MBS/FEM Co-Simulation Approach for Analyzing Fluid/Structure-Interaction Phenomena in Turbine Systems

Martin Busch and Bernhard Schweizer
Department of Mechanical Engineering
Multibody Systems
University of Kassel

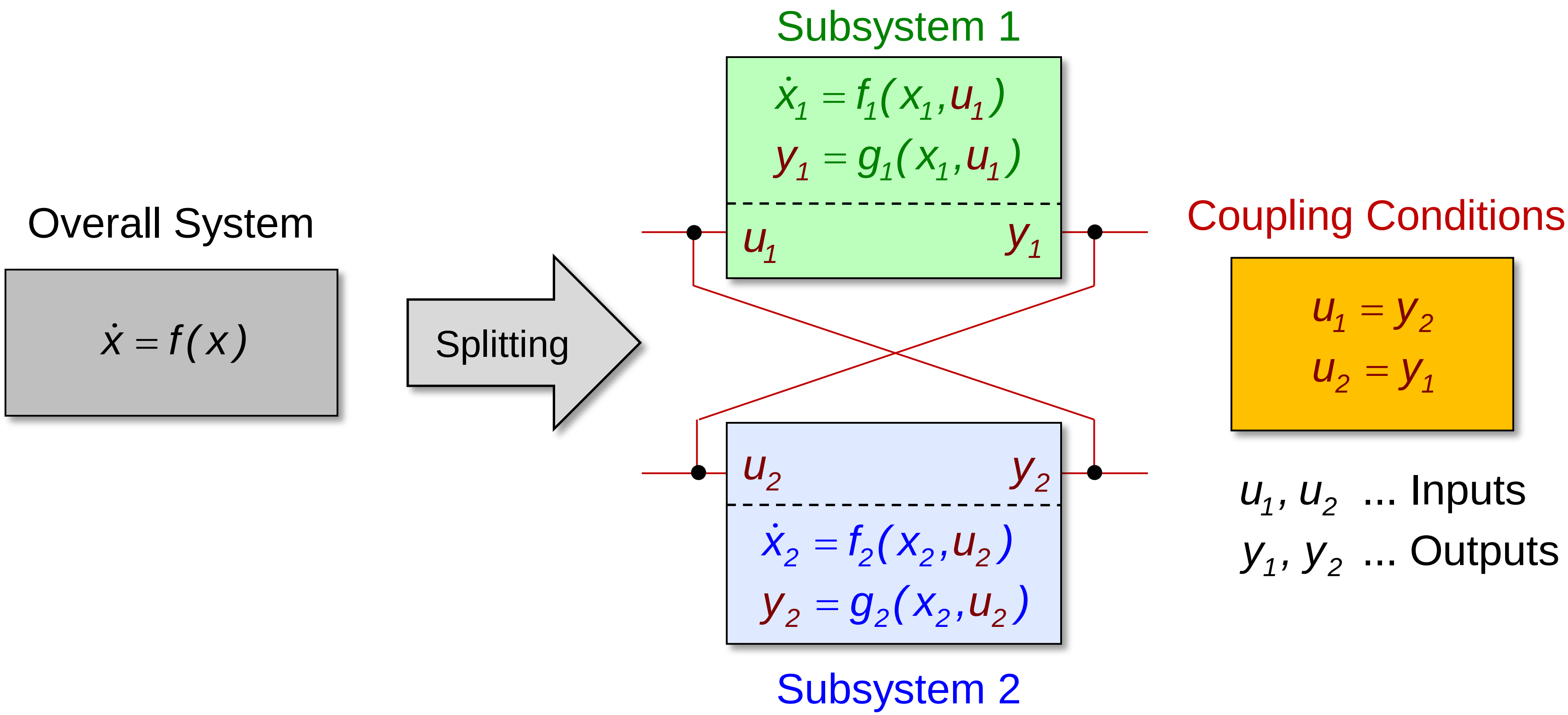
SIMPACK User Meeting

Salzburg, May 18-19, 2011

Outline:

- Introduction: General Aspects of Coupled Simulation
- Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger
- Three Coupling Approaches:
  - Full-Implicit Approach
  - Explicit Multirate Approach
  - Semi-Implicit Approach
- Numerical Results: Run-up Simulation of a Turbocharger

Aspects of Coupled Simulation: *Decomposition*



Idea:

- Split overall system into (two) subsystems, coupled by input and output variables

