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UNIVERSITÄT ROSTOCK , MSF , LEHRSTUHL FÜR STRÖMUNGSMASCHINEN

Windturbinen und alternative Energiequellen

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Lehrstuhl für Strömungsmaschinen

Inhalt der Vorlesung Windturbinen und alternative Energiequellen

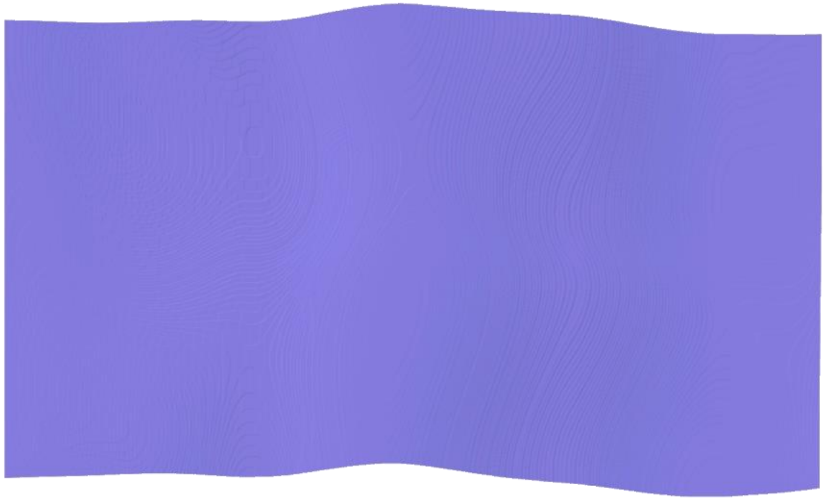
- Einführung / industrieller Hintergrund (Vorlesung 1)
- Energieinhalt im Wind und Aufbau von Windkraftanlagen (Vorlesung 2)
- Grundlagen der Aerodynamik (Vorlesung 3)
- Windentstehung und Messung der Windgeschwindigkeit (Vorlesung 4)
- Grundlagen für den Rotorentwurf (Vorlesung 5)

Inhalt der Vorlesung Windturbinen und alternative Energiequellen

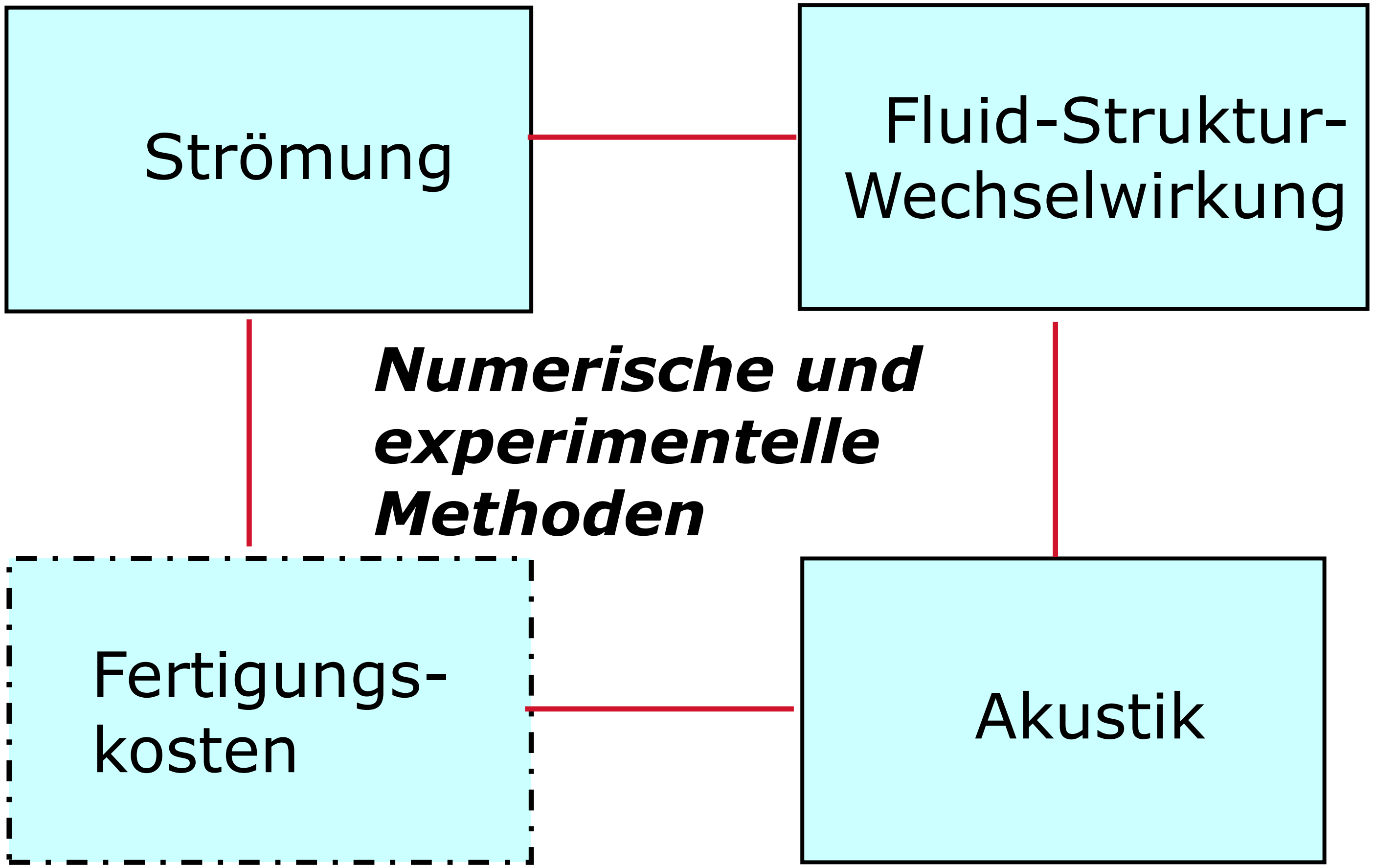
- Entwurf und aerodynamische Optimierung des Rotors (Vorlesung 5,6)
- Anpassung an veränderte Windverhältnisse und Verluste (Vorlesung 7)
- **Grundlagen der Aeroelastik, Fluid-Struktur-Wechselwirkungen (Vorlesung 8,9)**
- Schallquellen an Windkraftanlagen und Maßnahmen zur Lärmreduzierung (Vorlesung 10)

Inhalt der Vorlesung Windturbinen und alternative Energiequellen

- spezielle Herausforderungen an offshore-Windparks (Vorl. 11)
- Gezeitenturbinen (Vorlesung 12)
- Solarthermie und Photovoltaik (Vorlesung 13)
- Geothermie (Vorlesung 14)
- Zusammenfassung (Vorlesung 14)



Forschungsschwerpunkte
Lehrstuhl Strömungsmaschinen



Strömung

Fluid-Struktur-Wechselwirkung

Numerische und experimentelle Methoden

Fertigungskosten

Akustik

Begriffe

- Aeroelastik – untersucht die Wechselwirkungen zwischen aerodynamischen Kräften und elastischen Körpern
- Fluid-Struktur-Wechselwirkungen (engl. Fluid Structur Interactions – FSI)
- Anwendungen: Flugzeugtragflügel, Flugzeugrumpf, Rotorschaufeln aus Kunststoffen (Windturbine, Ventilator, Schiffspropeller, Rührwerke, etc.), Komponenten an Fahrzeugen …..

Belastungsfälle

- statisch (z.B. aus stationärer Zuströmung)
- dynamisch periodisch oder nicht-periodisch (z.B. aus fluktuierender Zuströmung durch Grenzschichteinfluss, Turmvorstau, turbulente Effekte, Böen, u.a.)
- Biegung
- Torsion

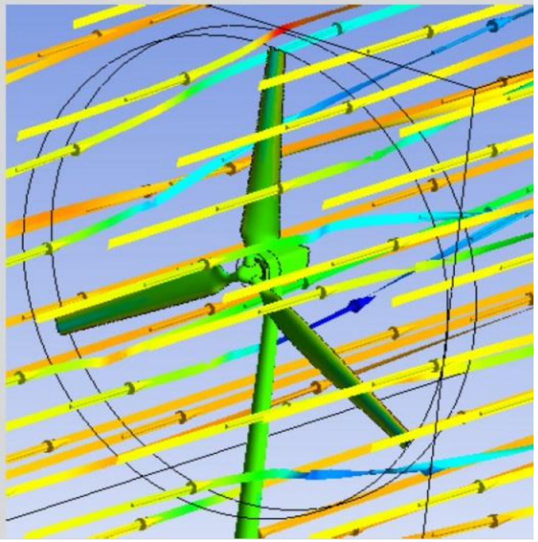
Tafelbilder

Materialverhalten

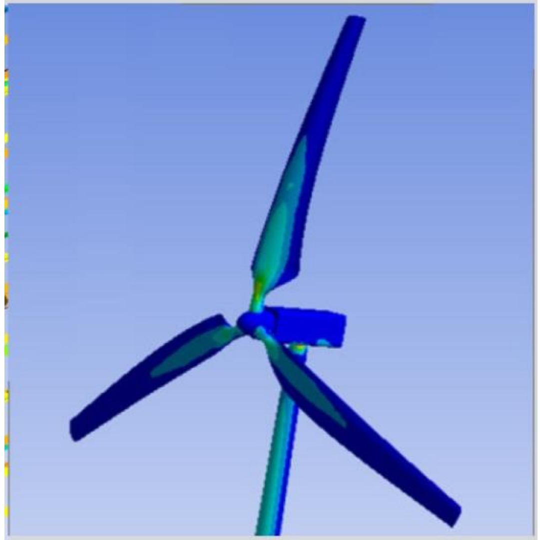
- linear elastisch
- nichtlinear elastisch
- isotrop
- anisotrop

Tafelbilder

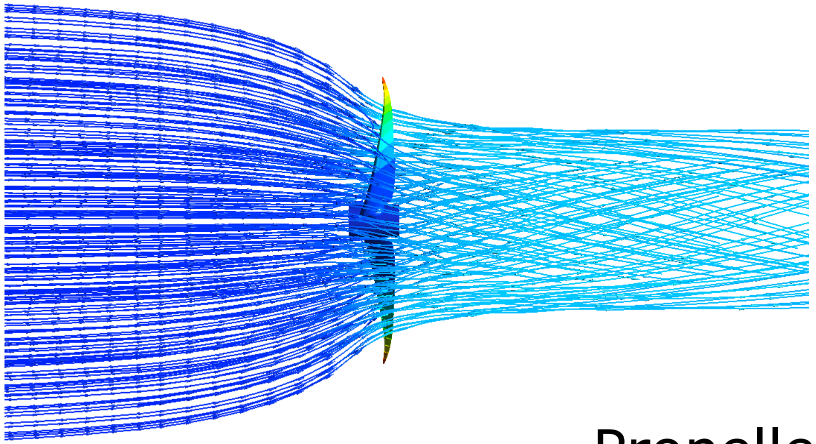
Motivation für FSI- Analysen



Turbinen



Deformation in Strömungsrichtung



Deformation entgegen der Strömungsrichtung

Propeller

Ziele

- Analyse der Änderungen im Betriebsverhalten durch die Verformungen
- Analyse der Betriebssicherheit
- Nutzung der anisotropen Eigenschaften von Faser-Verbund-Werkstoffen zur positiven Beeinflussung des Betriebsverhaltens
- Analyse der Schallabstrahlung

zu lösende Gleichungen

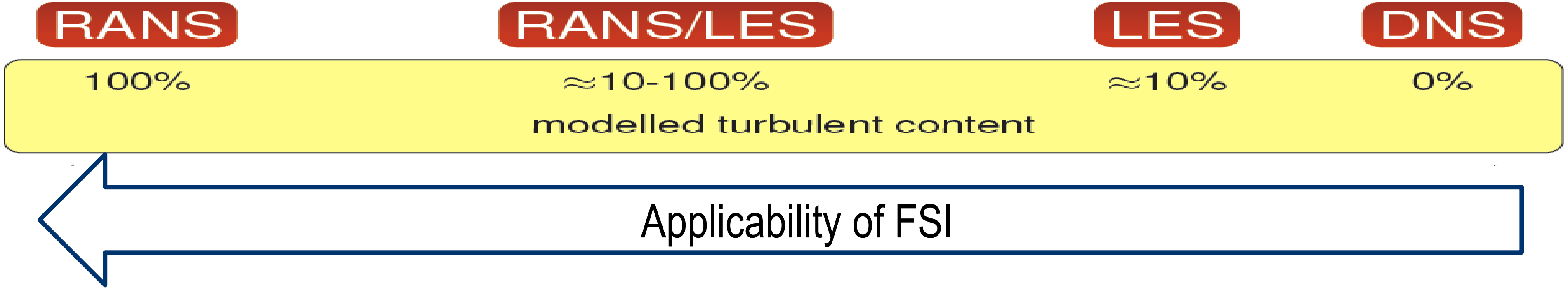
- Strukturmechanik

$$[M_s]\{\ddot{U}\} + [K_s]\{U\} = \{F_s\} + \{F_f\}$$

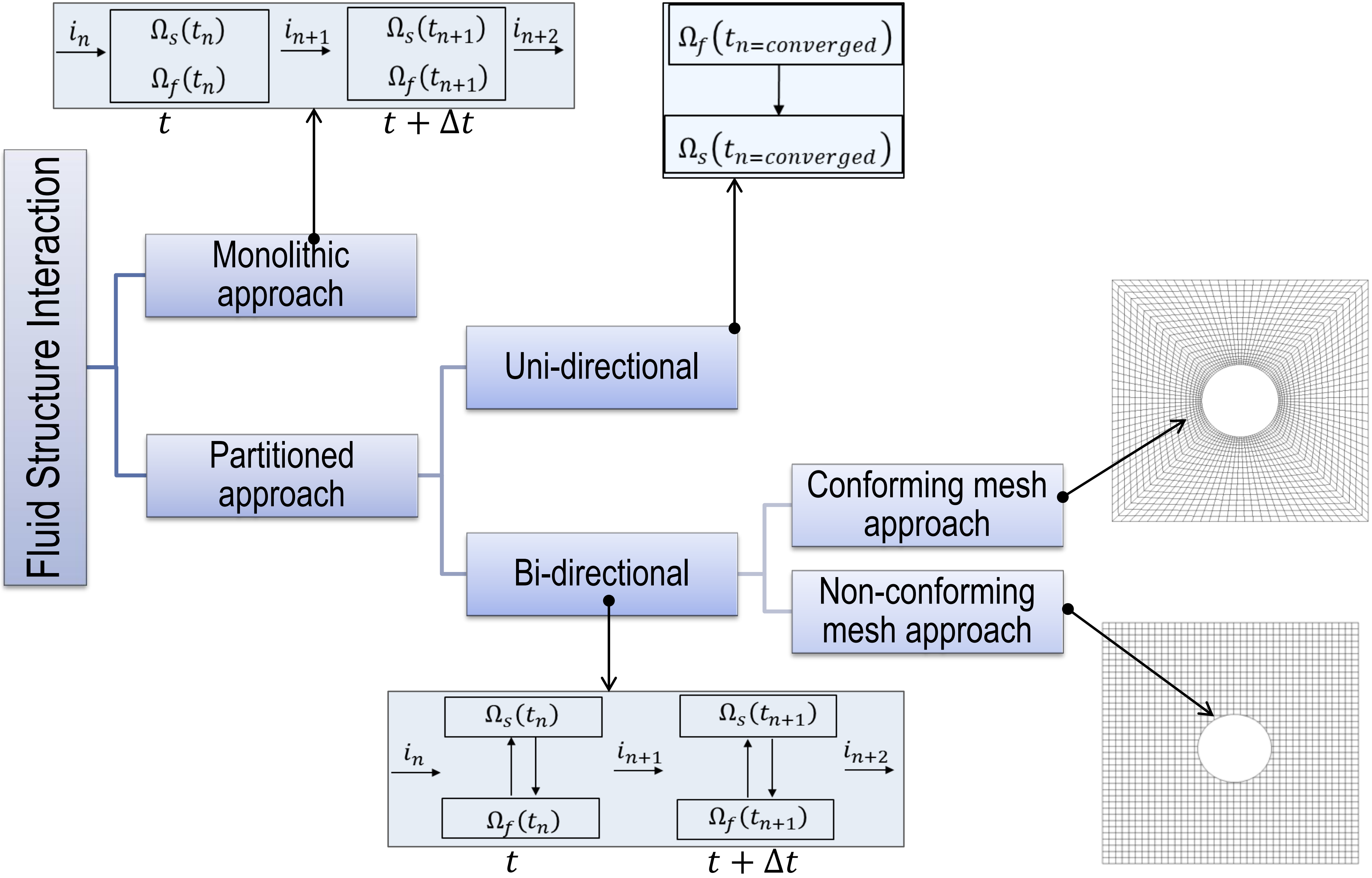
- Strömungsmechanik

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = 0$$

$$\rho\left(\frac{\partial \vec{V}}{\partial t} + \vec{V} \cdot \nabla \vec{V}\right) = -\nabla P + \nabla \cdot \tau_{ij} + F_b$$



Klassifizierung von FSI-Methoden



Fluid Structure Interaction

Monolithic approach

$i_n \rightarrow \boxed{\Omega_s(t_n) \quad \Omega_f(t_n)} \xrightarrow{i_{n+1}} \boxed{\Omega_s(t_{n+1}) \quad \Omega_f(t_{n+1})} \xrightarrow{i_{n+2}}$

