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Paper:

Design and Experiments of In-pipe Inspection Vehicles for φ 25, φ 50, φ 150 Pipes

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In this paper we outline the design of in-pipe inspection vehicle for pipes with φ 25, φ 50, φ 150mm in diameter, "Theseuse" series. First we introduce the concept "Whole Stem Drive". This concept is very effective to allow an in-pipe vehicle to travel long distance in the pipeline. Based on this concept, we have made three in-pipe vehicles, Theseus-I~III. First, for the pipe with 50mm in diameter, we propose two mechanisms, in-pipe vehicle with spiral motion (Theseus-I) and in-pipe vehicle for the practical gas pipe (Theseus-II). Next, for the pipe with 150mm in diameter, we propose the in-pipe vehicle based on the idea of Control Configured Vehicle (CCV), Theseus-III. Last, for the pipe with 25mm in diameter, we propose the in-pipe vehicle, which has an actuator outside of the pipe (Theseus-IV).

Keywords: In-pipe inspection vehicle, Whole Stem Drive,Spiral motion,Load-sensetive CVT, Gas pipe, CCV, Wire-driven

1. Introduction

In this paper, we describe the design method of four in-pipe vehicles (Theseus series) we have developed for pipes with relatively small diameters of φ 25, φ 50 and φ 150mm without branch. The requirements for in-pipe vehicles for each pipe as gas pipe for example is as follows: Pipes 50-150mm in diameter are usually buried underground and in buildings, and in order to carry out inspection for maintenance efficiently in time and economy, the mechanism capable of as long-distance travel as possible is required.

Pipes 25mm or so in diameter are used at the end of gas supply around gas meters as branches from larger pipes, and mechanism capable of passing over the elbow with big curvature and step of joints is required.

In this paper, we propose the Whole Stem Drive concept as design theory of in-pipe vehicles enabling long-distance travel in pipelines without branches, and introduce Theseus-I and II for 50mm pipe, and Theseus-III for 150mm pipe, both developed by introducing the Whole Stem Drive. Then we introduce Theseus-IV, which can travel through elbows with very big curvature and pipes with joint step of gas pipes of 25mm, not possible by most conventional in-pipe vehicles.

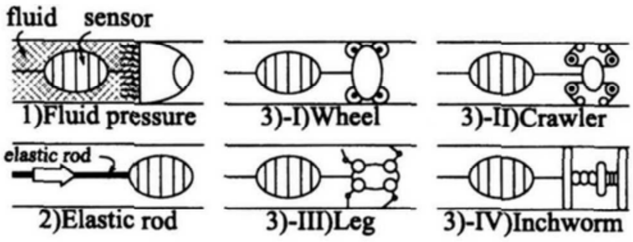

Fig. 1. Basic Forms

2. Basic Movement Forms

In order to inspect the defects inside long, narrow pipes that maintenance personnel cannot enter, a mechanism to move with a device necessary for inspection in pipes is required. Except special pipes preparatorily provided with a moving mechanism like rail or step in the pipe, in-pipe vehicles are divided broadly into three forms: 1)pressure sending, 2) pushing and 3) self-running (**Fig.1**).

The 1) pressure sending uses the pressure of fluid as the driving power when fluid exists in the pipe. This method cannot be used when the pressure of the working fluid is insufficient, and this has difficulty in stopping at optional locations and passing through the elbow.

The 2) pushing is the method to push in the inspection devices at the top of the elastic rod into the pipe and to operate the rod from outside the pipe. The structure of this method is simple, and it is put into practical use like industrial endoscopes. But when intending long distance inspection of a pipe having many elbows, the elastic rod is required to have contradictory properties of elasticity at the elbow and sufficient hardness to transmit the pushing force.

The 3) self-running is the form that the vehicle itself has driving power. This self-running form is divided into four types of I)wheel, II)crawler, III)leg and IV)inch-worm. Among these, the I)wheel type requires the mechanism to push the wheel against the pipe wall so that friction force is caused between the wheel and the pipe wall. But, compared with other types of self-running types, it is suited for pipes with small diameter because its mechanism is simple and small size design is easy, and the energy efficiency for running is high. Besides, as for the mechanism to push the wheel against the pipe wall, by making the action by elastic body-like spring, it is considered that the elasticity makes the wheel follow the unevenness inside the pipe and more stable travel can be realized. For the reasons mentioned above, in this study, we discuss the in-pipe vehicle for pipes with small diameter by use of the wheel form.

