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Numerical investigation into energy extraction of flapping airfoil with Gurney flaps

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A new type of Gurney flap is applied for energy extraction enhancement of a flapping airfoil. Two-dimensional Navier-Stokes simulations at $Re = 10^4$ are conducted to study the effect of Gurney flaps with various heights. The investigations are undertaken over a wide range of kinematic parameters (reduced frequency k, pitching amplitude θ_0). Numerical results show that the application of a Gurney flap notably increases the maximum output power and efficiency compared with a clean NACA0012 airfoil. By affecting the flow structure and the pressure distribution around the trailing edge of the airfoil, the Gurney flap is beneficial to the lift force generation, thus leading to a higher power coefficient. The maximum power coefficient increases with Gurney flap height h_g at first between $h_g = 0c$–$0.3c$ (c is the airfoil chord length), while a further increase in h_g provides no further energy extraction enhancement. Besides, the increasing h_g results in stronger trailing edge vortices and higher drag force.

1. Introduction

In the past decade, renewable energy extraction by flapping airfoil has been the subject of many studies due to its economic and technical viability as well as being environmentally friendly in terms of noise generation. The application of flapping airfoil to extract energy from the wind was firstly proposed by McKinney and DeLaurier [1]. With continuous rise of world energy demand and fuel prices, this novel concept has drawn gradually more attention for its academic attractiveness and potential engineering applications in the past few years. The energy extraction performance of a traditional flapping airfoil has been systematically studied by many researchers [2–6]. According to these studies, the optimal reduced frequency corresponding to the peak efficiency is observed within the range between 0.10 and 0.15. The energy harvesting efficiency increases significantly with the plunging amplitude at low plunging amplitudes, while the efficiency decreases once the plunging amplitude reaches one chord length. Besides, it is found that the peak energy extraction occurs when the pitch and plunge motions are 90° out of phase. Following these ideas, some real energy extraction devices and prototypes have been proposed and tested. The first commercial prototype of an oscillating hydrofoil hydrokinetic turbine is the 150 kW "Stingray" developed by the Engineering Business Ltd [7]. The turbine consisted of a single hydrofoil pivoted on a swinging arm. It reported a maximal production of 85 kW and power extraction efficiency of 11.5%. Paish [8] described a 100 kW prototype named Pulse Stream designed by the UK company Pulse Tidal. Two foils are pivoted at mid-chord at the end of the swing-arms. The foils are symmetric front-to-back so that the turbine can extract energy from both flow directions. Platzer [9] invented a fully passive device which requires no motor to drive the pitching motion. The foil plunges on a guide rail and pitches at the end of the rail so that the foil undergoes non-sinusoidal plunging and pitching motions. Kinsey [10] proposed a new concept of hydrokinetic turbine using oscillating hydrofoils to extract energy from water currents. The turbine includes two rectangular oscillating hydrofoils in tandem, with pitch motion of each foil linked to the plunge motion. They demonstrated a hydrodynamic efficiency of 40% for the experimental prototype.

Recently, some new mechanisms were adopted to further enhance the energy extraction performance of flapping airfoils. One of the improvements, namely nonsinusoidal airfoil motion, was inspired by the biological mechanism of the high propulsion

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Nomenclature

c	airfoil chord length
C_p	pressure coefficient
C_P	power coefficient
C_{Ph}	power coefficient of plunging motion
C_{Phmean}	time-averaged power coefficient of plunging motion
C_{Pmean}	time-averaged power coefficient
$C_{P\theta}$	power coefficient of pitching motion
$C_{P\theta mean}$	time-averaged power coefficient of pitching motion
C_{Tmean}	time-averaged thrust coefficient
C_l	lift coefficient
C_d	drag coefficient
f	flapping frequency
H_0	nondimensional plunging amplitude
h_g	Gurney flap height
$h(t)$	plunging motion
k	reduced frequency ($k = 2\pi fc/U_\infty$)
Re	Reynolds number
t	physical time
T	flapping motion period
U_∞	free stream velocity
V_y	plunging velocity
x	chordwise position
η	energy extraction efficiency
θ_0	pitching amplitude
$\theta(t)$	pitching motion

