Bi-rigid guide wire enables endoscope insertion into winding small gas pipelines

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Abstract
This paper presents a method to inspect the interior of a winding small gas pipe using a hollow guide wire. There is no conventional method to insert an endoscope into an 8-bend 25-mm-diameter gas pipe within 2 hours. In medical practice, a guide wire inserted in advance enables insertion of a catheter into a vessel. However, it is impossible to insert a normal guide wire into a gas pipe because the wire buckles in the pipe. Thus, we designed a hollow guide wire with a small front diameter and large rear diameter, making the front soft and the rear stiff. This guide wire can be inserted without buckling or meandering. First, we measured mechanical properties such as the torsional spring constant and damping coefficient of the wire and the frictional coefficient between the pipe and wire. Second, we conducted an experiment inserting guide wires with various tip pitches, front lengths, front outer diameters, and rear outer diameters. Third, we analyzed the insertion distance by simulating guide wire insertion using the Lagrange method, and optimized the guide wire shape via the response surface method. Finally, the optimized guide wires were tested experimentally to validate the analysis. As a result, an optimized guide wire and an endoscope can both be inserted into a gas pipe and removed within just 3 minutes.

Keywords: Pipeline, Inspection, Infrastructure, Gas pipe, Optimization

Received: 21 February 2020; Revised: 21 April 2020; Accepted: 11 June 2020

1. Introduction
Pipelines are indispensable for supplying resources to cities and homes (Takeshima and Takayama, 2018; Y. Li et al., 2019). In Japan, the underground gas pipeline extends for more than 1.5 billion km (Gas Pipe Overview, 2018). Generally, gas is sent through main pipes under the public road and branches into external gas pipes at residential sites (Fig. 1). The main pipes are of size “50A” (diameter: 52.9 mm), whereas the external gas pipes are of size “25A” (diameter: 27.6 mm) (Gas Pipe Overview, 2018). External gas pipes have four sets of two turns consisting of a bend and an elbow (Gas Pipe Overview, 2018). The total length of an external pipe is about 7.0 m. Because these pipes are installed underground, they are not being maintained. Therefore, corrosion often appears inside the pipes as they age (Cole and Marney, 2012).

The most widespread method of inspecting the interior of a gas pipe is visual inspection using an endoscope. One example is using a flexible microscope, as shown in Fig. 2. The operator uses the hand console to manipulate the tip with the microscope camera. However, it is impossible to insert a microscope into a buried pipe because the microscope buckles and stops in the pipe. Thus, when an accident occurs at an external gas pipeline, the buried pipes are dug up randomly until the staff finds the causes. This requires stopping the gas flow and digging up the branch pipe extending from the load (Ogai and Bhattacharya, 2018). The entire process takes more than 1 day, and the gas cannot be used while the pipes are being inspected. Furthermore, digging up and refilling the load has a high cost, which includes personal expenditure and catering (Cole and Marney, 2012).
This paper presents a method to insert a microscope from the gas meter of a house into an external gas pipeline without digging up buried pipes, as shown in Fig. 1. The IPLEX LX videoscope was used, as shown in Fig. 2. Just pushing a microscope does not insert it into a gas pipe. We can insert the microscope into a buried pipe using a specially shaped hollow guide wire. We investigate the performance of the designed guide wire through experiment and analysis.

2. Related works

Among many inspection methods studied (Takeshima and Takayama, 2018; Y. Li et al., 2019) have been various techniques for analyzing pipe corrosion (Khadom, Karim and Farhan, 2018; Khan et al., 2018; Norli et al., 2018; Zhang et al., 2018; Aquino et al., 2019; Maher and Swain, 2019; Mohammed et al., 2019; Parker et al., 2019). An inspection method is required to obtain images of pipe interiors. Therefore, many studies have been conducted on pipe inspection. There are three mechanisms of inspection (Fig. 3). One is pumping. For example, Okamura recently developed a soft robot that uses gas pressurization (Hawkes et al., 2017). Fukuda developed a gas-pressure robot using a hydrogen-storage alloy (Fukuda, Hosoki and Uemura, 1989). The simplest and most popular method proposed involves pushing. A flexible microscope (IPLEX, Olympus, Fig. 2) has been developed that can be inserted into a pipe for inspection to confirm the existence of corrosion (Videoscopes and Borescopes IPLEX RX/IPLEX RT, 2018). Indeed, IPLEX is already being used. The microscope is the most popular observation tool in many fields (Guo et al., 2018; Acemoglu, Pucci and Mattos, 2019; Ashwin and Ghosal, 2019; Hwang and Kwon, 2019; Joint et al., 2019; Sarli et al., 2019; Tappe, Ortmaier and Ponick, 2019; Zhou and Alici, 2019). Another method is self-propulsion. Komori developed a wheeled robot with Tokyo Gas (Komori and Suyama, 2012). Bertetto developed an inch-worm flexible robot (Bertetto and Ruggiu, 2001). However, even though many studies have investigated methods of pipe inspection, their target gas pipes are more than 50A. No method exists to inspect the inside of a small (25A) gas pipeline within 1 hour because these mechanisms cannot insert through pipes with many turns. Indeed, the most popular and practical inspection method is to dig up a buried pipe and insert a microscope into it.

