# Magnus effect

## Pavel Konečný

MU Faculty of Science, Department of Physical Electronics

Abstract

*If we accept the explanation of the Magnus effect as a force reaction according to Newton's third law, more specifically as the deflection of the fluid stream due to the displacement of the point where the flow breaks away from the surface of the cylinder due to the difference in friction on opposite sides of the cylinder, it is possible to compare this effect with other ways of influencing the boundary layer, such as suction, or the surface structure, the so-called turbulator. An apparatus was constructed with the aim of qualitatively demonstrating these effects.*

## Introduction

The Magnus effect is one of those physical phenomena that school physics cannot completely avoid, because it is encountered by anyone who plays or at least watches ball games. Thus, there is a fairly high probability that a teacher will be asked about this phenomenon. No hydrodynamic effect is easy to explain and the Magnus effect is even more complicated because of the fact that friction is its main cause, not a negligible disturbance. Therefore, the Bernoulli equation should be used with caution, since if the change in velocity is caused by friction, the conditions under which it is derived are not met. (Derivation of Bernoulli's equation [2], including examples of wrong application in [1]). Therefore, the assertion that on one side of the rotating cylinder the air accelerated by friction has less pressure than the air slowed down by friction on the other side of the cylinder as a result of Bernoulli's equation, according to the rule of “greater velocity means less pressure”, is therefore not correct. The direction of the resulting force derived from this is correct, but only for the normal Magnus effect, not for the negative Magnus effect.

Explanations of both the normal and negative Magnus effects can be found in a number of articles. A very detailed overview, including an excursion into history and applications, can be found in [3], or also in [4].

Published observations in a wind tunnel and computer simulations suggest that the effect is due to the influence of surface friction on the boundary layer. Usually, the more decelerated layer breaks away from the surface sooner than a less decelerated one. On the cylinder’s side, where air flows around it in the direction of its rotation, it’s decelerated less, on the opposite side it’s decelerated more. The further the flow gets on the surface of the cylinder, the more it deviates from a straight line. If it gets further on one side than on the other, it means that the air flow deviated from a straight line. The normal Magnus effect is then derived from Newton’s third law of motion [4]. The published experiments cannot be replicated without adequate equipment, such as a low-turbulent wind tunnel and a flow visibility device. However, some experiments, in which we can influence the boundary layer and also the place where the flow breaks away, can be done more easily.

The easiest way to influence the boundary layer, in addition to changing the relative speed of the surface flow relative to the flowing air, is to suck it out or stir it up using a structured surface, the so-called turbulator, for example in the form of a fiber of a suitable diameter glued to the surface.

## Boundary layer types

The boundary layer is an area significantly affected by the friction of the fluid against the surface. It can be laminar or turbulent. The laminar boundary layer can turn into a turbulent one due to instabilities. The thickness of the laminar boundary layer gradually increases in the direction of flow, as does the turbulent boundary layer.

In the case of no viscosity, the steady flow around the cylinder would be laminar, friction forces would be absent, and the moment of compressive forces would be zero. The boundary layer would not exist. The structure of the velocity profile would be symmetrical from back to front as would the pressure field [5] [6]. Then, there would be no friction forces acting on the cylinder and the sum of all compressive forces would be equal to zero, the cylinder would move without resistance.

In the case of a very large viscosity, or more precisely a very small Reynolds number, for example, in a situation where the cylinder moves evenly and slowly enough, for example, in molasses, turbulence also does not occur, but for other reasons than in the case of a non-viscous fluid, the viscosity prevents the turbulent behavior. In fact, the boundary layer does not exist either, it is impossible to find a boundary between friction affected and negligibly affected fluid. The distribution of the streamlines in this case is approximately symmetrical, similar to the previous example of a hypothetical ideal fluid [7]. However, friction forces are acting on the cylinder and the sum of all compressive forces is non-zero, the cylinder is being decelerated.

