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Flying with Both Wings and Body – A Supercomputer Analysis of Butterflies' Complex Flight

Imagine butterflies fluttering about in a flower garden. Despite their fluttering, joyful appearance, butterflies use very complex movements to generate lift and thrust. Dr. Kosuke Suzuki says, “The more complex the phenomenon, the more I want to understand it.” He uses numerical simulations to understand how butterflies fly in the air. Here, we introduce his research, which has a variety of potential applications, from Mars exploration to highly efficient refrigerants.

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Calculating the Unique Flying Style of Butterflies

In order to develop micro air vehicles such as drones, many studies are being conducted around the world to understand how flies and mosquitoes fly. “In contrast to these insects, which do not move their bodies in order to fly, butterflies move their abdomen and thorax (Fig. 1). In other words, to model the flight of butterflies, we must account for the movement of not only their wings, but also their abdomen and thorax. It is a very complex and challenging study,” Dr. Suzuki explains.

Butterflies gain lift by flapping their wings downward and thrust by flapping backward. At that time, the movement of the body is linked to the movement of the wings, and it is believed that the angle of the thorax controls the direction the wings move, but the details have not been clarified.

Immersed Boundary-Lattice Boltzmann Method (IB-LBM) with Good Balance of Accuracy and Computational Complexity

To understand the flight of a butterfly, it is not enough to simulate the motion of the fluid (air) and the motion of the object (butterfly). The interaction between the fluid and the object must also be calculated because they mutually affect each other – when the butterfly flaps its wings, it induces an air flow, which affects the motion of the butterfly.

Since he was a graduate student, Dr. Suzuki has been researching methods to accurately simulate systems in which the fluid and the object affect each other's motion while minimizing the amount of computation needed. There are several numerical methods for systems in which the fluid and the object interact (Fig. 2), and among them, Dr. Suzuki has been developing and improving the "immersed boundary-lattice Boltzmann method (IB-LBM)" (Fig. 2e), which is a combination of the immersed boundary method, which has been known since about 50 years ago, and the lattice Boltzmann method, which has been rapidly developing in recent years .

The immersed boundary method represents a moving object in a fluid by applying a force called a body force around the object (the red area in Fig. 2e). The body force makes the velocity of the fluid the same as the velocity of the object's surface, thus preparing a field in which the moving object can be embedded. When applied to the flight of a

