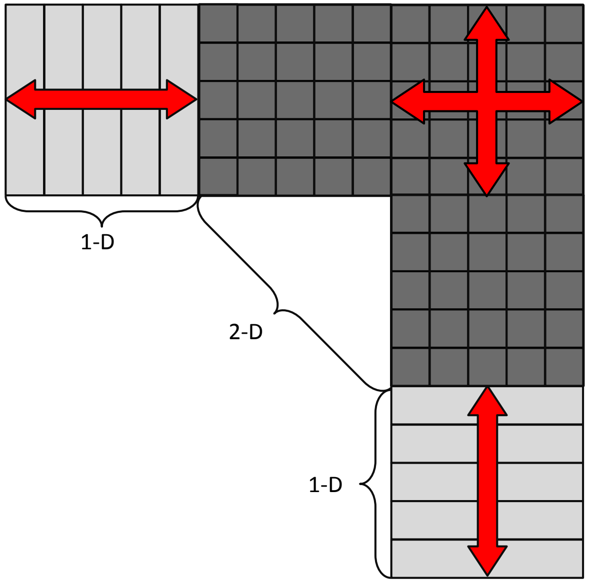
Transient simulation of a pneumatic sharp edged L-shaped pipe

Kratschun, Filipp
Enking, Joscha
Schmitz, Katharina



Institute for Fluid Power Drives and Systems
RWTH AACHEN UNIVERSITY

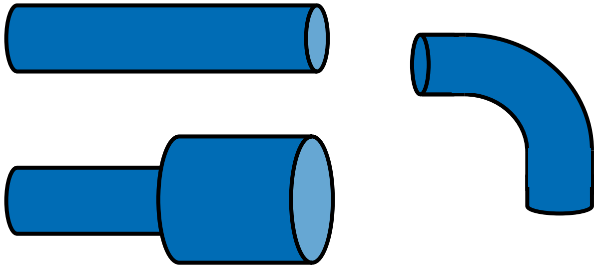
Motivation

System Prediction

- Increased dynamics in pneumatic systems
- Predictive Maintenance
- System prediction
- Time efficient system simulation

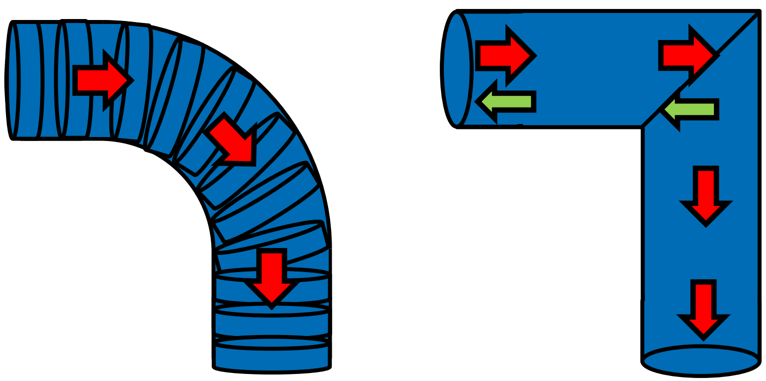
Trancient System Simulation

- Component library
- Basic pneumatic components
- One dimensional Riemann Solvers
- Limitation even for simple geometry



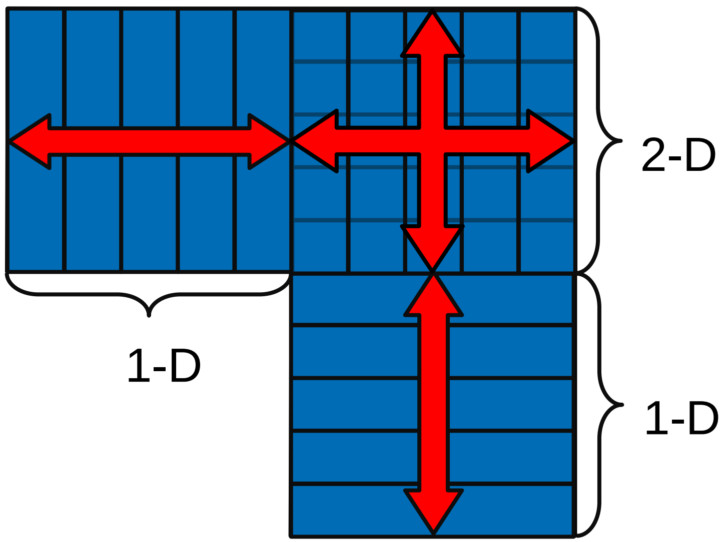
Sharp Edged Elbow

Smooth & Sharp Elbow



- Smooth elbow without reflection
- Sharp elbow with partial reflection
- Reflection in one dimensional solver not possible yet