## Effect of the boundary layer on the flow around an object

Imagine a cylinder around which an ideal fluid is flowing, where the flow and pressure distribution is symmetrical. Pressure is connected to velocity by Bernoulli's equation. There is an overpressure in front of the cylinder because there exists a streamline perpendicular to the surface of the cylinder. This is where the fluid stops, it also stops behind the cylinder due to the symmetry of the flow. Let’s call the pressure behind the cylinder contra-pressure. There is a negative pressure area near the sides of the cylinder, that is because the fluid bypasses the cylinder and therefore has higher speed and thus lower pressure in this part. The fluid in front of the cylinder is initially accelerated by a pressure gradient in the direction of the side part of the cylinder and then decelerated by the already mentioned contra-pressure. For an ideal fluid, the pressure conditions are such that the fluid is able to bypass the cylinder and restores itself to its original state behind the cylinder. The flow is symmetrical from back to front. The contra-pressure is equal to the overpressure in front of the cylinder, the resulting force acting on the cylinder is equal to zero, see Fig. 1.

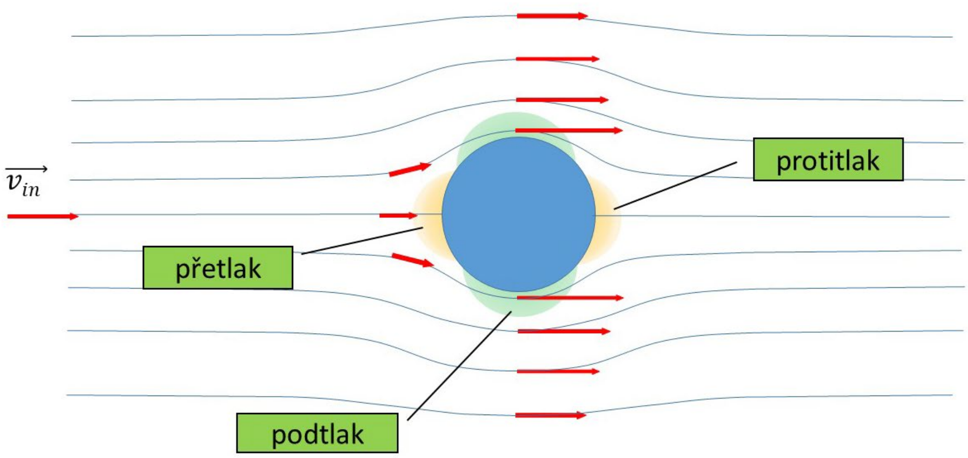



Fig. 1. Fluid flow without internal friction – schematically.

Imagine that the fluid flowing over the surface of the cylinder on the way from the front part to the side part is affected by a small disturbance in the form of friction and slows it down a little. This small disturbance changes the idyllic picture of symmetrical flow. The decelerated fluid no longer has enough kinetic energy to follow the same streamline as it would have in the case of a frictionless flow and is not able to create the same contra-pressure. In other words, the back-to-front symmetrical distribution of streamlines is no longer possible. The fluid ends its journey around the cylinder in the boundary layer much earlier and breaks off creating a vortex wake behind the cylinder, see Fig. 2.

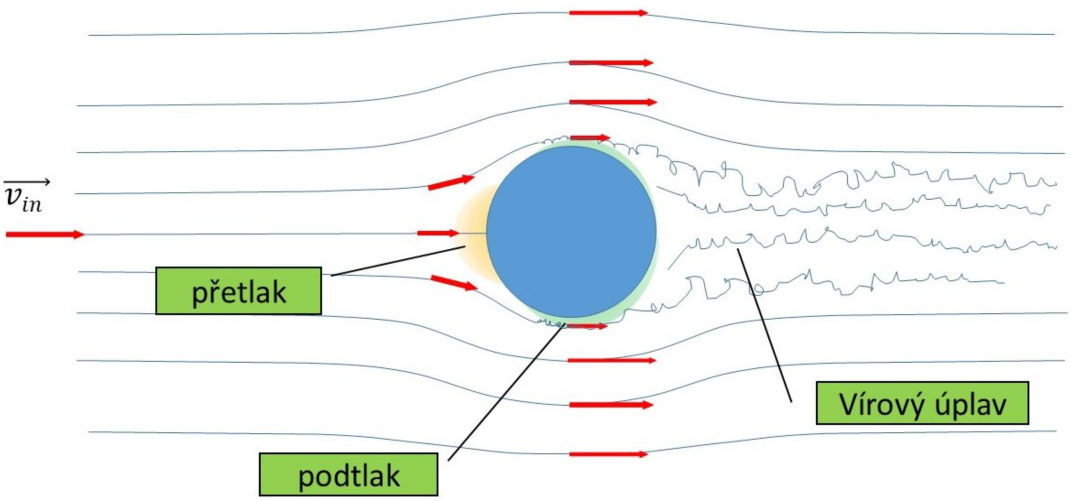



Fig. 2. Flow of a real fluid – schematically.

