Vehicle Aerodynamics

Lecture 1: Introduction

G. Dimitriadis
Textbooks

• Race car aerodynamics – Designing for speed, J. Katz, Bentley Publishers, Cambridge, MA
• Most of the course is based on these books.
Introduction

• In aircraft, aerodynamic forces are of crucial importance because they keep the aircraft in the air.

• In road vehicles aerodynamic forces play a less crucial role but are still of interest.

• Four main considerations:
  – Flow field in detail
  – Aerodynamic forces moments: performance, stability
  – Engine cooling
  – Heating, ventilation, noise
Aerodynamic objectives

Performance, Stability

Flow Field in Detail

Engine Cooling

Heating, Ventilating
Performance, stability

• The most important objective of modern car aerodynamics is the improvement of fuel efficiency.
• The fuel efficiency is increased by decreasing the aerodynamic drag acting on the car, especially at high speeds.
• Additional considerations concern turning performance and stability under crosswind.
• Turning performance is usually increased by creating aerodynamic downforce.
• Notice that some of these objectives are mutually exclusive: more downforce = more drag.
Flow field in detail

• Estimation of the detailed flowfield around a car help to determine where and how to obtain aerodynamic improvements.

• They help determine:
  – Areas of separated flow: these cause increased drag and noise.
  – Flow into the engine intake.
  – Aerodynamic interference between different parts of the car.
Engine cooling

- Engine cooling is of paramount importance for engine performance and lifetime.
- Most cars use external air to cool at least some parts of the engine assembly (e.g. radiator)
- Badly designed air intakes can cause engine overheating, bad cooling performance etc.
Heating, ventilating

• Heating and ventilation of the cabin appear to be secondary considerations but, in fact, they can be of paramount importance.

• Luxury car sales depend very heavily on driver and passenger comfort.

• Very few people will buy a 100,000 EUR car with bad air conditioning.
Modeling or experiment?

• Modeling:
  – Use laws of physics to derive the equations of motion of the air around or inside the car
  – Solve these equations in time and space to calculate the aerodynamic forces and pressures (as functions of time and space)

• Experiment:
  – Test car on the road or test car in a wind tunnel or test scale model of car in a wind tunnel
  – Measure aerodynamic forces and pressures (as functions of space and time)
Aerodynamic modeling

• The laws of physics are the usual three conservation laws:
  – Conservation of mass
  – Conservation of momentum
  – Conservation of energy

• When applied to the fluid flow problem, they give rise to the Navier-Stokes equations.
Navier Stokes for Aerodynamicists

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z}
\]

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho vv)}{\partial z} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}
\]

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}
\]

\[
\frac{\partial (\rho E)}{\partial t} + \frac{\partial (\rho uE)}{\partial x} + \frac{\partial (\rho vE)}{\partial y} + \frac{\partial (\rho wE)}{\partial z} = \frac{\partial (\rho q)}{\partial t} + \frac{\partial (\rho uq)}{\partial x} + \frac{\partial (\rho vq)}{\partial y} + \frac{\partial (\rho wq)}{\partial z}
\]

\[
+ \left[ \frac{\partial}{\partial x} \left( u\tau_{xx} + v\tau_{xy} + w\tau_{xz} \right) + \frac{\partial}{\partial y} \left( u\tau_{xy} + v\tau_{yy} + w\tau_{yz} \right) + \frac{\partial}{\partial z} \left( u\tau_{xz} + v\tau_{yz} + w\tau_{zz} \right) \right]
\]
Nomenclature

• The lengths \( x, y, z \) are used to define position with respect to a global frame of reference, while time is defined by \( t \).

• \( u, v, w \) are the local airspeeds. They are functions of position and time.

• \( p, q, \mu \) are the pressure, density and viscosity of the fluid and they are functions of position and time.

• \( E \) is the total energy in the flow.

