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CORPORATE TECHNOLOGY

COMPUTATIONAL AEROACOUSTICS INCLUDING FLUID-STRUCTURE-COUPLING WITH THE FINITE-ELEMENT- AND THE LATTICE BOLTZMANN-METHOD

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Corporate Technology

Production Processes
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Overview:

- Motivation
- Basics of Applied Methods
- Coupling approach
- Realization
- Examples
- Summary

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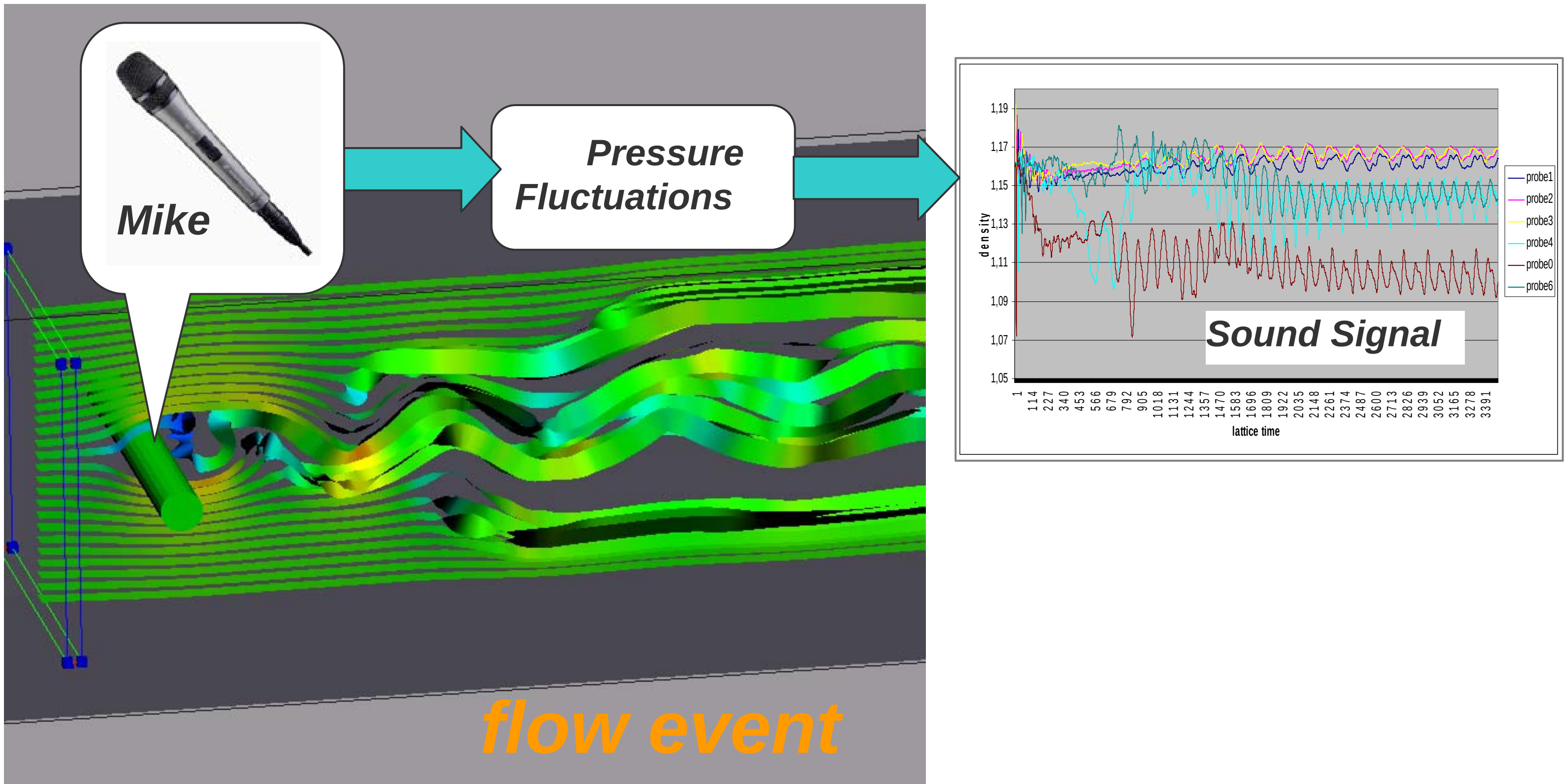
Aeroacoustics:

Flow Events lead to Sound Generation



Pressure Fluctuations in the hearable Range:
ca. 16-20 000 Hz,
ca. 20 dB (Hearing Threshold) –
130 dB (Threshold of Noise Pain)

}

Sound

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Flow Induced Sound…

i.e. Wind, Ventilation, Cooling …

- ***Flow around Obstacles ("v. Kármàn Eddy Streets")***
- ***Flow over Openings (Windows / Slots ...)***
- ***Moving Structures (Fans, Rotors)***
- ***Turbulence (i.e. Open Jets, Eddy Separation)***
- ***Oscillating Air Columns (Music Instruments)***
- ***Modulated Air Flows (Sirens, Human Voice)***
- ***Supply / Removal of Media (Explosions, Cavitation)***

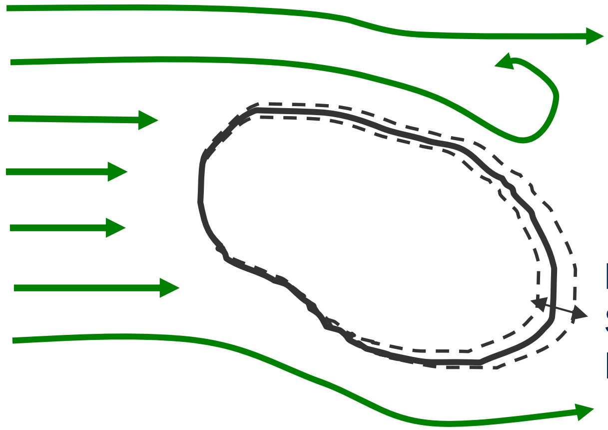
Interaction with structures

Structures can be

- ***Obstacles within a Flow*** ***or***
- ***Enclosures of Streaming Media***

A Flow leads to

- *Pressures Acting upon a Structure*
- *Deformation / Movement of a Structure*



These may lead to:

- *Variation of the Flow Enclosures*
- *Variation of the Fluids Boundary Conditions*

3 subproblems:

- Flow Field
- Acoustic Field
- Structure-mechanical Behaviour

different

- Numerical Approaches
- Discretization Requirements
- Frequencies, Scales ...

