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Development of an Active Flexible Cable by Ciliary Vibration Drive for Scope Camera

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***Abstract*— Proposed new actuation mechanism realizes active or semi-active mobility for flexible long cables such as fiberscopes and scope cameras. A ciliary vibration mechanism was developed using flexible ciliary tapes that can be attached easily to existing cables. Driving characteristics of the active cables were confirmed through experiments and numerical analyses. Finally, the actuation mechanism was applied for an advanced scope camera that can reduce friction with obstacles and avoid stuck or tangled cables.**

I. Introduction

Proposed new actuation mechanism realizes active or semi-active mobility for flexible long cables. Research to examine adding an actuation mechanism to a flexible cable is demanded. One example is addition of a scope camera that is used for seeking disaster victims. When the scope camera is inserted into narrow and circuitous spaces, it is difficult to insert it by pushing it from behind because of its flexibility. In such a case, by getting active mobility, it is expected that the scope camera itself can help humans insert it into a narrow space without sacrificing its advantageous flexibility. In other non-rescue cases, a cable having active mobility does not limit a mobile robot's capability. Such a mechanism would be useful as a main driving mechanism for robots such as a pipe-crawling or pipe-inspection robot.

Dynamics of flexible objects have been studied using strings[1] and flexible manipulators[2]. Flexible objects are modeled using rigid body links and joints that have driving forces. In the study of snake-like robot using self-excited vibration[3], the driving forces are generated only at the joints. Ciliary vibration mechanisms[4][5] were focused and examined , for the following two advantages: 1) those having distributional driving force; 2) those that are attachable easily to existing cables.

The method of getting a driving force by vibrating cilia is used in a parts feeder that can convey small parts on vibrated cilia. A linear actuator[6] has been proposed that applies that mechanism using two pairs of cilia arrays and vibrators. In addition, microrobots have been developed. A micro-mobile robot[7] is driven by differences of frictional force between forward and backward motion. A mobile micro-robot[8] uses centrifugal force by a vibration motor that is located on the robot with angled cilia. Our study develops and controls flexible long cables using a ciliary vibration mechanism and analyses of this driving mechanism.

This paper describes an outline of the mechanism of the active flexible cable that uses the applied ciliary vibration mechanism. The proposed ciliary tapes are described as a method of attaching the ciliary vibration mechanism to flexible cables. Basic characteristics of ciliary vibration are examined in the next section. Modeling and numerical analyses results are described next. Finally, an actuation mechanism was applied for the scope camera; it can reduce friction with obstacles and avoid stuck cables. The estimated ability of the scope camera is shown.

II. Principles of ciliary vibration mechanism

Trial models of active cables with ciliary vibration mechanisms were produced and its mobility mechanism was estimated. The ciliary vibration mechanism has plastic or metal thin wires called cilia and achieve driving power through cilia vibration[8]. As the cilia are angled and planted, by adding vibration to the cables, bending and rapid recovery occurs at the front edge of the cilia, which touch the running surface. Using energy stored by bending the cilia, the body can move very short lengths as the cilia recover their original shape. Repeating this bending and recovery motion very rapidly, a

