Incompressible Flows

Dr. Albert Ruprecht

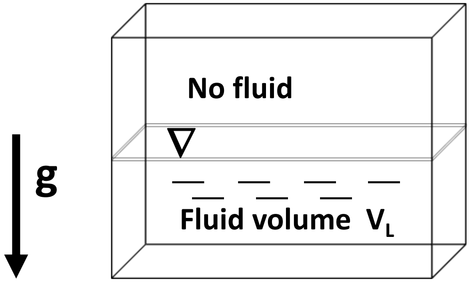
Former: Institute of Fluid Mechanics and Hydraulic Machinery

University of Stuttgart

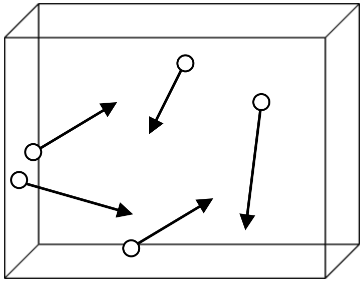
Fluids and gases

Fluid (flowing medium): gas or liquid

Solid body : dedicated volume, dedicated shape
Liquid : dedicated volume, no dedicated shape
Gas (Steam) : no dedicated volume, no dedicated shape



Container with liquid



Container with gas

here:
No flow,
No external forces
besides gravity

Fluids and gases

Container with liquid

$$V_{Fluid} \leq V_{container}$$

$$\rho = \frac{M_{Fluid}}{V_{Fluid}}$$

Constant density

Container with gas

$$V_{Fluid} = V_{container}$$

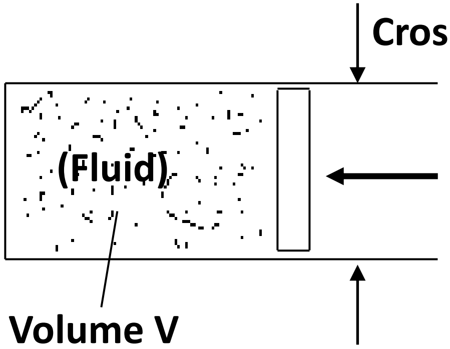
$$\rho = \frac{M_{Fluid}}{V_{container}}$$

variable density

V	m^3	Volume
M	kg	Mass
ρ	$\frac{kg}{m^3}$	*Density*
$\left(v = \frac{1}{\rho}\right.$	$\frac{m^3}{kg}$	specific Volume)

Fluids and gases

Compressibility of a fluid (isotherm)



Force F

$$\mathbf{p} = \frac{\mathbf{F}}{\mathbf{A}} \quad \text{(Pressure)}$$

Volume V

Mass M

Experiment:

Increasing load

$F \rightarrow F + dF\,,\ p \rightarrow p+dp$

$V \rightarrow V + dV \quad (\text{with } dV < 0)$

$\rho \rightarrow \rho + d\rho$

$$\frac{d\rho}{\rho} = \gamma_T \frac{dp}{p} \Leftrightarrow \frac{p}{\rho} = \gamma_T \frac{dp}{d\rho}$$

Isothermal
Compressibility coefficient

Water $\gamma_T = 45{,}4 \cdot 10^{-6}$

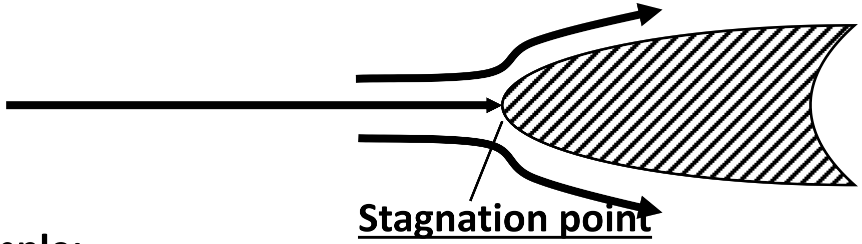
Ideal gas $\gamma_T = 1$

$$\textbf{weil für } T = \text{const} \rightarrow \frac{p}{\rho} = RT = \text{const.} = \frac{dp}{d\rho}$$

The compressibility of liquids is several orders of magnitude smaller compared to gases

Fluids and gases

Compressibility of a gas flow



Example:
Stagnation flow

Stagnation point
Velocity is zero
Pressure increases
Density can increase

Velocity $u \rightarrow 0$

Pressure $p \rightarrow p + dp$

Density $\rho \rightarrow \rho + d\rho$

incompressible: Density is constant, only pressure increases

compressible: Pressure change is large enough, that it results is a significant change of density (compression)

Bernoulli equation:

$$p + \frac{1}{2}\rho\, u^2 = \text{const.}$$

$$d\left(p + \frac{1}{2}\rho\, u^2\right) = 0$$

$$dp + \frac{1}{2}u^2 d\rho + \frac{1}{2}\rho\, d\left(u^2\right) = 0$$

$$\frac{d\rho}{\rho} = -\frac{1}{2}\frac{d\left(u^2\right)}{\frac{dp}{d\rho} + \frac{u^2}{2}}$$

Gas flow can be supposed to be incompressible, when this expression is small

Fluids and gases

Compressibility of a gas flow

$$\frac{dp}{d\rho} = a^2$$ a: speed of sound

$$\left.\frac{d\rho}{\rho} = -\frac{1}{2}\frac{d(u^2)}{a^2 + \frac{u^2}{2}} = -\frac{1}{2}\frac{d\left(\frac{u^2}{a^2}\right)}{1 + \frac{1}{2}\frac{u^2}{a^2}} = -\frac{1}{2}\frac{d(Ma^2)}{1 + \frac{1}{2}Ma^2}\right\}$$

This expression is small, when the Mach number is small, approximately **Ma < 0.3**

$$Ma = \frac{u}{a}$$ Mach number

$$\mathbf{a} = \sqrt{\kappa \cdot \mathbf{R} \cdot \mathbf{T}}$$ Ideal gas

Examples:	Mach number
Ventilation systems	0.1
Flow around cars	0.2-0.3
Wind rotor	0.2-0.5
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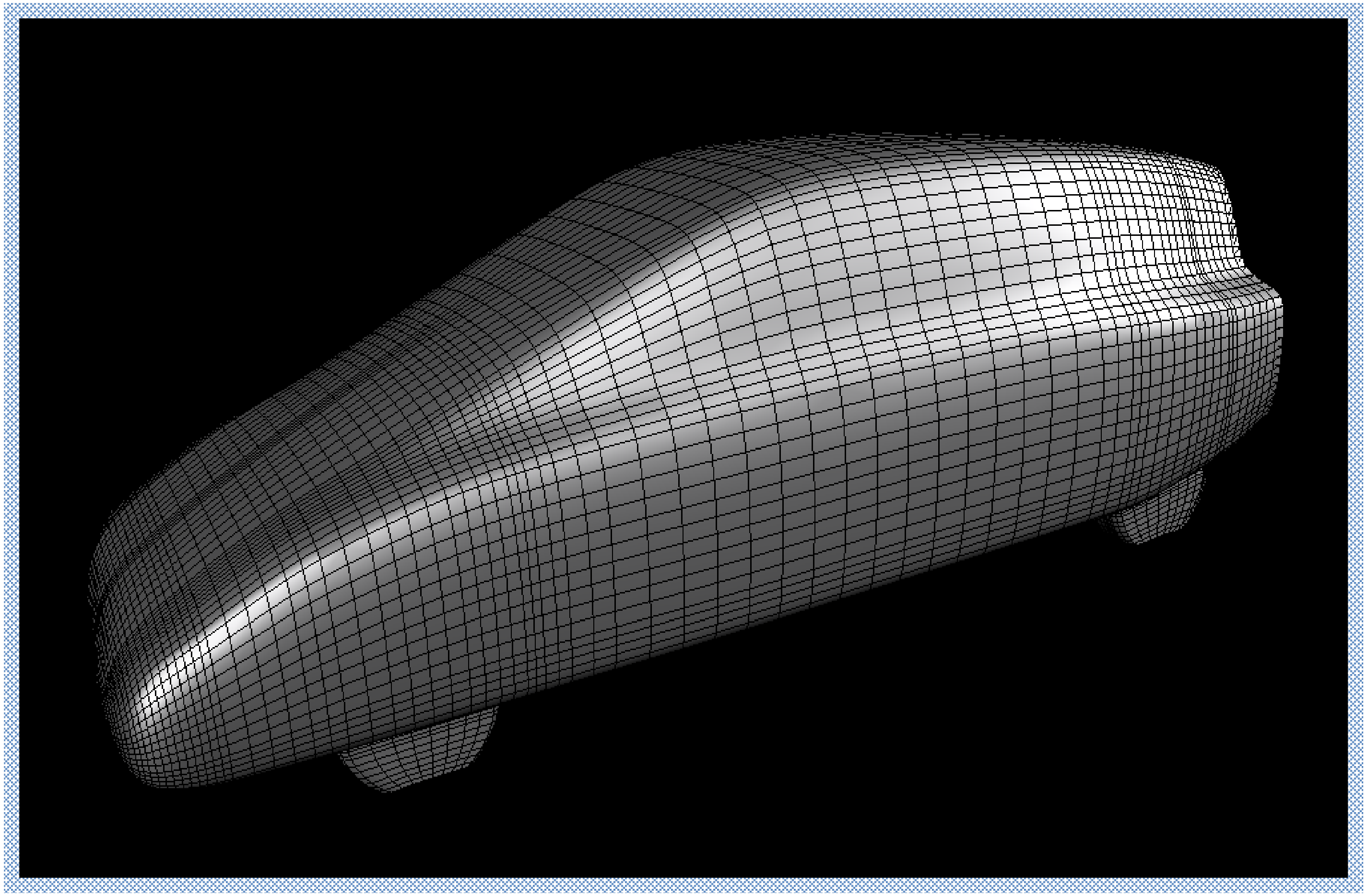
Steam turbine	0.7
Flow around Airplane	0.9
Explosion	>1,5

