Numerical Study of Millimeter-Scale Magnetorheological Elastomer Robot for Undulatory Swimming

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RESEARCH BACKGROUND
Swimming in low-Re regime

Scallop Theorem

\[ Re = \frac{pD_h v_{avg}}{\eta} \]

None Net Displacement

Time Unsymmetrical Locomotion

Helical

Flexible

Undulatory


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Distributed body torques cause the Cauchy stress to be asymmetric.

A user-defined element subroutine in Abaqus/Standard.

COMPUTATIONAL METHODS
Approximation of distributed torques

Simple Structure


- 2D Approximation
- Approximation of torques
(a) Sketch of the magnetorheological elastomer robots with 3.7 mm in length with the mechanics boundary conditions. Deflections of the robots composed of ten (b), twenty (c), forty (d), and eighty (e) elements under free-free end conditions and varying magnetic field flux. The deflections at $B = 0.003$ mT, 0.03 mT, 0.3 mT, and 3 mT, respectively, are multiplied by 1000, 100, 10 and 1, respectively. A theoretical curve under the field strength of 3 mT is plotted for comparison.
◆ The deformations of the robots are linear when the magnetic field strength is not more than 0.3 mT

◆ Non-linear deformations of the robots appear under the magnetic field strength of 3 mT
Deflection of the robots with ten (solid) and eighty (hollow) elements under free-free end condition and varying magnetic field flux.

- Increasing number of elements leads to more obvious deflection
- Below field strength of 3 mT, increasing number of elements plays a feeble role on deflection
- Above field strength of 7 mT, increasing number of elements obvious impact on deflection
RESULTS & DISCUSSION
Swimming speed

◆ Robot curls and rolls easily in the underwater case, resulting in deteriorated swimming performance

Taylor’s model: \[ V_{\text{swim}} = \frac{2\pi}{L} \left( \frac{3ML^3B}{2\pi^3Eh^2} \right)^2 f \]

Average swimming speed of the ten-element robot of \( L = 3.7 \text{ mm} \) under varied magnetic field strength (a) and at \( B = 0.03 \text{ mT} \) with various lengths (b). The rotating frequency is 5 Hz. The results obtained from 0.003 mT and 0.03 mT times 10000 and 100, respectively, for clear display.

<table>
<thead>
<tr>
<th>L (mm)</th>
<th>B (mT)</th>
<th>Re</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>0.003</td>
<td>$3.28 \times 10^{-6}$</td>
</tr>
<tr>
<td>3.7</td>
<td>0.03</td>
<td>$3.28 \times 10^{-4}$</td>
</tr>
<tr>
<td>3.7</td>
<td>0.3</td>
<td>$3.23 \times 10^{-2}$</td>
</tr>
<tr>
<td>1.85</td>
<td>0.03</td>
<td>$2.33 \times 10^{-6}$</td>
</tr>
<tr>
<td>5</td>
<td>0.03</td>
<td>$2.74 \times 10^{-3}$</td>
</tr>
<tr>
<td>6.35</td>
<td>0.03</td>
<td>$1.9 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

◆ Robots in all cases could be treated as low Re swimmers
Swimming pattern

Swimming gaits of the robot of 3.7 mm (a, b, c), 1.85 mm (d), 5 mm (e), and 6.35 mm (f) in length at 0.85 s (n=0) and 0.90 s (n=1) under the field strength of 0.003 mT (a), 0.03 mT (b,d,e,f), and 0.3 mT (c) with a rotating frequency of 5 Hz.

\[
y(x, t) = \frac{MAL^3 B}{8\pi^3 EI} \left( \frac{2\pi MAL^3 B}{L^2} x + \beta_R - \frac{2\pi}{f} t \right) \cos \left( \frac{2\pi}{L} x \right) + \frac{1}{2} \sin \left( \frac{2\pi}{L} x \right) \cos \left( \frac{2\pi}{f} t \right) + \frac{1}{2} \sin \left( \frac{2\pi}{f} t \right) \left( \frac{2\pi}{L} x \right)
\]

\[
- \sin (\beta_R - \frac{2\pi}{f} t) \left( \frac{2\pi}{L} x \right) - \frac{241}{50} \sin \left( \frac{2\pi}{L} x - \frac{101\pi}{200} \right)
\]
Amplitudes of the points along the neutral layer of the robot of 3.7 mm (a, b, c), 1.85 mm (d), 5 mm (e), and 6.35 mm (f) in length under the field strength of 0.003 mT (a), 0.03 mT (b, d, e, f), and 0.3 mT (c) with a rotating frequency of 5 Hz.

- **Amplitudes are inconsistent**
- **Largest beating amplitudes appear at the head and tail of the robot in both simulations and theories**
Amplitudes of the points along the neutral layer of the robot with 3.7 mm in length predicted by varied values of $k_1$, $k_2$, and $k_3$ under the field strength of 0.003 mT. The simulated results are plotted for comparison.

◆ Inconsistency also extensively exists in undulatory microbial swimmers with finite body lengths

*Caenorhabditis elegans*

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Trajectory of the tail

The trajectory of the tail in the robots with the length of 3.9 mm (a,b,c) and 1.85 mm (d) under the field strength of 0.003 mT (a,d), 0.03 mT (b), and 0.3 mT (c)

◆ Countermovement is more pronounced with higher field strength and shorter robot
CONCLUSION
Conclusion

1. Present an approximation method for the calculation of distributed magnetic torques in soft robot.

2. Demonstrate the invalidation of Taylor’s model in the soft robot with continuously magnetization profile.

3. Present a novel swimming gait function for the soft robot with continuously distributed magnetization profile.
Thanks for your attention!