# Simulating the Flight of the **Hawkmoth Manduca Sexta**

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For ages humans have used Nature as a source of learning and inspiration. Engineering simulation can be used to understand how organisms behave in the natural world. Design principles gathered from these studies can be translated into novel and efficient product designs. Simulation of organism behavior e.g. insect flight is fundamentally inter-disciplinary and requires the ability to capture mechanics, aerodynamics and morphology.

In a recent study, researchers at the Korea Advanced Institute of Science and Technology [1] developed a Multi-Body Dynamics model of the Manduca Sexta with Adams and simulated its flight. Commonly known as the Carolina Sphinx moth and the Tobacco Hawkmoth, the Manduca Sexta [2] is a moth of the Sphingidae family. Present through much of the American continent, the Manduca Sexta is used in a variety of Biomedical and Biological experiments.

Using a co-simulation framework (Figure 2), the flexible-body and the aerodynamic simulation domains were coupled together to describe the fluid-structure interaction. A quasi-steady model to simulate the aerodynamics around the wings was implemented. This model computes the instantaneous aerodynamics forces acting on the wing. The forces computed by the aerodynamics model are passed on to Adams which then returns the flight states and the wing sectional kinematic variables at every time instant.

## Body/Wing Morphology

Flying insects usually have six legs, two antennae, head, thorax, abdomen, and two or four wings. Each body component has specific effect to the overall flight dynamics

