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COMPARISON OF THE VORTEX METHOD AND THE IMMERSED BOUNDARY METHOD FOR 2D SIMULATIONS OF INSECT FLIGHT

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Painted lady butterflies are known to travel up-to 4000 miles during migration, from North Africa to Iceland. Sphinx Moths fly as fast as 33 m.p.h. A midge can beat it's wings at a frequency as high as 62760 beats per minute (bpm), while a swallowtail butterfly is beats them as slow as 300 bpm. The highest altitude gained by any insect is noted to be about 20000 feet [1]. The diversity among insets is unfathomable and so are their acrobatic manoeuvres. They can fly forward, up, down and side-ways. They can hover, land upside down on the bottom of a leaf and even manage to fly with damaged wings. Insects are surprisingly resistant to environmental perturbations despite their small size and consequently small inertia. The mesmerizing brilliance of insect flight notwithstanding, understanding the unsteady aerodynamics and the lift generating mechanisms have practical applications to Micro Air Vehicles (MAV) [2].
The theory and numerical simulation of insect flight in general and the *reduced* problem of the heaving and pitching motion of airfoils has seen an evolution from the early Rankine-Froude momentum theories [3, 4], quasi-steady models on thin airfoil theory [5, 6] to unsteady models using the full Navier-Stokes equations and fluid-structure interactions [7, 8, 9, 10, 11]. While being essentially a 3D phenomenon, two dimensional models are often used as an effective tool to understanding the basic theories like the Wagner effect [12], Kramer effect [13, 12] and the clap and fling Mechanisms [5, 13, 14]. The extra lift generated by insects is believed to be due to the attachment of the leading edge vortex [15, 16, 17]. Though this mechanism is stable for a longer duration in 3D, the shedding of vortices after stroke reversal enables a comparable simulation in 2D.

In this work, we compare numerical simulations for the *idealized* clap and fling mechanism of insect flight using a Vortex Method (VM) [18] and the Immersed Boundary Method (IBM) [19, 20, 21]. Our motivation is both, the understanding of the vortex shedding patterns for clap and fling and the feasibility of these numerical techniques to resolve the flow at various Reynold's numbers in the presence of complex moving/deformable bodies. An example simulation of the heaving and pitching motion of an ellipse using the Vortex Method is shown in Fig. 1. Our comparison is based on the accuracy of the results and the ease with which the codes can be extended to three dimensions with the possibility of adding new physics. The results from this work would guide the development work for a 3-dimensional code for general insect flight.

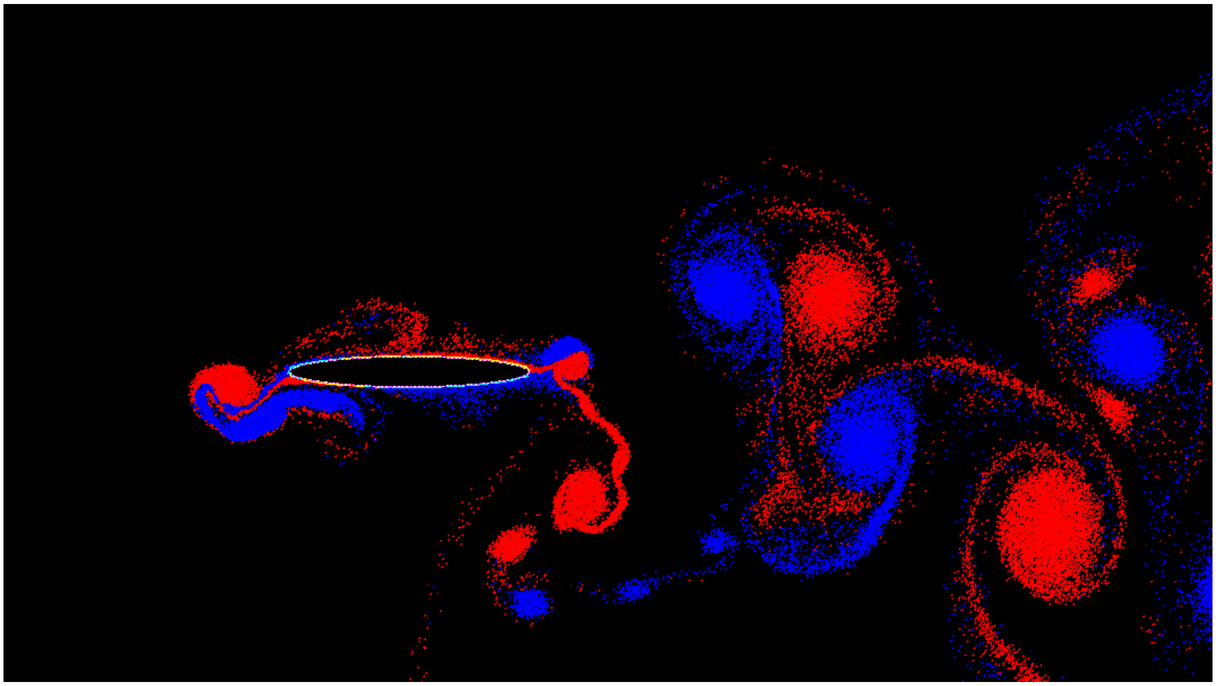

Figure 1. Heaving motion of an ellipse using a 2D Vortex Method.