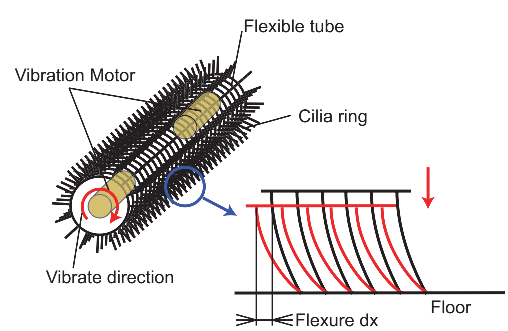

Fig. 1. Model of vibration type ciliary motion mechanism

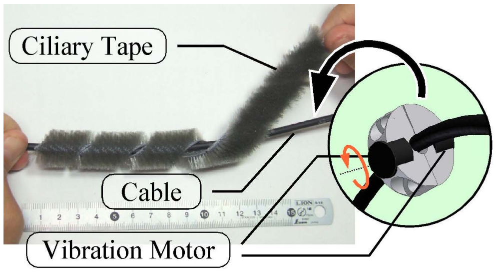

Fig. 2. Ciliary tape and motor location

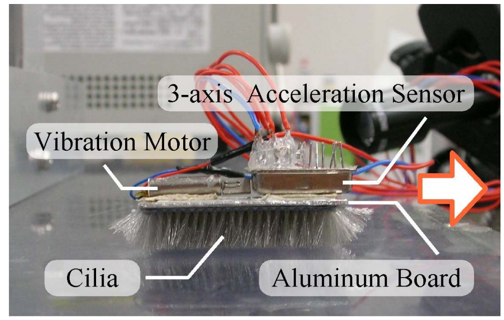

Fig. 3. Location of the parts on the testpiece

body can move forward through a falling-down and standing-up motion. Changing the angle of planted cilia can control the object's velocity and climbing ability.

This ciliary vibration mechanism was applied to cables and proposed an active scope camera [4][5]. The active scope camera body is covered with cilia all around (Fig. 1). Therefore, it is expected to have the following characteristics:

- it has distributive mobility throughout its body;
- it can generate driving forces in all directions around its body;
- it enables attachment to flexible cables;
- it is effective in avoiding cable sticking or tangling;
- it is a comparatively simple mechanism.

Developed prototypes showed highly mobile performance a particular vibration frequencies. It can escape from stuck conditions through a pulse motion. In addition, it can climb over steps, move into narrow spaces and climb approximately 10-degree slopes. However, prototypes were not practical because of their weight and size. In addition, attaching the ciliary vibration mechanism to existing cables degraded the cables' flexibility.

III. Proposal of Easy Attachment Structure of Ciliary Vibration Mechanism

A. *Structure of easy attachment with ciliary tape*

The method of adding a ciliary vibration mechanism was a problem in the prototypes. To add this ciliary vibration mechanism to existing cables, the mechanism must be readily attachable to various cables.

For that reason, flexible ciliary tape was developed. Wrapping such tape around the cables, the mechanism can be attached and adjusted easily over its length. Vibration motors are located at short discontinuities of cilia. The vibration motors that are used conventionally in mobile telephones are useful because they can provide a strong vibration force (1–2 G) without sacrificing flexibility of cables for their size.

Plastic cilia were confirmed through repeated tests to be suitable for attachment of a scope camera because of the cilia's few variations and smooth mobility of the scope camera. Repeated experiments used prototypes with several types of cilia, such as metal (brass, 0.15 mm diameter, 13 mm length) and plastic (0.01 mm diameter, 10 mm length) cilia[5]. Based on that knowledge, the cilia that are shown in Fig. 2 are chosen to use. This cilia tape is commercially available (Tsuchiya TSCO Co., Ltd.) produced by Tsuchiya TSCO Co., Ltd. Its surface is covered with cilia (nylon, 0.01 mm diameter, 7–10 mm length, 2500 cilia /cm^2). The cilia can be angled freely through application of heat because nylon's softening temperature is 70 °C. In addition, its flexibility does not degrade the body's flexibility.

TABLE I

Testpiece specifications

Length [mm]	38.8
Width [mm]	19.7
Height [mm]	15.1
Mass [g]	11.16/15.58
Cilia Height [mm]	7.2
Cilia Tape Length [mm]	37.0
Cilia Tape Width [mm]	13.0
Cilia's Angle [degree]	82.2

B. *Evaluation experiments*

When thinking about flexible cable with cilia, it is important to know the basic characteristics of cilia with regard to vibration. Therefore, the characteristics are confirmed through experiments. Cilia are attached in a plane to testpieces in experiments because all motor vibrations can be transmitted equally to all cilia.

Testpieces used in these experiments are shown in Fig. 3; testpiece characteristics are shown in Table I. A vibration motor (8 mm diameter, 19 mm length, 1.35 g mass, 1 G vibration force) and a three-axis acceleration sensor are located on an aluminum plate and cilia tape (0.01 mm diameter, 7 mm length) is attached under the plate. The rotation axis of the vibration motor is parallel to the direction of movement. Therefore, the motor generates motion that actuates the body up and down. Because the cilia are angled, the body can move forward through vibration up and down.