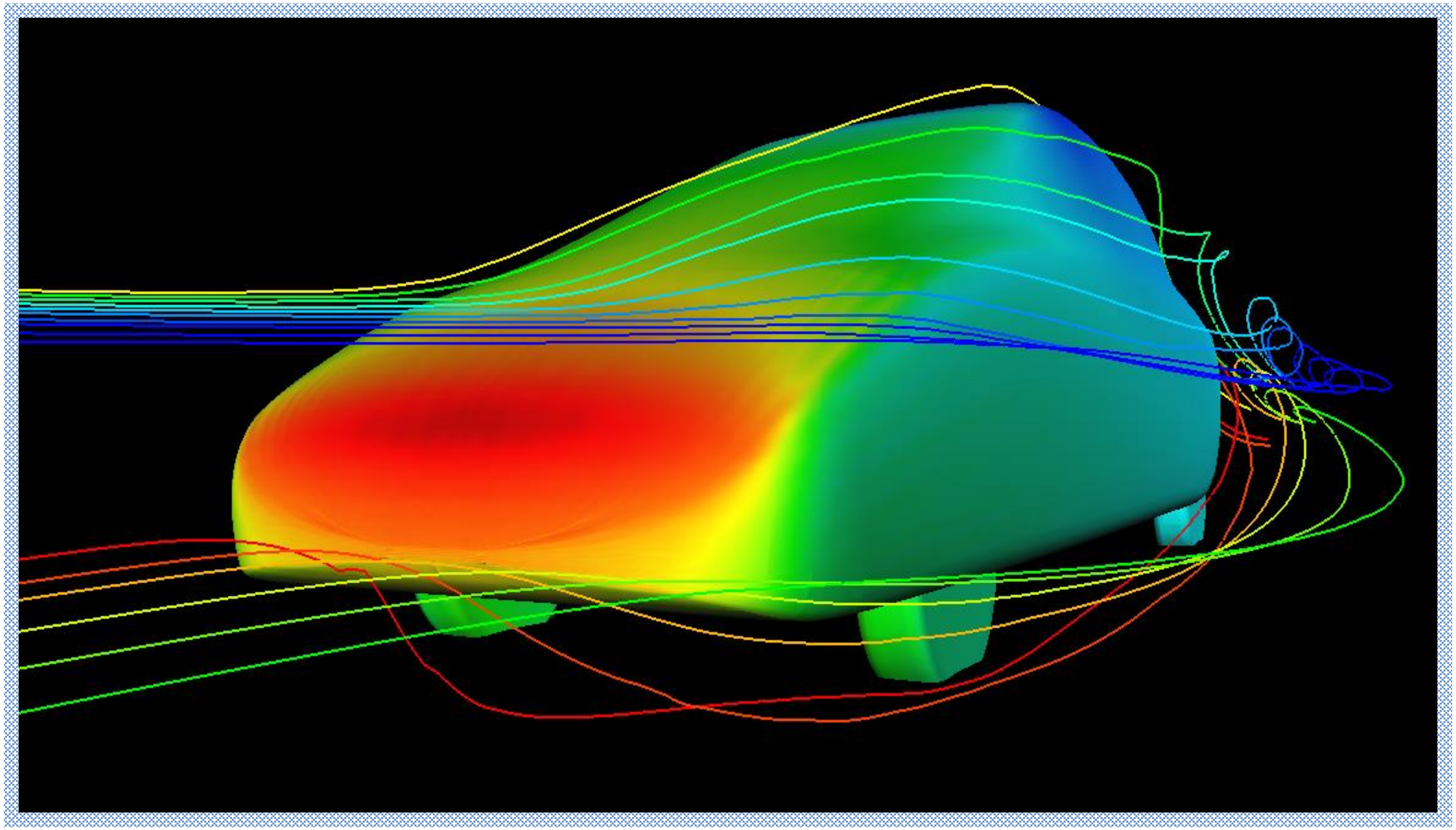
Example: Incompressible Fluid

Flow around a car



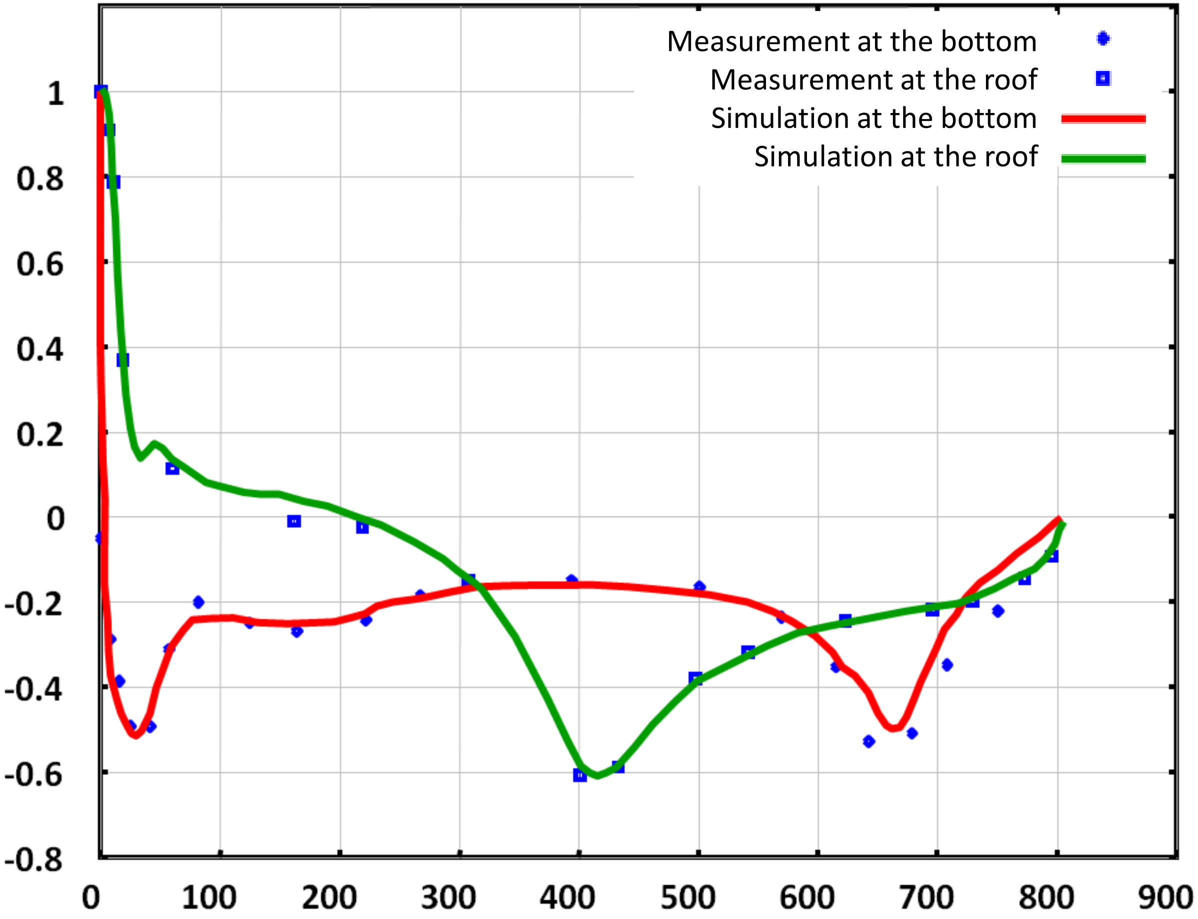
Example: Incompressible Fluid

Flow around a car



Example: Incompressible Fluid

Flow around a car



Pressure distribution in the middle of the car

Compressible Fluids

Speed of sound $a_{Fl} = \sqrt{\frac{E_{Fl}}{\rho}}$

Elasticity modulus

Density

1 m³

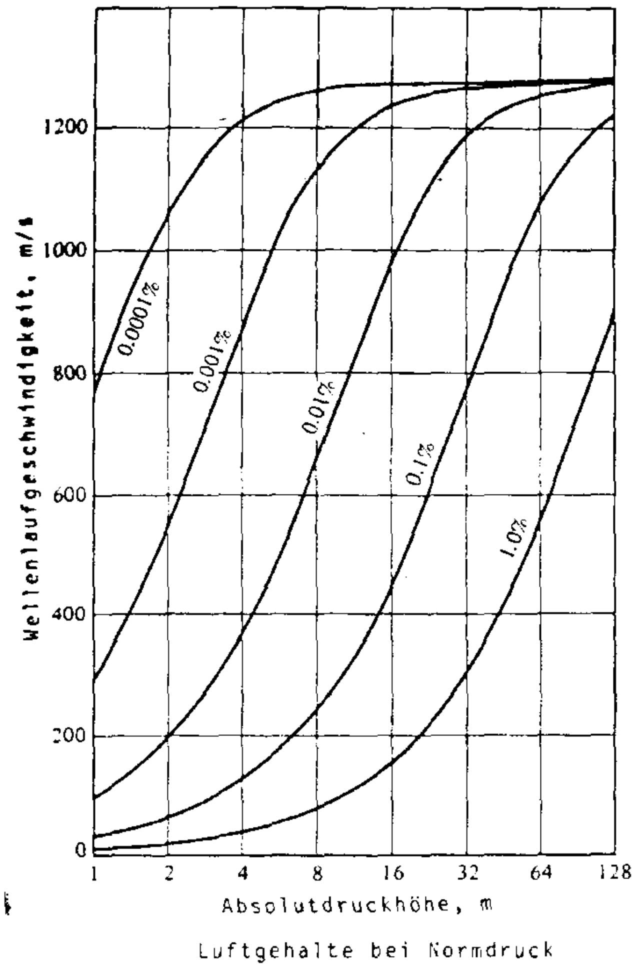
1 bar pressure increase

	E_{Fl} [bar]	ρ [kg/m³]	a_{Fl} [m/s]
Water	$2.06 \cdot 10^4$	1000	1440
Crude oil	$1.56 \cdot 10^4$	900	1310
Petrol	$0.88 \cdot 10^4$	750	1080
Air	$0.13 \cdot 10^1$	1.2	330

0.9995 m³

0.23 m³

Compressible Fluids



Speed of sound

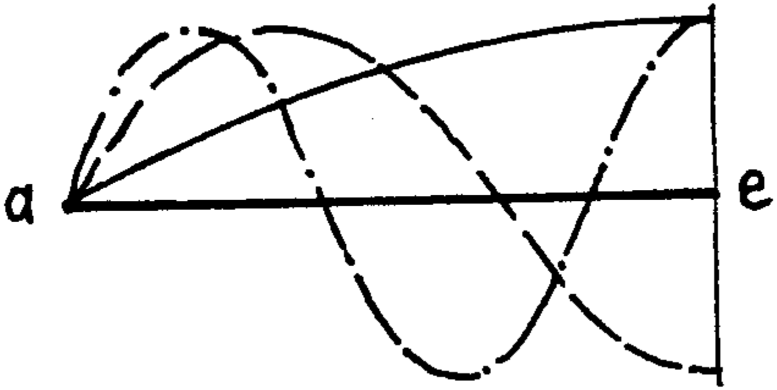
Water: appr. 1400 m/s

Air: appr. 330 m/s

Speed of sound in water decreases significantly with dissolved air

Compressible Fluids

Example: Compressible pipe flow



Eigenfrequencies:

1st Eigenfrequency: $f_1 = a/(4L)$

2nd Eigenfrequency: $f_2 = 3a/(4L)$

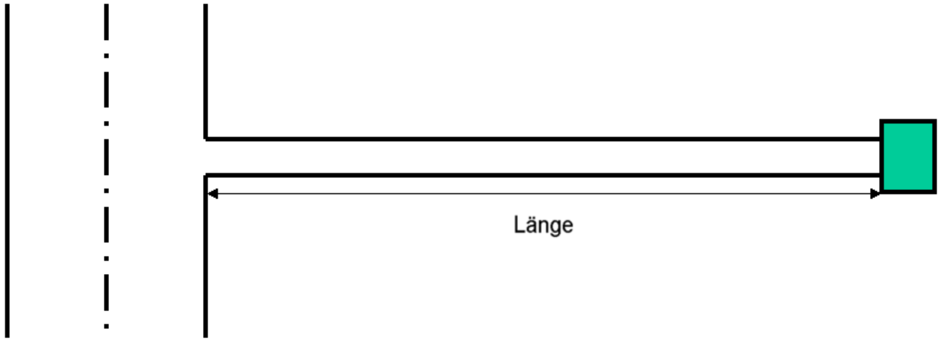
3rd Eigenfrequency: $f_3 = 5a/4L)$

Example:

Length: 5 m

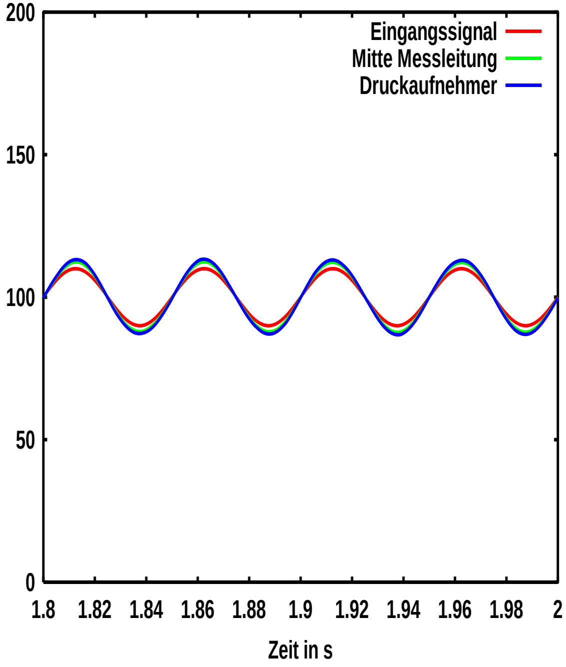
Speed of sound: 900 m/s

First Eigenfrequency: 45 Hz

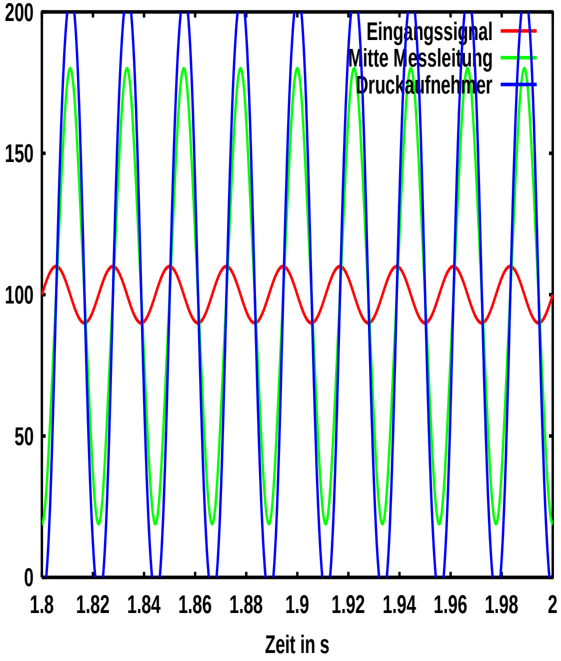


Compressible Fluids

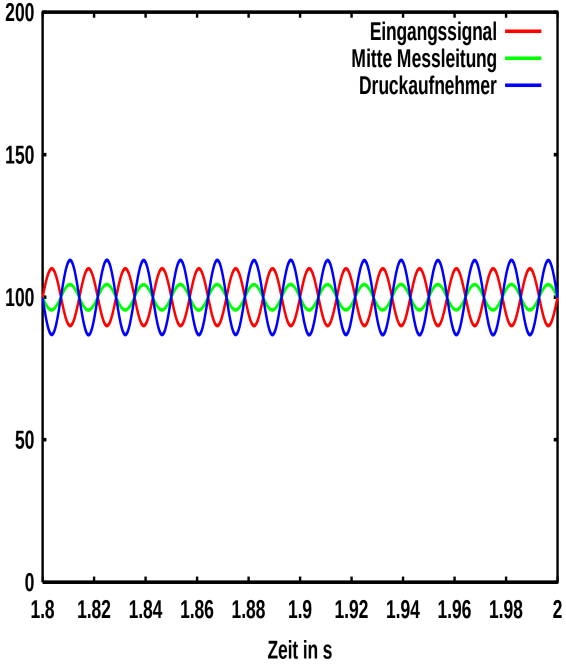
Exciting frequency 20Hz



Exciting frequency 45Hz

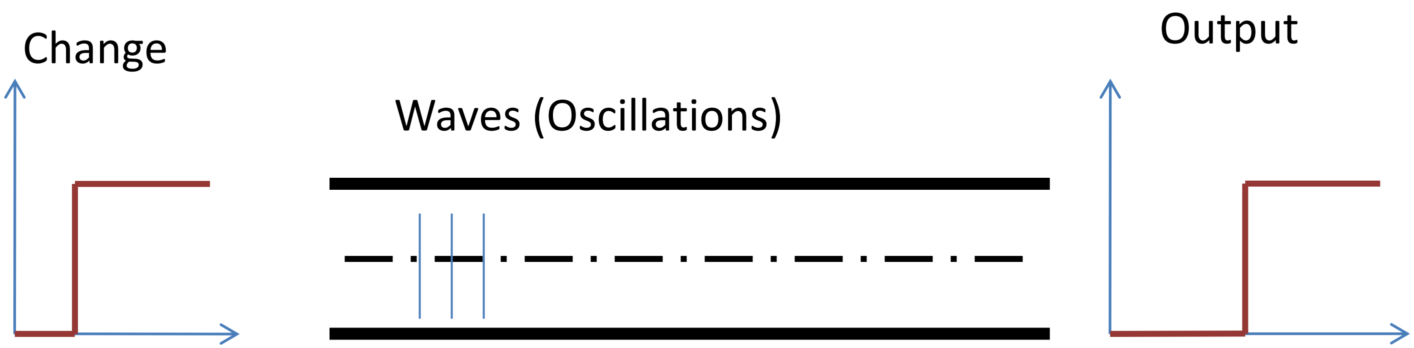


Exciting frequency 70 Hz

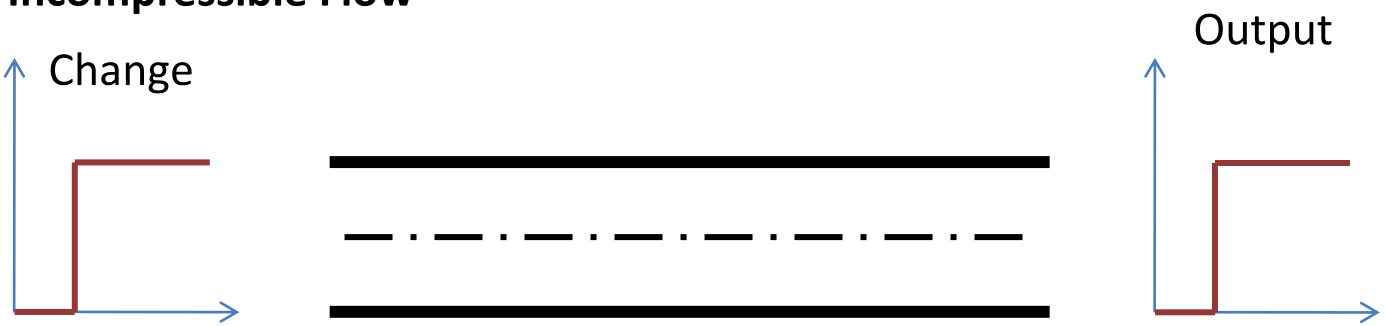


Difference in behavior of compressible and incompressible flows

Compressible Flow



Incompressible Flow



Changes have an immediate impact

For oscillations and resonance phenomena compressibility can be very significant

Compressible Navier-Stokes equations

Mass conservation: $$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0$$

Momentum conservation:

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}-\rho\frac{\partial\Psi}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu\frac{\partial u_k}{\partial x_k}\delta_{ij}\right]$$

Equation of state (e. g. ideal gas law): $$p=\rho R T$$

Energy conservation: $$\frac{\partial T}{\partial t}+u_j\frac{\partial T}{\partial x_j}-\alpha\left(\frac{\partial}{\partial x_j}\frac{\partial T}{\partial x_j}\right)=\Phi$$

Incompressible flow

Compressible mass conservation: $$\frac{\partial\rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0$$