If the limits of stability are exceeded, the laminar boundary layer turns into a turbulent one, or breaks off, with subsequent adhesion, usually as a turbulent boundary layer, or does not adhere at all. Even a turbulent boundary layer can break off. If, for some reason (for example, due to the structure of the object's surface, the so-called turbulator), a turbulent boundary layer develops in an area where it could otherwise still be laminar, the turbulent boundary layer will break off later.

Turbulence will ensure the mixing of the heavily decelerated layer close to the surface with the more distant, less decelerated layers. By this mechanism, the layer closest to the surface gains energy and can get much further to the contra-pressure area.

The reader may be somewhat confused as to why the faster moving air should copy the curved surface while the slower air does not, when after all it works just the other way around when air flows through a turn. The answer to this question, of why in a certain situation the "faster moving air" does not fly out of a turn, while the "slow air" does, is quite complicated and outside of the scope of this article. It is related to the Coand effect, which is described in detail in [8].

## Fluid flow around a rotating cylinder

In the case of a rotating cylinder the boundary layer behaves differently on the side of the surface moving in the direction of the flow to the boundary layer on the other side, where the surface of the cylinder moves in reverse relative to the flow. The loss of kinetic energy in the boundary layer where the surface of the cylinder is moving in the direction of the flow will be lower and the air will flow further along the back of the cylinder than on the opposite side, where the energy loss will be greater. The air stream will curl to one side. Now, we apply Newton's third law and compare the calculated direction of force with the experiment. The resulting forces are in accordance with the so-called normal Magnus effect, see Fig. 3.

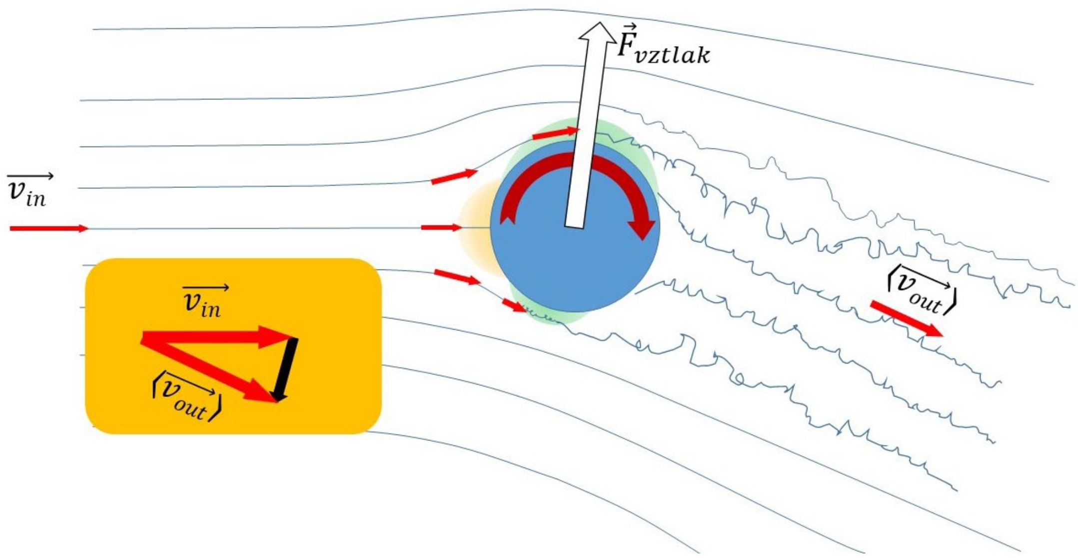



Fig. 3. Fluid flow around a rotating cylinder – schematically.

### Negative Magnus effect

Unfortunately, it’s not as simple in other cases. For certain combinations of aerodynamic parameters, such as the smoothness of the cylinder’s surface, the speed of rotation, the relative speed of the cylinder compared to air and the Reynolds number, an opposite effect occurs, the air flow breaks off earlier on the opposite side, where the relative surface-air velocity and friction is lower.

