DEVELOPMENT OF A PERISTALTIC CRAWLING MOTION TYPE DUCT CLEANING ROBOT COMPATIBLE WITH CLEANING EFFICIENCY AND RUNNING SPEED BY CLEANING JOINT

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Air conditioning equipment using duct piping is used to ventilate residences. If this residential ducting is used in a dirty environment, it will lead to adverse effects on human health. Therefore, a method to clean the ducts is required. However, with existing duct cleaning tools, it is difficult to clean the duct perfectly. Therefore, a duct cleaning robot is required. In previous research, we focused on a peristaltic crawling motion type robot, and developed a type of drive brush mounting. Cleaning and driving experiments confirmed a cleaning efficiency of 97.2%; however, the speed fell below the target value of 4.6 mm/s. In this paper, we propose a cleaning joint that strives for both cleaning efficiency and driving speed. We aim to realize an optimal duct cleaning robot by comparing the drive brush mounting types with a robot equipped with the proposed method.

Keywords: Duct cleaning, Peristaltic crawling motion , In-pipe inspection robot.

1. Introduction

Air conditioning equipment that uses ducting plays a key role in keeping the indoor air of various types of buildings clean. However, if dust in the duct is sent inside the building, together with the ventilation air, it causes a decrease in cleanliness and leads to health damage, such as sick house syndrome [1]. Therefore, duct cleaning is necessary.

The outline of the conventional cleaning method is shown in Fig. 1. The duct of a large building, such as a factory, has a large cross sectional area and has few curved parts, so cleaning in this way is relatively easy. cleaning agency use a propeller-attached brush and an Air lance (Nihon Winton, Tokyo, Japan), on a pneumatically driven cleaning device, as a cleaning tool for large building ducts [2]. A pneumatically driven cleaning tool has a cleaning portion at the tip of an air tube. This is pushed into the duct, and a cleaning portion at the tip removes the dust, by applying air pressure. On the other hand, the ducts in domestic housing, which are generally 75 mm inside diameter, have a relatively small duct diameter

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and many curved parts. In a housing duct, even if the cleaning tool is pushed inside, it cannot move deeply into the duct due to the friction at curved portions of the ducting. Hence, it is difficult to clean the housing duct completely. Therefore, the development of a duct cleaning robot capable of cleaning housing ducts is required. There are three requirements for a duct cleaning robot: being able to move while negotiating a number of curved parts in the duct, be capable of rapid cleaning, and to remove the dust from the duct. Existing in-pipe traveling robots include snake types, wheel types, cilia vibration types, and peristaltic crawling motion types. However, each of these has problems. Since the snake type robot meanders, it requires a large driving space. The wheel type of robot is difficult to miniaturize, because it is equipped with a motor. the cilia vibration type robot is unable to drive in reverse [3]-[7]. On the other hand, the peristaltic crawling movement type is a movement method that propagates through the expansion and contraction of the body segment in the axial direction, imitating the peristaltic crawling motion of the earthworm. Because of this, it is possible to drive with stability in a thin tube. Existing peristaltic crawling motion robots have been used as inspection devices for both sewer pipes, and gas pipes. They have a high traction force, and can break through right angle pipes [8][9]. The peristaltic crawling motion type of robot can be expected to satisfy the driving performance required, for a duct cleaning robot.

The authors considered a peristaltic crawling motion type duct cleaning robot, and devised a cleaning unit and a cleaning joint. In the previous study, we developed a type of drive brush mounting (type-A) with cleaning unit, and confirmed it had a cleaning efficiency of 97.2 %, and a speed of 4.3 mm/s, in a cleaning experiment using simulated dust [10]. However, we have not yet investigated the cleaning efficiency and speed performance of a robot equipped with a cleaning joint which is the other cleaning tool. Therefore, in this paper, we discuss the development of a robot equipped with a cleaning joint, and investigate the cleaning efficiency and driving speed. Based on the experimental results, we attempted to balance the cleaning efficiency and driving speed of the peristaltic crawling motion type duct cleaning robot.