Flow Field	Acoustic Field	Structure Mechanics
"classical" CFD (Finite Volume Methods)	(Boundary Element Method, Finite Element Method)	(Finite Element Method)

Flow and Acoustic Field:

Basic Step:
Solution of the Flow Problem
Navier-Stokes Equations
(containing the Acoustic Behaviour)

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \vec{u}_i)}{\partial x_i} = 0$$ ***(Continuity)***

$$\rho \left(\frac{\partial u_j}{\partial t} + u_i \frac{\partial u_j}{\partial x_i} \right) = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3} \delta_{ij} \frac{\partial u_i}{\partial x_i} \right) \right] + \rho g_j$$ ***(Momentum)***

$$\rho c_p \left(\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} \right) = \lambda \cdot \frac{\partial^2 T}{\partial x_i^2} + \frac{\partial P}{\partial t} + \mu \phi$$ ***(Energy)***

Resolution of

- ***Acoustic Wavelength***
- ***Relevant Flow Scales***

The Lattice Boltzmann-Method

Statistical Physics: Dynamics of Particle Distribution Probabilities (Boltzmann equation)

$$\frac{\partial f}{\partial t} + \vec{\xi}\,\frac{\partial f}{\partial \vec{x}} = \Omega(f)$$

Simplified Collision Operator (Bhatnagar, Gross, Krook), Valid for Ideal Gases / low Knudsen Numbers

$$\Omega(f) = -\frac{1}{\tau}\left(f - f^{(0)}\right)$$

Discretization in the microscopic Velocity Space (Discrete Boltzmann Equation)

$$\frac{\partial f}{\partial t} + \vec{e}_i\,\frac{\partial f}{\partial \vec{x}} = -\frac{1}{\tau}\left(f - f^{(0)}\right)$$

Discretization in Space and Time (Lattice-Boltzmann Equation)

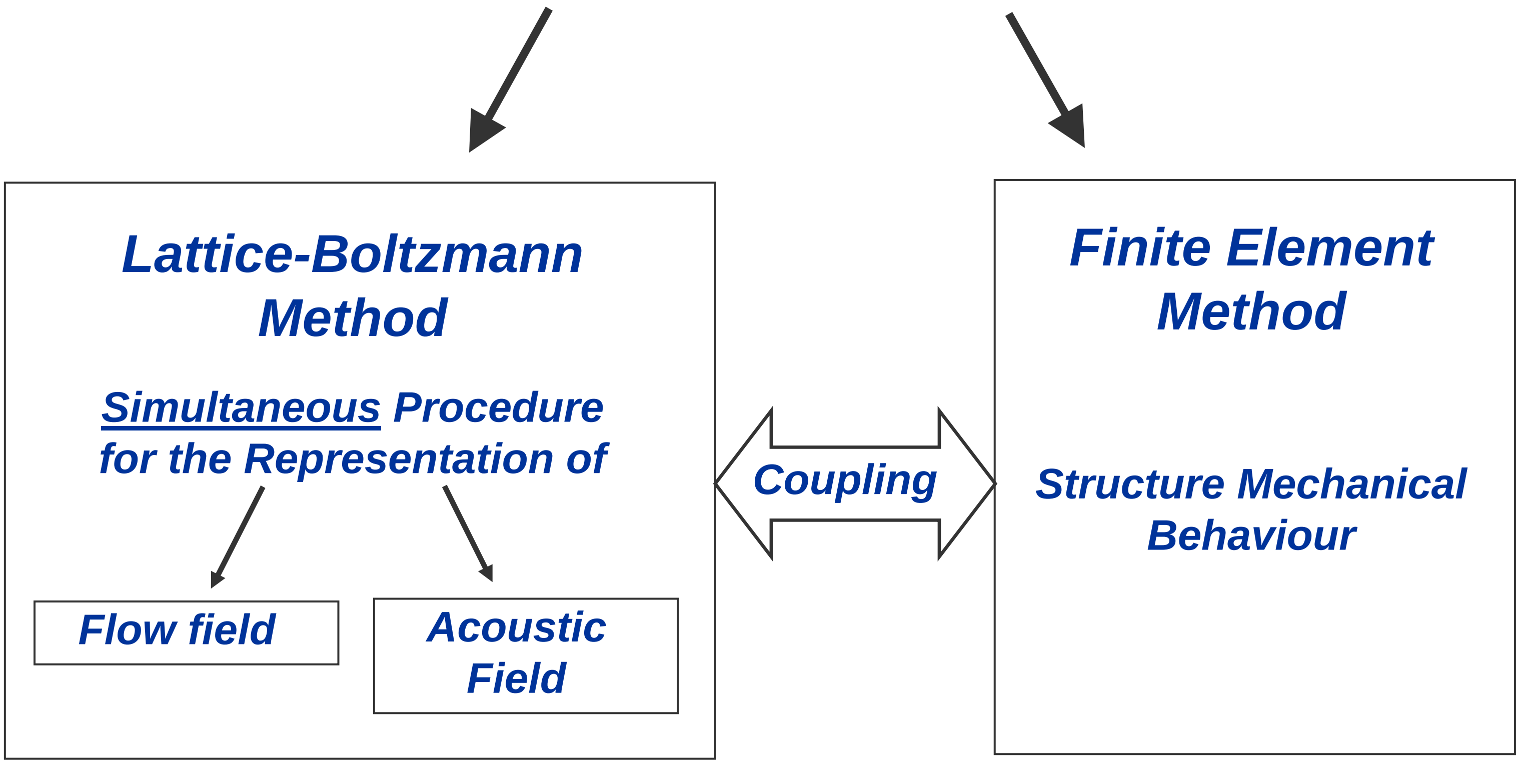
$$f_i\left(t + \Delta t, \vec{x} + e_i \Delta t\right) = $$
$$= f_i\left(t, \vec{x}\right) - \frac{\Delta t}{\tau}\left(f_i\left(t, \vec{x}\right) - f_i^{(0)}\left(t, \vec{x}\right)\right)$$

Some Characteristics of the Lattice-Boltzmann Method

- ***Description of the Movement of Distribution Probabilities f (t,x_i,ξ_i) on a regular Grid***
- ***Approximation of (macroscopic) Navier-Stokes Equations***
- ***Simulations always transient, explizcit Method***
- ***Weak Compressibility (expansion around equilibrium distribution $f^{(0)}$)***
- ***Validity: low Mach Numbers (< 0.3 – 0.4)***
    - ***Sound Waves resemble small Disturbances within a Flow***
    - ***Lattice-Botzmann Method contains the Description of linear Wave Propagation***