References

[1] Encyclopedia Smithsonian, "Insect Flight." `http://www.si.edu/Encyclopedia_SI/nmnh/buginfo/insflght.htm`.

[2] C. P. Ellington, "The novel aerodynamics of insect flight: applications to micro-air vehicles," *Journal of Experimental Biology*, vol. 202, pp. 3439–3448, 1999.

[3] Mises, R von, *Theory of Flight.* New York: Dover, 1959.

[4] C. P. Ellington, "The Aerodynamics of Hovering Insect Flight. V. A Vortex Theory," *Philosophical Transactions of the Royal Society of London*, vol. 305, pp. 115–144, 1984.

[5] T. Weis-Fogh, "Quick Estimates of Flight Fitness in Hovering Animals, Including Novel Mechanisms for Lift Production," *Journal of Experimental Biology*, vol. 59, pp. 169–230, 1973.

[6] C. P. Ellington, “The Aerodynamics of Hovering Insect Flight. I. A The Quasi-Steady Analysis,” *Philosophical Transactions of the Royal Society of London*, vol. 305, pp. 1–15, 1984.

[7] H. Liu, C. P. Ellington, K. Kawachi, C. V. D. Berg, and A. P. Willmott, “A Computational Fluid Dynamic Study of Hawkmoth Hovering,” *Journal of Experimental Biology*, vol. 201, pp. 461–477, 1998.

[8] H. Liu, “Computational Biological Fluid Dynamics: Digitizing and Visualizing Animal Swimming,” *Integrative & Comparative Biology*, vol. 42, pp. 1050–1059, 2002.

[9] Z. J. Wang, J. M. Birch, and M. H. Dickinson, “Unsteady forces and flows in low Reynold’s number hovering flight: two-dimensional computation vs robotic wing experiments,” *Journal of Experimental Biology*, vol. 207, pp. 449–460, 2003.

[10] R. Ramamurti and W. C. Sandberg, “A three-dimensional computational study of the aerodynamic mechanisms of insect flight,” *Journal of Experimental Biology*, vol. 205, pp. 1507–1518, 2002.

[11] R. Ramamurti and W. C. Sandberg, “3-D Unsteady Computations of Flapping Flight in Insects, Fish and Unmanned Vehicles,” in *Bio-mechanisms of Swimming and Flying*, pp. 205–217, Springer, 2008.

[12] S. P. Sane, “The aerodynamics of insect flight,” *Journal of Experimental Biology*, vol. 206, pp. 4191–4208, 2003.

[13] T. Weis-Fogh, “Unusual mechanisms for the generation of lift in flying animals.” `http://www.nature.com/scientificamerican/journal/v233/n5/pdf/scientificamerican1175-80.pdf`, 1975.

[14] C. P. Ellington, “The Aerodynamics of insect flight. IV. Aerodynamic Mechanisms,” *Philosophical Transactions of the Royal Society of London*, vol. 305, pp. 79–113, 1984.

[15] M. H. Dickinson and K. G. Götz, “Unsteady Aerodynamic Performance of Model Wings at Low Reynold’s Numbers,” *Journal of Experimental Biology*, vol. 174, pp. 45–64, 1993.

[16] C. P. Ellington, C. V. D. Berg, A. Willmot, and A. L. R. Thomas, “Leading-edge vortices in insect flight,” *Nature*, vol. 384, pp. 626–630, 1996.

[17] J. Wu, “Review of the physics of enhancing vortex lift by unsteady excitation,” *Progress in Aerospace Sciences*, vol. 28, pp. 73–131, 1991.

[18] Prabhu Ramachandran, *Development and study of a high-resolution two-dimensional random vortex method*. PhD thesis, Indian Institute of Technology Madras, 2004.

[19] R. Mittal and G. Iaccarino, “Immersed Boundary Methods,” *Annual Review of Fluid Mechanics*, vol. 37, pp. 239–261, 2005.

[20] S. Xu and Z. J. Wang, "An immersed interface method for simulating the interaction of a fluid with moving boundaries," *Journal of Computational Physics*, vol. 216, pp. 454–493, 2006.

[21] L. Zheng, T. L. Hedrick, and R. Mittal, "A multi-fidelity modelling approach for evaluation and optimization of wing stroke aerodynamics in flapping flight," *Journal of Fluid Mechanics*, vol. 721, pp. 118–154, 2013.