Improving the Aerodynamic Performance of a Cycloidal Rotor through Active Compliant Morphing

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The objective of this paper is to present the state-of-the-art on compliant mechanism structures and to discuss the results obtained at the University of Glasgow from applying leading edge morphing to blades from a cycloidal rotor. The paper is comprised of: a general overview of compliant mechanisms; various types of smart actuator that can be employed; the different choices of skin material that may be used; and specific applications to aeronautical engineering. Specific areas discussed in the general overview include what compliant mechanisms are, advantages and disadvantages of applying compliant mechanism structures, the past/current research carried out and useful applications where compliant systems could be employed as a replacement to conventional actuation systems.

A compliant mechanism is a single-piece structure which has the primary function of transmitting motion and force mechanically, dependent upon the elastic deformation of their constituent elements [1]. The compliant system consists of actuators and sensors embedded within the compliant structure required for motion transmission. Small strains generated by the embedded actuators produce large deflections due to stroke amplification from the compliant structure [2]. An visualisation of a simple compliant mechanism used as a gripper is shown in figure 1.

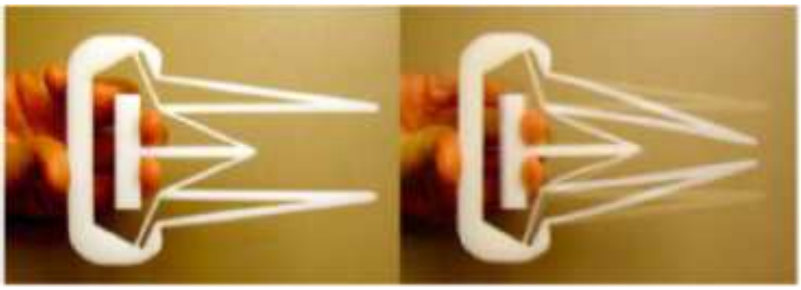

Figure 1: A simple compliant gripper mechanism [3]. The left picture represents the gripper position with no actuation force and the right picture with actuation force applied.

Possible smart actuation systems which could be embedded within a compliant system include shape memory alloy (SMAs) actuators, piezoelectric actuators in addition to conventional linear actuators such as hydraulic, pneumatic and electric actuators [1]. Traditional aircraft use conventional linear actuators to achieve a range of flap angle deflections to improve control authority at higher flight speeds. Using flaps however can lead to surface discontinuity over the wing surface resulting in possible flow separation and increases in drag [4]. This issue can be resolved by using a conformal wing containing a compliant structure with embedded smart actuators to produce continuous shape changes whilst maintaining wing surface continuity [5].

Another key component of a compliant mechanism relates to the choice of skin material selected to provide both the inherent flexibility required to deform the structure via the action of embedded actuators and the sufficient stiffness required to resist any unwanted deflections arising from external loads acting on the structure. The skin material has to be designed to produce a smooth, continuous surface with low membrane stiffness and high lateral stiffness. The low membrane stiffness is essential in reducing morphing actuation requirements and high lateral stiffness is desirable in order to maintain the aerodynamic shape. The various types of skin material that could be used for improving morphing efficiency in compliant structures are discussed, comparing results from past research.

A co-simulation analysis involving CFD and FEA is used to investigate changes in the aerodynamic performance characteristics of a cycloidal rotor with active blade morphing. Leading edge morphing is applied to the blades from a two-blade cycloidal rotor where the leading edge actively deflects when required to alter the flow-field characteristics. Leading edge compliant morphing is applied when the blade operates in the retreating region in order to mitigate poor aerodynamic performance characteristics resulting from dynamic stall effects. A two-dimensional, unsteady CFD analysis is carried out using STAR CCM+ to calculate the pressure loading and shear stress acting on the rotor blades. The advanced overset mesh technique is applied to simulate cycloidal rotor motion and the blade sinusoidal pitching kinematics. CFD validation is carried out for a NACA 0012 aerofoil operating at a set sinusoidal pitching arrangement to ensure that accurate dynamic stall conditions and flow-field representations occur. The results obtained for blade pressure loading and shear stress are exported into Abaqus to determine the modified, morphed blade structure.