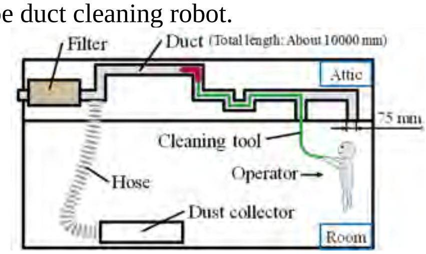


Fig. 1 Existing cleaning method

2. Duct cleaning and the need for a duct cleaning robot

We explain the procedure of cleaning a duct in a house. Firstly, ventilation is stopped in the whole house. Next, the operator takes one end of the duct installed in the attic, inserts a cleaning tool, and peels off dust adhering to the inside of the duct (Fig. 2). Finally, the operator applies suction to the peeling dust, using a dust collector attached to the other end. The time needed to clean the ducting in a house is about six hours. The duct used in houses (Fig. 3) has an inner diameter of 75 mm, a radius of curvature of 1000 mm, and a length of about 10 m. One house would require between 8–10 m of ducting. This ducting easily bends and stretches, and has many curved parts.

The requirements for a duct cleaning robot are as follows. The first is driving performance: it is necessary to be able to insert the robot into the duct and it must adapt to many bends. The second is speed performance: in order to clean 10 ducts within 6 hours, the target speed is 4.6 mm/s. The third is cleaning performance: it is necessary to be able to peel the dust from the inner wall of the duct, and to make it possible to use suction to remove it with the dust collector.

Fig. 2 Dust adhered in the duct

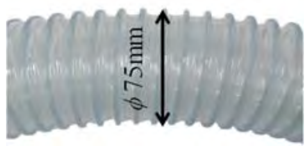


Fig. 3 Appearance of duct

3. Peristaltic crawling motion type duct cleaning robot

In this chapter, we discuss the movement and cleaning methods that satisfy the requirements described in Chapter 2.

First, we describe the movement methods. Existing in-pipe driving robots cannot be used as a cleaning robot, because they are difficult to make small enough, and do not operate in reverse. Therefore, we focused on a peristaltic crawling motion type robot, which is excellent in traction, and can be miniaturized.

The peristaltic-crawling-motion-type-robot consists of a driving unit responsible for movement, and a joint connecting the constituent parts. The driving unit uses a straight-fiber-type artificial muscle. This artificial muscle is a structure in which natural rubber, containing carbon fibers arranged in a single direction, is molded into a tube shape. Therefore, the expansion of the driving unit in the axial direction is restricted. Hence, when air pressure is applied, it expands in the radial direction and contracts in the axial direction, as shown in Fig. 5 (b). By propagating this movement from the head to the back, it moves as shown in Fig. 6. In a previous study, a peristaltic crawling robot with the same diameter as the duct (type-N) confirmed that it had a running speed of 9.8 mm/s [10]. This performance satisfies the requirements of the driving speed, which is 4.6 mm/s.

Next, we describe the cleaning method. Candidates for the cleaning methods are two existing cleaning tools: the Air lance, and a brush. The Air lance is a cleaning tool for large-sized ducts, and cannot clean inside a narrow duct. When a brush is used, it can be classified into three different types of robots: drive brush mounting type (type-A), top brush mounting type (type-B), and joint brush mounting type (type-C), as shown in Fig. 4.

Type-A is a robot equipped with a cleaning unit comprising a type-N driving unit wrapped around a brush. Type-A robots move while pressing the brush against the inner wall of the duct, ensuring it can be cleaned reliably.

Type-B is a robot with a cleaning joint comprising a type-N joint wrapped around a brush. Type-B robots peel off the dust by pushing out the brush while simultaneously advancing through the duct. However, the speed decreases due to the friction between the brush and the inner wall of the duct.

Type-C is a robot with a cleaning joint on the top, between the driving units. Cleaning can be performed reliably by increasing the number of cleaning points. However, since the friction between the brush and the inner wall of the duct also increases, it is predicted that the speed reduction is larger than type-B.

In the previous study, a type-A robot was examined. The type-A robot was confirmed to have a cleaning efficiency of 97.2 %, and a speed of 4.3 mm/s. Although the cleaning performance was sufficient, the speed fell below the target speed of 4.6 mm/s. That is, the type-A robot is inappropriate as a cleaning tool. Therefore, after considering the cleaning joint, we compared robots of types A, B and C.