$t \qquad t + \Delta t$

Partitioned approach

Uni-directional

$\Omega_f(t_{n=converged}) \downarrow \Omega_s(t_{n=converged})$

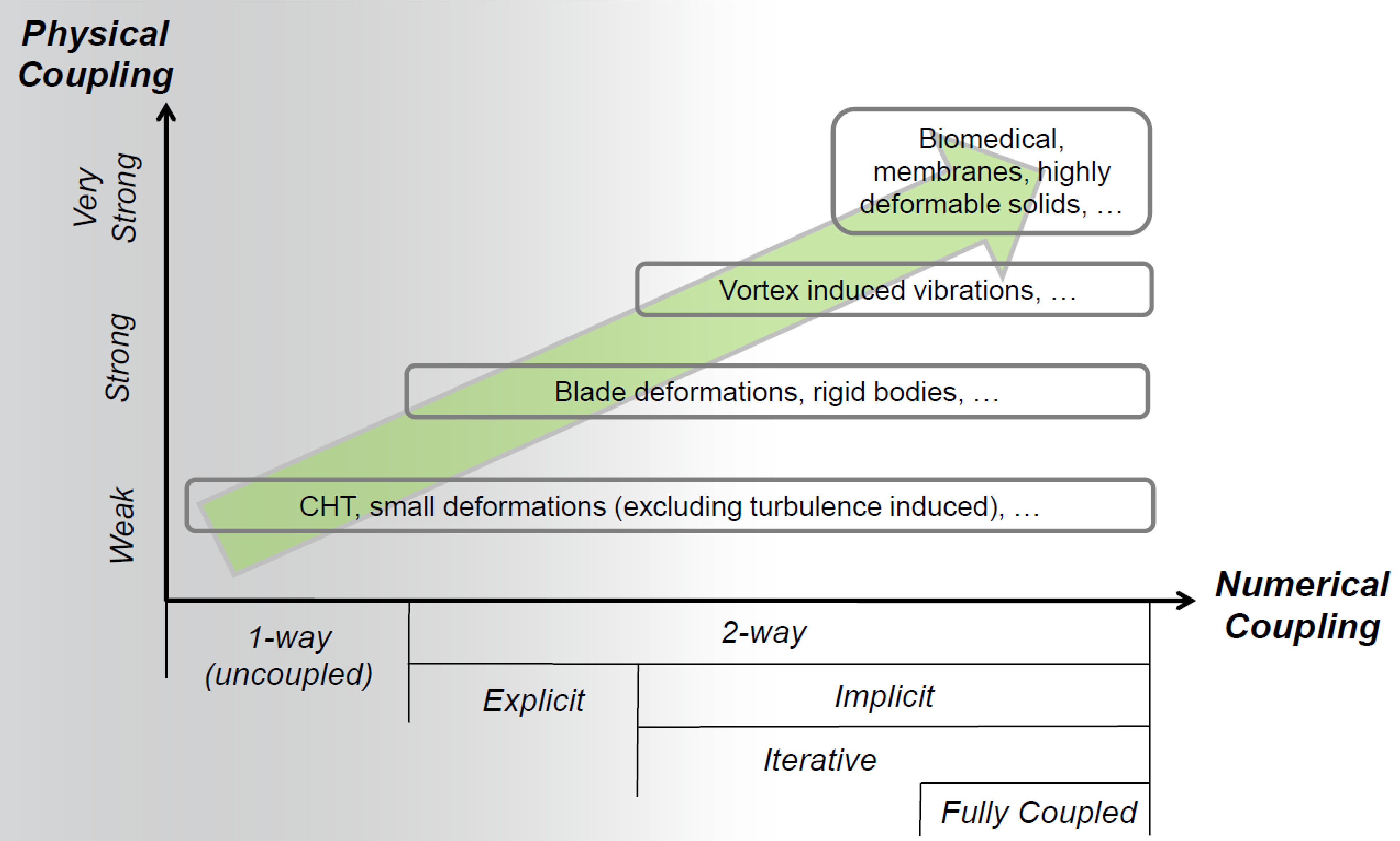
Bi-directional

$i_n \rightarrow \Omega_s(t_n) \rightleftarrows \Omega_f(t_n) \xrightarrow{i_{n+1}} \Omega_s(t_{n+1}) \rightleftarrows \Omega_f(t_{n+1}) \xrightarrow{i_{n+2}}$

$t \qquad t + \Delta t$

Conforming mesh approach

Non-conforming mesh approach



Physical Coupling

Very Strong

Strong

Weak

Biomedical, membranes, highly deformable solids, …

Vortex induced vibrations, …

Blade deformations, rigid bodies, …

CHT, small deformations (excluding turbulence induced), …

Numerical Coupling

1-way (uncoupled)

2-way

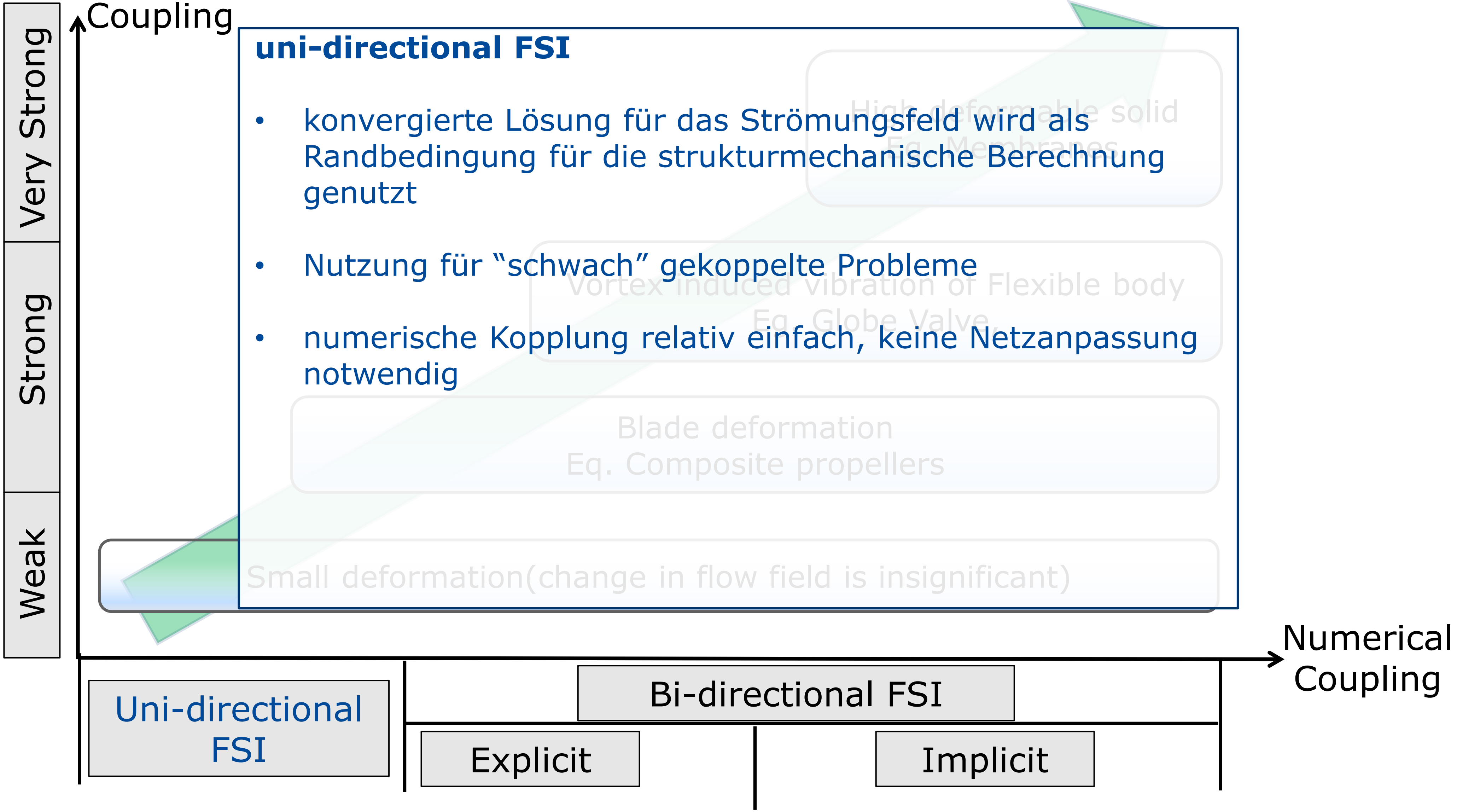
Explicit

Implicit

Iterative

Fully Coupled

uni-directional FSI



uni-directional FSI

- konvergierte Lösung für das Strömungsfeld wird als Randbedingung für die strukturmechanische Berechnung genutzt
- Nutzung für "schwach" gekoppelte Probleme
- numerische Kopplung relativ einfach, keine Netzanpassung notwendig

Physical Coupling

Very Strong

Strong

Weak

High deformable solid
Eq. Membranes

Vortex induced vibration of Flexible body
Eq. Globe Valve

Blade deformation
Eq. Composite propellers

Small deformation(change in flow field is insignificant)

Numerical Coupling

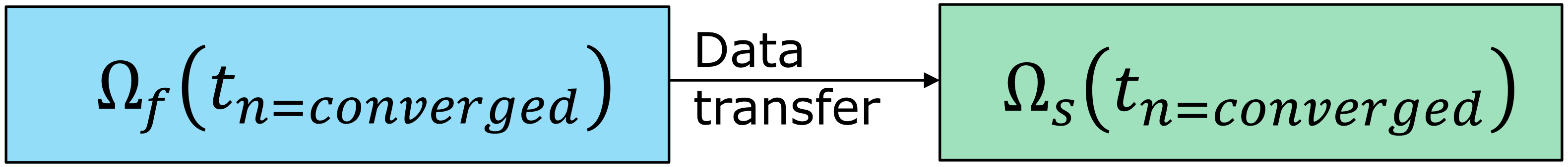
Uni-directional FSI

Bi-directional FSI

Explicit

Implicit

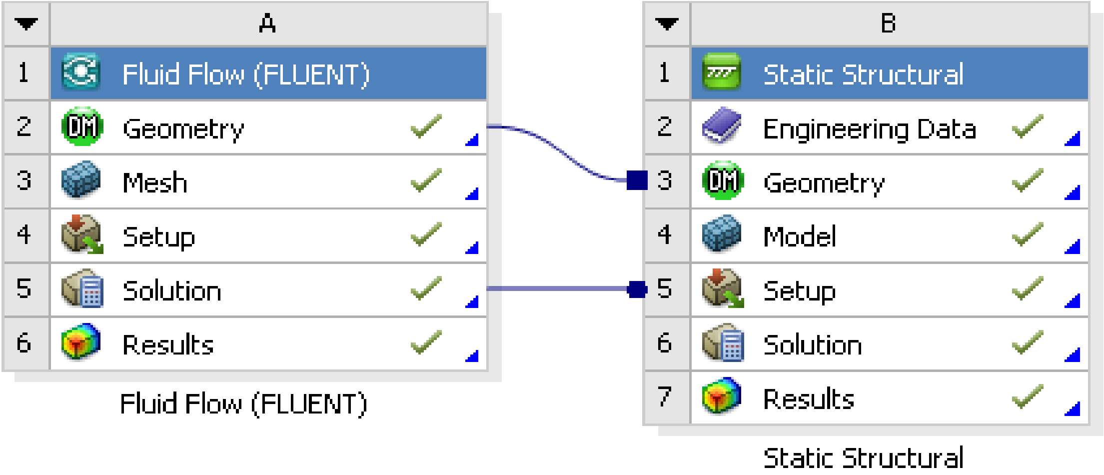
uni-directional FSI



$\Omega_f\left(t_{n=converged}\right)$ → Data transfer → $\Omega_s\left(t_{n=converged}\right)$

konvergierte Lösung des Strömungsfeldes

konvergierte Lösung der Verformung der Struktur



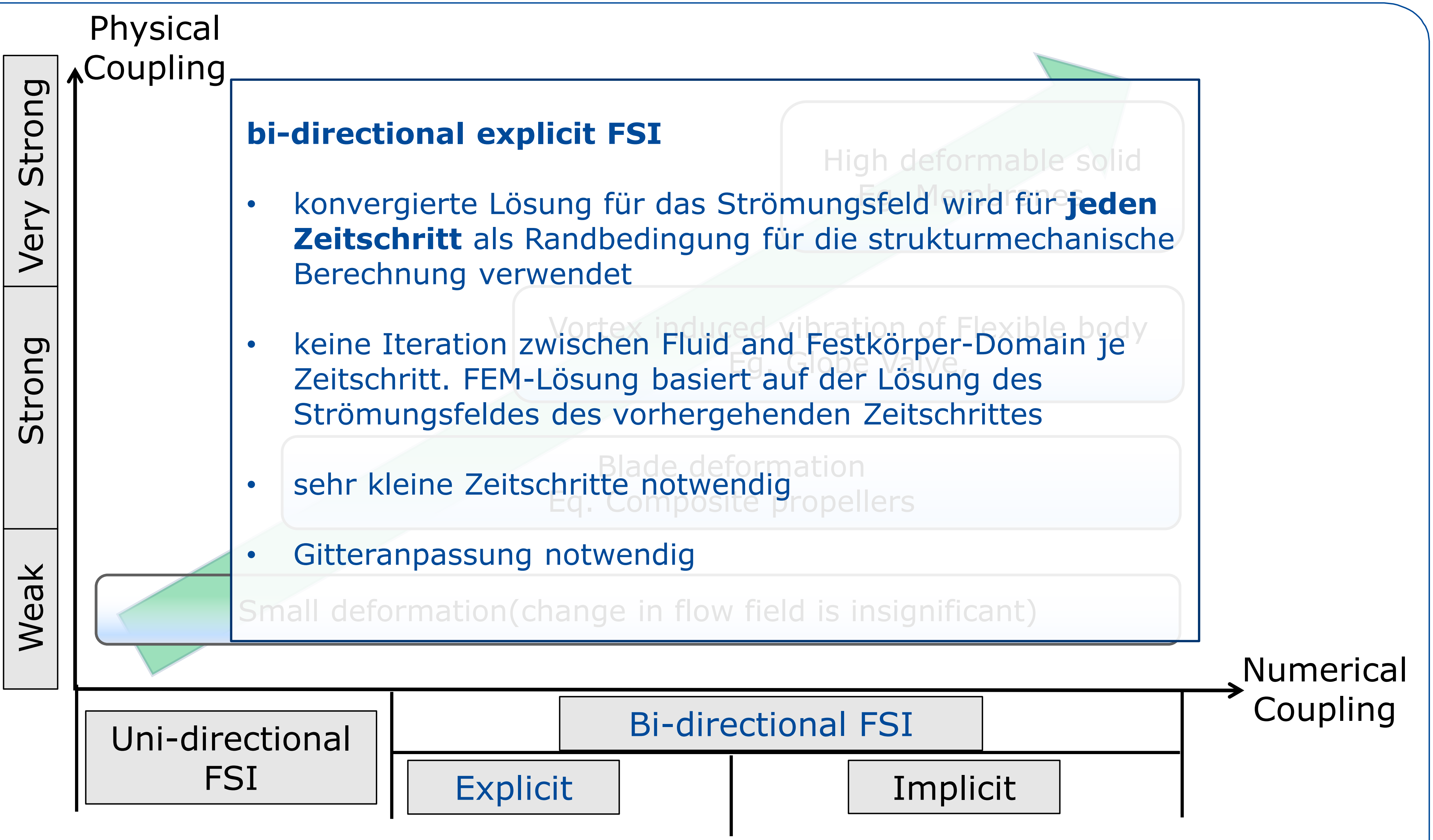
▼	A		
1	Fluid Flow (FLUENT)		
2	Geometry	✓	◢
3	Mesh	✓	◢
4	Setup	✓	◢
5	Solution	✓	◢
6	Results	✓	◢

Fluid Flow (FLUENT)

▼	B		
1	Static Structural		
2	Engineering Data	✓	◢
3	Geometry	✓	◢
4	Model	✓	◢
5	Setup	✓	◢
6	Solution	✓	◢
7	Results	✓	◢

Static Structural

bi-directional explicit FSI



Physical Coupling

Very Strong

Strong

Weak

High deformable solid
Eq. Membranes

Vortex induced vibration of Flexible body
Eq. Globe Valve,

Blade deformation
Eq. Composite propellers

Small deformation(change in flow field is insignificant)

Numerical Coupling

Uni-directional FSI

Bi-directional FSI

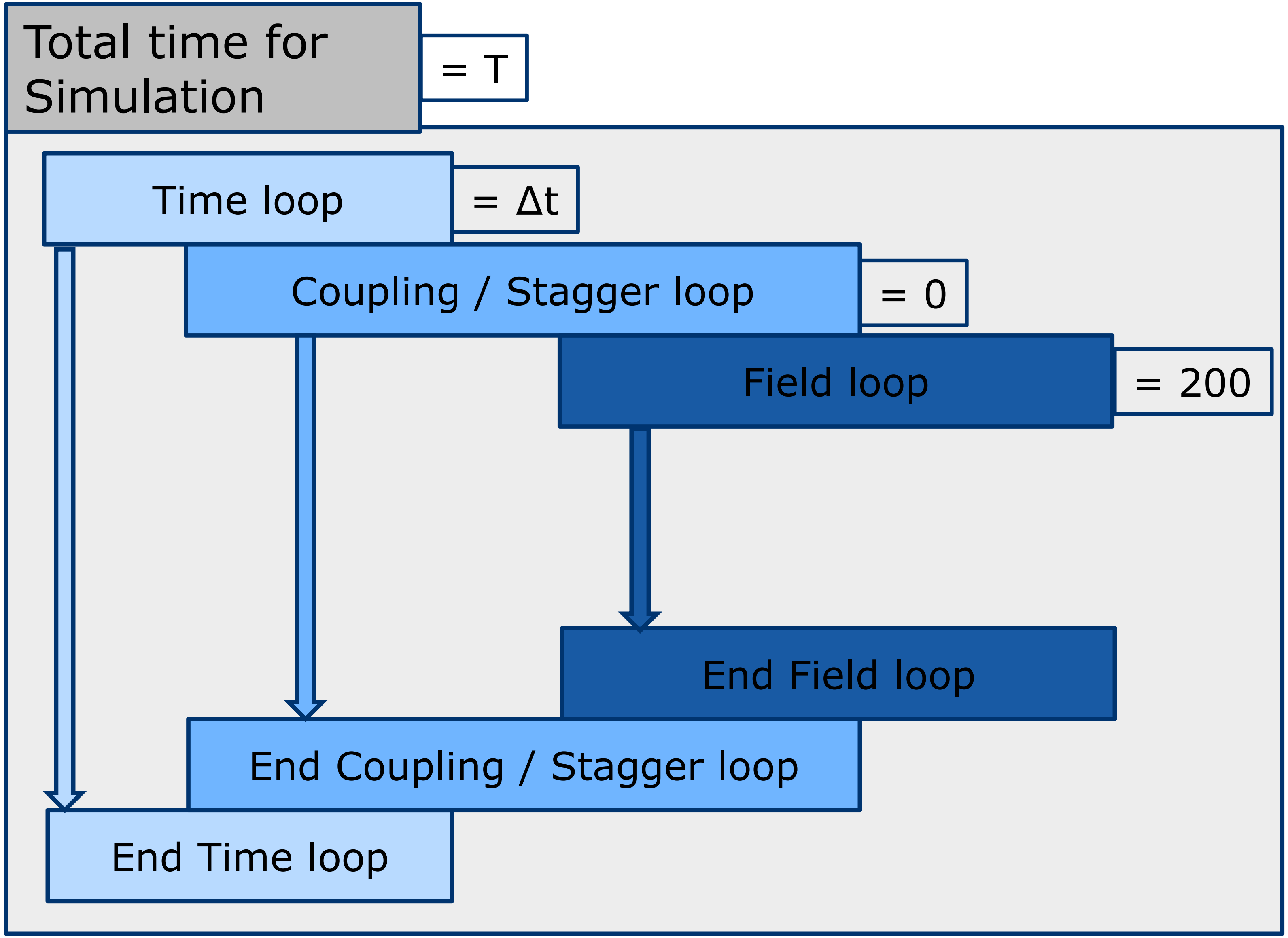
Explicit

Implicit

bi-directional explicit FSI

- konvergierte Lösung für das Strömungsfeld wird für **jeden Zeitschritt** als Randbedingung für die strukturmechanische Berechnung verwendet
- keine Iteration zwischen Fluid and Festkörper-Domain je Zeitschritt. FEM-Lösung basiert auf der Lösung des Strömungsfeldes des vorhergehenden Zeitschrittes
- sehr kleine Zeitschritte notwendig
- Gitteranpassung notwendig

