GEOMETRICALLY NONLINEAR AEROELASTIC CHARACTERISTICS OF WINGLETS FOR PASSIVE MORPHING WING APPLICATIONS

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ABSTRACT

The aircraft industry continues to seek ways to improve aircraft efficiency by reducing fuel consumption and structural weight. In this context, winglets have become an essential aerodynamic device for mitigating induced drag by increasing effective wingspan and reducing wing tip vortices strength. While conventional fixed winglets offer significant performance benefits, their design is optimized for a limited set of flight conditions [1]. Due to this limitation, morphing wing concepts have growing interest, as they aim to improve aerodynamic performance and load alleviation under a wider flight envelope.

While active morphing winglets rely on actuators to change their geometry during flight, passive morphing winglets exploit aeroelastic deformation to adapt their geometry under aerodynamic loads without the need for control systems. By relying on structural flexibility, passive morphing offers a promising solution for reducing system complexity, weight, and energy consumption compared to active morphing approaches. However, increased flexibility introduces critical aeroelastic stability challenges, as adaptive winglets may be more susceptible to instabilities such as flutter and divergence, especially when large deformations and geometric nonlinearities are involved.

Most existing studies on morphing winglets have focused primarily on aerodynamic performance [2-3] often neglecting dynamic aeroelastic phenomena. In addition, conventional flutter analyses used in preliminary design are based on linear structural assumptions and undeformed reference configurations which are inadequate for capturing the nonlinear behavior of such flexible components. Therefore, there is a clear need for an aeroelastic stability framework capable of overcoming these limitations in the context of adaptive winglet design. To address this, a geometrically nonlinear aeroelastic framework has been previously established by the authors [4-5] coupling corotational shell finite elements with an unsteady vortex lattice method (UVLM). The corotational approach enables the structural model to capture geometric stiffening under large deformations, while the UVLM captures unstable aerodynamic forces in a generalized aerodynamic force matrix. The coupled aeroelastic system is then solved using the p-k method, which determines the flutter speed and frequency by identifying neutral stability conditions in the coupled dynamic system. This approach has been validated using wind tunnel flutter test data and has been shown to accurately predict flutter speed trends for flexible wings.

In this study, we extend this framework to analyze three-dimensional adaptive winglet geometries, enabling the analysis of the influence of passive morphing winglets on aeroelastic behavior. The model can capture geometric stiffening under large deflections using the corotational formulation, while aerodynamic forces are integrated into a generalized coordinate system. The aeroelastic stability is evaluated by linearizing the coupled system around the nonlinearly deformed equilibrium state. This research specifically investigates how winglet design parameters such as twist, cant angle and structural flexibility influence the

flutter boundaries and divergence speeds. These findings provide essential guidelines for the design of stable, high-performance passive morphing winglets.

Preliminary results have already been obtained to support the development of the proposed three-dimensional aeroelastic stability framework. The aerodynamic model has been extended to capture three-dimensional flow effects using an updated formulation of the VLM/UVLM. This aerodynamic model has been verified through a validation study based on a previously published computational investigation of variable cant angle winglets conducted by Guerrero et al. [2], which examined the aerodynamic performance of an ONERA M6 wing equipped with a winglet over a range of cant angles using high-fidelity computational fluid dynamics (CFD). In the present work, the same wing–winglet geometry was reproduced using a three-dimensional VLM for four different cant angles (0°, 15°, 45°, and 80°) under low-speed conditions (Mach number $M = 0.3$), for which the assumptions of the VLM remain valid. The vortex lattice predictions showed close agreement with the CFD results regarding the lift coefficient, with discrepancies remaining below approximately 2% for all configurations considered. Moreover, the updated aerodynamic model correctly reproduced the trend of lift variation as a function of cant angle, demonstrating its ability to capture the dominant aerodynamic mechanisms associated with out of plane changes in winglet geometry. Although direct comparison of drag coefficients is limited due to the inviscid nature of the VLM, the predicted trends in induced drag were consistent with the expected reduction in wingtip vortex strength as the cant angle increases.

Building on this validated aerodynamic basis, ongoing work focuses on extending the framework to fully coupled three-dimensional flutter and divergence analyses, incorporating geometrically nonlinear structural effects and unsteady aerodynamic forces within a modal aeroelastic formulation.

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