Implicit and explicit controls of butterfly flapping flight

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The objective of this study is to clarify the principle of stabilization in flapping-of-wing flight of a butterfly, which is a rhythmic and cyclic motion. For this purpose, a dynamics model of a butterfly is derived by Lagrange's method, where the butterfly is considered as a rigid multi-body system. For the aerodynamic forces, a panel method is applied. Validity of the mathematical models is shown by an agreement of the numerical result with the measured data. Then, periodic orbits of flapping-of-wing flights are searched in order to fly the butterfly models. Almost periodic orbits are obtained, but the model in the searched flapping-of-wing flight is unstable. This research, then, studies how the wake-induced flow and the flexibly torsional wing's effect on the flight stability. Numerical simulations demonstrate that both the wake-induced flow and the flexible torsion reduce the flight instability. These effects can be considered as implicit controls. Because the obtained periodic flapping-of-wing flight is unstable, a feedback control system is designed, and a stable flight is realized. The feedback control is considered as explicit control. As a result, this study suggests the hierarchical control structure with the implicit and explicit controls.

Keywords: butterfly, flapping flight, experiment, numerical simulation, control