• \( q \) is the external heat flux.
The stress tensor

- Consider a small fluid element.
- In a general flow, each face of the element experiences normal stresses and shear stresses.
- The three normal and six shear stress components make up the stress tensor.
More nomenclature

- The components of the stress tensor:

\[
\begin{align*}
\tau_{xx} &= -p + 2\mu \frac{\partial u}{\partial x}, \\
\tau_{yy} &= -p + 2\mu \frac{\partial v}{\partial y}, \\
\tau_{zz} &= -p + 2\mu \frac{\partial w}{\partial z}, \\
\tau_{xy} &= \tau_{yx} = \mu \left( \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right), \\
\tau_{yz} &= \tau_{zy} = \mu \left( \frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right), \\
\tau_{zx} &= \tau_{xz} = \mu \left( \frac{\partial w}{\partial z} + \frac{\partial u}{\partial x} \right)
\end{align*}
\]

- The total energy \( E \) is given by:

\[
E = e + \frac{1}{2} (u^2 + v^2 + w^2)
\]

- where \( e \) is the internal energy of the flow and depends on the temperature and volume.
Gas properties

- Do not forget that gases are also governed by the state equation:

\[ p = \rho RT \]

- Where \( T \) is the temperature and \( R \) is Blotzmann’s constant.

- For a calorically perfect gas: \( e = c_v T \), where \( c_v \) is the specific heat at constant volume.
Comments on Navier-Stokes equations

• Notice that aerodynamicists always include the mass and energy equations in the Navier-Stokes equations.
• Notice also that compressibility is always allowed for, unless specifically ignored.
• This is the most complete form of the airflow equations, although turbulence has not been explicitly defined.
• Explicit definition of turbulence further complicates the equations by introducing new unknowns, the Reynolds stresses.
Constant viscosity

• Under the assumption that the fluid has constant viscosity, the momentum equations can be written as

\[
\begin{align*}
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} &= -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \\
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} &= -\frac{\partial p}{\partial y} + \mu \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \\
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} &= -\frac{\partial p}{\partial z} + \mu \left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)
\end{align*}
\]
Compressibility

• Air is a compressible gas (i.e. its density is variable) but only at very high airspeeds.
• Very few cars move at compressible airspeeds:

  Thrust SSC: broke the speed of sound in 1997
• Under the assumption that the fluid has constant density, the momentum equations can be written as

\[
\begin{align*}
\rho \frac{\partial (u)}{\partial t} + \rho \frac{\partial (u^2)}{\partial x} + \rho \frac{\partial (uv)}{\partial y} + \rho \frac{\partial (uw)}{\partial z} &= - \frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \\
\rho \frac{\partial (v)}{\partial t} + \rho \frac{\partial (uv)}{\partial x} + \rho \frac{\partial (v^2)}{\partial y} + \rho \frac{\partial (vw)}{\partial z} &= - \frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) \\
\rho \frac{\partial (w)}{\partial t} + \rho \frac{\partial (uw)}{\partial x} + \rho \frac{\partial (vw)}{\partial y} + \rho \frac{\partial (w^2)}{\partial z} &= - \frac{\partial p}{\partial z} + \mu \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\end{align*}
\]
There are several compact expressions for the Navier-Stokes equations:

**Tensor notation:**
\[
\rho \frac{Du_i}{Dt} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_i^2}
\]

**Vector notation:**
\[
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \frac{1}{2} \nabla \mathbf{u} \cdot \mathbf{u} + (\nabla \times \mathbf{u}) \times \mathbf{u} \right) = -\nabla p + \mu \nabla^2 \mathbf{u}
\]

**Matrix notation:**
\[
\rho \left( \frac{\partial \mathbf{u}}{\partial t} + \nabla^T \mathbf{u} \mathbf{u}^T \right) = -\nabla p + \mu \nabla^2 \mathbf{u}
\]
Non-dimensional form

• The momentum equations can also be written in non-dimensional form as

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho u^2)}{\partial x} + \frac{\partial (\rho uv)}{\partial y} + \frac{\partial (\rho uw)}{\partial z} = - \frac{\partial p}{\partial x} + \frac{1}{Re} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right)
\]