In medical practice, a surgeon inserts a catheter through a small opening (Ashwin and Ghosal, 2019; Hu et al., 2019; Lai et al., 2019; Sikorski et al., 2019) using a guide wire (Bruthans and Trča, 2019; Işık, 2019; Komiyama et al., 2019). First, the surgeon inserts the guide wire into the opening, and then inserts the catheter into the guide wire. Moreover, the surgeon pulls the guide wire to detain the catheter inside the vessel. Our study focuses on this type of guide wire. The guide wire is a hollow tube with a spiral wound wire. However, it is impossible to insert a normal guide wire into a pipe for two reasons. One is that the tip of the guide wire buckles easily at a corner if the wire is very rigid. The other is that the guide wire meanders inside the pipe if the rigidity is low. The degree of wire rigidity causes buckling or meandering inside the pipe.

![Fig. 1. Gas pipe. The target is the external gas pipe under the house area. The external diameter of the pipe is 25 mm. Our scenario is to insert the microscope from the gas meter into the external gas pipe without drilling the ground.](image1)

![Fig. 2. Videoscope (IPLEX LX(Videoscopes and Borescopes IPLEX RX/IPLEX RT, 2018)). The joystick is synchronized with the tip movement using a wire cable. We used the videoscope with the designed guide wire.](image2)
3. Proposed method

In this paper, we propose a specially shaped hollow guide wire. The front of the guide wire must have low rigidity to prevent buckling, and the rear must have high rigidity to prevent meandering. Thus, we designed a guide wire with a flexible front and highly rigid rear. The diameter at the front of the guide wire is small (1.0 mm), and the rear diameter is large (1.6 mm), as shown in Fig. 4. Specially designing the front and rear diameters realizes a bi-rigid guide wire.

Figure 5 shows how to use the guide wire. First is inserting the guide wire into the pipe (Fig. 5A). The guide wire can be inserted because its front is flexible, and its rear is rigid. Second is inserting an endoscope into the guide wire until the camera at the tip emerges from the wire tip (Fig. 5B). The endoscope does not pass through the gas pipe but can pass through the guide wire. The staff can observe the pipe interior because the camera at the endoscope tip sticks out from the guide wire. Third is observing the inside pipe while pulling the wire and endoscope together with the camera remaining at the tip and taking images of the pipe interior.

It is necessary to decide the shape of the guide wire. The design parameters are the front outer diameter \( L_1 \), pitch \( s \), front length \( l \), and rear outer diameter \( L_2 \), as shown in Fig. 6. Pitch is the interval of the center of the wire line. Thus, we used the mechanical properties of nine guide wires to analyze the insertion distance of each shaped guide wire shown in Table 1. We made the response surface to optimize the shape of guide wire. Finally, we validated the insertion distance of the optimized wire by comparing the analytical and experimental values.

Fig. 3. Conventional method. There are three types: pumping, pushing and self-propelled.

Fig. 4. Specially shaped guide wire. The guide wire is a hollow tube with a spiral wound wire. The tube allows for the insertion of a flexible endoscope into the guide wire.
4. Mechanical properties

4.1 Torsional spring constant

Analyzing the wire responses required the torsional spring constant and the damping coefficient of each shaped guide wire. The torsional spring constant was identified statically from an experiment and analysis.