Coupling Approach (1)

Partitioned Approach:



Coupling Approach (2)

Fluid
(Lattice-Boltzmann Method)

Pressures on Surfaces →

← Acceleration, Velocity

Structure
(Finite Element Method)

Software:

- ***Comercially Available Software Tools (Exa PowerFlow, ANSYS), executed als Child-Processes by the Coupling Routine***
- ***Advantages:***
  - ***Utilization of necessary and existing Features*** *(Turbulence Model, Distributed Computing, Element Libraries, Material Models, Optimized Solvers …)*
  - ***Industrial Standard***
- ***Disadvantages :***
  - ***Limited Possibilities of Interference with Programs***
  - ***Data Exchange Difficult***

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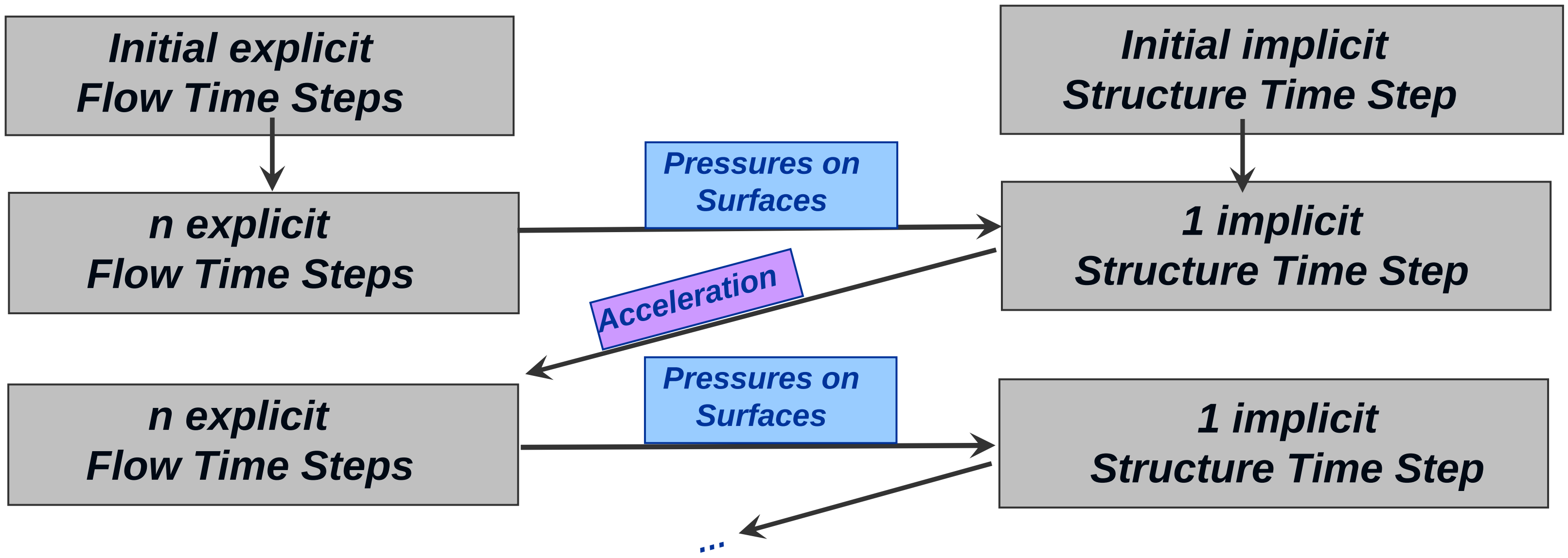
Coupling Algorithm:



2 Interfaces required:

Interface 1

Structure Results ⇒ Fluid

Interface 2

Fluid Results ⇒ Structure

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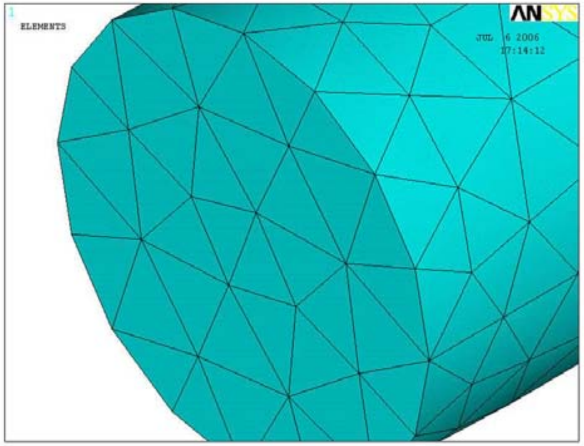
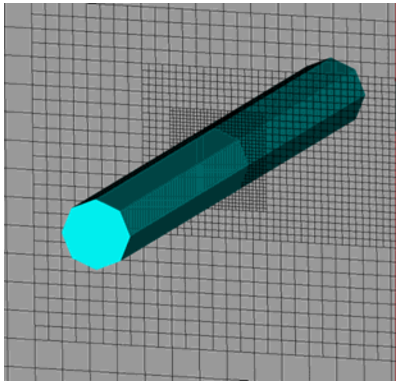
Data exchange between FE Mesh and CFD Grid

Structure:
FE Mesh



Fluid:
Regular Grid,
Surface Facets



Interface 1:

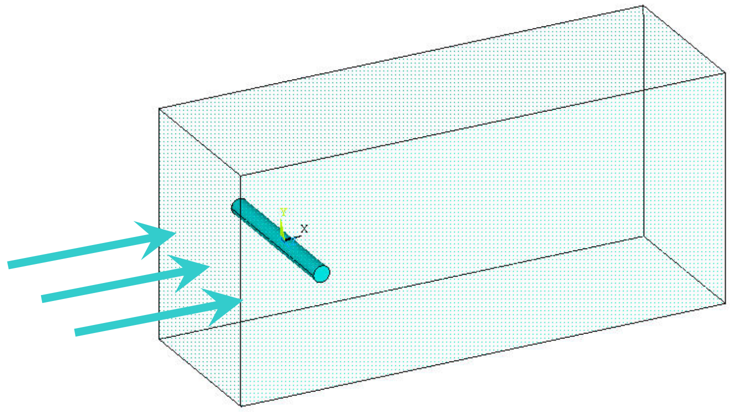
- ***Inter-, Extrapolation of Velocities on the Surface to a Grid suitable for the respective Frequencies***
  - ***suitable Accuracy for Sound Radiation Problems***
  - ***low Number of Export Values***
- ***Interpolation onto Surface Facets in the Flow Model***