bi-directional explicit FSI



Total time for Simulation = T

Time loop = Δt

Coupling / Stagger loop = 0

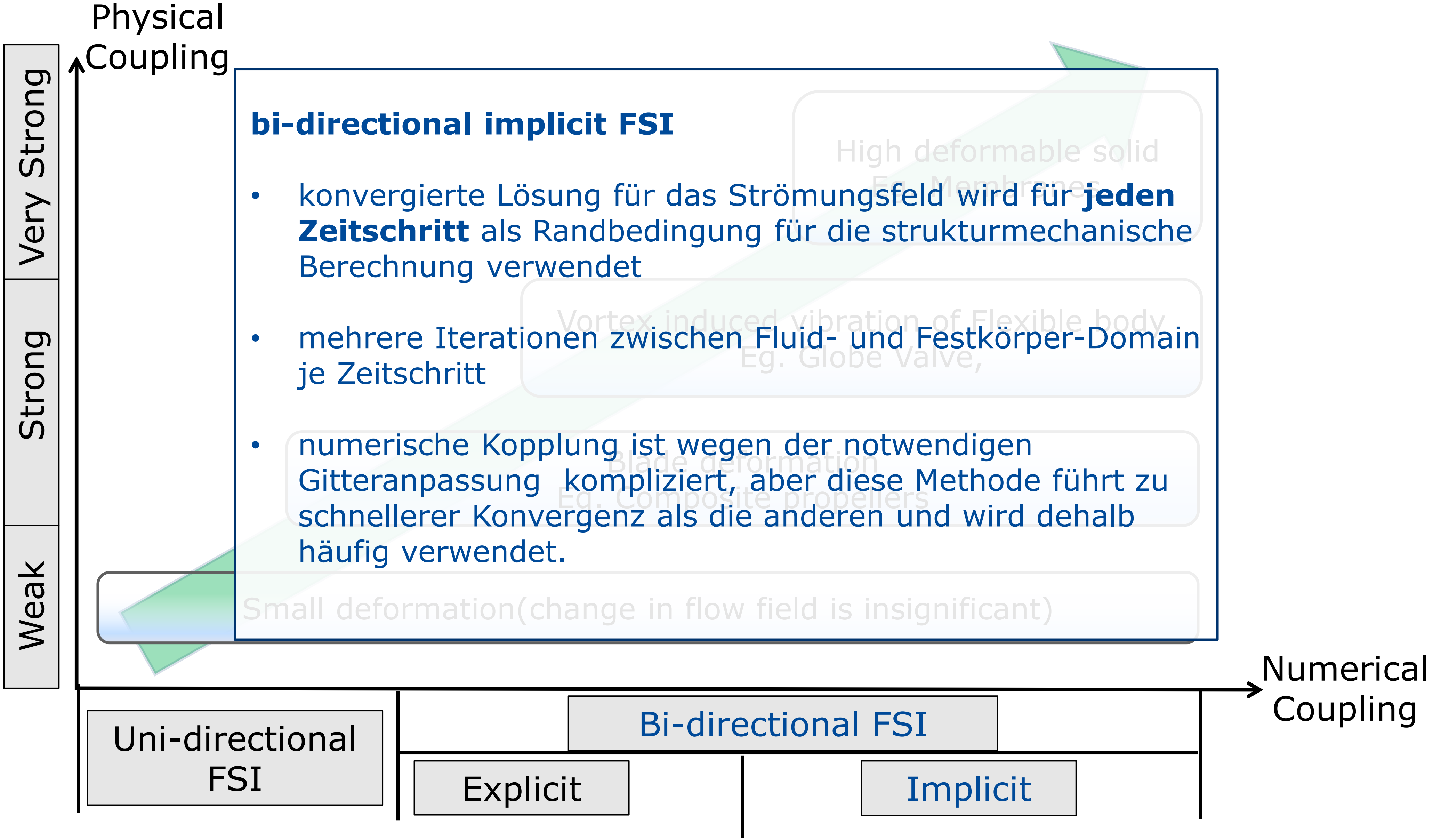
Field loop = 200

End Field loop

End Coupling / Stagger loop

End Time loop

bi- directional implcit FSI

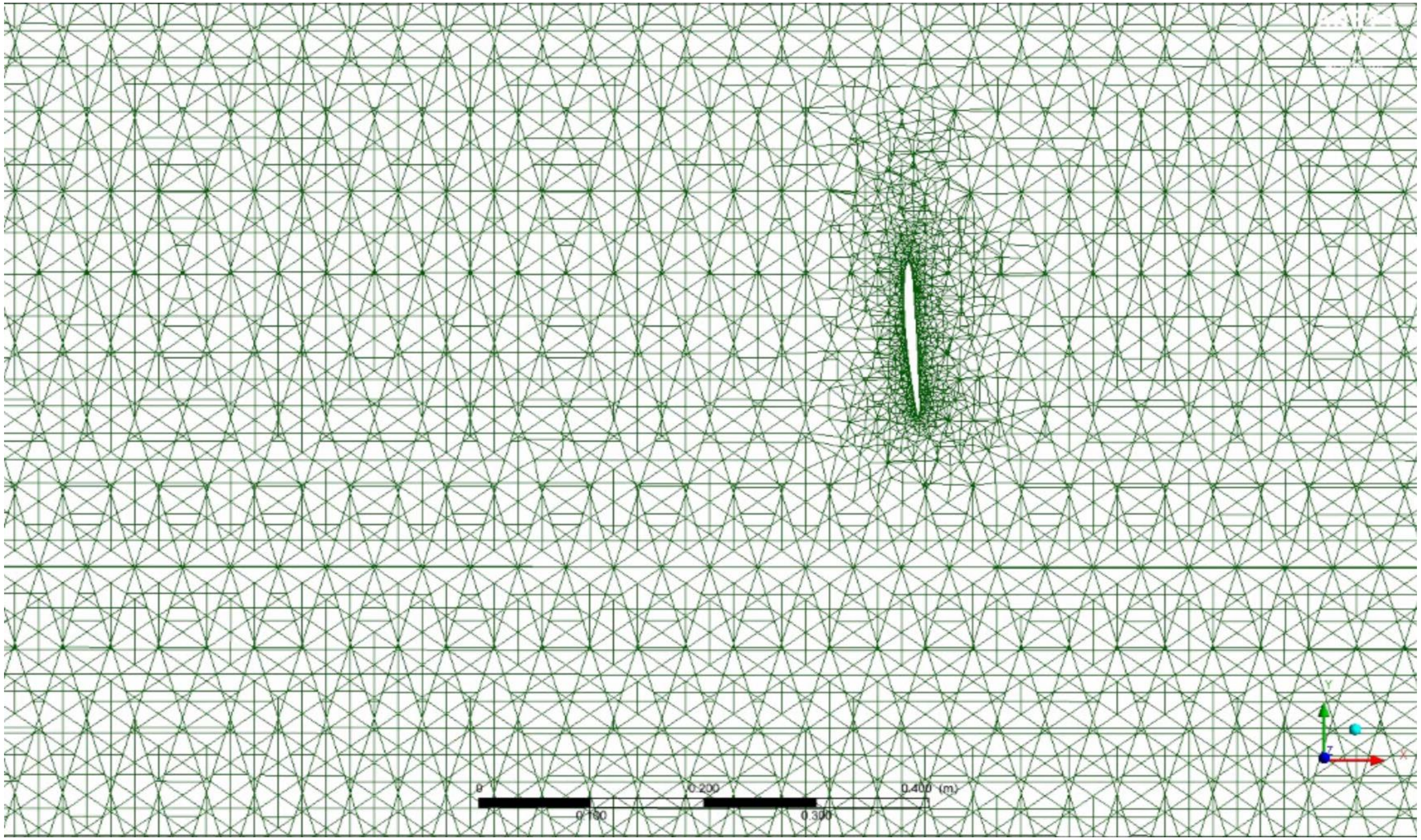


bi-directional implicit FSI

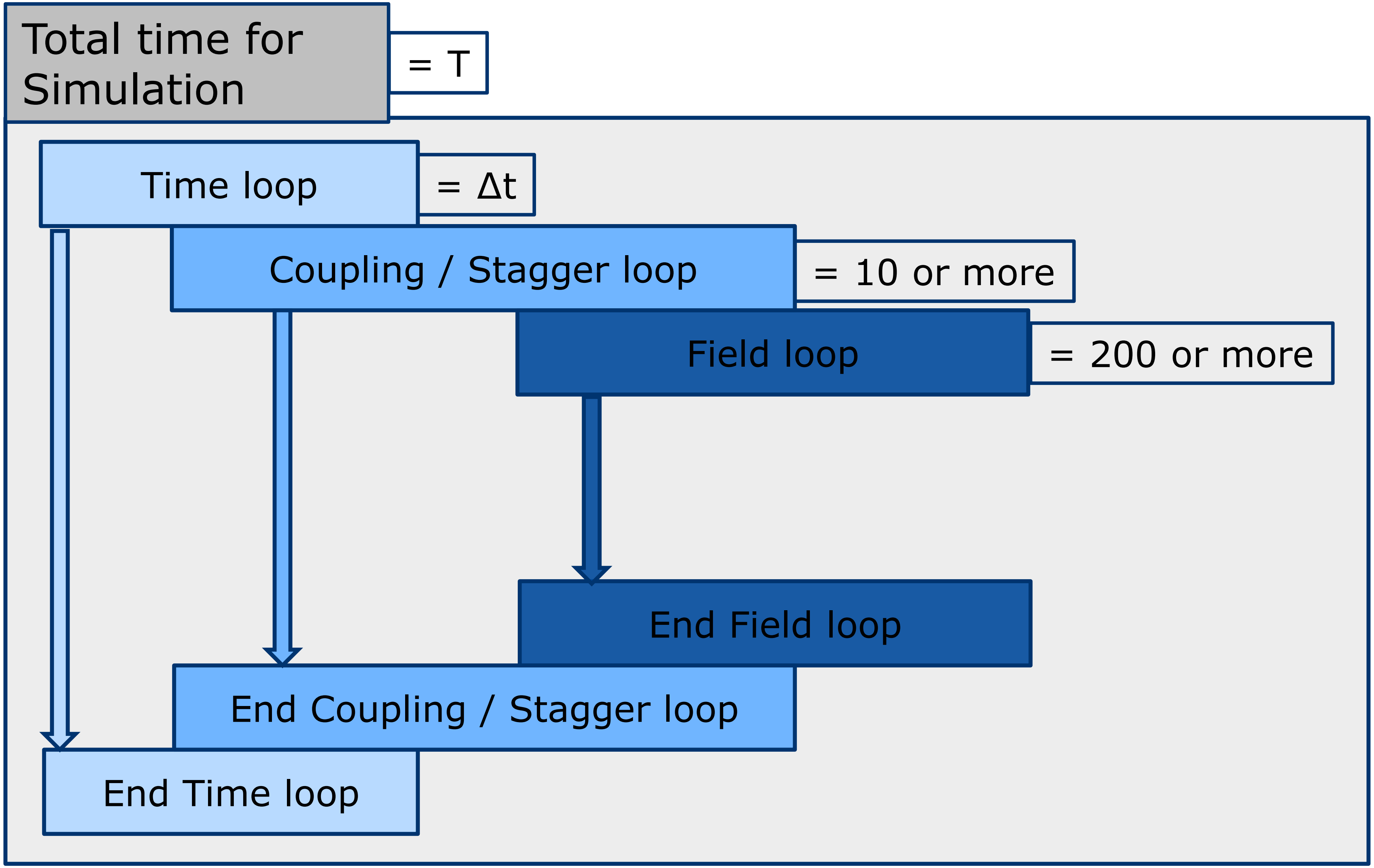
- konvergierte Lösung für das Strömungsfeld wird für **jeden Zeitschritt** als Randbedingung für die strukturmechanische Berechnung verwendet
- mehrere Iterationen zwischen Fluid- und Festkörper-Domain je Zeitschritt
- numerische Kopplung ist wegen der notwendigen Gitteranpassung kompliziert, aber diese Methode führt zu schnellerer Konvergenz als die anderen und wird dehalb häufig verwendet.

re-meshing

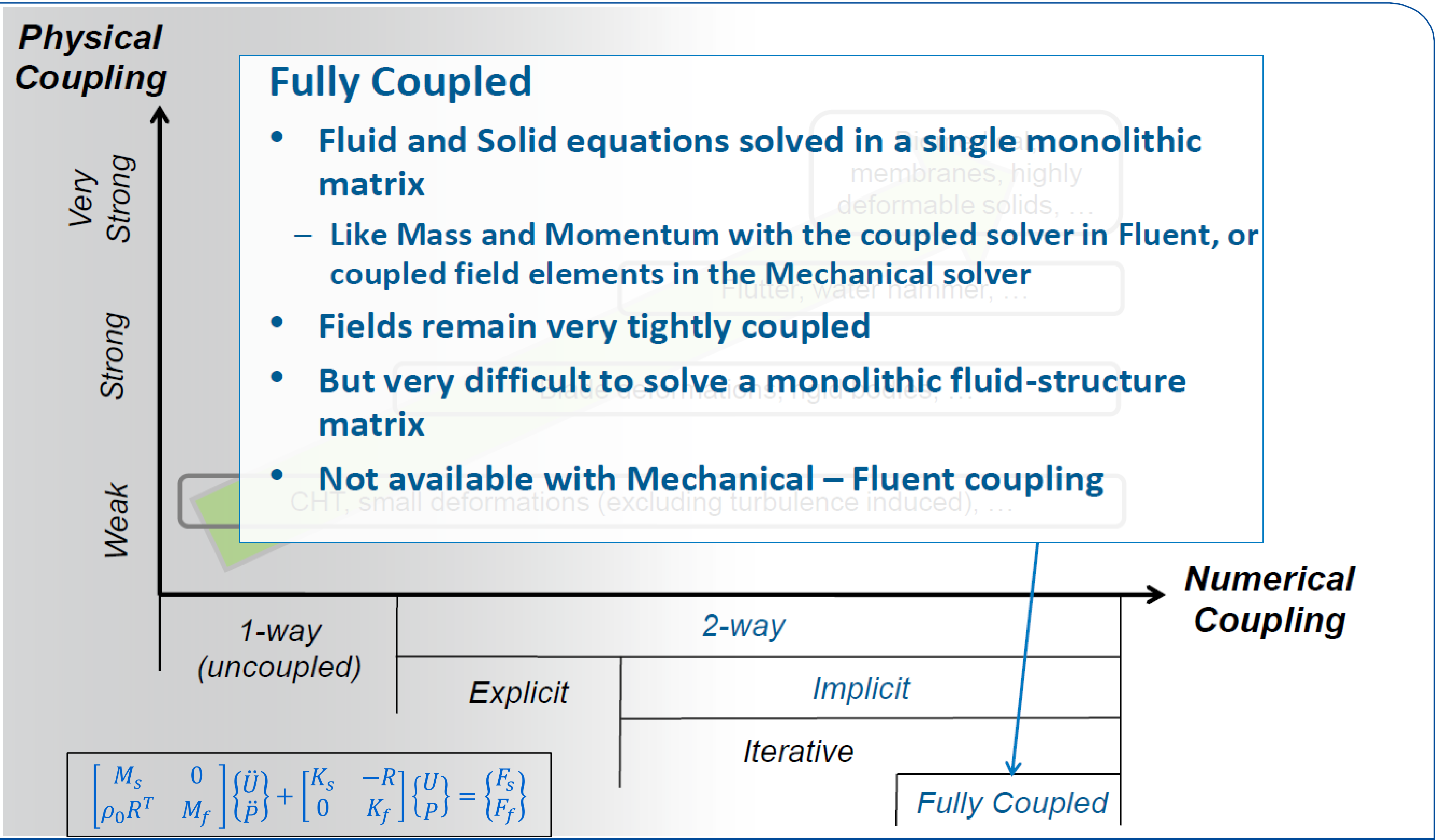
- notwendig, wenn Verformung so groß wird, das Gitterzellen negative Volumen erhalten



bi-directional implicit FSI



fully coupled FSI



Fully Coupled

- Fluid and Solid equations solved in a single monolithic matrix
    - Like Mass and Momentum with the coupled solver in Fluent, or coupled field elements in the Mechanical solver
- Fields remain very tightly coupled
- But very difficult to solve a monolithic fluid-structure matrix
- Not available with Mechanical – Fluent coupling

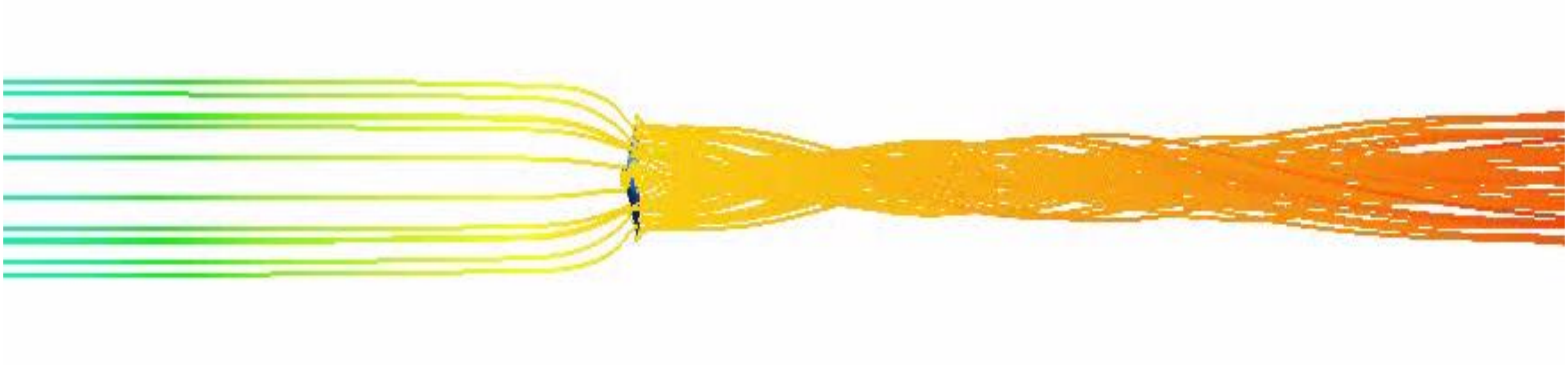
$$\begin{bmatrix} M_s & 0 \\ \rho_0 R^T & M_f \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{P} \end{Bmatrix} + \begin{bmatrix} K_s & -R \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} U \\ P \end{Bmatrix} = \begin{Bmatrix} F_s \\ F_f \end{Bmatrix}$$