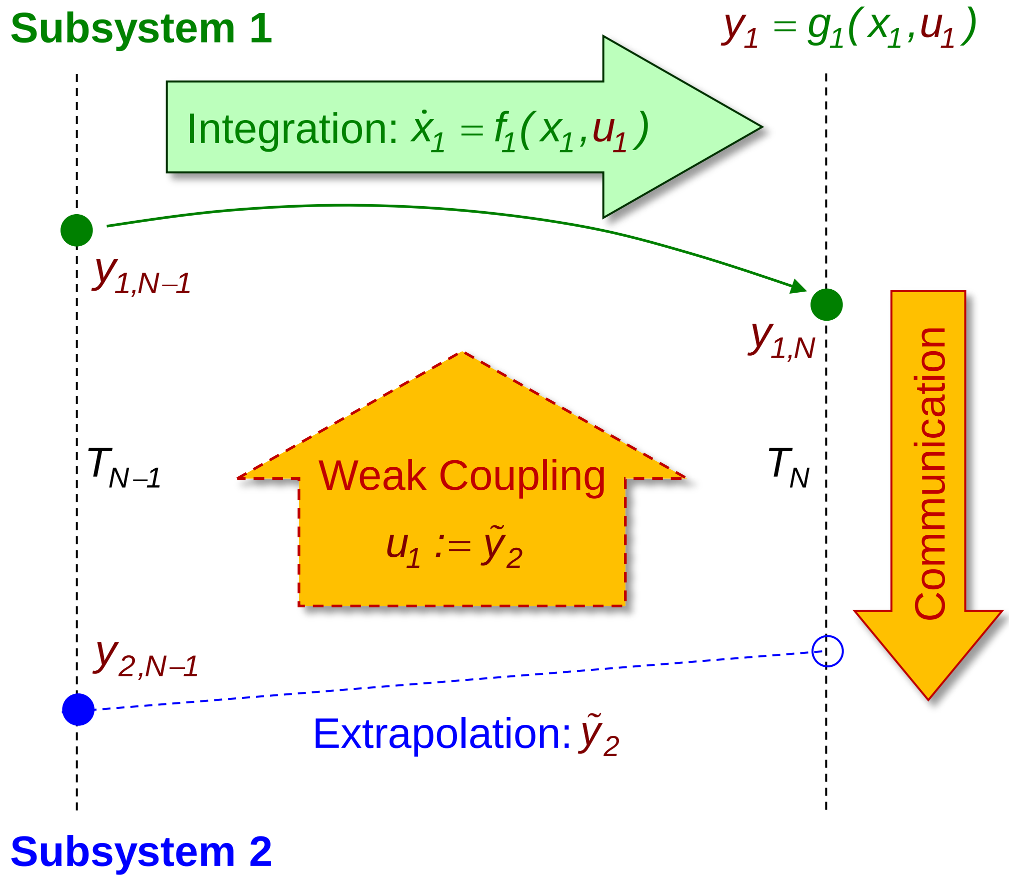
  → Coupling loop created

General Integration Scheme: *Multirate Approach*[1]

Macro-Time Step $T_{N-1} \rightarrow T_N$:

Step 1: Subsystem 1

- Coupling variables at T_{N-j} $(j=1,\ldots,N)$ are known
- Integrate **Subsystem 1** from T_{N-1} to T_N using extrapolated coupling variables $u_1 := \tilde{y}_2$
- Compute output variables $y_{1,N}$
- Communicate output variables $y_{1,N}$ to **Subsystem 2**



Remark:

- Weak Coupling: Coupling loop is cut through → Sequential or parallel integration of subsystems
- Communication-time grid (“macro-time grid”) is required for data exchange

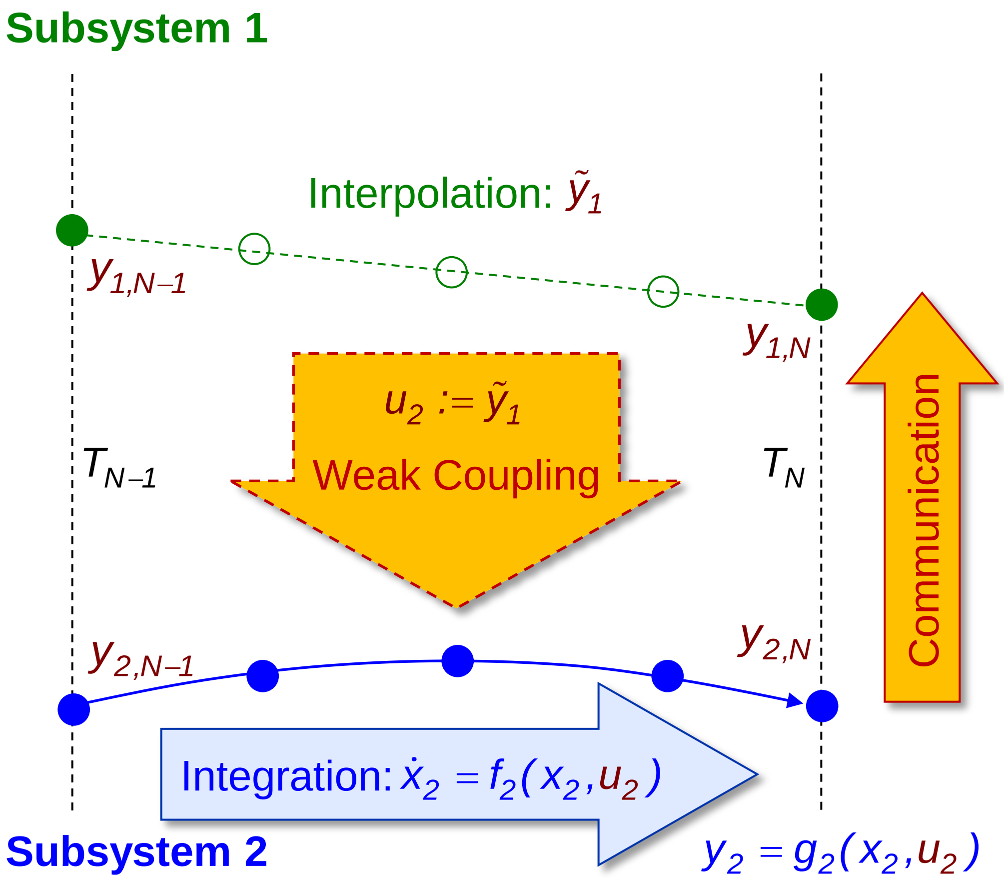
General Integration Scheme: *Multirate Approach*[1]

Macro-Time Step $T_{N-1} \rightarrow T_N$:

Step 2: Subsystem 2

- Integrate **Subsystem 2** from T_{N-1} to T_N using interpolated coupling variables $u_2 := \tilde{y}_1$
- Compute output variables $y_{2,N}$
- Communicate output variables $y_{2,N}$ to **Subsystem 1**

→ **Steps 1/2 are repeated at next macro-time step $T_N \rightarrow T_{N+1}$**



Remark:

- Coupling scheme is an explicit method w. r. t. the coupling variables
  → Numerical instabilities may arise[2]

Examples for Coupled Simulations

Coupling „*Multibody Systems*“ *(MBS)* with „*Partial Differential Equations*“ *(PDE)*:

- Fluid/structure interaction[3]
- Simulating contact between MBS and flexible structures[4]
- MBS coupled with electromechanical fields[5]
- etc.