1-D & 2-D Resolution



- Two dimensional solver needed
- Coupling between 1-D and 2-D required

1	Finite Volume Fundamentals and Approach
2	Analytical and Simulative Validation
3	Conclusion and Outlook

Fundamentals of Finite Volume Method

Fundamental Equations

Navier-Stokes-Equations

~~Friction~~

Euler-Equations

Mass
Momentum
Energy

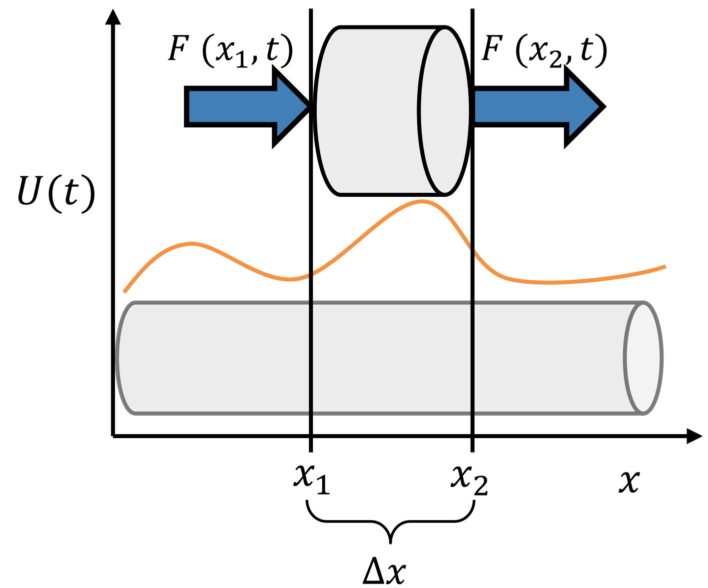
$$\begin{pmatrix} \rho \\ \rho v \\ E \end{pmatrix}_t + \begin{pmatrix} \rho v \\ \rho v^2 + p \\ v(E+p) \end{pmatrix}_x = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}$$

$$\frac{\partial U}{\partial t} = -\frac{\partial F}{\partial x}$$

Variable U

Flux $F(U)$

Integration in space



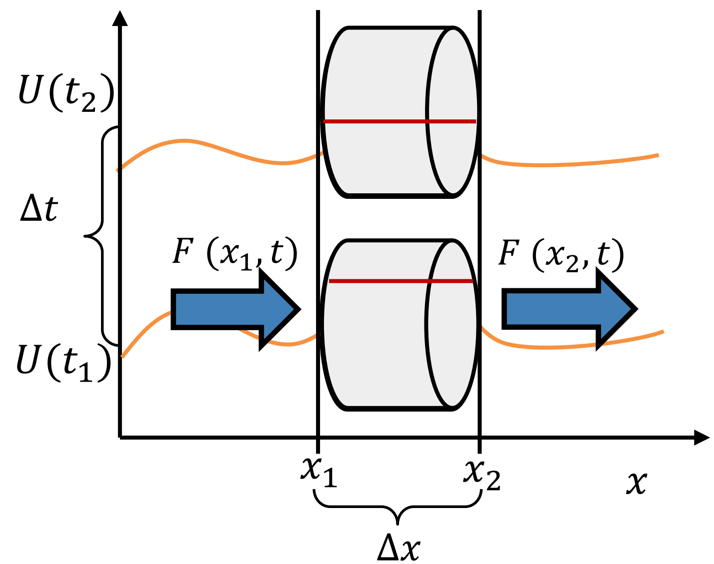
Integration within an arbitrary volume Δx

$$\int_{x_1}^{x_2} \frac{\partial U(x,t)}{\partial t}\, dx = -F(x_2, t) + F(x_1, t)$$

Fundamentals of Finite Volume Method

Integration in time

$$\underbrace{\int_{t_1}^{t_2}\int_{x_1}^{x_2}\frac{\partial U(x,t)}{\partial t}\,dxdt}_{①} = \underbrace{-\int_{t_1}^{t_2}\big(F(x_2,t)-F(x_1,t)\big)dt}_{②}$$



① $\int_{x_1}^{x_2} U(x,t_2)dx - \int_{x_1}^{x_2} U(x,t_1)dx \quad | \div \Delta x$

Fluxes are integrated in time numerically

② $\Delta t\big(F(x_2,t)-F(x_1,t)\big) \quad | \div \Delta x$

① $\tilde{U}\big(x_{\overline{2,1}},t_2\big)-\tilde{U}\big(x_{\overline{2,1}},t_1\big)$

