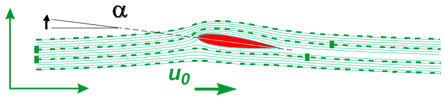
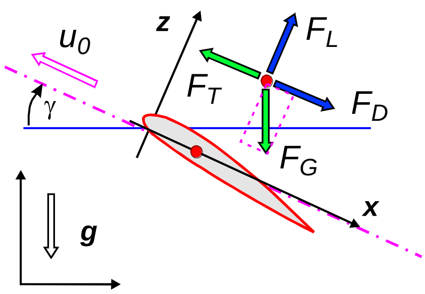
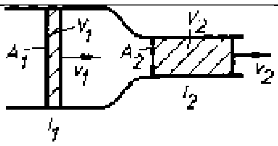
Glossary

Don't be scared! - This version shows the knowledge accumulated by preceding courses.
If not otherwise stated, all explanations refer to *incompressible* flow.

Term	Dimension, formula, graph	Supplementary explanations
Aerodynamics	Branch of Fluid Mechanics dealing with fast moving bodies relative to the fluid **air**. On purpose, the bodies are smoothly shaped ("streamlined"). For low speed compared to the speed of sound, the governing laws also apply to the fluid **water**. Hence, low-speed aerodynamic experiments often are carried out in water. This field is named Hydrodynamics ("incompressible flow").	Aerodynamics is distinguished by a primary fact: The motion of the body, which traverses the fluid assumed to be at rest "at infinity", is dominated by a translational motion u_0 (the **kinematic velocity**). This motion is assumed to be large compared to all other motions related to the body, in particular the fluid fluctuations, which are induced by the traversing body. The body displaces the fluid *particles* (a term which deserves to contemplate about!) and disturbs the original order of the resting fluid (the **induced velocity field**). This assumption allows of substantial approximations in the governing equations (the conservation laws for momentum, mass and energy), which lead to the first theoretical description of **lift** and **drag** at the beginning of the 20th century (among others, Ludwig Prandtl in Göttingen).
Amplitude ratio λ	$\lambda = \frac{h_0}{\alpha_0 \cdot (l/2)}$	The ratio of the amplitudes of a coupled sinusoidal *plunging* (*h*) and *pitching* (α) motion. These terms of the motions are applied in a 2D section of a wing. For the 3D wing *flapping* and *feathering* are often used.
Angle α	α measured in rad (radian) or α measured in deg (degree) (check our computer program for the setting applied!)	*Radian* and *degree* are two different units to describe an angle. A full circle is an angle of 360 degrees. Given as perimeter of the unit circle (radius 1) the angle of the full circle is the dimensionless value 2π. If the circular function *sin*(α) is expanded into an infinite series, i.e. $\sin(\alpha) = \alpha + \ldots$ (higher order terms of α), then the value of α has to be given in radian!
Angle of incidence α		Angle that is enclosed by a wing and the flow direction, respectively the direction of its trajectory. For birds, this angle changes during one stroke: $\alpha = \alpha(t)$. It can be separated into a stationary and a time dependent part: $\alpha(t) = \alpha_s + \alpha_i(t)$
Bernoulli equation	$p + \rho \cdot g \cdot h + \frac{1}{2}\rho \cdot u^2 = const$ static pressure + hydrostatic pressure + dynamic pressure = const For the same hydrostatic pressure, two locations *a* and *b* are compared by $p_a + \frac{1}{2}\rho \cdot u_a^2 = p_b + \frac{1}{2}\rho \cdot u_b^2$.	The Bernoulli equation describes the relation between pressure and velocity in steady, incompressible flow. A large static pressure *p* leads to a small velocity *u*, and vice versa. The equation also exists in a more complex form valid for unsteady and compressible flow. If pressure and velocity are known for one location in the fluid, the pressure at any other point may be determined from the given velocity field (leading to the definition of the **pressure coefficient**).
Climbing Force equilibrium		x: $F_D - F_T + F_G \cdot \sin\gamma = 0$ z: $F_L - F_G \cdot \cos\gamma = 0$ Required thrust F_T: $F_T = \frac{1}{\varepsilon} F_G \cdot [\cos\gamma + \varepsilon \sin\gamma]$, $\varepsilon = \frac{F_L}{F_D}$ Climbing is achieved by additional thrust. The lift force remains - by definition - perpendicular to the trajectory and consumes no power. ε is named the "L over D" coefficient or lift-to-drag ratio.