Problems:

- MBS is commonly solved by implicit time-integration method
- PDE models have large numbers of DOFs

→ MBS/PDE coupling: huge systems and large CPU time

Task:

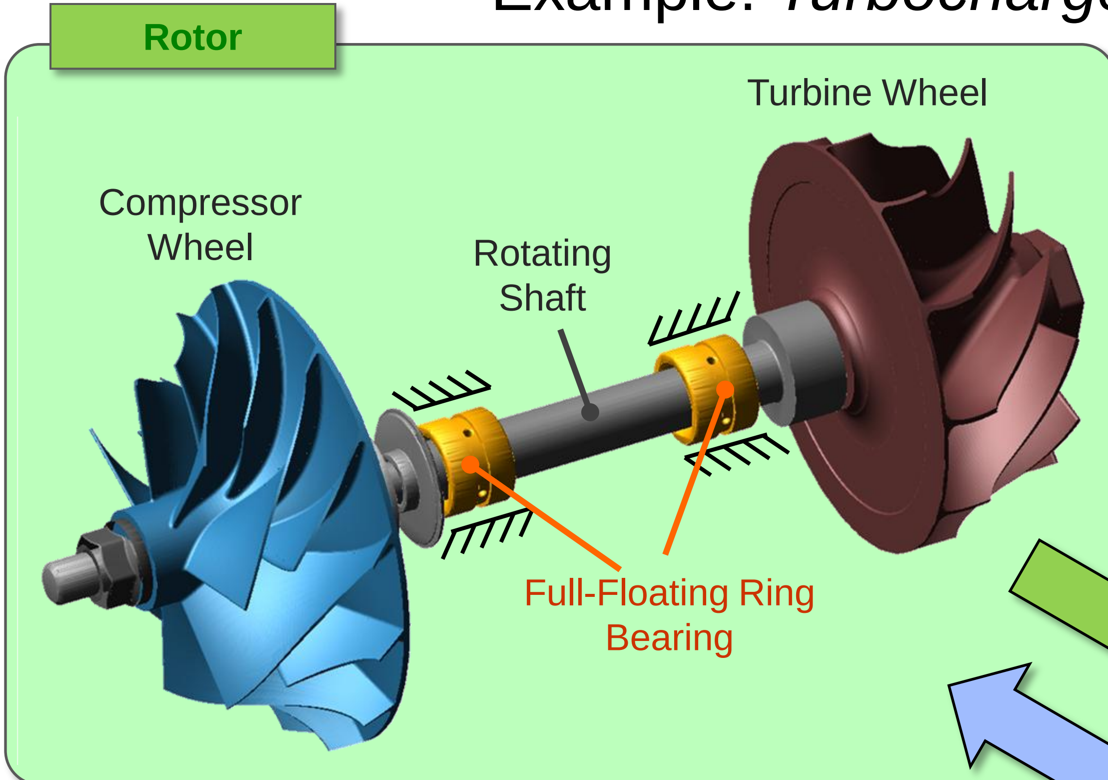
- Develop efficient co-simulation techniques