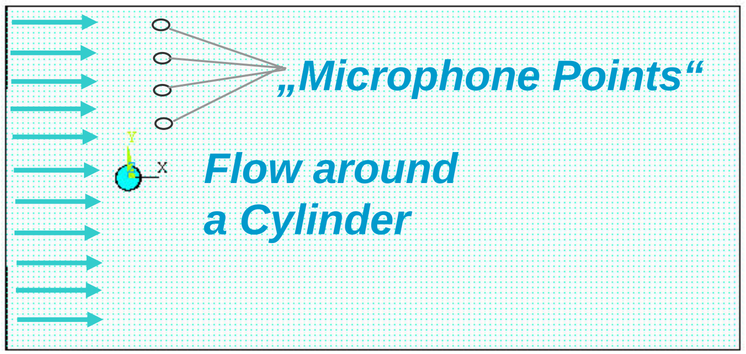
Interface 2:

- ***Flow Pressures: ‚Closest Facet' –Information for Pressure Load***
- ***Export, Application on FE-Mesh***

Example 1:
One-directional Coupling: Flow - Structure

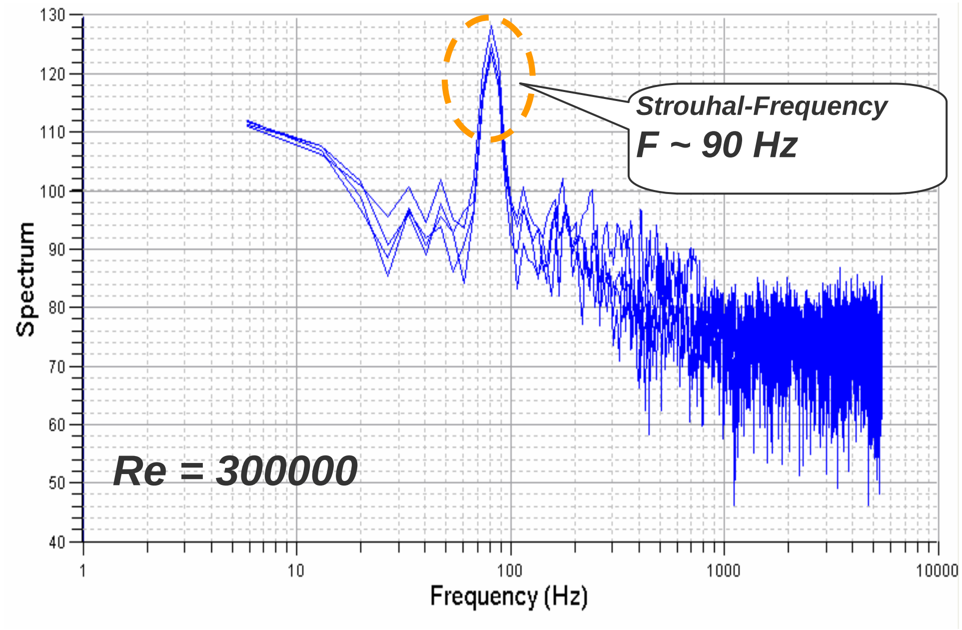
Flow around a Cylinder:
- ***Aeolian Tones***
- ***v. Kármàn Eddy Street***
- ***Digital Wind Tunnel:***





Example 1:
One-directional Coupling: Flow - Structure

- ***Analysis in the Frequency Domain***
- ***Frequency Spectrum***
- ***Identification of narrow-banded Sound***
- ***Frequency according to Strouhal Number***



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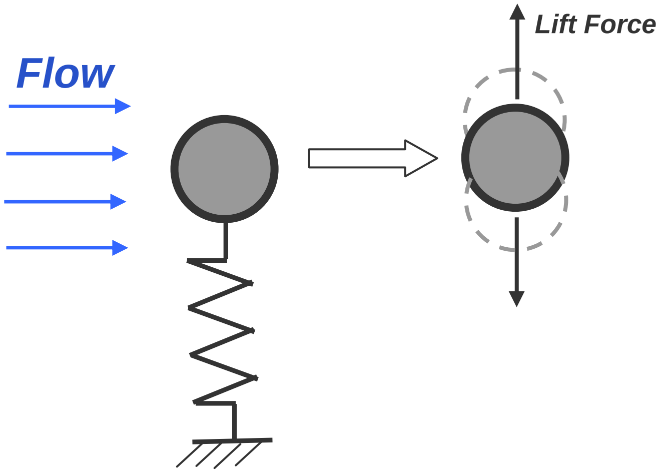
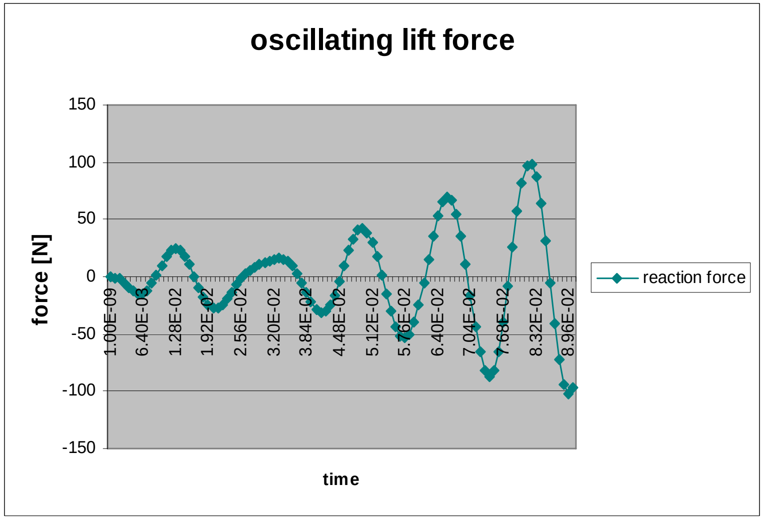
One-directional coupling: Flow - Structure Elastically Beded, Rigid Cylinder