Continuity equation	 $A_1 \cdot v_1 = A_2 \cdot v_2$	The volume flow in a tube is constant. Particles passing a tube with a large radius are slower than particles passing a narrow region of the tube. The figure shows how a volume element ($A_1 \cdot l_1$) is conserved. The volume flow is given by $A_1 \cdot v_1$, measured in m³/s.

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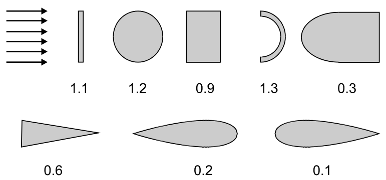
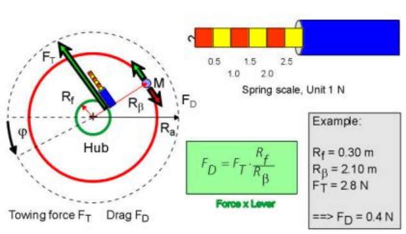
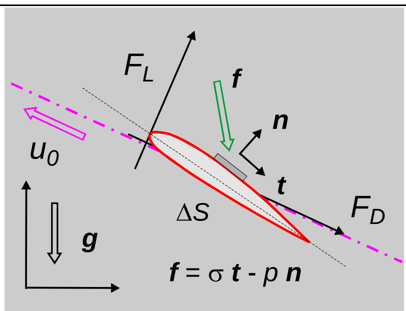
Degree of turbulence *Tu*	$Tu = \frac{1}{u_0} \cdot \sqrt{1/3 \cdot \left(\langle u'^2 \rangle + \langle v'^2 \rangle + \langle w'^2 \rangle \right)}$ Velocity of the fluid relative to an observer at rest (e.g. in front of a wind tunnel): $v_{rel}(\vec{x},t) = (u_0 + u', v', w')$	*Tu* is the degree of turbulence in a flow. For measurements in a wind tunnel, a typical value is $Tu = 0.01$, good tunnels reach values like $Tu = 0.001$. $u', v',$ and w' are he local fluctuations of the stream in all three spatial directions. The mean value $\langle \ldots \rangle$ is defined as: $\langle u'^2 \rangle = \frac{1}{N} \sum_{n=1}^{n=N} u_n'^2$
Density ρ	[kg/m³]	Mass per volume of a fluid or a solid. For varying density, a mass element Δm is divided by the volume element ΔV, the mass element occupies.
Drag F_D	[N]	Component of the fluid force acting on the moving body (aircraft, wing, profile) , which is by definition **tangential** to the body's trajectory. Also see *Fluid force*.
Drag coefficient c_D	[-] , $c_D = \frac{F_D}{1/2 \cdot \rho \cdot u_0^2 \cdot S} = \frac{F_D}{q_0 \cdot S}$ 	The impact of shape and surface of a body on drag is described by this coefficient. It reflects the proportionality between the dynamic pressure on an area *S* and the resulting force F_D. The picture shows typical values for the drag coefficient, which effectively depend on the *Reynolds number*. <u>Caution:</u> The reference area in the picture is the **frontal area** *S*. In Aeronautics, the area of reference usually is the **planform area** *A*, because the frontal area is a critical small-size value. The definition basically remains the same.
Drag F_D**, measurement using the RL3**	 **Mechanical Measurement of Drag** with the Test Stand ANIPROP RL3	The measurement is carried out either by observation of the spring scale or by evaluating the electric signal of the potentiometer integrated into the towing system.
Efficiency η	$\eta = \frac{-\langle P_g \rangle}{\langle P_h \rangle + \langle P_\alpha \rangle} \cong \frac{-\langle P_g \rangle}{\langle P_h \rangle}$	In flapping flight, the efficiency is the ratio of the power gained for the translational (gliding) motion to the power spent for the flapping motion. The power of the feathering motion is comparatively small and can be neglected in this calculation. The bracket <..> means the average value during one cycle of motion.
Feathering	clockwise: $\alpha_i(t) = \alpha_0 \cdot cos(\omega \cdot t)$ $\alpha(t) = \alpha_s + \alpha_i(t)$	Rotation of a bird's wing around wing axis causing a change in angle of incidence. The part of the force caused by this force standing normal to the wing profile (2D section of a wing): $F_\alpha^*(t) = q_0 \cdot A \cdot 2 \cdot \pi \cdot \alpha_i(t)$
Fluid force *f* **on a surface element**		... on a wing section moving with the velocity u_0 along a trajectory, which has an arbitrary direction relative to the gravity field ***g***. A wing section is also called *profile*. A surface element ΔS experiences the force ***f*** from the fluid with the direction ***t*** tangential and ***n*** normal to the surface element. ***f*** is split into the tangential and the normal component (see **lift** and **drag**). These components are calculated per square unit and named pressure *p* and shear stress σ . The unit is N/m².
