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THE OPTIMAL MOTION OF TWO-DIMENSIONAL UNDULATING PLATE SWIMMING IN FLUID FLOW*

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Abstract: The optimum shape of a two-dimensional undulatory plate in its motion in fluid flow is analyzed and the physical parameters (the thrust and the power) are calculated by the boundary element method. With the commonly used Lagrange multiplier method, only a saddle point of the optimum solution can be obtained, but not the solution itself due to the singularity of the problem. To eliminate the singularity, a method is proposed by adding an amplitude constraint. The new method is a generalization of that proposed by Wu, and it can be applied to more complex cases. The optimum shape of the linearly varying amplitude motion is studied in detail. It is shown that both the maximum and the minimum solutions exist when the frequency is higher than a critical value. For a high frequency, the maximum efficient motion with a large amplitude at the leading edge and a small amplitude at the trailing edge induces a large leading edge suction force. As the frequency decreases, the leading edge suction force decreases to a minimum and then increases. For high wavenumbers, there exists an optimum frequency with the maximum efficiency. High efficiency holds over a large range of frequency. The optimum efficiency increases as the wavenumber increases. The increase of the wavenumber can also reduce the leading edge suction force. The optimization method can also be applied to a quadratically varying amplitude motion. It is found that the optimum efficiency is larger than that for the linearly varying amplitude motion. However, the additional efficiency is relatively small, especially as the original efficiency is already high enough.

Key words: two-dimensional undulating plate, boundary element method, optimization

Introduction

Undulating propulsion is an effective way for aquatic locomotion[1-3], which has attracted considerable attention from investigators. Lighthill[1] and Wu[4] established the slender body theory for flexible elongated bodies and the two-dimensional waving plate theory for flat bodies of large aspect ratio. Cheng et al.[5] developed a three-dimensional waving plate theory, and discussed the effect of the aspect ratio on the propulsion. Recently, more sophisticated numerical methods based on the potential flow theory were proposed to predict the propulsion performance of fish-like bodies[6,7]. On the other hand, numerical simulations by solving the Navier-Stokes equations[8-11] and hydrodynamics experiments[12] were carried out. These results show that high propulsive efficiency can be obtained by undulating motions.

It is important to find the optimum plate motion that gives rise to the highest attainable hydrodynamic efficiency. As described by Wu[13], the optimal problem can be stated as to find one of rational motions that produce a prescribed level of thrust at a minimum energy cost. However, the optimal problem is singular, so that the solution is non-unique for the “invisible mode” as called by Ahmadi[14], and the

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