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Electro-aeromechanical modelling of actuated membrane wings

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ABSTRACT

This paper presents a numerical investigation on the aeromechanical performance of dynamically actuated membrane wings made of dielectric elastomers. They combine the advantages of membrane shape adaptability, which produces increased lift and delayed stall, with the benefits of simple, lightweight but high-authority control mechanism offered by integral actuation. High-fidelity numerical models have been developed to predict their performance and include a fluid solver based on the direct numerical integration of the unsteady Navier–Stokes equations, an electromechanical constitutive material model and a non-linear membrane structural model. Numerical results show that harmonic actuation can either increase or reduce the overall aerodynamic efficiency of the wing, measured as the mean lift-to-drag ratio, depending on the ratio between the actuation frequency and the natural frequency of the membrane. In addition, the definition of a reduced-order model based on POD modes of the complete high-fidelity system provides an insight of the main characteristics of the dynamics of the coupled system.

1. Introduction

Wind tunnel testing of membrane wings (Winter and Von Helversen, 1998; Newman, 1987; Rojratsirikul et al., 2009) has shown that they can offer a superior aerodynamic performance in low Reynolds number flows. This includes delayed stall, higher lift, and enhanced manoeuvrability and agility as compared with their rigid counterparts. These aerodynamic advantages are mostly related to the membrane compliance that allows the passive shape adaptation to the pressure gradients and energy-efficient coupling with the unsteady flow phenomena (Rojratsirikul et al., 2010). However, membrane wings also require a supporting frame, which in general will degrade their performance. The shape and the stiffness of the supports strongly influence the dynamics of the wing (Arbos-Torrent et al., 2013). With that as a starting point, further gains would be possible through wing actuation. While this has mostly been attempted using mechanical actuation (Stanford et al., 2008), integral electromechanical actuation could provide a much higher control flexibility. In particular, the use of dielectric elastomers (DEs) as material for the wing would allow the coupling of the advantages of the passive adaptation offered by the wing compliance, with the benefits of a simple, lightweight control mechanism from embedded actuation. DEs are composed of a thin polymeric layer sandwiched between two compliant electrodes. The application of a voltage through the thickness causes the compression of the material in that direction and its in-plane extension (Suo, 2010). This defines a variation of the tension in the wing that can be used to tune its dynamic behaviour.

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Nomenclature

B_{ij}	left Cauchy deformation tensor
$\mathbb{C}_{ijkl}$	tangent stiffness matrix
C_{ij}	right Cauchy deformation tensor
C_d	drag coefficient
C_l	lift coefficient
C_p	pressure coefficient
E	electric field magnitude
F_{ij}	deformation gradient
J	deformation gradient determinant
J_m	Gent model material constant
S_{ij}	second P–K stress tensor snapshot matrix
t^*	cycle time
U	volumetric energy function
V	velocity, voltage, volume
v_i	velocity vector
W	free energy function

Greek letters

α	angle of attack
δ	prestretch parameter
ϵ	dielectric permittivity
λ	stretch
μ	shear modulus
ν	Poisson ratio
ρ	density
σ_{ij}	stress tensor component
τ_{ij}	shear stress component
Φ	deviatoric energy function, projection matrix

Nondimensional constants

Re	Reynolds number
St	Strouhal number
We	Weber number

Subscripts

e	elastic
el	electromechanical
m	mechanical
s	structural
V	voltage
∞	equilibrium elastic, free stream
0	initial, reference, vacuum

The key characteristics of the resulting physical system are highlighted in Fig. 1 (left). As it can be seen, the design and the operation of actuated membrane wings define a heavily multidisciplinary problem, covering aerodynamics, structural dynamics, material modelling and control aspects. From the aerodynamic point of view and for Reynolds numbers typical of Micro-Air Vehicles (MAVs) applications (10^4–10^5), separation and recirculation are the main sources of unsteadiness in the interaction with the membrane, and cause the strong coupling between the fluid and the membrane vibrations (Rojratsirikul et al., 2009, 2010, 2011). On the structural side, Arbos-Torrent et al. (2013) have experimentally shown that mean camber and modes of membrane aerofoils are strongly influenced by the size and shape of the leading- and trailing-edge supports, which in practice, can never be neglected. The membrane compliance determines large structural displacements and the soft material used is usually accompanied by a rate-dependent constitutive behaviour. Rojratsirikul et al. (2011) and

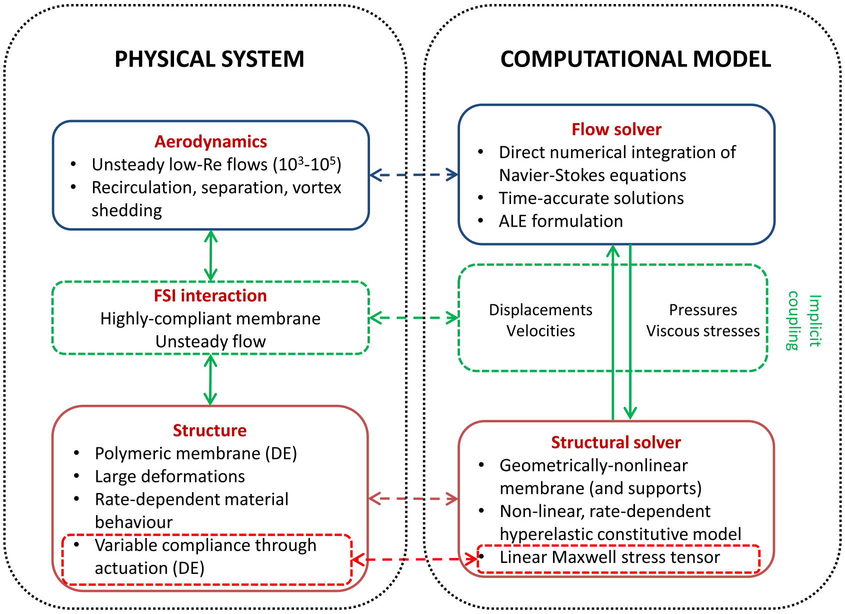

Fig. 1. Definition of the aeroelastic problem of actuated membrane wings: physical system and the corresponding computational model used in this work.