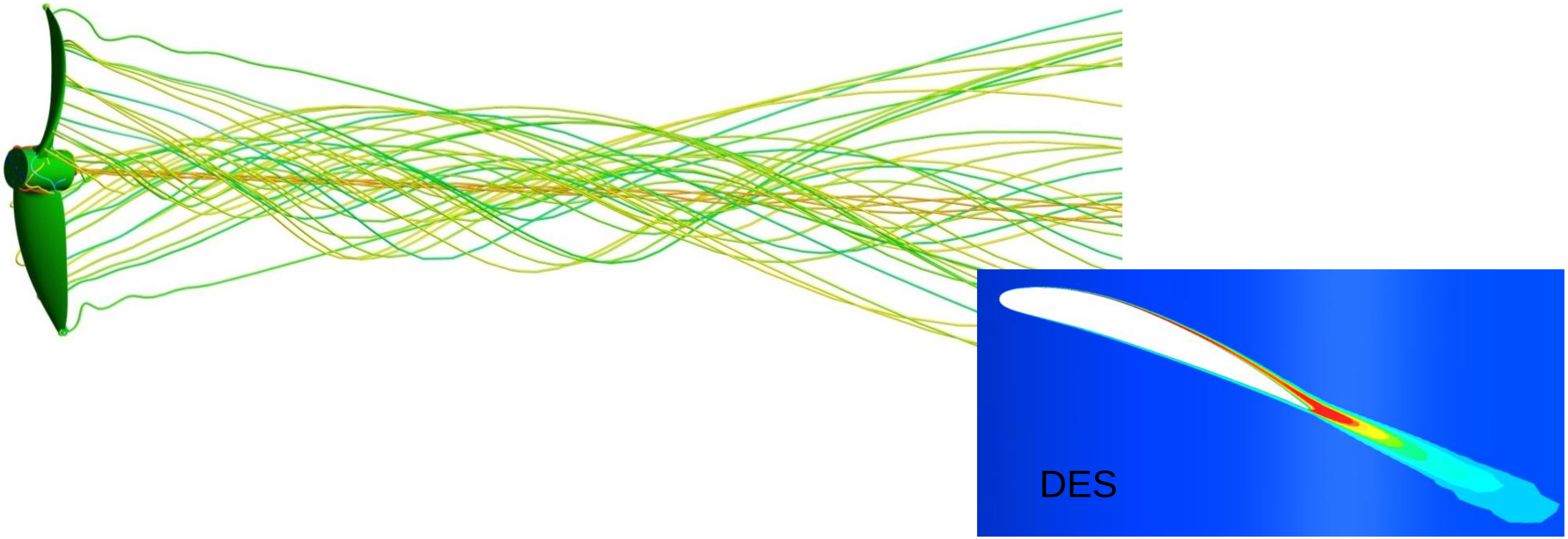
FSI Analysen

Anwendung auf

- Turbinen
- Rührwerke
- Pumpen
- Armaturen

Anwendung uni-directional und bi-directional implicit FSI
- Strömungssimulation -





mapping uni-directional FSI

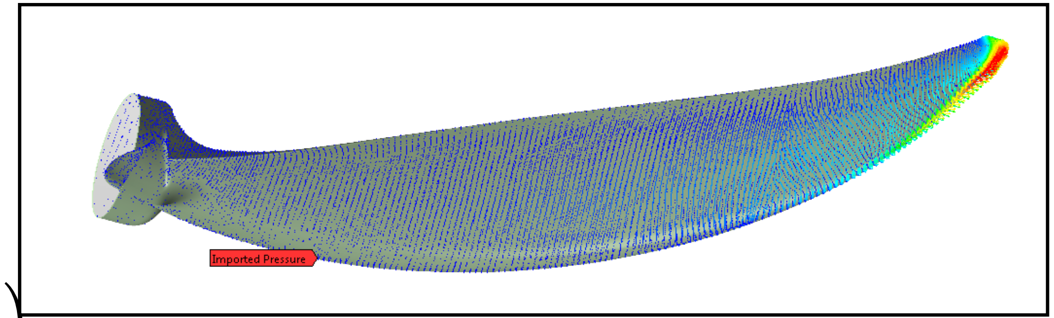
$$F_x = \ Pressure * Area * Normal\ X$$

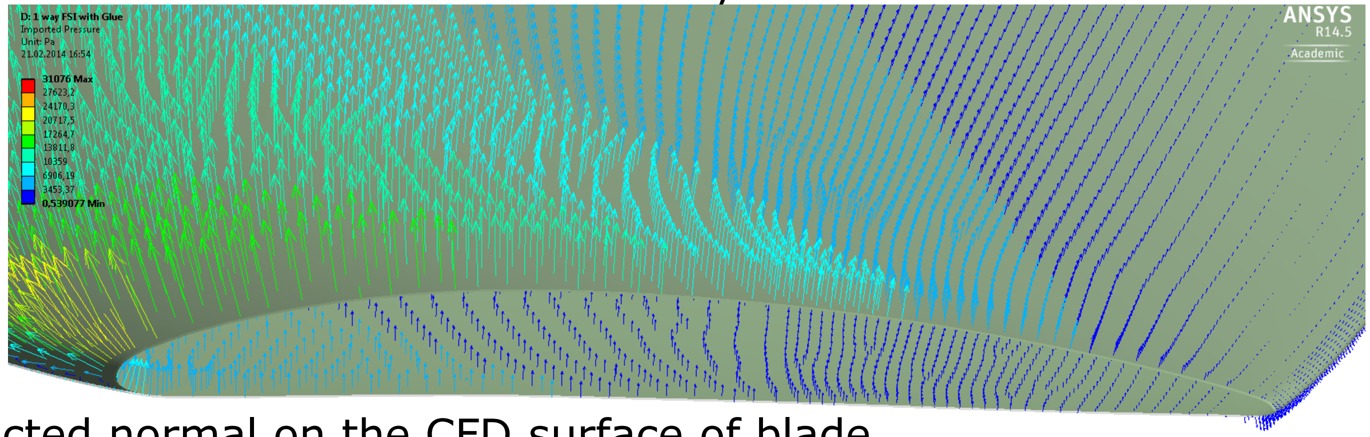
$$F_y = \ Pressure * Area * Normal\ Y$$

$$F_z = \ Pressure * Area * Normal\ Z$$

$$\overrightarrow{Pressure\ load} = \left({}^{F_x}\!/_{Area}, {}^{F_y}\!/_{Area}, {}^{F_z}\!/_{Area} \right)$$

$$|Pressure\ load| = Sqrt\left(\left({}^{F_x}\!/_{Area}\right)^2 + \left({}^{F_y}\!/_{Area}\right)^2 + \left({}^{F_z}\!/_{Area}\right)^2 \right)$$



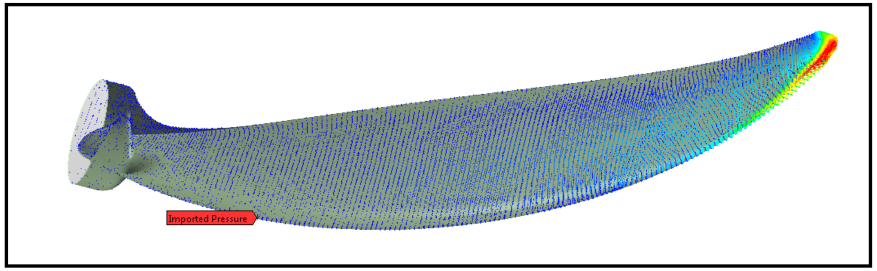


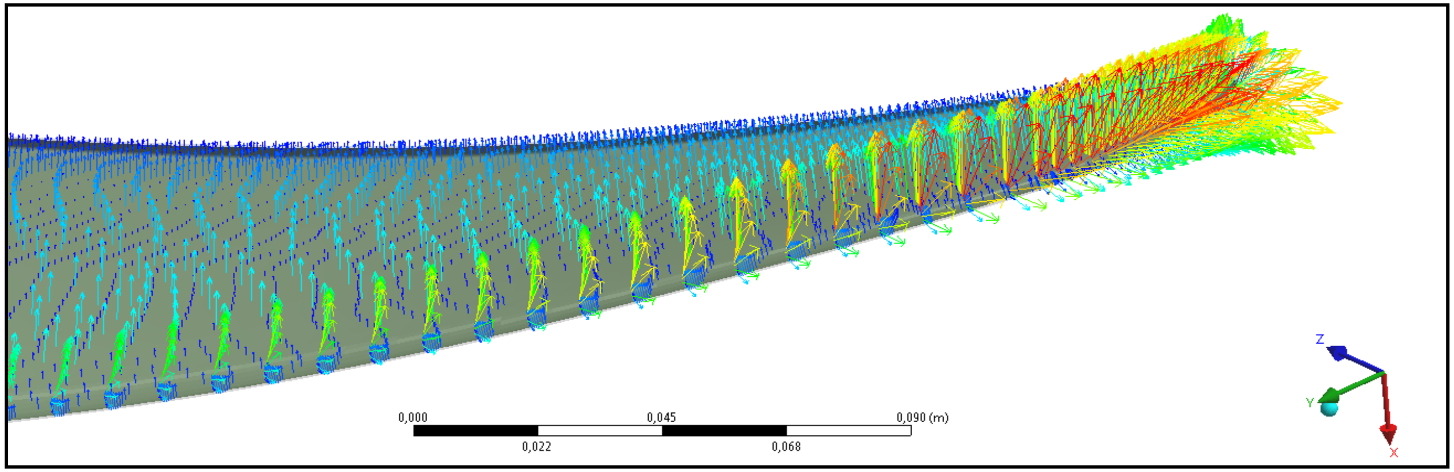
Mapping algorithm,

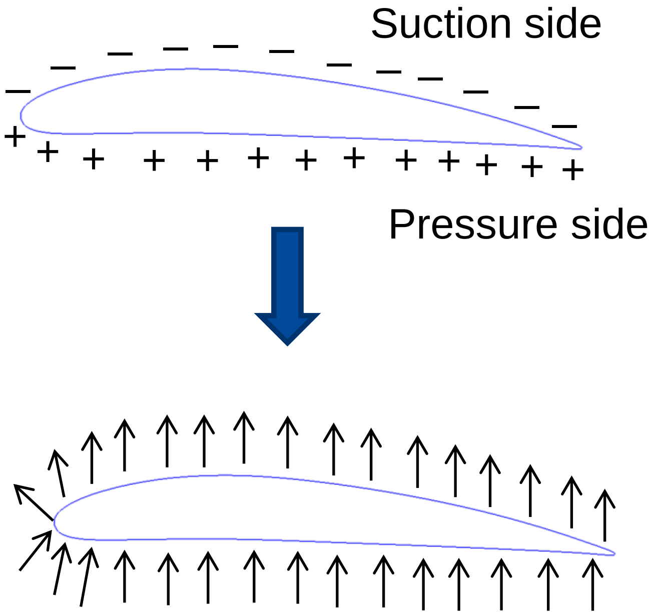
1. Mechanical nodes are projected normal on the CFD surface of blade.
2. Mechanical nodes are project on closest edge.
3. Mechanical nodes are projected to the closest node on CFD face.

mapping

Mapping	CFD Computed Force	Mechanical Mapped Force
X- component	-1957.5 N	-1964.6 N
Y- component	-531.4 N	-518.1 N
Z- component	-27.3 N	-9.2 N






Suction side

Pressure side

Mapping of Pressure force for mechanical solver

Geometriemodellierung

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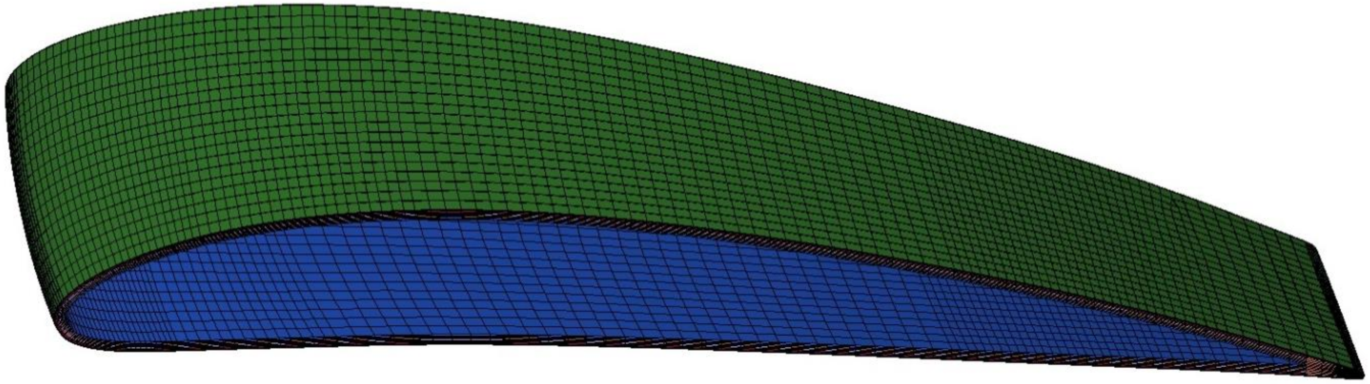
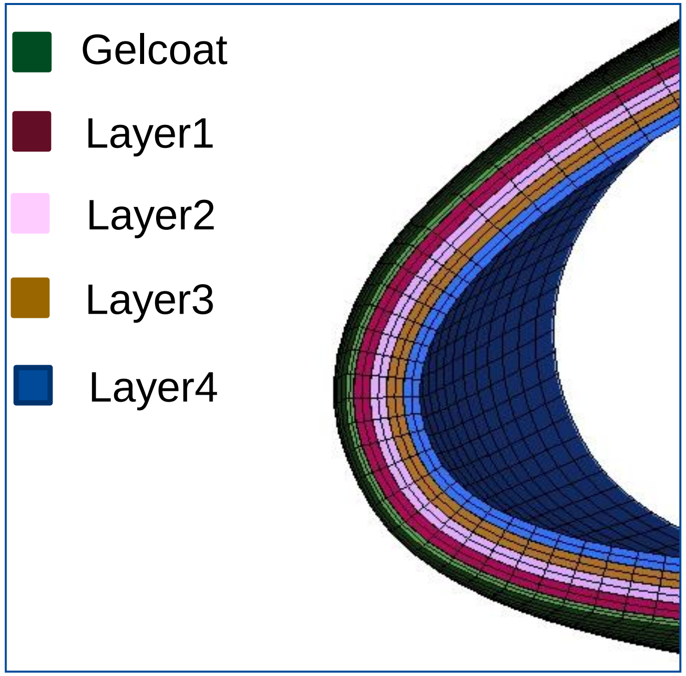
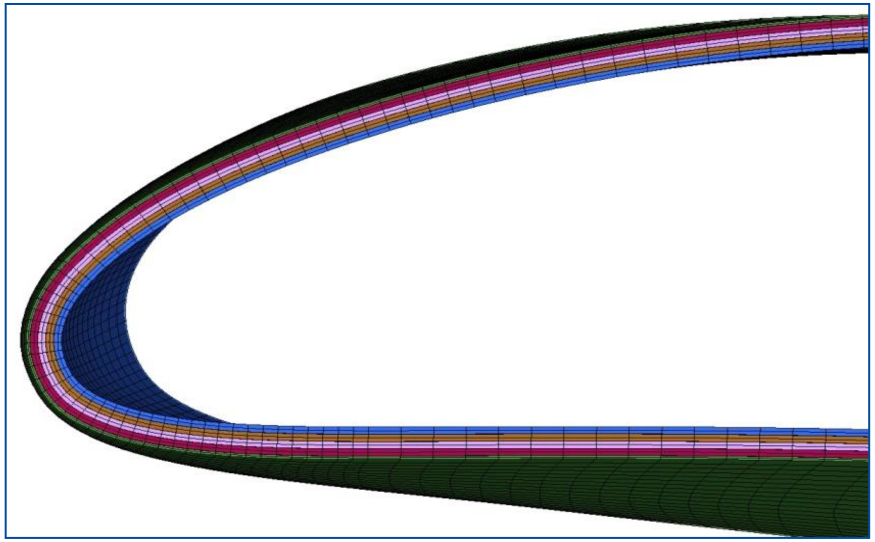
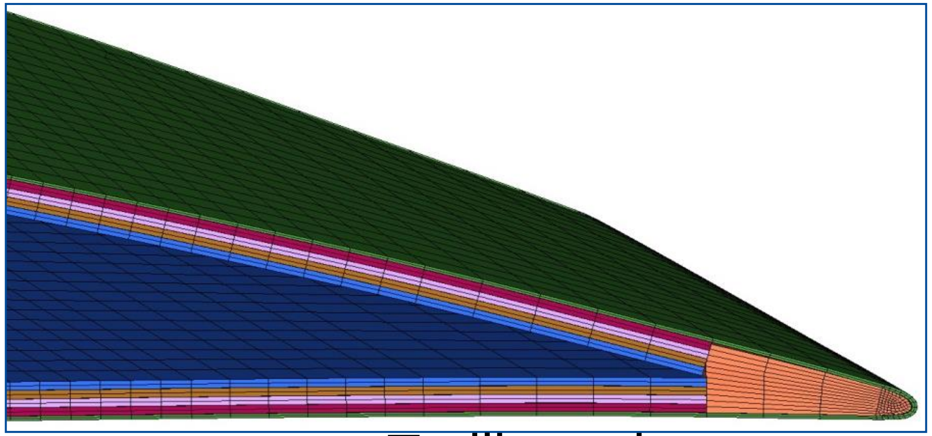




🟩 Gelcoat
🟥 Layer1
🟪 Layer2
🟧 Layer3
🟦 Layer4

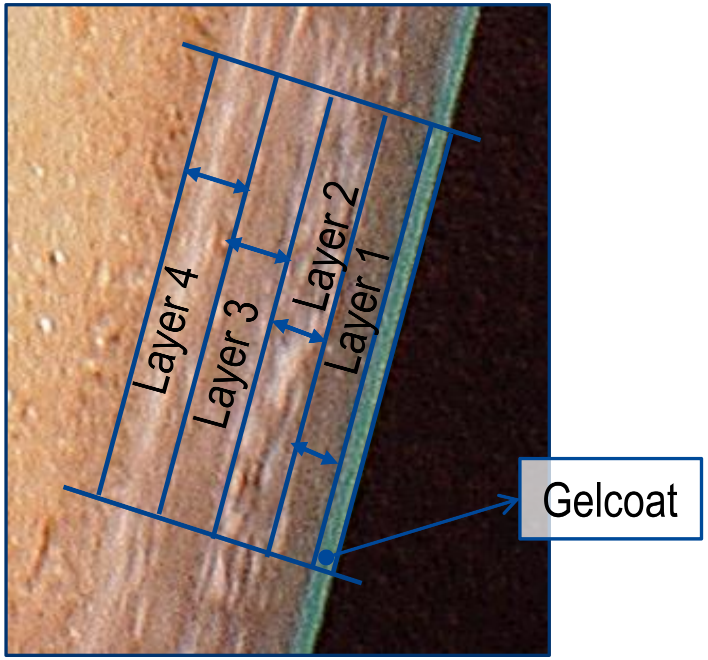


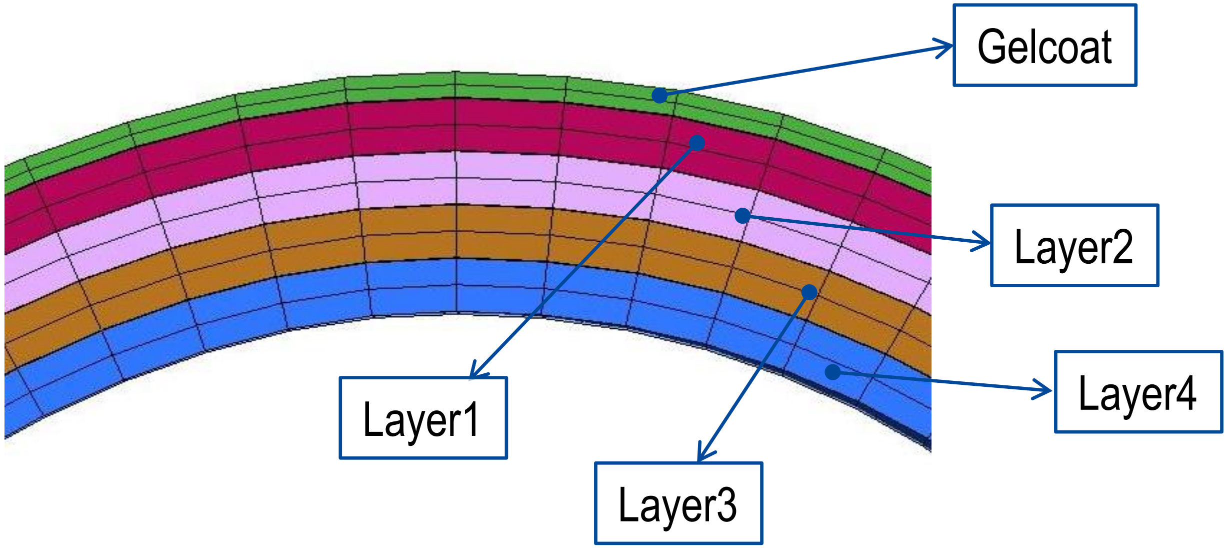
Leading Edge



Trailing edge

Geometriemodellierung





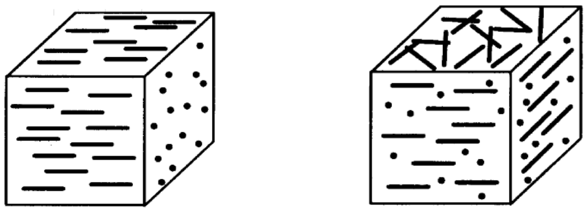
	Thickness	Material	Orientation
Gelcoat	0.42mm	Polyester resin	Uniform
Layer1	0.80mm	Glass fibers	Random
Layer2	0.84mm	Glass fibers	±45 degree
Layer3	0.80mm	Glass fibers	Random
Layer4	0.84mm	Glass fibers	±45 degree