3. Whole Stem Drive

3.1. Whole Stem Drive

Most of the conventional in-pipe vehicles have been constructed so that the driving unit is located at the front and it pulls the wiring system to transmit the power and the signal (hereafter called Stem) to the rear. Therefore when making a long-distance travel in pipes with elbow, the friction between this stem and pipe wall becomes big, and travel beyond a certain distance has been impossible. To make long-distance travel in this state, a big tractive force is required, resulting in larger driving unit, and it is incapable of application for pipes with small diameter.

On the assumption that the output of the driving actuator is sufficient, the tractive force of the vehicle running inside the pipe is expressed by a function with parameters of friction coefficient of the wheel, pushing force of wheel against the pipe wall, and the driving wheel. Among these, the friction coefficient is decided by the material of the wheel and the pipe wall. So either the pushing force or the number of driving wheels must be increased to increase the driving force. But when the pushing force is increased, the resistance when getting over the step is increased. So the degree of increase is limited. Thus it is considered that the effective method to attain big tractive force is to increase the number of driving wheels. But even if the tractive force is increased by arranging a number of driving wheels at the front, the same problem occurs at location far from the driving unit when the friction force is increased. Thus the travelling distance is limited in the same way.

Therefore, in this study, we introduce the concept of putting the driving unit over the total length of the stem to be inserted, and we call this a ''Whole Stem Drive''. By introducing this ''Whole Stem Drive'', it is possible to greatly decrease the friction force between stem and pipe wall in long-distance travel and at elbow, and a drive unit is theoretically required to pull only the stem up to the subsequent drive unit. Thus it is considered that the load on each drive unit can be decreased, and construction with small size and for long distance is possible.

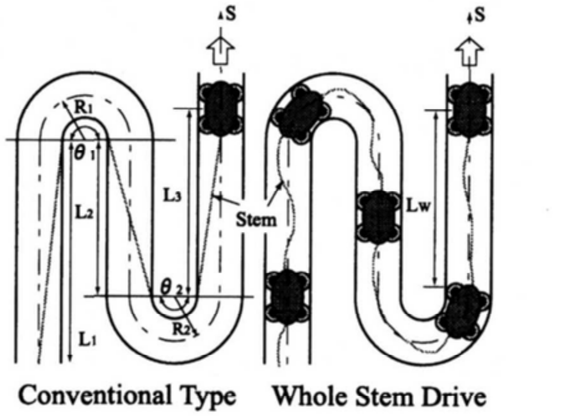

Fig. 2. Whole Stem Drive

Besides, by introducing the whole stem drive, tension on each stem is decreased. Therefore, less mechanical strength is required for each stem and thinner stem is possible, and flexion at elbow becomes easy.

On the other hand, many drive units are required in the whole stem drive, and the problem is the increased probability of occurrence of troubles in the drive unit. But by providing fail-safe like passivation of the wheel and removing reaction of wheel on pipe wall, the defective drive unit can be pulled by many other drive units. Thus, this can be a very redundant and highly reliable system.

Further, in the future, battery having high charging capacity and very small size actuator with high output will be developed, and completely autonomous in-pipe travelling robot will be realized which is loaded with sensors and control system and requires no wiring system for power and signal. Then the concept of this whole stem drive may be considered unnecessary. But we consider, even at that time, this concept of whole stem drive is sufficiently effective. Because, however refined those in-pipe running robots may be, when the robot cannot move at a location in the pipe by some troubles, it is required to pull the stem to recover the robot securely outside the pipe.

3.2. Validity of Whole Stem Drive

In order to examine the validity of this Whole Stem Drive, we compare the minimum tractive force required for the drive unit to move a distance of s[m] along the pipe axis, for each of the conventional in-pipe vehicle in which the front drive unit pulls the subsequent stem and the Whole Stem Drive.