Incompressible flow: $\rho\neq f(p),\ \rho\neq f(t)$ Mostly: $\boxed{\rho=\text{const.}}$

This results in

Continuity equation: $$\frac{\partial u_i}{\partial x_i}=0$$

Momentum equations: $$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}-\rho\frac{\partial\Psi}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

Dimensionless equations

The equations were made dimensionless by

- a characteristic length L and
- a characteristic velocity Û

$$u_i^* = u_i / \hat{U} \qquad t^* = t / \left(L / \hat{U} \right)$$

$$x_i^* = x_i / L \qquad p^* = p / \left(\rho \hat{U}^2 \right)$$

Dimensionless equations

Introduced into the Navier-Stokes equations results in

$$\frac{\partial u_i^*}{\partial t^*} + u_j^* \frac{\partial u_i^*}{\partial x_j^*} = -\frac{\partial p^*}{\partial x_i^*} + \frac{\partial}{\partial x_j^*}\left[\frac{1}{Re}\left(\frac{\partial u_i^*}{\partial x_j^*} + \frac{\partial u_j^*}{\partial x_i^*}\right)\right]$$

$$\frac{\partial u_i^*}{\partial x_i^*} = 0$$

With the Reynolds number $\mathrm{Re} = \frac{\hat{U}\,L}{\nu}$

→ The only relevant characteristic number for incompressible flows is the Reynolds number

→ Problem: No conditional equation for the pressure

Methods for calculation the pressure

- **Artificial compressibility**
  - Explicit, Implicit
- **Poisson equation for the pressure**
- **Pressure correction methods**
  - Usawa
  - SIMPLE, SIMPLEC, SIMPLEST, PISO
- others
  - Fractional Step Method
  - etc

Based on

Physical approximation

Physical modelling

Numerical approximation

Methods for calculation the pressure

- **Artificial compressibility**

  Explicit, Implicit

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  etc

Based on

“Physical” approximation

Physical modelling

Numerical approximation

Artificial compressibility

Continuity equation (Compressible)

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=0$$

Artificial compressibility

$$\frac{\partial p}{\partial \rho}=a_k^2$$

a_k ... Artificial compressibility

Numerical coefficient

Modified continuity equation

$$\frac{1}{a_k^2}\frac{\partial p}{\partial t}+\frac{\partial u_i}{\partial x_i}=0$$

Momentum equation

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

Correct steady state solution:

$$\frac{1}{a_k^2}\frac{\partial p}{\partial t}\rightarrow 0$$

=> **exact Solution**

Artificial compressibility

For **unsteady problems**

Introduction of a Pseudo time τ

Modified continuity equation

$$\frac{1}{a_k^2}\frac{\partial p}{\partial \tau}+\frac{\partial u_i}{\partial x_i}=0$$

Momentum equations

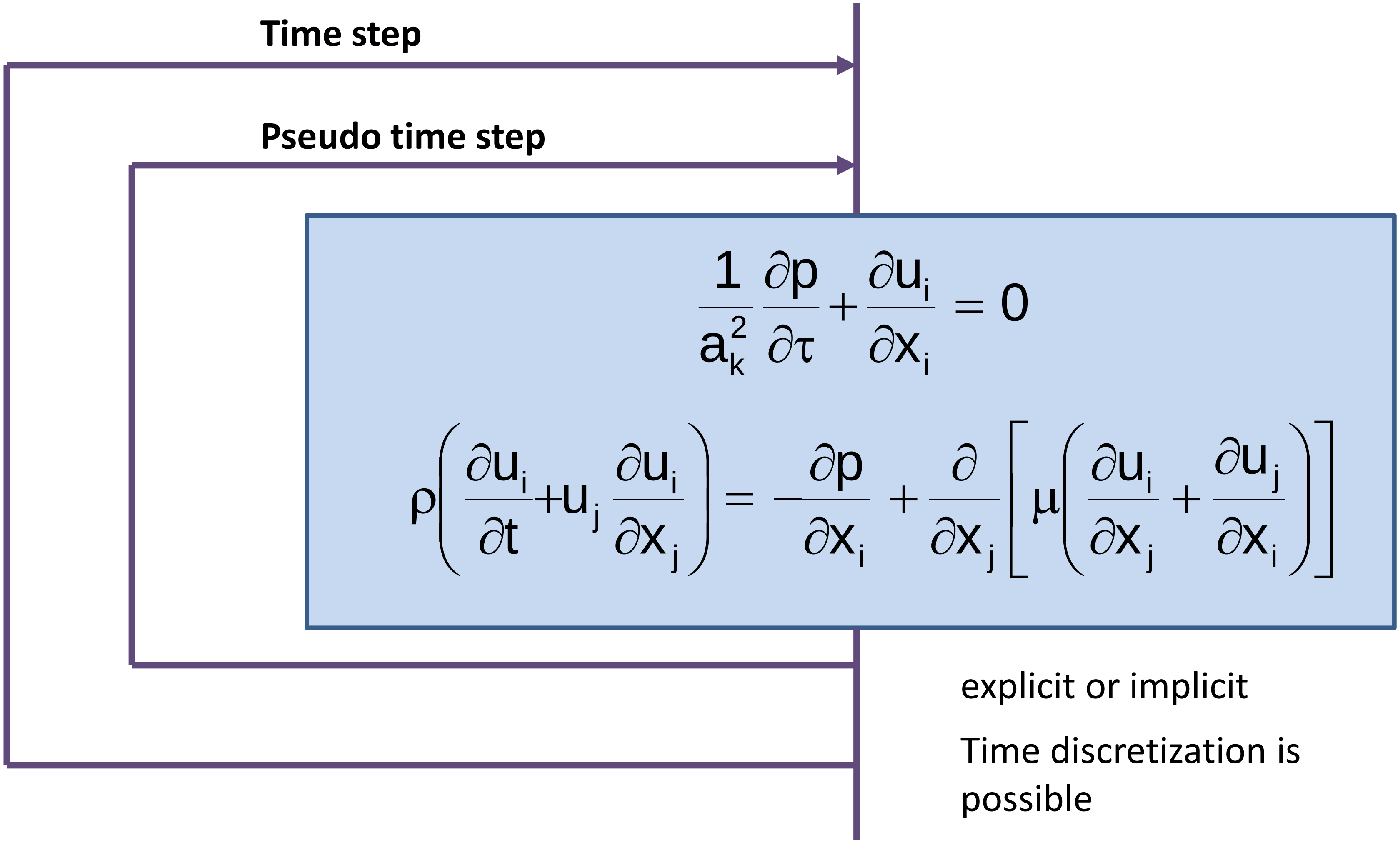
$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

Integration in each time step

$$\frac{1}{a_k^2}\frac{\partial p}{\partial \tau}\rightarrow 0$$

=> Exact Solution

Artificial compressibility



Time step

Pseudo time step

$$\frac{1}{a_k^2}\frac{\partial p}{\partial \tau}+\frac{\partial u_i}{\partial x_i}=0$$

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

explicit or implicit

Time discretization is possible

Methods for calculation the pressure

Based on

- **Artificial compressibility** — Physical approximation
  - Explicit, Implicit
- **Poisson equation for the pressure** — Physical modelling
- **Pressure correction methods** — Numerical approximation
  - Usawa
  - SIMPLE, SIMPLEC, SIMPLEST, PISO
- others
  - Fractional Step Method
  - etc

Poisson equation for the pressure

Taking the momentum equation and derive it

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]$$

Differentiate the x – equation with respect to x,
Differentiate the y – equation with respect to y
Differentiate the z – equation with respect to z

Sum up the resulting equations leads to

$$\frac{1}{\rho}\frac{\partial^2 p}{\partial x_i \partial x_i}=-\frac{\partial}{\partial x_i}\left(u_j\frac{\partial u_i}{\partial x_j}\right)+\frac{\partial}{\partial x_i}\left(\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]\right)$$

Exact equation for the pressure

Poisson equation for the pressure

$$\frac{1}{\rho}\frac{\partial^2 p}{\partial x_i \partial x_i} = -\frac{\partial}{\partial x_i}\left(u_j \frac{\partial u_i}{\partial x_j}\right) + \frac{\partial}{\partial x_i}\left(\frac{\partial}{\partial x_j}\left[\nu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]\right)$$

With the continuity equation $\frac{\partial u_i}{\partial x_i} = 0$

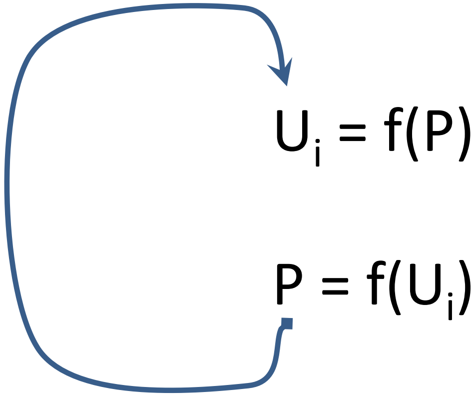
One obtains the conditional equation for the pressure

$$\boxed{\frac{1}{\rho}\frac{\partial^2 p}{\partial x_i \partial x_i} = -\frac{\partial}{\partial x_i}\left(u_j \frac{\partial u_i}{\partial x_j}\right)}$$

Needed: 2nd order derivatives of velocity

Poisson equation for the pressure

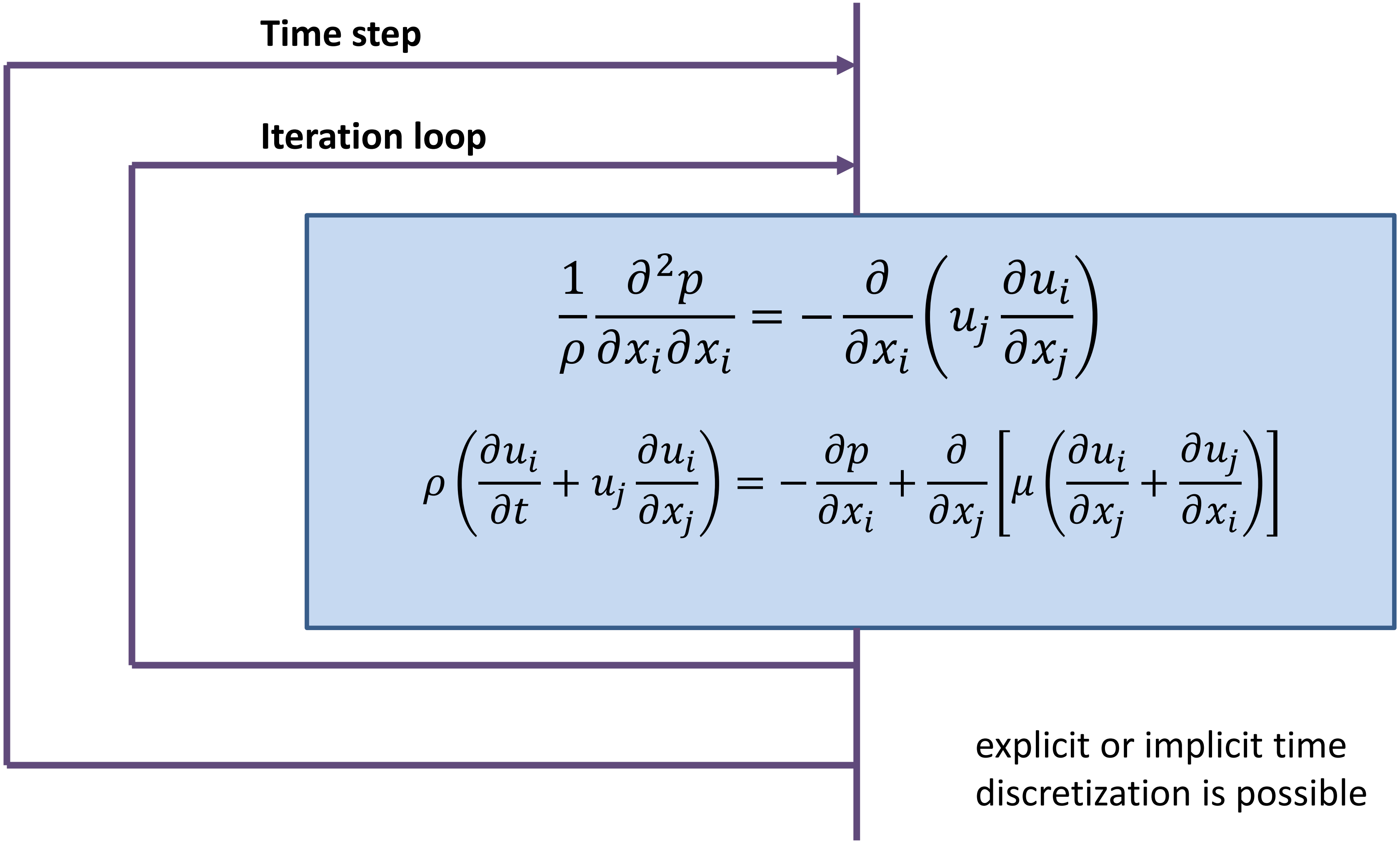
Coupled system, solved iteratively



Velocity is a function of pressure $U_i = f(P)$

Pressure is a function of velocity $P = f(U_i)$

Poisson equation for the pressure



Time step

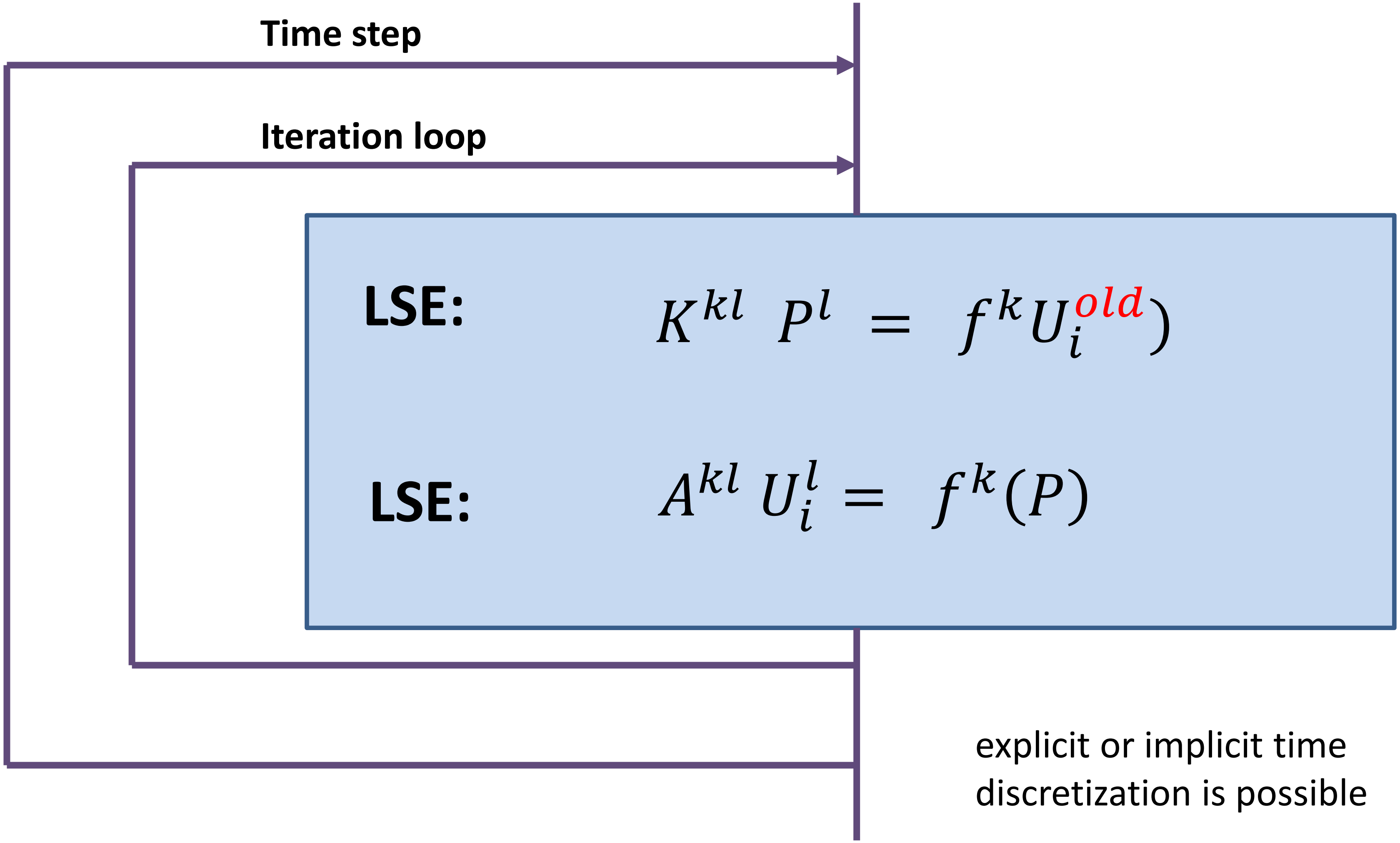
Iteration loop

$$\frac{1}{\rho}\frac{\partial^2 p}{\partial x_i \partial x_i} = -\frac{\partial}{\partial x_i}\left(u_j \frac{\partial u_i}{\partial x_j}\right)$$

