FABRICATION OF AN ARTIFICIAL EARTHWORM TYPE IN-PIPE MOBILE ROBOT MOVABLE IN PRIMARY COOLING-WATER PIPE OF AN ATOMIC POWER PLANT

Manabu ONO*, Takayuki NAITO** and Shigeo KATO**

* Department of Mechanical Engineering,
Tokyo Metropolitan College of Technology,
Shinagawa, Tokyo 140-0011, Japan
Phone: +81-33471-6331, FAX: +81-33471-6338
E-mail: m_ono@tokyo-tmct.ac.jp
** Department of Systems Engineering,
Nippon Institute of Technology,
Miyashiro, Saitama 345-8501, Japan
Phone: +81-480-34-4111, FAX: +81-480-33-7745
E-mail: kato@nit.ac.jp

1. Introduction

A few years ago, we had an accident that radioactive cooling-water flowed out from the primary cooling-water pipe of an atomic power plant in Japan. The cooling-water pipe whose inner diameter is 3 inches was cracked by vibration of the cooling-water. The cracked location was inspected after removal of heat insulating materials around the pipe. If we can insert an inspection robot and inspect the pipe, we are avoidable from the difficult removal of the heat insulating materials and radioactivity of the flowed water. The cooling-water pipe is 76 mm in inner diameter, about 30 m long and has some elbows and vertical parts. Robots driven by electric motor are difficult to move in the vertical pipes, because the ratio between the power and the weight of the electric motor is not large[1], [2].

Many researchers have researched a new inspection robot which is able to move in the long pipe that has some elbows and vertical parts and driven by pneumatic actuators, because the pneumatic actuators are advantageous concerning the ratio between the power and the weight. However, they could not move the long distance[3]-[5]. The former reason that robots driven by pneumatic actuator could not move the long distance is caused by the long distance between the air pressure generators and pneumatic actuators. Accordingly, we propose an idea that the robot is moved in the condition where the pneumatic actuators are worked near the air pressure generators. The idea was realized by attaching electromagnetic valves direct behind of the pneumatic actuators.

We fabricated an artificial earthworm type robot in which we use three rubber bellows of pneumatic actuators. 12 rubber friction rings are used to get friction force between bellows and the pipe. Three electromagnetic valves that control pneumatic pressure to the three bellows are attached direct behind of the robot in order to evade the flowing time-lag of the air pressures. The electromagnetic valves and air-feeding tubes are carried on trolleys in order to decrease friction force between the pipe and them. The Air-feeding tubes conveying mechanism consists of a chassis made of vinyl chloride pipe, 8 legs made of aluminum and 8 wheels made of plastics. The wheels smoothly rotate. The air-feeding tubes conveying mechanism can carry the air-feeding tubes in pipe whose inner diameter is more than 74 mm.

The fabricated artificial earthworm type mobile robot was confirmed to move in the pipe that has 4 "U" letter curving vertical pipes (double elbows) and is 32 m long.

2. Structure of the fabricated robot

An in-pipe mobile robot which is able to move in pipes whose inner diameter is 3 inches is shown in Fig. 1. The robot is constructed by three bellows for the pneumatic actuators, friction rings and three electromagnetic valves. The bellows are made of Nitrile Butyl Rubber whose outer diameter, inner diameter and natural length are 60 mm, 43 mm and 135 mm. Total 12 friction rings are attached at the end of the three bellows as moving legs of robot. The friction rings are 84 mm in outer diameter, 42 mm in inner diameter and 1.5 mm thick. When the friction ring is attached at the bellows, the inner diameter is enlarged, because the inner diameter of the friction ring is 4 mm smaller than the inner diameter of the bellows. Then, friction ring comes to the shape of a cone. Three electromagnetic valves which control pneumatic pressure and vacuum pressure to the three bellows. They are attached direct behind of the robot in order to evade the flowing time-lag of the air pressures. Three air-feeding tubes made of polyurethane (inner diameters is 4 mm) are attached to the electromagnetic valves in order to feed pneumatic and vacuum pressure. A power line for the electromagnetic valves is bundled with air-feeding tubes. They are 40 m long. The air-feeding tubes are carried on conveying mechanisms in order to decrease friction force between the pipe and them. The air-feeding tubes conveying mechanism consists of chassis made of vinyl chloride pipe, 8 legs made of aluminum and 8 wheels made of plastics. The wheels smoothly rotate.