Here we model the pipe and the drive unit as shown in **Fig.2**. In the case of the conventional type, the loads to be considered are the empty weight of the drive unit, weight of stem, friction resistance between stem and pipe wall of elbow. For example, the minimum tractive force till the drive unit moves to the position in the figure is

$$F(L) = mg + r\, gL_1\, Exp(mq_1) - r\, gL_2\, Exp(mq_2) + r\, gL_3 \quad (1)$$

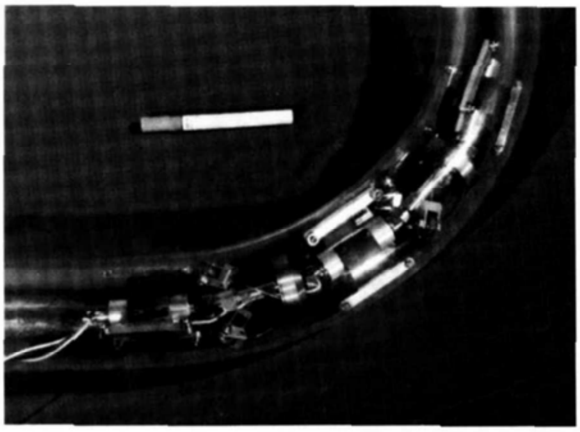

Photo. 1. Theseus-I

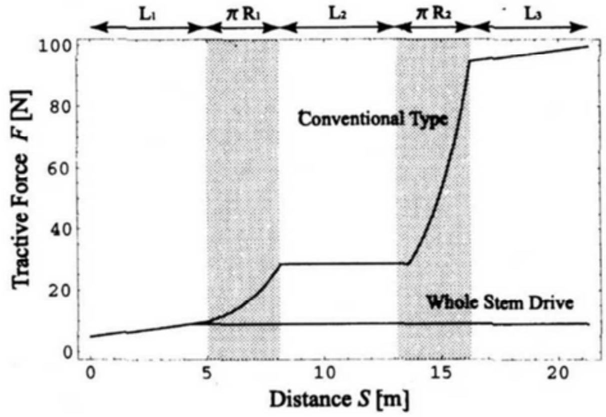

Fig. 3. Validity of Whole Stem Drive

On the other hand, in the case of the whole stem drive, when the stem is divided by n units of drive units so that friction is not caused between the stem and the pipe wall, the loads on each drive unit are only the empty weight and the weight of the stem up to the subsequent drive unit. Therefore the minimum tractive force required for the drive unit to move to $s=L$ along the same distance as conventional type is

$$F(L) = mg + r\ gL_w \quad (L_w = L/n) \; . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

In the formula and figure, m is the mass of the drive unit, g is the acceleration of gravity, r is the line density of the stem, $L_i(i=1,2,3)$ is the length of straight part of the pipe, $R_i(i=1,2)$ is the radius of curvature of the center axis at elbow, q_i $(i=1,2)$ is the bending angle of the elbow, m is the friction coefficient between the stem and the pipe wall, and n is the number of drive units.

The graph shown in **Fig.3** is the calculation results of this comparison for 0 £ s £ L. The value of each parameter used for the calculation is r =0.5kg/m, m =0.5, L_1=L_2=L_3=5m, q_1=q_2=180deg, R_1=R_2=1m, m=0.5kg, n=5units, g=9.8m/sec^2.

The graph shows that in the case of the conventional in-pipe vehicle, the drive unit requires a big tractive force every time when it passes through the elbow as shown in the netted zone. On the other hand, in the case of Whole Stem Drive, the minimum tractive force required for the drive unit is constant regardless of the distance of travel and the force is very small compared with the conventional types.

From these, we can consider that it is very effective to adopt the Whole Stem Drive when designing running vehicle for long-distance travel in pipes with elbows.

4. In-pipe Vehicle with Spiral Movement

We developed in-pipe vehicle with spiral movement, Theseus-I, shown in **Fig.4**, as a mechanism to effectively generate driving force in pipes with small diameter and realize the whole stem drive. The mechanism to use spiral

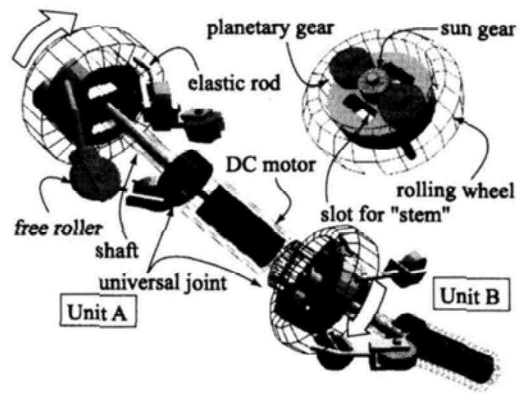

Fig. 4. Theseus-I

movement in in-pipe travel is not specifically new and practical application already exists. But the mechanism we propose realizes its micronization and has the new construction with added function of stepless reduction.