Flow leads to an oscillating Lift Force of the Frequency $f_{Strouhal}$

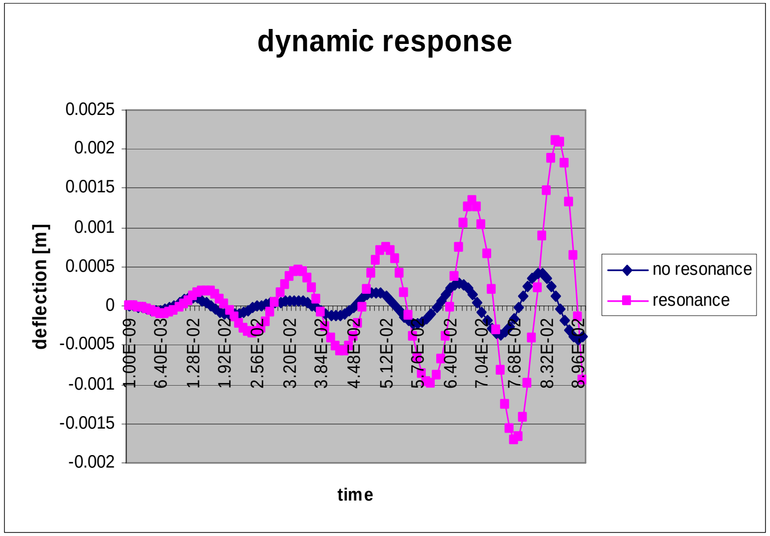




Structure dynamical answer:

1.) Eigenfrequency $\neq f_{Strouhal}$
no Resonance

2.) Eigenfrequency = $f_{Strouhal}$
Resonance,
Phase shift = π



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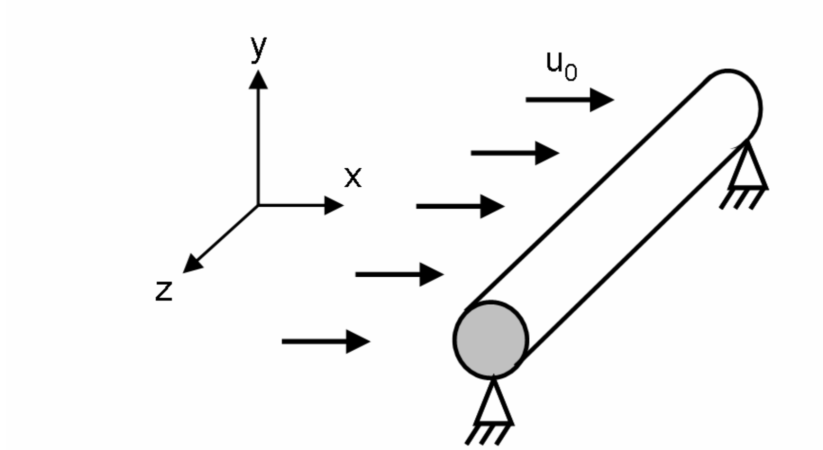
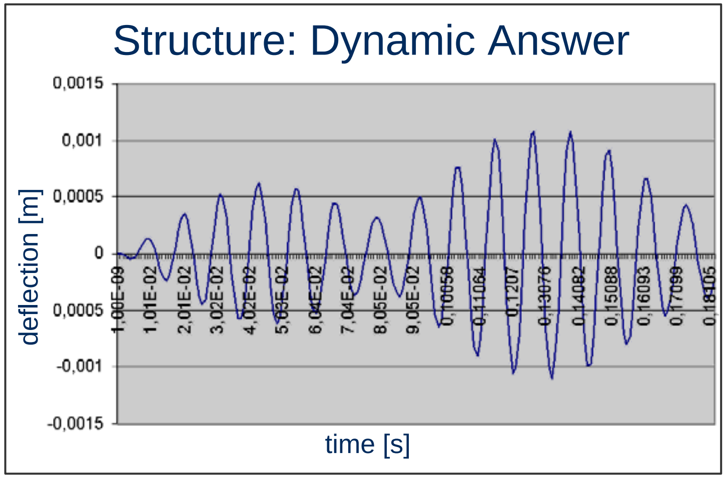
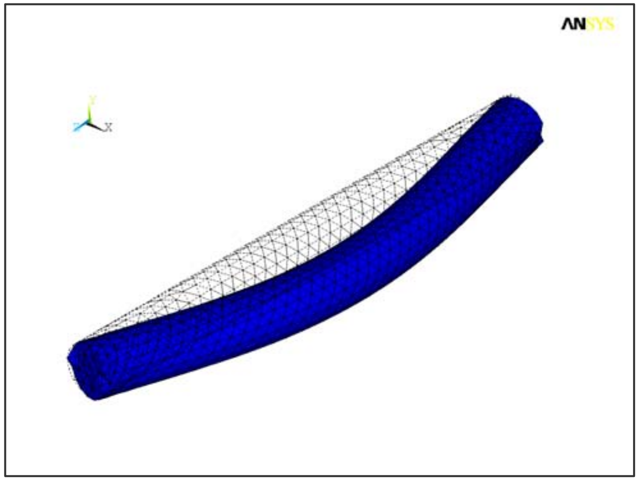
One-directional Coupling: Fluid - Structure End-Fixed, Elastic Cylinder

