

The role of vortices in animal locomotion in fluids

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Abstract

The aim of this paper is to show the significance of vortices in animal locomotion in fluids on two deliberately chosen examples. The first example concerns lift generation by bird and insect wings, the second example briefly mentions swimming and walking on water. In all the examples, the vortices generated by the moving animal impart the necessary momentum to the surrounding fluid, the reaction to which is the force moving or lifting the animal.

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1. Introduction

The topic is far too diverse to cover all aspects of animal locomotion both in (or on) water and air. All animals in water and air have inhabited this planet for 300 million years (fishes and insects, twice as long as birds who are here about 150 million years), and they have had well enough time to develop their skill of swimming and flying. From the whole number of existing animal species almost 80 % have the capability of flying, out of which almost 99 % are insects (about 10^6 species). It is only less than half a century when people have begun to uncover the mechanism of their — often uncomprehensible — way of locomotion.

In order for any animal to move, it must apply a force to its environment, the reaction force is then propelling the animal forward. The driving force is by most animals transmitted entirely to the environment by vortices.

In this article we will only deal with two examples – both incomplete and highly simplified – the *leading edge vortices on insect wings* and a *couple of two counterrotating vortices* (like, e.g., the *fish tail vortices* used in swimming and in *walking on water*). Most of the results relevant to the first example have been obtained while investigating aerodynamics of micro-air-vehicles [6].

2. Vortices in nature

Vortex is the most frequent phenomenon in fluid dynamics. In nature, it appears at dimensions ranging from 10^{-10} m in liquid helium, or 10^{-5} m in turbulent flows, up to 10^5 m in oceans and hurricanes, or even more in planetary atmosphere (e.g., orders of light years in galaxies).

There are many definitions of a vortex. Not in all cases we can see vortices directly or by visualizing the flow field investigated. We have to identify them even in cases where we can

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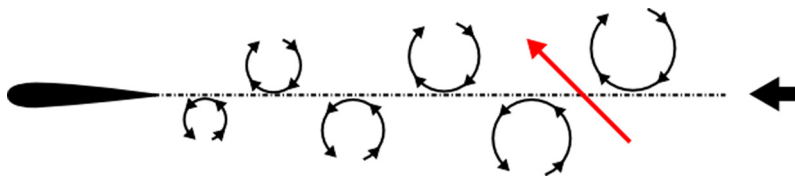


Fig. 1. Vortices in a von Kármán vortex street



Fig. 2. Vortices formed on leading edge (leading edge vortex) and trailing edge (starting vortex)

only deduce on their existence from measuring the whole flow field, or, by calculating the whole flow field with a CFD code. For more details see [5,9] and [11].

There are no vortices in uniform homogeneous flows. Vortices are generated by nonuniformity of the flow field, or by inserting any foreign body that will generate them. The behaviour of vortices is often described by applying the laws of vortex motion as described already by Helmholtz in 1858 (see, e.g., [5] and [11]).

For the vortices to survive in the flow field, they have to draw energy from the surrounding flow field, thus representing always a loss of energy. The same holds true for vortices used by animals to move in fluids. Even these vortices need an energy supply from the animal's musculoskeletal system, and it is amazing how efficiently can the animals control their motion to minimize the energy consumption.

3. Preliminaries

To understand why are the vortices so important in animal locomotion, it is useful to look first at the origin and behaviour of vortices in *steady uniform fluid flows*, and in flows past bodies immersed in fluids.

Vortices are generated on sharp edges of plates placed perpendicular to the fluid motion, or behind blunt trailing edges of various bodies and profiles. In steady flows they stick to these edges and their development depends mainly on velocity of the oncoming flow and — in real fluids — on the viscosity of the fluid. They depend also on the body dimensions, or strictly speaking, on the *Reynolds number* (a ratio of inertial and viscous forces), $Re = U \cdot L/\nu$. At small Re (typically order of unity) are the viscous forces so dominant that these vortices do not appear at all, i.e., there is not enough energy to establish these vortices.