Theseus-I is constructed by connecting unit A and unit B. In each unit, torque generated by small DC motor in the unit is transmitted to ring gear through universal joint, transmission shaft and planetary gear. The ring gear has four spiral elastic arms arranged at regular intervals around the circumference. And at the top of these spiral elastic arms, rollers attached obliquely to the pipe axis are pushed against the pipe wall. Further by the elasticity of this arm, it can flexibly adapt to some variations of pipe diameter and pipe shape.

Further by reverse revolution of the ring gears of unit A and unit B, the ring gear is rotated without rotating the unit itself around the pipe axis, so driving force is generated by spiral movement like screwing.

Further in Theseus-I, the stem can be inserted into pipe without being twisted by the spiral movement as it has through hole in the gear transmission composed of sun gear, planetary gear and ring gear.

Theseus-I has stepless transmission mechanism as its major characteristic. In designing in-pipe travelling vehicle, the reduction ratio of the reduction unit of the driving system is required to be calculated to meet the probable

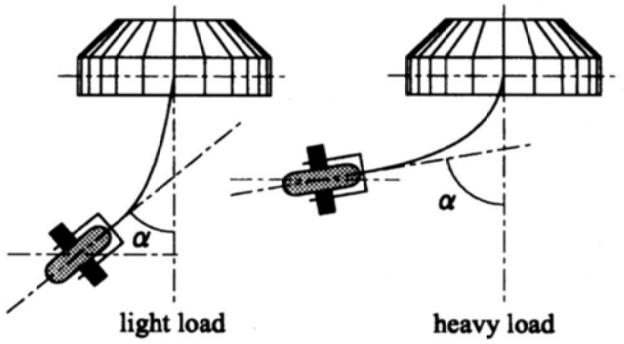

Fig. 5. Load-sensitive CVT

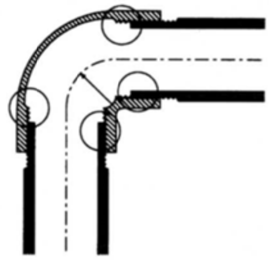

Fig. 6. Cross section of practical gas pipe

maximum load. So, the reduction ratio must be designed sufficiently high so that it can move in bad situations like unevenness during movement and upward perpendicular movement. But when the reduction ratio is designed so high, the speed can not be raised in horizontal pipe with smooth inner wall and downward perpendicular movement. In order to solve this problem, we introduced the drive mechanism of load-sensitive type to automatically control reduction ratio according to the working load, which is not considered to be proposed for small size machine up to present. This utilizes the driving mechanism itself with passive wheel and elastic rod as the stepless reduction mechanism, and realizes the load-sensitive function with a very simple mechanism.

The principle of this stepless reduction is simple as shown in **Fig.5**. When the load is light, the flexure angle of the elastic rod is small and the angle a made between the stem and the pipe wall is small, that is, the driving force is bigger. On the other hand, as the load increases, the compressive force on the elastic arm in the direction of pipe axis becomes bigger and the flexure angle of the elastic rod becomes bigger. As a result, the angle a made by passive wheel becomes big and the reduction ratio increases.

The prototype Theseus-I is shown in **Photo 1**. This is designed for pipe with 50mm in diameter.

5. In-pipe Vehicle for 50mm Gas Pipe

Maintenance of gas pipes is very important not only for stable supply of gas but also for preventing serious accident by gas leakage. We made the prototype of in-pipe vehicle for pipes with 50mm in diameter, Theseus-I, but it is difficult to apply this mechanism for practical gas pipes.

