25$\sim$35[kHz] (actuator B, mass: 0.518 [g]) and 20$\sim$25[kHz] (actuator C, mass: 0.683[g]). We were able to divide the band of the driving frequency. As a result, success has been attained in driving multi-actuators individually with only two wires.

Accordingly, it was verified that the minimum wire drive of multi-actuators could be realized by the analog control method using "FMVC". The optimum driving wave and precise control of speed are undergoing study now.

6 Conclusion

A new technique to minimize the number of lead wires for medical micro robots such as the "Hyper Endoscope" for minimally invasive surgery was proposed. A dynamic model of a cybernetic actuator, taking into account the piezoelectric effect was proposed, and detailed performance was analyzed. Frequency Modulation Velocity Control(FMVC) with two lead wires as an analog control method was invented and verified experimentally.

These results indicate the availability of FMVC not only for medical micro robots such as the Hyper Endoscope but also various other micro machines driven by actuators that use of vibration or resonance.

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