- **Alternating Pressures lead to bending Oscillations**







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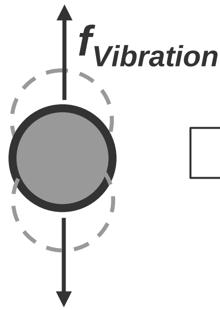
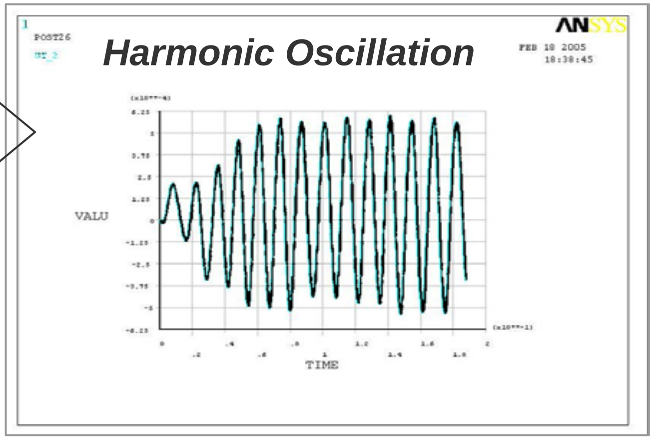
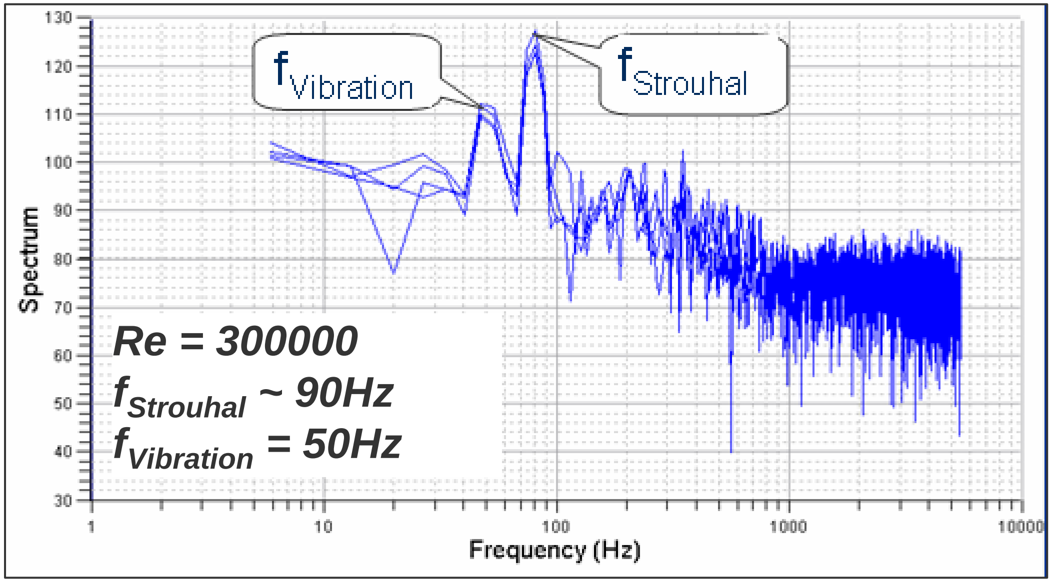
Example 2: One_directional Coupling: Structure - Fluid

- ***Flow around a rigid Cylinder***
- ***Forced, harmonic Oscillation of the Body***
- ***Vibrations cause further Sound Phenomena***







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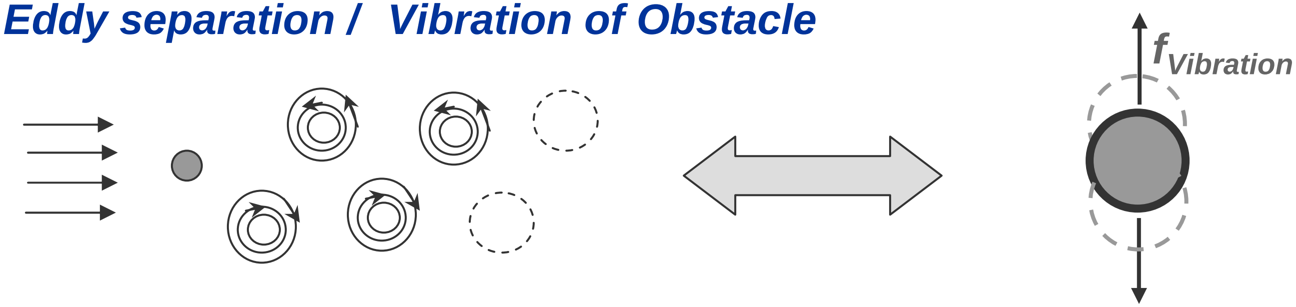
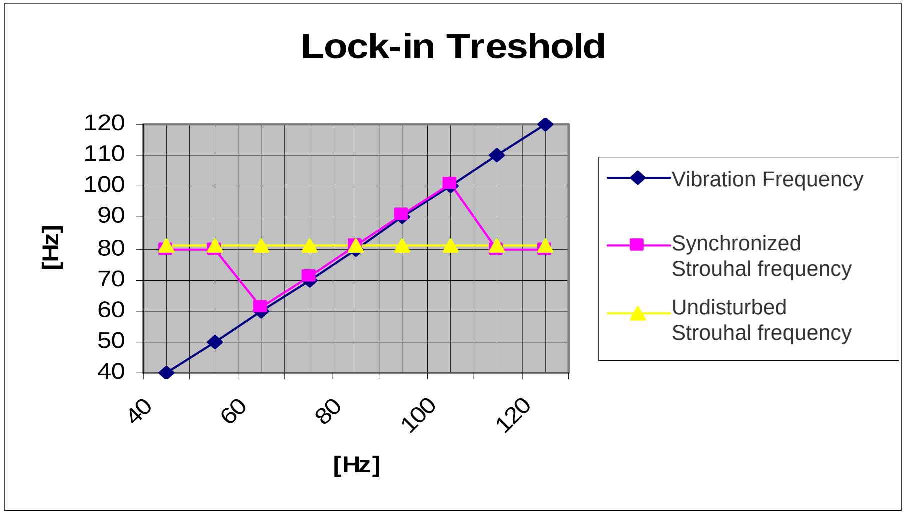
One Directional Coupling: Structure – Fluid Lock-in Effect

Interaction of weakly coupled Oscillators

Coupling of:

