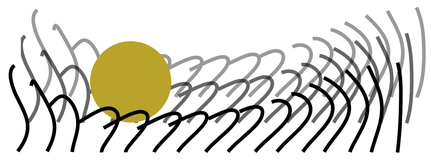
Computational Study of Cilia-Based Sensing Mechanism for Particle's Shape and Size

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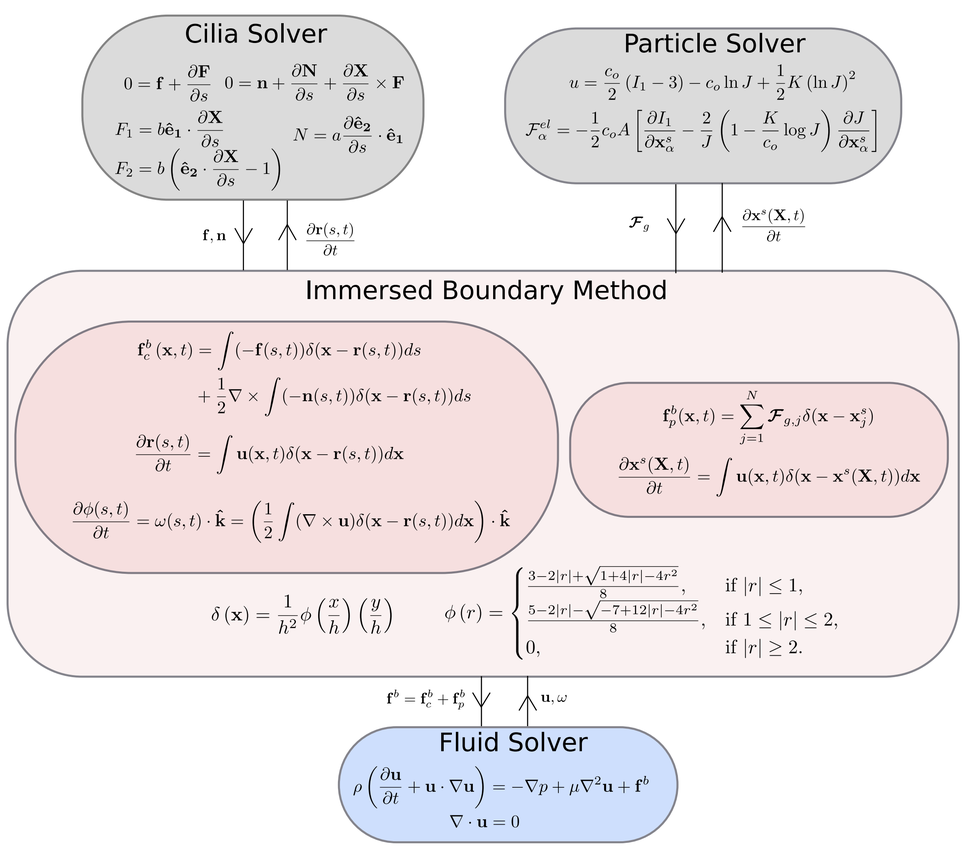
Introduction



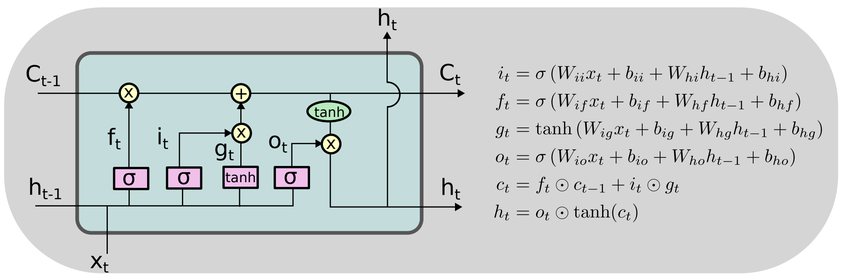
Biological cilia, serving as sensory organelles, are observed in a variety of animal cells and microorganisms in nature. In an effort to replicate this behavior, we conduct a computational study to assess the viability of a sensing mechanism capable of discerning particle properties. This mechanism relies on using perturbations, due to the particle's presence, in the deflection of a cilia array affixed to the bed of a channel with fluid flow.