Gap between each layer = 10 micron

Note: Gap is defined to incorporate the effect of glue and delamination of layer

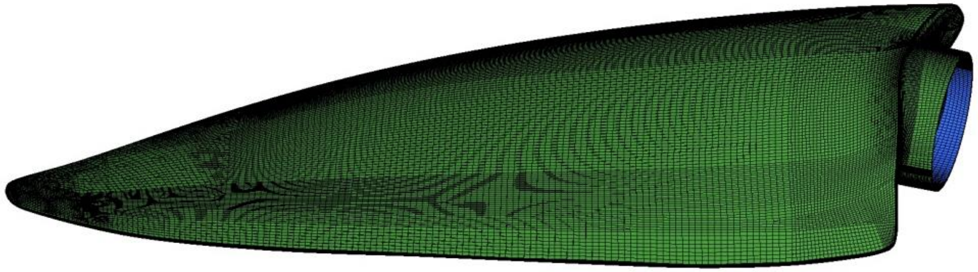
Werkstoffmodellierung

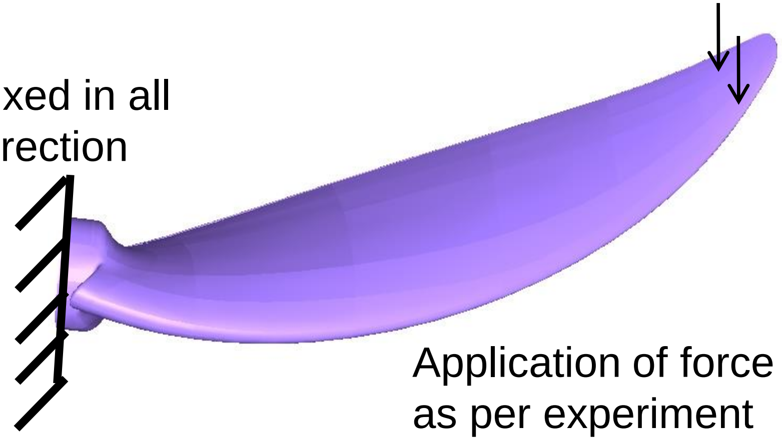
	45 degree Oriented fiber	Random
Young’s Modulus X direction	5500 MPa	5500 MPa
Young’s Modulus Y direction	8500 MPa	5500 MPa
Young’s Modulus Z direction	8500 MPa	5500 MPa
Poisson’s ratio XY	0.32	0.32
Poisson’s ratio YZ	0.32	0.32
Poisson’s ratio XZ	0.32	0.32
Shear Modulus XY	5500 MPa	5500 MPa
Shear Modulus YZ	5500 MPa	5500 MPa
Shear Modulus XZ	5500 MPa	5500 MPa



Experimentelle Überprüfung der Werkstoffmodelle

Elements:
586457
Nodes: 685593

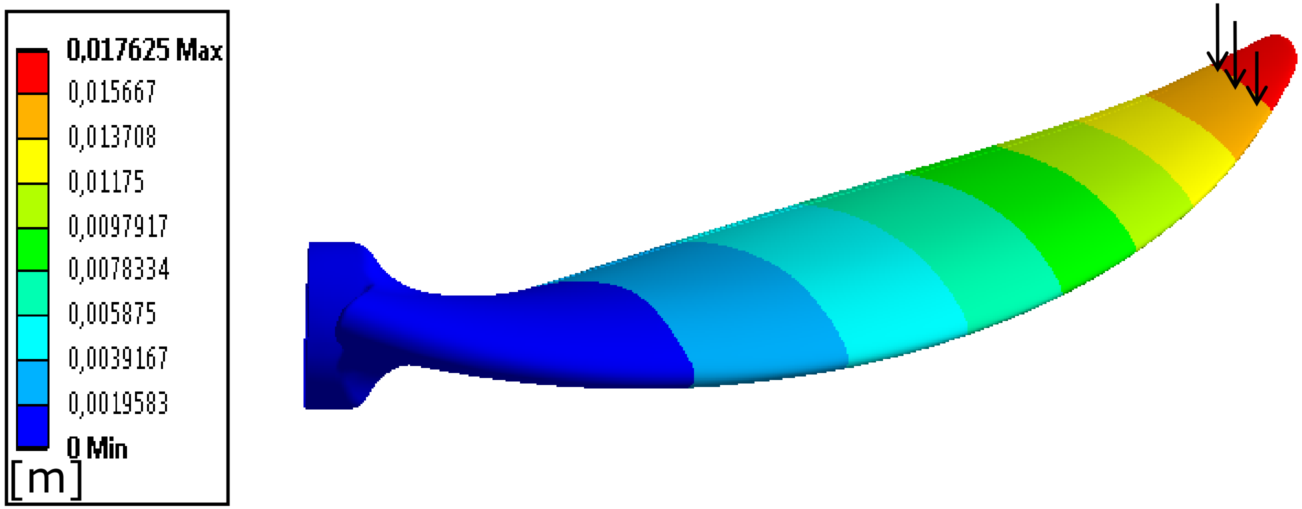




Fixed in all direction

Force = 400 N

Application of force as per experiment



Experimentelle Überprüfung der Werkstoffmodelle

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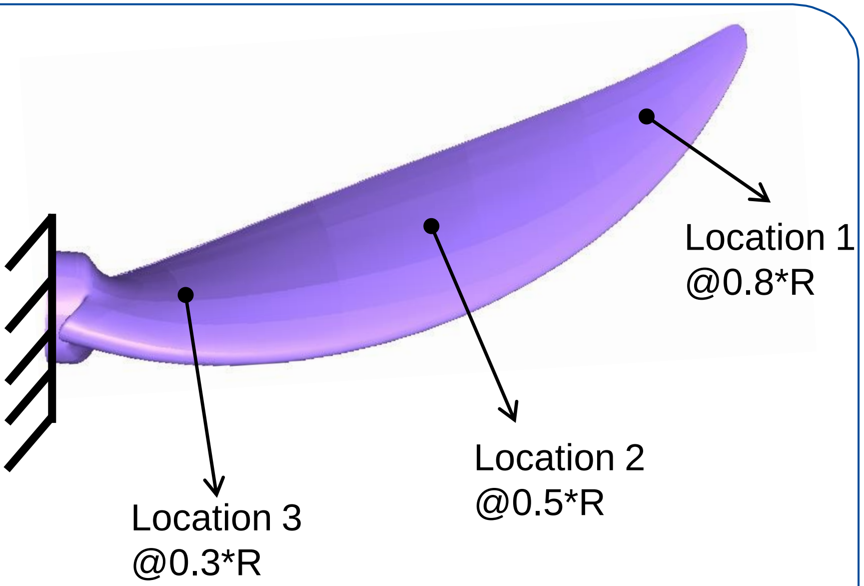
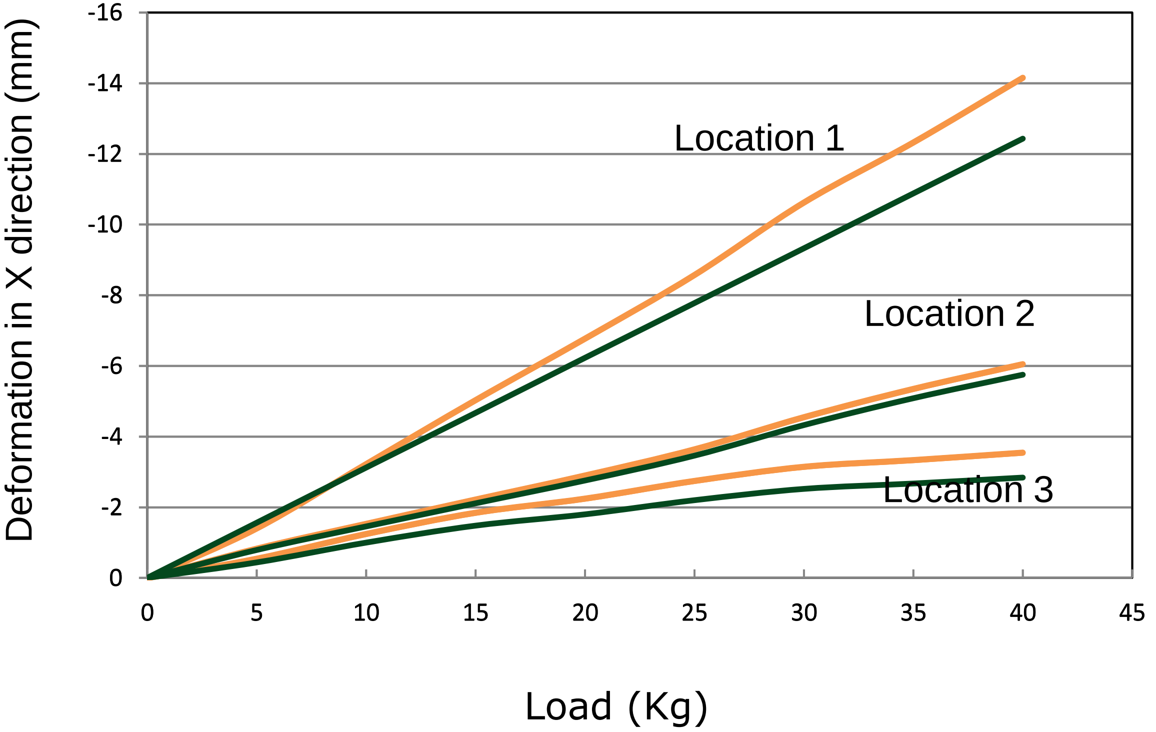
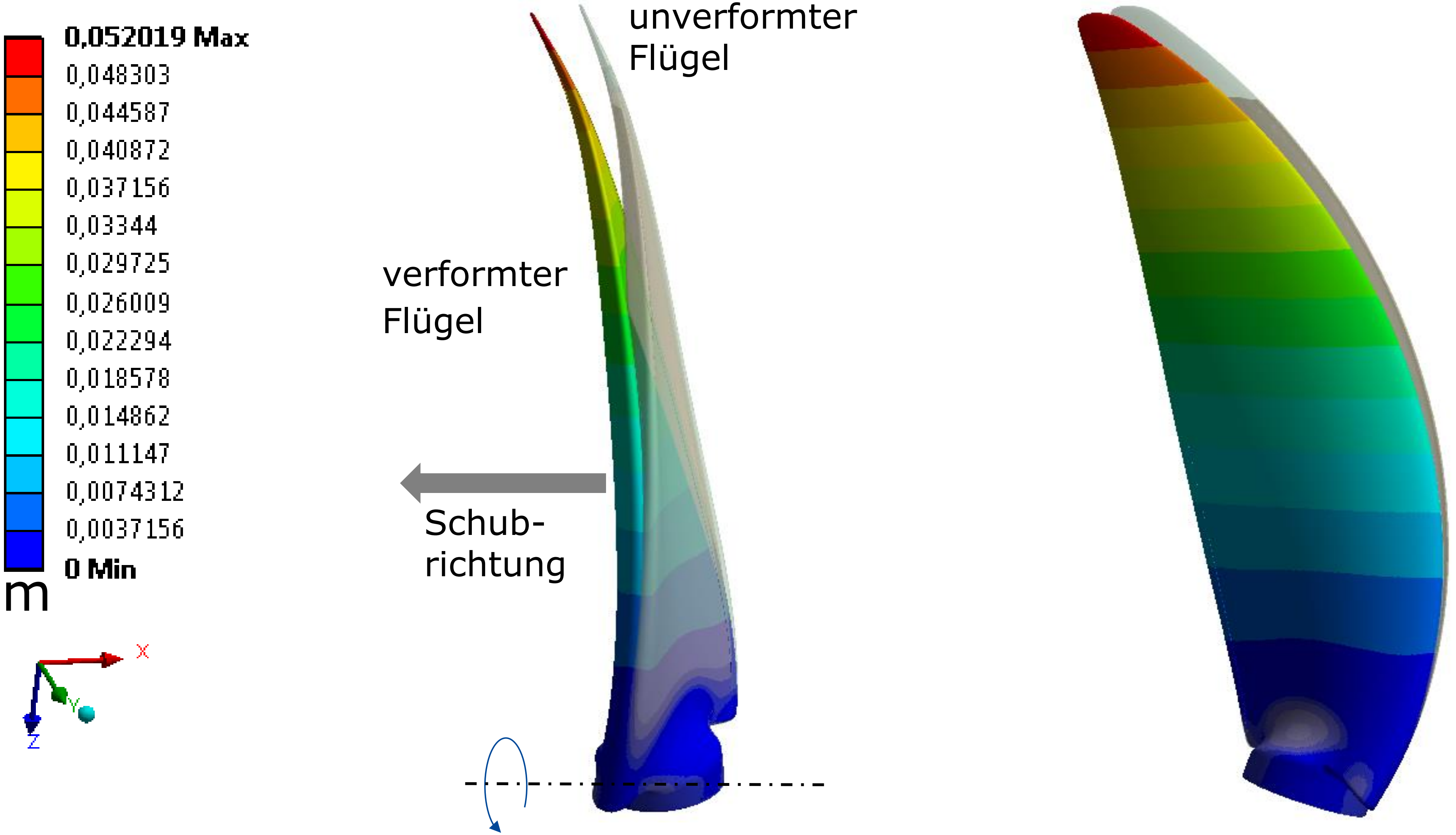