In real fluids the wake behind a 2D profile or bodies consists of a double row of alternating vortices, known as a *von Kármán vortex street* (Fig. 1). Any of the two neighbouring vortices form a couple driving the fluid against the direction the profile is moving, contributing thus to the loss of momentum and representing drag of the body.

If the profile is inclined against the oncoming stream under a certain angle of attack the starting vortex is formed behind the trailing edge as a result of different lengths of fluid paths on the upper and lower surfaces (Fig. 2). According to the *Kelvin's law*, circulation of this starting vortex generates in turn circulation of the same intensity, but opposite sense of rotation on the profile. This circulation multiplied by the mass flow density and the profile area determines the lift force (N. J. Žukovskij, 1902). Vortex at the edge remains there for the whole time the profile is moving. The starting vortex is blown off the trailing edge with the stream velocity.

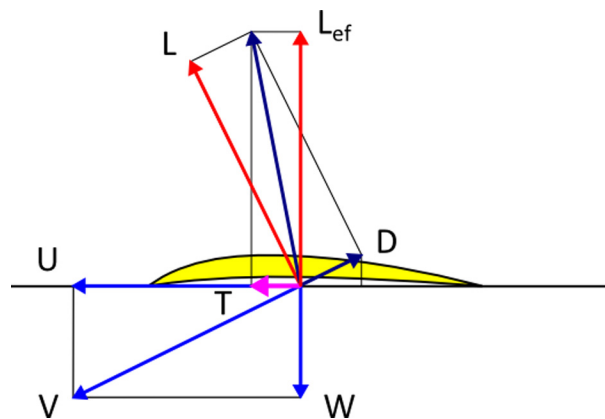


Fig. 3. Diagramme of forces acting on a moving wing, U – flight velocity, W – velocity of the moving wing, V – actual velocity of the moving wing, L – lift, D – drag, L_{ef} – effective lift (vertical component of the resultant aerodynamic force on the airfoil), T – thrust (horizontal component of the resultant aerodynamic force)

One of the already mentioned Helmholtz laws states that the vortex cannot have a free end inside the fluid. It can end on the free surface (if it is available), or it must form a closed loop (e.g. a ring). A good example is a wing of finite aspect ratio, as in the well known *Prandtl's wing theory*. The starting vortex and the circulation on the profile (the bound vortex) are joint together via tip vortices.

However, any animal locomotion in fluids (swimming, flying, hovering) requires a different approach. To generate lift and thrust the animals need either *moving wings* (birds, insects, bats), tails, fins, or *movement of the whole body or its part* (fishes). Flow past these moving parts is *unsteady* and *threedimensional*, i.e., much different from most aircraft wings.

A simple diagramme of forces on the profile during its movement is in Fig. 3. The actual velocity of the oncoming flow is now a vector sum of the flight velocity and the moving wing velocity. Lift is perpendicular to the actual velocity, however, to compensate the weight of the flyer, the vertical projection of the lift force (the effective lift) has to be considered. From the same diagramme we can infer that even a much higher drag and much smaller lift can result in an acceptable effective lift. The projection of the resulting aerodynamic force on the horizontal direction represents thrust of the flyer [4].

At this point we reveal the importance of considering the *Reynolds number*. At higher *Re* inertia dominates over viscosity and once the body (e.g., ship) is set into motion it has to generate a considerable force to stop it. This is not the case with small animals (fish) where also the *Re* is small (typically 1 or even less). Viscosity is in this case so dominant that the animal stops as soon as it ceases to propel itself. The same holds true for small insects, generating the leading edge vortex which is indispensable for lift production.

If the same profile as in Fig. 1 is set into motion perpendicular to the velocity of the oncoming stream, at certain values of the perpendicular velocity and frequency of this motion we arrive at a situation, where the vortex street behind the profile have opposite sense of the vortex circulation (Fig. 4), see, e.g., [10]. Any of the two neighbouring vortices now form a couple driving the fluid in the direction the profile is moving. Clearly, this vortex street generates thrust (this phenomenon is often called *Katzmayr effect*).