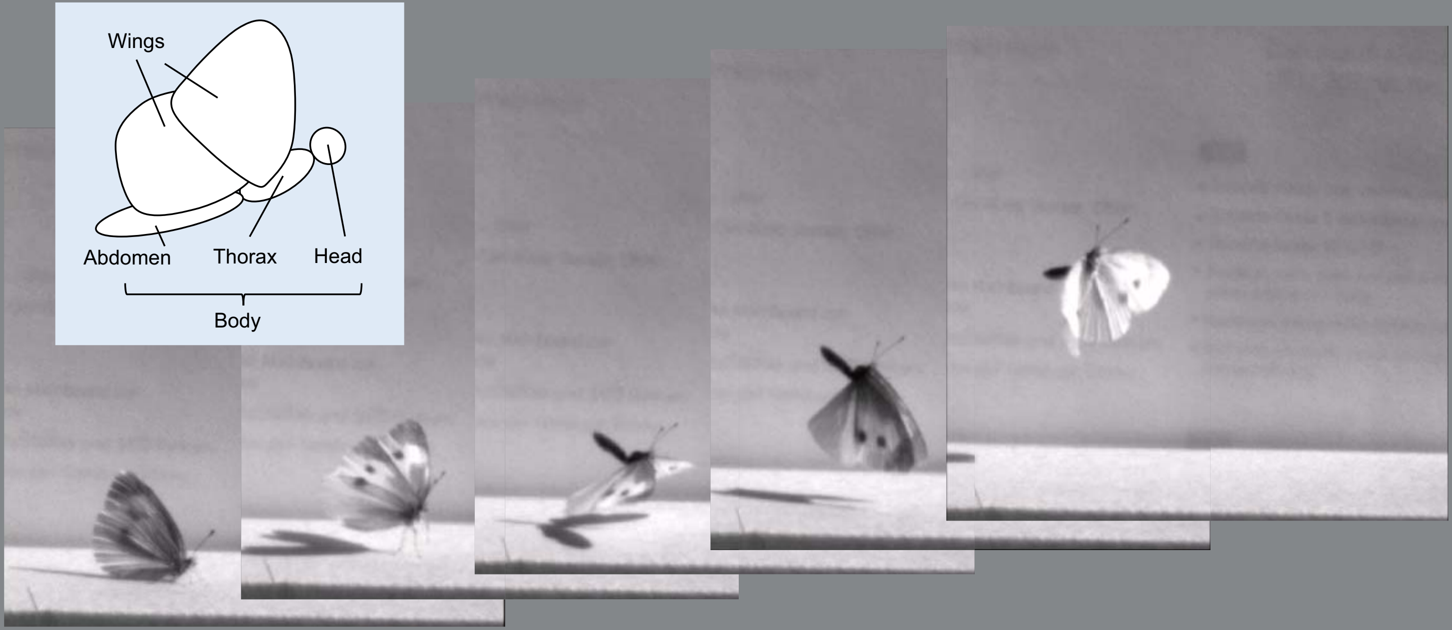

Fig. 1

A cabbage butterfly in flight

Captured from a video taken by Dr. Suzuki and his colleagues. It can be seen that when the butterfly flaps its wings downward, its body is flexed and it raises its abdomen significantly. The wings are raised and lowered 10 times per second while the wings, abdomen, and thorax move simultaneously.

butterfly, the butterfly is placed in this field and is moved according to the equations of motion.

On the other hand, the “lattice Boltzmann method” is a flow simulation technique that treats the fluid as a collection of fictitious particles that can only exist at the intersections of orthogonal lattices (lattice points). Each particle is assumed to move between the lattice points at some fixed velocity, and to collide with other particles. The density, velocity and pressure of the fluid can be obtained by averaging the mass and momentum of the particles that are distributed in a space according to the rule above-mentioned.

The lattice Boltzmann method, when applied to incompressible flows such as water and low-speed air flows, has been mathematically proven to result in the Navier-Stokes equations that describe the motion of fluids. The lattice Boltzmann method does not require solving Poisson equation to calculate the pressure, thus allowing for highly accurate calculations with low computational cost. It is also suitable for parallel computing because it uses only the information of particles on adjacent lattice points for the calculation of a particle on one lattice point and does not require information on faraway particles.

“Both the immersed boundary method and the lattice Boltzmann method use orthogonal lattices, so they are well suited for use in combination. The relative simplicity of the algorithms and the ease of writing program code for both are also favorable for research,”