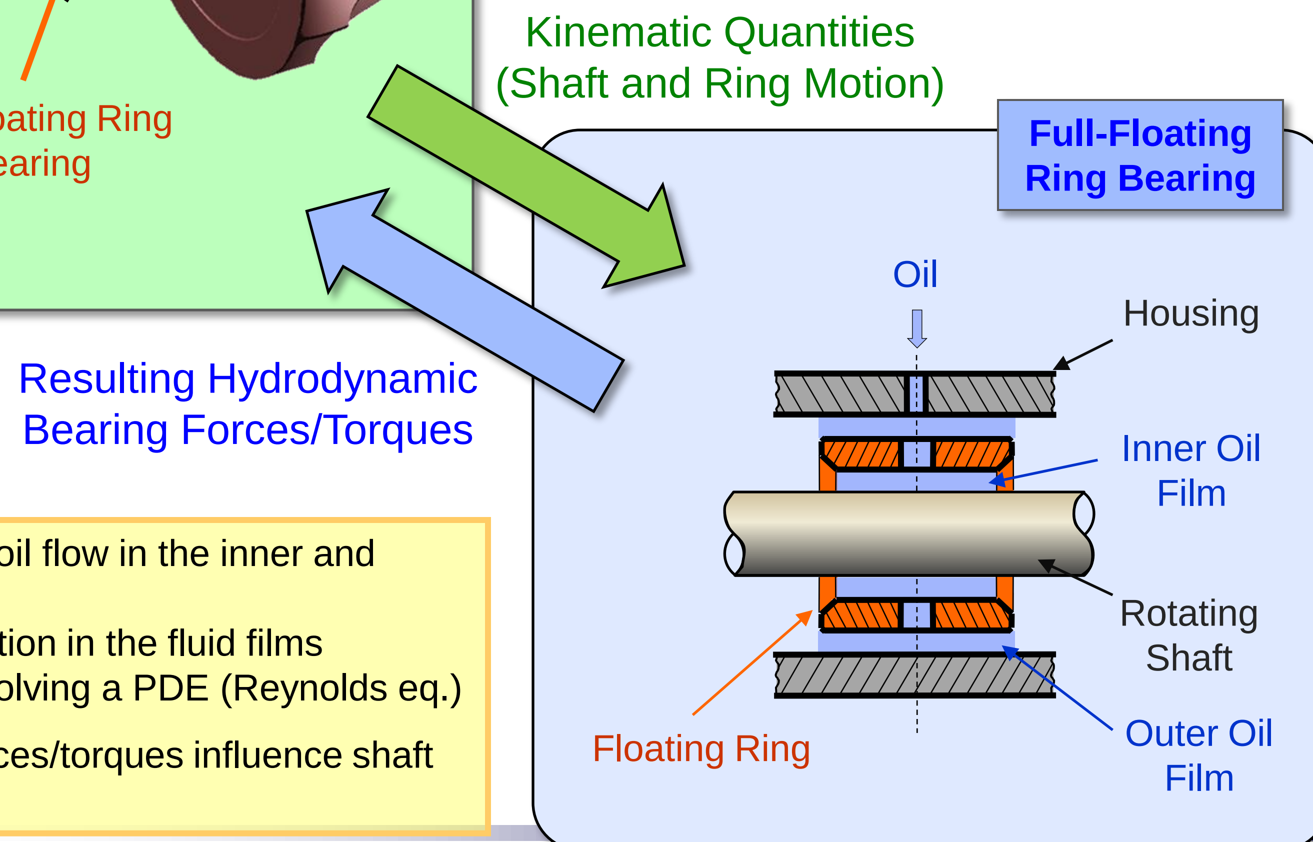
  → Reduce number of PDE computations

Outline:

- Introduction: General Aspects of Coupled Simulation
- Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger
- Three Coupling Approaches:
  - Full-Implicit Approach
  - Explicit Multirate Approach
  - Semi-Implicit Approach
- Numerical Results: Run-up Simulation of a Turbocharger

Example: *Turbocharger Simulation*





- Motion of shaft and ring induces an oil flow in the inner and outer oil gap of the bearing
  → Oil flow leads to pressure generation in the fluid films
  → Pressure fields are obtained by solving a PDE (Reynolds eq.)
- Resulting hydrodynamic bearing forces/torques influence shaft and ring motion

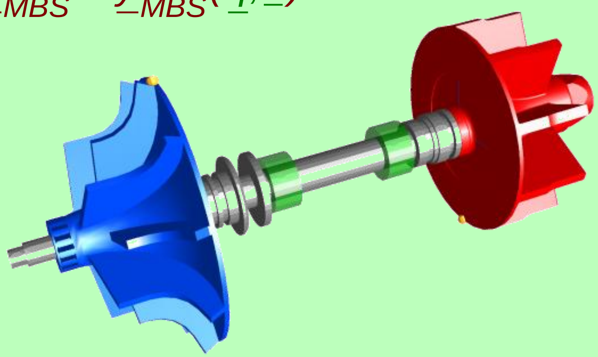
Force/Displacement Coupling

MBS: Equations of Motion

$$\underline{\underline{M}}(\underline{q})\dot{\underline{v}} = \underline{f}(\underline{q},\underline{v},t,\underline{u}^1_{MBS},\ldots,\underline{u}^4_{MBS}) - \underline{\underline{G}}^T \underline{\lambda}$$

$$\dot{\underline{q}} = \underline{v} - \underline{\underline{G}}^T \underline{\mu} \;,\; \underline{0} = \underline{g}(\underline{q},t) \;,\; \underline{0} = \underline{\underline{G}}^T \underline{v} - \dot{\underline{g}}$$

$$\underline{y}^i_{MBS} = \underline{y}^i_{MBS}(\underline{q},\underline{v})$$



Kinematical Quantities

$\underline{u}^i_{FEM} = \underline{y}^i_{MBS}$

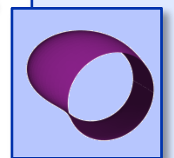
$\underline{u}^i_{MBS} = \underline{y}^i_{FEM}$

Hydrodynamic Bearing Forces/Torques

Model 1

⋮

Model *i*



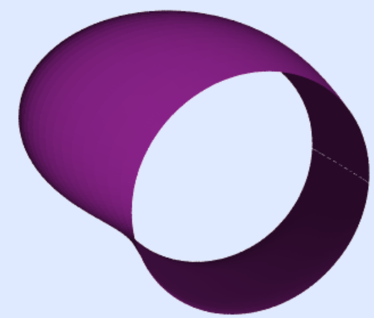
⋮

Model 4

FE Model: Discretized Reynolds Equation

$$\underline{0} = \underline{\Omega}(\underline{\Pi}^i, \dot{\underline{\Pi}}^i, \underline{u}^i_{FEM})$$

$$\underline{y}^i_{FEM} = \underline{y}^i_{FEM}(\underline{\Pi}^i, \underline{u}^i_{FEM})$$