Eddy separation / Vibration of Obstacle





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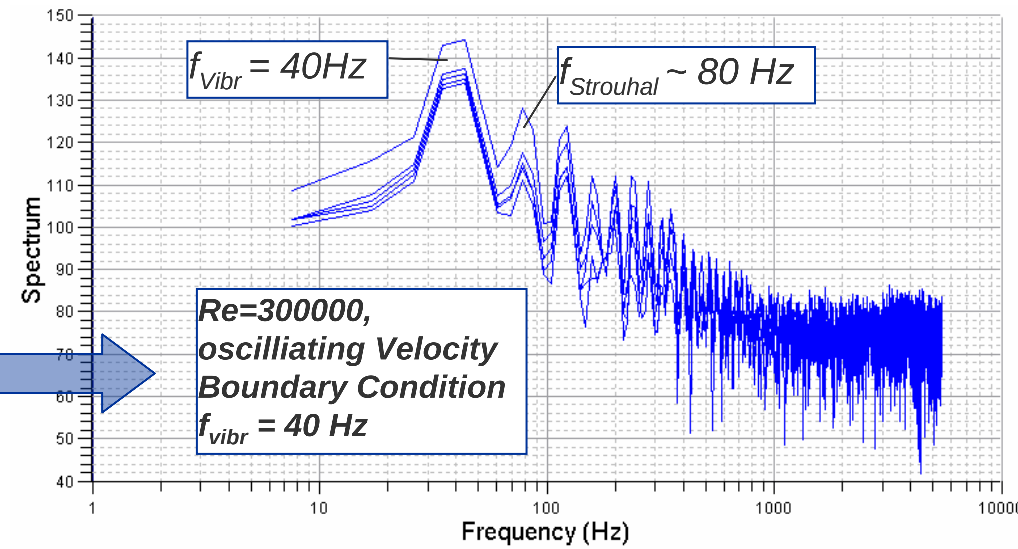
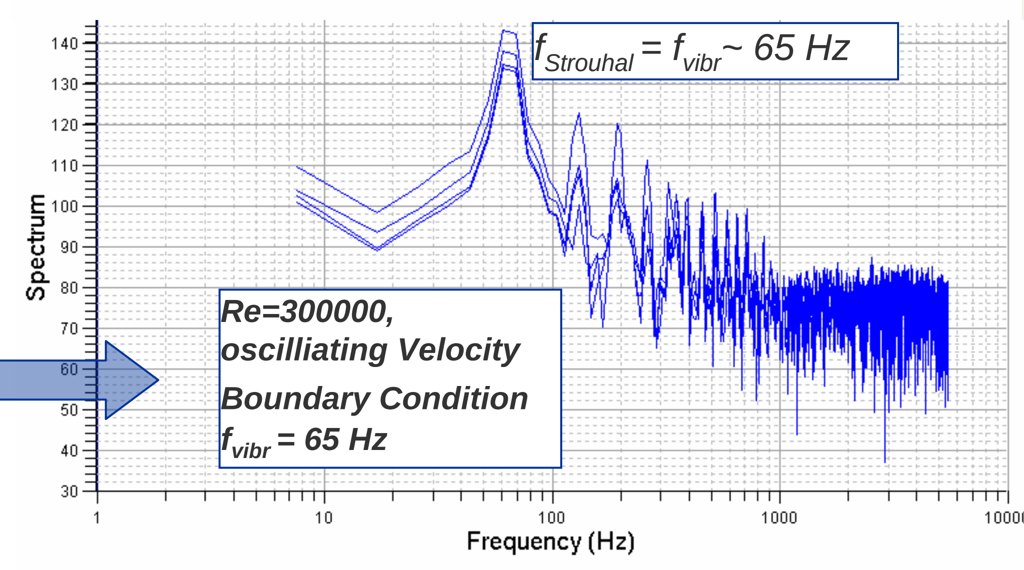
Lock-in Effect (2)

Vibration Frequency

far beneath undisturbed Strouhal frequency -> no Synchronization



close to undisturbed Strouhal frequency -> Synchronization



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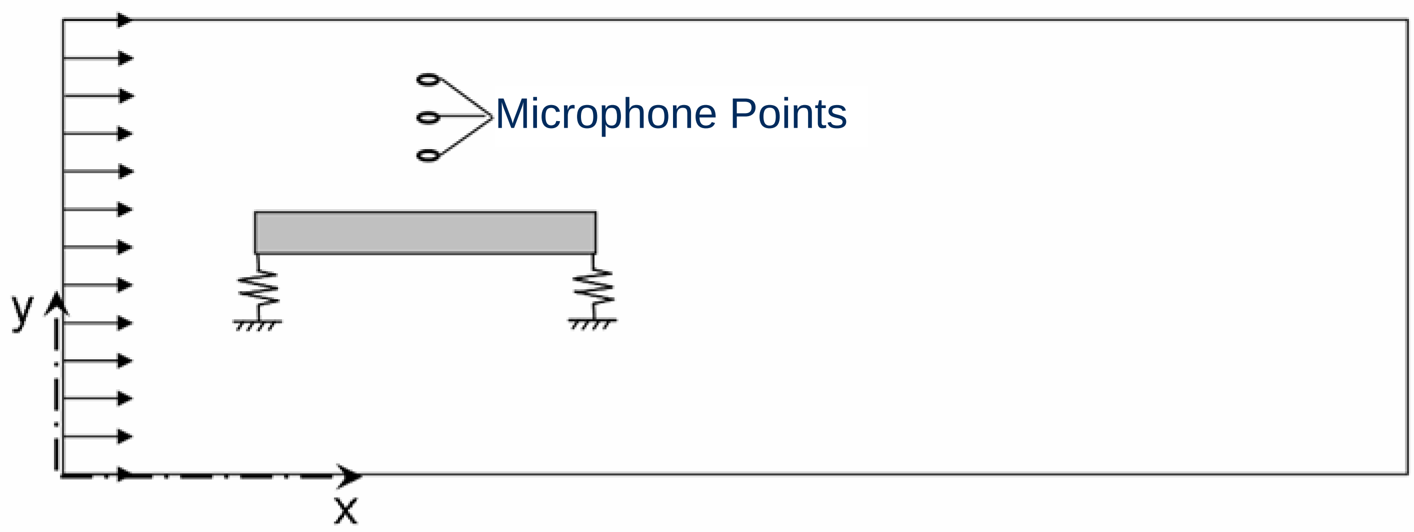
Example 3: Bidirectional Coupling
Flow around an elastically bedded Plate (1)

