Impulse-driven Micromechanism Capsule*

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Abstract
We have developed a traveling small capsule, which has a smooth outer surface and is driven by inertia force and friction force. Measuring only 7 mm in diameter and 12 mm in length, it is sufficiently small to be placed in the human gullet or intestines. The capsule contains a small magnet and a coil, and an electric pulse drives the magnet to move the capsule. We performed an experimental investigation on making our capsule travel on a plastic material, which has similar elasticity characteristics to the living body. We also showed that it can travel on the surface of a pig’s intestine. Our capsule may be useful for medical treatments such as inspection, drug delivery and operation.

Key words: Micromechanism, Capsule, Magnetic Force, Friction Force, Pulse

1. Introduction
Seventy percent of the human body is composed of soft tubes with diameter ranging from µm order to cm order. Therefore, capsules which can travel inside these tubes are useful for medical treatments such as inspection, drug delivery and operation. Various kinds of machines for this purpose have been proposed (1) but most of them had hands in order to crawl in tubes (2),(3),(4),(5),(6). However, the outer surface of the machine should not have any projections so as not to injure the surrounding site. Machines that have a smooth outer surface and crawl have been developed. Among them, some utilized a fluid actuator to move (7),(8), but it was more than 30 mm long and needed a high-power fluid pump. To avoid using legs or hands to crawl, eel-like mechanisms were theoretically analyzed (9),(10), and inchworm-type robots were developed (11), but they had relatively complicated mechanisms and it was difficult to make them as small as medicine tablets. This paper describes a traveling small capsule, which has a smooth surface and is driven by inertia force and friction force. Measuring only 7 mm in diameter and 12 mm in length, our capsule is sufficiently small to be placed in the human gullet or intestines.

2. Theoretical analysis

2.1. Structure and principle of the traveling capsule

Our capsule travels by a to-and-fro motion of an inner mass. The capsule consists of the body (M) with coil and the moving mass (m) as shown in Fig. 1. Their parameters are listed in Table 1. The coil is made by 200 turns of φ0.05 mm copper. The moving mass is an Nd-Fe-B permanent magnet and is driven by magnetic force $f_m$ by applying a step-shaped
current to the coil. The outside appearance of the capsule is shown in Fig. 2.

![Schematic illustration of the capsule (cross section).](image1)

**Table 1  Parameters of the capsule**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Symbol</th>
<th>Quantity</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capsule body mass</td>
<td>M</td>
<td>$1.25 \times 10^{-3}$ [kg]</td>
<td>Al</td>
</tr>
<tr>
<td>Permanent magnet mass</td>
<td>m</td>
<td>$0.426 \times 10^{-3}$ [kg]</td>
<td>Nd-Fe-B</td>
</tr>
</tbody>
</table>

![Photograph of the traveling capsule.](image2)

The physical model of the capsule is shown in Fig. 3. The movement of mass m is restricted between two stoppers A and B. The resistance force $f_r$ acts against the movement of the body M from the base. For simplicity, we neglected the friction force between m and M, which is relatively very small and does not play a major role in propelling the capsule. For the theoretical analysis, the motion of the capsule is divided into the following four steps.

Step 1: As shown in Fig. 3 (i), M and m pull each other by magnetic force $f_m$. The mass m that starts from stopper A is accelerated by the magnetic force $f_m$ and also the body M is accelerated by the force $(f_m - f_r)$ until m collides with M at stopper B. Defining that M moves by distance $x_0$ to right side and m $u_0$ to left side in time $t_0$ by that motion, we will be able to determine these values.

Step 2: As shown in Fig. 3 (ii), we assume that after collision, M and m move together with initial velocity $v_0$, are decelerated by friction force $f_r$ and finally come to a stop. Defining that M and m move by $x_1$ to the left within time $t_1$ by the motion shown in Fig. 3 (iii), we can determine these values.

Step 3: Like Step 1, upon applying magnetic force $-f_m'$ by adding a (-) step-shaped current to the coil, M and m push each other. The mass m that starts from stopper B is accelerated by magnetic force $f_m'$ and also the body M is accelerated by the force $(f_m' - f_r)$ until m collides with M at stopper A. Defining that M moves by distance $x_0'$ to the left within time $t_0'$ in that motion, we can determine these values.

Step 4: Like Step 2, M and m move together with initial velocity $v_0'$, are decelerated by friction force $f_r$, and then come to a stop. Defining that M and m move by $x_1'$ to the right within $t_1'$ in that motion, we can determine these values.

As a result, defining that the body M moves $x_f$ to the left within time $t_f$, they will be expressed by the following two equations:

$$x_f = (x_1 - x_0) - (x_1' - x_0')$$  \hspace{1cm} (1)

$$t_f = t_0 + t_1 + t_0' + t_1'$$  \hspace{1cm} (2)
In the design, we should aim to increase the value of $x_T$ and decrease the value of $t_T$.