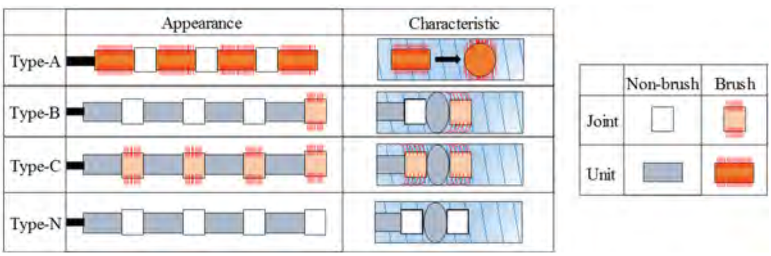
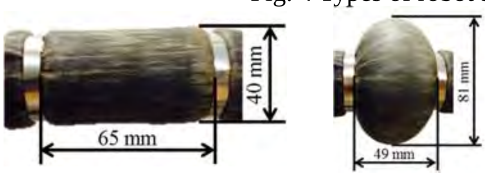


Fig. 4 Types of robot structure



(a) Unpressurized (b) Pressurized

Fig. 5 Appearance of a driving unit

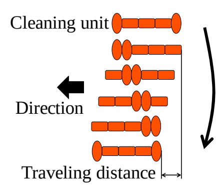


Fig. 6 Operation progress of the air duct cleaning robot

4. Drive brush mounting type (type-A) robot

Figure 7 and Fig. 8 show the drive brush mounting type robot (type-A) and cleaning unit, developed in the previous research. Type-A is a robot with a brush seat wound around the driving unit of a peristaltic crawling motion type robot, without a cleaning function (type-N). When air pressure is applied to the type-A robot, the brush is pressed against the inner wall of the duct due to expansion of the driving unit in the radial direction, thereby removing the dust. The brush uses nylon bristles, with a hair length of 11 mm. A cleaning efficiency 97.2 %, and speed 4.3 mm/s were confirmed by a cleaning experiment.

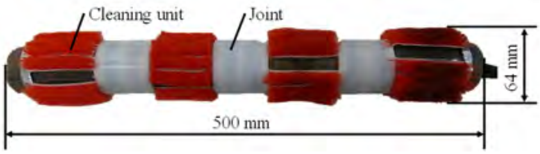


Fig. 7 Appearance of the drive brush mounting type (type-A)

Fig. 8 Appearance of the cleaning unit

5. The peristaltic motion type duct cleaning robot using a cleaning joint

In Chapter 5, we propose a cleaning joint as a cleaning method, which works by attaching brushes to places other than the driving unit. Further, we considered the optimum shape of the brush.

5.1. *Cleaning unit*

The cleaning joint shown in Fig. 9 has a structure in which a sheet of nylon brush material (Fig. 10), is wrapped around the joint of the duct cleaning robot (type-N). The cleaning joints can be mounted at both ends of the type-N robot, or between the driving units. Since it drives while also rubbing the brush against the inner wall of the duct, it can be expected that the duct would be cleaned thoroughly.

Fig. 9 Appearance of the cleaning joint

Fig. 10 Appearance of the brush sheet

5.2. *Consideration of the cleaning joint*

We estimate that the diameter of the cleaning joint, and the area of the brush, will both affect the cleaning efficiency and speed of the robot. However, it is difficult to determine how the interaction of all the different design parameters can affect the performance of the robot. Therefore, we limited the range of parameters to be investigated to the diameter of the cleaning joint, and conducted an experiment where we considered the influence of the diameter of the cleaning joint on both cleaning efficiency and speed. We conducted experiments with two patterns of top brush mounting type (type-B), and joint brush mounting type (type-C), as shown in Fig. 11. We investigated the optimum diameter for each type. Furthermore, by comparing the experiment results of type-B and type-C robots, with the experimental results of a drive brush mounting type (type-A) and peristaltic crawling motion type robot without cleaning function (type-N), we decided on a practical peristaltic crawling motion type duct cleaning robot. The diameter of the cleaning joint used in the experiment was equal to, greater than, and less than the inner diameter of the duct. Specifically, a cleaning joint with three outer diameters of 73 mm, 75 mm, and 77 mm were prototyped. They were each mounted in both a type-B and a type-C robot. Hereinafter, these are referred to as type: B-1, B-2, B-3, C-1, C-2 and C-3.