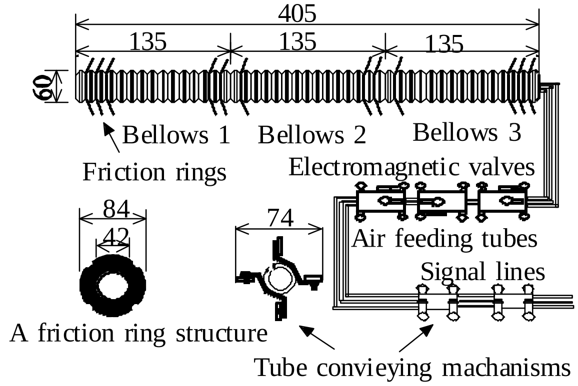

Fig. 1 Structure of the fabricated mobile inspection robot

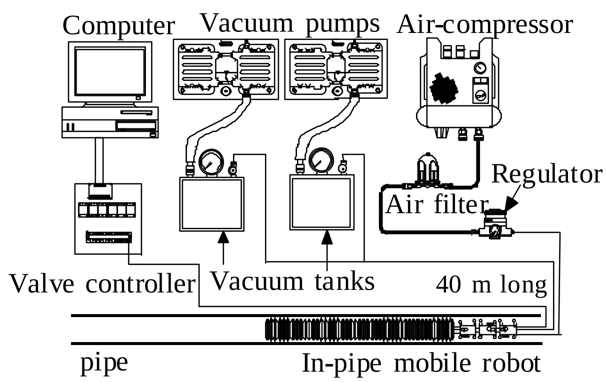

Fig. 2 Experimental apparatus of the mobile robot

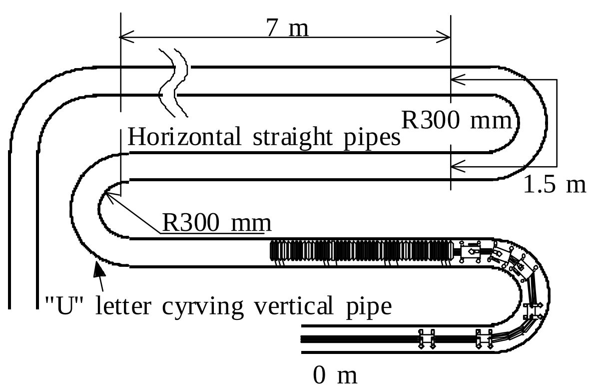

Fig. 3 The pipeline for an experiment

Experimental apparatus of the mobile robot is Fig. 2. Moving sequence is programmed in a computer. The computer controls the electromagnetic valves which are 40 m long far away through a valve controller, using the air-feeding time schedule program for the actuators. The other ends of air-feeding tubes are attached to the air-compressor and two vacuum pumps.

The pipeline for an experiment is shown in Fig. 3. The pipeline is 79 mm in inner diameter whose horizontal straight pipes are 7 m long and "U" letter curving vertical pipe are R300 mm, 1.5 m long.

3. Moving principle

The air-feeding time schedule and moving principle of the robot are shown in Fig. 4. The bellows are stretched by pneumatic pressure of 0.1 MPa, and shrunk by vacuum pressure of

-0.08 MPa. The supplying time of the pneumatic pressure (=t_1) is 1.5 seconds and the supplying time of the vacuum pressure (=t_2) is 7.0 seconds. Consequently, the supplying time of the one cycle is 8.5 seconds.

Step 0: All bellows are in the shrunk condition, because the vacuum pressure is supplied.

Step 1: The pneumatic pressure is supplied to the bellows 1 and the bellows 1 is stretched. Front end of the bellows 1 moves to the forward direction, because the friction force of the friction rings at the front end of the bellows 1 is smaller than friction force of the friction rings at the junction between bellows 1 and bellows 2.