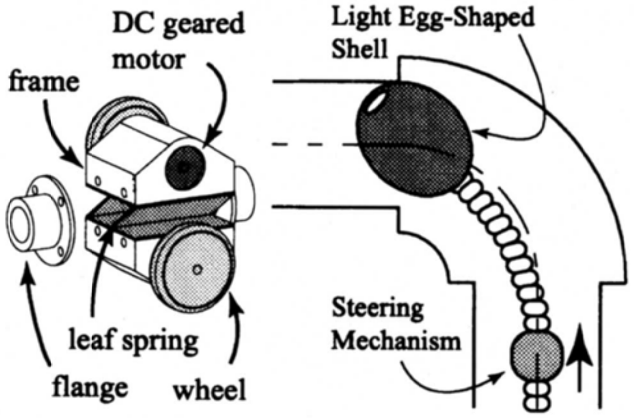

Fig. 7. Drive unit **Fig. 8.** Steering mechanism

Photo. 2. Theseus-II

One of the reasons is, as shown in cross section of the practical gas pipe shown in **Fig.6**, the radius of curvature of the elbow is very small as 1 - 1.5times the pipe diameter. Another reason is that big steps exist at the portions shown by circles. For these reasons, there have been few prototype mechanisms that can move in the practical pipes. Therefore we considered that the drive unit should be short in the direction of pipe axis so that it can pass easily through the elbow and it should have large wheel so that it can get over the step by making the step height relatively small. And we developed the mechanism Theseus-II, only for the practical gas pipes as the object.

The construction of Theseus-II is broadly divided into two parts of the drive part and the steering part at the front.

The drive part is constructed with plural drive units connected with cylindrical elastic body having through hole for stem to compose the Wholes Tem Drive. Each drive unit uses two units of the smallest DC geared motors available on the market. Each motor has a large wheel on the output shaft and the wheels are pushed against the pipe wall by putting a leaf spring between the

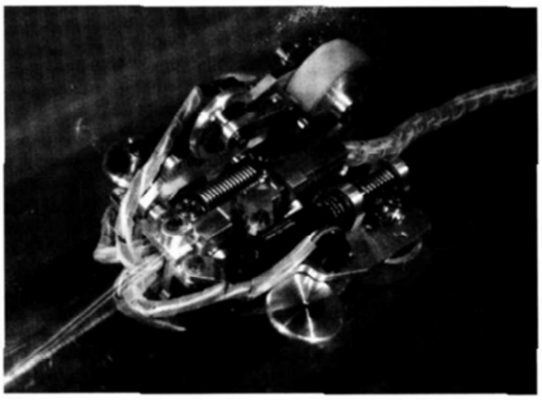

Photo. 3. Theseus-III

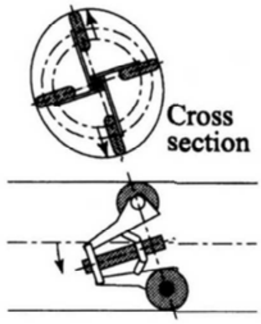

Fig. 10. Independent of two links

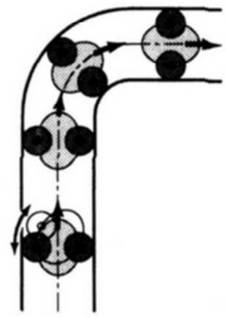

Fig. 11. Control configured vehicle (CCV)

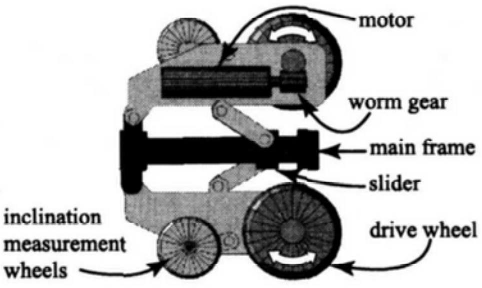

Fig. 9. Theseus-III

Photo. 4. *Field test*

two motors (**Fig.7**).

The steering mechanism is constructed with light egg-shaped shell rotated around the pipe axis with an inclination of 30 degrees so that secure travelling is assured at the step of elbow, which is impossible only by the drive unit (**Fig.8**). This is a simple mechanism constructed with as few degrees of freedom as possible. This is important for in-pipe vehicle for pipes with small diameter. Further when considering to load a CCD camera inside the egg-shaped shell, it is considered that by watching the entire inner wall of the pipe by rotating it, and the direction of bending of the elbow can be confirmed, thus it is possible to bend the front part to that direction.

6. CCV Type In-pipe Vehicle

Next, we intended to develop a mechanism to move in gas pipe with 100mm to 200mm in diameter called the main pipe. With the pipe with larger diameter as the object, the margin of designing of the drive unit is enlarged, which is restricted in the case of 50mm gas pipe, and it also makes it possible to load the sensors to detect the state of the vehicle. This is important to realize in-pipe travelling with higher stability and reliability.

