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

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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*\textsuperscript{[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 \( \rightarrow \) Sequential or parallel integration of subsystems
- Communication-time grid (“macro-time grid”) is required for data exchange
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
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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**

\[
\ddot{u}_{MBS} = \ddot{u}_{MBS}(q, v)
\]

**FE Model: Discretized Reynolds Equation**

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

**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.
**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
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**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 all corrector steps $k=0, \ldots, k_N$
- Approach is implicit w. r. t. coupling variables $\rightarrow$ Coupling approach is stable
- Large number of FE-subsystem calls

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

**Diagram:**
- **Subsystem 1**
  - Predictor
  - Corrector Iteration
  - FE-Subsystem Call
- **Subsystem 2** (FE Subsystem)
  - Polynomial $\tilde{y}_{2,N}(t)$
  - $u^{(k)}_{1,N} = \tilde{y}_{2,N}(T_N)$
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Coupling Approaches: *Semi-Implicit Approach*[^9]

**Coupling Approach 3:**

- **Linearization** $\psi$ 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

[^9]: [9]
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Numerical Results: *Rotor Run-Up Simulation*

- Run-up simulation of rotor: Increase angular velocity $\omega$ 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*

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<tbody>
<tr>
<td><strong>CPU Time:</strong></td>
<td>~5,5 Months</td>
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<td>~39 Days</td>
<td>~32 Days</td>
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<td><strong>RHS Calls of MBS Solver</strong></td>
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<td><strong>BDF-Step Size for Stable Time Integration</strong></td>
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<td><strong>TOL=1e-1</strong> G</td>
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**Global Error of Reduced Semi-Implicit Approach**

**Relative Global Error**

**User-defined Tolerance TOL**

**Number of Calls**

**RHS Calls of MBS Solver**

[^9]: Reduced Semi-Implicit Approach
**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