Two type testpieces having different weights are used in experiments. The vibration motor is vibrated at frequencies of 40–150 Hz by changing the input power voltage. Frequencies of the vibration motor are measured using the acceleration sensor on the body. The running surface is a flat acrylic board. Images of the moving testpieces are recorded using a high-speed video camera. The velocity and behavior of the body

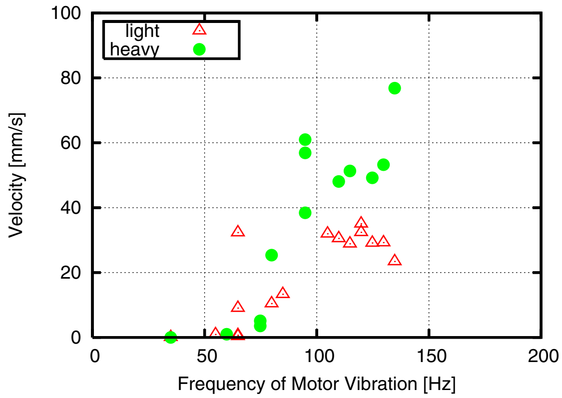

Fig. 4. Experimental result of the velocity-changing frequency

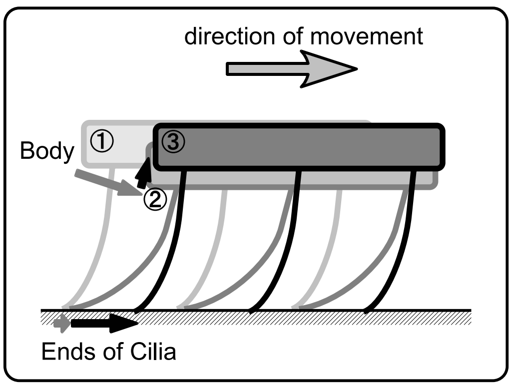

Fig. 5. Estimation of the actuation mechanism

are measured from that recorded series of images when the testpiece runs stably.

C. Relation between frequency and body velocity

The relation between frequency and body velocity is shown in Fig. 4. That illustration shows that as the frequency increases, the velocity increases overall. However, in that case, the velocity cannot increase when the frequency is greater than about 100 Hz. As the frequency increases, the centrifugal force in inferred to increase in relation to the body's weight and the body's motion becomes unbalanced. Therefore, the velocity of the heavy testpiece increases as the frequency increases without becoming unbalanced. Consequently, the heavy testpiece can move more rapidly than a light one at high frequencies. At low frequency, testpieces almost stop because of their mass. It is considered that the static friction considerably affects the body.

D. Observations of body and cilia

The actuation mechanism can be estimated from video images captured using high-speed video camera. For falling-down motion, the front edge of a cilium stops on the surface; consequently, the body can move forward. Using a standing-up motion, the front edge of a cilium slips forward on the surface. Consequently, the body can hold its position without

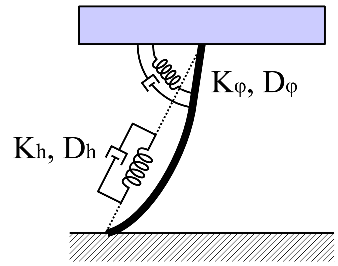

Fig. 6. Linear model of cilia

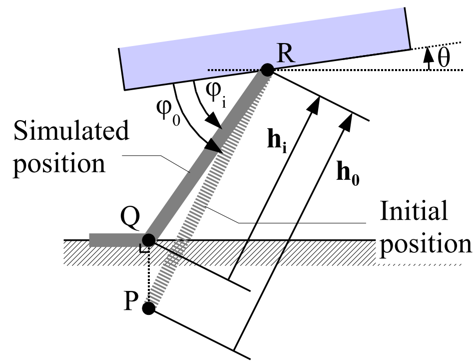

Fig. 7. Calculate contact force

moving backward. By repeating this motion, a body moves forward through the use of vertical vibration (Fig. 5). It is considered that the strain energy is stored by bending cilia in a falling-down motion and that the body can move forward by using that energy in a standing-up motion.

In addition, through observations obtained by changing the motor's revolution speed, it is apparent that the body has some vibrations aside from those for the motor's vibration. It is confirmed that various patterns of body vibration exist. The reason is considered to be the resonance of the body and the cilia's stick-slip behavior at the contact face.