Despite the apparent similarity of both cases (Fig. 1 and Fig. 4), the mechanism generating the vortex streets is in both cases different. In the first case the boundary layers from either sides

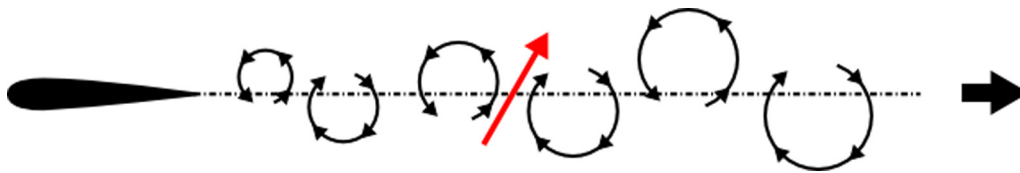


Fig. 4. “Reversed von Kármán vortex street” on perpendicularly oscillating wing (Katzmayer effect)

of the profile turn into vortices at the trailing edge, and a certain kind of instability transfer them into the vortex street as described in Fig. 1. In case of the perpendicularly moving profile (Fig. 4) vortices appear at the trailing edge during the profile movement. At the point where the profile begins to return the vortex is blown down with the stream velocity. The phase lag between the vortices blown off the trailing edge at the points where the profile stops to return is proportional to the velocity, frequency and amplitude of the profile motion, and it determines the position of the vortex in the vortex street (Fig. 5). Evidently, the situation is not so univocal as in case of the Kármán vortex street.

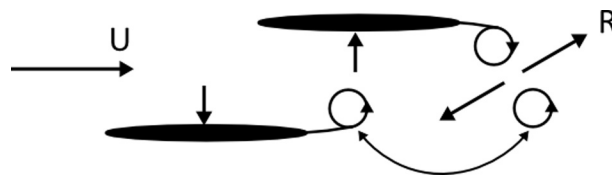


Fig. 5. Mechanism explaining the Katzmayer effect, R is the reaction of the fluid

Bird’s wing during the working phase (downstroke) moves almost perpendicularly to the flight velocity. It generates vortices on both edges — on the leading edge and the trailing edge — rotating towards the wing (Fig. 6). They thus form a vortex couple driving the fluid downwards and giving it a considerable momentum. The reaction to this momentum is the lift, generated by the bird’s wing.

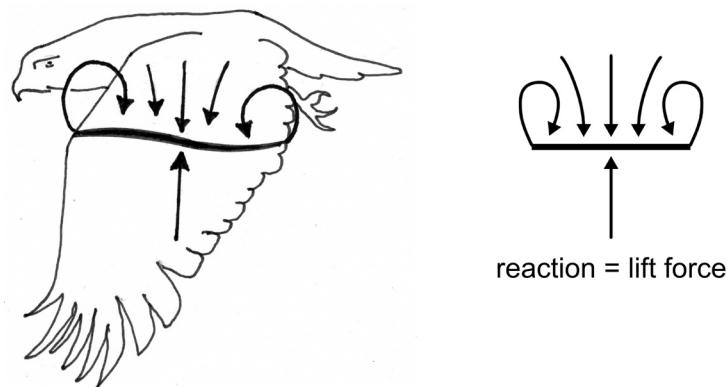


Fig. 6. Leading edge and trailing edge vortices impart downward momentum to the fluid they drive in from the surrounding atmosphere; reaction to this momentum is the lift force

4. Leading edge vortices on insect wings

To keep the insect flying the insect has to generate sufficient lift to compensate the weight (body + payload). The lift force is a reaction to the downward velocity and momentum imparted by the wing to the air. There are two basic forms of insect wing movements — the “bird-like” form — wings are moving up and down as in Fig. 6 — and the actual “insect-like” form — wings are oscillating almost in one plane. Lift generation in both these cases aptly uses *leading edge vortices*, as apparent from Fig. 7.