FEA analysis is carried out to determine key parameters such as blade stress, strain and nodal displacements generated by the external pressure loading results exported from CFD. Compliant morphing is simultaneously applied and the active compliant blades are exported back into STAR-CCM+ to re-evaluate the changes in the flow-field characteristics. This process is repeated until time-averaged results in lift, thrust and power characteristics converge. Three cases of rotor advance ratio are assessed and the aerodynamic characteristic results obtained from blade compliant leading edge morphing are compared to the baseline cycloidal rotor results. The rotor RPM and blade pitching kinematics remain constant therefore changes in aerodynamic performance characteristics such as lift, thrust and power are affected mainly by active leading edge morphing.

The baseline CFD results for the lift and thrust characteristics of a cycloidal rotor in forward flight for three cases of advance ratio are shown in figures 2 and 3 respectively. The rotor radius and blade chord length is 76.2 mm and 49.53 mm respectively. Negative lift is generated for all cases of advance ratio when the blade operates in the rotor retreating region. Initial investigations indicate that selective morphing of the blade leading edge will improve the aerodynamic performance characteristics. The particular avenue currently being investigated is active deflection of the blade's leading edge in the retreating region to improve the lift characteristics due to mitigating the dynamic stall effect. Work is ongoing in this area at the University of Glasgow.

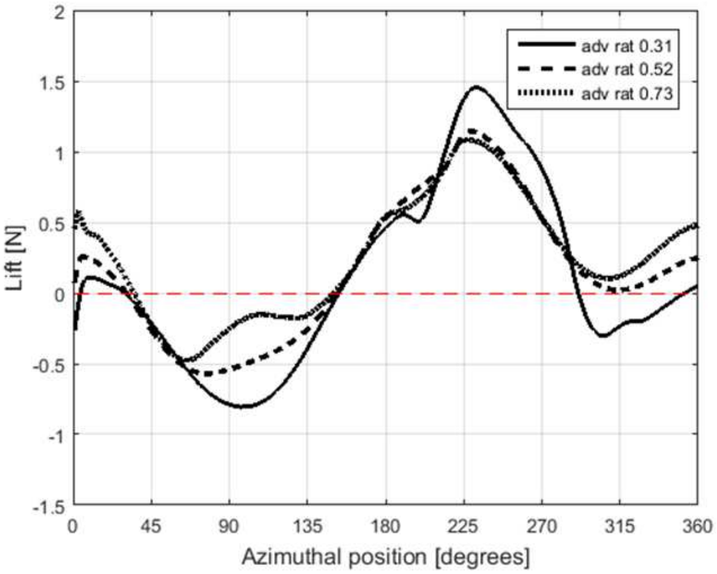

Figure 2: CFD results of instantaneous blade lift against rotor azimuthal position for varying advance ratios. The zero crossing is represented as the red dashed line.

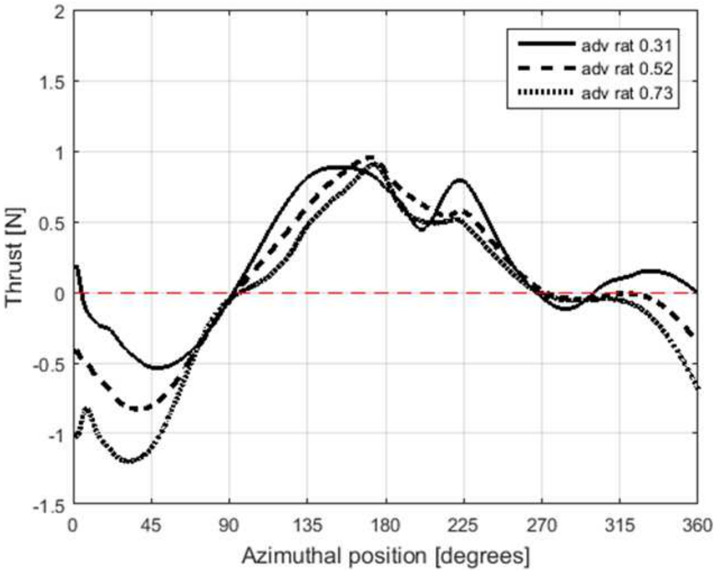

Figure 3: CFD results of instantaneous blade thrust against rotor azimuthal position for varying advance ratios. The zero crossing is represented as the red dashed line.

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