Frequency *f*	[1/s]=[Hz], $f = \omega / 2 \cdot \pi$	

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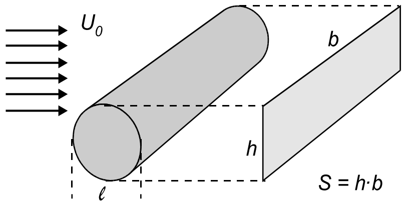
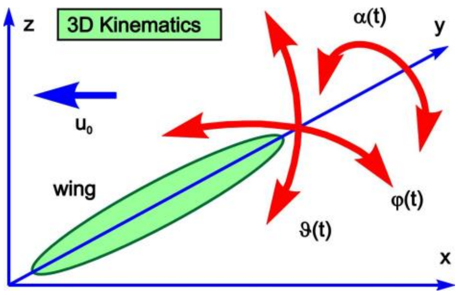
Frontal area S	$S = h \cdot b$ = height · span 	As this quantity of a wing, may it be bird or aeroplane, usually is quite small, one rather uses the *planform area*, which takes into account the chord length *l* of the body. For a cylinder, the chord length is the diameter.
Hagen-Poiseuille-law	$\dot{V} = \frac{\pi \cdot R^4 \cdot (p_1 - p_2)}{8 \cdot \eta \cdot L}$ L is the length of the tube; η is the viscosity.	This law for laminar flows shows the R^4-dependency of the rate of volume flow. That means that it is much more effective to increase the radius *R* of a tube rather than to increase the pressure difference $(p_1\text{-}p_2)$ between the two ends of a tube. Multiplying the radius with a factor of 2, leads to a volume flow (indicated by the dot above the *V*) 16 times larger than before!
Incompressible fluid	A fluid with constant *density*.	Changes of pressure travel in an incompressible fluid without delay. The propagation speed is infinitely large compared to all other motions in the fluid.
Instationary (or unsteady) X	X arbitrary quantity (pressure, density etc.) $X(t)$	Depending on time; quantity may change value in the course of time.
Kármán vortex street (named after Theodore von Kármán, a notable scientist)		
Kinematics of a 3D wing		• *Flapping* $\vartheta(t)$ is the up and down motion of a wing, equivalent to the plunging motion $h(t)$ in 2D. • *Feathering* $\alpha(t)$ is the torsional motion equivalent to pitching motion in 2D kinematics. • *Lagging* $\varphi(t)$ is an in-plane motion back and forth in the direction of the trajectory. In a 2D section this motion is named sliding motion $s(t)$. All motions may be assumed to be rigid or flexible. In the latter case the functions also depend on span *y*. We adopted the notation for 3D kinematics from A.R.S. Bramwell, *Helicopter Dynamics*.
Lagging motion	$\varphi(t) = \varphi_S + \varphi_i(t)$	Also named in-plane motion of a wing. Motion back and forth in trajectory direction. Flying animals pull back the wing during upstroke, and push it forward during down-stroke.
Laminar flow	Characterises a flow without disorder.	A flow which is built up by layers streaming with different velocities. In a cylindrical stream (pipe), the velocity is biggest in the middle of the stream, decreasing to the walls (because of friction).
Lift F_L	[N]	Component of the fluid force acting on the moving body (aircraft, wing, profile) which is by definition **normal** to the body's trajectory.
Lift coefficient c_L	[-], $c_L = \frac{F_L}{1/2 \cdot \rho \cdot u_0^2 \cdot A}$ $c_L = 2 \cdot \pi \cdot \alpha$ for the 2D flate plate. The angle is given in rad	The lift force made dimensionless. The force is divided by the stagnation pressure and the planform area. For the two-dimensional flat plat, c_L is approximately determined by the sine of the angle that a wing chord encloses with its trajectory multiplied by $2 \cdot \pi$ (as a result from a theoretical description). For small angles, the slope is $dc_L / d\alpha = 2 \cdot \pi$
Lift-drag-ratio ε	[-], $\varepsilon = \frac{F_L}{F_D}$	Typical values: modern aeroplane $\varepsilon \cong 16$ - 20, small birds $\varepsilon \cong 8$ – 15. Sailplanes from 30 – 50. Also named the "L over D" ratio or lift-to-drag" ratio. Caution: There is some confusion on using ε also for its inverse value, the glide ratio (only German-speaking area). Keeping just the notation (L/D) instead of ε is widespread in American textbooks.