### 2.2. Equations of capsule motion

We can obtain equations of motion in each step as follows:

**Step 1:** We define that $x$ and $u$ are displacements of $M$ and $m$ respectively, and that $a$ is the total gap between the moving mass and stoppers. For $M$ and $m$, equations of motion are expressed by,

\begin{align*}
M \cdot \ddot{x} + f_r &= f_m, \\
m \cdot \ddot{u} &= f_m.
\end{align*}

(3) \hspace{1cm} (4)

Actually, magnetic force $f_m$ varies depending on the displacement $x$, $u$ but for simplicity, we set $f_m$ to be constant as an approximation.

From equations (3) and (4), the velocities $\dot{x}$, $\dot{u}$ and the displacements $x$, $u$ become as follows:

\begin{align*}
\dot{x} &= \frac{f_m - f_r}{M} \cdot t, \\
\dot{u} &= \frac{f_m}{m} \cdot t, \\
x &= \frac{f_m - f_r}{M} \cdot \frac{t^2}{2}, \\
u &= \frac{f_m}{m} \cdot \frac{t^2}{2}.
\end{align*}

(5) \hspace{1cm} (6)

As collision occurs when $x + u = a$, the time $t_0$ and the displacement $x_0$ at that moment become,

\begin{align*}
t_0 &= \frac{1}{\sqrt{(n+1)f - 1}} K_r, \\
x_0 &= \frac{f - 1}{(n+1)f - 1} a
\end{align*}

(7) \hspace{1cm} (8)

where the mass ratio $n$ and force ratio $f$ are defined as follows:

\begin{align*}
n &= \frac{M}{m}, \hspace{1cm} f = \frac{f_m}{f_r}.
\end{align*}

(9)

**Step 2:** Assuming that the collision is inelastic, that is, the coefficient of restitution $e = 0$, the initial velocity $v_0$ of the body (combined mass $M+m$) is expressed as follows:

\begin{align*}
v_0 &= \left(\frac{m \cdot \dot{u} - M \cdot \dot{x}}{M + m}\right)_{t=t_0}
\end{align*}

\begin{align*}
&= \frac{n}{(n+1)f - 1} \sqrt{2af_r} \\
&= \frac{n}{(n+1)f - 1} \sqrt{M}.
\end{align*}

(10)

Therefore, the equation of motion for the combined mass becomes,

\begin{align*}
(M + m)\ddot{x} + f_r &= 0, \\
\left(\dot{x}\right)_{t=0} &= v_0
\end{align*}

(11)

Solving the above equation,

\begin{align*}
\dot{x} &= v_0 - \frac{f_r}{M + m} \cdot t, \\
x &= v_0 t - \frac{f_r}{M + m} \cdot \frac{t^2}{2}.
\end{align*}

(12)

As the combined mass moves until $\dot{x} = 0$, the time $t_1$ and displacement $x_1$ at this moment are expressed as follows:

\begin{align*}
t_1 &= \frac{1}{\sqrt{(n+1)f - 1}} \sqrt{\frac{2aM}{f_r}} \\
x_1 &= \frac{n}{(n+1)(n+1)f - 1} a
\end{align*}

(13) \hspace{1cm} (14)

**Step 3:** Similar equations as used in Step 1 can be used. However, the direction of motion $x$ is reversed and the value of driving force $f_m'$ must be different from $f_m$, so the
values of $t_0'$ and $x_0'$ are obtained as follows:

$$
t_0' = \frac{1}{\sqrt{(n+1)f' - 1}} \sqrt{\frac{2aM}{f_M}} \quad (15)
$$

$$
x_0' = \frac{f'^{-1}}{(n-1)f'^{-1}} a \quad (16)
$$

Step 4: Similar equations as used in Step 2 can be used. Changing the direction of $x$ and changing $f_m$ to $f_m'$, the values of $t_1'$ and $x_1'$ are obtained as follows:

$$
t_1' = \frac{1}{\sqrt{(n+1)f' - 1}} \sqrt{\frac{2aM}{f_M}} \quad (17)
$$

$$
x_1' = \frac{n}{(n+1)(n+1)f'^{-1}} a \quad (18)
$$

The motions obtained from these equations are summarized in Fig. 4.

2.3. Examination of the theoretical analysis

The following important results are derived from the above theoretical analysis. (1) Regarding the traveling, stroke $x_T$ is expressed by the following equations:

Fig. 3  Traveling mechanism of the capsule.