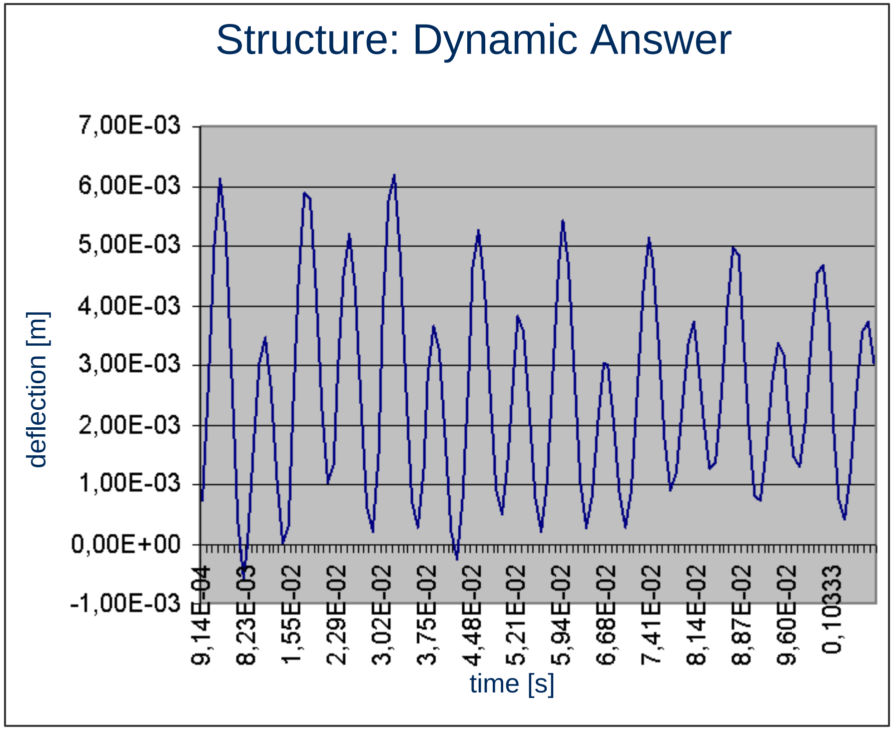
- ***Vibrating plane Structures cause higher Sound Pressure Levels***
- ***Wind Tunnel: Model Setup***



Example 3: Bidirectional Coupling Flow around an elasically beded plate (2)

- ***Flow leads to mechanical Vibration in the Systems Eigen Frequency***

- ***Vibrations act back onto the Fluid***



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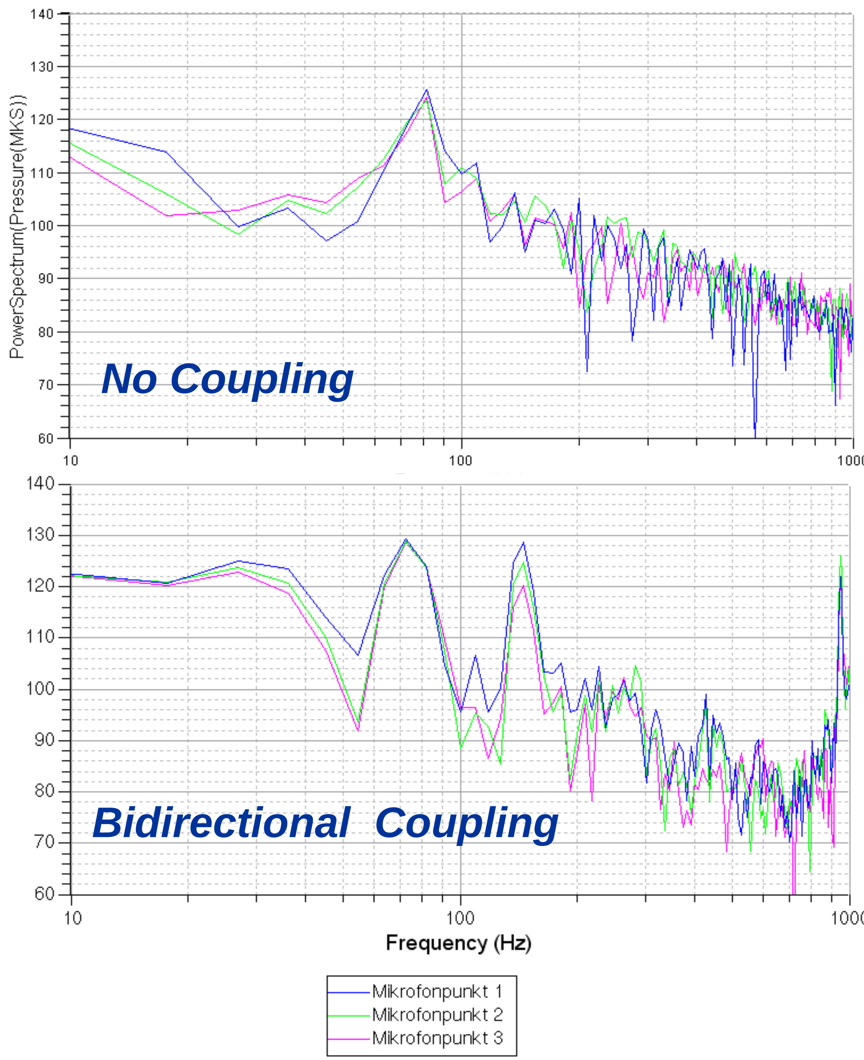
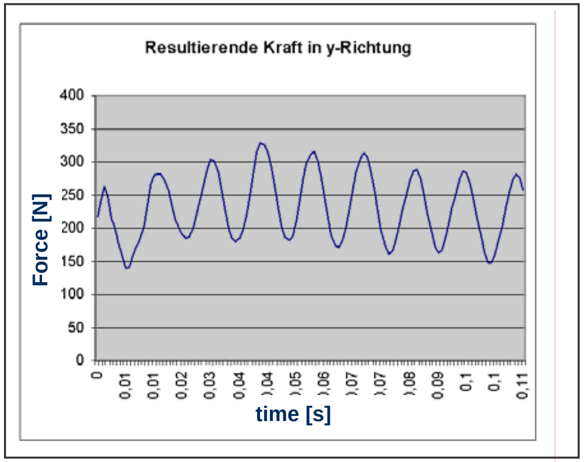
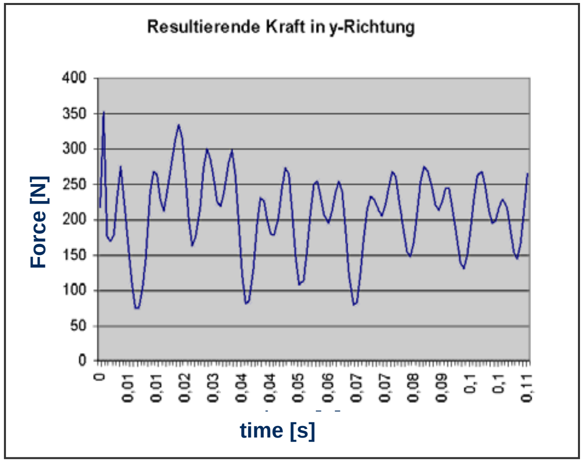
Example 3: Bidirectional Coupling

Comparison of Results in Frequency and Time Domain:







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Application Cases:

- *High Speed Trains (Pantographs, ...)*
- *Automotive*
- *Aviation*
- *Consumer Goods*
- *Civil Engineering*
- *....*