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2019
CASE STUDY

Float Like A Butterfly, Swim Like a Bee

With the help of Phantom high-speed cameras, researchers at the University of South Florida (USF) study how planktonic sea butterflies move and discovered that their swimming resembles insect flight.

They're not called "sea butterflies" for nothing. According to the research team at the University of South Florida's Murphy Lab, Limacina helicina—a species of small, swimming sea snail—behave more like fruit flies than actual snails.

The goal of the lab is to explore fluid mechanics in the context of biology, ecology and the environment—inspiring new design principles that can potentially solve human engineering problems. As part of their multidisciplinary research, the research team uses a range of tools, including particle image velocimetry (PIV) and high-speed imaging.

David Murphy, Assistant Professor with USF's Department of Mechanical Engineering, heads the lab and its team of graduate and undergraduate students. "One of our latest areas of study is fluid mechanics in the context of animal biomechanics," says Murphy. To that end, he and his students recently investigated how sea butterflies "fly" underwater. Using Phantom high-speed cameras, they analyzed and measured the three-dimensional flow fields produced by these zooplankton as they swam. From the same recordings, they also measured the three-dimensional kinematics of their bodies and wingtips—and discovered that sea butterflies swim in the same way small insects fly through the air. Not only does this discovery point to a remarkable example of convergent evolution within the animal kingdom, but it has implications for the development of future micro aerial vehicles (MAVs).

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THE UNIQUENESS OF SEA BUTTERFLIES

Most species of zooplankton, such as krill and other small crustaceans, paddle through the water using drag-based propulsion: using their hairy, jointed appendages, these organisms maximize viscous drag during the power stroke and minimize drag during the recovery stroke. Conversely, fruit flies and other insects use their wings as airfoils to generate lift and drag on both the power and recovery strokes.

But sea butterflies are different. Using soft, wing-like appendages, they flap in the water in a complex three-dimensional stroke pattern that resembles the wingbeat kinematics of flying insects. "This similarity suggests that sea butterfly locomotion is also lift-based," Murphy says.

TOMOGRAPHIC PIV AND HIGH-SPEED IMAGING

To help them determine if sea butterfly locomotion is drag- or lift-based, Murphy and his team utilized a tomographic PIV system in conjunction with high-speed imaging, enabling them to quantify the flow fields associated with the free-swimming animals. In terms of setup, the researchers filled a small aquarium with L. helicina collected off the coast of Newport, Oregon, and seeded the flow using 11.7-µm diameter hollow glass spheres. On one side of the aquarium, they positioned four Phantom v210 high-speed cameras, which synchronously recorded the sea butterflies at a speed of 500 frames per second (fps). Illumination was provided by 808-nm near-infrared lasers.

"Using this optical setup, we recorded the animals as they flowed through the field of view," Murphy says. "Generally, they would swim vertically upwards until reaching the surface, after which point they would sink to the bottom and begin swimming upwards again."

WHY HIGH-SPEED CAMERAS MATTER IN TOMOGRAPHIC PIV

There are many different kinds of PIV techniques, but some are better than others when it comes to measuring the flow fields created by the swimming sea butterflies. In tomographic PIV, several cameras simultaneously record a seeded, illuminated volume. From these recordings, researchers can reconstruct the tracer particles in order to analyze and measure the three-dimensional velocity vectors surrounding the moving sea butterflies. "This tells us a lot about how the animals are moving," Murphy says.

But quantifying the flow fields surrounding zooplankton, in particular, poses a number of challenges. For one, these animals swim in three dimensions. They are also small—between 0.1 and 5 mm. Analyzing their movement therefore requires high particle seeding, which creates very dense fields of velocity vectors. And finally, zooplankton swim very quickly, causing them to generate unsteady flows and requiring cameras with high magnification to resolve their movement.

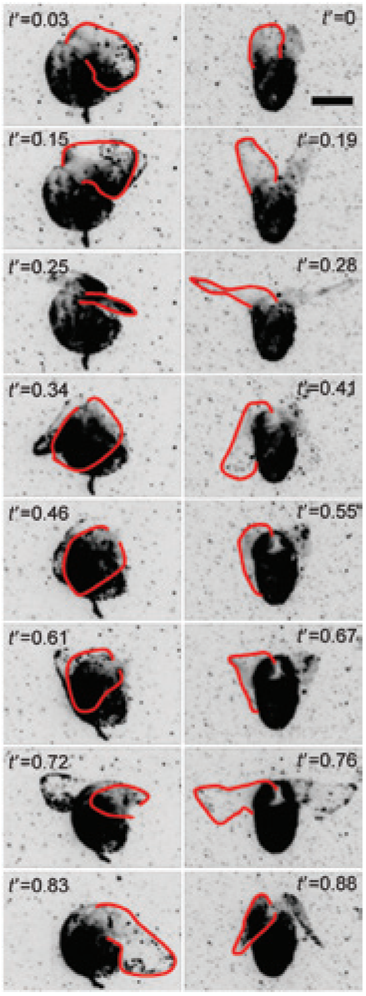
With the help of four Phantom v210 high-speed cameras, the Murphy Lab's Tomographic PIV system overcomes these challenges. By positioning multiple cameras on one side of the aquarium, the researchers can record the animals' movement in three dimensions. In addition, they address the animals' small spatial scale and high speeds with the v210's high frame rate and magnification: 2,190 fps allows the team to track the animals' high-speed swimming while resolving the unsteady flows. The 1,280 x 800-pixel resolution is also sufficient to resolve the fine velocity vectors.

