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企鹅翅膀后掠角对流体动力推进性能的影响

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摘 要：前缘后掠角是生物结构中一个重要几何特征，其广泛存在于鱼尾、水生动物鳍状肢以及鸟类或昆虫翅膀的几何结构中。在对于类尾和类鳍状运动学的研究中发现，对于恒定展弦比的翼型，后掠角与推进力和功率之间的相关性可以忽略不计。通过研究企鹅滑翔时其鳍状翼的水动力学发现，后掠角可以有效地防止翅膀突然失速，同时最佳后掠角取决于游泳速度。在最近关于企鹅翅膀的实验研究中，Shen 还发现后掠角对水动力效率没有显著影响。然而，当运动参数相同时，较小的后掠角会导致较大的推进力。由于设备制造的困难，实验研究中的顺桨轴只能设置为垂直于拍打轴，这与企鹅翅膀的实际运动不同。因此，本文通过数值模拟研究了不同后掠角下更真实的翅膀运动，以探讨后掠角对企鹅推进性能的影响。这项工作对企鹅翅膀的流体动力学进行了详细分析，企鹅翅膀具有不同的顺桨轴线，固定顺桨轴和随体顺桨轴，以及在向前推进中预定义的后掠角。基于直接数值模拟（DNS）和浸没边界法（IBM）的计算流体动力学（CFD）求解器计算了流体特性并可视化鳍状翼周围的流动结构。

关键词：浸没边界法；拍打运动；企鹅；攻角；后掠角

EFFECT OF SWEEP ANGLE OF PENGUIN WING ON THE HYDRODYNAMIC PROPULSION PERFORMANCE

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Leading edge sweep angle is a key geometric feature observed in biological structures, such as fish tails, mammal flukes, aquatic-animal flippers, and bird or insect wings. In the study of constant aspect ratio foils undergoing tail-like and flipper-like kinematics, the correlation between the sweep angle and the propulsive force and power for both tail-like and flipper-like motions is negligible. Simulating gliding penguin flippers suggests that sweepback effectively prevents abrupt wing stalls, with the optimal sweepback angle dependent on swimming speed. In a recent experimental study on penguin wings, Shen also found that hydrodynamic efficiency is not significantly affected by sweep angle. However, when the motion parameters are the same, a smaller sweep angle results in larger propulsion force. Due to the difficulty of equipment manufacturing, the feathering axis in experimental research can only be set perpendicular to the flapping axis, which is different from the actual motion of penguin wings where feathering axis rotates in the spanwise direction. Therefore, this paper investigates more realistic wing motion under different sweep angles through numerical simulation to explore the effect of sweep angles on penguin propulsion performance. This work offers a detailed analysis of the hydrodynamics of a penguin wing with different feathering axes, e.g. fixed and local, and predefined sweep angles in forward propulsion. The computational fluid dynamics (CFD) solver based on direct numerical simulation (DNS) and immersion boundary method (IBM) calculates the fluidic properties and visualizes the flow structure around the wing.

Key Words: Immersed Boundary Method; Flapping Motion; Penguin; Angle of Attack; Sweep Angle