Various sized wires were used in this experiment to determine the torsional spring constant. One end of a length of wire was fixed using a clamp, and a forced displacement in the negative X direction was applied to the other end. Several wires of different diameters were used, with each wire denoted by a letter (Table 1). The coordinates at certain sites along the wire were measured from the tips of wires A, C, E, F, H, and I. Wires B, D, and G were measured at spatial intervals of 10 mm from the tip to determine the torsional spring constant.

First, 20 mm intervals were marked off from the tip of the wire (Fig. 7). Then, a forced displacement was applied placing the free tip at (−120, 0) for wires A, C, and F, (−140, 0) for wires E, H, and I, (−50, 0) for wire B, and (−40, 0) for wire D. The coordinates of the points by 20 mm from the tip were recorded for each wire. We calculated the error based on the experimental and analytical coordinates as follows.

\[
\text{Minimize: } \sum_{i=1}^{k} \left( |x_i - \tilde{x}_i| + |y_i - \tilde{y}_i| \right)
\]

Where \(x\) and \(y\) are the experimental coordinates, \(x_i\) and \(y_i\) are the analytical coordinates. The analytical coordinates were calculated according to the change of the torsional spring constant on analysis. The analytical torsional spring constant was determined to minimize the error between the experimental and analytical coordinates. Figure 8 presents the experimental results for the wires displaced by a specified force. An error of less than ±3.0 mm was obtained. The result for each torsional spring constant is shown in Table 1.

4.2 Damping coefficient

With the obtained torsional spring constant, the damping coefficient was determined by conducting an experiment and an analysis on free vibration. The tip displacement was measured while the wire vibrated freely, and this value was compared with the analytical result to determine the torsional spring constant and damping coefficient.

Various sized wires were used as in the experiment as section 4.1. Figure 9 is the sketch of the free-vibration experiment. With the top end of the wire fixed, a piece of vinyl tape was attached as a marker at the bottom end of the wire. The tape...
was removed instantly to measure the wire vibration. The free vibration of the wire was tracked and recorded using a high-speed camera (VW-6000, Keyence, Japan). This experiment was repeated with different wires. The parameter values of the wires are listed in Table 1.

After wires A, C, E, F, H, and I were displaced separately to (−160, −120), and similarly wires B, D, and G to (−40, −30), the edge of the wire was released. The wires were on the free vibration. Hence, we carried out the free vibration analysis to calculate the coordinates of the wire’s tip using the change of the damping coefficient. We calculated the error between experimental and analytical coordinates as follows.

Minimize: $\sum_{i=1}^{n}(|A| - |A_i|)$

(2)

Where $A$ is the experimental vibration amplitude, and $A_i$ is the analytical vibration amplitude. The analytical vibration

Fig. 7. Given forced wire displacement. (a) the guide wire is shown in experiment (b) the guide wire is shown on analysis.

![Experiment](image)

![Analysis](image)

Fig. 7. Given forced wire displacement. (a) the guide wire is shown in experiment (b) the guide wire is shown on analysis.

![Graph](image)

Fig. 8. Results of the forced-displacement wire experiment. The red and blue line shows the experimental and analytical results, respectively.

| Wire | Outer diameter (mm) | Wire diameter (mm) | Pitch (mm) | Density (kg/mm$^3$) | Torsional constant (Nmm/deg.) | Spring coefficient (Nmm/deg.) |
|------|---------------------|--------------------|------------|----------------------|-------------------------------|-------------------------------|
| A    | 9                   | 1.0                | 1.0        | 2654                 | 1.0                           | 0.01                          |
| B    | 9                   | 1.0                | 2.0        | 1327                 | 0.25                          | 0.0005                        |
| C    | 10                  | 1.0                | 1.0        | 2122                 | 1.0                           | 0.01                          |
| D    | 10                  | 1.0                | 2.0        | 1061                 | 0.75                          | 0.0006                        |
| E    | 10                  | 1.6                | 1.6        | 3692                 | 5.0                           | 0.06                          |
| F    | 12                  | 1.0                | 1.0        | 1768                 | 1.1                           | 0.0075                        |
| G    | 12                  | 1.0                | 2.0        | 884                  | 0.8                           | 0.0009                        |
| H    | 12                  | 1.6                | 1.6        | 3947                 | 6.0                           | 0.09                          |
| I    | 14                  | 1.6                | 1.6        | 4807                 | 7.0                           | 0.08                          |
amplitude was calculated as to the change of the damping coefficient. The damping coefficient was determined to minimize the error of the vibration amplitude between experiment and analysis. Figure 10 presents the results of the free-vibration experiment. The displacement error was less than 30.0 mm, and the phase error was less than 0.20 s. The result for each damping coefficient is shown in Table 1.