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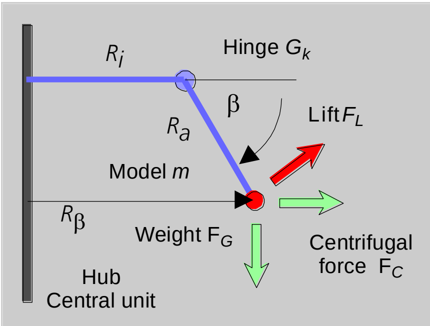
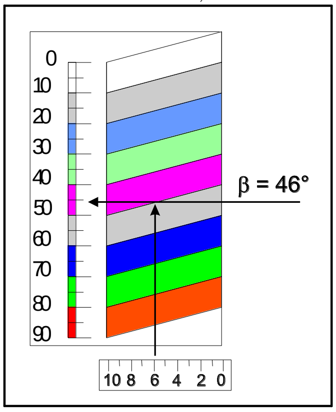
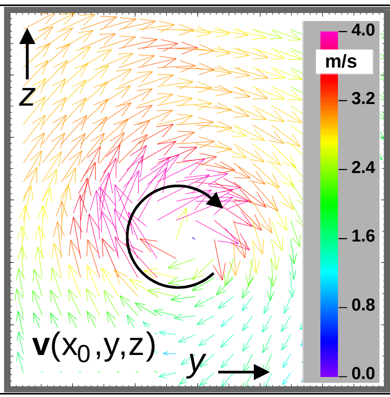
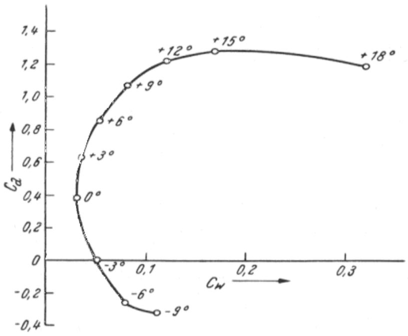
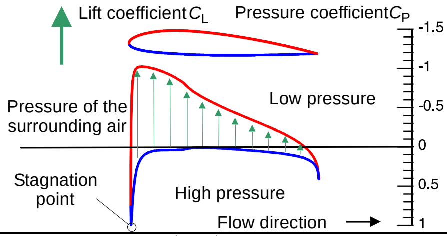
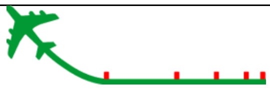
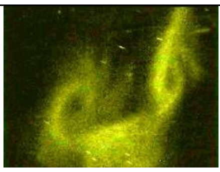
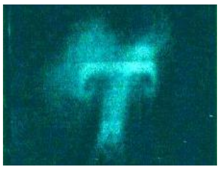
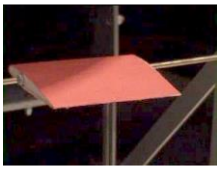
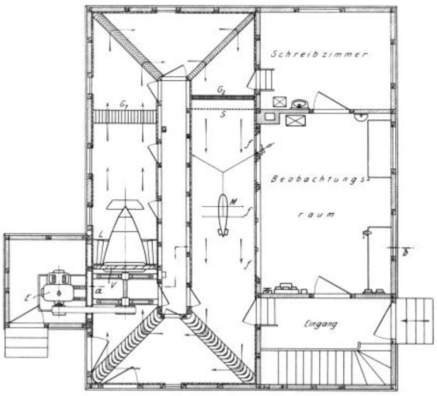
Lift F_L , measure-ment using the test stand RL3	$F_L = \cos\beta \cdot m \cdot \left[g - \omega^2 \cdot R_\beta \cdot \tan\beta\right]$ $R_\beta = R_i + R_a \cdot \cos\beta$  	Gravity acceleration *g*; circular frequency $\omega = 2\cdot\pi / T$, where *T* is the time for one rotation. The relationship extends the law for a centrifugal motion, which is given inside the square brackets, in the presence of a third force, the lift. The lift induces a disturbance of the centrifugal angle β compared to the no-lift condition, which is measured: 
Mach number *Ma*	$Ma = u_0 / c_s$	The Mach number is an important figure to describe flow. It is ratio of the velocity u_0 and the velocity of sound, c_s. $c_s(h = 0m) = 340$ m/s; $c_s(h \approx 11\,000$ m$) = 300$ m/s For a modern transport aircraft: $Ma \approx 0.8 - 0.85$
Particle Image Velocimetry (PIV)	 	Method to visualise a velocity field, e.g. the flow around or behind a wing. A flow containing small particles (diameter *d* in the order of 10^{-6} m) streams around an obstacle. Two subsequent pictures of this flow are taken while illuminating the stream with two laser flashes. A computer programme tries to identify the particles in the first picture also in the second picture (i.e. finding the trace). The figure shows he velocity field around a vortex pointing perpendicular into the paper sheet.
