Improving the SuperMagnet model; recent developments and future activities

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SuperMagnet model

Version 1.0
September 2007

L. Bottura, SuperMagnet Benchmarking Close-out meeting, ITER-IO Cadarache, 15th May, 2012
Its basic idea is “binding” independent executables.

Based on the specially developed codes, in particular, for the thermo-hydraulic behaviors in quench propagation...

- Hyperbolic PDE + Nonlinear diffusion-reaction wavefront
- Wide range of time scale + Steep frontend (needs fine mesh)
Background (2/3)

✓ Its basic idea is “binding” independent executables.

→ based on the specially developed codes, in particular, for the thermo-hydraulic behaviors in quench propagation…

Like any other competing tool as a coupled simulation platform…

Key point: The conductor model makes it special.
The special features

✓ Hyperbolic PDEs (fluid dynamics) without approximation

➡ No regular description for the propagating discontinuity
  : However, instability is suppressed by the artificial viscosity.

➡ Implicit time stepping as the preferred option
  : The time steps should be large enough, e.g., for the time span to observe the recovery from quench.

➡ Linearization for the implicit scheme
  : It is a concept to avoid iterations for the nonlinear solution.
The special features made issues

- No regular description for the **propagating discontinuity**
  - The **interfaces are vulnerable** in case of rapid transient..

- **Implicit time stepping is preferred.**
  - Its robustness is lost outside the individual code.
  - The **co-simulation models are unstable** in practical..

- **Linearization** for the implicit scheme.
  - Time stepping has to be **minute** in case of abrupt heat deposition..
Recent Progress

✴ New BC in terms of the propagating discontinuity

\[ [AU]_i = \sum_j f_j \int_0^L \frac{\partial U_i}{\partial t} \, dx \quad \text{for} \quad i \neq L, 0 \]

\[ [AU]_{L0} = -a(U_i)U_{i0} - \sum_j f_j \int_0^L \left( \frac{\partial a(U_i)}{\partial U_j} \frac{\partial U_j}{\partial U_i} - \frac{\partial a(U_i)}{\partial U_j} \frac{\partial U_i}{\partial U_j} \right) \, dx \quad \text{for} \quad i = L \]

\[ [AU]_{0i} = a(U_{i0})U_i - \sum_j f_j \int_0^L \left( \frac{\partial a(U_{i0})}{\partial U_j} \frac{\partial U_j}{\partial U_i} - \frac{\partial a(U_{i0})}{\partial U_j} \frac{\partial U_i}{\partial U_j} \right) \, dx \quad \text{for} \quad i = 0 \]

✴ New steady state (quasi-1d) model

\[ \frac{m_i}{A \rho_i} \] leads \( v_i \)

A single element of FEM

✴ Improved stability of THEA-FLOWER coupling

✴ Issue solved in adaptive time stepping

\[ \text{The boundary temperature follows the constraint in the flow velocity.} \]

\[ \text{Eventually, accuracy issue is resolved during this study.} \]

2017

2019

2021
#1. Steady state model (1/3)

✓ Steady state models are quite useful! For instance…

- Simplification for the winding packs which are computationally heavy.
- Functional components: Valves, Pumps, etc.

L. Bottura et al. “A Physics-based Simplified Model for the ITER Cooling Loop”
#1. Steady state model (2/3)

✓ So, we have to remove the effect of volume nodes. Because...

\[ v_1 = \frac{\dot{m}}{A\rho_1} \quad v_2 = \frac{\dot{m}}{A\rho_2} \]

The pump is a steady-state component

D. K. Oh and S. Oh, "Improved 1-d thermohydraulic network modeling for cryogenic circuits coupled to CICC models of fusion magnet system." Cryogenics 97 (2019): 133-143.
**#1. Steady state model (3/3)**

✓ So, we have to remove the effect of volume nodes.

\[
L \frac{dv_i}{dt} = \frac{\bar{c}}{2} \left( \frac{m(p_1, p_2)}{A \rho_i} - v_i \right)
\]

- **Upwind temperature Transferred by the mass flow**
- **Delay of the sound wave (v-p) coupling**