② $\big(F(x_2,t)-F(x_1,t)\big)\frac{\Delta t}{\Delta x}$

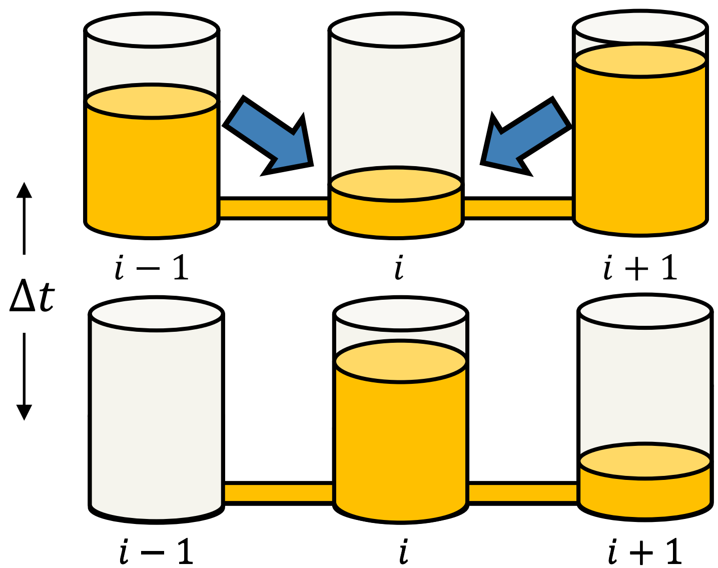
Numerical error due to Δt possible!

$$\tilde{U}\big(x_{\overline{2,1}},t_2\big)=\tilde{U}\big(x_{\overline{2,1}},t_1\big)-\frac{\Delta t}{\Delta x}\big(F(x_2,t)-F(x_1,t)\big)$$

Riemann Solver

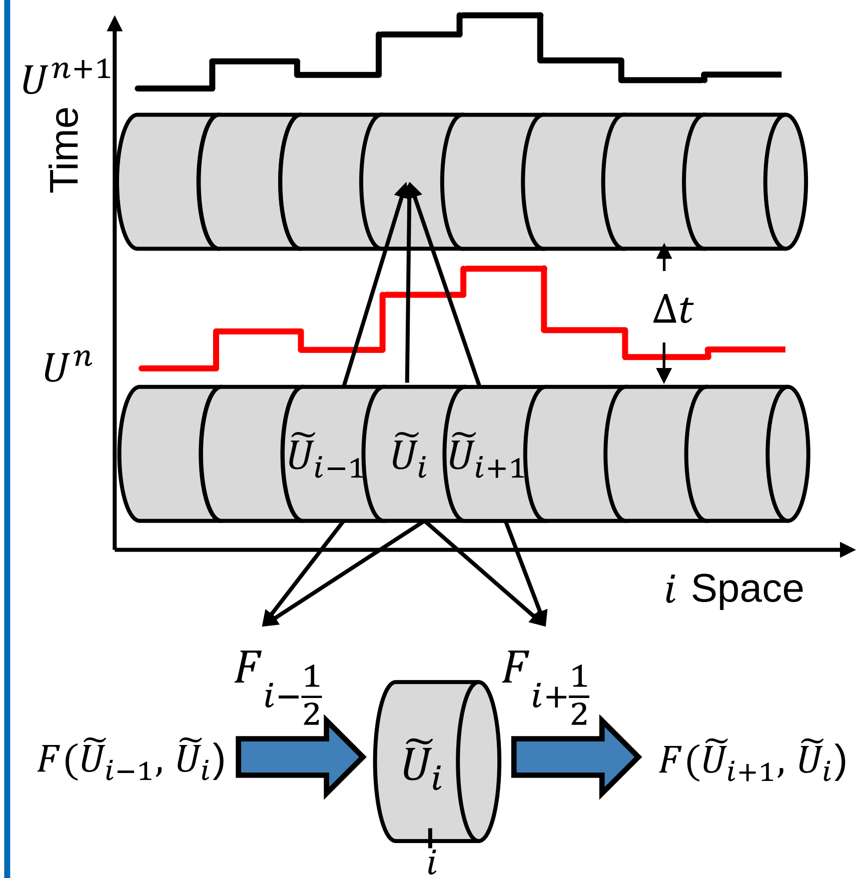
CFL-Criteria

$$\widetilde{U}_i^{n+1} = \widetilde{U}_i^n - \frac{\Delta t}{\Delta x}\left(F_{i+\frac{1}{2}} - F_{i-\frac{1}{2}}\right)$$



