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Passive load alleviation bi-stable morphing concept

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In wind turbines, large loads caused by fluid structure interaction leading to fatigue failure and added robustness to withstand high bending stresses on the root of blades constitute important design bottlenecks. Implementation of morphing offers a potential solution for such challenges in wind turbine blades. In this letter, a passive load alleviating bi-stable morphing concept is proposed. A bi-stable specimen designed to have different stiffness and dynamic response characteristics on each stable state is devised as a compliant structure. Passive alleviation mechanisms require no active components to achieve the load alleviation objective, resulting in lighter and simpler designs in comparison to actively morphed solutions. [http://dx.doi.org/10.1063/1.4739412]

In the context of wind turbine blades, large loads due to fluid structure interaction leading to high bending stresses and fatigue failure constitute a design bottleneck. In particular, restrictions to the upscaling of designs and high inspection costs as a result of these problems represent a major challenge for wind turbines to operate cost efficiently in remote locations.[1] A possible solution for such design obstacles can be provided by implementing morphing concepts in wind turbine applications. The idea of morphing has attracted much attention from researchers within the aerospace community given the potential performance gains offered and, in particular, in view of augmented optimal operation in a wide range of conditions.[2] Similarly, gains in terms of reduced inspection costs, lighter actuation systems, and particularly, extended fatigue life can be achieved implementing morphing in wind turbine blades allowing for upscaling to higher more efficient ratings. Most studies have concentrated on actively actuated morphing control surfaces for load alleviation in wind turbines.[3] Less attention is been directed to passive alternatives. One such example showing preliminary results for load alleviation is the passive airfoil concept based on hinged cambering presented by Lambie.[4] Despite the encouraging results shown both for active morphing and passive hinged cambering concepts for load alleviation, the added actuator weight and moving parts required by internal mechanism hinders the applicability of these concepts for high performance, remotely located wind turbine.

This letter proposes a conceptual passive load alleviating morphing compliant mechanism relying solely on conformal change of shape, as opposed to using hinges, exploiting structural deflection of bi-stable composite laminates. These composite structures are capable of attaining two statically stable states,[5] and can be manufactured to be attached to a more complex structure by adequate design of the lay-up.[6] In addition to the bi-stability, the usual high strength, lightweight, and, crucially, high fatigue resistance of composites, renders bi-stable laminates suitable for morphing solutions in wind turbine applications. Recently, the idea of tailoring the dynamic response of bi-stable composites to achieve more efficiently configuration changes has been proposed.[7] This concept is extended herein to design such composites as a passive external load alleviation morphing structure. To this end, a bi-stable composite laminate in the shape of a winglet is designed such that

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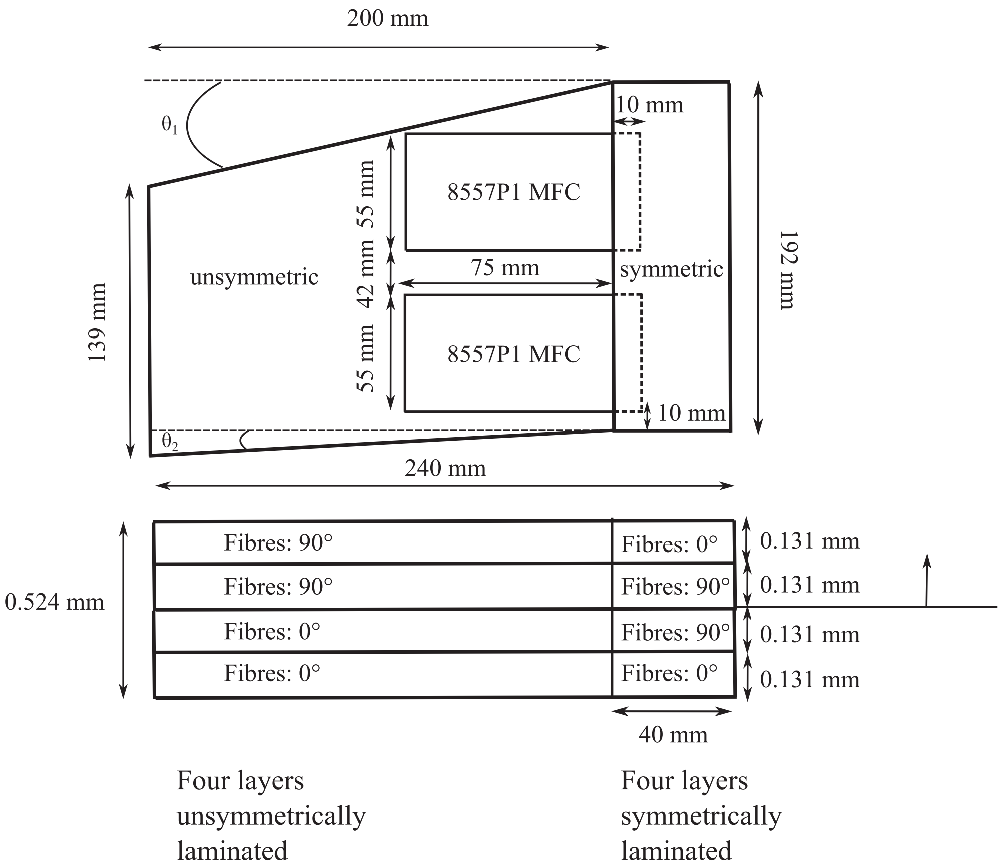