IV. Numerical Analysis

A. Modeling

For analysis of the actuation mechanism, experiments and numerical analyses with modeling are needed. As a model of cilia vibration mechanism, Ioi's model[8] was adopted with some modifications[9]. In this model, numerous cilia are treated as one linear spring and one rotational spring as a whole. The cilia model is shown in Fig. 6. Important variables are: K_h, the spring constant; D_h, the damping constant of a linear spring; K_ϕ, the spring constant; and D_ϕ, the damping constant of a rotational spring.

The force affected by the surface is calculated as follows. $\boldsymbol{h}_0$ and ϕ_0 in Fig. 7 are initial vectors from a front edge to a root and an initial angle of the i th cilium. The current cilium state $\boldsymbol{h}_i, \phi_i$ is always calculated compared with the initial cilium state. Point P is a front edge of the cilium under the surface; point Q is a foot of a perpendicular from point P to the surface considering the point as a contact point of

TABLE II

SIMULATION PARAMETERS

Length [mm]	38.8
Width [mm]	19.7
Height [mm]	15.1
Mass [g]	11.16/15.58
Inertia [gmm^2]	1090/1150
Virtual Number of cilia	15
K_h [N/mm]	3.080
K_ϕ [Nmm/rad]	4.132
D_h [Ns/m]	1.2 $\times 10^{-2}$
D_ϕ [Nms/rad]	1.4 $\times 10^{-5}$
Friction coefficient	0.010

the cilium's front edge and the surface. From point Q and the cilium's root point R, a current vector $\boldsymbol{h}_i$ from the front edge to the root of the cilium and a current angle ϕ_i of the cilium. Using the calculated $\boldsymbol{h}_i$ and ϕ_i, a linear viscoelastic force F_{Ki} and a rotational viscoelastic force N_{Ki} of the i th cilium are calculated as follows.

$$F_{Ki} = K_h(|\boldsymbol{h}_0| - |\boldsymbol{h}_i|) - D_h|\dot{\boldsymbol{h}}_i| \quad (1)$$
$$N_{Ki} = K_\phi(\phi_0 - \phi) - D_\phi\dot{\phi} \quad (2)$$

It is considered that the cilia's weight is negligible compared to the body's weight. For that reason, the force $\boldsymbol{f}_i$ is equal to a force acting on the body affected by the cilia. This $\boldsymbol{f}_i$ is calculated for each cilium, thereby producing a dynamic equation that includes centrifugal force by the vibration motor. This dynamic equation is solved through numeric calculation.

In addition, for f_{xi} and f_{yi}, which are the x component and y component of the $\boldsymbol{f}_i$, it was considered that f_{xi}, which is the x component of the force acting on cilia affected by the surface, cannot exceed a dynamic friction force f_{ci}. Therefore, the following condition expression is considered.

$$f_{xi} = min(f_{ci},\ f_{xi}) \quad (3)$$

B. Parameters for numerical analyses

The behavior of testpieces that were used in experiments was simulated. In addition, to confirm the characteristics shown in experiments, we compared experimental results using calculated results. The simulation parameters are shown in Table II. The actual cilia are planted 2500 /cm^2 on the ciliary tape, but we treat cilia planted in 2 mm $\times$ 2 mm area as one virtual cilium. Therefore, the testpieces are considered to have 15 virtual cilia in the driving direction. The two spring constants were measured through experimentation. From the relation between displacement and buckling force, the linear spring constant was calculated. From the relation between the root angle and pushing force, a rotational spring constant was calculated. Damping constants are given appropriate values that force convergence of the simulation. The coefficient of friction was measured through experiments; the apparent coefficient of friction was calculated and used.

C. Calculated results and discussion

The relation between the frequency and velocity of the body is shown in Fig. 8, which is examined in two different weights

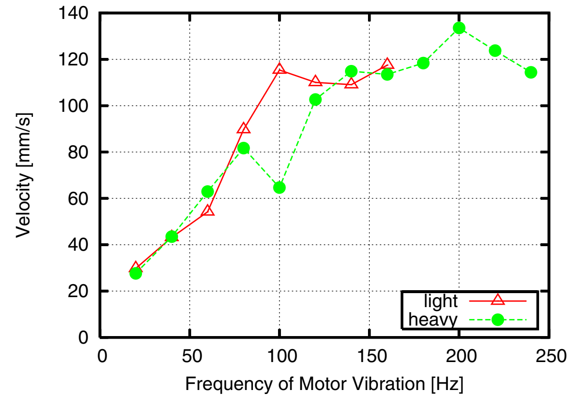

Fig. 8. Simulated result of the velocity changing frequency

of testpieces, as in the case of the experiments. The velocities of testpieces in Fig. 8 were measured at a steady state.