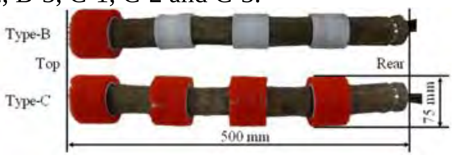


Fig. 11 Appearance of duct cleaning robots equipped with a cleaning joint.

6. Driving experiment of top brush mounting type (type-B) and joint brush mounting type (type-C) robots

In this chapter, we perform driving experiments with all six types of brush format mentioned in section 5.2. The robot was driven into the duct, then the time taken to travel through a 500 mm section was measured, from which the speed was calculated.

6.1. *Experimental environment of the driving experiment*

The experimental environment is shown in Fig. 12. The pressure applied to the driving unit was set to 0.1 MPa, and the contraction and extension time were set to 0.6 s.

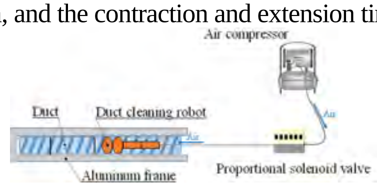


Fig. 12 Environment of the driving experiment

6.2. *Experimental results of the driving experiment*

The experimental results are shown in Fig. 13. We confirmed that all six robots of type B and type C exceeded the target speed of 4.6 mm/s. In addition, we confirmed that type B-1, B-2, and C-1 speeds were equivalent to a type-N speed. We considered that the type-C robot speed is lower than the type-B robot speed because the movement of the driving unit was hindered. The movement of the driving unit was hindered by the expansion and contraction of the duct, caused by the friction of the multiple brushes.

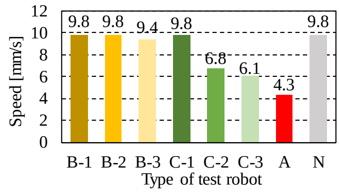


Fig. 13 Speed of robot

7. Cleaning experiment of top brush mounting type (type-B) and joint brush mounting type (type-C) robots

In this chapter, we perform cleaning experiments with all the six types mentioned in section 5.2. Evaluation of the cleaning experiment was conducted using the parameter of cleaning efficiency E (%). The cleaning efficiency (E) is shown in equation (1):

$$E = (1 - \frac{m}{M}) \times 100 \tag{1}$$

where m is the mass of the object to be cleaned (after cleaning), and M is the mass of the object to be cleaned (before cleaning).

7.1. *Experimental environment of the cleaning experiment*

The experimental environment is shown in Fig. 12. The object to be cleaned (50 g of silica sand) was fixed to the 500 mm section of the inner wall of the duct.

7.2. *Experimental results of the cleaning experiment*

The experimental results are shown in Fig. 14. It was confirmed that the cleaning efficiency increased as the diameter of the cleaning joint increased, and that the cleaning efficiency of type C-3 robot was higher than that of type A robot. The reason why the cleaning efficiency increases as the diameter of the cleaning joint increases, is because the friction increases between the brush of the cleaning joint and the inner wall of the duct. From the experimental results in Sections 6.2 and 7.2, it can be confirmed that type C-3 exceeds a type-A robot in both cleaning efficiency and speed. Therefore, we consider that the optimum cleaning tool for the duct cleaning robot is a cleaning joint, with a diameter of 77 mm.

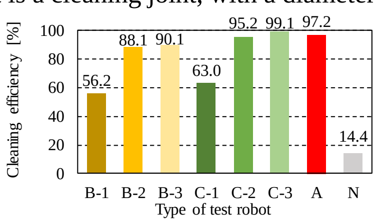


Fig. 14 Cleaning performance of the robot

8. Conclusion

A cleaning joint was proposed to achieve both the required cleaning efficiency and speed. In order to explore the optimum diameter of the cleaning joint, a trial production of three different diameter cleaning joints were made. The cleaning efficiency and speed of both a top brush mounting type (type-B), and joint brush mounting type (type-C) were measured, using three different diameters of cleaning joints. From the results, it was confirmed that the type-B robot, equipped with the 77 mm diameter cleaning joint, had a cleaning efficiency of 99.1%, and a speed of 6.1 mm/s. Therefore, we consider that a type-B robot equipped with a 77 mm diameter cleaning joint is best suited as a peristaltic crawling motion type duct cleaning robot.

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