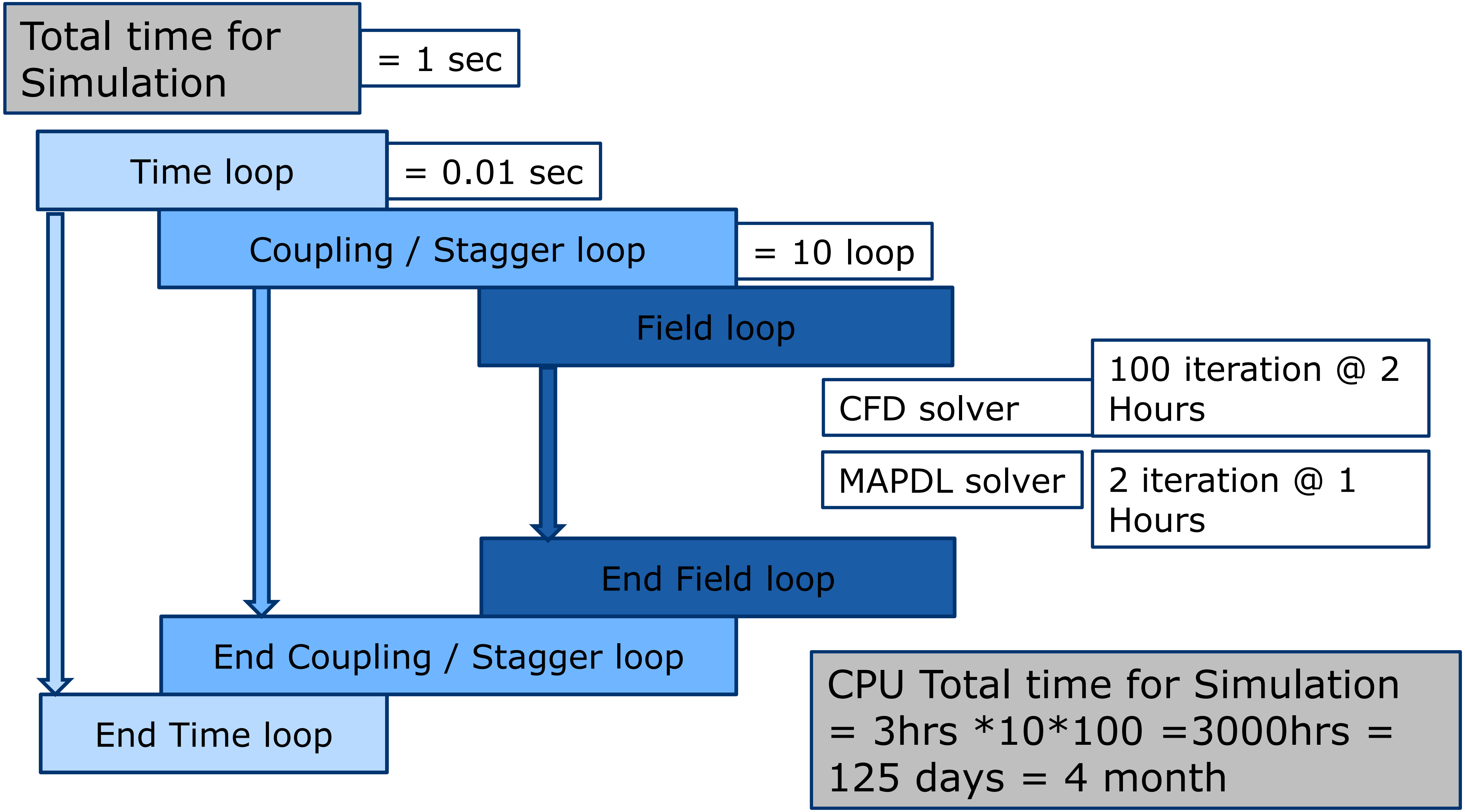
━ Experimental results

━ Numerical simulation results

Deformation



Computation time



Total time for Simulation = 1 sec

Time loop = 0.01 sec

Coupling / Stagger loop = 10 loop

Field loop

CFD solver | 100 iteration @ 2 Hours

MAPDL solver | 2 iteration @ 1 Hours

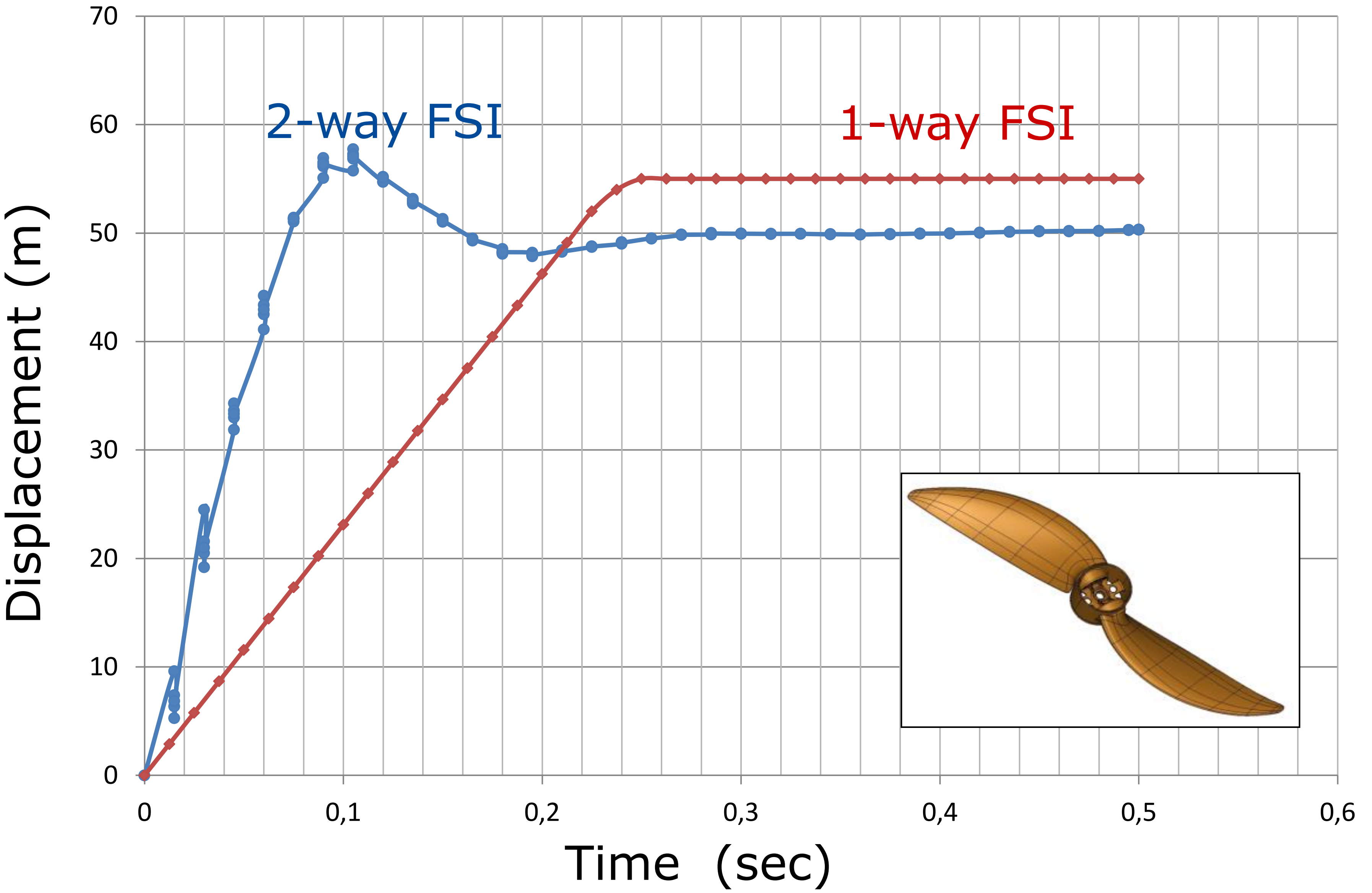
End Field loop

End Coupling / Stagger loop

End Time loop

CPU Total time for Simulation = 3hrs *10*100 =3000hrs = 125 days = 4 month

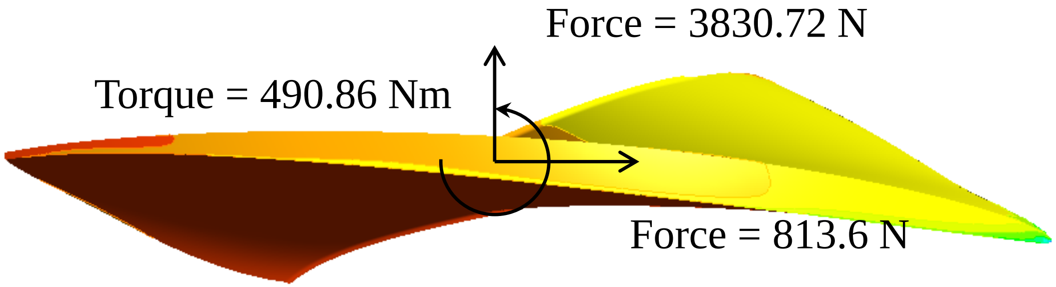
Vergleich uni-directionale und bi-directionale Simulation -Verformung -



Bewertung mit Bruchkriterien

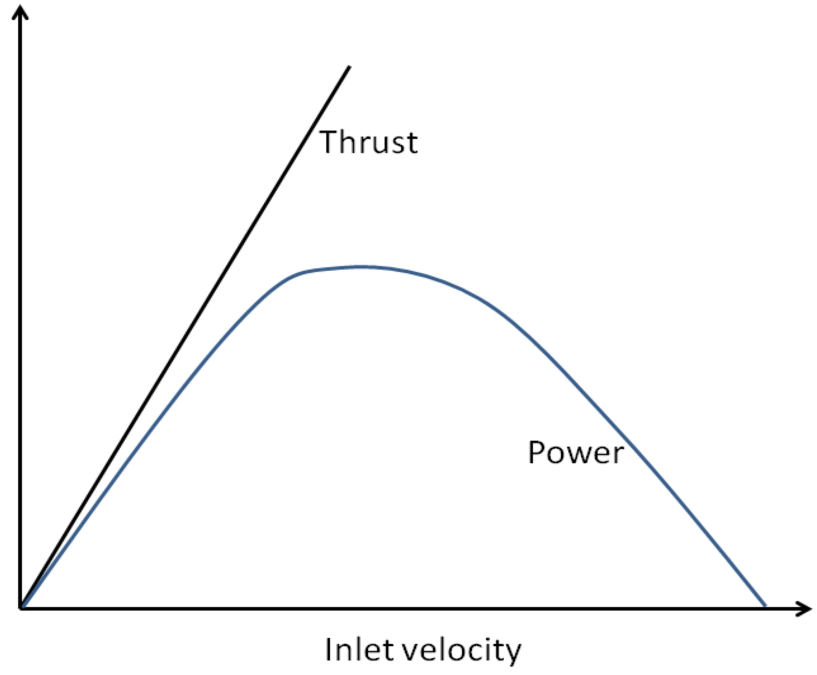
- von Tsai Wu
- von Puck
- LaRC-Kriterien
- etc.

Nutzung der anisotropen Eigenschaften von Faser-Verbund-Werkstoffen

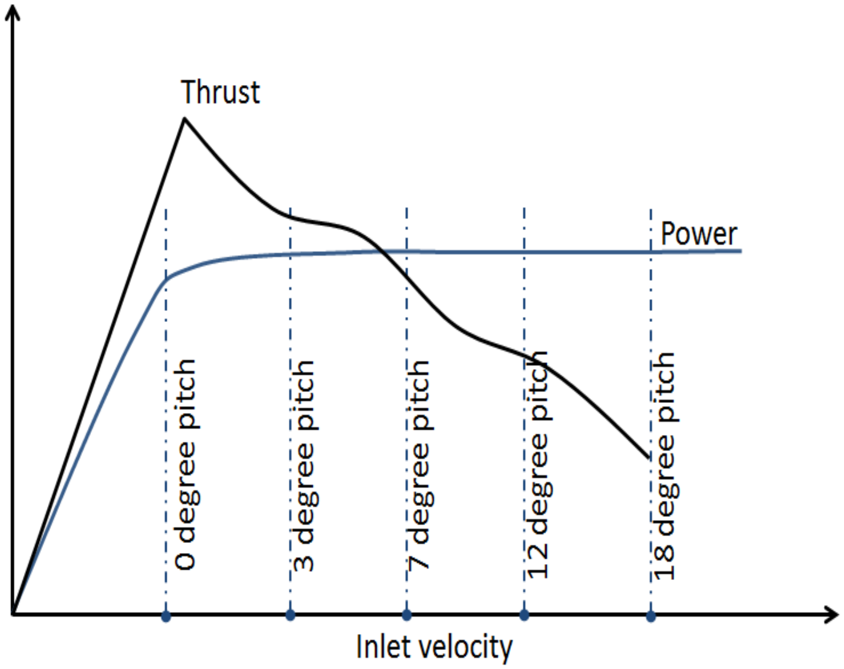


Beeinflussung der Schubkurve

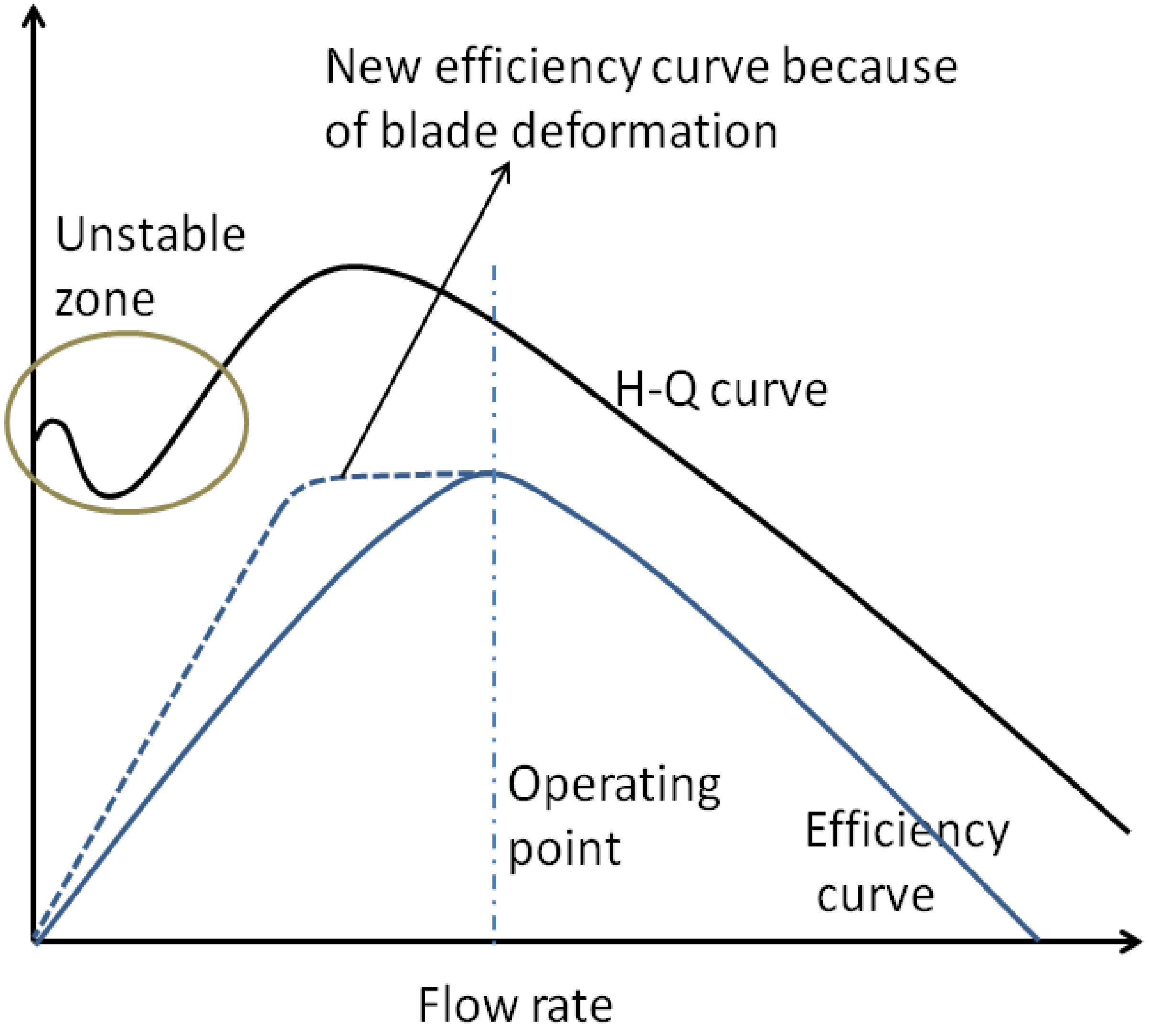
Standardverhalten



selbständiger pitch der Schaufel

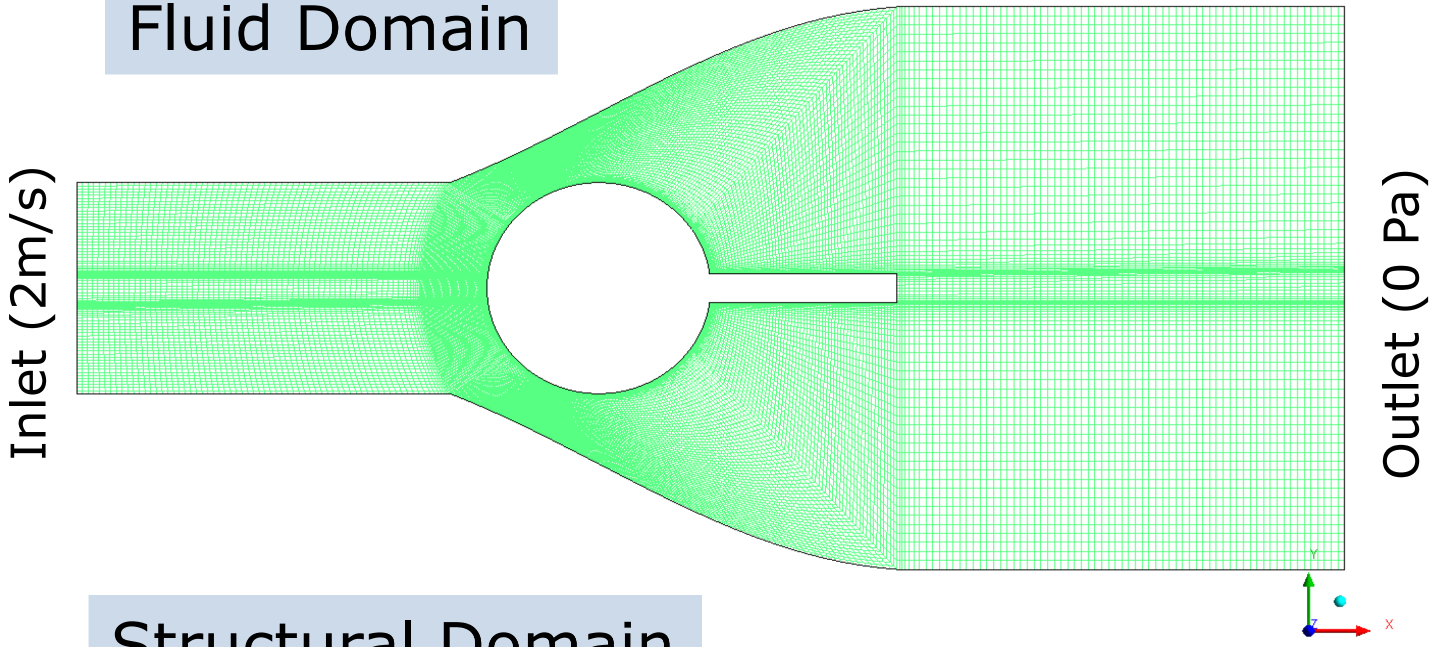


Beeinflussung der Kennlinien einer Propellerpumpe – Ziel!



strömungsinduzierte Anregung von Armaturenbauteilen (bi-directional implicit FSI)