Comparison of experimental results with calculated results revealed characteristics qualitatively as follows.

- A light testpiece moves more rapidly than a heavy one in the low-frequency area (80–120 Hz).
- The velocity cannot be increased beyond a certain point for these frequencies.
- The front edge of the cilia repeatedly stops and slips on the surface.

Because of variations in velocity resulting from the body's uncertain condition, the velocity of the body cannot converge. For that reason, the light testpiece shows no results in the high-frequency area. In addition, the velocity of the body in the low-frequency area is higher than shown in the experimental results because static friction was not incorporated in this model. However, effective results were obtained regarding the behavior of increasing velocity; as the frequency increased, the velocity saturated.

V. APPLICATION FOR AN INDUSTRIAL SCOPE CAMERA

A. Active scope camera

A prototype of an active scope camera was produced (Fig. 9). This ciliary vibration mechanism was attached to a general

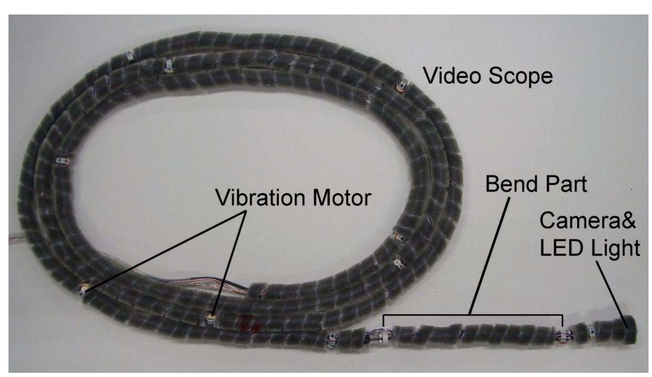

Fig. 9. Prototype of the active scope camera

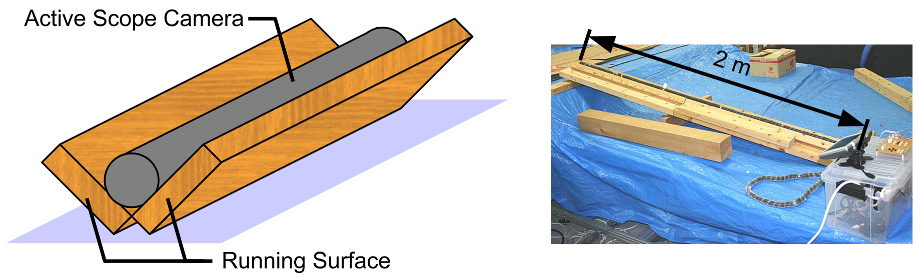

Fig. 10. Experiment equipment

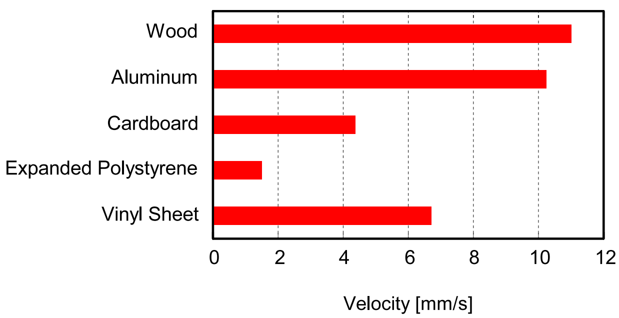

Fig. 11. Experimental results of velocity change: running on floor material

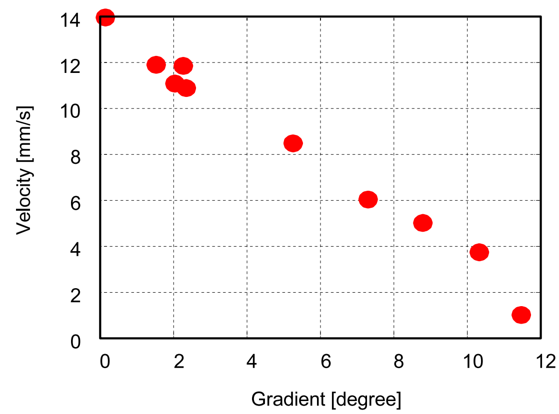

Fig. 12. Experimental results of velocity change: angled slope

industrial scope camera. The dimensions of the active scope camera are 30 mm diameter and 5 m in length. It has 18 vibration motors (8 mm diameter, 5.1 mm thickness, 1.25 g weight, 2 G vibration force, FMIU-004; Fujikura Shoji Co. Ltd.), which are located in pairs at ca. 40 cm intervals (Fig. 2). The attached cilia (0.01 mm diameter, 10 mm length, made from nylon) are angled at about 80 degrees from the camera center.

