Project Report for *A High-Speed Time-Resolved Planar Particle Image Velocimetry (PIV) System for Zooplankton Flow Field Measurements* funded by WHOI Ocean Life Institute Research Award Program

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With funding from this award, we have successfully developed and tested two particle image velocimetry (PIV) setups for measuring zooplankton-generated water flows. First, we have tested a “standard” PIV setup (Fig. 1, left panel). In a PIV measurement, flow is seeded with small tracer particles that follow the flow. In the standard setup, a laser beam is formed into a thin sheet of laser light. Two images of the particles approximately in the laser sheet-illuminated plane are recorded consecutively with a short time delay by a high resolution CCD camera. The recorded image pair is then analyzed via the cross-correlation technique to generate the instantaneous flow velocity vector field. We have demonstrated that this standard setup is only suitable for measuring flow fields imposed by relatively larger zooplankton (≥ 1 mm in body size), e.g. krill, larger copepods, jellyfish, etc. This limitation is due to the technical restriction that the typical light sheet thickness ranges ~ 200 μm – 1 mm, and that it is required to form a light sheet that is thinner than the body size of the zooplankton that is being studied.

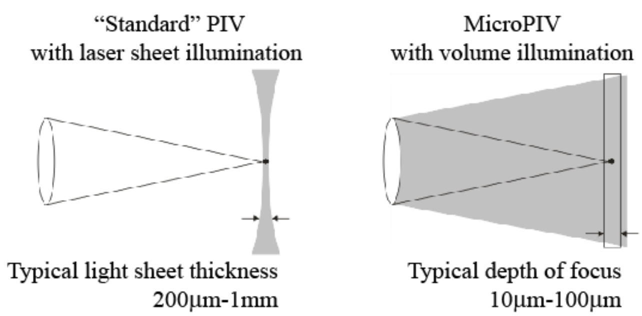

Fig. 1. Difference in light illumination between “standard” PIV (left) and μPIV (right).

Second, we have developed and tested a MicroPIV setup that does not use the standard laser sheet illumination but volume illumination (Fig. 1, right panel). This MicroPIV setup is designed for measuring flows imposed by microzooplankton, typically ~ 20-200 μm in body size, including flagellates, dinoflagellates, ciliates, copepod nauplii and meroplanktonic larvae. Because this setup uses a long-working-distance high-powered microscope objective to achieve high magnification, its depth-of-focus is thinner than the typical size range of microzooplankton. Therefore, imaging tracer particles along the thin focus plane is similar to imaging particles in a laser-sheet-illuminated PIV (i.e. the “standard” PIV). Then, the same cross-correlation algorithm can be used to calculate the flow field.

Finally, we have demonstrated that it is both necessary and advantageous to use high frame rate recording (≥ 1000 frames per second) for PIV measurements of zooplankton-imposed flows. The reasons are: (1) High frame rate recording is necessary for temporally resolving fast behaviors where the flow evolves very fast due to fast limb and body motion and subsequent viscous decay; and (2) The chance that a zooplankter and the associated flow appear in the thin focus plane is low and therefore it is necessary to use high frame rate recording to capture the short interval when an event is actually in focus. By doing so, enough replicates can be obtained for further analysis.

This internal award has provided leverage in obtaining the following two NSF awards:

1) National Science Foundation (NSF) OCE-1129496 ($265,804, 09/01/2011-08/31/2014): H. Jiang - Collaborative Research: Linking propulsive morphology, swimming behavior and sensory perception by marine planktonic protists to their trophic roles within marine food webs;
2) National Science Foundation (NSF) OCE-1433979 ($282,606, 10/01/2014-09/30/2017): H. Jiang and K. Chan - Functional diversity and performance of ciliated marine invertebrate larvae: measuring and modeling larval swimming, feeding and hydrodynamic signaling.

Six peer-reviewed papers have acknowledged the support of this award:

1) Chan, K. Y. K., Jiang, H. and Padilla, D. K. (2013) Swimming speed of larval snail does not correlate with size and ciliary beat frequency. *PLoS ONE* 8(12): e82764. doi:10.1371/journal.pone.0082764.
2) Jiang, H. (2011) Why does the jumping ciliate *Mesodinium rubrum* possess equatorially located propulsive ciliary belt? *Journal of Plankton Research*, 33, 998-1011 (Featured article).
3) Jiang, H. and Kiørboe, T. (2011) The fluid dynamics of swimming by jumping in copepods. *Journal of the Royal Society Interface*, 8, 1090-1103.
4) Jiang, H. and Kiørboe, T. (2011) Propulsion efficiency and imposed flow fields of a copepod jump. *Journal of Experimental Biology*, 214, 476-486.
5) Katija, K. and Jiang, H. (2013) Swimming by medusae *Sarsia tubulosa* in the viscous vortex ring limit. *Limnology and Oceanography: Fluids and Environments*, 3, 103-118.
6) Katija, K., Colin, S. P., Costello, J. H. and Jiang, H. (2015) Ontogenetic propulsive transitions by medusae *Sarsia tubulosa*. *Journal of Experimental Biology*, 218, 2333-2343.

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