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

explicit or implicit time discretization is possible

Poisson equation for the pressure



Time step

Iteration loop

LSE: $$K^{kl} \; P^l = f^k U_i^{old})$$

LSE: $$A^{kl} \, U_i^l = f^k(P)$$

explicit or implicit time discretization is possible

Methods for calculation the pressure

- **Artificial compressibility**

  Explicit, Implicit

- **Poisson equation for the pressure**

- **Pressure correction methods**

  Usawa

  SIMPLE, SIMPLEC, SIMPLEST, PISO

- others

  Fractional Step Method

  etc

Based on

Physical approximation

Physical modelling

Numerical approximation

Pressure correction methods

Continuity equation: $$\frac{\partial u_i}{\partial x_i} = 0$$ **Constrain**

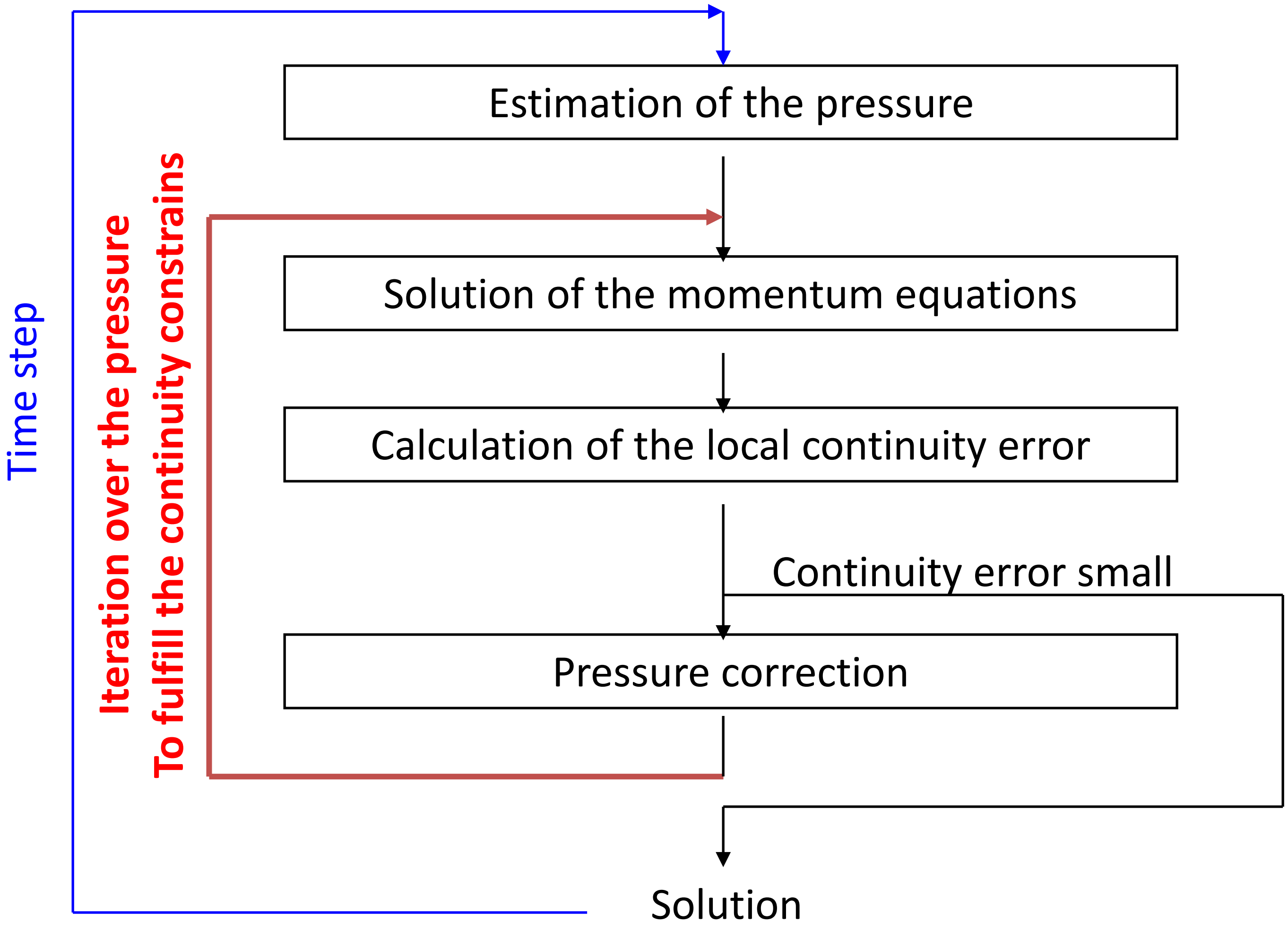
Momentum equation: $$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = -\frac{\partial p}{\partial x_i} - \rho\frac{\partial \Psi}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right]$$

Conditional equation for the velocities

Pressure represents a parameter to fulfill the continuity equation

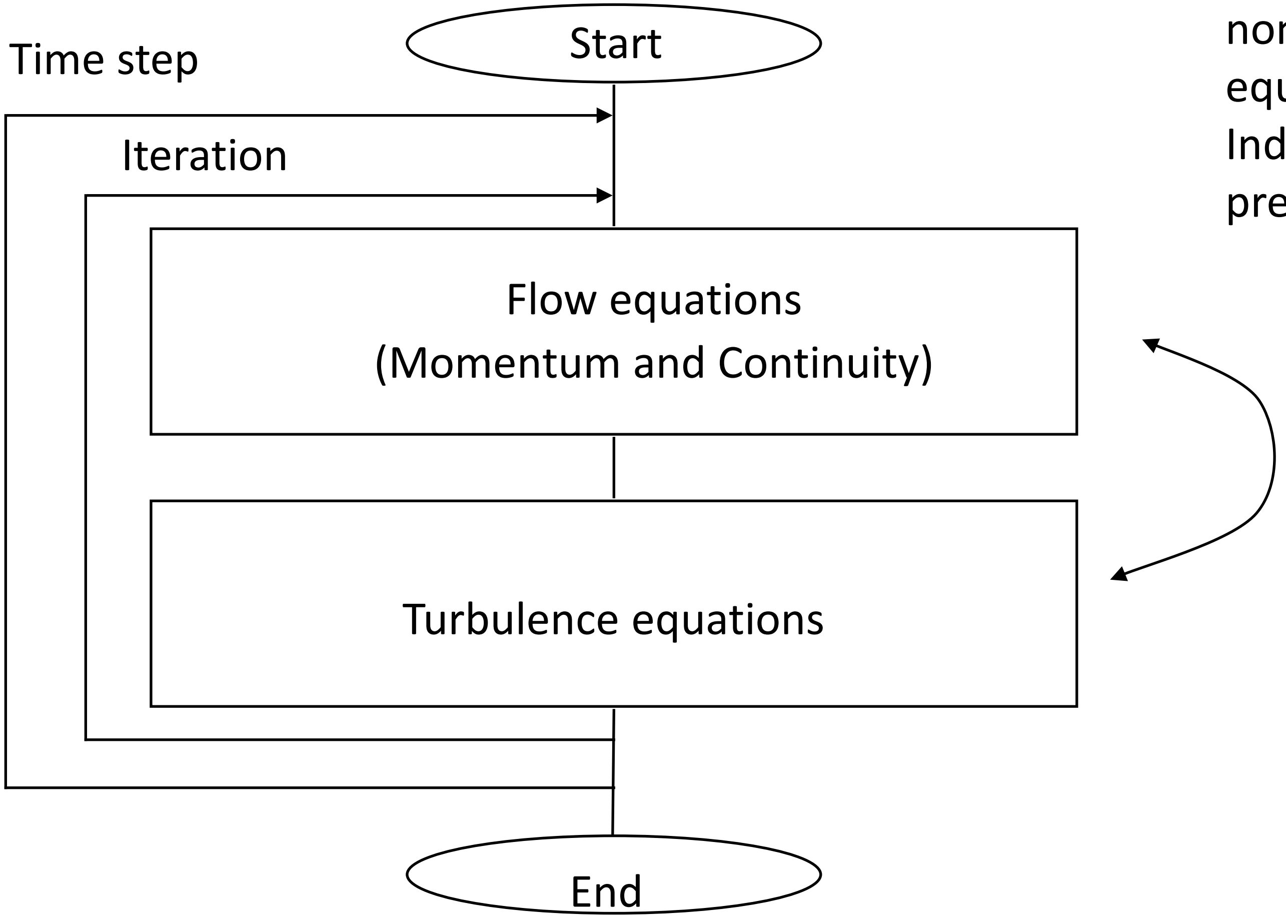
Mathematical: Pressure is a Lagrange Multiplier

Pressure correction methods



Global iteration procedure

Iteration is anyway necessary because of non-linearity, coupled equations etc. Independent of the pressure correction



Time step

Start

Iteration

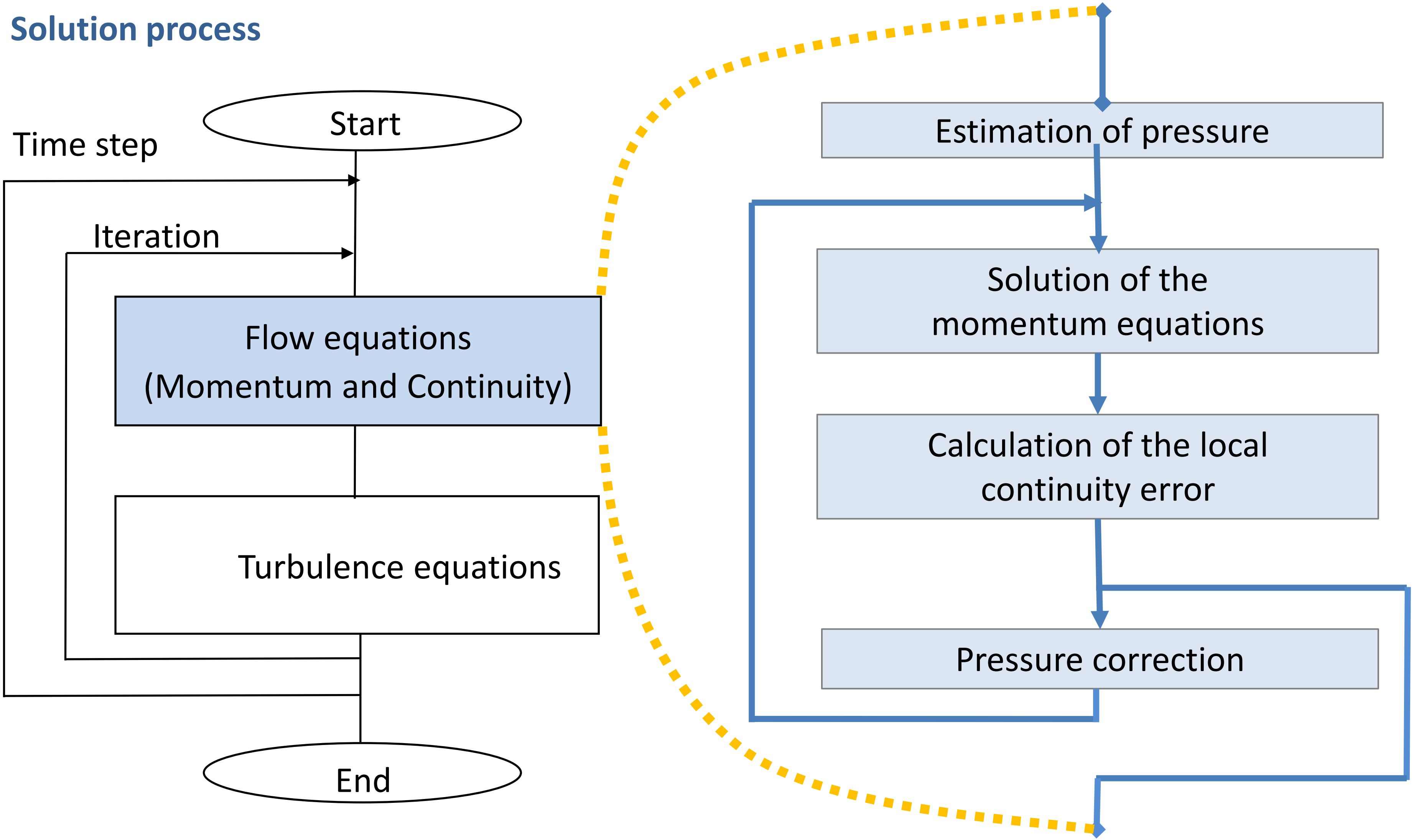
Flow equations
(Momentum and Continuity)

Turbulence equations

End

Coupled,
e. g. over ν_t

Solution process



Time step

Start

Iteration

Flow equations
(Momentum and Continuity)

Turbulence equations

End

Estimation of pressure

Solution of the momentum equations

Calculation of the local continuity error

Pressure correction

Uzawa algorithm

Discretized equations

$$\begin{bmatrix} \underline{\underline{A}} & \underline{\underline{H}} \\ \underline{\underline{Q}} & 0 \end{bmatrix} \begin{bmatrix} \underline{U} \\ \underline{P} \end{bmatrix} = \begin{bmatrix} \underline{b} \\ \underline{0} \end{bmatrix}$$

Momentum equations

Continuity equation

Calculation of the velocities from the momentum equation (1. row)

$$\underline{U} = \underline{\underline{A}}^{-1} \underline{b} - \underline{\underline{A}}^{-1} \underline{\underline{H}}\, \underline{P}$$

Introduced into the continuity equation (2. row) results in an equation for the pressure

$$\left(\underline{\underline{Q}}\, \underline{\underline{A}}^{-1} \underline{\underline{H}} \right) \underline{P} = \underline{\underline{Q}}\, \underline{\underline{A}}^{-1} \underline{b}$$

This equation is very complex and must be solved iteratively.