Methodology

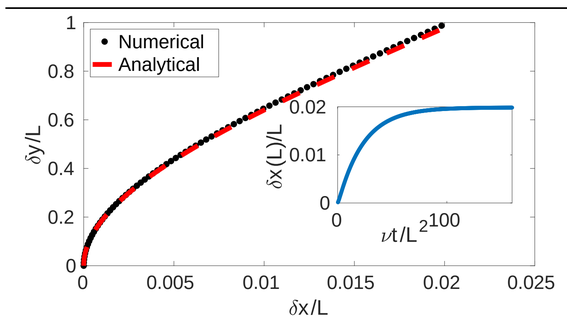
In the numerical model, cilia are represented as slender, massless structures using Kirchoff rod theory [1]. Their interactions with the surrounding fluid are modeled using Peskin's continuous forcing Immersed Boundary Method (IBM) [2]. Elliptical particles are modeled as neo-Hookean massless solids and solved using the Finite Element Method [3].



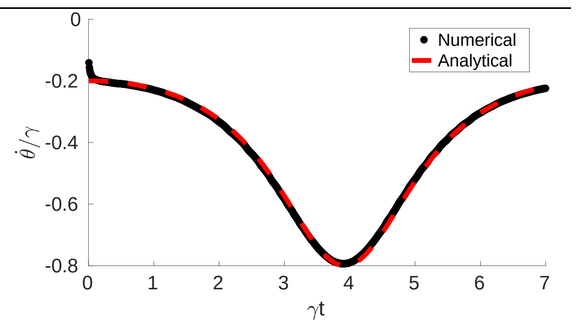
A Long Short Term Memory Network (LSTM) is utilized to capture spatial and temporal dependencies in the cilia perturbation data to predict particle properties.



Validation

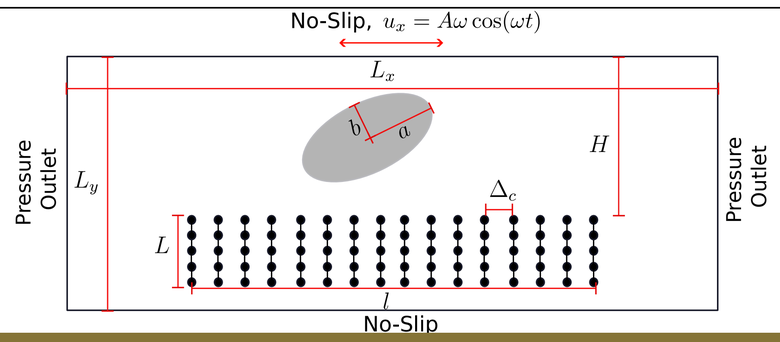


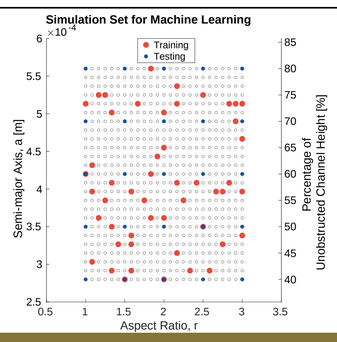
Validation against deflection predicted by the Euler-Bernoulli beam theory for a tip force applied to a cantilever beam.