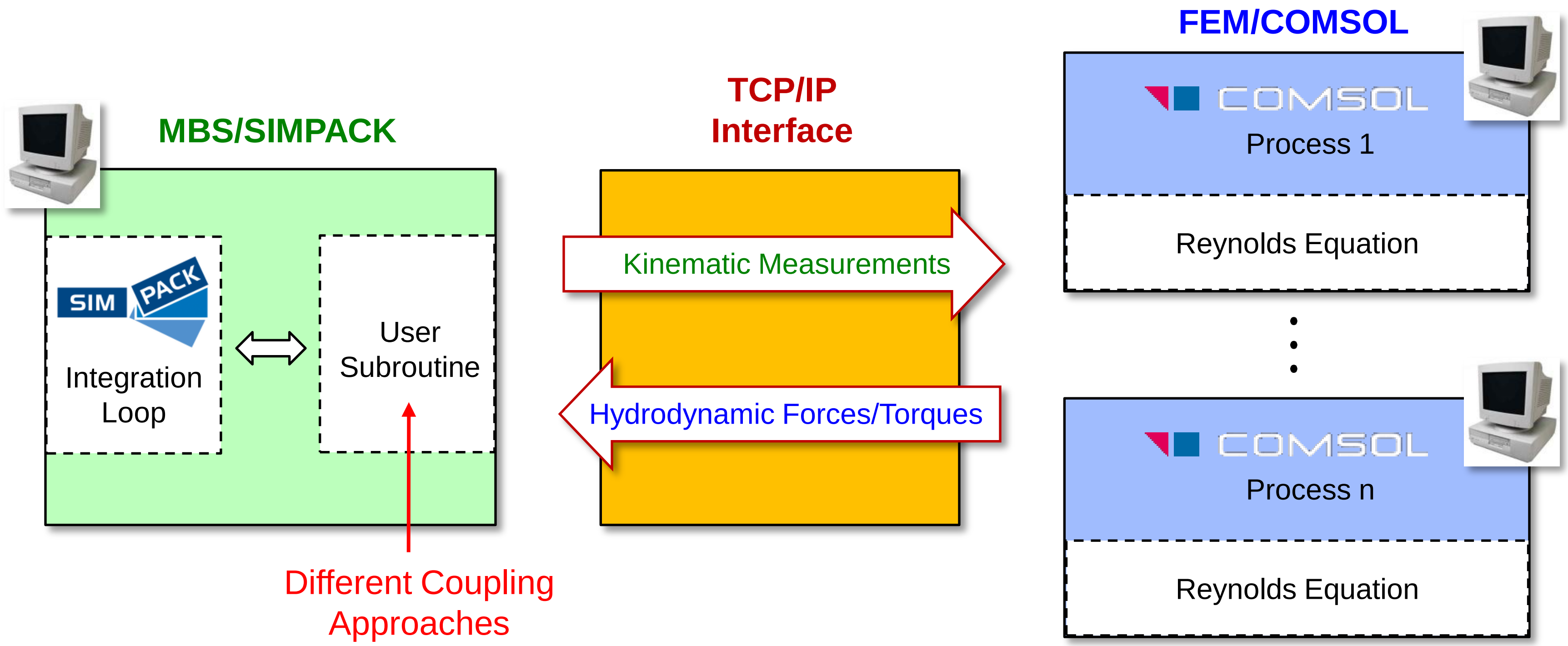
Remark:

- Bearing forces/torques of the 4 fluid films are computed by 4 FE models
- No „direct feed-through“ in both output equations

  → Numerical coupling approaches are zero-stable, if zero-stable solvers are applied[6]

  → Co-simulation will converge, if communication-step size is sufficiently small

SIMPACK-COMSOL-Interface



IPC Interface:

- Instances of FE model are computed in parallel on different CPUs
- COMSOL processes are coupled with SIMPACK solver by user subroutine
  → Implicit SIMPACK solver is master and defines the (variable) communication-step size
- Communication is accomplished with TCP/IP network interface
- Different coupling approaches are implemented in a user subroutine

Outline:

- Introduction: General Aspects of Coupled Simulation
- Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger
- Three Coupling Approaches:
  - Full-Implicit Approach
  - Explicit Multirate Approach
  - Semi-Implicit Approach
- Numerical Results: Run-up Simulation of a Turbocharger

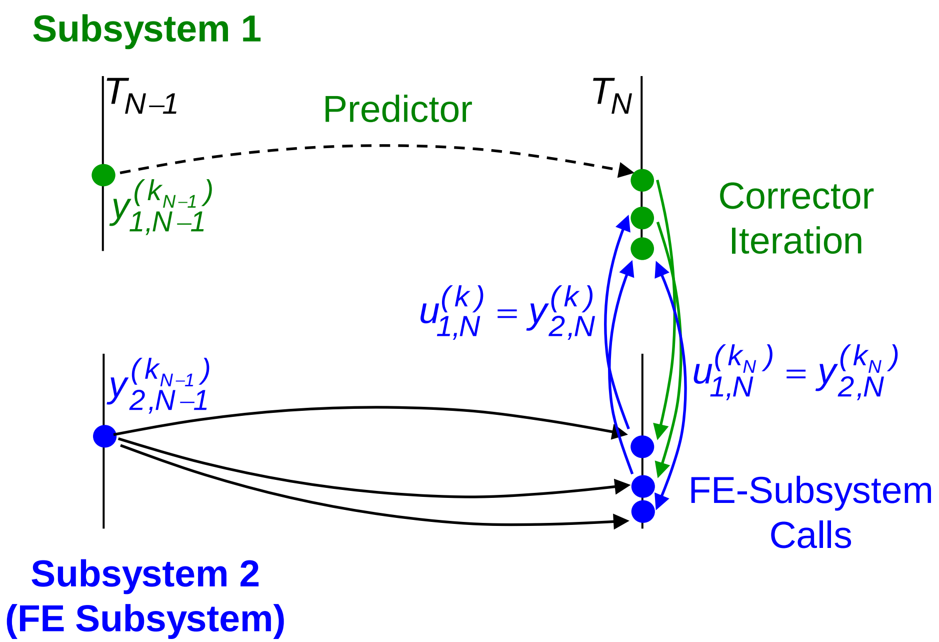
Coupling Approaches: *Implicit Waveform Iteration*[7,8]

Remark:

- Consider two subsystems:
  Subsystem 1 (SIMPACK),
  Subsystem 2 (COMSOL)
- Macro-time step $T_{N-1} \rightarrow T_N$

Coupling Approach 1:

- PECE solver of **Subsystem 1** calls **Subsystem 2** after <u>all</u> corrector steps $k=0,\ldots,k_N$
- Approach is implicit w. r. t. coupling variables
  → Coupling approach is stable
- Large number of FE-subsystem calls