The existence of the negative Magnus effect illustrates the problematic nature of qualitative descriptions of aerodynamic phenomena. It was not observed with the apparatus described in this text. Analysis of this effect is outside of the scope of this article.

## The influence of suction and a turbulator

The effect of suction (see Fig. 4) is obvious, by removing the heavily decelerated boundary layer, the breaking off occurs later, a similar effect is achieved by generating a sufficiently fine turbulence, which leads to the mixing of the heavily decelerated layer closest to the surface with a more distant, less decelerated layer, see Fig. 5.

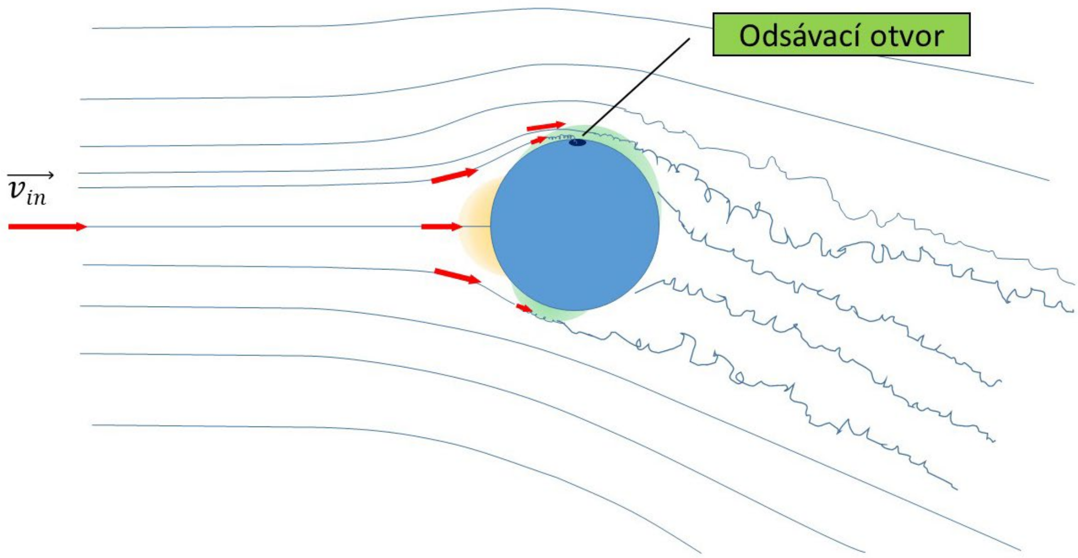



Fig. 4. The influence of suction – schematically.

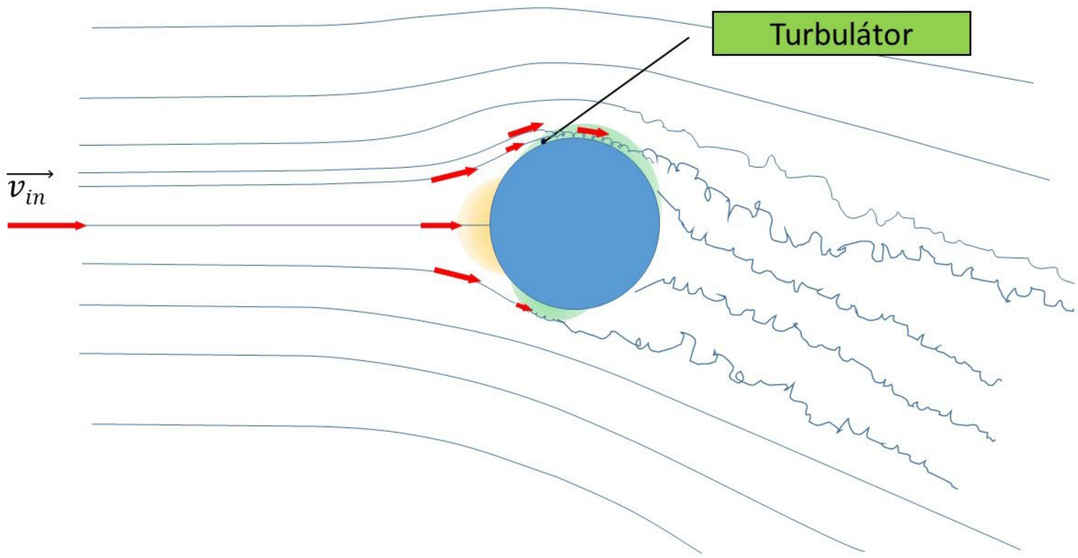



Fig. 5. The influence of a turbulator – schematically.

