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# The Body Deformation and Energy Transfer of Undulatory Propulsion in Fish Swimming

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## ABSTRACT

During the steady swimming of carangiform or anguilliform swimmers, the fish body shows significant fluctuation characteristics. The formation of waving body is not only related to the driving force of fish muscle, but also to the material properties of fish body and fluid forces. In fluid mechanics, the propulsive force of fish body is closely related to reverse Kármán vortex street. However, there is still a lack of comprehensive understanding of the work done by the driving force, the formation of the fluctuation and propulsion of the fish. Based on the kinematic chain integration framework, the deformation of the fish body under the action of active bending moment is studied through theoretical analysis and numerical simulation, and the effect of the different component of fluid forces is analyzed. The study covers the discussion about wave propagation in both elastic bodies and fluid media, and re-examines the physical phenomenon of fish body deformation from the perspective of wave propagation.

The fish body is modelled as a freely supported Euler-Bernoulli beam, then the deformation of the beam and the energy transport under the active bending moment excitation are investigated. Furthermore, we discuss the approximation degree of the fluid force to the quadratic force model after removing the added mass term. In detail, the beam undergoes active and passive deformation due to the combined action of fluid forces and an active bending moment that is transmitted from the head to the tail as a right-hand traveling wave, and finally the forward propulsion is realized with the characteristic wake structure of the flow field. When the fluid action is absent, the bending wave that propagates in the beam reflects completely at both free ends of the beam, causing the deformation of the Euler-Bernoulli beam to exhibit standing wave characteristics and the center of mass of the beam to remain stationary. When the fluid action is considered, the right-traveling bending wave that occurs on the beam does not undergo complete reflection at the tail end, causing the beam to display a deformation of right-traveling wave and the beam to move to the left under the action of fluid force, leaving behind a wake structure of counter-Kármán vortices in the flow field. In general, the fluid forces acting on the undulatory beam can be decomposed into the added mass force and the resistive force, that are proposed by Lighthill and Taylor respectively. The present result shows that the resistive component corresponds to the vortex structure and the integral effect of the added mass term is zero in the steady swimming. In this process, the bending wave on the beam transfers the energy from front to anterior and transfers it into the flow field at the tail. Of course, there is a small amplitude wave is reflected from the tail end and superposed with the original right traveling bending wave, which makes the fish body still have a weak standing wave form although the travelling wave is the dominant feature in deformation. Thus, the undulatory propulsion of the fish body is an inevitable result of active excitation of the distributed muscles and the coupling between the fluid and the fish body. Energy is transferred to the fluid through the fish tail to generate thrust, and a reverse Kɑ́rmán vortex street is formed in the flow field, which correspond to the undulatory propulsion.

## KEYWORDS

Undulatory; energy transfer; fish swimming; wave reflection; transmission

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