Fig. 4  Summary of result of analyzed motion.
(2) Regarding the period \( t_r \) for a stroke,

\[
\Delta t = C_s \cdot a \quad , \quad C_s = \frac{(2n+1)-(n+1)f}{(n+1)((n+1)f-1)}
\]  

(21)

(22)

(3) The traveling speed is the most important factor when designing the traveling capsule. From the above analysis, it is clear that one stroke motion of inner mass \( m \) dominates the total speed. To see the tendency of the force-speed relation, one stroke motion is considered first as follows. The equations for traveling speed \( S \) are expressed as follows:

\[
S = \frac{\Delta x}{\Delta t} = C_s \cdot K_s
\]  

\[
C_s = \frac{C_t}{C_s} = \frac{2(n+1)-(n+1)f}{2(n+1)(n+1)f-1} \quad , \quad K_s = \frac{a \cdot f_s}{2M}
\]  

The effect of \( n \) and \( f \) on the coefficient of traveling speed \( C_s \) is summarized in Fig. 5. In the figure, force ratio \( f (= f_m/f_s) \) should be greater than 1, because friction force between the capsule and the base cannot be greater than magnetic force \( f_m \) while the capsule is moving. From the figure, it is found that we can choose the parameters as follows to design the high-speed capsule:

(a) Mass ratio \( n \) should be small.
(b) Force ratio \( f \) should be large.

![Image of Fig. 5: Speed–force characteristics (calculation).]
speed of the capsule decreased to about half of that on the plastic plate, the capsule could also travel on the pig’s intestine.

![Graph of Traveling speed vs Voltage](image)

**Fig. 6** Speed characteristics measured in the experiments.

(capsule: aluminum, d = 7 mm, on dry plastic plate)

### 3.2. Magnetic force measurement

To use the results of the theoretical analysis and to improve the capsule traveling capability, it was necessary to measure the parameters of the actual capsule by experiments. Therefore, we measured magnetic force $f_m$. The measurement setup is shown in Fig. 7 and the results are shown in Fig. 8.

As shown in Fig. 8, within 4-mm displacement, the magnetic force increases depending on the displacement of the permanent magnet. Therefore, impact force at stopper A in Fig. 1 is bigger than that at stopper B. This asymmetric structure causes the capsule to travel in one direction.

![Setup for measuring magnetic force](image)

**Fig. 7** Setup for measuring magnetic force $f_m$.

![Displacement–force characteristics](image)

**Fig. 8** Displacement–force characteristics.

The actual values of the parameters of our capsule were obtained as mentioned above. Using these parameters and capsule parameters shown in table 1, the relation between the
force ratio and speed was obtained as shown in Fig. 9. For the calculation, the go and return motion of the inner mass (permanent magnet) \( m \) is considered, as shown in Fig. 4. Speed \( S_T \) is defined by equation (25) using \( x_T \) and \( t_T \). Coefficient of speed \( C_{ST} \) is expressed as equation (26). The value of returning magnetic force \( f_m' \) was set to be 0.04[N] smaller than \( f_m \) according to the result shown in Fig. 8 above. This value of \( (f_m - f_m') \) was derived from the difference between the average magnetic force at the displacement of 0 to 1[mm] and that of 2 to 3[mm] at 2.5[V] in Fig. 8. Experimental results are also plotted in Fig. 9. For the value of friction force \( f_r \), 0.005[N] which was also obtained by experiments, was used. The results of both the experiment and the theory seem to coincide well.

\[
S_T = \frac{x_T}{t_T} = \frac{-x_0 + x_1 + x_0 - x_1}{t_0 + t_1 + t_0 + t_1} \quad (25)
\]

\[
C_{ST} = \frac{S_T}{K_s}, \quad K_s = \sqrt{\frac{\alpha \cdot f_r}{2M}} \quad (26)
\]

Fig. 9  Capsule speed characteristics (calculation) and experimental results

3.3. Arranging the input signal for speedup

To make the capsule travel faster, we examined the theoretical analysis. We gave the capsule a standard rectangular input signal as shown in Fig. 10 (i). The capsule proceeded with to-and-fro vibration. Although the capsule moves forward, its backward motion is inefficient. Therefore, the capsule can proceed efficiently, if a greater input is given in the forward motion of the moving mass and a smaller input is given in the backward motion of the moving mass. The input signal shown in Fig. 10 (ii) was given to the capsule coil and the speed increased. The speed of the capsule with the proposed waveform (14 mm/s) was about twice as fast as that with the conventional waveform (6 mm/s).

Fig. 10  Improvement of input voltage waveform: (i) conventional; (ii) proposed.
4. Small Circuit for Traveling Capsule

To make the capsule wireless, the capsule should be driven by small batteries inside the capsule. We made the small electronic circuit that is made of chip ICs driven by batteries in the capsule (Fig.11). This circuit can drive the to-and-fro motion of the magnet inside the capsule by DC power with just one set of electromagnetic coil.

Fig. 11  Schematic of the driving circuit for the capsule.

5. Conclusion

Even though the capsule has no wheels or legs, it can travel utilizing inertia force and friction force. We conducted theoretical analyses for the capsule and showed how the capsule mechanism worked. To increase capsule speed, a new input waveform was proposed and tested, proving that the new waveform approximately doubles the capsule speed compared with the conventional one. Our capsule may be useful for medical treatments such as inspection, drug delivery and operation.

References

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