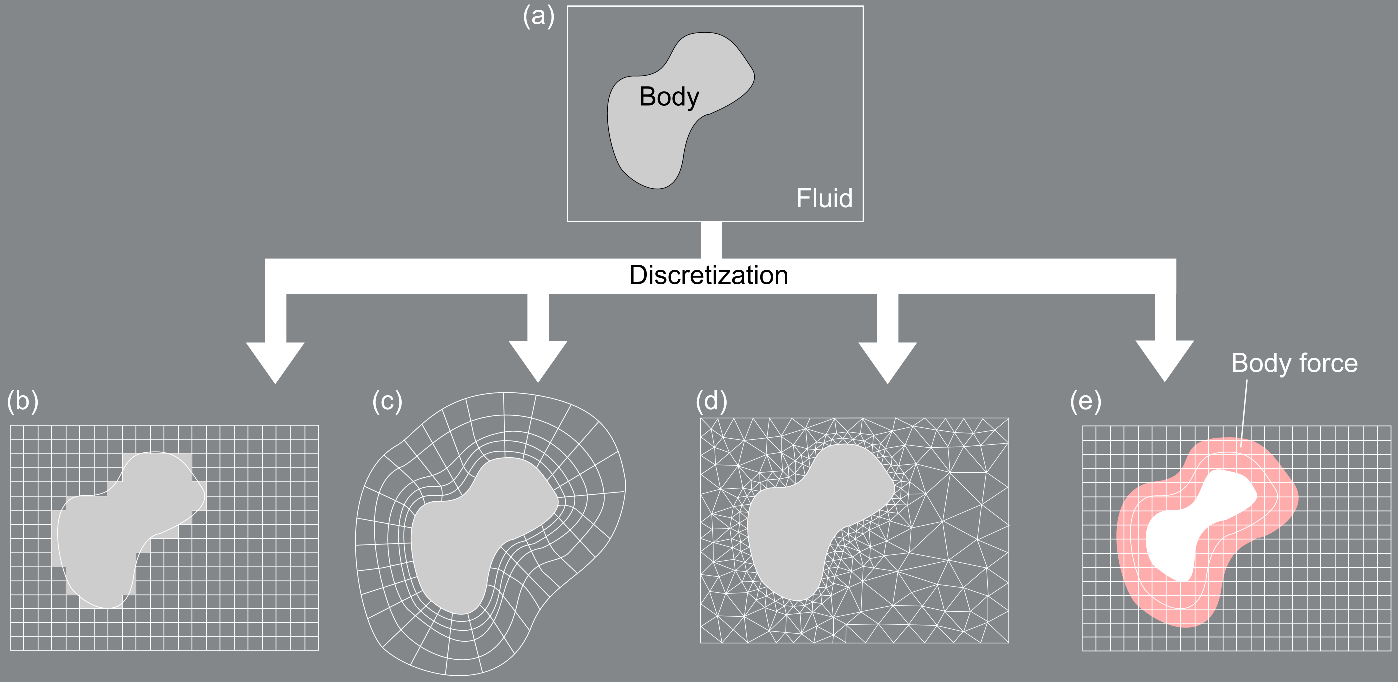

Fig. 2

Comparison of numerical computing methods for fluid-object interaction

(a)The fluid and the object (body) to be calculated. (b) A method of stepwise approximation of the space around an object. (c) Boundary-fitted grid method. Creating a grid along the object. (d) Unstructured grid method. Using small and large triangles. (e) IB-LBM.
In the methods in (b), (c) and (d), the computational load is high because the grid is recreated each time the object moves. In (e), it is only necessary to move the body force field, so the motion of the object can be expressed with the suppressed computational load.

Suzuki, K.: “Development of an immersed boundary-lattice Boltzmann method for moving boundary flows and its application to flapping flight.” *NAGARE* (Journal of the Japan Society of Fluid Mechanics) 37 (2018) 215-220.

Dr. Suzuki says, explaining the advantages of combining the two methods.

Dr. Suzuki's team was the first in the world to apply IB-LBM to butterfly flight in 2012, and in 2013 they succeeded in creating a simulation of a butterfly in flight. "At first, the butterfly did not fly like a real butterfly because it flipped over or ran in reverse," Dr. Suzuki says. "Other researchers are working on butterfly flight research, but we are the only team in the world that has solved the equations of motion by linking the motion of the butterfly, including its body, with the motion of the fluid," he added proudly.

Two Approaches to Understanding Flight

"We use two approaches to analysis: top-down and bottom-up," Dr. Suzuki explains (Fig. 3).

The top-down approach incorporates the actual movements of butterflies into the computational model. A cabbage butterfly caught on a riverbank is filmed from three directions with a high-speed camera, and its shape and movement are recorded using motion capture. From this data, a computational model of the butterfly is created and made to fly in a fluid. The result is shown in Fig. 3a.