Uzawa Algorithmus

Pre-conditioned Richardson iteration:

Assumption: $\underline{P}^{0}$

Calculation: $\underline{P}^{n+1} = \underline{P}^{n} - \underline{\underline{\rho}}\,\underline{r}^{n}$ with $\underline{r}^{n} = \underline{\underline{Q}}\,\underline{U}^{n}$

Conditioning matrix

Local continuity error

Acceleration of the convergence by penalization

Uzawa algorithm

Iteration:

Assumption: $\underline{P}^0$

LSE to determine velocity: $\left[\underline{\underline{A}} + \lambda \underline{\underline{H}}\,\underline{\underline{Q}}\right] \underline{U}^n = \underline{b} - \underline{\underline{H}}\,\underline{P}^n$

„Penalty“-parameter

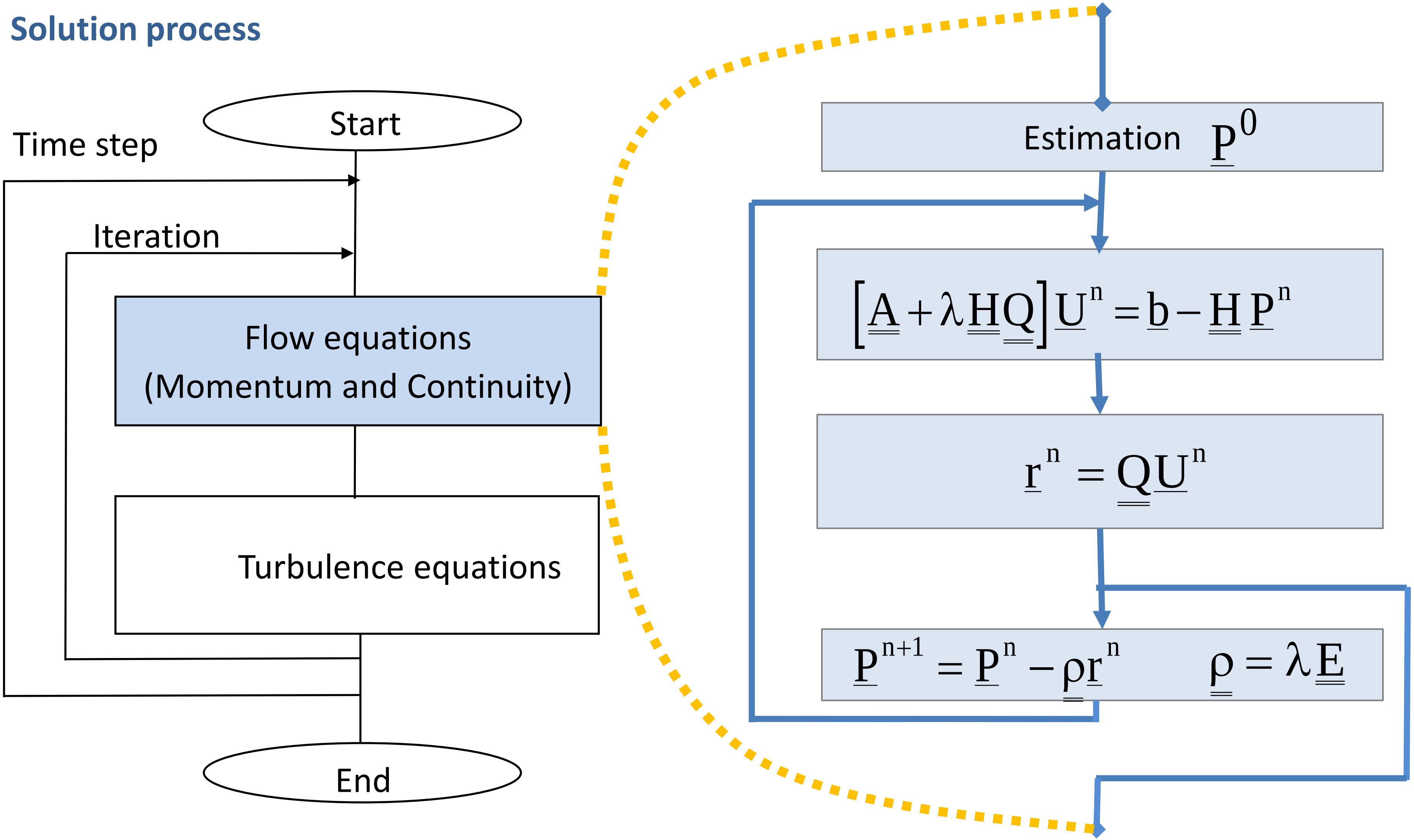
Local continuity error: $\underline{r}^n = \underline{\underline{Q}}\,\underline{U}^n$

New pressure: $\underline{P}^{n+1} = \underline{P}^n - \underline{\underline{\rho}}\,\underline{r}^n$

Iteration

Suitable choice of conditioning matrix: $\underline{\underline{\rho}} = \lambda \underline{\underline{E}}$

Solution process



$\underline{P}^0$

$[\underline{\underline{A}}+\lambda\underline{\underline{H}}\,\underline{\underline{Q}}]\underline{U}^n=\underline{b}-\underline{\underline{H}}\,\underline{P}^n$

$\underline{r}^n=\underline{\underline{Q}}\,\underline{U}^n$

$\underline{P}^{n+1}=\underline{P}^n-\underline{\underline{\rho}}\,\underline{r}^n \qquad \underline{\underline{\rho}}=\lambda\underline{\underline{E}}$

Pressure correction

Two – stage correction methods

Discretized equations

$$\begin{bmatrix} \underline{\underline{A}} & \underline{\underline{H}} \\ \underline{\underline{Q}} & 0 \end{bmatrix}\begin{bmatrix} \underline{U} \\ \underline{P} \end{bmatrix} = \begin{bmatrix} \underline{b} \\ \underline{0} \end{bmatrix}$$

Momentum equation

Continuity equation

LU – Decomposition (lower and upper triangle matrices)

$$\begin{bmatrix} \underline{\underline{A}} & 0 \\ \underline{\underline{Q}} & -\underline{\underline{Q}}\,\underline{\underline{A}}^{-1}\underline{\underline{H}} \end{bmatrix}\underbrace{\begin{bmatrix} \underline{\underline{E}} & \underline{\underline{A}}^{-1}\underline{\underline{H}} \\ 0 & \underline{\underline{E}} \end{bmatrix}\begin{bmatrix} \underline{U}^{n+1} \\ \underline{P}^{n+1} \end{bmatrix}}_{\begin{bmatrix} U^{*} \\ P* \end{bmatrix}} = \begin{bmatrix} \underline{b} \\ \underline{0} \end{bmatrix}$$

Pressure correction

Forward substitution

$$\begin{bmatrix} \underline{\underline{A}} & 0 \\ \underline{\underline{Q}} & -\underline{\underline{Q}}\,\underline{\underline{A}}^{-1}\underline{\underline{H}} \end{bmatrix} \begin{bmatrix} \underline{U}^{*} \\ \underline{P}^{*} \end{bmatrix} = \begin{bmatrix} \underline{b} \\ \underline{0} \end{bmatrix}$$

Backward substitution

$$\begin{bmatrix} \underline{\underline{\mathrm{E}}} & \underline{\underline{\mathrm{A}}}^{-1}\underline{\underline{\mathrm{H}}} \\ 0 & \underline{\underline{\mathrm{E}}} \end{bmatrix} \begin{bmatrix} \underline{\mathrm{U}}^{\mathrm{n+1}} \\ \underline{\mathrm{P}}^{\mathrm{n+1}} \end{bmatrix} = \begin{bmatrix} \underline{\mathrm{U}}^{*} \\ \underline{\mathrm{P}}^{*} \end{bmatrix}$$

Procedure

$$\underline{\underline{A}}\,\underline{U}^{*} = \underline{b}$$

$$\underline{\underline{Q}}\,\underline{\underline{A}}^{-1}\underline{\underline{H}}\,\underline{P}^{*} = \underline{\underline{Q}}\,\underline{U}^{*}$$

$$\underline{P}^{n+1} = \underline{P}^{*}$$

$$\underline{U}^{n+1} = \underline{U}^{*} - \underline{\underline{A}}^{-1}\underline{\underline{H}}\,\underline{P}^{n+1}$$

Pressure correction

Calculation of A^{-1} to expensive

=> Approximation of A^{-1}

$\underline{\underline{A}}\,\underline{U}^{*} = \underline{b}$ → **LSE for velocities**

$\underline{\underline{Q}}\,\underline{\underline{B}}_1\,\underline{\underline{H}}\,\underline{P}^{*} = \underline{\underline{Q}}\,\underline{U}^{*}$ → **Simplified equation for pressure**

$\underline{P}^{n+1} = \underline{P}^{*}$ → **Pressure update**

$\underline{U}^{n+1} = \underline{U}^{*} - \underline{\underline{B}}_2\,\underline{\underline{H}}\,\underline{P}^{n+1}$ → **Velocity update**

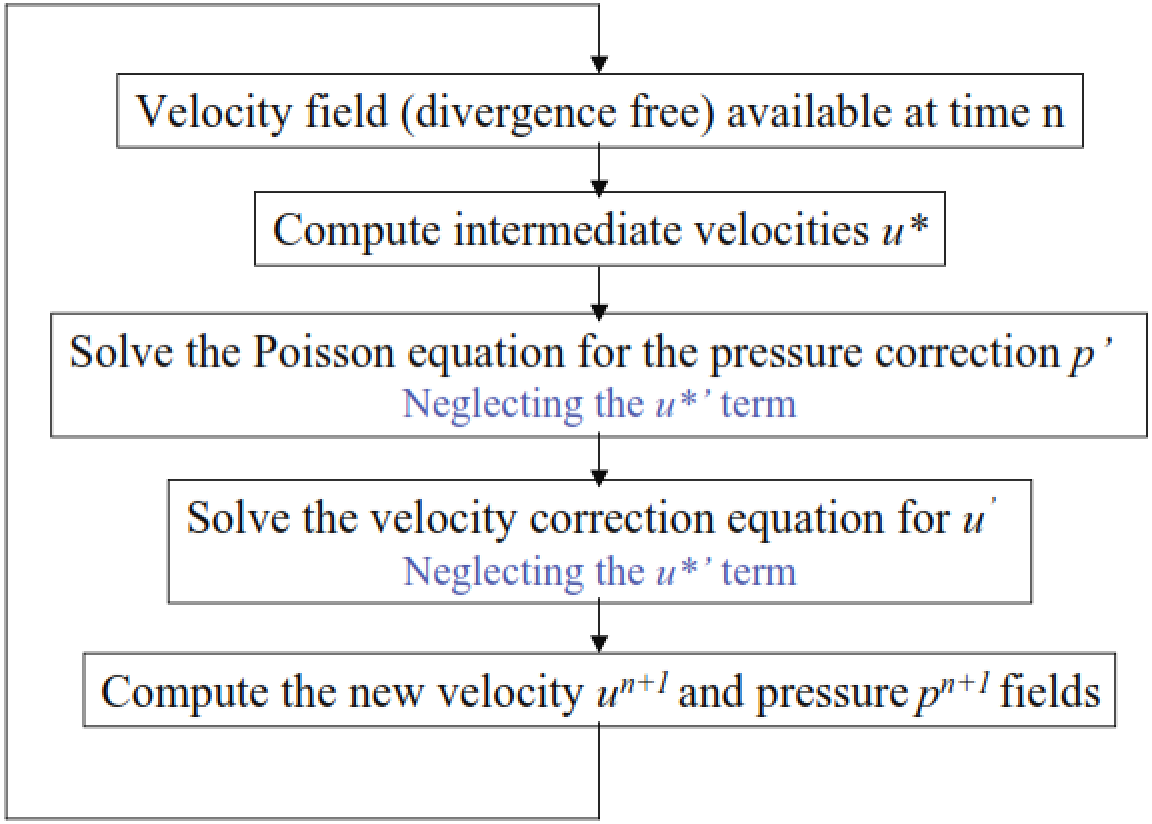
Various pressure correction methods differ by the choice of the approximation for B_1 und B_2

Simplest choice for unsteady flow (projection method)

$$\underline{\underline{B}}_1 = \underline{\underline{B}}_2 \approx \Delta t \, \underline{\underline{E}}$$

Implicit pressure-based scheme for NS equations (SIMPLE)