When the wings move down from the initial dorsal position, a vortex is formed at the leading edge, entraining the surrounding fluid into the gap between the wings and thus generating lift. The leading edge vortex left at the wing initial position from the wing’s returning motion, together with the leading edge vortex of the downward moving wing, form a vortex couple which helps to open the wings and start the already described process of lift generation. This process has been called “*clap and fling*” and was described by Thorsten Weis-Fogh in 1976 (see, e.g., [13]). It is used by butterflies, moths, and many other insects who use even the other mode (the oscillating wing).

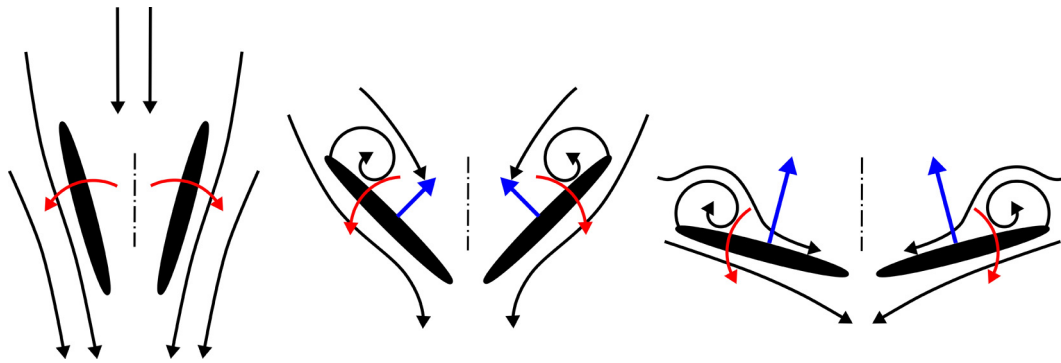


Fig. 7. Mechanism of the “clap and fling” insect wing motion

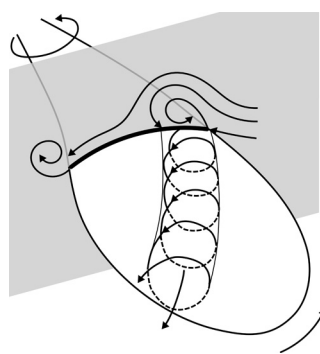


Fig. 8. Leading edge vortex on an oscillating wing

The whole process of lift generation on *oscillating insect wings* is, however, much more sophisticated. The leading edge vortices, or mainly their displacement effect, create a high-lift-profile by enlarging effectively the wing upper side (Fig. 8). The wing is moving on semicircular paths with very high frequency within about 160° and at each end of the wing amplitude it has to revert (rotate) to move always with the leading edge ahead. This movement generates intensive centrifugal flow inside the leading edge vortex, which stabilizes the vortex.