The active scope camera has four memory metals (TOKI Corp. BMF) at the head; its head can be bent by about 40 degrees in four directions. Bright LED lights are located beside the camera.

B. Performance evaluation

First, the basic mobile performance was estimated. The active scope camera was set as in Fig. 10. The active scope camera was located between V-formation surface with length of 2 m. The active scope camera was driven in this situation. Two experiments were made: 1) changing the running surface, and 2) changing the angle of inclination. Results of experiments are shown in Fig. 11 and Fig. 12. The active scope camera achieves high performance on a wood surface. Because wood is plentiful in rubble spaces in which scope cameras are used, this result can illustrate the effectiveness of this active scope camera. In addition, this scope camera was believed to be incapable of driving on expanded polystyrene because of its softness and asperity, but it was able to run on expanded polystyrene at a low speed. The maximum gradability was 11.5 degrees; it showed higher climbing ability than previous prototypes (about 5 degrees)[4][5].

Next, to estimate the ability of escaping from a stuck situation, friction forces were measured by pulling the cable in the supposed stuck situation and located three obstacles. In Fig. 13 set d=ϕ 5 cm and a=40 cm, static friction forces and dynamic friction forces were measured while changing distance b from 0 to 35 cm at 5 cm intervals. Static friction forces were forces at which the body began to move; dynamic friction forces required the force of tension to pull at a constant velocity of 3.3 cm /s.

Static friction forces and dynamic friction forces are shown in Fig. 14 and Fig. 15 changing length b. In the case of adding vibration compared to using a cable alone, the static

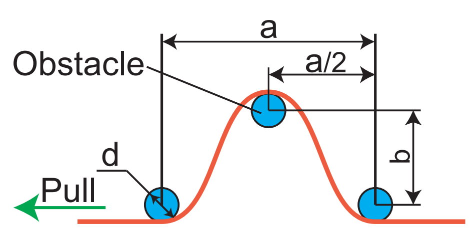

Fig. 13. Measurement of the pull friction. The active scope cable is set along the obstacles and pulled.