efficiency in flying and swimming animals. The influence from nonsinusoidal airfoil motions has been studied by Ashraf [11], Xiao [6] and Lu [12]. Ashraf's results indicate around 17% increase in power generation and around 15% increase in efficiency over those with sinusoidal motions. Xiao [6] reported even higher power coefficient and efficiency increases as much as 63% and 50% at an optimal parameter β. Corrugation and camber observed in flying insects and swimming animals were discovered to enhance the propulsive performance of the flapping airfoils. Inspired by this concept, Le et al. [13] numerically explored the effect of corrugation and camber on the airfoil's ability to extract energy from flow. Their results show that an optimized airfoil shape with corrugation and camber can improve the efficiency by around 6% in comparison to the NACA0012 profile. Liu et al. [14] computationally studied the role of wing deformation in the hydrodynamics of flapping wing devices. Their simulation results show that the impact of wing flexibility on efficiency is more profound at low nominal effective AOA (angles of attack). At a typical flapping frequency of 0.15 and nominal effective AOA of 10°, a flexible wing generates 7.68% higher efficiency than a rigid wing. Furthermore, some experimental and numerical studies by Jones et al. [15], Platzer et al. [16] and Ashraf et al. [11] suggests that the energy extraction capacity may be increased by using two airfoils in a tandem arrangement. The detailed numerical investigation conducted by Ashraf et al. [11] shows that both phase lag and distance between the two airfoils have significant impacts on the energy extraction capacity and efficiency. Over their tested range of parameters, it is found that in the tandem arrangement both averaged power coefficient and efficiency per airfoil are reduced by around 20% compared with a single airfoil. However, the overall efficiency of the tandem configuration is increased by up to 59% compared to a single airfoil.

Apart from above innovations, a simple and low-cost device, namely Gurney flap, has been widely considered in applications to enhance the lift force. Fig. 1(a) presents a traditional Gurney flap, which consists of a small flat plate positioned at the trailing-edge, perpendicular to the pressure side of the airfoil. The common applications of this device are in racing-car spoilers, aircrafts and wind turbines. The Gurney flaps have been proved effective to enhance the lift in these applications. We intend to use the Gurney flaps to enhance the lift force of the flapping airfoil and achieve a higher power coefficient.

Original investigation of the Gurney flap was conducted on a Newman airfoil by Liebeck [17] to increase the down-force for the lateral traction. Liebeck [17] found that the Gurney flap of 1.25% height increased the lift coefficient and reduced the drag coefficient at the same time. The drag increased noticeably beyond heights of

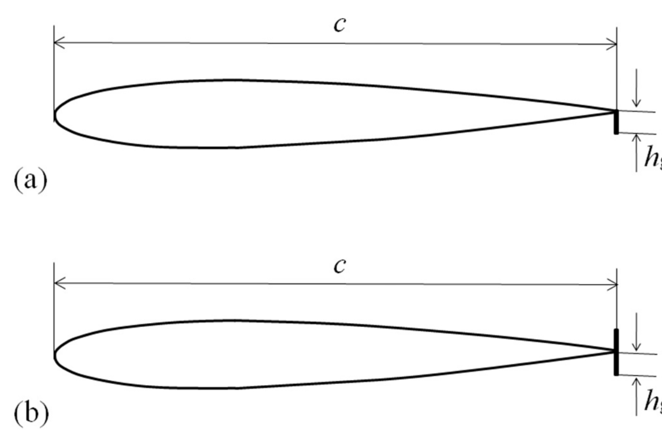

Fig. 1. (a) Traditional application of the Gurney flap, (b) new Gurney flap used in this paper.

approximately 2% chord, even though there was a continuing increase in downward force. Experimental wind tunnel investigations into racing-car wings with addition of a Gurney flap were later conducted by Katz and coworkers [18,19]. Katz and Largman [19] reported that 5% chord Gurney flap significantly increased the lift above the baseline airfoil by about 50%. Another important application of the Gurney flap is in aircraft wings, where it is used for lift enhancement. Storms and Jang [20] obtained the pressure distributions and wake profiles on an NACA4412 airfoil equipped with the Gurney flaps. They observed that the drag decreased near the maximum lift condition, but increased at low to moderate lift conditions. Giguère et al. [21] measured the lift and drag forces, wall-pressure distributions and boundary-layer thickness on two airfoils, LA203A and Göttingen797, with the Gurney flaps ranging in height from 0.5 to 5% chord. The results reveal that the Gurney flaps provide a significant increase in lift at very small cost in drag, and that the optimum Gurney flap height scales with the boundary layer thickness at the trailing-edge of the baseline airfoil on the pressure side. Myose et al. [22], Li et al. [23] and Liu et al. [24] provided further information about the effect of Gurney flap on the aerodynamics of the airfoil. The general conclusion is that the Gurney flap significantly increases the lift and nose-down pitching moment with a slight increase in drag coefficient.

More recently, some researchers paid attention to the application of Gurney flaps on oscillating airfoils. Geronatkos and Lee [25,26] conducted a comprehensive study on a pitching NACA0012 airfoil