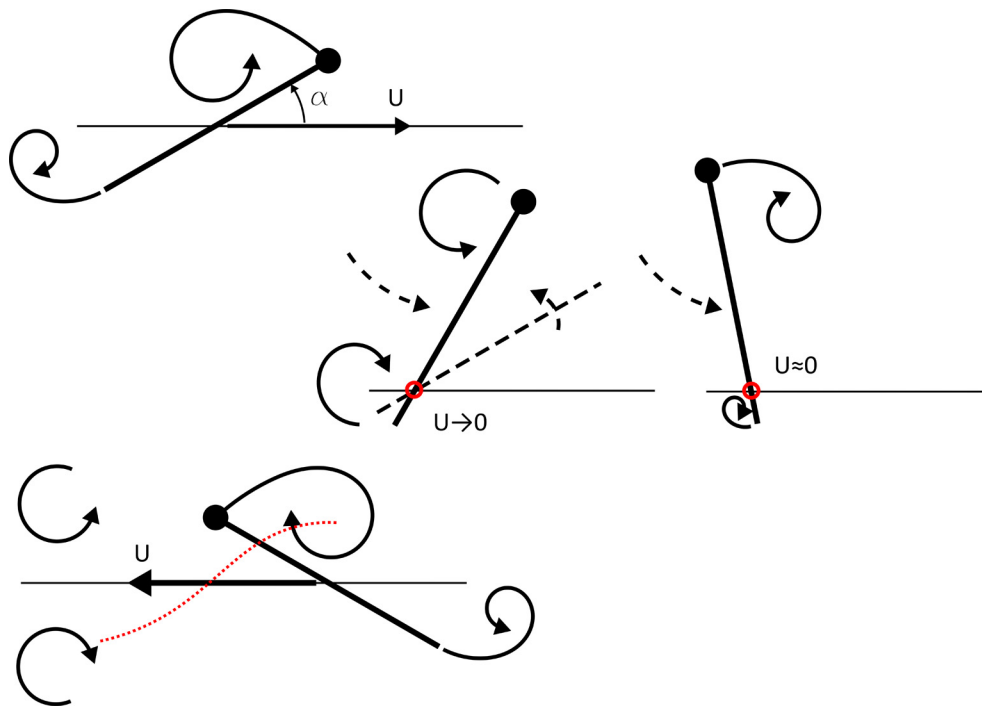


Fig. 9. Mechanism of increased lift generation by oscillating insect wings

Measurements, as well as numerical simulation, has shown that lift is not only generated by the wing oscillation between the two end points, but also by rotating (reverting) the wing (see, e.g., [3] and [13]). Leading edge vortex generated during rotation can contribute up to 35 % of total lift, depending on the position of the center of rotation and on the moment (phase) of the rotation beginning. Even more, when the wing returns it may meet the starting vortex from the preceding cycle, and — both vortices having the same sense of rotation — increase thus intensity of the leading edge vortex. The whole process is schematized in Fig. 9. This process of lift generation is quite unique for insects, and is made possible only by a special wing base — a pivotal joint with the capability to set almost any required wing motion, and a system of the flight muscles, controlling all the degrees of freedom the wing has.

The aerodynamics of insect wings is strongly affected by small values of the Reynolds number, i.e., by low ratio of inertial to viscous forces. Reynolds number for large insects is of the order 10^3 to 10^4 , however, for smallest insects it may be 10 or even less. At these Reynolds numbers the flow past insect wings is even in air highly “viscous”.

Only at these Reynolds numbers the wings can operate at high angles of attack with a strong leading edge vortex, which almost does not move during one stroke. The strong centrifugal flow inside the vortex stabilizes it during wing oscillations. Nothing similar can happen at high Reynolds numbers — as, e.g., on aircraft wings where the flow at these angles of attack will separate, leading ultimately to complete break-down of the lift.

Also only at these Reynolds numbers the wings can have very unusual surface (from the classical aerodynamics point of view), and nevertheless achieve very good lift and drag. In Fig. 10 is an example of the cross section of a corrugated dragon-fly wing. Wind tunnel experiments, as well as numerical simulation has proved that at very small Re the corrugation grooves are filled in with highly viscous vortices, so that the effective final shape of the wing profile acquires good aerodynamic quality (see, e.g., [8, 12]).

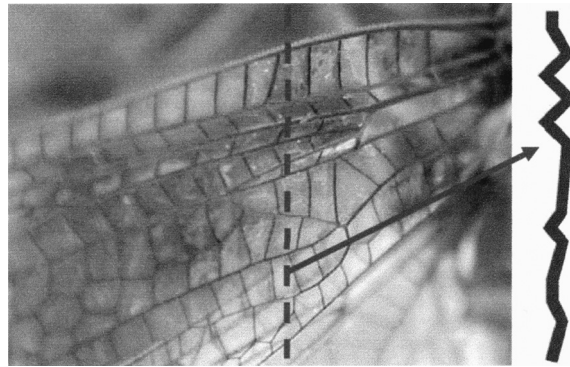


Fig. 10. Corrugated dragon-fly wing (adapted from [8])

There is still another possible view on the high lift generation by insect wings, similar to that we have already used in describing the bird's wing-lift-generation and to that we shall use in explaining the driving mechanism in aquatic locomotion. The leading edge vortex together with the starting vortex (see Fig. 2) represent a couple of counter-rotating vortices, which impart downward oriented momentum to the entrained air. Reaction of the surrounding stagnant air to this momentum is the insect-wing-generated lift. Explaining the lift of the oscillating insect wing using this model seems much more relevant than referring to the analogy with an "aircraft-like-generated-lift". Everybody can easily feel the vortex-generated momentum when putting his hand under the flying or hovering insect.