**Figure 1 The Hawkmoth Manduca Sexta**

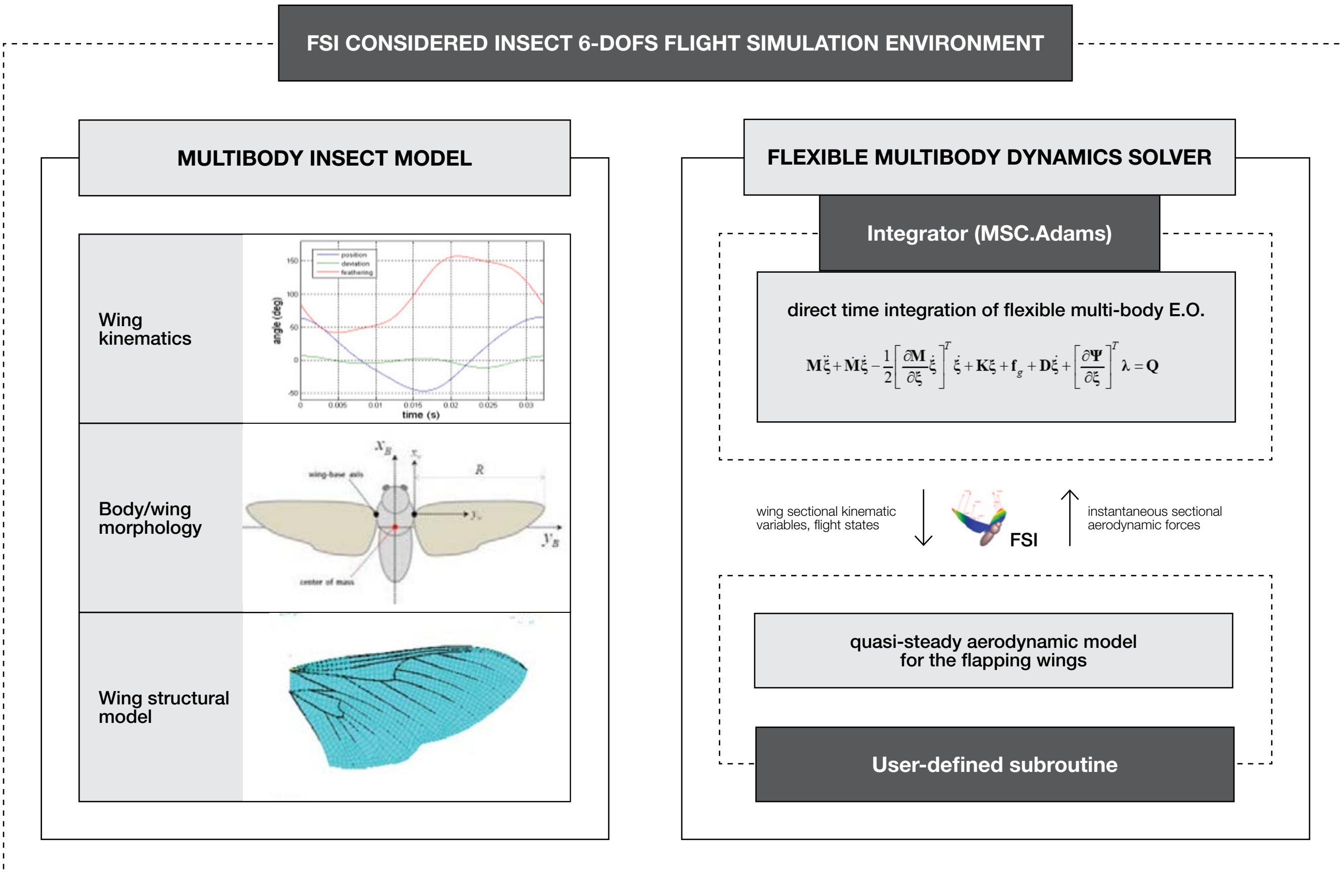


**Figure 2 Co-simulation framework**

| Parameter | $m_w$ | $m/m_{total}$ | $R$ | $\bar{c}$ | $S$ | $t$ | $r_2/R$ |
|---|---|---|---|---|---|---|---|
| (Unit) | (mg) | (%) | (mm) | (mm) | ($mm^2$) | (mm) | ( - ) |
| **Value** | 48.33 | 3.32 | 48.30 | 18.09 | 883.75 | 3.67E-2 | 0.51 |

**Figure 3 Morphological data used to model the Hawkmoth**

because these are connected to each other via compliant structures such as muscle and exoskeleton, which allows all the components translate/rotate relative to each other. In this study, a multibody model of the Hawkmoth was created, and each body component was modeled using morphological data from Ellington [3] and O'Hara et al [4]. As the wing of the Hawkmoth is a complex structure consisting of intricate patterns of venation and skin, the actual measurement data of 30 Hawkmoth wings by O'Hara et al [4] was used to model the vein's outer/inner radius distribution and also elastic modulus as shown in Figure 3, where $\boldsymbol{m_w}$ is the wing mass, $\boldsymbol{m_{total}}$ is the total mass of the Manduca sexta, $\boldsymbol{R}$ is the span, $\bar{c}$ is the main chord; $\boldsymbol{S}$ is the area, t is the thickness and $\boldsymbol{r_2}$, is the radius of gyration.

## Wing Structural Model

A critical element to accurately modeling dynamical systems with multi-bodies is accounting for part flexibility. The Manduca Sexta has wings with flexibility due to the intricate patterns of venation and skin on the wing. This flexibility makes the wing undergo deformation during the flight. Also, the passive deformation of the wing impacts the surrounding aerodynamics, which in turn directly affects the overall flight dynamics and stability characteristics. Therefore, for a sound understanding of the underlying mechanics of the insect flight dynamics and stability, the fluid-structure interaction (FSI) of the *flexible* wings, with the surrounding air, must be taken into account when developing a flight dynamics model of the insect. Typically, the flight dynamics and stability analysis of the insect is conducted based on a simple, linear rigid-body dynamics model. With these simplified rigid body approaches, the effect of the body component's movement, the effect of the wing inertia or the effect of flexibility to the flight stability are not easily analyzed.

In the current implementation the two wings of the Hawkmoth are modeled as flexible bodies with similar properties to the real Hawkmoth, and the other body components are also modeled independently. Based on this flexible multibody model, a hovering flight is simulated and its 6-DOF flight states are compared with the result of rigid-winged model to see the effect of the flexibility. A finite element analysis program (ANSYS) (Figure 4) is used to model the flexible wing structure of the Hawkmoth. Mode shapes and corresponding natural frequencies are depicted in Figure 2. These mode shapes are used as input into the Adams MBD model to incorporate flexibility to the Wings.