Step 2: The vacuum pressure is supplied to the bellows 1 and the bellows 1 is shrunk. At the same time, the pneumatic pressure is supplied to the bellows 2 and the bellows 2 is stretched. The junction between bellows 1 and bellows 2 moves to the forward direction, because the friction force of the friction rings at the front end of the bellows 1 is larger than friction force of the friction rings at the junction between bellows 1 and bellows 2, beside the friction force of the friction rings at the junction between bellows 1 and bellows 2 is smaller than the friction force of the friction rings at the junction between bellows 2 and bellows 3.

Step 3: The vacuum pressure is supplied to the bellows 2 and bellows 2 is shrunk. At the same time, the pneumatic pressure is supplied to the bellows 3 and the bellows 3 is stretched. The junction between bellows 2 and bellows 3 moves to the forward direction, because the friction force of the friction rings at the junction between bellows 1 and bellows 2 is larger than friction force of the friction rings at the junction between bellows 2 and bellows 3, beside the friction force of the friction rings at the junction between bellows 2 and bellows 3 is smaller than the friction force of the friction rings at the end of bellows 3.

Step 4: The vacuum pressure is supplied to the bellows 3 and the bellows 3 is shrunk. The end of bellows 3 moves to the forward direction, because the friction force of the friction rings at the junction between bellows 2 and bellows 3 is larger than the friction force of the friction rings at the end of bellows 3. One cycle of stretching and shrinking motion of the robot becomes end. The robot can move a stretching distance in the cycle time. If the cycle is reversed, the robot can move to the

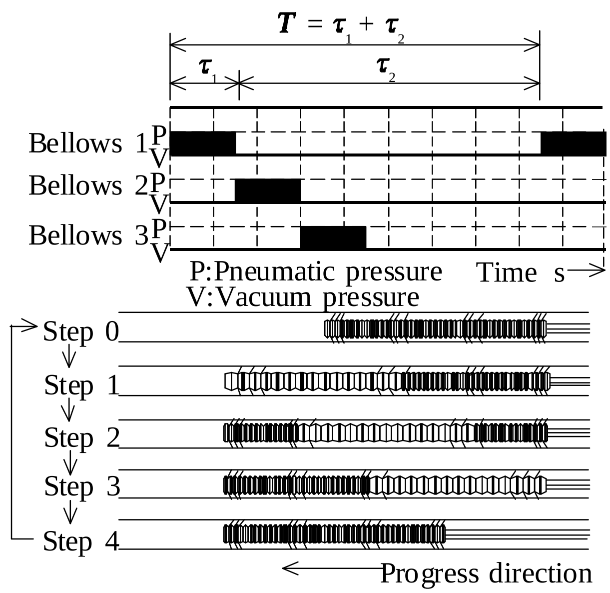

Fig. 4 Moving principle of mobile robot

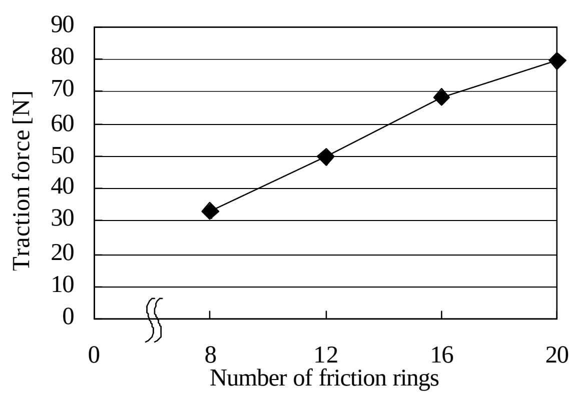

Fig. 5 Relationship between number of friction rings and traction force

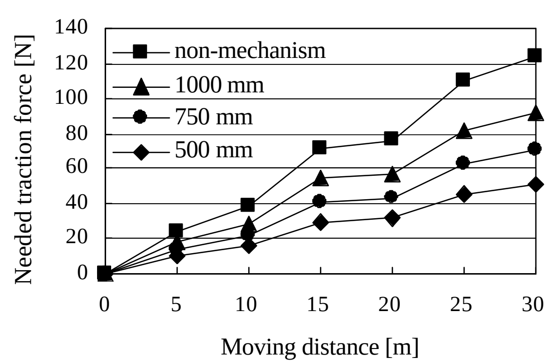

Fig. 6 Relationship between moving distance and needed traction force

backward direction.

