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Effect of a Tail with Non-Uniform Flexibility on Flapping Foil Dynamics

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Abstract. The effect of a tail with non-uniform flexibility on flapping foil dynamics is studied systematically in this work. Both the power extraction and propulsion behaviors of a flapping foil are checked. Three distinct kinds of non-uniform flexibility distribution are considered, i.e., linear distribution, piecewise distribution and heterocercal distribution. Based on the numerical results obtained, it is found that the tail when the flexibility decreasing along the length is beneficial for power extraction, especially for the piecewise distribution. The reason is that the non-uniform flexible tail can generate bigger bending deformation than the uniform flexible tail, which is good for the leading edge vortex (LEV) capture and then results in the significant rise of the lift. On the other hand, the tail with the decreasing flexibility is harmful to the thrust generation, whilst the flexibility increasing along the length has little benefit on propulsion. The results obtained may have implications for the optimization of the flapping foil propeller and energy harvester.

AMS subject classifications: 68U20, 74F10, 76D17

Key words: Non-uniform flexible tail, power extraction, propulsion, flapping foil.

1 Introduction

Vortex-object interaction can be frequently observed in nature and engineering applications [1–5]. One typical example is flapping foil motion mode, which is commonly used by many swimming/flying animals to produce thrust and lift for their daily locomotion.

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Inspired by the excellent maneuverability and high efficiency of the swimming/flying animals, the flapping foil is extensively employed in the design of biomimetic swimming/flying robots [6] and energy extraction devices [7]. However, the current man-made flapping foil is often rigid and still performs much worse than the animal flapping fins/wings [8], although many studies are carried out to improve the performance of the flapping foil through the optimization of the flapping parameters [9], such as the angle of attack [10], the flapping frequency and amplitude [11], the flapping path [12] and so on. Thus, it is still worthwhile to study the dynamics of flapping foil to further enhance its performance.

Deformation during flapping motion is one of great characteristics of animal fins/wings [13] and a number of efforts have been made in this aspect [14, 15]. Nevertheless, it should be noted that the flexibility distribution of flapping foil was generally set to be uniform in previous studies. Non-uniform flexibility is one noteworthy feature of the animal fins/wings [16]. In recent years, some attempts have been taken with the aim of investigating the advantages of the non-uniform flexibility. Through experimental measurements, Lucas et al. [17] found that larger thrust could be generated by a flapping plate with non-uniform stiffness. Shoele & Zhu [18] mimicked the fin as several two-dimensional flexible plates connected by springs and they indicated that the strengthened leading edge could significantly improve the thrust and efficiency. In these studies, however, the foil was simply modelled as a flexible plate and the effect of foil section shape was neglected.

More recently, a model combining a rigid airfoil with a flexible tail, which is denoted as a combined model, has also been utilized to represent a flapping fin/wing. This model considers not only the flexibility but also the section shape which is very important for both propulsion and power extraction [7, 9, 19]. Cleaver et al. [20] indicated that the use of flexible tail could improve the thrust of plunging foil and the long tail was suggested for large thrust. David et al. [21] found that the flexible tail with moderate flexural rigidity could enhance both the thrust and efficiency of pitching foil. Shinde & Arakeri [22] reported that the thrust improvement attributed to the suppression of wake meandering generated by the flexible tail. Moreover, Wu et al. [23] found that the flexible tail also could enhance the power extraction and efficiency significantly. However, the flexibility of tail in such combined model was still considered as uniform.

In current work, the effect of a tail with non-uniform flexibility on the energy extraction and propulsion performances of a combined model is investigated numerically. A rigid NACA0015 airfoil with a non-uniform flexible tail is immersed in the two-dimensional viscous flow, as shown in Fig. 1(a). To perform the numerical simulations, an immersed boundary-lattice Boltzmann method [24] was adopted. Three kinds of non-uniform distribution of tail flexibility are considered, i.e., linear distribution, piecewise distribution and heterocercal distribution. A non-uniformity coefficient L_b is proposed for controlling the non-uniform level of tail flexibility. The dynamics of combined model under the conditions of different non-uniformity coefficients and mean flexibilities are investigated in detail.