Design of a self-propelled mechanism to be mounted on a capsule endoscope that made it possible to observe the stomach

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Endoscopic examination is a method examination of the digestive tract, and a scope endoscope is mainly used. However, since the scope endoscope continuously stimulates the pharynx when inserting camera, it gives pain to the patient. In order to remedy this drawback, a capsule endoscope has been developed. Since the capsule endoscope only corresponds to the small intestine and the large intestine, a scope endoscope is used for the examination of the stomach. Therefore, examination of the stomach gives a pain to the patient. In this study, we design a self-propelled mechanism to be mounted on a capsule endoscope that made it possible to observe the stomach. In this paper, we propose and design and evaluate the self-propelled mechanism that enables the observation of the stomach. And we also construct a motion analysis system that uses motion simulation.

Keywords: Capsule endoscope, self-propelled mechanism, stomach, Magnetic actuator, Piston pump

1. Introduction

The scope endoscope continuously stimulates the pharynx when inserting the camera [1]. Therefore, it has a drawback that pain is given to the patient. The capsule endoscope was developed to remedy this drawback. Fig. 1 is a capsule endoscope (Given imaging Ltd.). Since the capsule endoscope has a shape like a tablet, it can be inspected simply by swallowing. Therefore, the pain caused by the scope endoscope was alleviated. However, the capsule endoscope propell according to the peristaltic movement of the digestive tract. Therefore, it cannot be used in the examination of the stomach with a wide lumen. Therefore, examination of the stomach gives a pain to the patient. A capsule endoscope that enables observation of the stomach is necessary to alleviate the pain of the patient. Several studies conducted to observe the stomach have capsule endoscopes with magnets that are propelled by applying a magnetic field from outside the body [2] [3] [4]. Also, some are propelled using projections and fins attached to the capsule endoscope [4] [5]. Since there have large equipment outside, there are problems such as restraining the patient and the possibility that protrusions and like may hurt the stomach and intestines. Therefore, we aim to develop a self-propelled mechanism that mounts the mechanism inside the capsule endoscope without using large external equipment.

In this study, we design a self-propelled mechanism to be mounted on a capsule endoscope that made it possible to observe the stomach. In this paper, we propose and design and evaluate the self-propelled mechanism that enables the observation of the stomach.

Fig.1 Capsule endoscope (Given imaging Ltd.).

And we also construct a motion analysis system that uses motion simulation.

2. Proposal of self-propelled mechanism to be mounted on a capsule endoscope

In this chapter, we describe the concept and design of a self-propelled mechanism mounted on a capsule endoscope [6].

2.1 Concept of proposed capsule endoscope

Currently, the capsule endoscope is propelled according to the peristaltic movement of the digestive tract. Therefore, it cannot be used in the stomach having a large lumen. Because the scope endoscope is used for the examination of the stomach, it gives pain to the patient. In this study, we design of a self-propelled mechanism to be mounted on a capsule endoscope that made it possible to observe the stomach. Table 1 shows the concept of the proposed capsule endoscope.

In the case of endoscopic examination, since the stomach is in a deflated state, adopted an inspection method that fills the stomach with water. Therefore, we proposed a capsule endoscope mounted with self-propelled mechanism which can propel using water pressure.

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Table 1 The concept of the proposed capsule endoscope.

| Operation               | Remote         |
|-------------------------|----------------|
| Power supply            | Wireless power transmission |
| Operating environment   | Underwater     |
| Direction of motion     | Promotion, Slope, Retention |
| Propulsion method       | Water pressure |

In addition, since the driving source is mounted inside the capsule endoscope, it is necessary to utilize a mechanism capable of downsizing. By using the positive displacement pump, we realize the function to adjust the discharge amount. A reciprocating pump was selected from the positive displacement pump. This is because the structure is simple and it is easy to control the discharge amount. Also, a direct drive which is easy to raise the driving force without taking a large capacity is suitable. Therefore, a magnetic actuator was used as the driving source. Fig. 3 shows the operating principle of the driving source. The flow of the magnetic flux generated from the piston composed of the permanent magnet returns to the piston through the iron.