4. Moving experiment

Traction force generated at the friction ring is measured and shown in Fig. 5. The traction force of about 53 N is generated by 12 friction rings of 1.5 mm thick. Friction force of the air-feeding tubes conveying mechanism in the pipe is measured. Space between each mechanism is selected as 500 mm, 750 mm and 1000 mm.

(a) Horizontal straight pipe

Friction force is constant and 0.41 N/m at any space of mechanism.

(b) "U" letter curving vertical pipe

Friction force depends on space of mechanisms, and is 12.3 N at 500 mm, 18.1 N at 750 mm and 24.7 N at 1000 mm. Relationship between the friction force and the moving distance of the robot is shown in Fig. 6. Friction force for the robot move to 30 m (passing of 4 "U" letter curving vertical pipes) may be 51 N, if we choose the space of the mechanisms to be 500 mm. Consequently the robot attached 12 friction rings is expected to move more than 30 m.

Relationship between moving distance and speed is shown in Fig. 7. The moving speed decreases according to the increasing of moving distance, and is 13 mm/s at 30 m. Finally, maximum moving distance was confirmed to be 32 m.

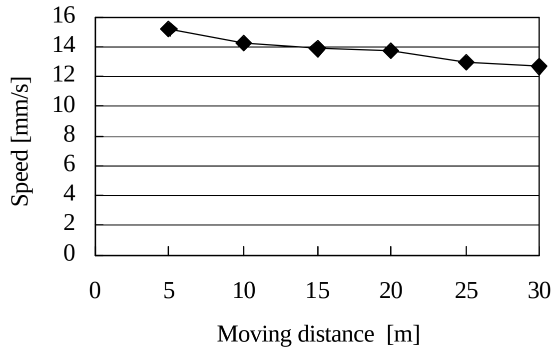

Fig. 7 Relationship between moving distance and speed

5. Conclusions

(1) We fabricated an artificial earthworm type mobile robot which is constructed by three bellows, 12 friction rings and three electromagnetic valves.

(2) The robot was confirmed to move in the pipe which has 4 "U" letter curving vertical pipes and is 79 mm in inner diameter and 32 m long.

(3) The traction force depends on the number of friction rings. The increasing to 20 friction rings may be able to move more than 40 m. We obtained feasibility on an in-pipe inspection robot for the primary cooling-water pipe of atomic power plant.

References

[1] Miyagawa, T., Suzumori, K., Kimura, M. and Hasegawa, Y.,: Development of Micro-Inspection Robot for Small Piping, Proceedings of tenth World Congress on the Theory of Machines and Mechanism Vol. 2 (1999), 856.

[2]Kawaguti, K., Yoshida, O., Iwao, K. and Kikuta, T.,: Control of an In-pipe Inspection Robot for Iron Pipes, Journal of the Robotics Society of Japan, Vol 15, No. 3 (1997), 387.

[3] Noritugu, T. and Kubota, M.,: Development of In-pipe Mobile Robot using Pneumatic Soft-Actuator, Journal of the Robotics Society of Japan, Vol 18, No. 6 (2000), 831.

[4] Kato, S. and Hirayama, T.,: Fabrication of Artificial Earthworms Driven by Pneumatic Pressure, Proceedings of the Japan Society of Mechanical Engineers, Centennial Grand Congress, Intelligent Motion-control, Power transmission and Tribology, (1997), 661.

[5] Takahashi, M., Hayashi, I., Iwatsuki, N., Suzumori, K. and Ohki, N.,: The Development of an In-pipe Microrobot Applying the Motion of an Earthworm, Journal of the Japan Society for Precision Engineering, Vol. 61, No. 1 (1995), 90.