We developed CCV type in-pipe vehicle, Theseus-III, as shown in **Photo 3**.This mechanism is constructed so that in-pipe travelling is possible by controlling the position of the drive wheel to constantly face the centerline of the pipe, while the four drive wheels are constantly pushed against the inner wall of the pipe as shown in **Fig.11**. This is an intentionally unstabilized system in view of the mechanism in order to improve the environment-adaptive travelling performance. Because this mechanism is designed in this point of view, we call this type of in-pipe vehicle CCV (Control Configured Vehicle).

The drive mechanism of the Theseus-III is four drive wheels arranged at regular intervals around the body and they are driven by DC motors. Four passive wheels having potentiometer to measure the angle of the body with the pipe wall are arranged in the circumference direction together with the drive wheels. Further two diagonal sets of the four wheels are connected with independently movable link so that they are constantly pushed against the inner wall of pipe. This mechanism enables it to adapt to variation of the pipe diameter as in **Fig.10**. Further the body is provided with space at the center to pass the wires through to transmit signals and force in order to construct the Whole Stem Drive.

This mechanism is a CCV type and so control of the position is necessary to achieve stable travelling performance. So, the angle of the body made with the inner wall of the pipe is measured by passive wheel for angle meas-

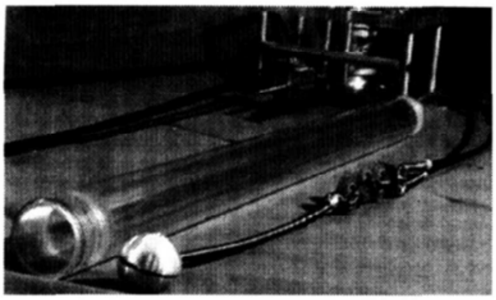

Photo. 5. Theseus-IV

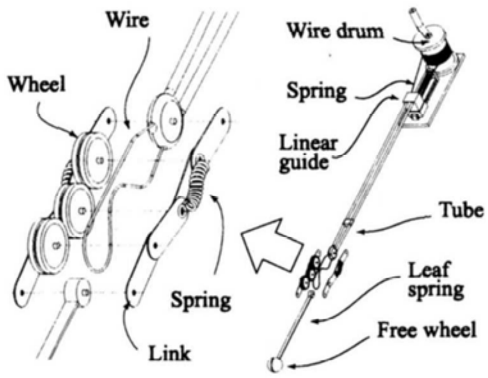

Fig. 12. Theseus-IV

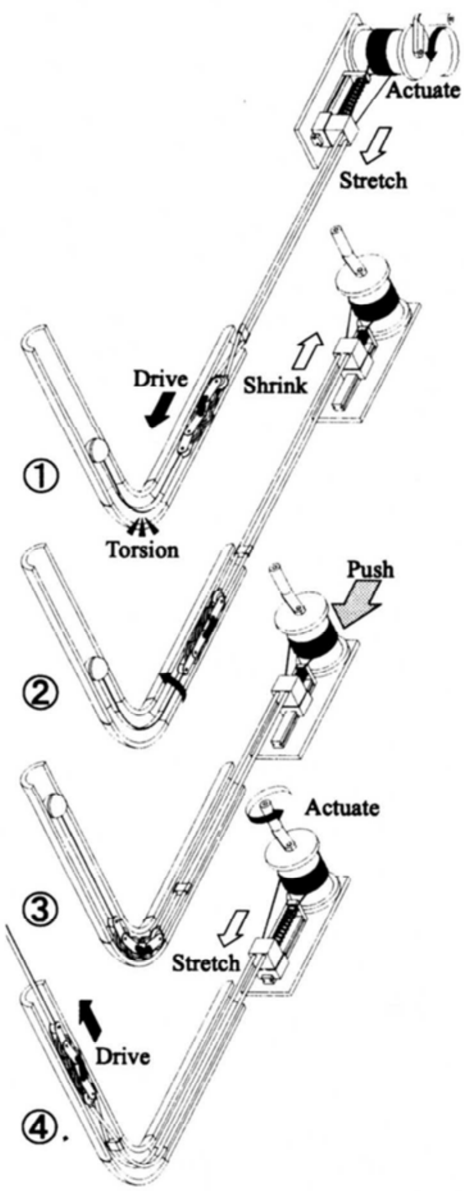

Fig. 13. Drive sequence at elbow

urement, and the system is provided with minor feedback loop to give rotation difference to the wheels so that the angles of the facing passive wheels are equal. By this control, the position of the body can constantly coincide with the pipe axis.

