

AEROLAB - Method Paper

A digital wind tunnel based on the lattice Boltzmann method, with parameter study, component optimisation and STL output

Version 4.0, 20 October 2026 (English translation of the German original 01_Methodenpapier_AEROLAB.md; the German text prevails) Author: Thomas Schüller, Schicht-Werk, Tulln an der Donau, Austria Status: working result of the business, all rights reserved (see verwertung.md)

Summary

AEROLAB computes the planar (two-dimensional) flow around a body in a virtual wind tunnel, returns drag and lift coefficients, displays velocity, vorticity and pressure, runs parameter series (polars) automatically and searches the best shape with an optimisation method. The result can be exported as a print-ready prism body (STL). The tool runs entirely in the browser, without a server and without data transfer. This paper describes the computational model, boundary conditions, force evaluation, optimisation and self-checks. Validity limits are given in Section 10 and in the validation report (04_Validation_Report_AEROLAB_EN.md).

1 Purpose and scope

Printed parts in an air stream (fan covers, fairings, housings, guide vanes, profiles for models and test bodies) are often shaped by feel. AEROLAB is meant to improve the pre-selection: which of several shapes opposes the flow less, which angle of attack gives the best lift-to-drag ratio, what a leading-edge radius does. The tool provides **comparison values**. It replaces neither a measurement on a prototype nor a three-dimensional computation.

2 Computational model

The lattice Boltzmann method on the D2Q9 lattice (nine velocity directions) with the single-relaxation operator of Bhatnagar, Gross and Krook (BGK) is used. For each cell and direction i the distribution f_i is advanced in two steps:

1. Collision: $f_i^* = f_i + (1/\tau) \cdot (f_i^{\text{eq}} - f_i)$
2. Streaming: $f_i(x + e_i, t + 1) = f_i^*(x, t)$

The local equilibrium is $f_i^{\text{eq}} = w_i \cdot \rho \cdot (1 + 3 e_i \cdot u + 4.5 (e_i \cdot u)^2 - 1.5 u^2)$ with the usual weights $w = 4/9, 1/9, 1/36$. Density and velocity follow from the moments of f_i . The kinematic viscosity is $\nu = (\tau - 0.5)/3$ in lattice units. The method is weakly compressible; the free-stream velocity is set to $U = 0.06$ in lattice units (lattice Mach number about 0.10) to keep the compressibility error small (reason: validation report, Section 3).

The Reynolds number $Re = U \cdot L / \nu$ is set through the resolution: for a given reference length L (cells across chord or diameter) and given Re , ν and hence τ follow. If τ is close to 0.5 the computation becomes unstable; the interface warns below $\tau < 0.502$ and recommends turbulence damping below $\tau < 0.515$.

3 Wind tunnel boundaries

- **Inlet:** equilibrium distribution at free-stream velocity; the density is taken from the neighbouring column to reduce reflections. The velocity is ramped over about 0.6 chord times so that the start-up shock decays.
- **Outlet:** zero gradient (distribution copied from the neighbouring column) with an absorbing sponge layer.
- **Upper and lower wall:** either slip wall (specular reflection, no wall friction; idealised wind tunnel wall) or periodic (a row of identical bodies spaced by the channel height).
- **Body:** no-slip wall with interpolation (Section 4).

The domain size is chosen automatically: slender bodies (projected height below 0.25 reference lengths) get a domain of 9×4.5 reference lengths; compact bodies get 14 reference lengths in flow direction and a height limiting blockage to about 10 % (at most 16 reference lengths).

4 Body boundary and force evaluation

The body is given as a polygon and rasterised on the grid (cell centre inside the polygon: solid). For every link between a fluid and a solid cell the distance q (fraction of the link length) to the polygon edge is determined. The no-slip condition follows **Bouzidi, Firdaouss and Lallemand (2001)** with linear interpolation; for $q = \frac{1}{2}$ it equals simple bounce-back. The wall position therefore stays more accurate on inclined and curved surfaces than with a staircase approximation.

The force on the body follows from **momentum exchange** (Ladd 1994) over all boundary links: $F = \sum e_i \cdot (f_i^* + f_i^{\text{new}})$. The coefficients are

$$C_d = F_x / (\frac{1}{2} \cdot \rho \cdot U^2 \cdot L), C_l = F_y / (\frac{1}{2} \cdot \rho \cdot U^2 \cdot L)$$

with the **reference length L** (chord, length or diameter of the body, not frontal height). Coefficients refer to unit span. For comparisons between bodies of different height, drag at equal length is meant.

5 Turbulence damping

Optionally a Smagorinsky lattice eddy-viscosity model (Hou et al. 1996) is switched on: an effective relaxation time is computed per cell from the non-equilibrium stress tensor. The option stabilises higher Re on coarse grids but changes the flow picture (additional damping). It is switched on automatically when τ falls below 0.515. Two-dimensional computations cannot represent real turbulence anyway; the approach serves stability, not turbulence modelling.