5. Vortices in animal locomotion in water

It is not easy to understand and describe how movements initiated by the muscoskeletal and nervous system result in producing thrust and in generating forces to manoeuvre the body. In aquatic locomotion forces exerted by the body and fins against the surrounding water (or stream) yield in response to this action forces needed for propulsion and manoeuvring. However, if we concentrate only on the most simple way of animal locomotion in water, we will see again, that the propelling force is a reaction of water to the action of vortices.

The basic fluid dynamic mechanism is astonishingly simple. A couple of two counterrotating vortices entrains fluid from their environment and drives it against the mass of stagnant water. Reaction against the momentum of the vortex driven fluid imparts a momentum to the vortices and sets them into motion off the stagnant water (Fig. 11) The most simple generator of a vortex couple is a caudal fin, or the whole fish tail (like at dolphins), or the leg of a water strider, etc. The pectoral fins are used mainly in manoeuvring. However, the most important vortex couple that forms in rapidly turning fish is generated by bending the whole body (see, e.g., [14]).

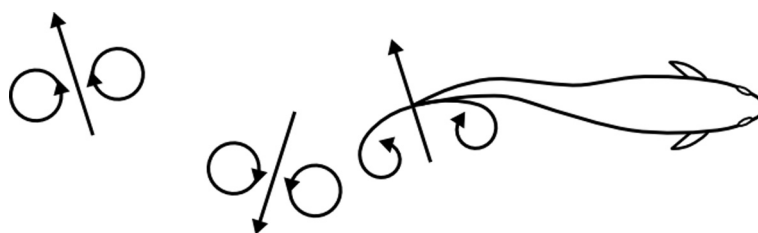


Fig. 11. Forward momentum generation in water — a reaction of the surrounding mass of fluid against a 2D vortex couple (adapted from [14])

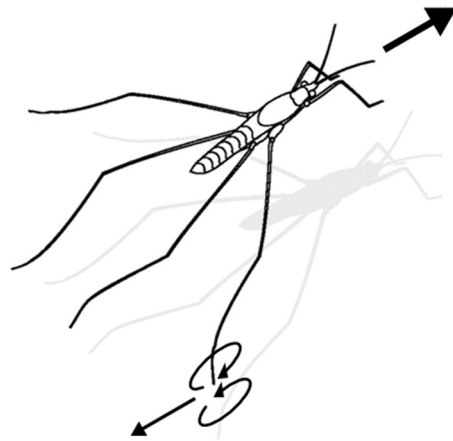


Fig. 12. Subsurface vortices generated by a water strider's leg penetrating the water level (from [2])