waiter‘s time $\Delta t < \frac{\Delta x}{c}$ glas volume / drinking speed

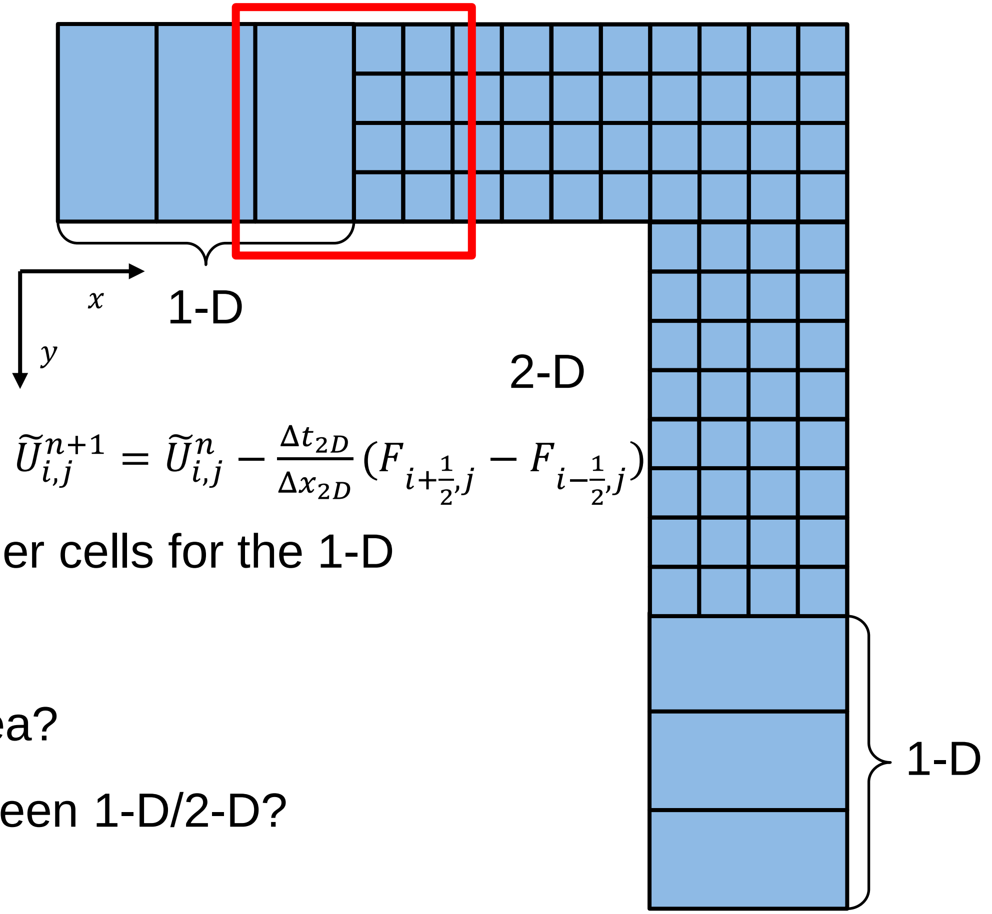
Flux Definition



Two Dimensional Elbow

Coupling 2-D with 1-D elements

Coupling for given Δt in 1-D elements

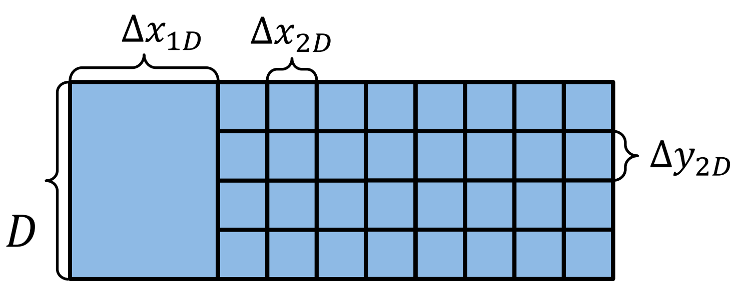


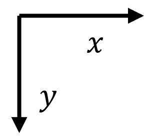
$$\tilde{U}_{i,j}^{n+1} = \tilde{U}_{i,j}^{n} - \frac{\Delta t_{2D}}{\Delta x_{2D}} \left(F_{i+\frac{1}{2},j} - F_{i-\frac{1}{2},j}\right)$$

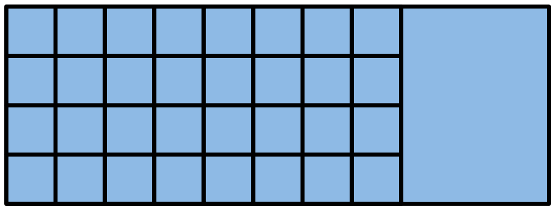
1. How to average the 2-D border cells for the 1-D elements?
2. How to discretise the 2-D area?
3. How to build the Fluxes between 1-D/2-D?