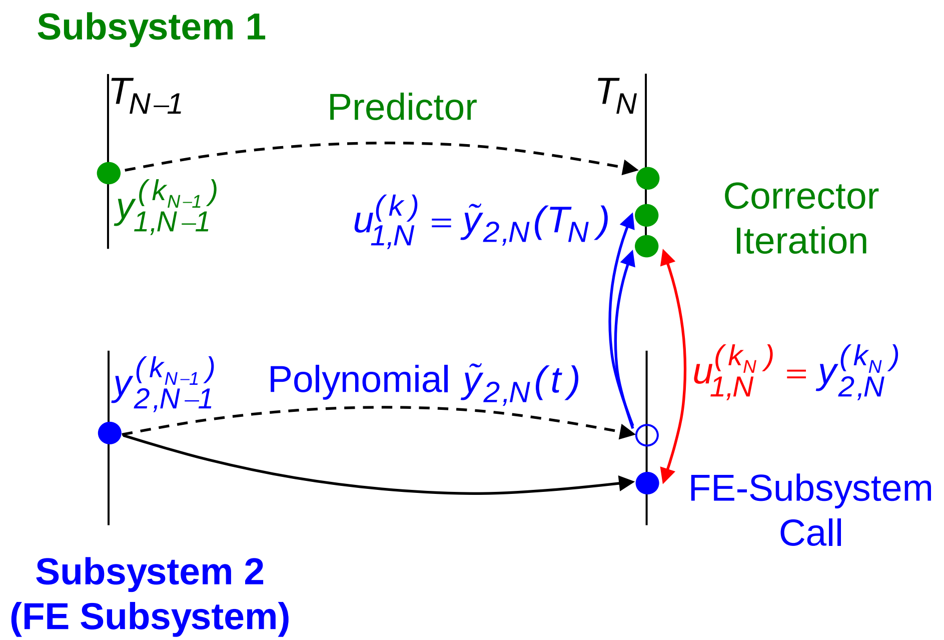
Outline:

- Introduction: General Aspects of Coupled Simulation
- Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger
- Three Coupling Approaches:
  - Full-Implicit Approach
  - Explicit Multirate Approach
  - Semi-Implicit Approach
- Numerical Results: Run-up Simulation of a Turbocharger

Coupling Approaches: *Explicit Multirate Approach*

Coupling Approach 2:

- Using polynomial extrapolation $\tilde{y}_{2,N}(t = T_N)$ for approximating input u_1 during corrector iteration
  → Inputs do not vary during corrector steps k
- PECE solver of **Subsystem 1** calls **Subsystem 2** only after the last corrector step k_N
  → Only 1 FE-subsystem call in each macro step
- Approach is explicit w. r. t. coupling variables
  → This may entail numerical instabilities



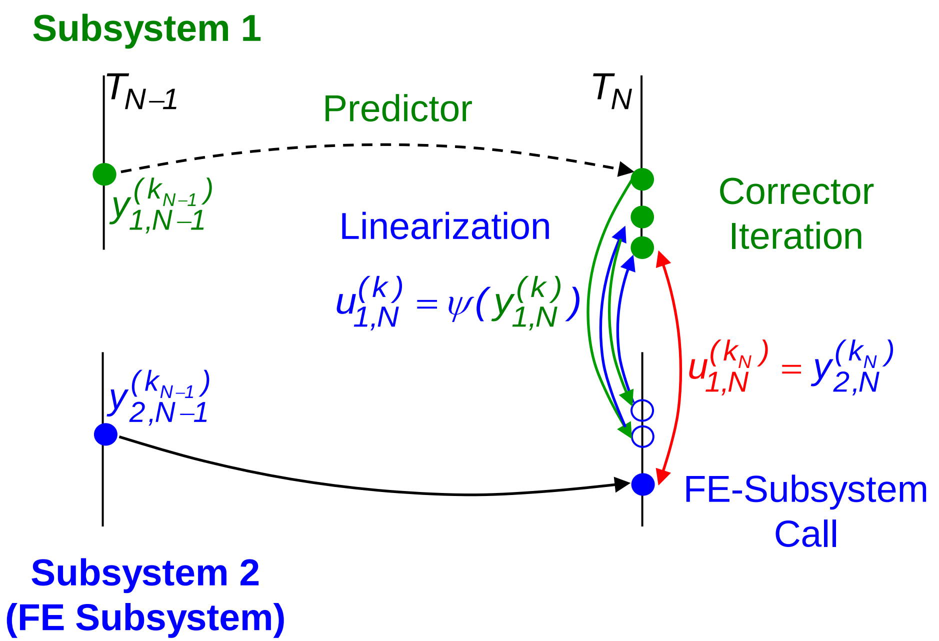
Outline:

- **Introduction: General Aspects of Coupled Simulation**
- **Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger**
- **Three Coupling Approaches:**
  - **Full-Implicit Approach**
  - **Explicit Multirate Approach**
  - **Semi-Implicit Approach**
- **Numerical Results: Run-up Simulation of a Turbocharger**

Coupling Approaches: *Semi-Implicit Approach*[9]

Coupling Approach 3:

- Linearization ψ of output y_2 w. r. t. y_1 at time T_{N-1}
  → Used for approximation of input u_1 at T_N
  → Varying input during corrector iteration
- PECE solver of **Subsystem 1** calls **Subsystem 2** after the last corrector step k_N
  → Only 1 FE-subsystem call in each macro step
- Approach is semi-implicit w. r. t. coupling variables
  → More stable than explicit multirate approach
  → Number of FE-subsystem calls may further be reduced[9]
- Jacobian required for linearization
  → Computed numerically and in parallel