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho uv)}{\partial x} + \frac{\partial (\rho v^2)}{\partial y} + \frac{\partial (\rho vw)}{\partial z} = - \frac{\partial p}{\partial y} + \frac{1}{Re} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right)
\]

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho w^2)}{\partial z} = - \frac{\partial p}{\partial z} + \frac{1}{Re} \left( \frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2} \right)
\]

• where

\[
\rho = \frac{\rho}{\rho_\infty}, \quad u = \frac{u}{U_\infty}, \quad v = \frac{v}{U_\infty}, \quad w = \frac{w}{U_\infty}, \quad x = \frac{x}{L}, \quad y = \frac{y}{L}, \quad z = \frac{z}{L}, \quad t = \frac{tL}{U}, \quad p = \frac{p}{\rho_\infty U_\infty^2}, \quad Re = \frac{\rho_\infty U_\infty L}{\mu}
\]
Solvability of the Navier-Stokes equations

• There exist no solutions of the complete Navier-Stokes equations

• The equations are:
  – Unsteady
  – Nonlinear
  – Viscous
  – Compressible

• The major problem is the nonlinearity
Millennium Prize

• The Millennium Prize by the Clay Mathematical Institute (Cambridge, Massachusetts) promises $1,000,000 to the first person to prove the existence and smoothness of solutions of the Navier-Stokes equations.

• Notice that the prize is not awarded for finding a solution; merely for proving that a smooth solution exists in 3D.
Flow unsteadiness

- Flow unsteadiness in the real world arises from two possible phenomena:
  - The solid body accelerates
  - There are areas of separated flows
- The flow over most bodies (including car bodies) is separated at least locally.
- Therefore, flow unsteadiness is important for most vehicle aerodynamic applications.
- The only exceptions are flow of car wings and flow over fully streamlined car bodies
Unsteadiness Examples

Flow past a circular cylinder visualized in a water tunnel. The airspeed is accelerating. The flow is always separated and unsteady. It becomes steadier at high airspeeds.

Flow past an airfoil visualized in a water tunnel. The angle of attack is increasing. The flow attached and steady at low angles of attack and vice versa.
Fully streamlined car bodies

Honda solar powered car

Shell Eco-Marathon 2007

Such car designs are generally chosen when engine power is very low (solar or human) and drag must be an absolute minimum.
Viscosity

- Viscosity is a property of fluids
- All fluids are viscous to different degrees
- However, for attached flows, viscous terms are only important in a very thin layer of fluid very close to the surface.
- Everywhere else the fluid can be assumed to be inviscid.
Cases where viscosity is important

Shock wave

Boundary layer

Wake

Experimental Aerodynamics
Inviscid flow

• For inviscid flow, all the viscous terms are neglected from the equations of motion, leading to the Euler equations

\[
\begin{align*}
\rho \frac{\partial u}{\partial t} + \rho \frac{\partial (u^2)}{\partial x} + \rho \frac{\partial (uv)}{\partial y} + \rho \frac{\partial (uw)}{\partial z} &= -\frac{\partial p}{\partial x} \\
\rho \frac{\partial v}{\partial t} + \rho \frac{\partial (uv)}{\partial x} + \rho \frac{\partial (v^2)}{\partial y} + \rho \frac{\partial (vw)}{\partial z} &= -\frac{\partial p}{\partial y} \\
\rho \frac{\partial w}{\partial t} + \rho \frac{\partial (uw)}{\partial x} + \rho \frac{\partial (vw)}{\partial y} + \rho \frac{\partial (w^2)}{\partial z} &= -\frac{\partial p}{\partial z}
\end{align*}
\]
Euler/Laplace equations

- The Euler equations are great because they can be solved numerically with relative ease.
- They can be further simplified if the flow is assumed to be steady and irrotational, to yield Laplace’s equation.
- Laplace’s equation has analytical solutions!
Car Aerodynamic Modeling

