Structural Simulation of Jellyfish Propulsion*

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***Abstract*— This report details the structural simulation of jellyfish propulsion, with a focus on post-contraction dynamics. Our study aims to model jellyfish propulsion accurately by implementing a node-based framework and analyzing the velocity profile throughout the contraction-relaxation cycle. The report also discusses current results, limitations, and future improvements.**

I. Introduction

Jellyfish are among the most energy-efficient swimmers, largely due to their unique propulsion mechanism. By contracting their bell, they expel water to move forward, followed by a relaxation phase in which the bell passively returns to its original shape. This passive recovery allows jellyfish to maintain forward motion while using minimal energy. Understanding this mechanism through structural modeling will provide valuable insights into bio-mimetic designs in underwater propulsion.

This project focuses specifically on the dynamics of the relaxation phase, where the bell's flexible structure facilitates continuous propulsion. By simulating simplified elements such as rods, rings, and plates, we aim to capture the core principles of jellyfish propulsion mechanics.

II. Background

Past research has primarily focused on the fluid dynamics of jellyfish swimming, while the structural mechanics underlying their movement remain less explored. Jellyfish possess flexible tissues that allow their bell to undergo elastic recovery after each contraction, achieving propulsion in a low-energy manner. This flexibility is crucial for generating and maintaining movement in the viscous ocean environment.

III. Implementation

The jellyfish model consists of three nodes submerged in a fluid with a density of $10\,\mathrm{kg/m^3}$. The propulsion mechanism is driven by changes in the angle of the side nodes. During contraction, which takes 0.2 seconds, the side nodes reach an angle of $-85°$. The subsequent relaxation phase occurs over 1.3 seconds, during which the side nodes return to an angle of $0°$. This oscillatory motion mimics the natural swimming behavior of jellyfish in aquatic environments.

Operating in the high Reynolds number regime, the drag force acting on the jellyfish is described by the equation:

$$F_D = C_D A \cdot 0.5 \rho v^2 \cdot \hat{v},$$

where $A = dL \cdot r_0$ represents the effective area and $\hat{v}$ is the unit vector of velocity.

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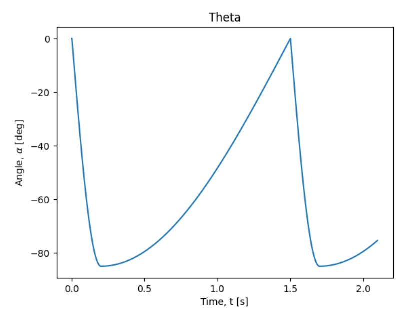

Fig. 1. Angle between side node, middle node, and horizontal axis

IV. Results

As shown in Figure 2, the vertical displacement of the middle node demonstrates a clear cyclical pattern that corresponds to the contraction-relaxation motion of the jellyfish. The velocity in the y-direction also oscillates over time, consistently reaching zero at the end of each contraction cycle. This behavior reflects the interplay between the elastic recoil of the jellyfish bell and the fluid dynamic forces acting on it. The zero-velocity points mark the transition between contraction and relaxation, serving as a reset mechanism for the propulsion cycle. These observations highlight the efficient energy transfer mechanisms that characterize jellyfish propulsion.

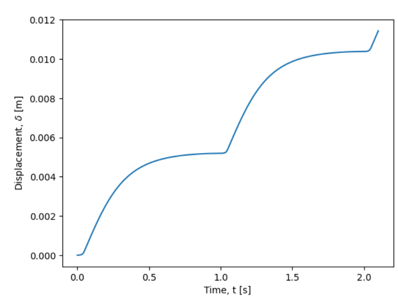

Fig. 2. Vertical Displacement of Middle Node

V. Discussion on Velocity Dynamics

During each contraction cycle, the velocity of the jellyfish in the y-direction reaches zero. This phenomenon occurs at the end of the contraction phase, when the elastic recoil of the bell momentarily counteracts the forward momentum of the jellyfish. Additionally, fluid resistance decelerates the movement, bringing the velocity to zero before the jellyfish transitions into the relaxation phase. This momentary pause in motion is essential for resetting the structure of the

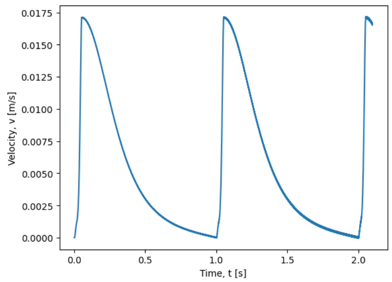

Fig. 3. Velocity of Middle Node

jellyfish and preparing it for the next phase of propulsion. By maintaining this rhythmic motion, the jellyfish achieves an efficient swimming pattern without unnecessary energy dissipation.

VI. Future Improvements

To improve the accuracy and applicability of the simulation, several enhancements are proposed. First, increasing the number of nodes in the model would allow for a more refined structural representation of the jellyfish. Second, the addition of trailing tentacles could provide more realistic dynamics by simulating the natural flow interactions observed in real jellyfish. Third, the model should be tested under varying parameters, such as fluid density, bell length, and elastic modulus, as well as different contraction functions for the angle θ. These improvements would increase the fidelity of the simulation and broaden its potential applications in understanding and designing bio-inspired propulsion systems.

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