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On the nonlinear dynamics of self-sustained limit-cycle oscillations in a flapping-foil energy harvester

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ABSTRACT

The nonlinear dynamics of an airfoil at Reynolds number $Re = 10{,}000$ constrained by two springs and subject to a uniform oncoming flow is studied numerically. The studies are carried out using open source computational fluid dynamics toolbox OpenFOAM. Under certain conditions related to aerodynamic flutter, this two-degree-of-freedom system undergoes self-sustained limit-cycle oscillations (LCOs) with potential application as an energy harvester. When the system is given a small initial perturbation, it is seen that the response of the system decays to zero at flow velocities below the flutter velocity, or oscillates in a limit cycle at velocities greater than the flutter velocity. The flutter velocity at $Re = 10{,}000$ is shown to deviate significantly from the theoretical prediction (which is derived with an assumption of infinite Reynolds number) owing to the effect of viscosity. The LCOs at freestream velocities higher than the flutter velocity result in unsteady flows that are heavily influenced by leading-edge vortex shedding as well as trailing-edge flow separation. The influence of different system parameters on the onset of flutter and on the limit-cycle response characteristics is investigated in this research. This is done by defining a baseline case and examining the effects of varying aerodynamic parameters such as freestream velocity, and structural parameters such as the pitch-to-plunge frequency ratio and the type of spring stiffnesses. The conditions corresponding to the lowest flutter velocities (and consequently the lowest "cut-in" speeds for power extraction) and the parameter space that provide single-period, single-amplitude and harmonic LCOs (ideal for power extraction) are identified. Calculation of instantaneous and time-averaged power is presented by modeling the extraction of energy through a viscous damper. The highest power coefficients and efficiencies are obtained at velocities just higher than the flutter velocity. Introduction of positive cubic stiffening in the system springs is seen to make the system more stable, LCOs more harmonic and single-period, and to potentially increase power extraction efficiency of the system.

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Nomenclature

α	Pitch angle
α_A, h_A	Amplitude of LCO in pitch and plunge
$\bar{\omega} = \omega_h/\omega_\alpha$	Frequency ratio
β_α, β_h	Coefficient of cubic stiffening in pitch and plunge
$\dot{\alpha}^* = d\alpha/dt^*$	Nondimensional pitch rate
$\dot{h}^* = d(h/c)/dt^*$	Nondimensional normalized plunge rate
η_P	Power capture efficiency
$\kappa = \pi\rho c^2/4m$	Inverse mass ratio
$\omega = 2\pi/T$	Angular frequency of sinusoidal motion
$\omega_\alpha = \sqrt{k_\alpha/I_\alpha}$	Characteristic frequency of pitch mode
$\omega_h = \sqrt{k_h/m}$	Characteristic frequency of plunge mode
$\overline{C_P}$	Time-averaged power coefficient
$\zeta_h = c_h/2m\omega_h$	Nondimensional damping ratio for plunge
c	Airfoil chord
C_l, C_d, C_m	Lift coefficient, drag coefficient and pitching-moment coefficient, per unit span
C_P	Power coefficient per unit span
C_W	Nondimensional accumulated work per unit span
c_α, c_h	Pitch and plunge structural damping coefficient, per unit span
$F(\alpha)$, $F(h)$	Restoring force by rotational (pitch) and translational (plunge) springs
h	Plunge displacement
I_α	Airfoil moment of inertia about pivot
$k = \omega c/2U$	Reduced frequency of sinusoidal motion
k_α, k_h	Linear pitch and plunge stiffness, per unit span
m	Mass of airfoil
$r_\alpha = 2\sqrt{I_\alpha/mc^2}$	Airfoil radius of gyration about pivot
Re	Reynolds number based on c and U
S_α	Static moment of airfoil about pivot
T	Time period of sinusoidal motion
t	Physical time
$t^* = tU/c$	Non-dimensional time
U	Freestream velocity
$U^* = U/\omega_\alpha c$	Nondimensional velocity
U_F	Flutter velocity
$x_\alpha = 2S_\alpha/mc$	Distance of center of gravity aft of pivot, nondimensionalized by c
DOF	Degree of freedom
LCO	Limit-cycle oscillation
LEV	Leading-edge vortex
TEV	Trailing-edge vortex

1. Introduction

Classical aeroelasticity treats fluid–structure interaction and its associated phenomena (such as divergence, control reversal and flutter) as undesirable (Bisplinghoff and Ashley, 1996; Fung, 2002), but recent studies have shown that it to beneficial in biological flight and swimming (Hamamoto et al., 2007; Nakata and Liu, 2012; Taylor et al., 2010). One potential application is the development of novel energy harvesters mimicking the motion of fish tails and based on the principle of aerodynamic flutter, using the motion of a flapping wing to drive a generator (Young et al., 2014). These harvesters claim significant advantages over the majority of existing wind/water energy harvester designs which utilize horizontal-axis or vertical-axis turbines and present challenges related to economic viability and environmental impact (Xiao and Zhu, 2014).

The objective of this research is to investigate the nonlinear aeroelasticity and dynamics of the flapping-foil energy harvester in the $Re = 10{,}000$ regime through a detailed parametric study. The system consists of a two-degree-of-freedom (2DOF) foil constrained by rotational and translational springs. The system may exhibit various responses at different freestream velocities, depending on the several aerodynamics and structural parameters that govern the system. The ideal response for power generation is expected to be single-period, single-amplitude oscillations, and hence it is important to characterize the response and behavior of the system as a function of the various underlying parameters.