Phase shift κ		The difference in phase between the flapping and feathering. Following Lilienthal's observations: $\kappa = 90°$. The flight of a bird is especially effective, when flapping is 90° in front of feathering.
Planform area *A*	$[A] = m^2$, $A = l \cdot b$	The area of the projection of the wing perpendicular to the flow.
Polar line	 	Lift and drag, respectively their coefficients, may be thought as functions depending on the angle of incidence α: $c_L(\alpha),\ c_D(\alpha)$ In the left graph the angle of incidence acts as parameter, which orders the values in a X-Y curve (parametric representation, no function!).
Power	$[P]$ = N m/s = W	Defined as force times velocity. In other words: Energy (work) per time unit.
Power coefficient $c_{\Pi,D}$	$[-]$, $c_{\Pi,D} = \dfrac{P_D}{1/2 \cdot \rho \cdot u_0^3 \cdot A} = c_D$	Power P_D made dimensionless with the term $q_0 \cdot A \cdot u_0$.

Term	Dimension, formula, graph	Supplementary explanations
Power of drag P_D	$P_D = F_D \cdot u_0 = c_D \cdot ½ \cdot \rho \cdot u_0^3 \cdot A$	When moving against a drag F_D with a certain velocity u_0, the power P_D is needed.
Pressure coefficient c_P	$p - p_\infty = \frac{1}{2}\rho \cdot u_0^2 - \frac{1}{2}\rho \cdot u^2$ leads to $c_p(\mathbf{x}) = (p(\mathbf{x}) - p_\infty) / \left(\frac{1}{2}\rho \cdot u_0^2\right) = 1 - \left(\frac{\mathbf{u(x)}}{u_0}\right)^2$ 	The coefficient is derived from the Bernoulli equation. $\mathbf{x}=(x,y,z)$ is the co-ordinate vector of an arbitrary point x in the flow field $\mathbf{u}(\mathbf{x})$ relative to a moving body. If the relative flow velocity is zero, the pressure coefficient is 1. That is the highest value of c_p. The graph shows a typical pressure distribution on the surface of a profile.
Reduced frequency ω^*	$[-],\ \omega^* = \frac{\omega \cdot (l/2)}{u_0}$	The reduced frequency is a dimensionless degree for how often the wing flaps in relation to the path velocity. The smaller ω^*, the longer the way reached with one flap. Typical values in nature for ω^* are between 0.05 and 0.5
Reynolds number *Re*	$\mathrm{Re} = \frac{u_0 \cdot \rho \cdot l}{\eta}$	Dimensionless number used to characterise flows. η: viscosity [Pa s], ρ: density [kg / m³], u_0: velocity, l: length of a body. Typical range of Reynolds numbers: 10^4 to 10^5. For modern transport aircraft up to 10^7
Span *b*	$[b] = \mathrm{m}$	Lateral extension of a wing perpendicular to the onset flow.
Stagnation pressure q_0	$[q_0] = \mathrm{N/m^2} = \mathrm{Pa}$ $q_0 = \frac{W_{kin}}{\Delta V} = \frac{1}{2} \cdot \rho \cdot u_0^2$ sometimes also named “dynamic pressure”	q_0 is the kinetic energy W_{kin} of a mass element (particle) with mass $m = \rho \cdot V$ per volume element ΔV. **Caution:** There is some confusion about the proper name for q_0. Some definitions for the stagnation pressure also include the static pressure p_∞ (read: “p infinity”) in the fluid, which is measured in a fluid domain, where the fluid is totally at rest.