FIG. 1. Bi-stable winglet planform and schematic lay-up.

its stable states have different snap-through loads and vibration modes. When subject to an external perturbation, for instance a gust exceeding the static or dynamic snap-through force the morphing structure alleviates the sudden increase in external load by changing to another statically stable state which generates less lift. This effectively alleviates the load imparted to the structure. The structure is reset to the high lift configuration using two M8557-P1 surface bonded Macro Fiber Composite (MFC) actuators employing the dynamic morphing strategy described in Ref. 7 once the external spike in aerodynamic load recedes.

A carbon fibre epoxy bi-stable composite with unsymmetrical lamination sequence $[90_2/0_2]$ made of E022-T700 prepreg is cut to the winglet planform seen in Fig. 1. The resulting stable states of the test specimen, named state 1 and 2 for the high lift and alleviating shape, respectively, are shown in Fig. 2. The stiffness for each state is designed to have different static and dynamic snap-through loads governing the change between stable configurations. More specifically, the device is designed such that the first bending modes, associated to minimum snap-through force on each stable state, lie well separated from one another reducing the possibility of undesired jumps between stable configurations previously observed for bi-stable structures, albeit for a different application.[8] These features are paramount to achieving passive alleviation by diminishing the risk of triggering cross-well oscillations leading to large forces being transferred to the structure, constituting a major improvement for implementation of bi-stable structure technologies.

First, the dynamic response is obtained experimentally by exciting the winglet with voltage driven MFC actuators arranged as shown in Fig. 1. The measured displacement-to-MFC voltage frequency response functions (FRF) for the structure show the desired separation between the first bending modes of vibration on each state with the chosen geometry, as can be seen in Fig. 3. The

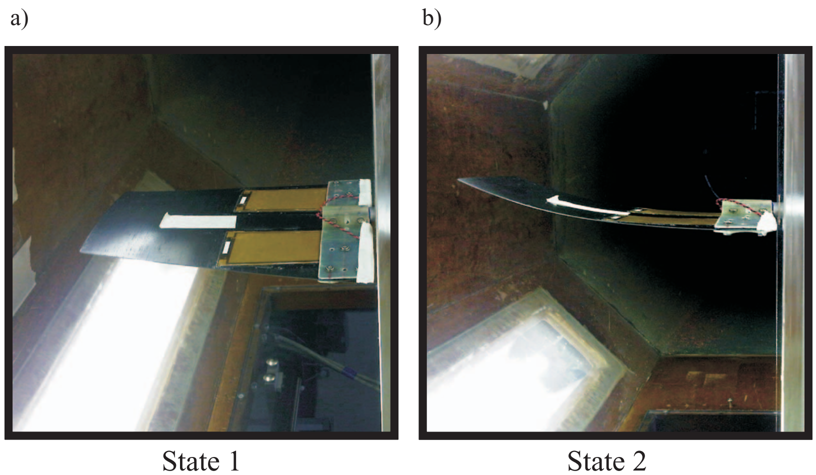

FIG. 2. Statically stable states of the proposed load alleviation concept. a) State 1: high lift configuration. b) State 2: load alleviation configuration.