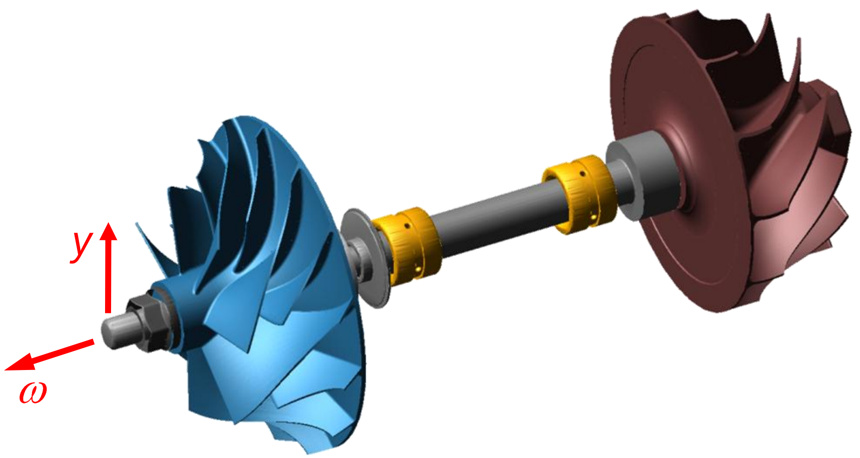


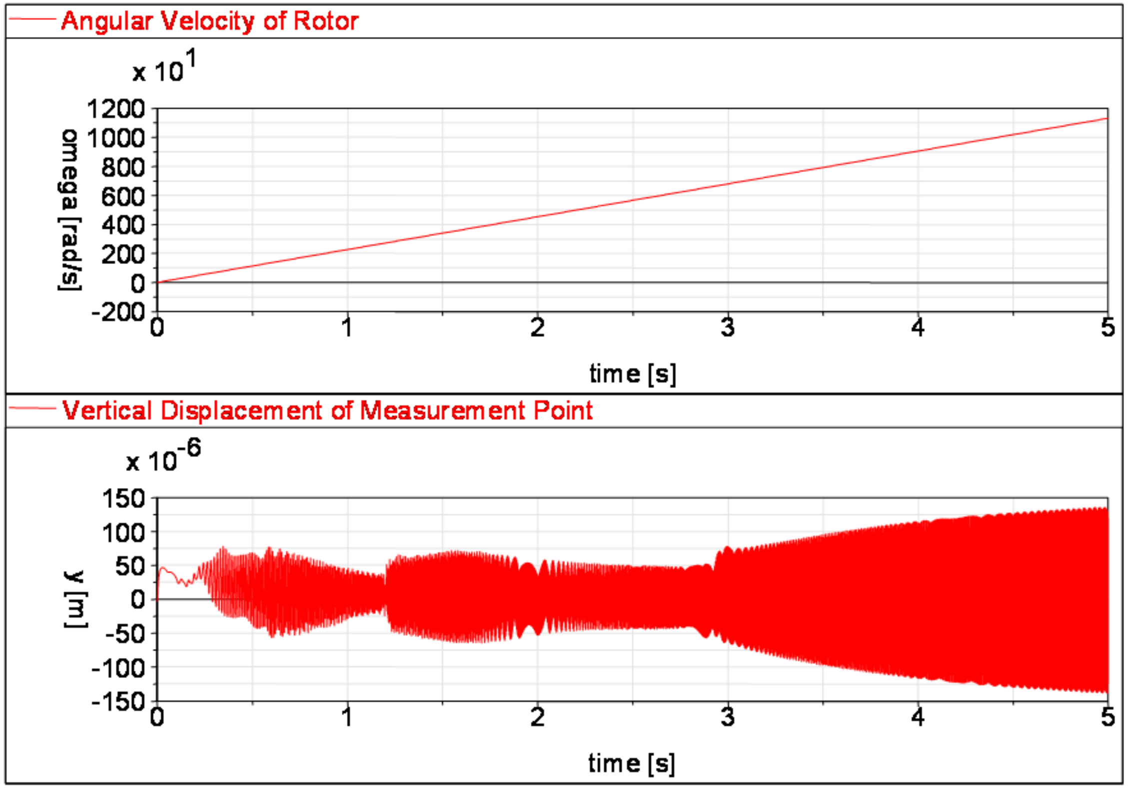
Outline:

- **Introduction: General Aspects of Coupled Simulation**
- **Example of MBS/PDE Coupling: Rotor/Bearing System of a Turbocharger**
- **Three Coupling Approaches:**
  - **Full-Implicit Approach**
  - **Explicit Multirate Approach**
  - **Semi-Implicit Approach**
- **Numerical Results: Run-up Simulation of a Turbocharger**

Numerical Results: *Rotor Run-Up Simulation*

- Run-up simulation of rotor: Increase angular velocity ω linearly up to 1800Hz in 5s
- Semi-implicit approach: 16 parallel processes (4 forces and 12 gradients) computed on 4 quadcores
- CPU time for one Reynolds equation (PDE) ~ 2s