## Apparatus construction

In all three cases (rotation, suction, turbulator), the cylinders have the same diameter of 28 mm and are placed on a rotating arm. The length of the arm is about 45 cm. The wind tunnel can be placed either on the arm or on an independent stand. The second option allows us to observe the effect more easily, rotation and its changes cannot be missed. On the other hand, some doubts about the interpretation of the observed effect may arise, since the reaction forces of the wind tunnel may not be zero, also a change in the aerodynamic pressure acting on the cylinder creates a torque. The device is also sensitive to a pair of forces. For example, when starting a cylinder, we should be noticing the whole turntable spinning in the opposite direction. However, the moment of inertia of the cylinder is so small that this effect did not need to be compensated (by a second reverse motor).

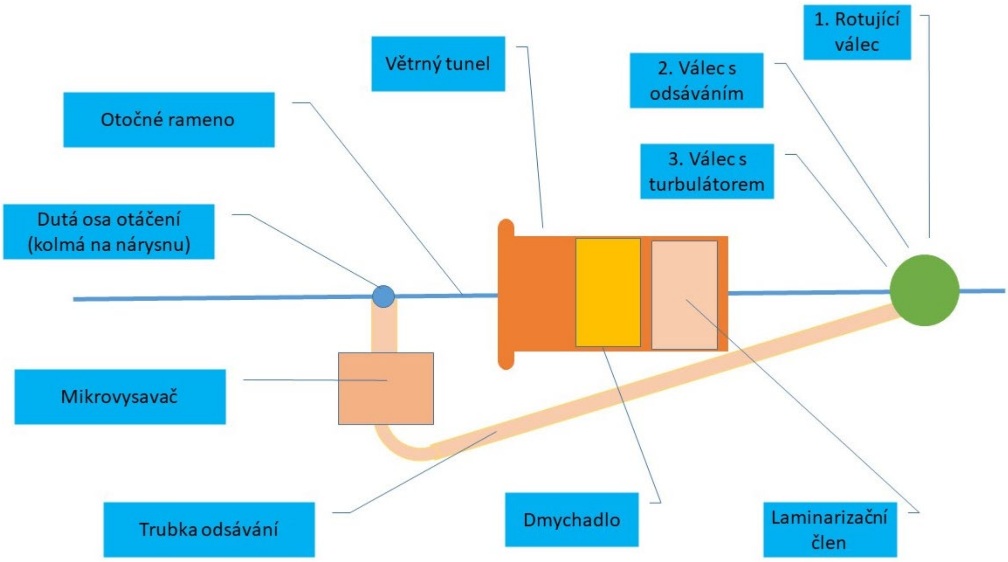



Fig. 6. Diagram of the apparatus.

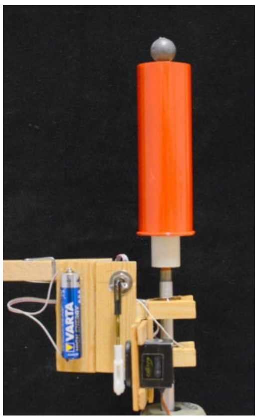


Fig. 7. Rotary cylinder.

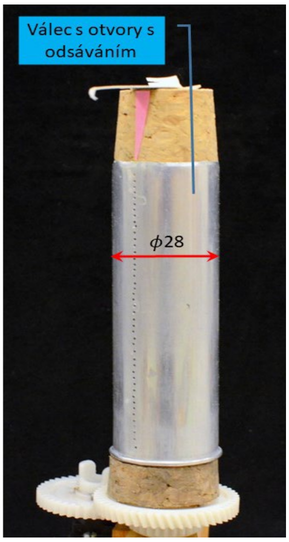
### Suction

Suction is carried out by a system of 45 holes with a diameter of 0.6 mm in a vertical line with an average distance of 1.75 mm. The negative pressure is provided by a miniature vacuum cleaner powered by four AA batteries originally designed to clean electronics. The pump can be switched on and off remotely. The centrifugal pump generates a maximum negative pressure of about 1000 Pa when all 4 AA batteries are used and about 900 Pa when pumping a cylinder with holes. It extracts 9 ± 10% l of air/min. Using three AA batteries, it creates a negative pressure of about 450 Pa when pumping the cylinder, the extracted amount of air per minute is 6.5 ± 10% l. It is positioned horizontally and therefore does not change the angular momentum in the direction of the turntable axis during start-up. The escaping goes through the hollow shaft of the turntable and therefore does not affect it by its torque.