LIFT-BASED SWIMMING AND FUTURE MAV DESIGN

Murphy and his team selected three recordings to process using LaVision's DaVis 8.2 software, which allowed them to measure the three-dimensional flow fields surrounding the swimming animals. From these same recordings, the software extracted the kinematics of the sea butterflies in three dimensions—tracking the animals' wingtips, as well as three distinct locations on their shells, in order to calculate body angle.

Based on their results, the researchers confirmed that sea butterflies employ lift-based swimming rather than the typical drag-based swimming used by most other zooplankton. Like flying insects, they stroke their "wings" in a figure-of-eight pattern. But unlike insects, the sea butterfly accomplishes this insect-like stroke by rotating its body to an extreme extent—a motion known as hyper-pitching.

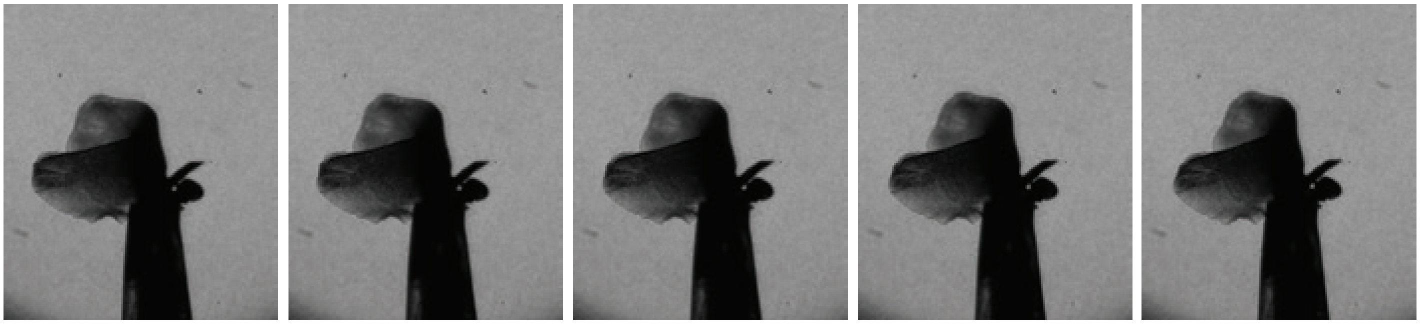
"In terms of human engineering, we can apply these findings to the development of biologically-inspired underwater robots or even micro aerial vehicles," Murphy says. While pitching is typically avoided in MAV design because of the challenges it poses for vehicle stability and control, sea butterfly flight suggests that incorporating hyper-pitching may in fact provide aerodynamic benefits.



Sequence of inverted-color PIV images for two sea butterflies, illustrating the stroke cycle. One wing in each image is outlined in red.

CONCLUSION

By analyzing the high-speed footage from the Phantom v210 cameras, Murphy and his team demonstrate that sea butterflies uniquely employ lift-based swimming—a form of locomotion that resembles the way fruit flies and other tiny insects fly. Thanks to the footage, the team also observed the animals' hyper-pitching, which significantly provides an alternative vision for flapping MAV design. In addition to the implications for aerial vehicle development, however, these discoveries shed light on a remarkable evolutionary convergence between very different animals.



High-speed footage reveals that millimeter-sized sea butterflies employ lift-based locomotion like fruit flies and other tiny insects.

"In terms of human engineering, we can apply these findings to the development of biologically-inspired underwater robots or even micro aerial vehicles," Murphy says.

THE PHANTOM VEO 640S: FAST, POWERFUL AND RUGGED

In their original tomographic PIV system, Murphy and his team utilized four 1-megapixel Phantom v210 cameras that can film up to 2,190 fps. To further their research, the lab recently acquired a Phantom VEO 640S. This powerful and rugged 4-megapixel camera achieves over 6 Gigapixels/second throughput, translating to recording speeds up to 1,400 fps at full 2,560 x 1,600 resolution and up to 290,000 at reduced resolutions. Thanks to its small, 10-μm pixel size, the VEO 640S is also capable of higher magnification and resolution than its v210 predecessors—leading to more image detail in the millimeter-sized sea butterflies.

At only 2.5 kg, the VEO 640S is also a highly versatile camera, enabling Murphy and his team to use it in both the laboratory or out in the field. For one, its heavy-duty aluminum housing is rated up to 100 G. It is also designed to withstand a wide range of temperatures: -10° to +50°C. And finally, the camera's mechanical design isolates all internal components from airflow and the outside elements. "Thanks to its faster frame rate, high resolution and rugged features, this new camera is critical to furthering our work with the sea butterflies," Murphy says.

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