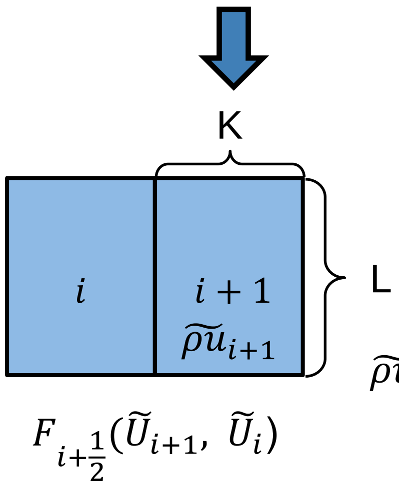
Two Dimensional Elbow

Idea: Conservative Averaging





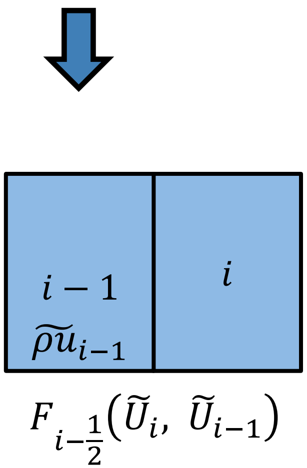




1: Δx_{2D} fits exactly K times into Δx_{1D}

2: Δy_{2D} fits exactly L times in D

$$\widetilde{\rho u}\Delta x D = \Delta x_{2D}\Delta y_{2D}\left(\sum_{i=1}^{i=K}\sum_{j=1}^{j=L}(\rho u_{i,j}) + \left|\sum_{i=1}^{i=K}\sum_{j=1}^{j=L}(\rho v_{i,j})\right|\right)$$



Averaging and mesh generation

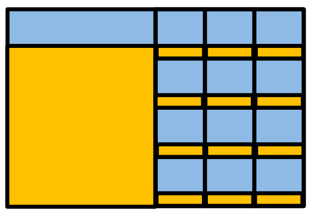
Two Dimensional Elbow

Problem 2-D Solver‘s border

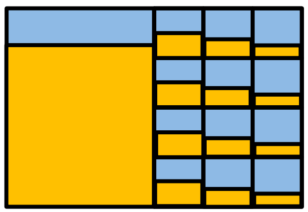
Smaller volume and greater c

$$\Delta t_{2D} < \frac{\Delta x_{1D}}{c_{2D} K} \quad \Rightarrow \quad \Delta t_{2D} = \frac{1}{2}\frac{\Delta t_{1D}}{K}$$