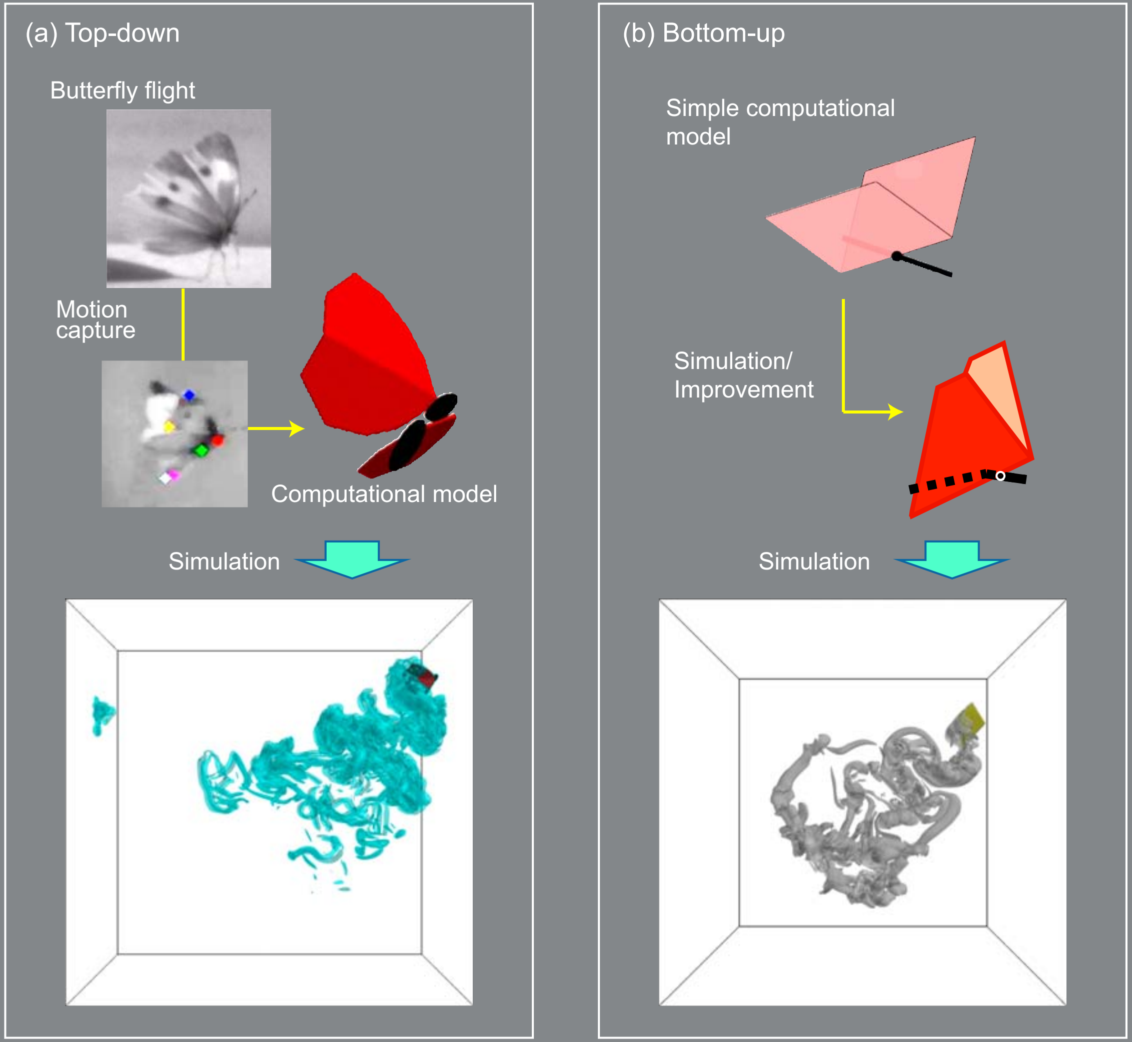

Fig. 3

Butterfly flight as elucidated by the supercomputer

(a) Top-down approach. Butterfly flight was simulated using a computational model of a butterfly that faithfully simulates the shape and behavior of an actual butterfly. (b) The simulation was performed using a computational model created in the bottom-up approach. The figures in (a) and (b) obtained from the simulations trace the changes in the vortex behind the butterfly.

Conversely, the bottom-up approach starts with a simple model and improves it through repeated simulations. First, Dr. Suzuki considered the flight of a simplified model of a butterfly on a computer, consisting of a pair of square wings and a stick with no thickness. Based on the results, he examined how factors such as the shape and mass of the wings affected the butterfly's flight, and improved the model to make it fly more like a butterfly. Fig. 3b shows a simulation of the model he created in this way.