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**sspipe**

1. Fixed \( p_1 \) 
2. \( T_1 \) ruled by \( T_0 \) 
3. \( v_1 \) 
4. \( v_2 \) 
5. Fixed \( p_2 \) 
6. Free \( T_2 \)
D. K. Oh and S. Oh, "Improved 1-d thermohydraulic network modeling for cryogenic circuits coupled to CICC models of fusion magnet system." Cryogenics 97 (2019): 133-143.
Recent Progress

✴ New BC in terms of the propagating discontinuity

\[
[AU]_w = \sum_j f_j \left( v_j a_j U_j^i \right) \frac{du_j}{dx} \quad (i = 1, 2)
\]

\[
[AU]_{L} = -a''(U)U_w - \sum_j f_j \left( \frac{du}{dx} a'(U)w_j - w_j a'(U) \frac{du_j}{dx} \right) \quad (i = 1)
\]

\[
[AU]_{w} = a''(U)U_w - \sum_j f_j \left( \frac{du}{dx} a'(U)w_j - w_j a'(U) \frac{du_j}{dx} \right) \quad (j = 1)
\]

✴ New steady state (quasi-1d) model

\[
\frac{m}{A \rho_i} \text{ leads } v_i
\]

A single element of FEM

✴ Improved stability of THEA-FLOWER coupling

\[
\text{The boundary pressure follows the constraint in the speed of sound.}
\]

\[
\text{The boundary temperature follows the upward constraint in the flow velocity.}
\]

✴ Issue solved in adaptive time stepping

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#2. Improved stability (1/4)

✓ The loss of stability is intrinsic, if models use the “implicit stepping”

: Get the future values looking “backward”!

\[
\begin{align*}
p_n^{n+1} &= p_n^n - \Delta t \sum_{i=1}^{2} v_i^n f_i (u_{vol}^n, u_i^n) + \Delta t q_n^n / V \\
T_n^{n+1} &= T_n^n - \Delta t \sum_{i=1}^{2} v_i^n g_i (u_{vol}^n, u_i^n) + \Delta t q_n^n / \rho C_v^n V
\end{align*}
\]

Implicit stepping of volume
(Backward Euler)
#2. Improved stability (2/4)

✓ It is possible to improve the stability by means of ..

Idea: implicit stepping using “interface Jacobian”

So, now..

- **time step**: 10 ms (Flower)
- 10 µs ~ 5 ms (THEA)

→ 20 times bigger time step!
→ It takes less than 2 hours!
#2. Improved stability (4/4)

✓ So, now..

- time step: 10 ms (Flower)
- 10 μs ~ 5 ms (THEA)

→ 20 times bigger time step
→ It takes less than 2 hours!

Note) This idea surely works in the other platforms.

\[ \Delta t_{\text{modelica}} = 2.5 \times 10^{-3} \]
\[ \Delta t_{\text{THEA}} = 10^{-5} \approx 5 \times 10^{-3} \]

i) The delay function is essential.

\[ x = (p_b(t), T_b(t)) \]
\[ y = U(x, \Delta t) \]
\[ y = (\dot{m}_0(t + \Delta t), h_0(t + \Delta t)) \]
\[ y = (\dot{m}_0(t), h_0(t)) \]

Delay \[ \Delta t \]

ii) The interface jacobian must be taken into account.

\[ \dot{m} = \dot{m}_0 + \Delta t \alpha \rho \delta \frac{dp}{dt} \]
Recent Progress

- New BC in terms of the propagating discontinuity
  \[ [AU]_1 = \sum_i \int_{x_i}^{x_{i+1}} \alpha_i \frac{dU}{dx} \frac{dU}{dx} \, dx \quad (i = L, a) \]
  \[ [AU]_{1a} = -\alpha' U U_p \sum_i \int_{x_i}^{x_{i+1}} \left( \frac{dU}{dx} \frac{dU}{dx} - \alpha' U \frac{dU}{dx} \right) \, dx \quad (i = 1) \]
  \[ [AU]_{1a} = -\alpha' U U_p \sum_i \int_{x_i}^{x_{i+1}} \left( \frac{dU}{dx} \frac{dU}{dx} - \alpha' U \frac{dU}{dx} \right) \, dx \quad (i = t) \]

- New steady state (quasi-1d) model

- Improved stability of THEA-FLOWER coupling

- Issue solved in adaptive time stepping
  - a)
  - b)