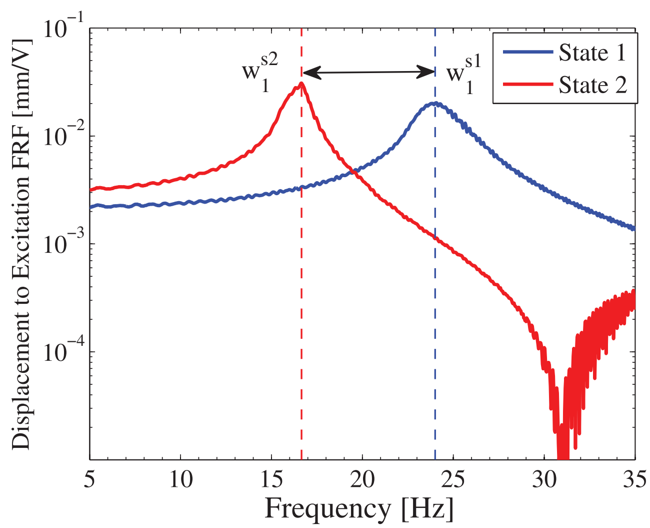

FIG. 3. Experimental displacement-to-MFC Voltage FRF for stable state 1 and 2 of the tested specimen.

low frequency region of the FRF also indicates that the required difference in static stiffness for each stable state is achieved.

Wind tunnel tests aerodynamically loading the specimen are carried out choosing flow velocity and angle of attack as parameters. The alleviation behaviour of the proposed bi-stable morphing concept is investigated by studying the generated lift as a function of the velocity for different angles of attack, α, as shown in Fig. 4. At low flow velocities both states retain their stability with stable state 1 generating larger lift forces for the studied range of angles of attack. As the flow velocity increases, a critical force of approximately 1450 mN is reached where the lift generated by stable state 1 exceeds the snap-through load, marked by the dashed line in Fig. 4, triggering a jump to state 2. The change in configuration results in an effective reduction of the lift load on the morphing device, 60 % for a flow velocity of 15 m/s at an angle of attack of 0 deg, and 32 % for a flow velocity of 5 m/s at an angle of attack of 5 deg. At higher flow velocities, state 2 holds its stability for both 0 deg and 5 deg up to 20 m/s, which is the highest possible velocity with the current test configuration.

The behaviour of the lift force generated by the specimen on each stable state is also studied by conducting an angle of attack sweep for constant flow velocities. The results for the lift force as

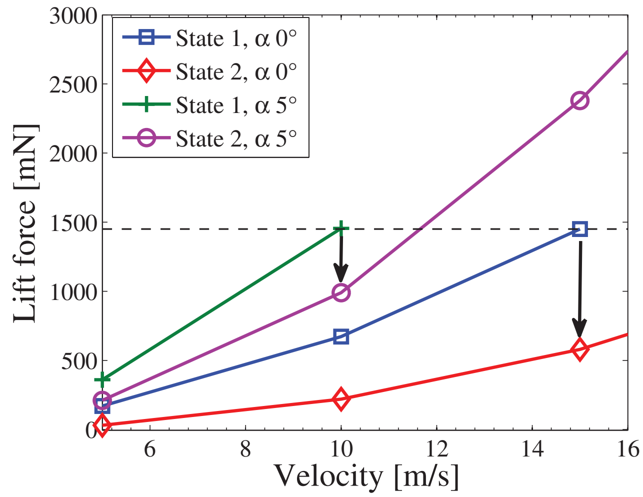

FIG. 4. Velocity sweep for the lift force as a function of the angle of attack. The downward arrows (↓) indicate the occurrence of snap-through. The dashed line shows the critical force for snap-through from state 1 to 2.