Comparing the two simulations shown in Fig. 3, the butterfly calculated by the bottom-up approach flutters in the same way as the butterfly calculated by the top-down approach, and a stepped vortex structure forms behind the wings. The bottom-up approach also reproduces the butterfly's movement quite well (Fig. 3b). However, there are still some challenges. There is a hypothesis that butterflies adjust the angle of their thorax by moving their abdomen up and down, but if we include this adjustment in the calculation using the bottom-up approach, the abdomen swings at an angle that is impossible in reality. Therefore, in the calculation shown in Fig. 3b, the thorax angle is calculated by inputting the value obtained from the experimental data, and the control of the thorax movement by the movement of the abdomen is not included in the calculation.

"In the bottom-up approach, our goal is to identify the minimum elements necessary to reproduce the butterfly's flight as we refine the model," Dr. Suzuki says. By bringing the bottom-up and top-down flying manners closer together, he is trying to elucidate "what is butterfly flight?"

To perform these calculations, Dr. Suzuki and his team have been using two of HPCI's supercomputers, System A (CRAY XC40) at Kyoto University and the "Flow" Type I subsystem (FUJITSU FX1000) at Nagoya University *1. They also use their own computer cluster, but as the number of elements to be calculated increases, they need the computing power and large memory of a supercomputer.

One of the reasons they chose the "Flow" is that it is compatible with the supercomputer Fugaku. What kind of calculations would he like to perform if he had the chance to use the methods developed on Fugaku, which has enormous computational power? Dr. Suzuki says, "Currently, in order to reduce the amount of calculations, we are slightly lowering the Reynolds number*2 and making the butterfly's wings flap more slowly than they actually do, but eventually we would like to do calculations at the actual Reynolds number. It is also believed that the streaks and scales on a butterfly's wings also affect its flight. We do not include these factors in our calculations at this time, but we would like to include them in our calculations as well."

Potential Applications Range from Small Ice Pellets to Mars Exploration

Dr. Suzuki is also working on applying IB-LBM to phenomena other than butterfly flight. One such application is "ice slurry" (tiny ice particles dispersed in water), which is expected to find use as an excellent refrigerant. "We are applying IB-LBM to calculate the interaction between ice flow and water flow, and studying what kind of ice slurry is suitable for efficient heat exchange," he says.

Meanwhile, he is also looking to develop his butterfly flight research. Micro air vehicles such as drones that imitate the flight of flies are not good at recovering their correct attitude instantly once they lose it. If Dr. Suzuki can elucidate a flight model of a butterfly that recovers its attitude while swinging its body, he may be able to develop a flying object that can instantly recover and continue to fly even if it loses its attitude.

The Martian atmosphere is much less dense than Earth's and gives a lower Reynolds number, so it is difficult to fly on Mars for the fixed-wing aircrafts used on Earth, which are designed for high Reynolds number conditions. This is why insect flight is attracting so much attention. "I would like to develop my research and make large-scale calculations on how to fly in a Mars environment," Dr. Suzuki says, expanding on his dreams for the future.

About the Researcher

Dr. Suzuki was fascinated by the shape of insects and used to collect them in his childhood. He fell in love with mathematics and physics, and majored in aerospace engineering at university. "I wanted to know what kind of theory could explain what it means to fly," he says. "I was impressed by the depth of understanding that could be achieved using fluid engineering, plasma engineering, and electromagnetics," he says. Once he began his research, he wanted to unravel complex things that could not be explained by simple fluid engineering, and his application was to flying insects, specifically butterflies. He and his students go to the riverbank early in the morning to collect cabbage butterflies sleeping on the underside of leaves. His hobby is sake tasting. In Nagano, where there are many sake breweries, he enjoys drinking sake while thinking about the brewer and the production process.

Associated Research Projects

Numerical analysis of flapping flights of insects by IB-LBM using a massive parallel computer (hp210037/hp220037)
Principal Investigator: Kosuke Suzuki, Department of Mechanical Systems Engineering, Faculty of Engineering, Shinshu University

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*1 System A (CRAY XC40) was used in FY2021 and the "Flow" Type I subsystem (FUJITSU FX1000) in FY2022.

*2 Reynolds number: Ratio of inertial force to viscous force. A small value indicates a regular flow (laminar flow), while a large value indicates an irregularly turbulent flow (turbulent flow).

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