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Viscoelastic effects in the aeromechanics of actuated elastomeric membrane wings

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ABSTRACT

This work is a numerical investigation on the influence of viscoelastic effects on the aerodynamics of integrally actuated membrane wings. For that purpose, a high-fidelity electro-aeromechanical computational model of wings made of dielectric elastomers has been developed. The structural model is based on a geometrically non-linear description and a non-linear electro-viscoelastic constitutive material law. It is implicitly coupled with a fluid solver based on a finite-volume discretisation of the unsteady Navier–Stokes equations. The resulting framework is used for the evaluation of the dynamics of passive and integrally actuated membrane wings at low Reynolds numbers under hyperelastic and viscoelastic assumptions on the constitutive model. Numerical simulations show that the damping introduced by viscoelastic stresses can significantly reduce the amplitude of membrane oscillations and modify key features in the coupled system dynamics. The estimated wing performance metrics are in good agreement with previous experimental observations and demonstrate the need of including rate-dependent effects to correctly capture the coupled system dynamics, in particular, for highly compliant membranes.

1. Introduction

The successful development of micro air vehicles (MAVs) has brought renewed interest in energy-efficient solutions to facilitate outdoor flight. Rotary-wing concepts offer robust performance in gusty conditions, but, despite their widespread use, have very low power efficiency. Consequently, there is still a need for a fixed-wing equivalent that would be capable of achieving very high manoeuvrability. Membrane wings, as seen in bats and other natural fliers, could provide the required performance and several experimental investigations (Attar and Dowell, 2005; Song et al., 2008; Attar et al., 2012; Bleischwitz et al., 2015) have proven substantial aerodynamic advantages. In particular, high compliance provides passive means to mitigate the impact of flow disturbances (Gursul et al., 2014) and further improvements could be achieved by means of bio-inspired actuation strategies to change wing compliance during flight, as observed in bats. Experimental (Hays et al., 2013; Curet et al., 2014) and numerical (Buoso and Palacios, 2015) investigations have demonstrated high control authority of embedded actuation through the use of dielectric elastomers (DEs) as membrane materials. This combines the aerodynamic benefits of membrane wings with a lightweight and simple, but high authority, control mechanism offered by dielectric elastomers.

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Nomenclature

C_{ij}	left Cauchy deformation tensor
C_l	lift coefficient
D	deviatoric energy function
E	electric field magnitude
F_{ij}	deformation gradient
J	deformation gradient determinant
J_m	gent model material constant
t^*	non-dimensional time
U	volumetric energy function
V	velocity
v_i	velocity vector
W	free energy function

Greek letters

α	angle of attack
ϵ	dielectric permittivity
λ	prestretch
μ	shear modulus
ρ	density
σ_{ij}	stress tensor component
Φ	voltage

Subscripts

e	elastic
el	electromechanical
m	mechanical
s	structural
θ	angle correction
v	voltage
∞	equilibrium elastic free stream
0	initial, reference, vacuum

Acronyms

LEV	leading edge vortex

High-fidelity computational modelling is an essential ingredient to understand the physical phenomena behind the complex global behaviour of actuated membrane wings. Structural and fluid details have to be accurately represented to capture the strong coupled-system dynamics. A big effort has been done towards the high-fidelity modelling of low Reynolds number flows around membranes. Viscous laminar solvers (Smith and Shyy, 1995; Tiomkin et al., 2011), turbulent models coupled with transition models (Lian and Shyy, 2007) and LES models (Gordnier, 2009; Visbal, 2009) have been extensively used in order to reproduce the unsteady flow phenomena typical of membrane wings. From the structural point of view, a similarly high level of fidelity is often missing in these models, since typically a nonlinear geometric solver is coupled with a linear elastic constitutive law. Indeed, despite membrane strains easily reaching values above 100%, relatively few papers (Lian and Shyy, 2007; Stanford et al., 2008; Buoso and Palacios, 2015, among others) have considered hyperelastic material behaviour to characterise the large deformations of highly compliant wings.

Experimental testing of DEs has identified strong rate-dependent material behaviour, even for small deformation rates (Ask et al., 2012; Mokarram et al., 2012). To date, only Wissler and Mazza (2007), Fox and Goulbourne (2009) and Mokarram et al. (2012) have published fully relaxed experimental data for the characterisation of the purely elastic constitutive behaviour of acrylic DEs. However, most previously proposed constitutive models for DEs (Fox and Goulbourne, 2009; Carpi et al., 2011) have neglected the viscous stresses typical of these polymers. Several phenomenological models have been proposed to model rate dependent effects. Wissler and Mazza (2007) have suggested a viscoelastic model based on Prony series, while Ask et al. (2012) and Mokarram et al. (2012) have used the multiplicative decomposition of the deformation tensor to define a nonlinear viscoelastic model for uni-axial tensile cases. More recently, Li et al. (2013) have shown that material constants obtained from uni-axial or equi-biaxial loading conditions predicted a significantly different behaviour, highlighting the importance of the boundary conditions for the material identification. This was found to be linked to the hyperelastic behaviour of thin membranes, which significantly differs from more conventional (bulk) material behaviour.

It is therefore expected that the coupled electro-aeromechanical response of DE membrane wings will be significantly affected by the viscoelastic characteristics of the material. Recently, the authors have presented a high-fidelity model for actuated wings that assumes a purely hyperelastic material behaviour (Buoso and Palacios, 2015). Therefore, this paper proposes a nonlinear viscoelastic model suitable for DE membrane wings that will be coupled with that electro-aeromechanical model and used to investigate the importance of viscoelastic effects in the wing dynamics.

Section 2 introduces the mathematical model for the constitutive material behaviour, which is developed in the finite deformation framework. Section 3 describes the analytical dynamic model for the identification of the viscoelastic material properties from experimental data, and Section 4 outlines the fully coupled electro-aeromechanical model for membrane wings. This is finally used in Section 5 to evaluate the behaviour of passive and actuated membrane wings for the hyperelastic and viscoelastic material models, providing the basis for a comparison of the impact of the structural level of fidelity in the characterisation of the aeroelastic system.