SIMPLE: Semi-Implicit Method for Pressure-Linked Equations



Velocity field (divergence free) available at time n

Compute intermediate velocities $u*$

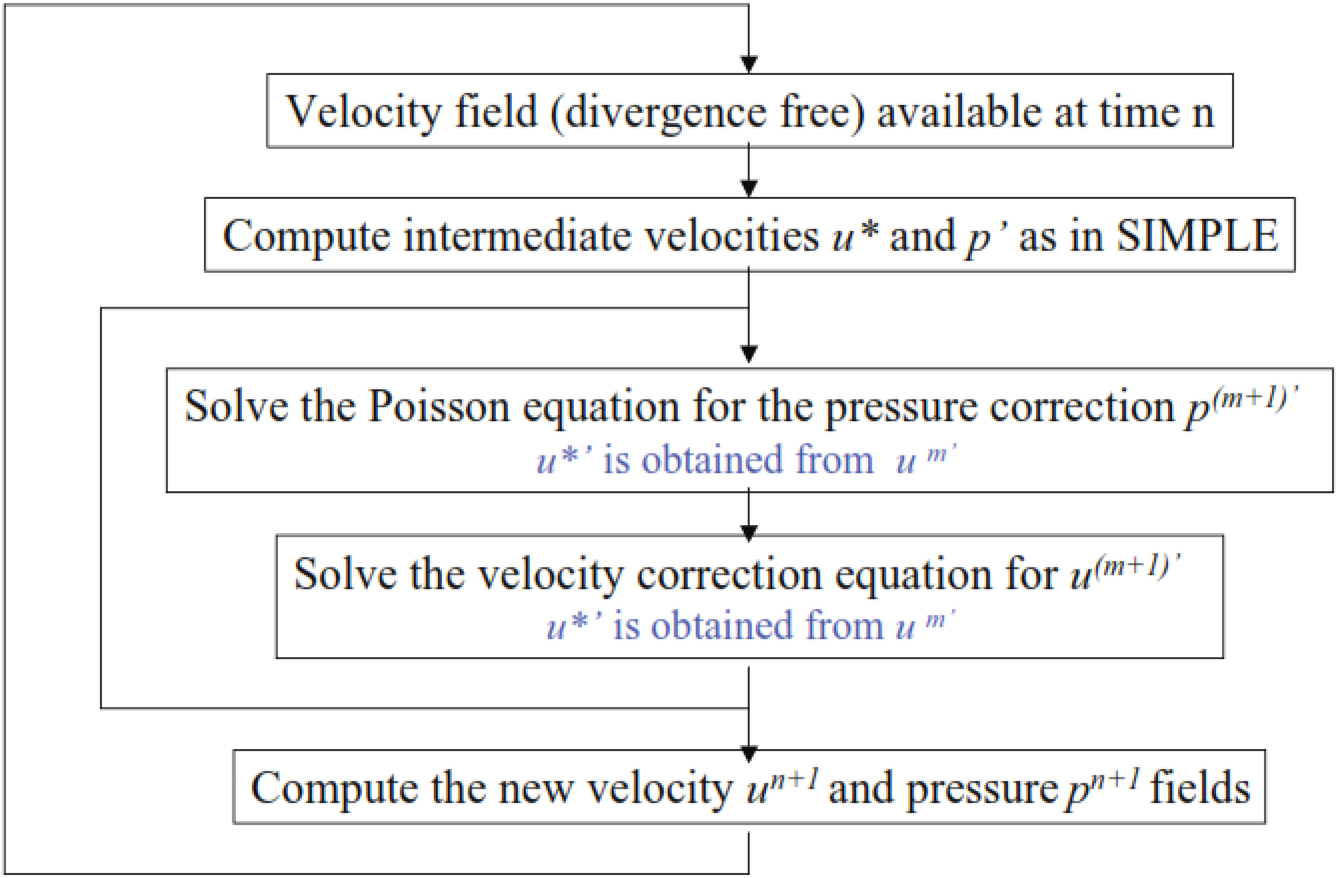
Solve the Poisson equation for the pressure correction p'
Neglecting the $u*'$ term

Solve the velocity correction equation for u'
Neglecting the $u*'$ term

Compute the new velocity u^{n+1} and pressure p^{n+1} fields

Implicit pressure-based scheme for NS equations (PISO)

PISO: Pressure Implicit with Splitting Operators



Velocity field (divergence free) available at time n

Compute intermediate velocities u^* and p' as in SIMPLE

Solve the Poisson equation for the pressure correction $p^{(m+1)'}$

$u^{*'}$ is obtained from $u^{m'}$

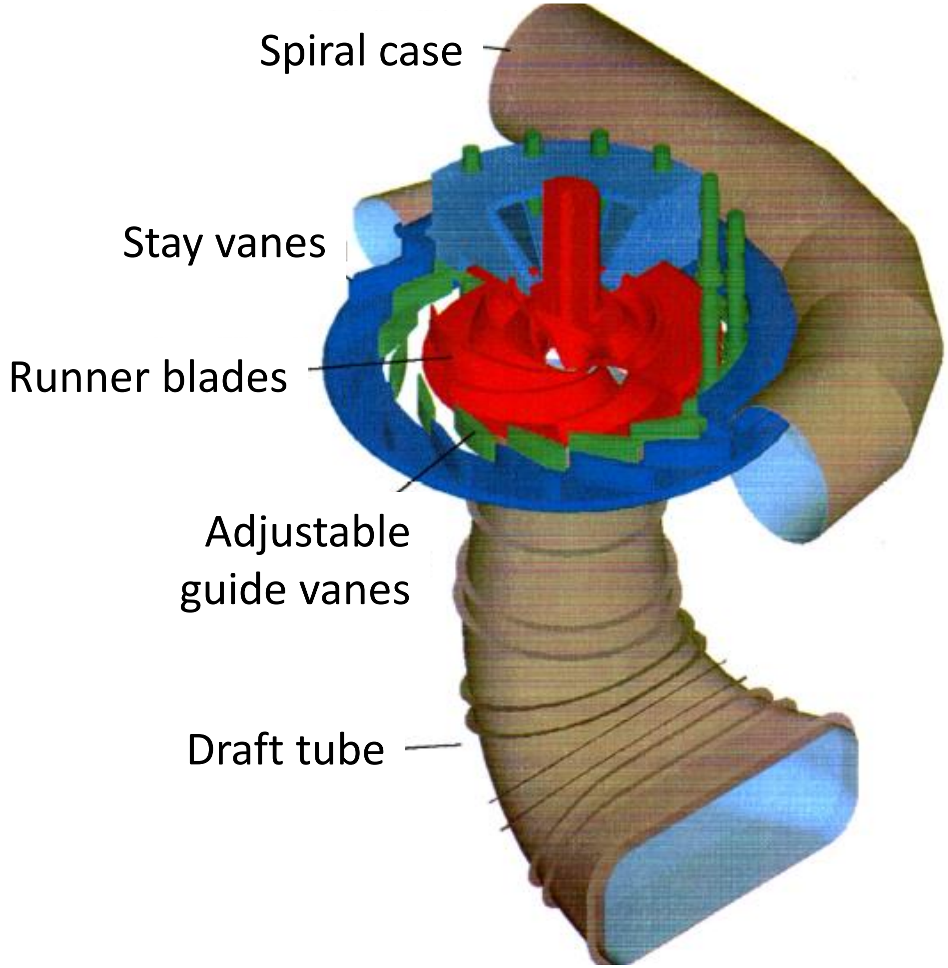
Solve the velocity correction equation for $u^{(m+1)'}$

$u^{*'}$ is obtained from $u^{m'}$

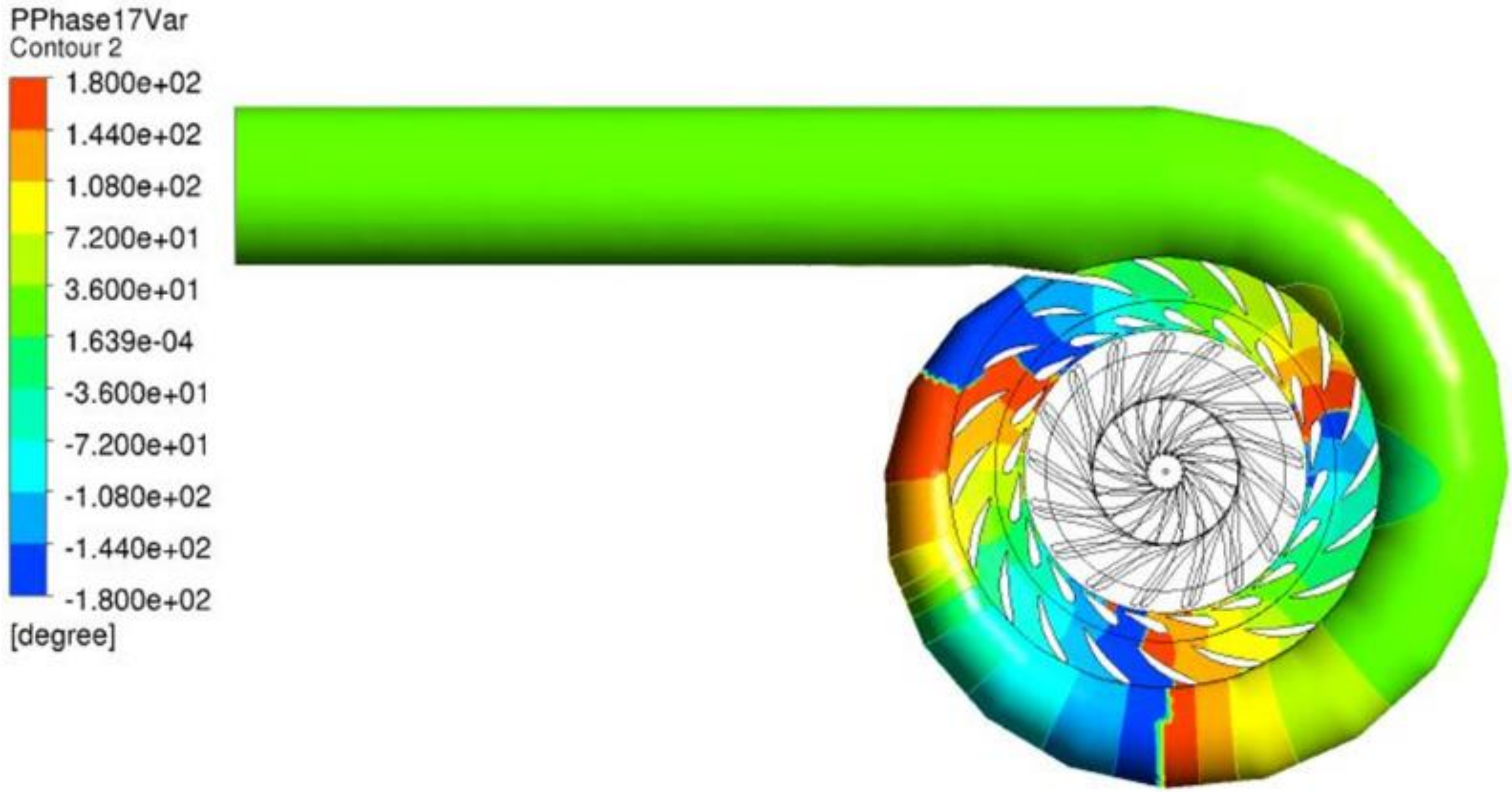
Compute the new velocity u^{n+1} and pressure p^{n+1} fields

Example: Phase resonance

Francis turbine

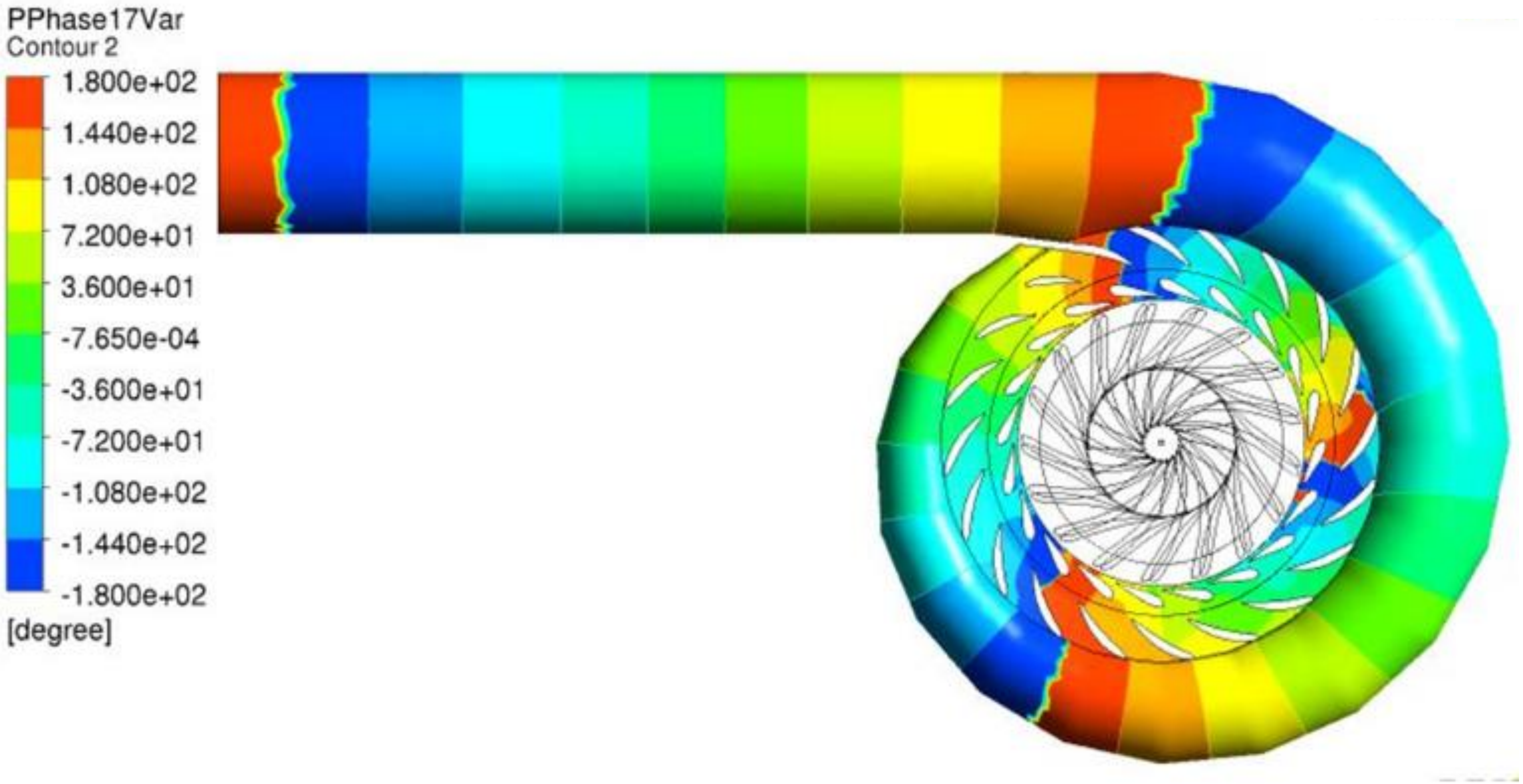


Incompressible calculation



Ruchonnet, N. et al., Simulation of phase resonance in radial hydraulic machines, Vienna Hydro 2014