4.3 Frictional coefficient between gas pipe and wire

For the analysis, we calculated the frictional force between the guide wire and inside of the pipe. The static and dynamic coefficients of friction between the wire and gas pipe needed to be determined for the analysis. However, measuring the pipe–wire friction is difficult. Instead, estimates of friction were obtained using the measurement method (Fig. 11) specified by the Japanese Standards Association protocol, JIS K 7125 (Takeshita et al., 2009).

The setup for this experiment required a stepping motor (AS911-ACE, Oriental Motor, Japan), motor driver (ASD-20A-C, Oriental Motor, Japan), and microcontroller (Arduino Uno, Arduino, Italy). Fastened with a piece of thread via a spring weighing scale (WH-A01A, Weiheng, USA), the wire was inserted into the pipe set on a platform. The free end of the thread was attached to the rotating arm of the stepping motor. By pulling the thread at a constant speed, the frictional force between wire and pipe was read from the spring scale. The coefficient of static friction was determined from the frictional force $F_S$ immediately before the test material started moving. The coefficient of dynamic friction was determined from the average value $F_D$ of the frictional force after movement. The experiment was performed three times, and the average was taken as the value for the coefficient of friction. The static and dynamic forces (Table 2) were divided by the wire mass of 0.6 kg to determine the static and dynamic friction coefficients as 0.0238 and 0.0211, respectively.

![Fig. 9. Free-vibration experiment. The red point was fixed and the blue point was freely vibrated.](image)

![Fig. 10. Result of free-vibration experiment. The red and blue line shows the experimental and analytical results, respectively.](image)

| Table 2 |
| --- |
| **Static and dynamic force values** |
| &nbsp; | $F_S$ (N) | $F_D$ (N) |
| 1st | 0.15 | 0.13 |
| 2nd | 0.13 | 0.12 |
| 3rd | 0.15 | 0.13 |
| Average | 0.143 | 0.127 |
5. Analysis

5.1 Modeling of guide wire

We analyzed the dynamics of the guide wire using the simultaneous equations of motion and numerical time integration. In designing a guide wire with different rigidities, it is necessary to simulate the movement of the wire inside the pipe. However, the movement of the wire cannot be measured directly. Therefore, the motion was estimated from wire simulation using computer modeling.

The guide wire was modeled by joining a rigid link with a rotatable spring with damping (Fig. 12). The length of one link is 1.0 cm. Each link was assumed to have rotational degrees of freedom in its X’-Y’ plane. Because the coordinates of the tip twists compared with the base when the guide wire is inserted into the pipeline. Local coordinates $X'_i$, $Y'_i$, and $Z'_i$ were selected for each link, and Euler angles were used for the global xyz coordinates.

5.2 Equation of motion

We derived the equations of motion for a finite number of rigid links. The Newton–Euler (Guo et al., 2018) and Lagrangian methods (Jafarinasab, Sirouspour and Dyer, 2019) are commonly used to derive the equations of motion. The configured wire model consisted of over 100 rigid links. However, deriving the individual equations of motion for each link is cumbersome. Furthermore, it is difficult to obtain the acceleration directly in the experiment. This makes it difficult to use the Newton–Euler method to derive the equations of motion in this case. However, the equations of motion for a rigid link can be derived deterministically from the Lagrangian. Thus, we used the Lagrangian method. The Lagrangian $L$ is expressed as

$$\dot{L} = T - U$$

where $T$ is the kinetic energy and $U$ the potential energy. The equation of motion was obtained from

$$\frac{d}{dx} \left( \frac{\partial L}{\partial \dot{\theta}_i} \right) - \frac{\partial L}{\partial \theta_i} + \frac{\partial D}{\partial \dot{\theta}_i} = Q_i(i = 1, 2, \ldots, n)$$

The quantities $T$, $U$, and $D$ were calculated as follows using Adams software (MSC Software, Newport Beach, California, USA):

![Fig. 11. Friction measurement. The motor rotated to pull the wire in the gas pipe.](image)

![Fig. 12. Guide wire model and coordinate systems. Since the tip of the guide wire goes along the shape of the pipeline, the coordinates of each link changes.](image)
\( T = \sum_{i=1}^{n} \frac{m_i(x_i^2 + y_i^2)}{2} + \sum_{i=1}^{n} \frac{i\theta_i^2}{2} \) (5)