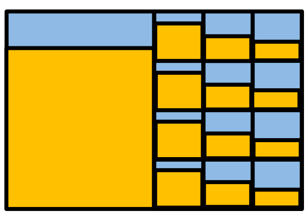
t_1



$t_1 + \frac{1}{2}\Delta t_{1D}$



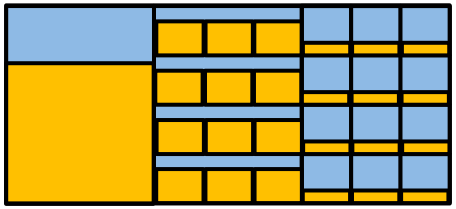
$t_1 + \Delta t_{1D}$



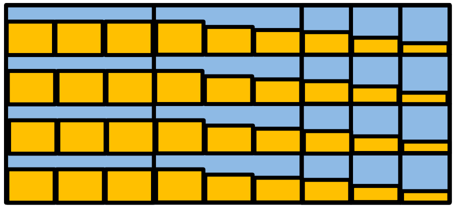
Idea: Buffer Cell+Dynamic Mesh

Additional buffer cell

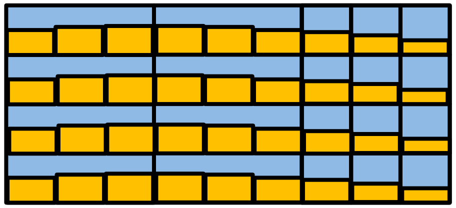
t_1



$t_1 + \frac{1}{2}\Delta t_{1D}$



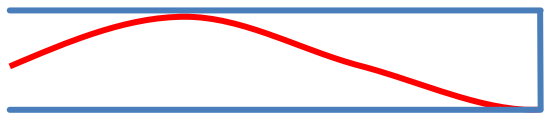
$t_1 + \Delta t_{1D}$



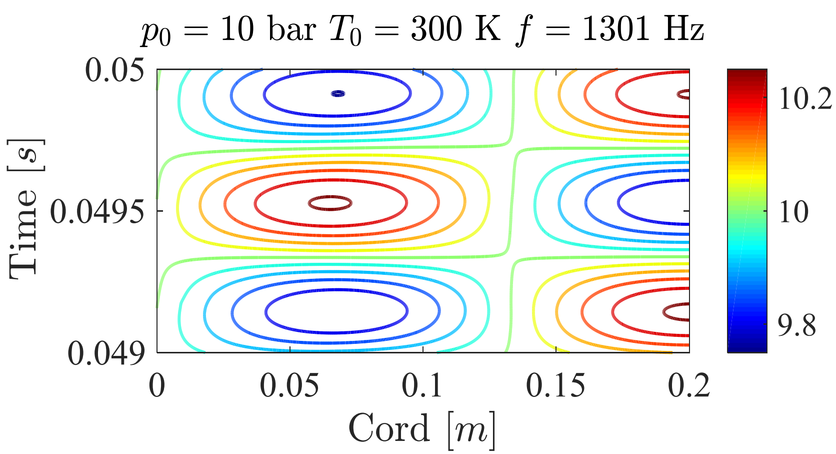
Acoustic Theory Validation

1D Pipe

Closed end standing wave

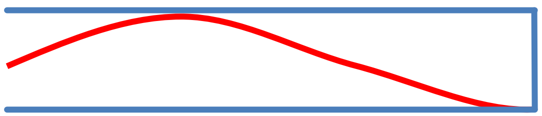


