

Vortex dynamics and hydrodynamic performance enhancement mechanism of a swimming batoid fish

Wei-Xi Huang^{1†}, Dong Zhang²

¹AML, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

² Qingdao Innovation and Development Base, Harbin Engineering University, Qingdao 266000, PR China

†Email address for correspondence: hwx@tsinghua.edu.cn

Abstract

To provide a new insight into the role of vortices and the force enhancement mechanism in aquatic swimming, flow around a tethered model of a swimming batoid fish is studied by using the immersed boundary method. Fin kinematics were prescribed based on biological data. Effects of the travelling wavenumber (W) and the ratio of the half-amplitude above the longitudinal axis to that below (HAR) of the flapping fin were examined. By using the derivative-moment transformation theory at several subdomains to capture the local vortical structures and a force decomposition, it was shown that, at high Strouhal numbers (St), the tip vortex is the main source of thrust, whereas the leading-edge vortex (LEV) and trailing-edge vortex weaken the thrust generation. On the other hand, at lower St , the LEV would enhance the thrust. A Reynolds number (Re) up to 148,000 was further considered, which is comparable to that of a medium-sized aquatic animal in cruising swimming state. At such a high Re , we provided, to the best of our knowledge, the first evidence of hairpin vortical (HV) structures near the body surface using three-dimensional high-fidelity flow field data. It was observed that such small-scale vortical structures are mainly formed through two mechanisms: the leading-edge vortex (LEV)–secondary filament– HV and LEV – HV transformations in different regions. In addition, effect of turbulent inflow on the hydrodynamic performance of a swimming batoid fish was studied and some preliminary results will also be presented.

Keywords: swimming/flying, propulsion, vortex dynamics

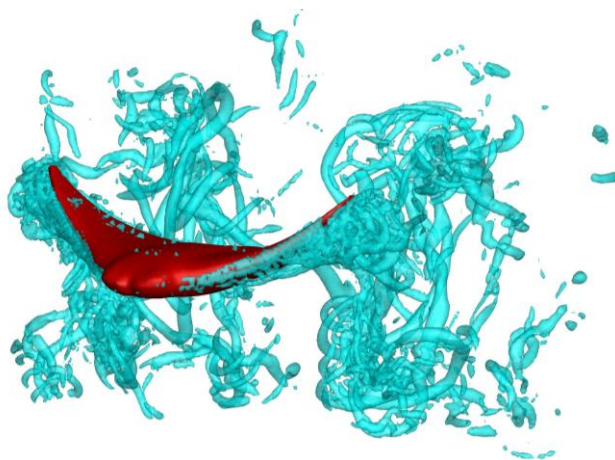


Figure 1. Instantaneous vortical structures around a swimming batoid fish

Acknowledgments

We sincerely thank the Asian Fluid Mechanics Committee (AFMC) for their exceptional efforts in organizing the 18th Asian Congress of Fluid Mechanics (ACFM) scheduled to be held in Seoul, Korea, from September 10 to 13, 2025. Support from NSFC with grant nos. 12425206, 12272206, 92252204 and 12388101 is gratefully acknowledged.