\( U = \sum_{i=1}^{n} \frac{k\theta_i^2}{2} - \sum_{i=1}^{n} m_i g y_i \) (6)

\( D = \sum_{i=1}^{n} \frac{1}{2} c \dot{\theta}_i^2 \) (7)

where \( D \) is the damping energy; \( n \) is the number of tube links; \( m \) is the mass of a link; \( \theta \) is the joint angle; \( I \) is the moment of inertia; \( c \) is the damping coefficient; \( x_i, y_i, \) and \( z_i \) are the barycentric coordinates of the \( i \)-th link; and \( g \) is the gravitational acceleration. The values used for \( m_i \) and \( I_i \) in the analysis were the mass and inertia of the actual guide wire, and \( k \) and \( c \) were calculated using the experimental results of section IV.

5.3 Numerical time integration

We used the backward differentiation formula (BDF) (Choi, 2008), which involves the linear multistage solution method (multistage form). The multistage form uses not only the state quantity at time \( t_n \), but also past values that have been already obtained, from which a value at \( t_{n+1} \) is obtained via a formula with \( k \) steps including \( k+1 \) state quantities \( q_{n+1-k} \) from \( t_{n+1-k} \) to \( t_{n+1} \). Denoting \( F(q_i, t_i) \) as \( F_i \), the linear combination of coefficients \( F_{n+1-i} \) is obtained by setting the following equation to zero:

\[
\sum_{i=0}^{k} \alpha_i q_{n+1-i} + h \sum_{i=0}^{k} \beta_i F_{n+1-i} = 0
\] (8)

Because \( \alpha_0 = -1 \) is normally used for \( q_{n+1} \),

\[
q_{n+1} = \sum_{i=1}^{k} \alpha_i q_{n+1-i} + h \sum_{i=0}^{k} \beta_i F_{n+1-i}
\] (9)

Therefore, various methods are conceivable depending on the number of stages \( k \) and coefficients \( \alpha_i \) and \( \beta_i \). However, the method becomes implicit for \( \beta_0 \neq 0 \).

Next, the BDF method is briefly described. If \( \beta_i = 0 \) \( (i = 1, 2, ..., k) \) in (8), the following relation holds:

\[
q_{n+1} = \sum_{i=1}^{k} \alpha_i q_{n+1-i} + h \beta_0 F_{n+1}
\] (10)

where \( h \) is the step size. This form is the BDF (Brayton, Gustavson and Hachtel, 1972) and sets the function value \( F_{n+1} = F(q_{n+1}, t_{n+1}) \) at time \( t_{n+1} \) to \( t_{n+1} \) using the states \( q_{n+1-k} \) to \( q_{n+1} \). Unconditional stability is ensured by the implicit method using \( F(q_{n+1}, t_{n+1}) \) in the second term on the right side of (9). Typical methods of this type include those proposed by Gear (Gear, 1971) and Park. The former was used in this study. This method was devised to ensure stability against a hard system, which is expressed by an equation wherein the gradual change of the solution is mixed with an abrupt change. The algorithm used the equation

\[
q_{n+1} = \sum_{i=1}^{k} \alpha_i q_{n+1-i} + h \beta_0 F(q_{n+1-k}, t_{n+1})
\] (11)

The coefficients \( \alpha_i \) and \( \beta_0 \) are listed in Table 3 for \( k = 2 \) to 6. The Gear method ensures stability against product \( h \).

| Step | 2  | 3  | 4  | 5  | 6  |
|------|----|----|----|----|----|
| Denominator | B  | 3  | 11 | 25 | 137| 147|
| Element | \( \beta_0 \) | 2  | 6  | 12 | 60 | 60 |
|        | \( \alpha_1 \) | 4  | 18 | 48 | 300| 360|
|        | \( \alpha_2 \) | -1 | -9 | -36| -300| -450|
|        | \( \alpha_3 \) | 2  | 16 | 200| 400 |
|        | \( \alpha_4 \) | 3  | -75| -255|
|        | \( \alpha_5 \) | 12 | 72 |
|        | \( \alpha_6 \) | 10 |    |