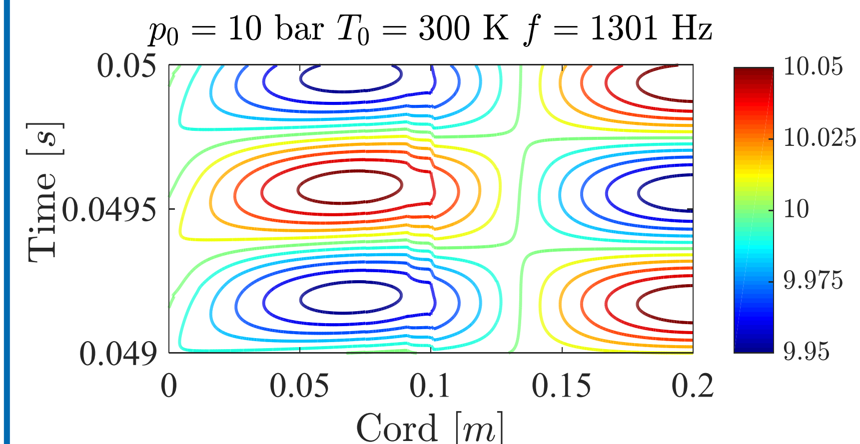
$$f = \frac{3a}{4L}$$



2D Elbow

Closed end standing wave



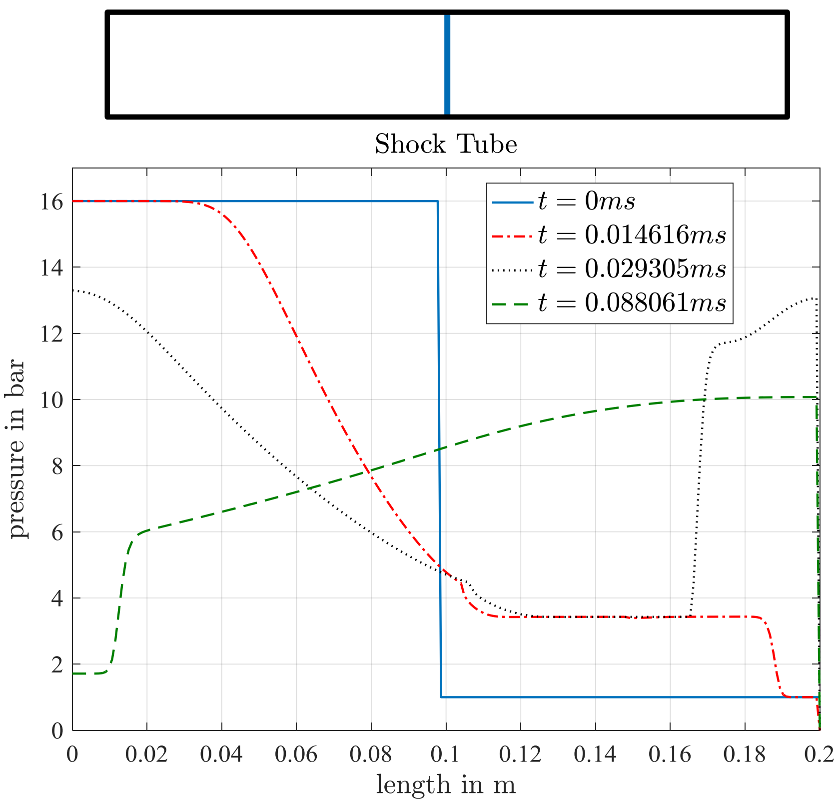


- Correct resonance pattern
- Lower magnitude

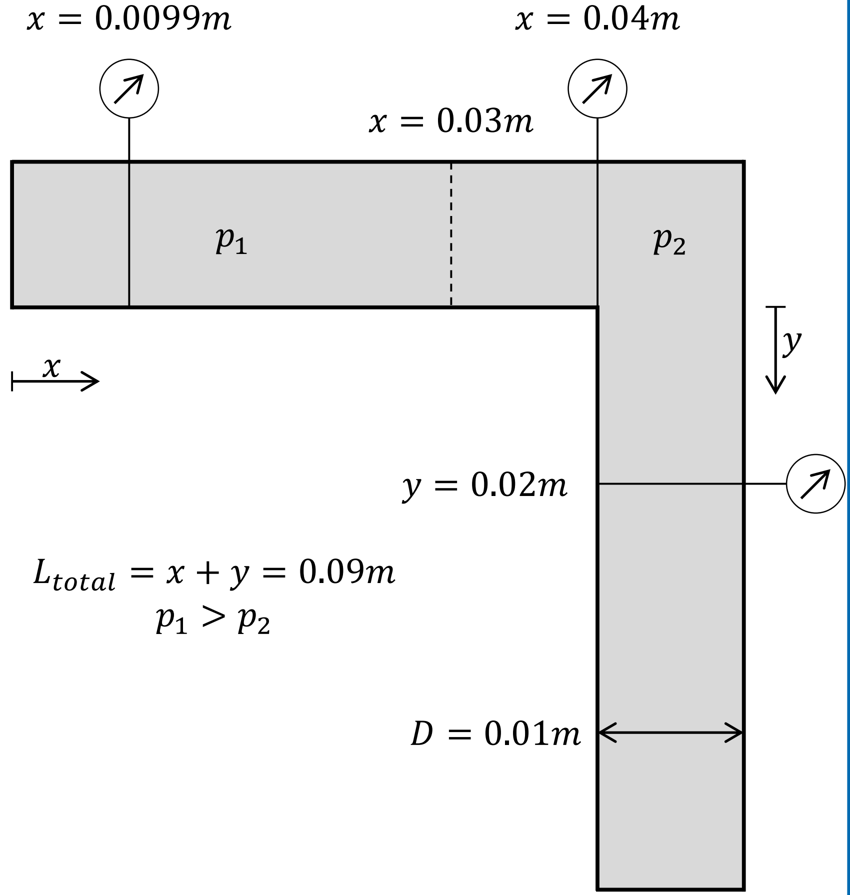
Shock Tube Theory

1D Pipe

Sod‘s Shock Tube Test

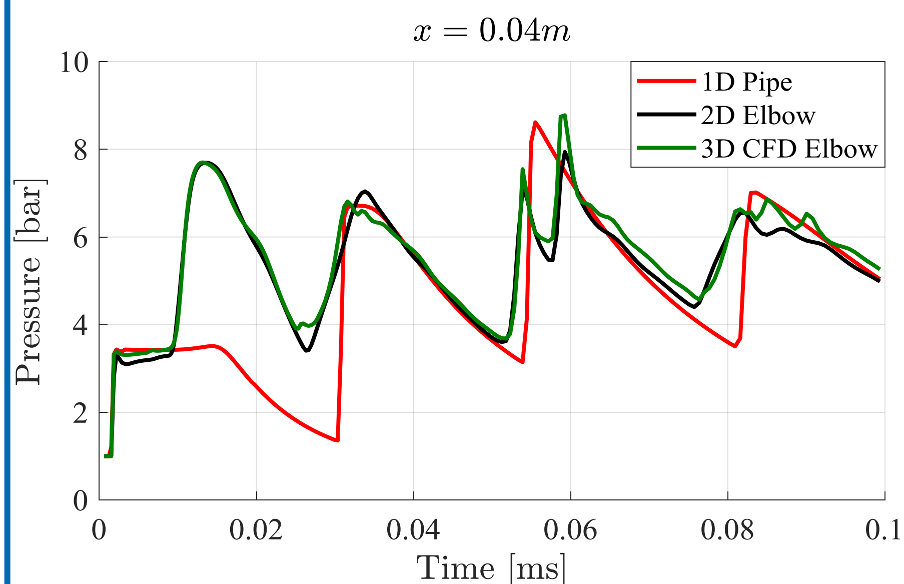


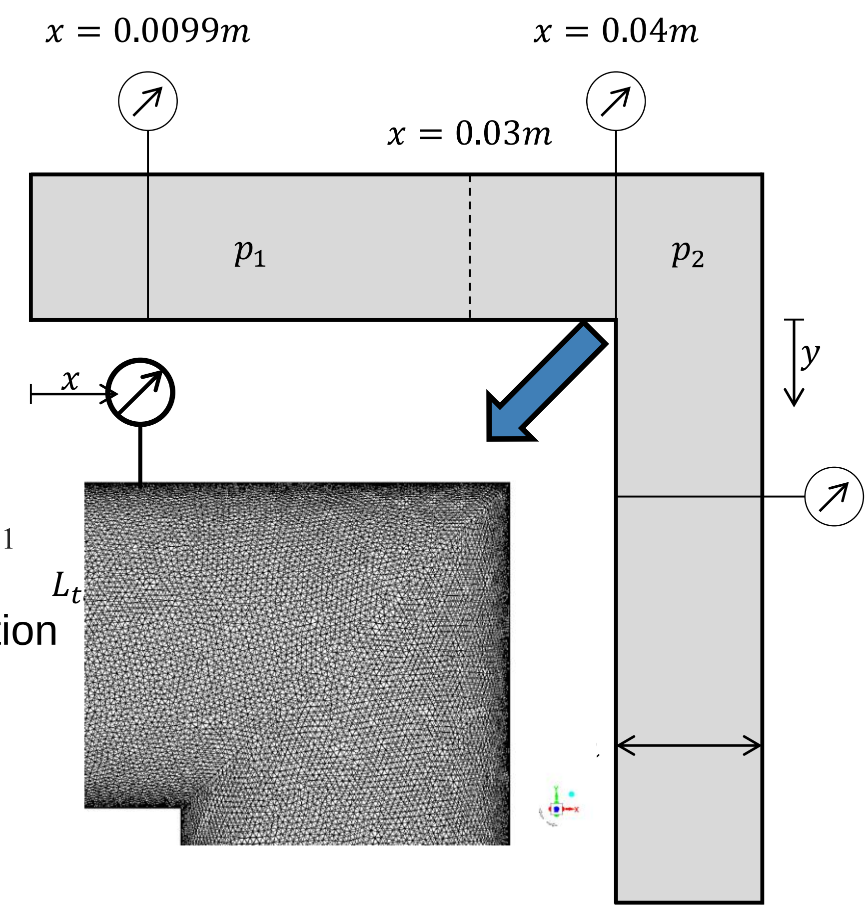
2D Elbow



Shock Tube Theory

Comparison to CFD



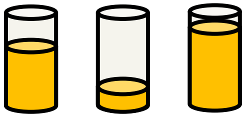


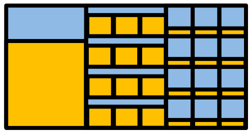
- Partial reflection corresponds to CFD solution