Photo 4 shows the appearance of the field test made by Tokyo Gas Co., Ltd. In this test, a model with two units of Theseus-III connected with an interval of 1m was constructed, and a CCD camera and lighting were loaded. The smooth travelling performance was confirmed in the 112.5m horizontal pipe, and it was also confirmed that the state inside the pipe could be actually inspected.

7. In-pipe Vehicle for 25mm Gas Pipe

The important point in designing in-pipe vehicle for gas pipe 25mm in diameter is that the step height at the elbow is relatively big to the pipe diameter compared with larger diameter pipes. Another trouble is that sufficiently small DC motor is not available on the market which can construct the drive unit to pass through the elbow.

Therefore we considered that as the mechanism to move in this kind of pipe having elbow, the method to make the wheel diameter sufficiently large nearly to the pipe diameter, and provide the actuator outside the pipe, and transmit the drive force to the wheel with a light and flexible wire. And we developed the vehicle, Theseus-IV as shown in **Photo 5**.

The construction of Theseus-IV is broadly divided into the guide part and the drive part in view of the roles.

The drive part is constructed mainly by three wheels, tube, wire and wire drum as shown in **Fig.12**. The three wheels are connected to the two tubes through the links. The other end of the tube is connected to the block of linear guide equipped on the wire drum. The wire is shaped with a loop being wound on the wheel and the wire drum as shown in the figure. A spring is equipped between the wire drum and the linear guide so that proper tension is constantly applied on the wire by the balance with the spring on the wheel row side.

This drive part is mechanically restricted in that the wheel row can turn only in one direction. So we provided a guide part at the top of the drive part to move in pipe with elbow. This guide part is very simply constructed and functions passively at the elbow without the need of additional actuator. The guide part is mainly constructed with leaf spring and the spherical passive wheel.

We explain the drive sequence of Theseus-IV in the state that the bending direction of the wheel row and the bending direction of the elbow do not coincide by using **Fig.13**. As shown in (1) in the figure, at the straight pipe part, in the state that pushing force of wheel to the pipe wall is caused by separating the location of the block connected with tube on the linear guide from the wire drum, the wire drum is actuated to generate drive force on the wheel row. And when the leaf spring on the guide part is twisted at the elbow, the pushing force on wheel to the pipe wall is removed by making the position of the block connected with the tube on the linear guide closer to the wire drum. Thus by the twisting torque of the leaf spring, the direction of the wheel row coincides with the direction of the elbow as shown in (2). In this state, the whole Theseus-IV is pushed into the pipe and it is passed over the step at the elbow by the large wheel as shown in (3).After the wheel row passed through the elbow, the wheel is given the pushing force against the pipe wall to generate driving force again, as shown in (4).

The gas pipe with 25mm in diameter as the object is mainly used around gas meter in general houses and the length is about several meters. Therefore, the running experiment was carried out by experimental pipeline of three-dimensional arrangement by joining three 1m long straight pipes with two 90 degree short elbows. Sufficient travelling performance was confirmed on the entire straight pipe part and at the elbow, and the twisting effect of the leaf spring and getting over of step by the large wheels were confirmed.

8. Conclusion

In this study, we proposed the concept of Whole Stem Drive as the design theory of in-pipe vehicle to travel a long distance in the pipe having many elbows, and demonstrated its validity.

By introducing the concept of Whole Stem Drive we developed three in-pipe vehicles for pipes with 50mm and 150mm in diameter. Among these, for pipes with 50mm in diameter, we developed two units: spiral movement in-pipe vehicle with load-sensitive stepless reduction gear, Theseus-I, and in-pipe vehicle for gas pipe taking more practical in-pipe movement into consideration, Theseus-II. And for pipes with 150mm in diameter, we developed a CCV type in-pipe vehicle having excellent environment-adaptive travelling performance, Theseus-III. For pipes with 25mm in diameter, with gas pipe as the object, we developed in-pipe vehicle of wire actuator type having passive steering mechanism, Theseus-IV, to make it possible to realize the movement in bending pipe with large curvature and step at the elbow, which was difficult with many of conventional mechanisms.

Acknowledgments

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