Table 3: Parameter settings for Gear method
5.4 Insertion distance analysis

We developed a three-dimensional computer-aided design model of the gas pipe using SolidWorks (Fig. 13). The pipe model was configured with 25A piping with a length of 7.0 m like that of the external pipe. The pipe had eight turns consisting of four sets of two turns. An insertion analysis was performed for a completely rigid pipe. We assumed that the gas staff inserts the guide wire from the gas meter into the pipe by hand. Thus, the force applied to the wire during insertion was on average 80 N, which is the average force of gravity exerted on an adult male according to the human characteristics database of the National Institute of Technology and Evaluation, Japan (Human Characteristics Database, 2016). In addition, the force was applied to the wire at a position 10 cm away from the pipe entrance (Fig. 14) using a user-defined function. The wire parameters used in the analysis are listed in Table 4. The density, spring constant, and damping and friction coefficients were calculated using the Lagragian method above. The insertion distance was measured when the guide tube could not insert in the pipeline.

5.5 Optimization

We used the response surface method to optimize the length and rigidity of the guide wire. The response surface is a popular method to clarify the relationship between objective functions and design factors (Cheng, Mugge and de Bont, 2018; Hu et al., 2018; Ramos Barbero, Melgosa Pedrosa and Castrillo Peña, 2018; Abi Akle, Yannou and Minel, 2019; Belkadi et al., 2019; Benavides and Lara-Rapp, 2019; Paparistodimou et al., 2019; W. Li et al., 2019; Wang et al., 2019; Stylidis, Wickman and Söderberg, 2020). The design variables were the front external diameter $L_1$, rear external diameter $L_2$, front length $l$, and front pitch $s$, as shown in Fig. 6. The front and rear wire diameters were set to 1.0 mm and 1.6 mm, respectively. The objective function was to maximize the insertion distance of the guide wire.

An optimized solution was derived from the objective function. From the analytical results for the model selected by the experimental design method, we approximated the relationship between the design factors and the characteristic value using least squares. We estimated the analytical result for the model using the design variable.

The insertion distance of each guide wire was analyzed using the L18 orthogonal table (Table 4). The orthogonal table was based on the experimental design method for determining the efficient experimental condition without waste. In addition, we developed the response surface and derived the optimized solution (Table 5).
6. Experiment

We verified that the optimized guide wire enables insertion of an endoscope into external gas pipelines. We made the guide wire with the optimized solution in Table 5. Furthermore, we set the external gas pipeline to consist of the 25A pipes shown in Fig. 15. The total length was about 7.0 m. The gas pipeline was fixed.

The experimental procedure was as follows. First, the participant inserted the optimized guide wire into the external gas pipeline by hand, as shown in Fig. 16. Second, the participant inserted an endoscope (IPLEX RT IV9675RX, Olympus, Japan; Fig. 2) into the pipe. The endoscope was also inserted with its tip reaching the wire tip. Third, the participant withdrew the endoscope and the guide wire from the external gas pipe. We recorded the inside pipe using the camera with the endoscope.

Five individuals (all males, right-handed, 20–24 years old) participated in this study. We obtained informed consent from all participants before the experiments. It was the first time any of the participants had performed this experiment.

The result was that all participants were able to insert the guide wire and the endoscope, and observe the pipe interior while withdrawing the endoscope and the wire. The guide wire and endoscope can be inserted by the end of the pipe (7.0 m) by any participants. Figure 17 shows the snapshot of the recorded inside view of the gas pipe. The entire length of the pipe was checked within just 3 minutes. To validate the effectiveness of the guide wire design, the insertion experiments were carried out with a variety of the guide wires on Table 6. The guide wire (ii) is the optimized parameter. The insertion distances were measured by the rest length of the guide wire after inserting into the pipeline. As results, only the optimized guide wire enabled to be inserted into the pipeline whose length is 7.0 m, shown in Fig. 18.