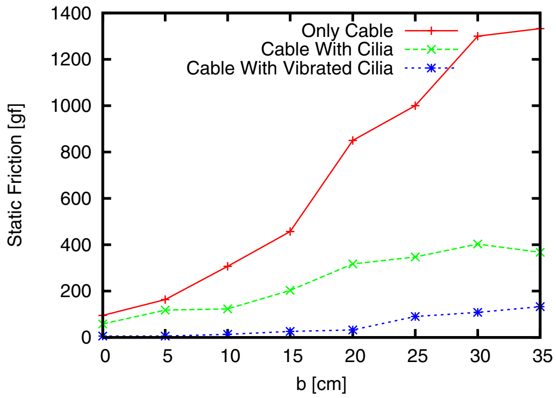

Fig. 14. Results of static friction experiments

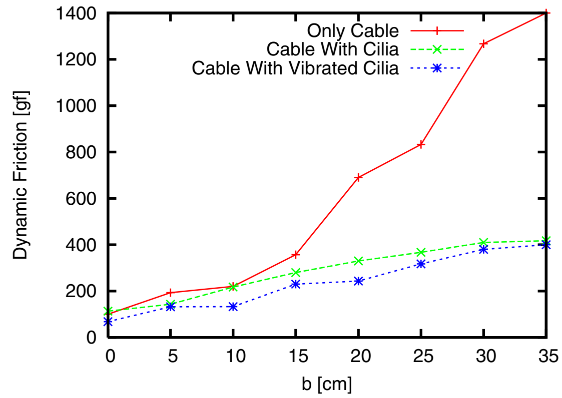

Fig. 15. Results of dynamic friction experiments

and dynamic forces are reduced greatly in spite of an enlarged diameter. Especially regarding static friction forces, forces are reduced in the case of adding vibrations compared with no vibration. From this tendency, it is considered that application of this mechanism is available because the scope camera repeats stopping and motion.

Merely attaching cilia without vibration reduces the cable friction greatly because the contact between the scope camera and surface becomes a point contact as a result of the cilia; furthermore, repulsive forces are generated by the bending of the cilia. The stick-slip behavior occurred only with a cable, but the attached cilia reduced this behavior.

VI. Conclusion

This paper described a new actuation mechanism that uses a ciliary vibration mechanism with proposed ciliary tape. Basic characteristics of the ciliary vibration mechanism were confirmed through experiments and numerical analyses. This actuation mechanism was applied for an advanced scope camera and its performance was examined.

Regarding cilia characteristics, experiments confirmed the relation between frequency and velocity of the body and allowed observation of the body's various vibrations. Results demonstrate that certain frequencies were able to drive the body effectively. Numerical analyses and calculated results show similar characteristics qualitatively, thereby confirming that differences in weight affected the testpiece behavior with the cilia vibration mechanism. Furthermore, the developed advanced scope camera had insufficient mobility in narrow rubble spaces, but friction forces were greatly reduced by attaching the ciliary vibration mechanism. For that purpose, attaching this mechanism was effective.

Acknowledgments

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References

[1] M. Hashimoto, T. Ichikawa, S. Inui, and Y. Horiba, "Dynamic Manipulation of a String using a Manipulator – Parameter identification and control based on a rigid body link model –," *Proceedings of the 2004 IEEE International Conference on Robotics & Automation*, pp.4815-4820, 2004-4.

[2] T. Yoshikawa and M. Tamura, "Study on Effectiveness of Virtual Joint Model for Flexible Manipulators," *Journal of the Robotics Society of Japan*, vol.17, no.2, pp.250-259, 1999.

[3] J. Ute, M. Nakashima, and K. Ono, "A Study on Locomotive Mechanism of Snake-Like Robot Utilizing Self-Excited Vibration," *Transactions of the Japan Society of Mechanical Engineers*, vol.68 no.668, pp. 1096-1103, 2002.

[4] A. Niitsuma, F. Takemura, and S. Tadokoro, "Development of the Vibrated Drive Type Cilia Locomotion Mechanism for Fiberscopes," *2005 JSME Conference on Robotics and Mechatronics*, 2A1-S-073, 2005.

[5] A. Niitsuma, F. Takemura, K. Isaki, M. Konyo, and S. Tadokoro, "Development of the Vibrated Drive Type Cilia Motion Mechanism for Fiberscope," *The 23rd Annual Conference of the Robotics Society of Japan*, 1A23, 2005.

[6] T. Hatsuzawa, M. Hayase, and O. Toshiaki, "A linear actuator based on cilia vibration," *Sensors & Actuators: A. Physical*, vol.105, no.2, pp. 183-189, 2003.

[7] T. Fukuda, N. Mitsumoto, F. Arai, and H. Matsuura, "A study on Micro Robot (1st Report, Design, Experiment and Mathematical Model of Micro Mobile Robot)," *Transactions of the Japan Society of Mechanical Engineers*, vol.59 no.562, pp. 1787-1794, 1993.

[8] K. Ioi, "Study on Mobile Micro-Robot using Centrifugal Force", *Journal of the Robotics Society of Japan*, vol.17-3, pp. 396-401,1999.

[9] K. Isaki, A. Niitsuma, M. Konyo, F. Takemura, and S. Tadokoro, "Development of an Active Flexible Cable Driven by Ciliary Vibration Mechanism," *11th Robotics Symposium*, 2006.