- Aerodynamic modeling is much more relevant to aircraft than cars.
- Aircraft are designed to be streamlined: the airflow around them is always attached to the surface.
- Under attached flow conditions, it is possible to carry out simple and useful aerodynamic modeling.
- Car shapes are such that the flow is not attached over the whole surface. There are significant areas of separated flow.
- Under separated flow conditions, aerodynamic modeling is quite challenging and the results are not always trustworthy.
Computational Fluid Dynamics

• There are several modeling strategies that can be used for cars.
• They all involve discretizing the space around the car using a grid that is very fine near the surface and coarser away from the surface.
• The Euler or Navier Stokes equations are solved numerically on this grid, using either finite difference or finite volume techniques
Some strategies

- Direct Numerical Simulation: The complete Navier Stokes equations are solved. These require unrealistically fine grid sizes near the surface.
- Reynolds Averaged Navier Stokes (RANS) equations: The Navier-Stokes equations are solved in a form that requires less fine grids near the surface. They are combined with a turbulence model.
- Large Eddy Simulation (LES): A low pass filtered version of the Navier-Stokes equations is solved, which eliminates the smaller turbulent length scales (and hence the need for very fine grids).
- Hybrid schemes: Combinations of RANS and LES are solved. RANS is used near the surface and LES in the wake.
The grid is finer near the surface and in the wake.
Computed flow examples

External flow simulation

Internal flow simulation
Hybrid vs RANS

RANS

Hybrid
Some remarks on modeling

- Such CFD solutions are very computationally expensive. They can take weeks to calculate on supercomputers.
- Furthermore, they are not universally trustworthy. The results depend on the choice of strategy, grid, turbulence model, time step and many other parameters.
- Only comparison with experiment can validate results obtained from such calculations.
Wind tunnel testing

• The flow field around road vehicles is very complex:
  – Large regions of flow separation
  – Ground effect
• Simulation is less adapted to road vehicles than to aircraft
• Wind tunnel tests are more suitable
Wind tunnels

• The types of wind tunnel that can be used in road vehicle tests are the same as for aircraft tests.
• However, full-scale tests are much more popular (and feasible) for cars than for aircraft.
• For full-scale tests, the size of the wind tunnel is of crucial importance:
  – If it is too small the blockage effects will be enormous
  – If it is large, it will be very expensive to build and run
Apart from the closed section, all the working sections attempt to limit the blockage effects.
Types of working section (2)

- Open: allows the streamline above the car to curve naturally
- Slotted walls: allows the streamlines around the car to expand to a certain extent
- Streamlined walls: the walls follow the natural curves of the streamlines
- Adaptive walls: same as streamlined walls but can be used for any geometry/wind condition
Streamline matching

It is possible to match the cross-section of the working section to the isobars around the car.
Adaptive walls

In practice, streamline matching is carried out using an adaptive wall mechanism.
Road representation

• In reality a car moves on a static road inside static air and its wheels roll.
• In a wind tunnel the car and floor are static and the air moves. The wheels may or may not roll.
• This is representative of the air-car relative motion but not of the air-floor relative motion.
• In order to represent the latter, the floor must move with the free stream airspeed.
Possibilities for road simulation
Explanations

a. No road simulation
b. Car and mirror image in the middle of the working section
c. Rolling floor and boundary layer suction
d. Boundary layer suction
e. Lifting the car and floor outside the boundary layer
f. Lifting only the car outside the boundary layer
g. Sucking air through the floor
h. Injecting air in the boundary layer to straighten it
i. Multi-point air injection
j. Blocking the boundary layer
Choice of floor simulation

• The choice of the solution depends on the size of the wind tunnel, its configuration and the available budget.