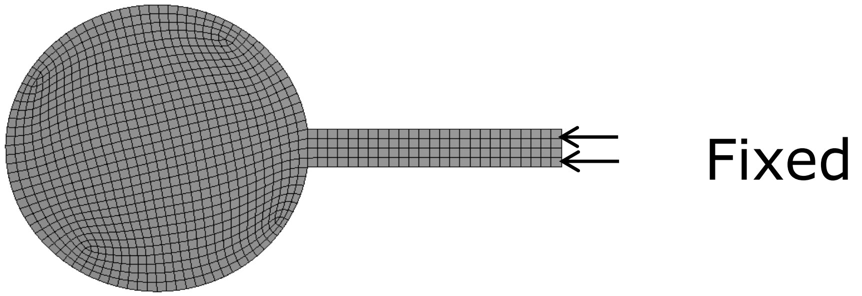
Fluid Domain

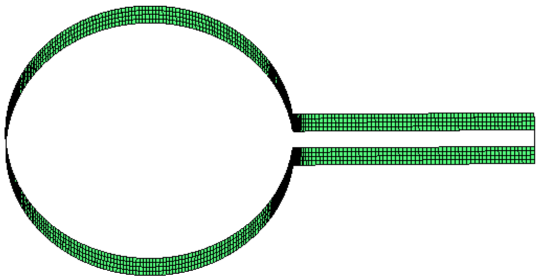


Re = 60000
Min. Angle = 36 degree

Transient Simulation
SST turbulence model

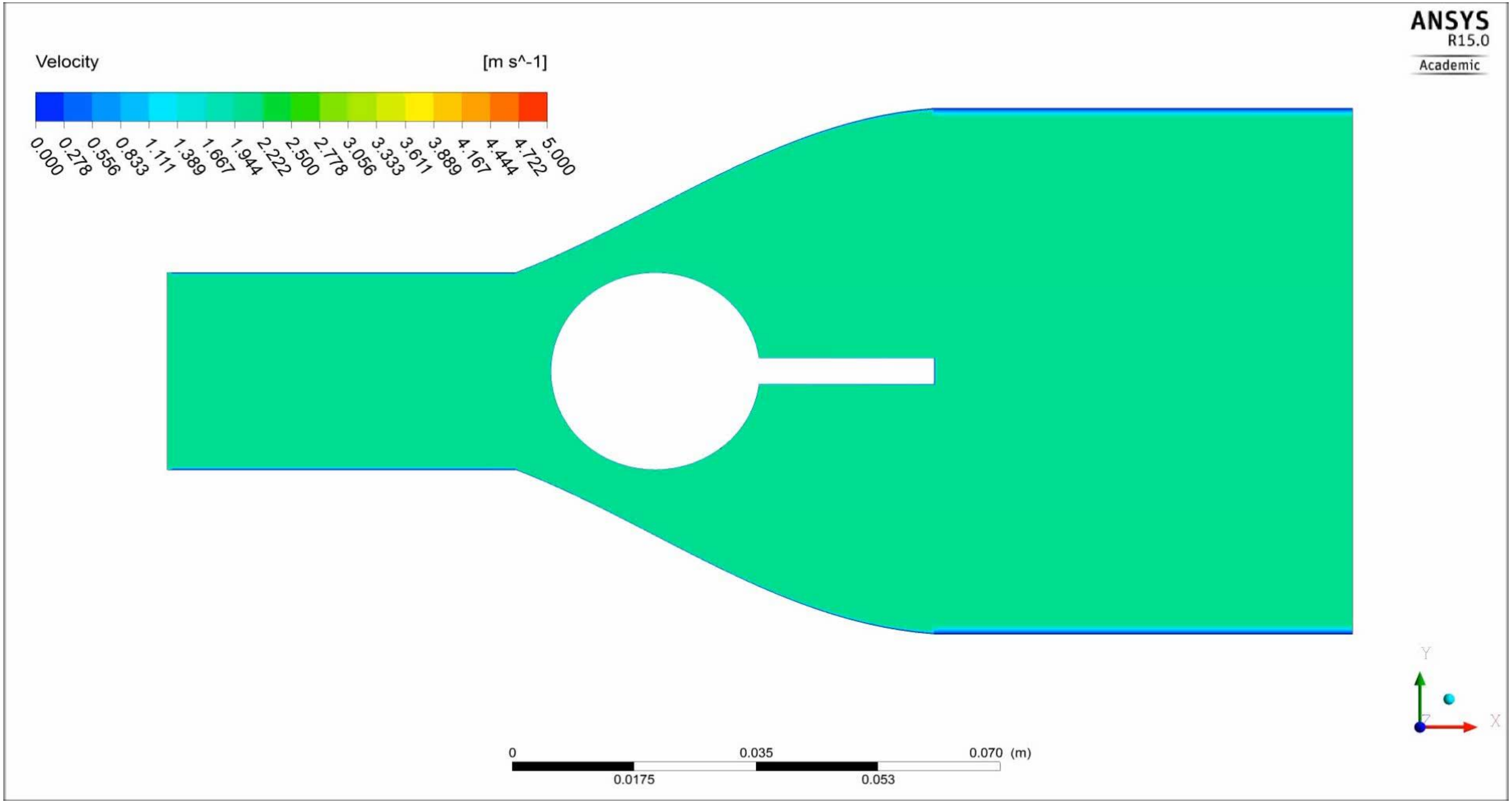
Structural Domain



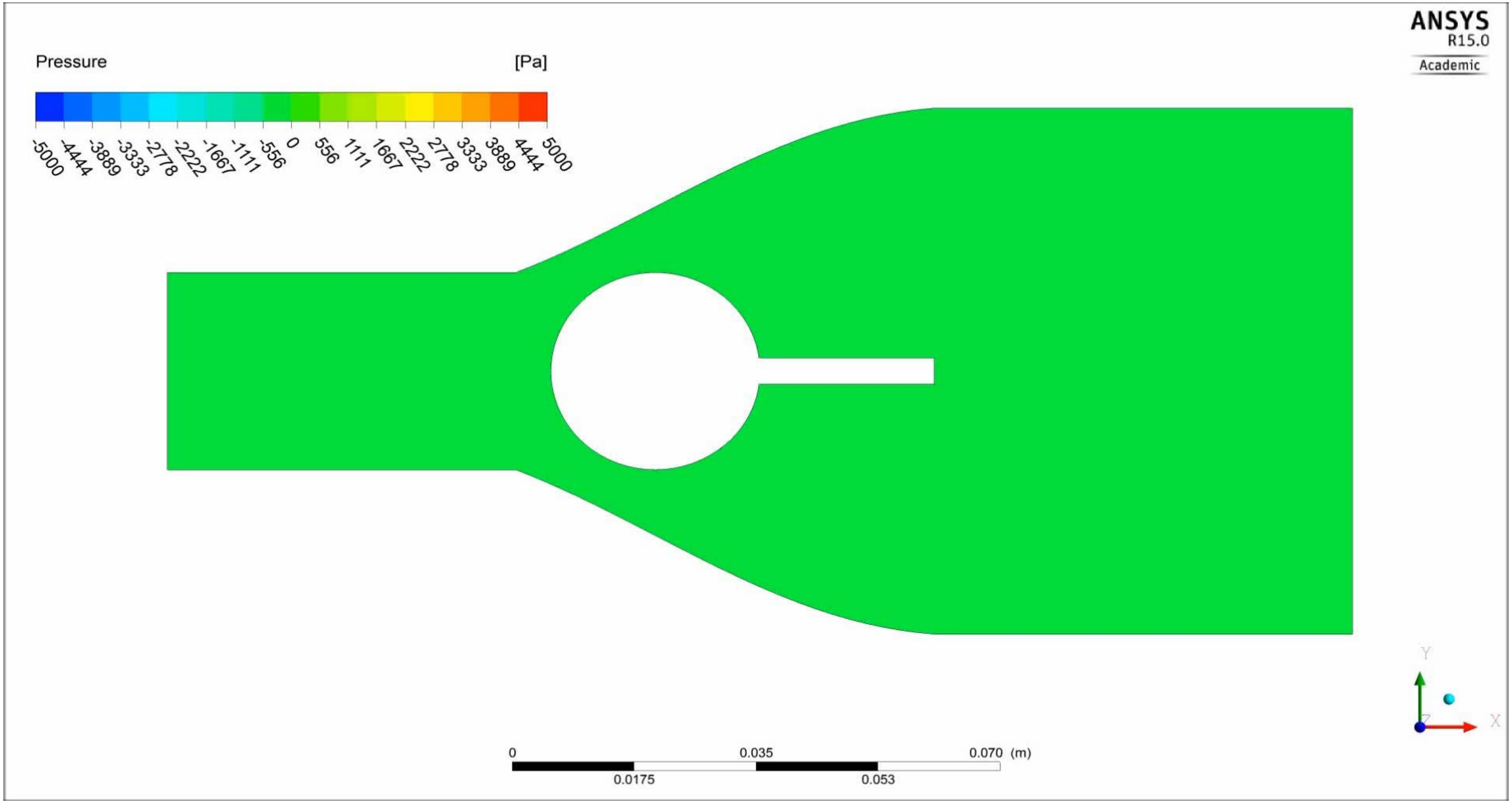


Fluid structure interface

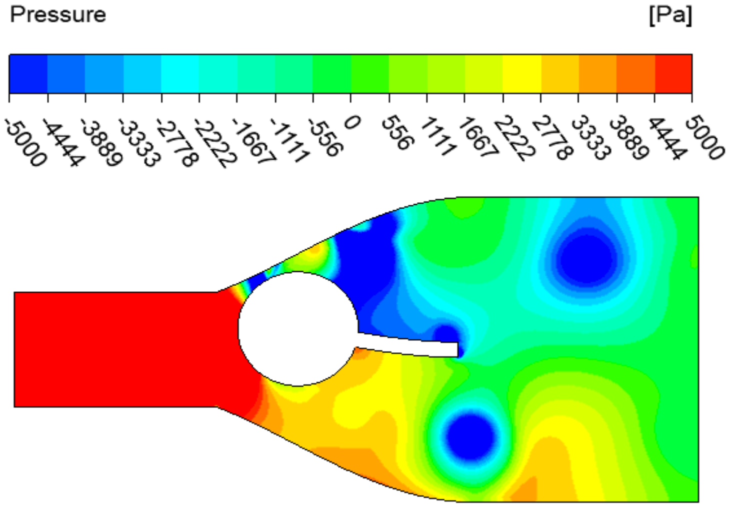
instationäres Geschwindigkeitsfeld

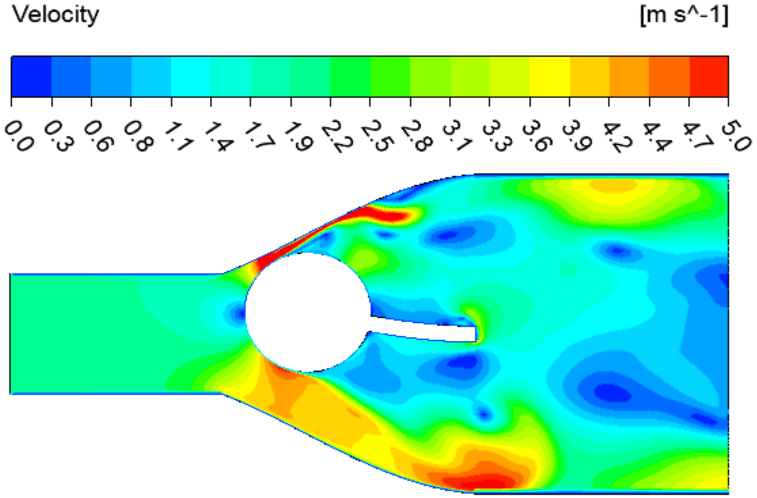


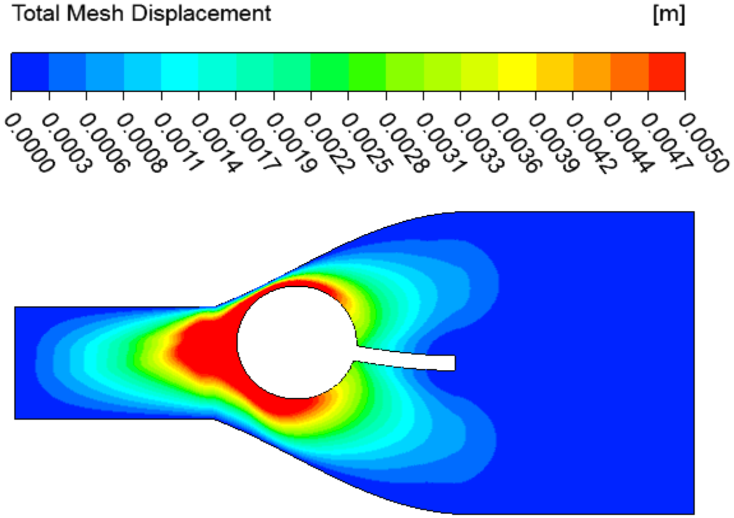
instationäres Druckfeld

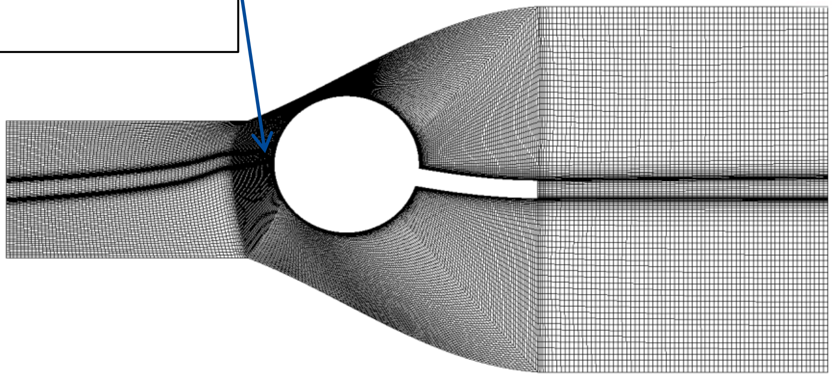


Simulationsergebnis nach 0.52 sec



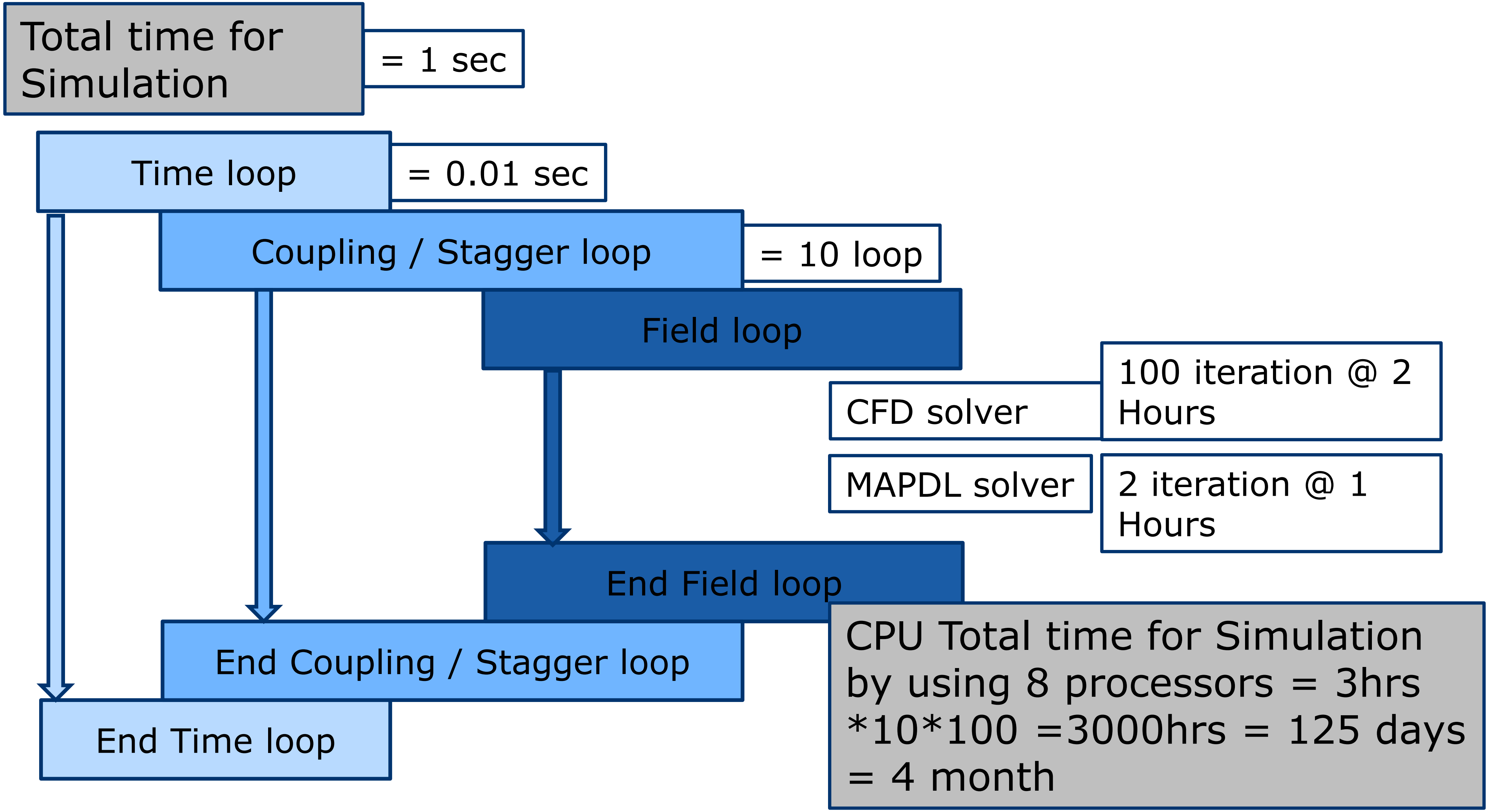






Negative volume created and simulation crashed

Problem: Rechenzeitbedarf



Total time for Simulation = 1 sec

Time loop = 0.01 sec

Coupling / Stagger loop = 10 loop

Field loop

CFD solver: 100 iteration @ 2 Hours

MAPDL solver: 2 iteration @ 1 Hours

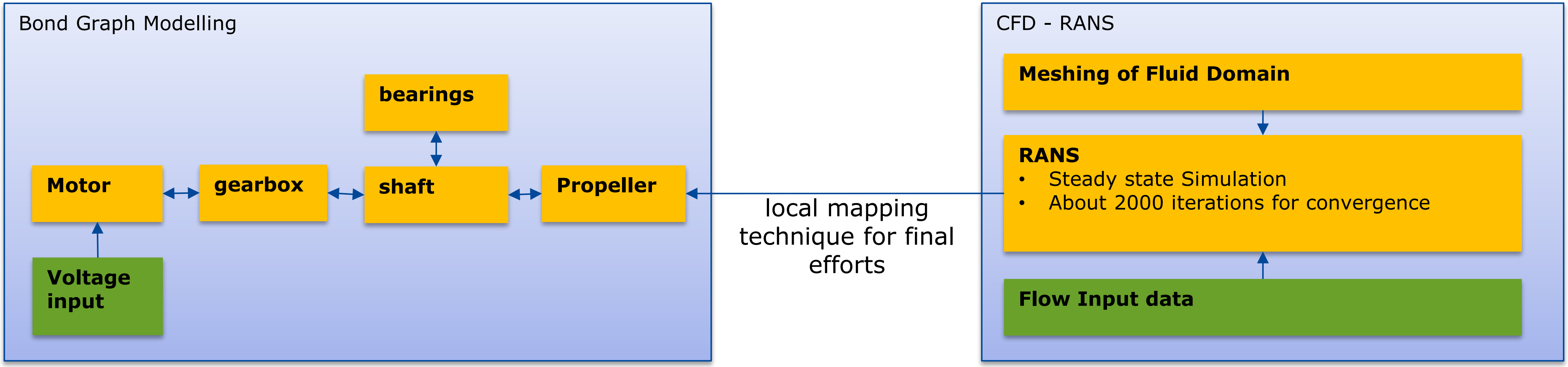
End Field loop

End Coupling / Stagger loop

End Time loop

CPU Total time for Simulation by using 8 processors = 3hrs *10*100 =3000hrs = 125 days = 4 month