The parameters of the individual elements of the device are not critical to its function. In aerodynamics (subsonic velocities), the Reynolds number, which is relatively small for the apparatus in question, determines the similarity.

$$R_e = \frac{\rho * D * v}{\mu} \approx \frac{28 * 10^{-3} * 5,6}{16 * 10^{-6}} \approx 9800$$

The question is, how would the experiment turn out if the apparatus was further miniaturized.



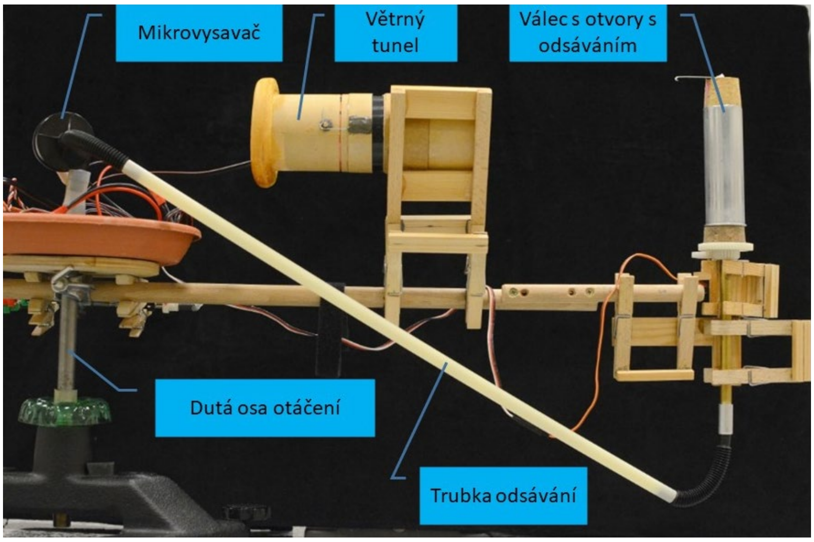




Fig. 8. A cylinder with a suction device.    Fig. 9. The apparatus with the cylinder

**Controlling of the apparatus**

The whole device is remotely controlled by a 4 channel HITEC Laser4 modelling kit, operating at a frequency of 40,765 MHz. The speed of the wind tunnel air flow can be regulated, for most experiments the air speed was set to 5.6 m/s (with an accuracy of 5%. The cylinder rotates at the speed of 1200 revs/minute. It is possible to remotely control the shutdown and the direction of rotation of the cylinder. In the case of the cylinder with the vacuum and the turbulator cylinder, the orientation of the intake holes or the turbulator relative to the air flow can be remotely controlled (in the 0° position the intake holes or the turbulator are positioned against the incoming air flow, in the 90° position, they're perpendicular to it).

### Turbulator

The turbulator consists of two fibers with a diameter of 0.6 mm stretched on the surface close to each other. The position of the turbulator is indicated by a pointer.

Fig. 10. Cylinder with a turbulator.

### Wind tunnel

In the wind tunnel, air is accelerated by a blower from a model kit with an internal diameter of 50 mm and a weight of only 30 g. The tunnel shell is made of laminated paper. Straws with a diameter of 5 mm and a length of 16 mm are glued inside of the tunnel creating a honeycomb pattern. This honeycomb directs the flow but does not prevent turbulence, therefore it can be expected that effects that require very low environmental turbulence will not occur, for example the negative Magnus effect.

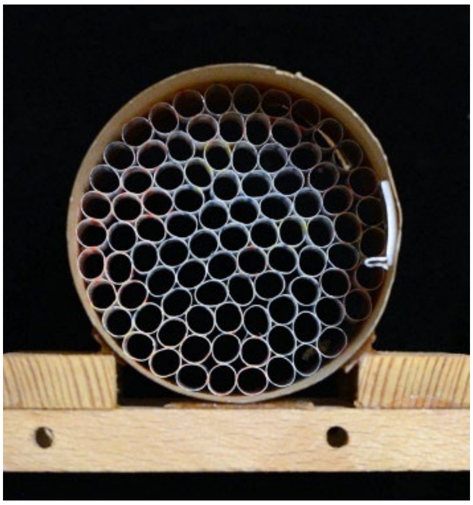


Fig. 11. Flow rectifier.