| Table 4 | Analytical results based on L18 orthogonal table |
|---------|-----------------------------------------------|
| Wire model | $L_1$ (mm) | $L_2$ (mm) | $l$ (mm) | $s$ (mm) | Insertion distance (m) |
| 1 | 9 | 10 | 250 | 1 | 1.08 |
| 2 | 9 | 12 | 500 | 1 | 1.08 |
| 3 | 9 | 14 | 750 | 1 | 1.08 |
| 4 | 10 | 10 | 500 | 1 | 1.08 |
| 5 | 10 | 12 | 750 | 1 | 1.08 |
| 6 | 10 | 14 | 250 | 1 | 1.07 |
| 7 | 12 | 10 | 750 | 1 | 1.08 |
| 8 | 12 | 12 | 250 | 1 | 1.08 |
| 9 | 12 | 14 | 500 | 1 | 1.08 |
| 10 | 9 | 10 | 250 | 2 | 4.52 |
| 11 | 9 | 12 | 500 | 2 | 4.52 |
| 12 | 9 | 14 | 750 | 2 | 1.74 |
| 13 | 10 | 10 | 500 | 2 | 1.25 |
| 14 | 10 | 12 | 750 | 2 | 1.25 |
| 15 | 10 | 14 | 250 | 2 | 1.25 |
| 16 | 12 | 10 | 750 | 2 | 1.08 |
| 17 | 12 | 12 | 250 | 2 | 1.08 |
| 18 | 12 | 14 | 500 | 2 | 1.08 |

| Table 5 | Optimized guide wire parameter values |
|---------|-------------------------------------|
| Front outer diameter $L_1$ [mm] | 9.00 |
| (wire diameter 1.0 mm) | |
| Rear outer diameter $L_2$ [mm] | 11.30 |
| (wire diameter 1.6 mm) | |
| Front length l [mm] | 417.60 |
| Front pitch s [mm] | 2.00 |
| Insertion distance [m] | 4.52 |
Fig. 15. Gas pipeline used in the validation experiment. The pipeline was made of 25A pipe with eight turns consisting of four sets of two turns. The total length was about 7.0 m. This pipeline was the same as a buried external gas pipeline.

Fig. 16. Experimental overview: participants inserted the guide wire into the gas pipe by hand.

Fig. 17. Snapshot of the inside of the gas pipeline.

| Wire model | Front diameter $L_1$ mm | Front out $L'_1$ mm | Rear diameter $L_2$ mm | Rear out $L'_2$ mm | Pitch $s$ mm | Front part length $l$ mm |
|------------|-------------------------|---------------------|-------------------------|-------------------|-------------|-------------------------|
| (i)        | 9                       | 1.0                 | 12                      | 1.6               | 1.0         | 500                     |
| (ii)       | 9                       | 1.0                 | 11.30                   | 1.6               | 2.0         | 500                     |
| (iii)      | 12                      | 1.6                 | 12                      | 1.6               | 1.6         | 0                       |
| (iv)       | 10                      | 1.0                 | 12                      | 1.0               | 1.0         | 250                     |
| (v)        | 10                      | 1.0                 | 12                      | 1.0               | 2.0         | 250                     |
7. Discussion

It is usually impossible to observe the inside of a 25A gas pipe consisting of eight turns. We were able to obtain the inside view of a gas pipe using the optimized guide wire. Furthermore, the guide wire made it easy for amateurs to get the inside view of the gas pipe. All participants succeeded within just 3 minutes in their first time carrying out the experiment, compared with the more than 1 day needed in the conventional method because the buried gas pipe must be dug up.

The reason the guide wire could be inserted was its bi-rigidity, i.e., its different rigidities at its front and rear. The smaller wire diameter at the front made the front more flexible, which prevented the wire tip from buckling. Moreover, the larger rear diameter made the rear more rigid, which prevented the wire from meandering. Therefore, the low front rigidity and high rear rigidity of the optimized wire allowed it to pass through the entire test pipe.

Furthermore, the analytical and experimental insertion distances were different shown in Fig. 18. It could be caused by the change of the insertion forces by participant’s hands. However, the tendency of the wire insertion distance is similar between analysis and experiment. In future work, we will measure the forces of the participant’s hands during inserting and feedback the forces on analysis.

8. Conclusion

In this paper, we proposed a hollow guide wire with different front and rear rigidities to enable insertion of an endoscope to inspect the interior of a pipe. The guide wire was designed with different outer diameters at its front and rear segments. We measured the torsional spring constant of the wire and the coefficients of damping and friction of its segments. We simulated and analyzed insertion of the guide wire into the gas pipeline. The wire parameters were optimized, and we constructed the optimized wire to assess whether it enabled endoscope insertion to observe the inside of a gas pipe. All amateurs succeeded in the insertion experiment within just 3 minutes, making this guide wire more practical for observing a pipe interior than the conventional method of digging up a buried pipe. In future work, we will use such a wire to observe an actual buried pipe from a house gas meter with the cooperation of a gas company.

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