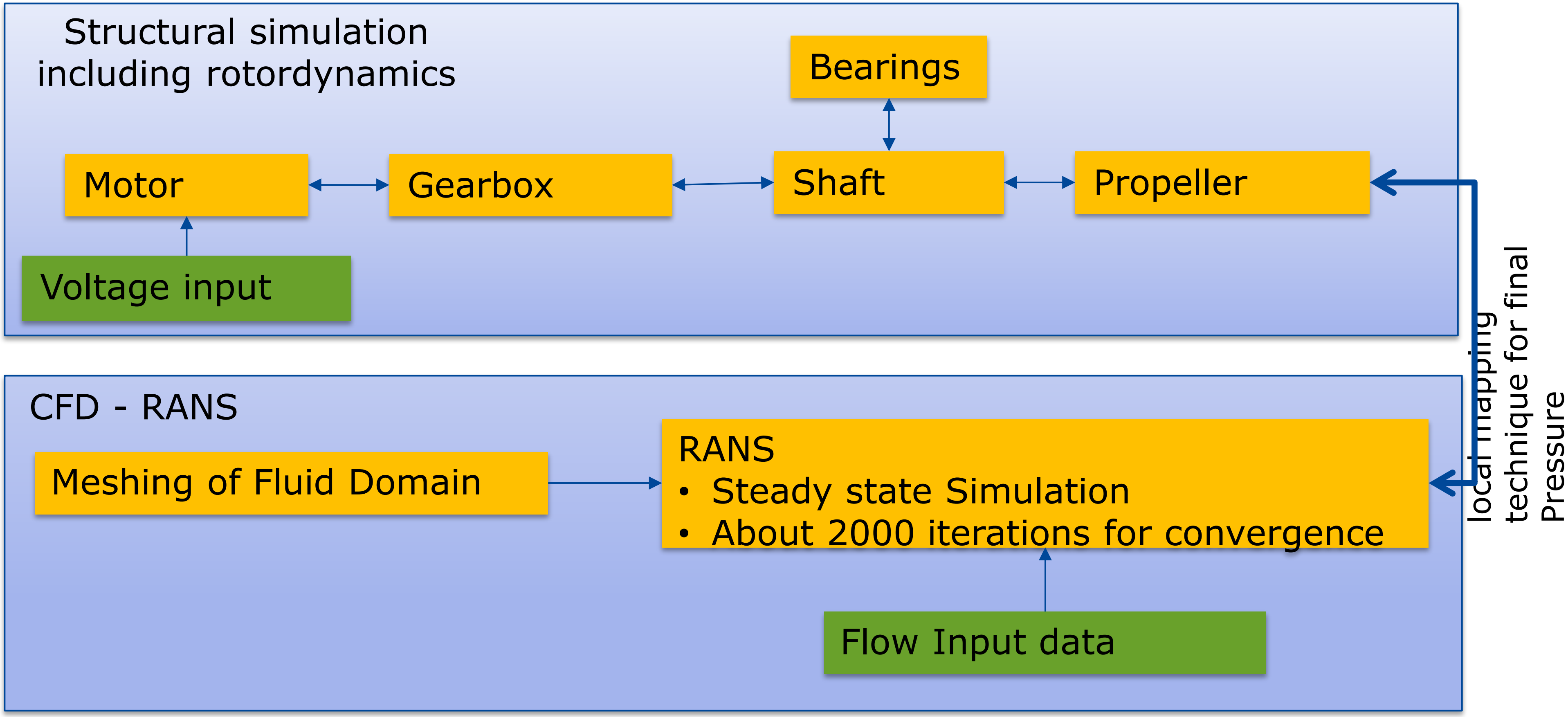
Grenzen für die Anwendung implicit FSI



- Steady state Simulation
- About 2000 iterations for convergence

1. Very long CFD-calculation time for solving RANS-equations (est. 3 weeks for 3.2m diameter of propeller) because of large mesh size in stator and rotor domain including boundary layers.
2. Limited to steady state flow conditions because of large computational effort to simulate variations of boundary conditions.
3. No experimental data is available to validate numerical results properly

weiteres Problem: keine sinnvolle Kopplung zu rotordnamischen Berechnungen möglich



Structural simulation including rotordynamics

Bearings

Motor

Gearbox

Shaft

Propeller

Voltage input

local mapping technique for final Pressure

CFD - RANS

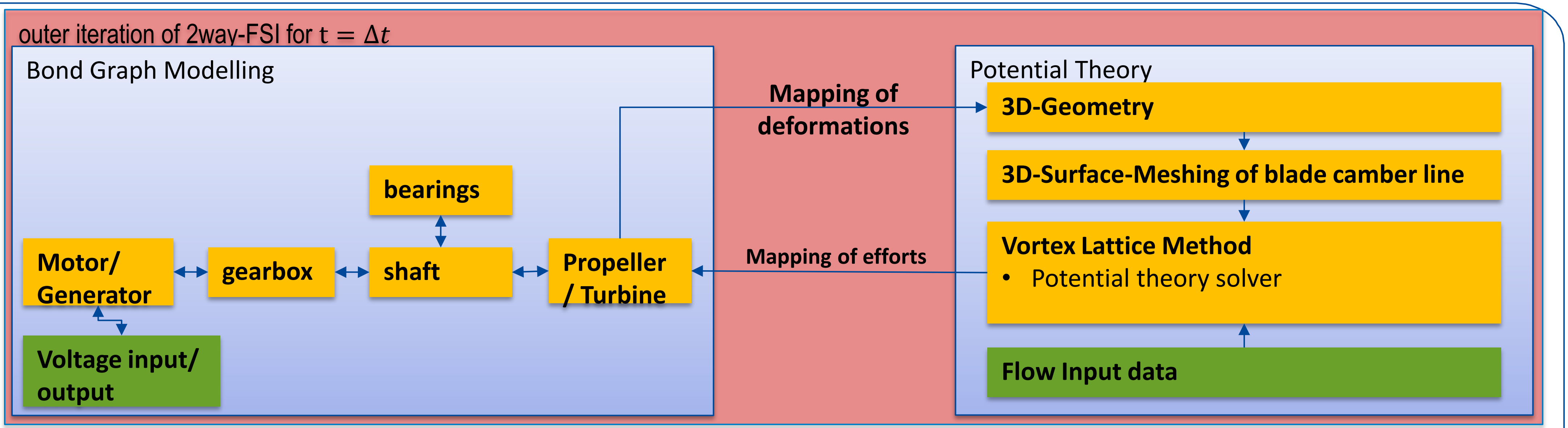
Meshing of Fluid Domain

RANS
- Steady state Simulation
- About 2000 iterations for convergence

Flow Input data

- ☐ Very long CFD-calculation time for solving RANS-equations (est. 3 weeks for 3.2m diameter of propeller) because of large mesh size in stator and rotor domain including boundary layers.
- ☐ Rotordynamics analysis including dynamic blade loading will have significantly large computational time.

Alternative



outer iteration of 2way-FSI for t $= \Delta t$

Bond Graph Modelling

bearings

Motor/ Generator

gearbox

shaft

Propeller / Turbine

Voltage input/ output

Mapping of deformations

Mapping of efforts

Potential Theory

3D-Geometry

3D-Surface-Meshing of blade camber line

Vortex Lattice Method

- Potential theory solver

Flow Input data

1. To overcome the long CFD - calculation time it is necessary to reduce the computational effort of the CFD-method by using a potential theory based Vortex-Lattice Method (VLM).
2. Bi-directional Fluid Structure Interaction (2way-FSI) can be simulated
   - Deformations of blade and its influence to fluid domain can be considered, because of reduced CFD-calculation time.
   - Force and torque fluctuations for one flow condition can be considered because an outer iteration process can be added to analyse the dynamic system behaviour.
3. Simulation of transient flow conditions can be possible by reducing the computational effort.

Technical background

1. The Vortex lattice method(VLM) is a numerical method in computational fluid mechanics. It is based on the theory of potential flow. In this ideal fluid flow viscous effects, turbulence, dissipation and boundary layers are neglected, which is valid for a wide variation of engineering applications such as propellers, mixers, wings, etc.
2. VLM provides the pressure distribution on a thin gridded surface by modelling the flow field through horse-shoe shaped vortices (see Fig. 2). Meshing of fluid domain is not necessary.
3. The computational effort of this method is very small compared to common CFD-methods based on the Navier-Stokes equations (DNS, LES, RANS), while accuracy is still in good agreement to reality.

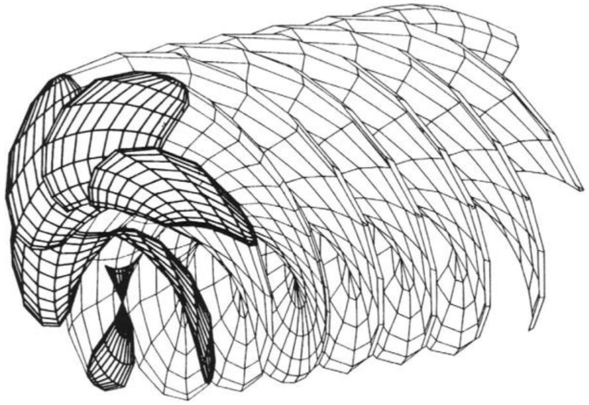
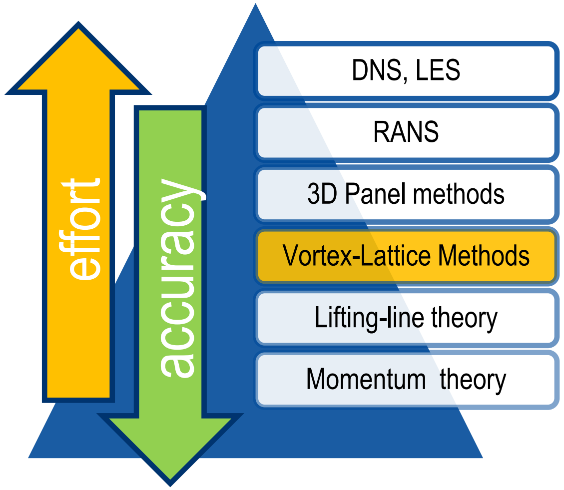


Fig. 1: vortex lattice model of propeller with wake vortex (Volker Bertram – *Practical Ship Hydrodynamics,* Butterworth-Heinemann, 2000)



DNS, LES

RANS

3D Panel methods

Vortex-Lattice Methods

Lifting-line theory

Momentum theory

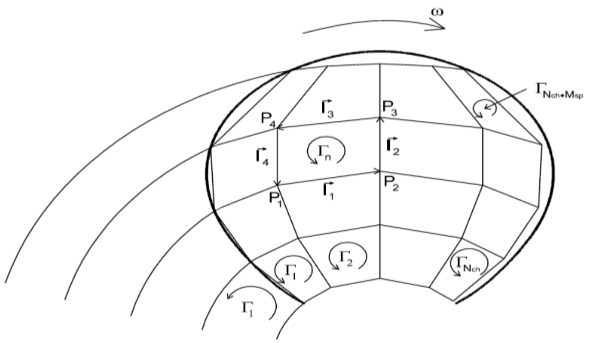
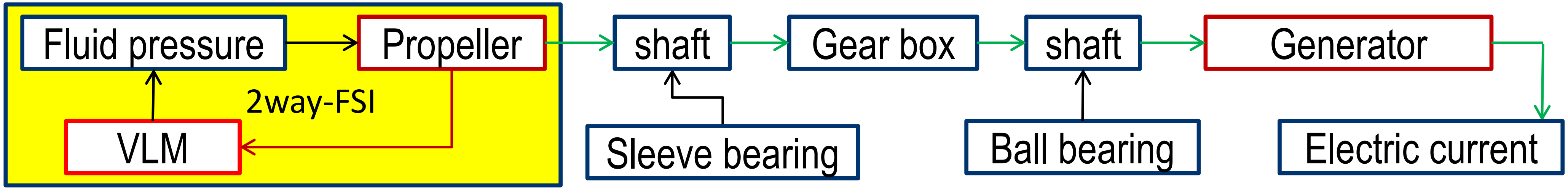


Fig. 2: schematic calculation grid for vortex-lattice-method (Anders Smaerup Olsen – Optimization of Propellers Using the Vortex-Lattice Method, PhD thesis, 2001)

Modeling & Simulation technique



Fluid pressure

Propeller

2way-FSI

VLM

shaft

Sleeve bearing

Gear box

shaft

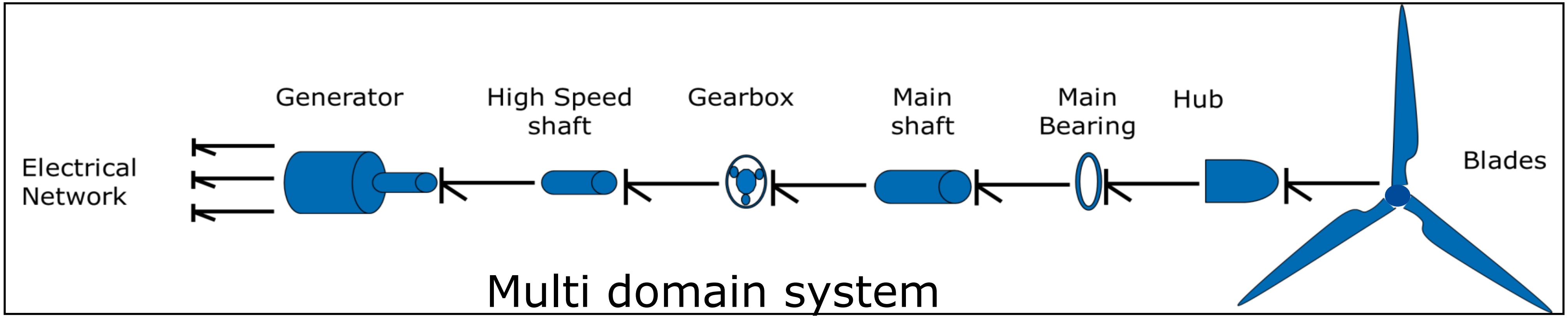
Ball bearing

Generator

Electric current

The most important aim is to achieve a fast working **2way-FSI analysis environment**, which models the **dynamic behaviour of a diverse energy domain system** and able to dramatically reduce the **computational effort** of the used CFD-method. So, **Vortex-Lattice Method could be solution for it**!

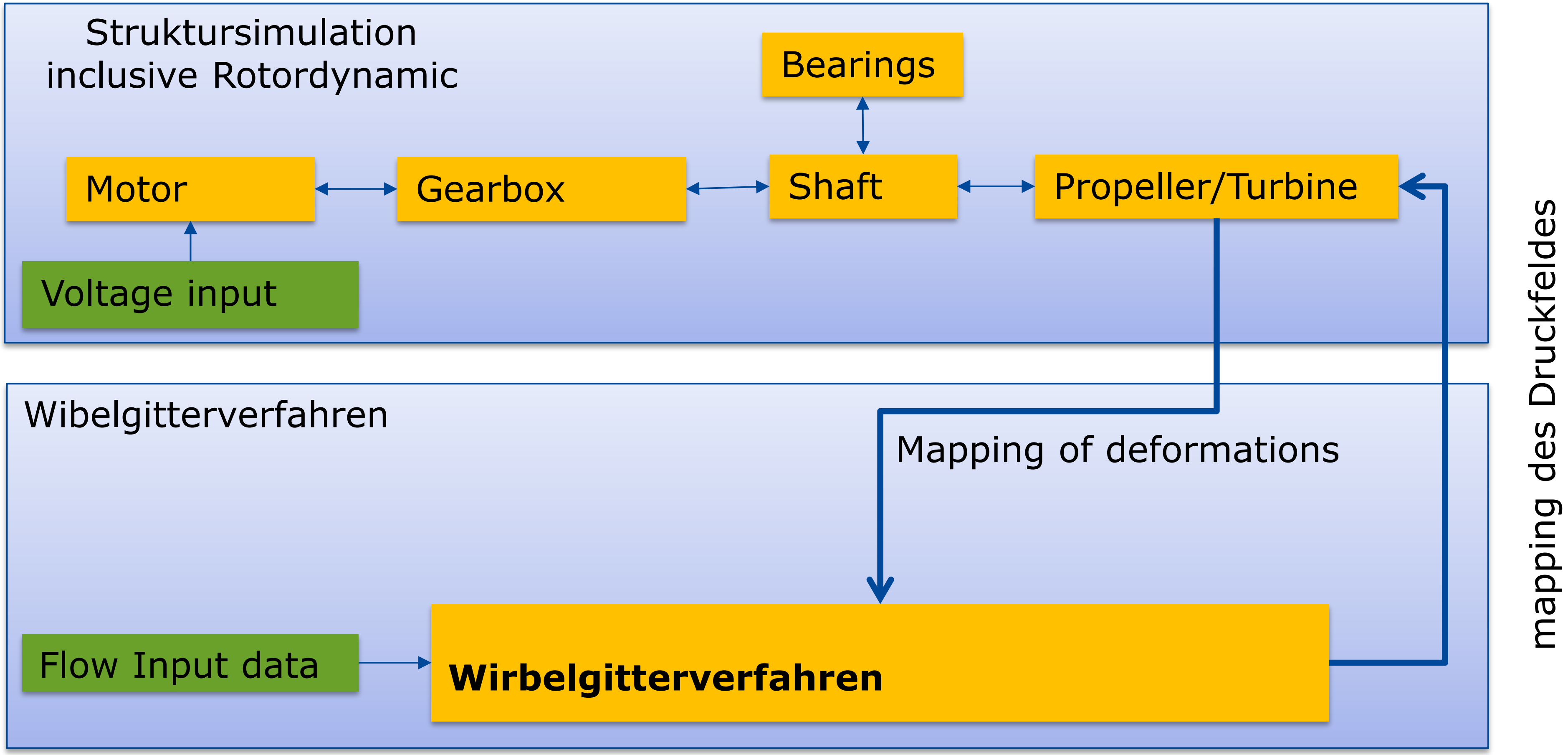
xFSI



- ❑ Kräfte am Rotor sind in vielen Anwendungen nicht konstant, dies kann zu Schwingungen an den Rotorschaufeln führen. Diese verursachen eine dynamische Belastung von Lager und Motor, gleiches gilt sinngemäß in entgegengesetzter Richtung.
- ❑ Es ist sinnvoll, eine Methode für die “schnelle” Simulation der verschiedenen Energiedomainen zu haben: Elektromotor mit FU, Mechanik und Strömungsfeld

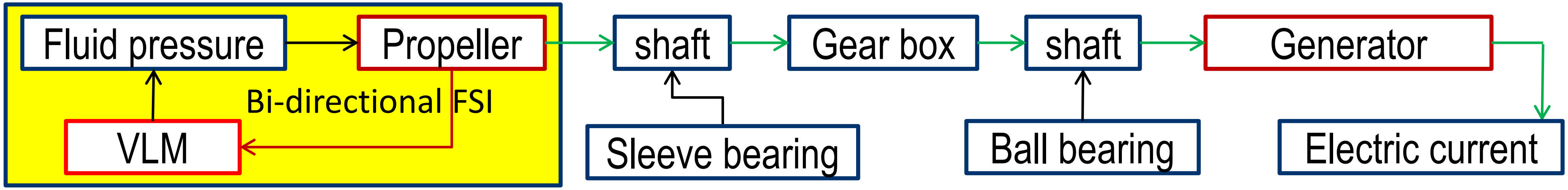
$$\begin{tikzcd}
 & \boxed{\Omega_e(t_n)} \arrow[d, shift right] & & \boxed{\Omega_e(t_{n+1})} \arrow[d, shift right] & \\
{} \arrow[r, "i_n"] & \boxed{\Omega_s(t_n)} \arrow[u, shift right] \arrow[d, shift right] & {} \arrow[r, "i_{n+1}"] & \boxed{\Omega_s(t_{n+1})} \arrow[u, shift right] \arrow[d, shift right] & {} \arrow[r, "i_{n+2}"] & {} \\
 & \boxed{\Omega_f(t_n)} \arrow[u, shift right] & & \boxed{\Omega_f(t_{n+1})} \arrow[u, shift right] & \\
 & t & & t + \Delta t &
\end{tikzcd}$$

Ausblick



- ❑ geringer Rechenzeitbedarf des Wirbelgitterverfahrens
- ❑ Rotordynamische Analyse inklusive der dynamischen Blattbelastung ist mit relativ geringem Zeitaufwand möglich.

Ausblick



Das wesentliche Ziel ist es, eine **schnelle bi-directionale FSI Simulationsumgebung** zu erarbeiten, die die Modellierung des **dynamischen Verhaltens mehrerer Energie-Domainen erlaubt** und dafür einen akzeptablen **Rechenzeitbedarf** erzeugt.