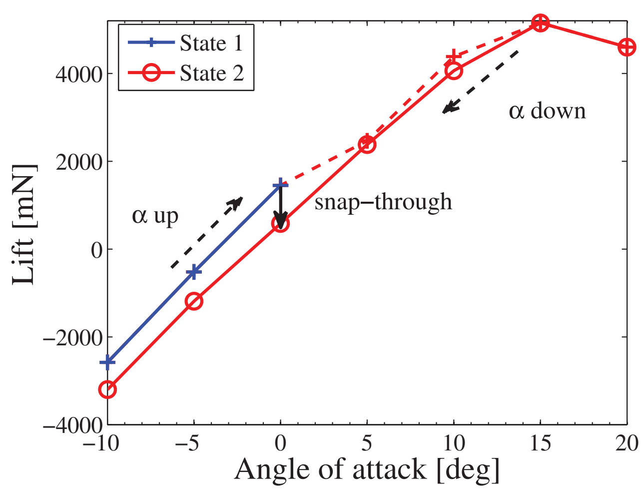

FIG. 5. Lift force as a function of the angle of attack for a constant flow velocity of 15 m/s. An upward sweep (- -→) starting from stable state 1 follows the solid line with + markers (blue) until a snap-through is induced, marked by (↓) arrow at the critical force of state 1. The upwards sweep continues following the dashed line with + markers (red). A downward sweep (←- -) following the solid line with ○ markers (red) is also shown. It can be seen that as a snap-through is triggered the generated lift force is reduced.

a function of the angle of attack holding the flow velocity constant at 15 m/s for each stable state are presented in Fig. 5. Starting initially at stable state 1, the angle of attack is increased between 0 and 5 deg where the critical snap-through force is reached around 1450 mN resulting in passive morphing to the shape of state 2, as shown in Fig. 5. The dashed line shows the continuation of the angle sweep from this point onward up to the maximum angle of attack of 20 deg. The results for a similar angle of attack sweep this time starting from stable state 2 are also presented in Fig. 5. The two angle sweeps, starting from stable state 1 and 2 respectively, show consistent results for higher angles of attack once the snap-through from stable state 1 to 2 is triggered. It can be seen that the generated lift force for stable state 1 is larger than that of stable state 2 for the angles of attack for which it is stable. The effective behaviour of the bi-stable specimen shows that the stability of state 1 is lost at approximately 1450 mN of lift, above this force level only the shape of stable state 2 can be attained. As the shape of state 2 generates less lift, the passive (aerodynamically induced) change of shape effectively alleviates the loads on the structure as the lift increases past the critical snap-through force of state 1.

State 2 loses its stability triggering constant snap-through between the stable configurations, or cross-well oscillations, at approximately 7900 mN achieved with an angle of attack of 20 deg at a velocity of 20 m/s. The critical force of state 2 is thus 5.5 times larger than the critical force for stable state 1, showing the robustness of the concept. This parameter boundary marks the design limit for which the herein proposed load alleviation device works adequately. It should be noted that this critical lift force can be increased by an optimised design of the bi-stable component, which can be realised by using stiffer pre-stressed bi-stable composites.[9] Increasing the stiffness of the bi-stable structure results in higher critical lift force, hence in a higher design limit which is more suitable for the intended wind turbine applications.

A passive load alleviation morphing concept using bi-stable composites is presented. Tailoring the structure such that the frequencies of the first bending modes of the stable states are well spaced allows for the structure to snap to a lower energy state when subject to sudden external perturbations. In particular, for an abrupt increase in the lift load, for instance due to a wind gust, the mechanism passively alleviates the load imparted on the morphing structure. This concept offers the possibility of developing a passive load alleviation mechanism allowing for leaner structural design of aerodynamic control surfaces, as the critical snap-through force limits the maximum stresses on the structure. The passive nature of the proposed concept ensures the robustness of the load alleviation mechanism. The proposed bi-stable specimen should serve as a conceptual design which can be used as the internal mechanisms of a more complex morphing airfoil. Such a mechanism would be particularly suited for applications where design restrictions to added complexity and weight of actuators are in place as for wind turbines. Attention is directed to the fact that the added control needed to reset the aerodynamically favourable state can be achieve by much lighter actuators in comparison to the heavy mechanisms pitching turbine blades from the root currently in use. A localised control and actuator pair can be included to snap-back the structure to its aerodynamically favourable shape once the fluid structure interaction causing the spikes in generated lift load recedes.[7] The bi-stable nature of the proposed alleviation mechanism for which energy is only needed to trigger snap-through to achieve large changes in geometry, as opposed to constant actuation required for active morphing solutions, results in much simpler and light-weight actuators.

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