- Phase and amplitude accurate
- Deviation 2D elbow 7%
- Deviation 1D elbow above 20%

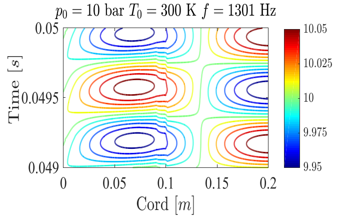
Conclusion and Outlook

Conclusion

- Fundamentals of Finite Volume
- 2D/1D-Coupling
- Analytical and simulative validation

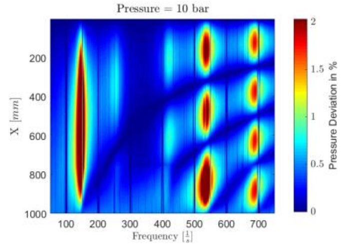


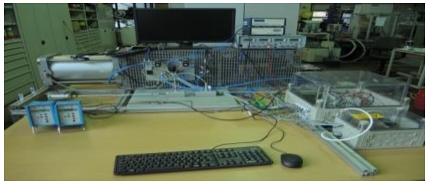




Outlook

- Acousctic reflection coefficient
- Curvature influence by source term modulation
- Test rig validation





Thank you for your attention!

Contact:

- Kratschun, Filipp
- filipp.kratschun@ifas.rwth-aachen.de