![Fig.3 Principle of drive source mechanism.](image)

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Electromagnetic force is generated by magnetic flux and current. The electromagnetic force generated causes the piston to operate. Fig. 4 shows an operation image of the drive source. Water was inhaled by moving the piston in the +z axis direction with the valve closed. Then the water move to the right side of the piston by opening the valve and returning the piston to its original position. Also, by closing the valve and moving the piston in the +z axis direction, water is discharged and sucked, and by repeating the above operation, it plays a role of a pump.

2.3 Design of drive source

The size of the drive source to be designed was \( \Phi 10 \text{mm} \times 15 \text{mm} \), which scale is the half size of the capsule endoscope undergoing clinical experiments. We evaluated the number of turns of the coil and the electrical current density. We seted the space factor on 50\%. Also we set the average value of the hand winding coil and the current density value on 10 A/mm\(^2\) or less. The cross-sectional area of the copper wire was 0.53 mm\(^2\) [7].

2.3.1 Selection of drive source dimensions

Calculation of the number of turns of the coil and the electrical current density was carried out using the above required requirements and the expressions (1) and (2).

\[
N = \frac{S_w}{S_i} \times \frac{\sigma}{100} \tag{1}
\]

\[
J = \frac{NI}{N} \times \frac{1}{S_i} \tag{2}
\]

\( N \): Turn [turn] \hspace{1cm} \( S_w \): Cross-sectional area of coil [mm\(^2\)]

\( S_i \): Cross section of copper wire [mm\(^2\)] \hspace{1cm} \( \sigma \): Space factor [%]

\( J \): Current density [A/mm\(^2\)] \hspace{1cm} \( NI \): Magnetomotive force [A]

Fig. 5 shows the calculated sectional area of the coil. As a result of substituting the cross-sectional area 14 mm \( \times \) 1 mm for the formulas (1) and (2), the current density was 8.49 A / mm\(^2\) and the number of turns was 66 turn. Next, in order to select the size of the piston, analysis was performed using J-mag designer 2013. Tables 2 and 3 show conditions and setting materials for analysis of generated force in piston dimensions. Also, Fig. 6 shows the analysis result of the force based on the dimension of the piston. When the piston dimensions were 7 [mm], no force value in the minus direction was generated, and the result that the change depending on the position of the piston was also small was obtained.

2.3.2 Structure of drive source

Fig. 7 shows the structure of the designed drive source. The reciprocating pump has a size of \( \Phi 10 \text{mm} \times 15 \text{mm} \) equipped with a piston to which a valve was attached. Two reversed coils were attached and the piston reciprocates by changing the direction of the current applied to the coil.

| Table 2 | Conditions for analysis of generated force in piston dimensions |
|---------|---------------------------------------------------------------|
| Number of turns: \( N \) | 60 [turn] |
| Current: \( I \) | 0.5[A] |

| Table 3 | Setting material for analysis of generated force in piston dimensions. |
|---------|-------------------------------------|
| Parts | Material |
| permanent magnet | NEOMAX-35H |
| Iron | S10C |

Fig. 6 The analysis results of the force based on the dimensions of the piston.
2.4 Characteristics of the designed drive source

The relationship between the generated force and the magnetomotive force was analyzed. Fig. 8 and 9 show the analysis results of the designed driving source. The result in Fig. 8 shows that the generated force increased as the magnetomotive force increased.

Also, the result in Fig. 9 shows that the generated force symmetrically occurs around $z = 0$. From this, it can be said that the design of the drive source was made easier.

3. Construction of motion analysis system

3.1 Deriving necessary parameters

The flow promoted by the capsule endoscope is three functions: Apply current alternately, the piston reciprocates and ejects water, the capsule endoscope propels by the reaction force of injected water. From the above, in order to construct a motion analysis system, a relational expression between thrust and injection force, relational expression of piston force and injection force, relational expression of generated force and piston force is required. Therefore, an operation model was prepared and a relational expression was derived.