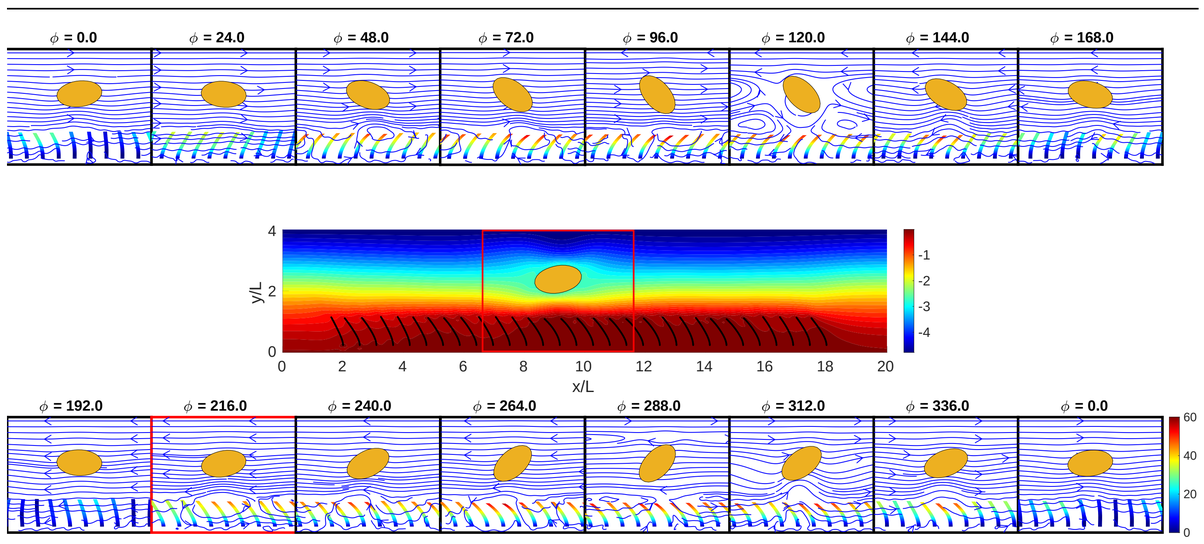


The angular velocity of the particle in shear flow is validated against the analytical results of Jeffery [4]

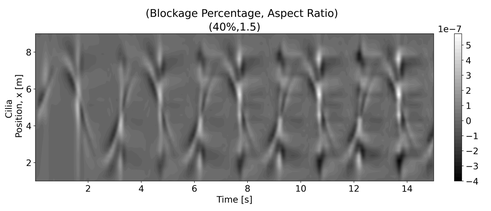
Numerical Simulation and Machine Learning







Simulations are performed at a Reynolds number of 49 and a Sperm number of 0.35. ($Re = HA\omega/\nu$, $Sp = L(4\pi\nu\omega/EI)^{1/4}$). Snapshots depict streamlines at different phase angles, ϕ, during the oscillations of the particle above the cilia bed. The filled contours within the cilia represent the angular deviation of the cilia, measured in degrees from their initial vertical position. The filled isocontours of $u_x L/\nu$ are presented in the plot positioned at the center.