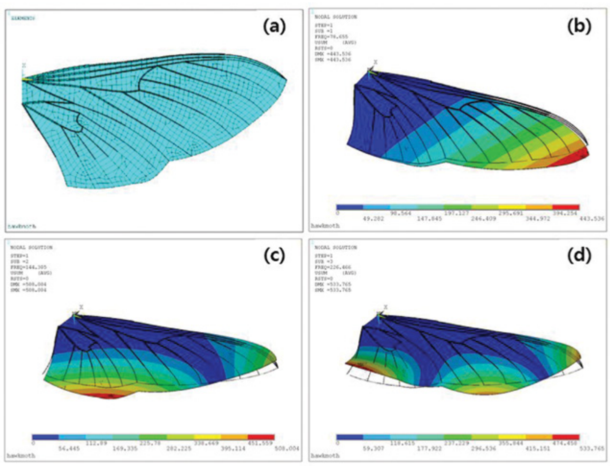


**Figure 4**

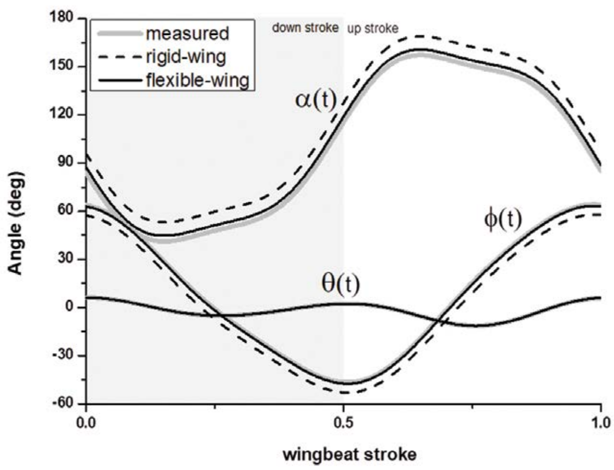


**Figure 5. Flight kinematic inputs for the hovering condition**

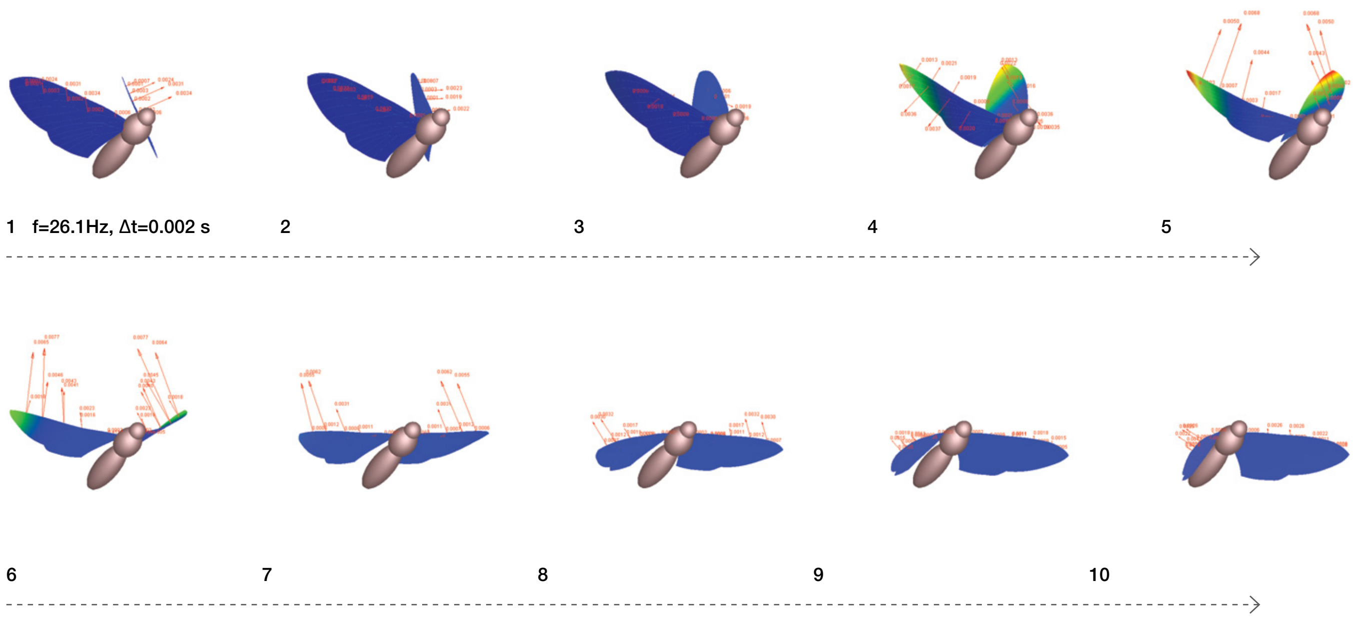


**Figure 6. Fluid-structure interaction considered 6-DOF free flight simulation; flexible-winged Hawkmoth model is in its hovering condition; a down-stroke wing motion is depicted (flapping frequency = 26.1Hz, time between each frame is 2ms)**

## Model Inputs and Results

Based on the abovementioned co-simulation environment, 6-DOF flight simulations were conducted. For a comparative analysis, a rigid-winged Hawkmoth model was also established using the same morphological data to the flexible-winged model. The rigid- and flexible-winged Hawkmoth models are identical except for the wing flexibility.

The wing kinematic inputs for the hovering condition of the insect are shown in Figure 5. In the figure, the thick gray line indicates the measured wing kinematics. The other two lines indicate wing kinematics inputs for the two Hawkmoth models to maintain hovering: rigid-winged model, and flexible-winged model. The commanded inputs include $\varphi(t)$, wing positional angle; $\alpha(t)$, feathering angle; $\theta(t)$, deviation angle at the wing root joint.

These commanded inputs develop spatially varying deformation distributions on the flexible wing due to the FSI which is illustrated in Figure 6.

The comparative study between the models with the rigid and the flexible wing representations also show some interesting distinctions. The first difference between two Hawkmoth models is the flapping frequency: 26.1Hz for the flexible-winged model and 29.5Hz for the rigid-winged model are needed for the Hawkmoth models to maintain the hovering flight. This implies the flexible wings can produce more lift than the rigid wing under a similar wing kinematics. Qualitatively, it seems to be the effect of wing flexibility which alters the direction of the aerodynamic vectors to the direction of the opposite to its weight vector. Therefore, it appears that a choice between a simplified rigid or a detailed flexible representation of the wing can have a substantial impact on the Hawkmoth's flight dynamics. In essence, simulation tools like Adams can help us understand and appreciate the world we live in.

## References

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