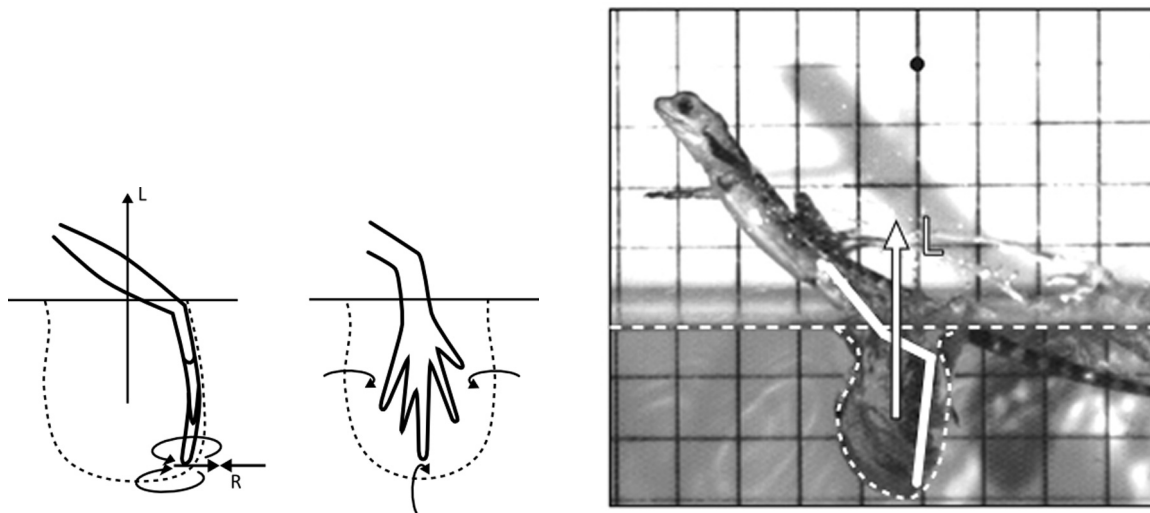


Fig. 13. Subsurface vortices generated by a basilisk lizard's leg penetrating the water level. Note the great cavity behind the lizard's leg, L is the Archimedes lift of the cavity, R is the reaction of the mass of water (adapted from [7])

Similar vortices are generated in swimming frogs. Each leg generates a separate vortex ring and no interference by the other leg has been observed. As intensity of the generated vortices is much smaller than in fishes, even the propulsion effectivity is smaller. This experience has also influenced the swimming style in humans.

Vortices are used for propulsion even in water-walking arthropods (Fig. 12). Flow visualization revealed that the wakes of water walkers are formed by a series of subsurface vortices shed by the driving stroke. The water strider when not moving rests on the water surface due to surface tension, however, even they use the vortex reaction to water walking [1].

There is, however, a much heavier creature capable of water-walking (or better “running”) — the basilisk lizard — who can sprint across the water surface at speeds about 1.6 ms^{-1} . To run on water he does not use only the vortices, but makes a very clever use of the Archimedes lift. Fig. 13 explains the way he does it. After he strikes the water level with one of his legs the leg gradually penetrates into water forming a bubble in its wake. It is this bubble which receives the

Archimedes lift and supports the lizard. The bubble closes very quickly, so the lizard does not have much time to drive the leg back with minimum friction, and to continue the same action with the other leg. The reaction of the water which represents here the actual lift force has in this case two parts — the reaction to the momentum imparted to the stagnant water by the lizard's leg during the stroke, and the Archimedes lift of the bubble and the volume of the leg. The whole trick is in repeating the strokes with such a frequency that the described model can be applied. The frequency depends on the bubble volume and its closing time, and, through it on the water density and viscosity.

The reaction force which develops in response to the stroke of the lizard's leg is generated by the same mechanism as in water-walking arthropods (see Fig. 12 and Fig. 13). The leg penetrating the water surface generates vortices — two counter-rotating vortices in a 2D case, or a vortex- ring- like structure in a 3D case. These vortical structures remain where they were generated even when the leg is driven off this place. They entrain the water from their neighbourhood and drive it in the direction of the stroke. The reaction has then the same momentum but opposite direction.

6. Closing remarks

It was only as late as the second half of the last century that scientists were successful in unveiling the secrets of animal locomotion in fluids — capabilities that the animals have been developing for millions of years.

Investigation into physics of animal locomotion has revealed that it depends largely on vortices. A couple of two counterrotating vortices or a vortex ring entrain fluid from their environment and drive it against the mass of stagnant fluid. Reaction of the momentum of the vortex driven fluid imparts a momentum to the vortices (vortex ring) and sets them into motion.

Investigation into birds' and insects' flight has also discovered the incomprehensible perfection of the neuroskeletal system controlling and moving the wings. This represents another large category of problems still open to research. Only after such research has been completed, can we think of successfully building and exploiting the micro-air-vehicles.

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