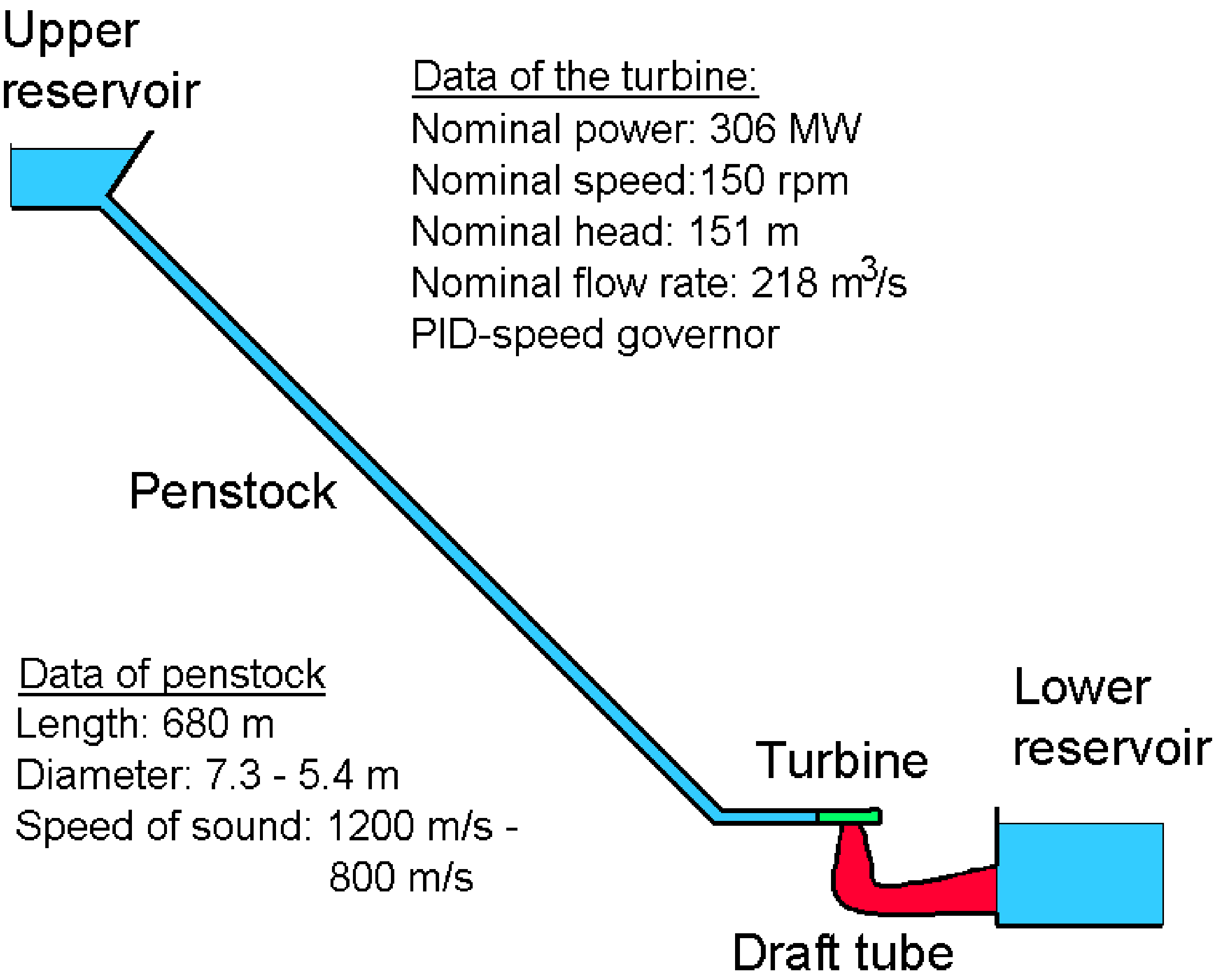
Compressible calculation



Ruchonnet, N. et al., Simulation of phase resonance in radial hydraulic machines, Vienna Hydro 2014

Coupled compressible – incompressible calculation

Example



Data of the turbine:

Nominal power: 306 MW

Nominal speed:150 rpm

Nominal head: 151 m

Nominal flow rate: 218 m^3/s

PID-speed governor

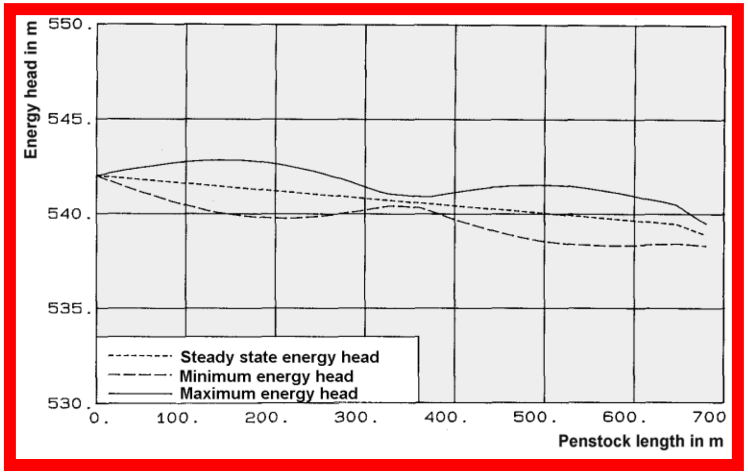
Data of penstock

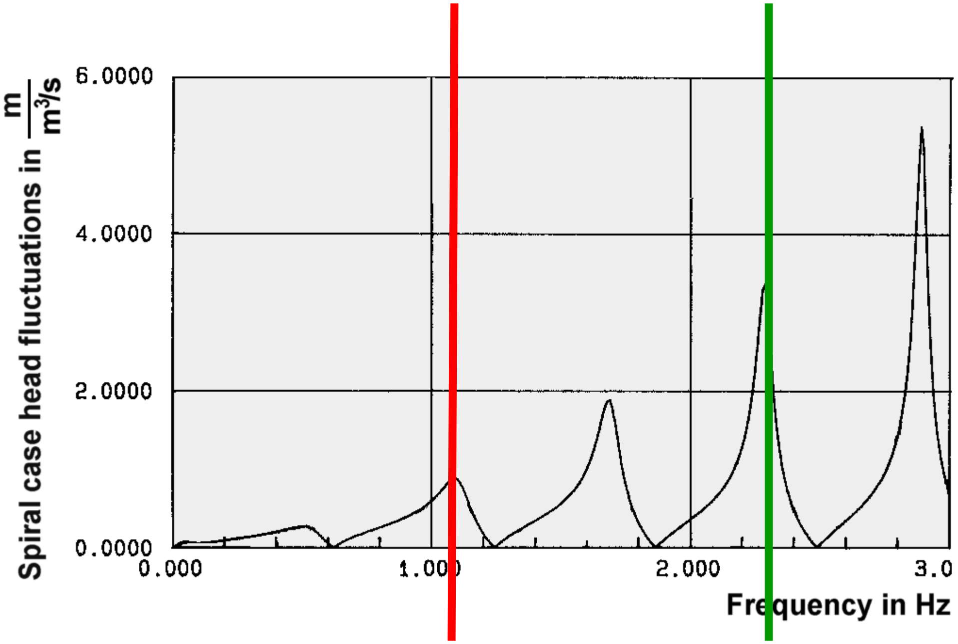
Length: 680 m

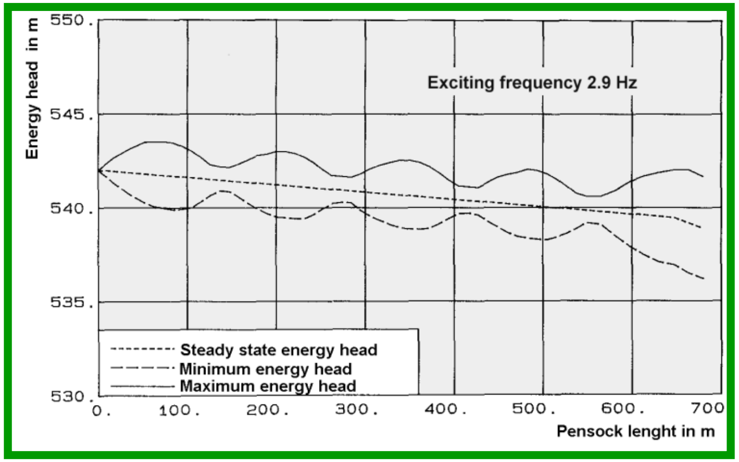
Diameter: 7.3 - 5.4 m

Speed of sound: 1200 m/s - 800 m/s

Resonance analysis



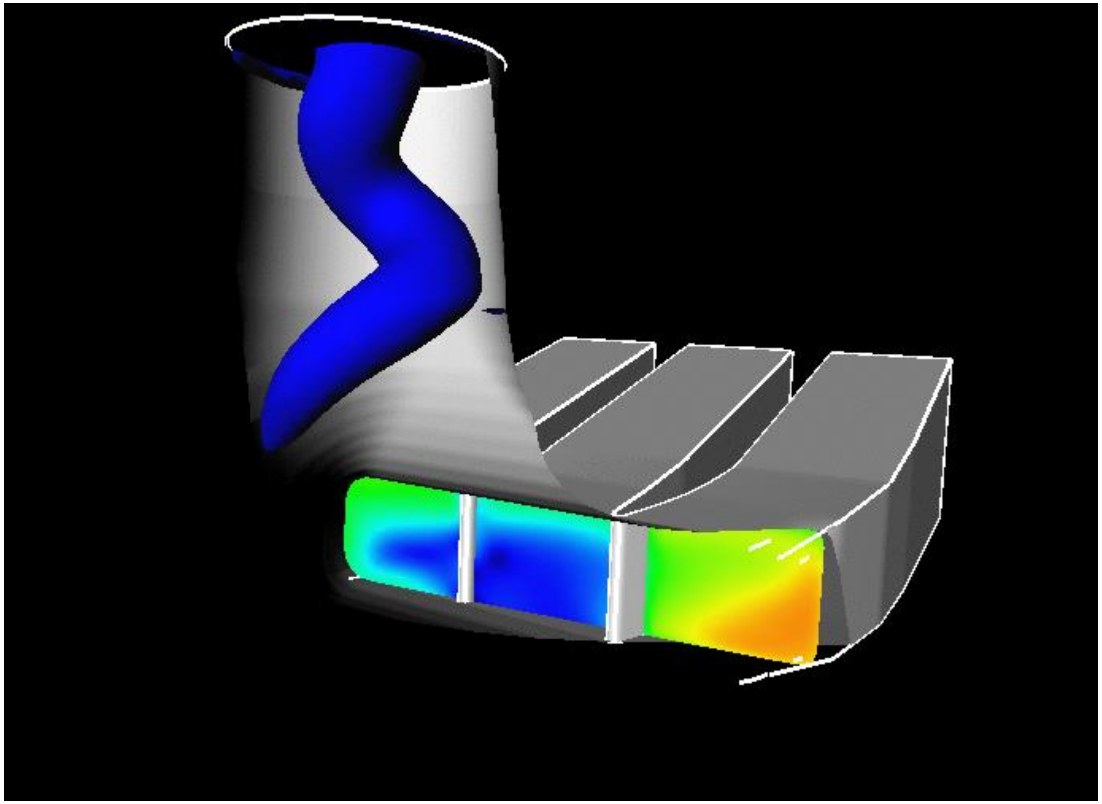


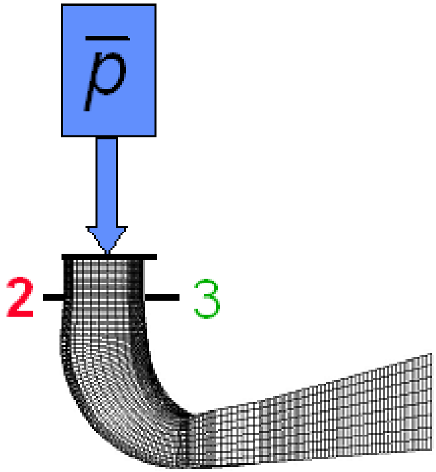


Ellbow draft tube

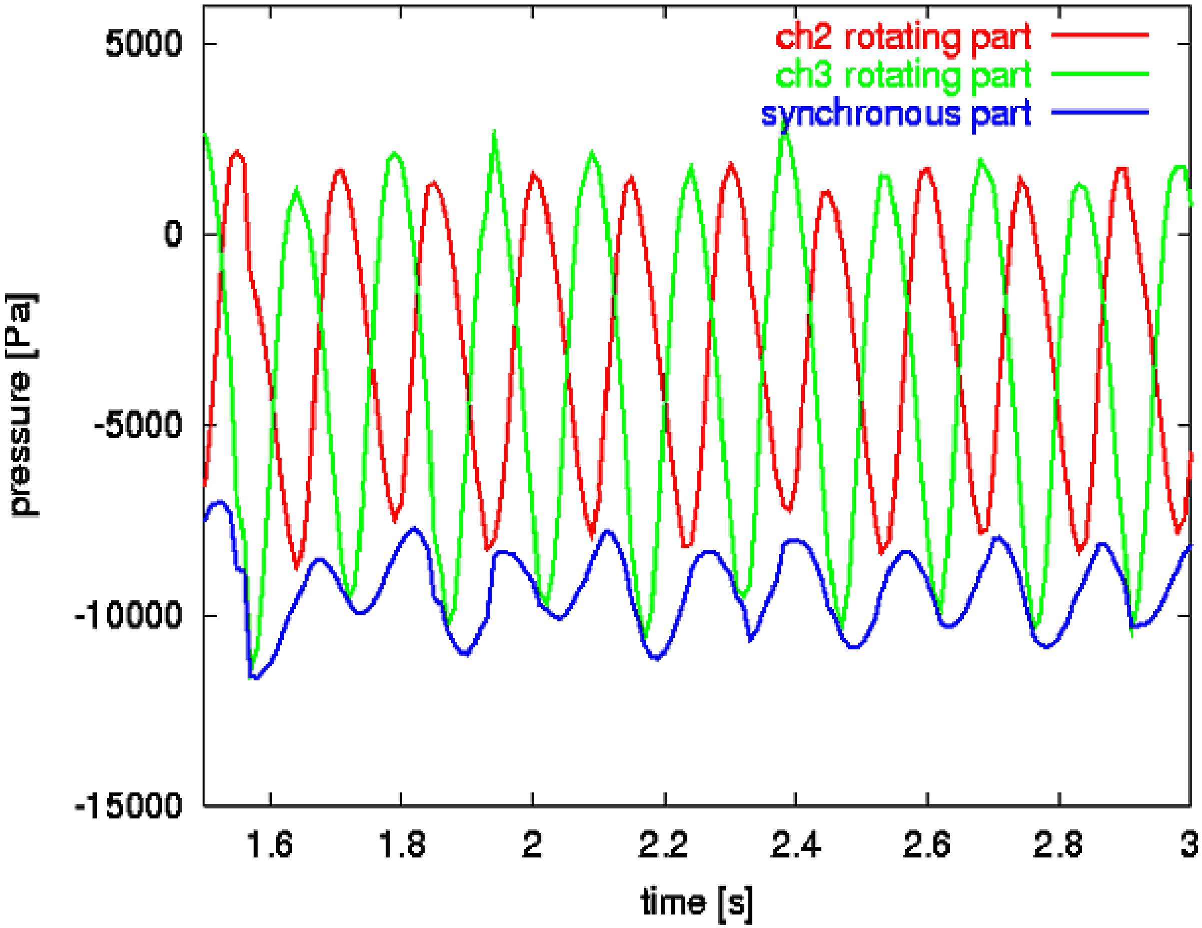
- Unstable flow can result in a vortex rope
- Vortex rope leads to a rotating pressure field
- Dynamic loading on the draft tube structure
- Synchronous pressure pulsation