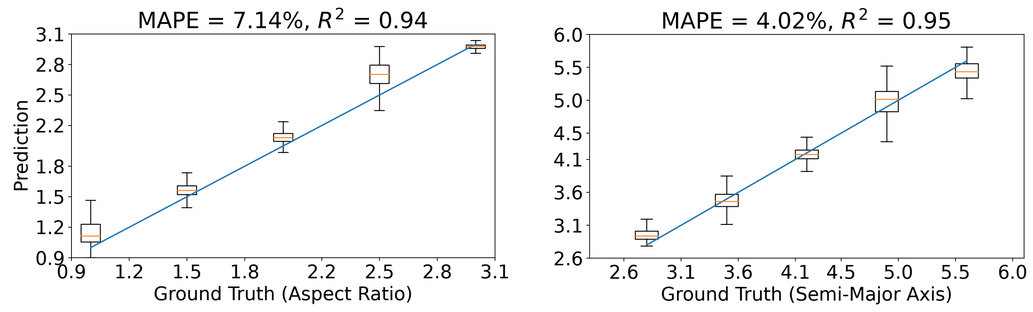


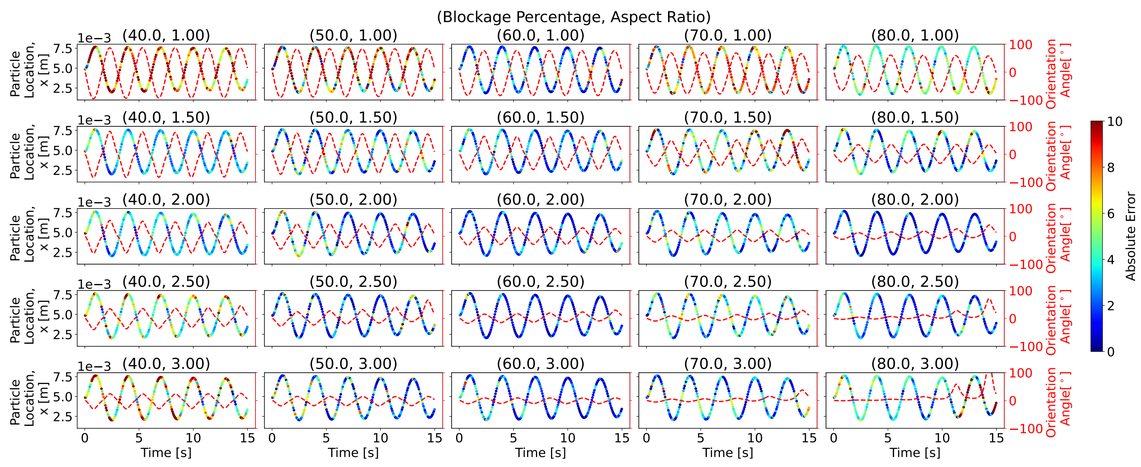
Filled contours of cilia perturbations (y component)
$\mathbf{r}_{\mathbf{pert}}^{\mathbf{i,j}}(\mathbf{t}) = \mathbf{r}_{\mathbf{ref}}^{\mathbf{i,j}}(\mathbf{t}) - \mathbf{r}_{\mathbf{sim}}^{\mathbf{i,j}}(\mathbf{t})$, where $\mathbf{r} = \langle x^i, y^i \rangle$, i and j (=1, base node) denote the cilia number and node number respectively.

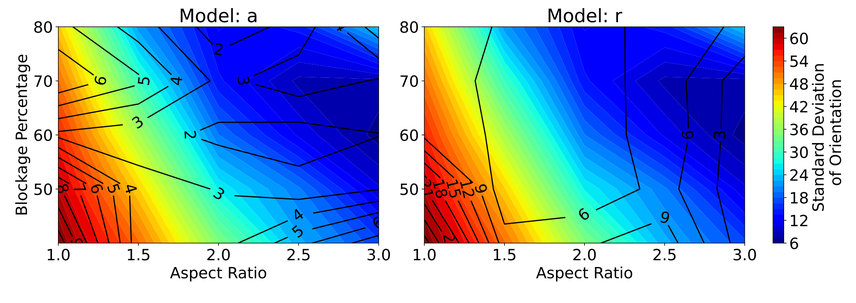
Time Instants	Cilia Bottom Perturbations								Size /Shape
	$x^{1,1}$	$x^{2,1}$	...	$x^{N_c,1}$	$y^{1,1}$	$y^{2,1}$	...	$y^{N_c,1}$	
1									
2									
3									
...									
N_t									

Input data to the ML algorithm

Results and Conclusion







Contours of absolute percentage error are superimposed on filled contours of the standard deviation of particle's orientation

- The trained models can reasonably predict both the shape and size, with the size model exhibiting superior performance compared to the shape model.
- The accuracy of predictions is dependent upon the extent to which the orientation of the particle undergoes changes during its motion.

References

[1] S. Lim, A. Ferent, X. S. Wang, and C. S. Peskin, "Dynamics of a Closed Rod with Twist and Bend in Fluid," en, *SIAM Journal on Scientific Computing*, vol. 31, no. 1, pp. 273–302, Jan. 2008, ISSN: 1064-8275, 1095-7197.

[2] C. S. Peskin, "The immersed boundary method," en, *Acta Numerica*, vol. 11, pp. 479–517, Jan. 2002, ISSN: 0962-4929, 1474-0508.

[3] A. Bhattacharya and A. C. Balazs, "Stiffness-modulated motion of soft microscopic particles over active adhesive cilia," en, *Soft Matter*, vol. 9, no. 15, pp. 3945–3955, Mar. 2013, Publisher: The Royal Society of Chemistry, ISSN: 1744-6848.

[4] G. B. Jeffery, "On the Steady Rotation of a Solid of Revolution in a Viscous Fluid," en, *Proceedings of the London Mathematical Society*, vol. s2_14, no. 1, pp. 327–338, 1915, ISSN: 00246115.

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