6 Evaluation

- **Averaging:** forces are recorded every 10 time steps, averaged over 10 steps. The result is the mean over the last quarter to third of the record.
- **Convergence check:** after a minimum run time (12 to 14 chord times) it is checked at intervals of four chord times whether the means of C_d (0.4 %) and C_l (1 %) still change appreciably. A run then counts as converged; otherwise it ends at the budget (at most 40 chord times) and is flagged as not reliably converged.
- **Unsteady:** a run is unsteady if the lift fluctuation exceeds 0.02 and 3 % of the mean. The Strouhal number $St = f \cdot L / U$ is determined from the zero crossings of the lift fluctuation.
- **Angle of attack:** the body is rotated about the quarter-chord point; a positive angle raises the leading edge (positive lift upward). To trigger vortex shedding the body is offset by 0.31 cells from the channel centre, because an exactly symmetric arrangement never triggers the instability numerically.

7 Shapes

All shapes are polygons in chord coordinates (leading edge at 0, trailing edge at 1):

- **Cylinder / ellipse:** ellipse with thickness ratio t .
- **NACA 4-digit:** camber m , camber position p , thickness ratio t , closed trailing edge (Abbott and von Doenhoff 1959).
- **Plate:** rectangle with thickness ratio d .
- **Box with radius:** height h , relative corner radius r .
- **Streamlined body with tapered tail:** elliptical nose (length n), straight middle part, linearly tapered tail (length s , residual height k).

8 Optimisation

The shape search uses the simplex method of Nelder and Mead (1965) over the chosen parameters, normalised to $[0, 1]$. Each function evaluation is a complete flow computation. The objective is selectable (minimise drag, maximise glide ratio, maximise lift, maximise downforce). Violations of parameter bounds and falling below the **minimum part thickness** (printability, strength) enter the objective through penalty terms. The method is derivative-free and finds local improvements, not guaranteed global optima; with noisy coefficients (vortex shedding, coarse resolution) the search may stagnate. The working rule is therefore: **search at coarse resolution, recompute the best and the initial design at fine resolution** (“Fein nachprüfen” button) and report only the verification result.

9 STL output

The polygon is scaled to the desired chord length (mm) and extruded over the span (mm) to a prism body. The cap faces are triangulated by ear clipping. An **edge check** ensures that every triangle edge occurs exactly once in each direction (closed shell); if it fails, the output is reported as defective. Optionally a raised signature ("SW", raster lettering, 0.4 mm high) is placed on the front face if the profile is thick enough; the signature can be switched off. Volume and estimated mass follow from area, span, material density and infill.

10 Validity and limits

1. **Two-dimensional:** real flows around a cylinder are three-dimensional above about Re 190; the 2D vortex street above that is qualitative.
2. **Re range:** reliably comparable for laminar flow up to about Re 200 (compact bodies) or about Re 1000 (slender profiles). Typical applications of printed parts (Re 10^4 to 10^6) lie **outside** the quantitatively valid range; there AEROLAB gives only rough trends of the effect of shape, no coefficients.
3. **Profiles:** absolute profile coefficients have not been checked against an independent reference (validation report).
4. **Wall blockage:** with slip walls and 10 % blockage the cylinder C_d is one sixth to one fifth above the free-stream value (see validation report). Blockage is displayed; never compare coefficients without it.
5. **Resolution:** below 4 cells of body thickness drag is overestimated (warning in the interface).
6. **Not included:** surface roughness, layer lines of 3D printing, end plates, span effects, deformation, separation at high Re, compressibility. The lattice velocity is $U = 0.06$ (lattice Mach number about 0.10); at $U = 0.08$ an artificial, compressibility-driven lift oscillation appeared on profiles (validation report, Section 3).
7. **Not suitable** for approval, safety verification, load-bearing parts or applications with risk to persons.

11 Self-checks in the package

05_BUILD/validate_physics.js computes reference cases (cylinder, plate, profiles) headless; 05_BUILD/ui_test.js operates the interface in a DOM stub (tabs, study, optimisation, STL); 05_BUILD/pruefen.js checks package rules. Results are in 04_META.

12 Conflict of interest and use of AI

The author runs a 3D-printing and additive-manufacturing business (Schicht-Werk) and has a commercial interest in printed parts. The tool was designed and programmed with an AI assistant (Claude, Anthropic); computational core, tests and texts were commissioned and approved by the author. The tool is not provided for armaments, military, weapons or military-usable aviation.

References

Note: the references were compiled from domain knowledge without online research, because automatic research was not commissioned. Before publication, titles, years, volumes and pages must be checked against the originals.

The reference list is identical to the German original (01_Methodenpapier_AEROLAB.md, section "Literatur"):

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Disclosure: commercial interest in printed parts; developed with the help of an AI assistant. Schicht-Werk acts as a contract manufacturer to customer specifications. Contact: office@schicht-werk.eu · www.schicht-werk.eu. Not provided for armaments, military, weapons or military-usable aviation.