    at the draft tube inlet

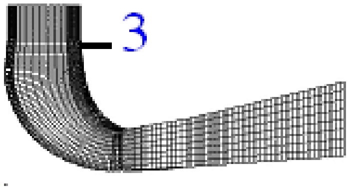


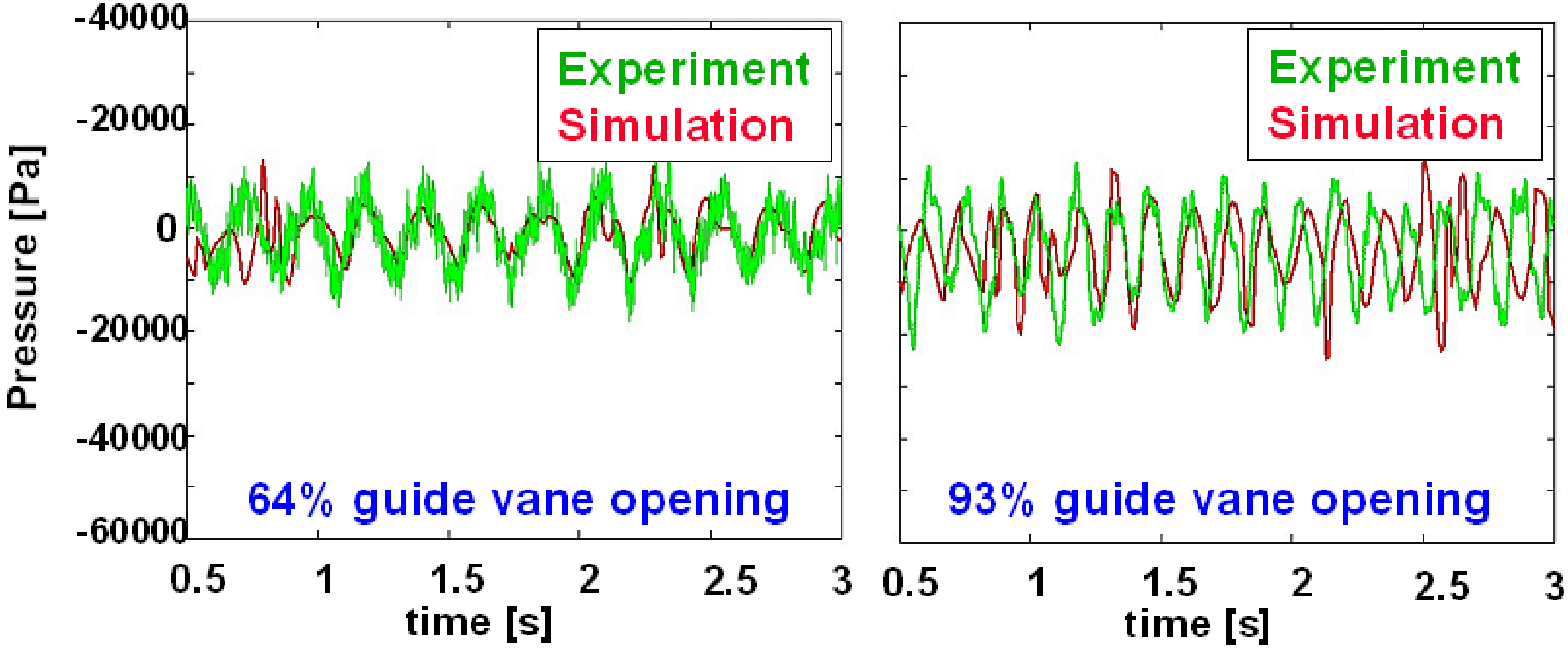


Modellturbine



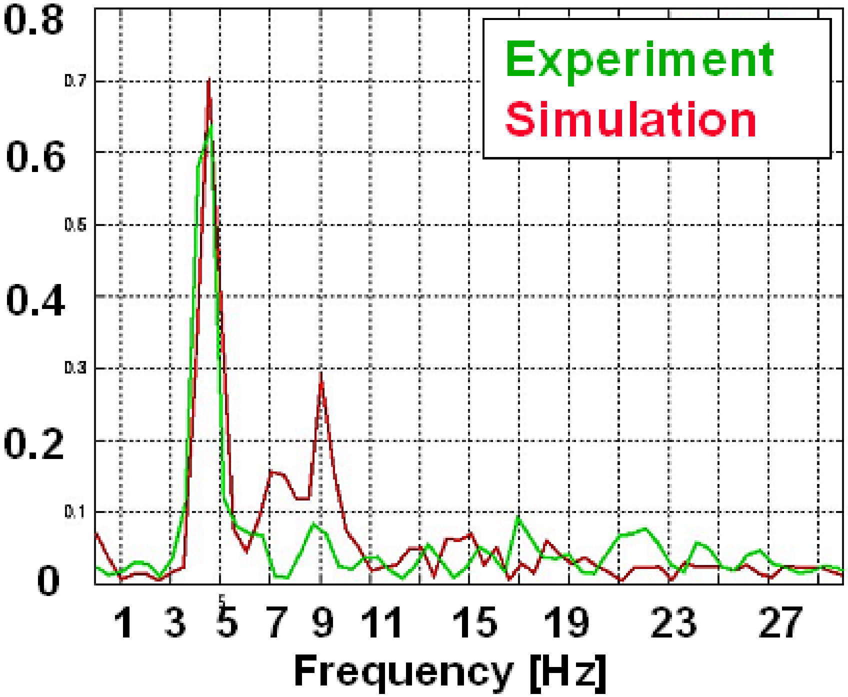
Vortex rope vibration



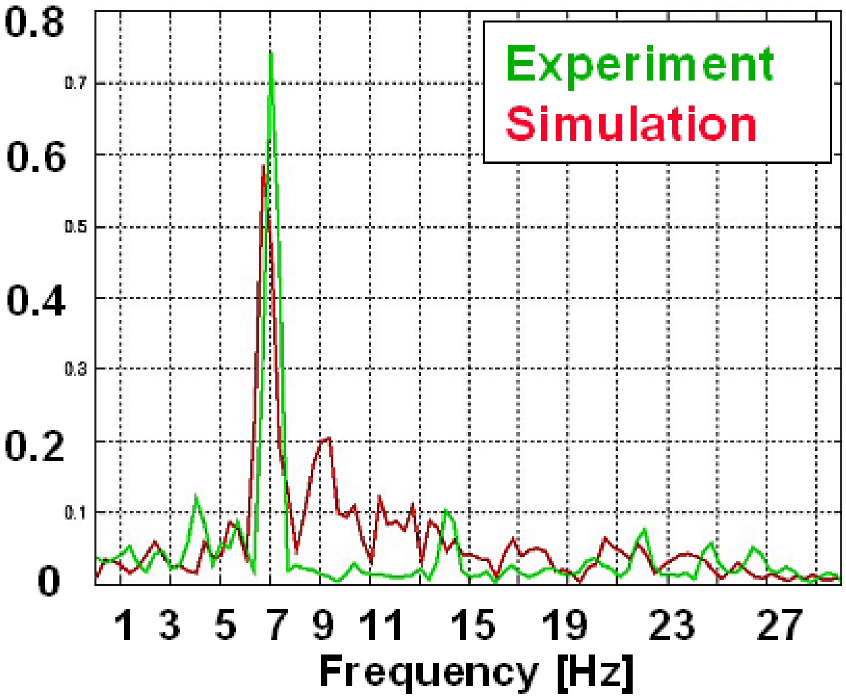


Model turbine

64% Guide vane opening



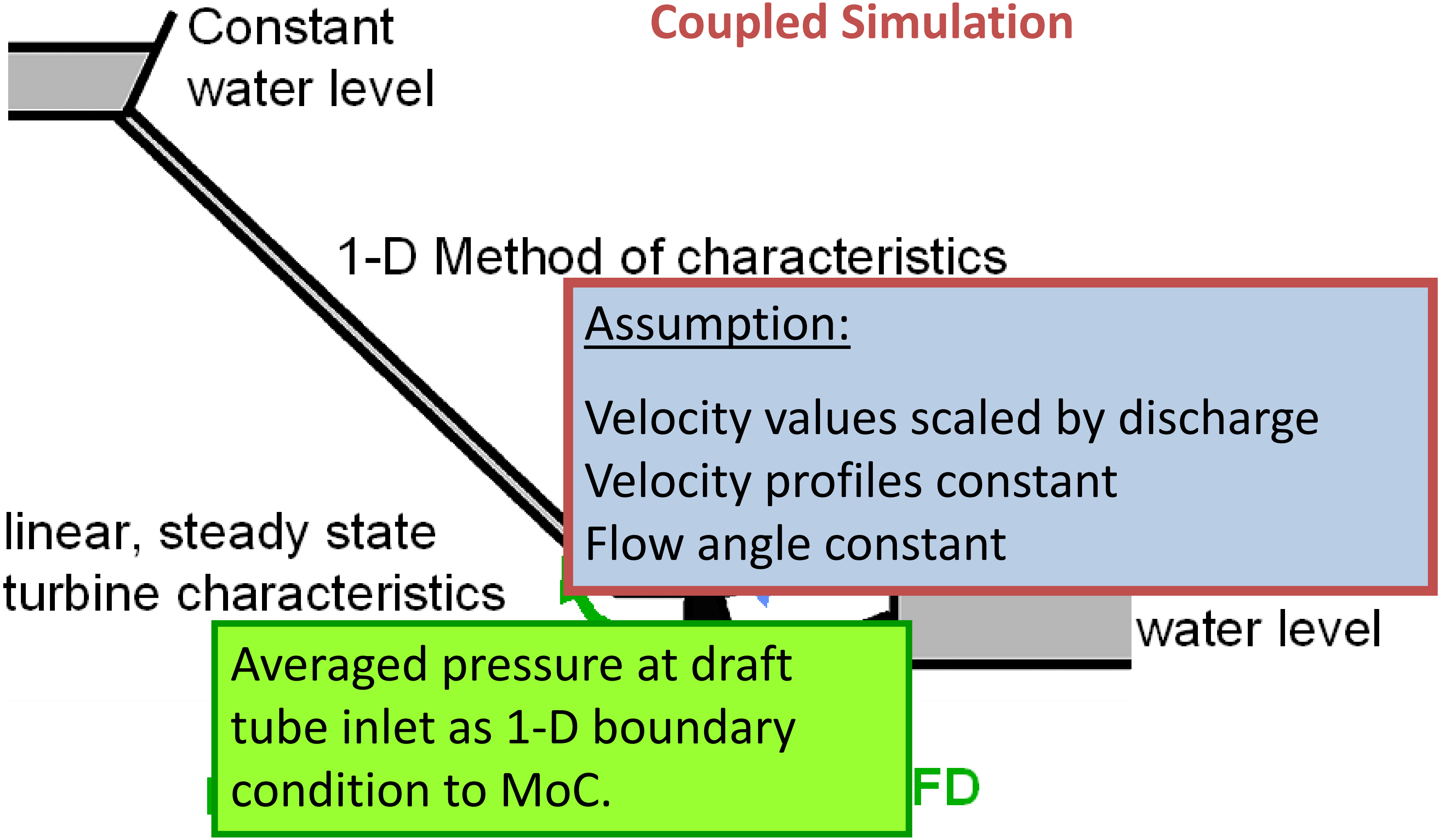
93% Guide vane opening



Model turbine

If the excitation is in resonance with the penstock, it can result in extreme pressure amplitudes

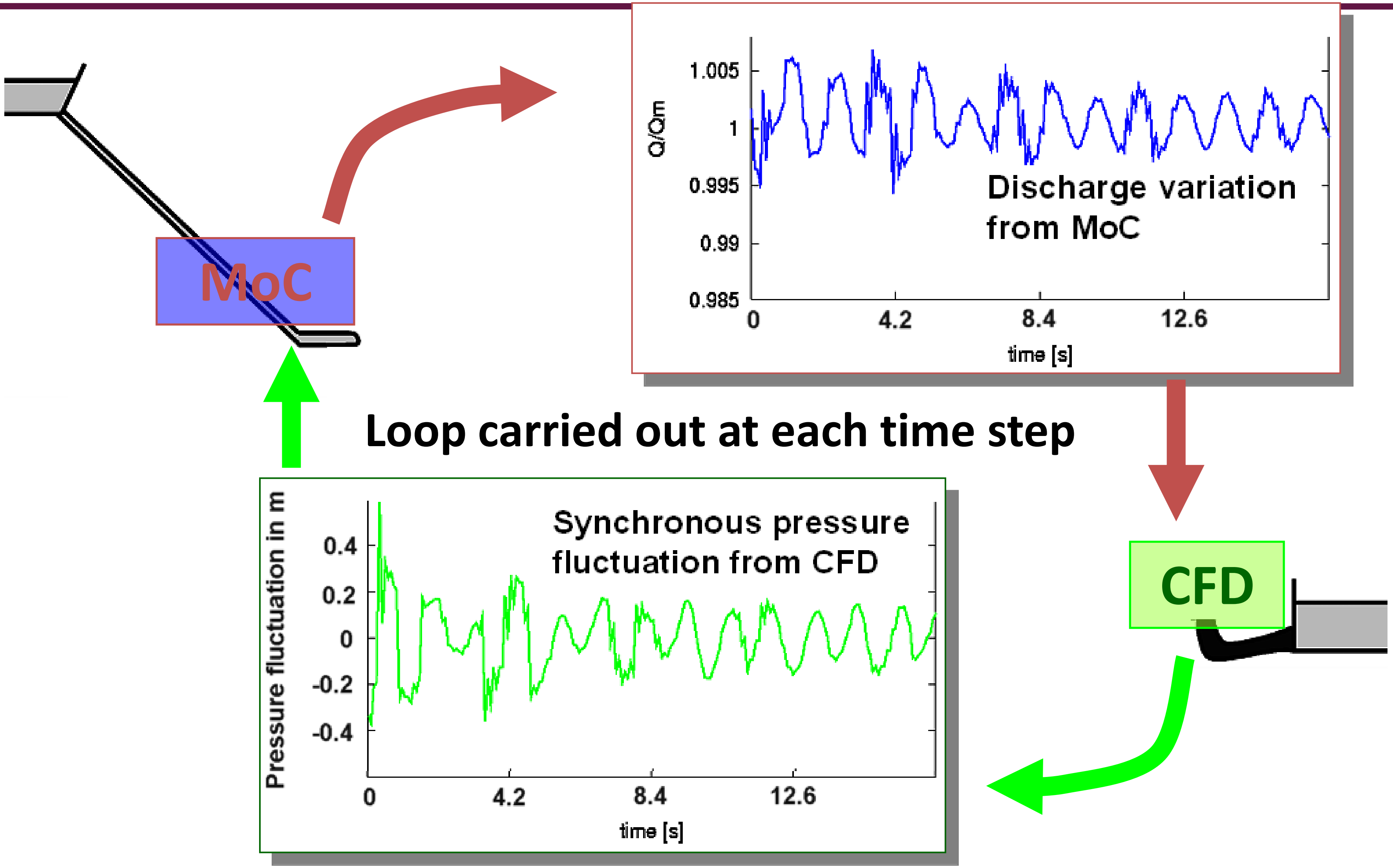
Coupled Simulation



<u>Assumption:</u>

Velocity values scaled by discharge
Velocity profiles constant
Flow angle constant

Averaged pressure at draft tube inlet as 1-D boundary condition to MoC.



MoC

Discharge variation from MoC

Loop carried out at each time step

Synchronous pressure fluctuation from CFD

CFD

Summary

- Relevant physical effects determine if a flow shall be treated incompressible or compressible

    Applying compressible calculation for low Ma leads to stiff problems, immense computational effort

- Gas flows can be treated incompressible up to a Ma = 0.3
- Liquid flows must be treated compressible when pressure waves plays an important role (resonance phenomena)
- Physical relevance For incompressible flows there exists no direct equation to determine the pressure. Therefore, a special treatment is required:
    - Artificial compressibility
    - Pressure correction
    - Poisson equation
    - Others
- Coupled simulations (partly compressible, partly incompressible) can be a good compromise