• A moving floor is ideal but very expensive:
  – it must be perfectly synchronized with the free stream
  – it must not be sucked up into the working section because of the pressure difference

• Solutions without a moving floor are cheaper but they cannot force the wheels to turn – motors must be attached to the wheels.
In fact, only the floor directly under the car needs to move. This leads to the ‘narrow belt’ concept. It requires mini-belts for turning the wheels.
All the wheels must touch the floor. Significant measurement errors can result from a gap between the floor and the wheel.
Wheel rotation can have a significant effect on the measured aerodynamic loads.

In this example, a rotating wheel produces downforce, while a static wheel produces lift for non-zero ground clearance.
Wheel rotation and clearance

Example of the combined effect of wheel rotation and clearance. The baseline is $\Delta h=0$ and rotation. A negative $\Delta h$ can cause a decrease in drag in the rolling case.
Mercedes Benz example
Wind tunnel measurements

- Wind tunnel measurements for cars are similar to those already mentioned for wings:
  - Flow visualization
  - Aerodynamic loads
  - Pressure measurements
  - Temperature measurements
  - Acoustic measurements
Flow visualization is usually carried out using thick smoke streaks. In general, they smoke comes out of a tube that is directed by a human operator inside the wind tunnel.
PIV in cars

- Particle Image Velocimetry is becoming increasingly popular for visualizing details, e.g. internal flow or flow around a side mirror

Internal cabin flow with ventilation turned on: a. panel mode, b. defrost mode
Aerodynamic loads

- Aerodynamic loads are measured using aerodynamic balances.
- There are several types of aerodynamic balance that can be used:
  - Suspension balance
  - Platform balance
  - Multiple-platform balance
  - Internal (sting balance)
  - Pyramidal balance
Balance types

Suspension

Multi-platform

Single platform

Pyramidal
Balance + moving floor

Installing a balance and a moving floor can be tricky. There are two popular solutions:

- **Internal balance**
- **Mini-belts are multi-platform balance**
Other measurements

• Other types of instrumentation used in car wind tunnel tests:
  – Pressure transducers for static and total pressure measurements
  – Hot wires for local flow velocity and direction measurements
  – Temperature probes
  – Microphones for noise measurements
Types of tests

• Aerodynamic load measurements
• Airflow management tests
• Airflow rate through the passenger compartment
• Passenger compartment heating and ventilation
• Engine cooling tests
• Wind noise measurements
Aerodynamic loads

- Aerodynamic load measurement tests are similar to tests carried out on aircraft and wings.
- One difference the degree of unsteadiness of the flow. Around wings at low angles of attack the flow is attached and steady.
- Around cars the flow is always separated and unsteady; measurements have to be taken over a long time and must include all the frequencies of interest.
Airflow management tests

• Airflow can cool things down!
• Such tests can have several objectives. Some examples are:
  – Measurement of flow through the radiator. Usually performed using a hot wire in front of and behind the radiator
  – Measurement of the cooling of the brakes by the airflow. Usually performed using smoke visualisation or break cooling performance measurements.
Cabin ventilation

• Estimation of the efficiency of the vehicle ventilation system.
• These tests usually involve the use of a separate fan blowing air into the cabin while measuring the pressure in the cabin.
• Two tests are performed, one without wind and one with wind.
Cabin heating/air-conditioning

• For such tests, climatic wind tunnels can be used, i.e. wind tunnels that can heat or cool the air.
• Prior to the test the air is set at the desired temperature.
• Then the engine is started and the temperature change with time is recorded at several positions in the cabin.
Engine cooling

- Engine cooling tests only require the correct airflow only around the front part of the vehicle. Smaller/cheaper wind tunnels can be used.
- As the full airflow is not simulated, the drag is smaller than normal.
- The full driving resistance is simulated using a chassis dynamometer (e.g. MOT tests).
Other types of tests

- Wind noise tests: they are usually carried out in aero-acoustic wind tunnels.
- Cross-wind tests: they are carried out in wind tunnels blow at right angles to a moving car.
- Windscreen and windscreen wiper tests: they require water to simulate rain.
- Defrosting/demisting tests
- etc