Stationary		Not depending on time, constant in the course of time. Flow: in a stationary flow, the forces on the body do not change as time goes by.
Tacoma Narrows Bridge		A bridge in the USA with 1.5 km span which broke down Nov. 7th 1940 as a consequence of periodic forces caused by strong winds and the periodic separation of vortices.
Take off	 $\mathbf{T} = \frac{\mathbf{M} \times \mathbf{v}_{LOF}^2}{\mathbf{2\ s}_{LOF}}$ T: thrust, s: length of the runway, v: velocity at take off, M: mass of the aeroplane, a: acceleration. From $\mathbf{s}_{LOF} = \frac{1}{2}\mathbf{a} \times \mathbf{t}_{LOF}^2,\ \mathbf{v}_{LOF} = \mathbf{a} \times \mathbf{t}_{LOF}$	The start of an aeroplane. Taking off (Index LOF means “Lift Off”) requires the maximum thrust available. It’s the thrust which characterises the performance of an engine. This is different from cars, where the engine is described by its power. Newton’s law *Force = mass x acceleration* governs the take off. The formula applies this law to obtain a rough estimate of the required thrust. For example: Each of the four engines (type CFM 56) of an Airbus A340 produces a thrust of about 140 kN.
Translation	$g(t) = u_0 \cdot t$	Moving forward.
Turbulence	Disorder of an initially layered flow field.	When a certain value of the **Reynolds number** is reached, the stream changes from being laminar to turbulent (Reynolds’ famous experiment). This can be achieved by increasing the velocity. The streamlines end to show the layered structure.
Velocity u_R	$u_R = \frac{2 \cdot \pi \cdot R_\beta}{T} \cong u_0$	Velocity of the model's centre of gravity used for the test stand RL3 to approximate the uniform motion.
Velocity v	[m/s]	In general, the velocity $\mathbf{v}(\mathbf{x},t)$ is the mathematical term to describe the three-dimensional motion of a fluid at any location $\mathbf{x}$ in space and at any time t. Velocity $\mathbf{v}$ is named a **vector field**. The vector $\mathbf{v}$ possesses a magnitude $\lvert\mathbf{v}\rvert$, measured in m/s, and a unit vector $\mathbf{v}/\lvert\mathbf{v}\rvert$, which indicates the local direction of the flow.

Term	Dimension, formula, graph	Supplementary explanations
Viscosity η	[Pa s] 1 Pa = 1 N/m² ------- $[\Delta F] = N$ $[\sigma] = [\Delta F / \Delta A] = N/m^2 = Pa$ $[\Delta u / \Delta z] = 1/s$ $\eta = \sigma / (\Delta u / \Delta z)$	Consider a thin fluid layer of thickness Δz poured on a fixed plane. On top of the fluid rests a probe surface of area ΔA . The probe is now moved with the velocity Δu relative to the plane, for which the force ΔF is required: $\Delta F = \eta \cdot \Delta A \cdot \Delta u / \Delta z.$ The constant η in this equation is named **viscosity**. The tangential force per square unit is called **shear stress**: $\sigma = \Delta F / \Delta A = \eta \cdot \Delta u / \Delta z$
Vortex		When a fluid passes an edge, differences in pressure cause the fluid particles to flow into the region of the lower pressure, which causes a complicated twisting of their streamlines. The picture is taken by W. Send in his private water tunnel. It shows the genesis of the so-called tip vortex behind a lifting surface.
Vortices, tip ~	  Positive lift Negative lift	 The flow around the both tips of a three-dimensional wing forms a pair of counter-rotating vortices. The orientation depends on the direction of the lift force. The picture above shows the view direction.
Vorticity j	[1/s]	Vorticity **j**(**x**,t) is a property of the flow field like the velocity field **v** itself (see **velocity**). It indicates the regions in a flow field where – due to the **viscosity** - momentum is transferred to neighbouring particles (the process of *diffusion*). These regions also have the potential to convert kinetic energy into thermal energy. This process is named *dissipation* and mostly neglected.
Weight F_G	[N], $F_G = m \cdot g$	Mass m, gravity acceleration g.
Wind tunnel, closed air flow		The first wind tunnel with a closed air flow, designed by Ludwig Prandtl in Göttingen in 1907. Thereafter named world wide as Göttingen-type wind tunnel. The air flow is indicated by arrows.

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Last revision: October 2013. The misprint of “Poiseuille” remained undiscovered for a long time.