3.1.1 The force applied to the capsule endoscope

Fig. 10 shows an operation model of the capsule endoscope. From Fig. 10, equation (3) holds.

$$F = F_n - R$$

$$= f_n - \frac{1}{2} \rho C_d S V^2$$

(3)

$F$: Injection force [N]  
$f_n$: Reaction force [N]  
$R$: Resistance [kg·m/s²]  
$\rho$: Fluid density [kg/m³]  
$S$: Cross-sectional area of capsule [m²]  
$C_d$: Drag coefficient  
$V$: Speed [m/s]

Also, from the theory of conservation of momentum, it becomes equation (4).

$$f_n = f_m = \rho S m v_m^2$$

(4)

$f_n$: Jet power [N]  
$\rho v_m$: Water speed [m/s]  
$S_m$: The area of the discharge port [m²]
When equation (4) was substituted into equation (3) and the mass of the capsule endoscope is m, equation (5) was obtained.

\[ F = \rho S_m v_m^2 - \frac{1}{2} C_d \rho S V^2 \]  

\( F \): Injection force \([\text{N}]\)  
\( f_r \): Reaction force \([\text{N}]\)  
\( R \): Resistance \([\text{kg} \cdot \text{m/s}^2]\)  
\( \rho \): Fluid density \([\text{kg/m}^3]\)  
\( S \): Cross-sectional area of capsule \([\text{m}^2]\)  
\( C_d \): Drag coefficient  
\( v_m \): Water speed \([\text{m/s}]\)  
\( V \): Speed \([\text{m/s}]\)  
\( S_m \): The area of the discharge port \([\text{m}^2]\)  

Therefore, substitute values into equation (5) and perform motion simulation.

3.1.2 Relationship between speed of piston and speed of water to be injected

Fig. 11 shows the image of the discharge port of the capsule endoscope. The method in which three discharge ports were mounted on the rear portion of the capsule endoscope and the discharge direction was controlled using a valve is studied. Since the proposed capsule endoscope had an outer diameter of \( \Phi \) 10 mm, the diameter of one ejection port was set to \( \Phi \) 4.6 mm. When advancing straight through the capsule endoscope, we assumed that the area of the discharge port was 49.9 mm\(^2\) in order to open all three valves. Also, assuming that the speed of the water in the self-propelled mechanism and the speed of the piston were the same, the relationship between the piston speed and the speed of the injected water was given by equation (6) from the momentum conservation law.

\[ S_m v_m = S_p v_p \]  

\( S_m \): The area of the discharge port \([\text{m}^2]\)  
\( v_m \): Water velocity \([\text{m/s}]\)  
\( S_p \): Piston area \([\text{m}^2]\)  
\( v_p \): Piston speed \([\text{m/s}]\)  

From the above, the equation (7) holds.

\[ v_p = 1.76 v_m \]  

Therefore, used the equation (7), the current which realizes the required piston speed is obtained and the operation of the piston is controlled.
Introduction in the $I, x_{outer}$-F Block, we stored the thrust characteristic waveform of the analysis result done in Section 2.4, and output the thrust of the actuator based on the current value $I$ and displacement $x_{outer}$. In the $F$ Loss block, calculate how the capsule endoscope that got the reaction force of $x_{outer}$ loses thrust due to friction in the water. Finally, the $X_{ce}$ Calculation block calculates the displacement and speed of the capsule based on the propulsion force obtained by the capsule. The above system is created using numerical analysis software MATLAB Simulink. We will consider whether the propulsion distance of the capsule endoscope which the self-propelled mechanism designed by using the constructed system can be realized.

4. Conclusion

In this paper, we proposed a proposal, design, analysis, motion analysis system of self-propelled mechanism installed in a capsule endoscope that can observe the stomach. From the analysis results, it was found that the designed drive source can easily control the power generation power $F$ by the current $I$. Therefore, it can be said that the drive source can be controlled by constructing a system that controls the current $I$. Therefore, in order to construct a system controlled by electric current, an operation model was created and an image of motion analysis system was constructed. In the future, we build a system using MATLAB Simulink numerical analysis software and simulate whether capsule endoscope can be propelled underwater. After performing the simulation, the actual machine of the self-propelled mechanism is made and the operation evaluation is carried out.

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