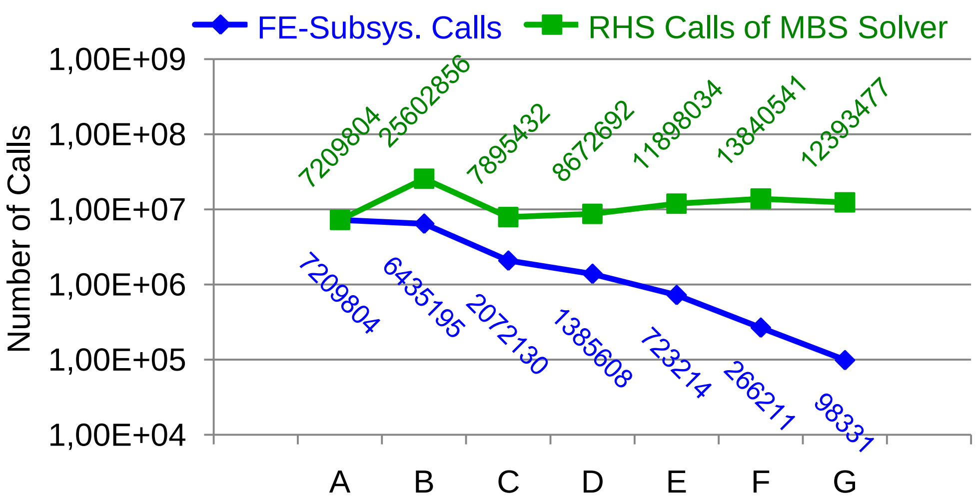


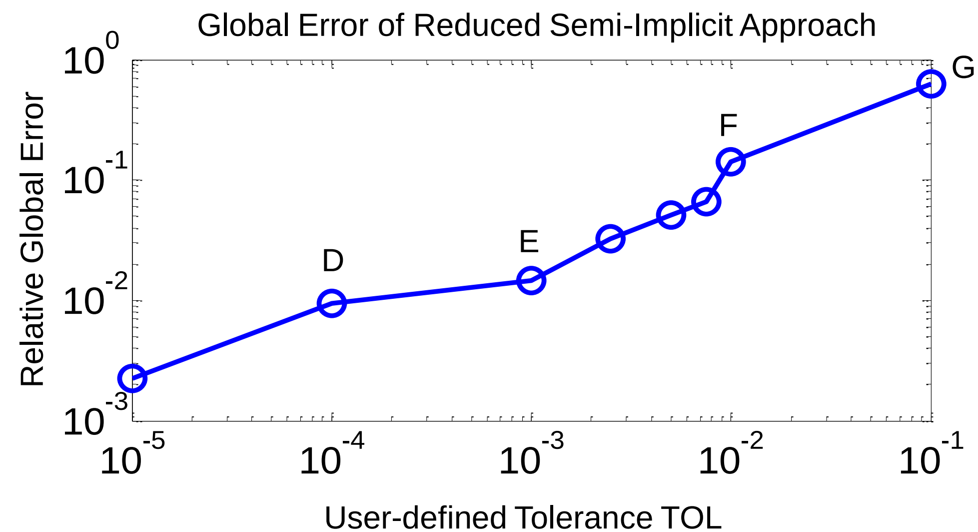


- Vibration behavior of rotor is highly nonlinear[10]
  - → Different bifurcations occur
  - → Complex quasiperiodic rotor motion

Numerical Results: *Comparison of Coupling Approaches*

	Full-Implicit Approach A	Explicit Multirate Approach B	Semi-Implicit Approach (unreduced) C	Reduced Semi-Implicit Approach[9]			
				TOL=1e-4 D	TOL=1e-3 E	TOL=1e-2 F	TOL=1e-1 G
CPU Time:	~5,5 Months	~5 Months	~39 Days	~32 Days	~16 Days	~6 Days	~2 Days
RHS Calls of MBS Solver	7209803	25602856	7895432	8672692	11898034	13840541	12393477
Number of FE-Subsystem Calls:	7209803	6435195	1702765	1385608	723214	266211	98331
BDF-Step Size for Stable Time Integration	1e-5	5e-7	1e-5	1e-5	1e-5	1e-5	1e-5





Conclusions

Aim: Develop an efficient coupling interface for MBS and FE tools

SIMPACK/COMSOL-Interface:

- Variable communication-time grid
- Parallel computation of FE models
- Standard coupling approaches practically fail because of large CPU times:

  → Full-implicit approach entails large number of FE-subsystem calls

  → Explicit multirate approach requires small communication-time steps for stable simulation
- Semi-implicit coupling approach yields practicable CPU times:

  → Approach is stable

  → Number of FE-subsystem calls can be reduced significantly

References

[1] C. W. Gear and D. R. Wells. *Multirate linear multistep methods*. BIT Numerical Mathematics 24:484-502, 1984.

[2] M. Busch and B. Schweizer. *Numerical stability and accuracy of different co-simulation techniques: analytical investigations based on a 2-dof test model*. Proceedings of The 1st Joint International Conference on Multibody System Dynamics (IMSD), Lappeenranta, Finland, May 25-27, 2010.

[3] A. Carrarini. *Coupled multibody-aerodynamic simulation of high-speed trains manoeuvres.* Proc. Appl. Math. Mech. (PAMM) 2:114-115, 2003.

[4] M. Arnold and B. Simeon. *Pantograph and catenary dynamics: a benchmark problem and its numerical solution*. Applied Numerical Mathematics 34:345-362, 2000.

[5] A. Andreykiv and D. J. Rixen. *Numerical modeling of electromechanical coupling using fictitious domain and level set methods.* International Journal for Numerical Methods in Engineering 80:478-506, 2007.

[6] R. Kübler and W. Schiehlen: *Two methods of simulator coupling*. Mathematical and Computer Modelling of Dynamical Systems 6:93-113, 2000.

[7] E. Lelarasmee, A. Ruehli, A. Sangiovanni-Vincentelli. *The waveform relaxation method for time domain analysis of large scale integrated circuits*. IEEE Trans. on CAD of IC and Syst. 1:131-145, 1982.

[8] M. Arnold and M. Günther: *Preconditioned dynamic iteration for coupled differential-algebraic systems*. BIT Numerical Mathematics 41:1-25, 2001.

[9] M. Busch and B. Schweizer: *MBS/FEM co-simulation approach for lubrication problems*. Proc. Appl. Math. Mech. (PAMM) 10:729-732, 2010.

[10] B. Schweizer and M. Sievert: *Nonlinear oscillations of automotive turbocharger turbines*. Journal of Sound and Vibration 321:955-975, 2009.