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#3. Issue of adaptive time stepping (1/3)

**Option 9, L1, Q_{NH1}**

- MaximumSize = 0.5 m
- MinimumStep = 1e-6 s
- MaximumStep = dt

Open symbols: "false positive" quench detection

\[ \Delta t_{\text{max}} = 0.1 \]

\[ \Delta t_{\text{max}} = 0.001 \]

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M. Lewandowska et al. “Thermal-hydraulic Analysis of the HTS Demo TF Coil”
CHATS-AS workshop, Sendai, Dec. 10-12, 2017
#3. Issue of adaptive time stepping (2/3)

✓ It is practically impossible without iteration!

\[ \Delta t = 0.005 \sim 0.1, \text{TOL} = 1.0 \times 10^{-4}, \text{without iteration} \]

\[ \Delta t = 0.005 \sim 0.1, \text{TOL} = 1.0 \times 10^{-3}, \text{with iteration} \]

So, we propose a new non-iterative control scheme

Algorithm: update $\Delta t \leftarrow$ evaluate the solution of $t_n + \Delta t$

1. $\text{update} \ \text{ERR} \leftarrow \max \left( \frac{Q_i(t_n + \Delta t)}{\rho \frac{C_v}{V} T_i} - \frac{\Delta T_i}{T_i} \right)$

2. $\text{if} \ \text{ERR} \neq \text{TOL}, \ \text{update} \ \Delta t \leftarrow a \left( \frac{\text{TOL}}{\text{ERR} + \varepsilon} \right)^p \Delta t$

3. $\text{if shrinking } \Delta t,$
   $\text{set the limit for ratcheting}$

4. $\text{if ERR > TOL,}$
   $\text{update} \ t_{\text{lim}} \leftarrow t_n + \Delta t$

5. $\text{if ERR < TOL and } t_{\text{lim}} < t_n + \Delta t,$
   $\text{update} \ \Delta t \leftarrow \frac{(t_{\text{lim}} - t_n) \Delta t}{2}, \ t_{\text{lim}} \leftarrow \infty$

6. $\text{update} \ \Delta t \leftarrow \min (\max (\Delta t_{\text{max}}, \Delta t), \Delta t_{\text{max}})$

// evaluate the PDE step

Perspective for the next..

- New decomposed BC
- New steady state (quasi-1d) model
- Improved stability of the SuperMagnet model
- Issue solved in adaptive time stepping
- Improved stability of the SuperMagnet model

Component-wise Modulation

An FMU is built, as a pilot

Versatile Connection

MPI or ZeroMQ?

Usability

GUI or other utilities

Pythonization is the most tangible now..
FMI as a standard interface (1/2)

- Actively supported for an industrial standard
- Developed in a part of Modelica Association – Linköping Univ. Sweden
- Interoperable with commercial packages – ANSYS, Simulink etc.
- Wrapping compiled C or Fortran code with interface description in XML

* Modelica is a meta-language to generate simulation code (in C) from the equation (ODE, DAE) based codes…
FMI as a standard interface (2/2)

THEA modules in FMU format

The improved stability is already checked as previously mentioned..

The mass flows at the terminals

The temperature

mixer1

mixer2
Connectivity of SuperMagnet (1/2)

✓ The SuperMagnet model has a room to be extended..

→ Process-based design
  : Submodules are independent executables.

→ UNIX native interprocess communication (pipe) and process control (signal)
  : So, we just examined a possibility of other systems; MS Windows version is attempted replacing the signals with Windows Event Objects.

→ Socket based communication is considerable in the near future
  : Actually, I’m have 0MQ (ZeroMR) in my mind..
Connectivity of SuperMagnet (2/2)

You are watching the SuperMagnet code running in MS Windows 10.
The Fortran codes are exported as Python classes almost without modification.
Conclusion

➡ Improvements are done taking into account the peculiar design of the thermal-hydraulic model.
   : It’s a brute-force modification so that we expect regular code work for a stable version - it depends on the agreement and plan.

➡ The special features commonly belong to the other tools (4C & TACTICS).
   : A benchmark activity is recommendable based on discussions for improvement.

➡ There are some important items for the future development.
   : Versatile connectivity (in the consideration for parallel computing), Modulization (in FMU format or any other standard), and Usability (Pythonization, GUI, etc)