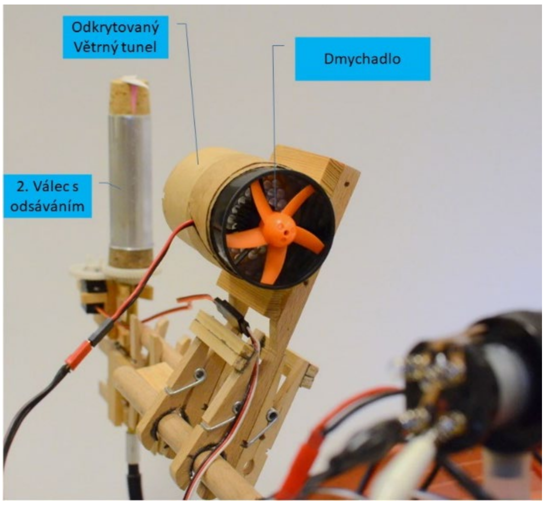



Fig. 12. Uncovered wind tunnel.

## Experiment

### Balancing the turntable

Attention should be paid to the balance of the turntable and the adjustment of the vertical axis of rotation. If the turntable was perfectly balanced, the verticality of the axis of rotation would not matter. But since it is not possible to perform one or the other precisely enough, it is possible to prevent swaying (with a very long period) only by setting both.

**Wind tunnel and cylinder adjustment**

This is relevant equally to all three of the experiment variants, i.e. rotation, suction and turbulator. First, the tunnel position is adjusted so that its thrust at maximum blower speed does not produce a measurable torque. Then the position of the cylinder is adjusted so that the turntable does not spin at both low and high air velocities.

**Magnus effect**

Adjust the air flow to a speed of 5,6 m/s. Higher speed amplifies the effect only slightly. (Note: it is not clear why. The reason probably lies in the fact that, unlike the movement of a rotating cylinder in an infinite environment, where the buoyant force should increase linearly with velocity, here we have a narrow inhomogeneous slightly turbulent air flow with turbulence at the boundary. As the blower power increases, not only does the speed of the air flow change, but also its profile, as well as turbulence.) The remote control turns on the rotation of the cylinder, first in one direction and after a while in the other direction. The turntable rotates in the direction opposite to the rotation of the cylinder, which corresponds to the Magnus effect.

**The experiment using suction**

For this experiment, it is necessary to replace the end module of the rotating cylinder with the suction module. The turntable is adjusted in the manner described previously. With the position of the suction holes perpendicular to the wind tunnel axis (position 90°) with the vacuum on and the wind tunnel off, it shall be verified that the suction itself does not generate a parasitic torque. A significant buoyancy force in the air flow is created if the suction holes are positioned perfectly, which is manifested by the rotation of the turntable. The turntable rotates to the side where the suction keeps the flow adjacent for a longer time. By rotating the cylinder through the holes to the other side, the reverse effect is achieved. For best results, adjust the position to around 90°. By turning off the vacuum, the effect disappears.

**Turbulator experiment**

For the turbulator experiment, the cylinder with holes is replaced with a cylinder with a turbulator. The position is measured in the same way as with the previous cylinder. The effect is most visible when the position of the turbulator is in the angle range of approximately 45° to 60°. The buoyant force appears at the side where the turbulator-modified boundary layer remains adjacent to the cylinder for a longer time.

## Discussion

The most common objection to this method of demonstration of the above-mentioned phenomena concerns the possibility of false effects caused by the fact that the turntable is sensitive to moments of force that have nothing to do with the Magnus effect or the buoyant forces acting on the cylinder and (in principle) to pairs of forces that would not play any role if the cylinder was placed, for example, on tracks. If the apparatus is well adjusted, these parasitic effects are significantly weaker, but this is not obvious at first glance. To support this claim with analysis and experimentation means to play with it, so to speak, and this will take more time.

## Literature

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