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SIMULATION OF THE ACOUSTIC WAVE PROPAGATION IN STEEL COMPONENTS: VALIDATION AND VERIFICATION

11th OpenFOAM® Workshop Guimarães, Portugal

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Introduction
Non destructive testing

- **Increasing safety requirements**
  - **Nondestructive testing for detection of defects in structures**
- **Main motivation is using propagation of elastic waves and the time reverse method [1]:**
  - **Record time signals at different positions during T**
  - **Calculate the reversed time signals urev= u(T-t)**
  - **Retransmit the reversed signals at the different positions into the structure Maximum interference = defect position**
- **The goal of the presentation is to show the status of the developent and achieved validation and verification steps**

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[1] Leutenegger, T.,(2002). Detection of defects in cylindrical structures using a time reverse numerical simulation method. PhD thesis.

Introduction
Elastic wave propagation

- **Elastic wave**
  Mechanical wave traveling in a solid
  - Surface waves
  - **Body waves**
    - **Primary waves**
    - **Secondary waves**

Hypotheses:

- Small deformations
- Ideally elastic and isotropic solid

→ Linear equations of solid motion

Equations:

- Hooke’s Law
- Newton’s second Law

→ First order in time hyperbolic system of partial differential equations.

$$\frac{\partial \boldsymbol{q}}{\partial t} + \mathbf{A}\frac{\partial \boldsymbol{q}}{\partial x} + \mathbf{B}\frac{\partial \boldsymbol{q}}{\partial y} + \boldsymbol{C}\frac{\partial \boldsymbol{q}}{\partial z} = 0$$

Introduction
Riemann formulation

Difficulty of direct solving with discontinuities at cell interfaces

⇨ Riemann problem for hyperbolic systems

$$\begin{cases} \dfrac{\partial q}{\partial t} + \mathbf{A}\dfrac{\partial q}{\partial x} = 0 \\ q(x, t = 0) = \begin{cases} q_L & if \quad x < 0 \\ q_R & if \quad x > 0 \end{cases} \end{cases}$$

Solution of the Riemann problem for linear systems

In terms of eigenvalues and eigenvectors of **A**.

See also [2]

[2] H. Rusche, M. Rehm, P. Kodet, Simulation of the Acoustic Wave Propagation in Steel Components, 8th OpenFOAM Workshop, 2013.

Introduction
Numerical method

Finite volume discretization method for partial differential equations

- Integration on small control volumes ➡ fluxes at the surfaces
- $Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x} \sum_{interfaces} Fluxes$

Godunov’s Method

- Solving of the Riemann problem at each cell interface
- Piecing together the Riemann solutions ➡ condition on Co

Workflow
Grid generation

- **Depending on the frequency of the excitation a certain grid size is needed**
- **First: Formally estimate the grid size from the input signal [1]**

$$\lambda = \frac{c}{f}$$

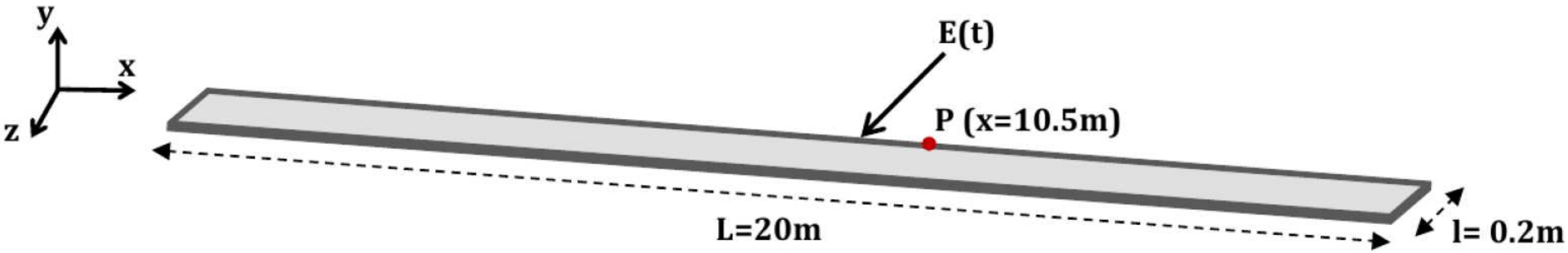
$$\max\left(\triangle\, x\right) < \frac{\lambda}{8} = \frac{c}{8f} = \frac{3140\ \mathrm{m/s}}{8 \cdot 20000\ \mathrm{kHz}} = 20\ \mathrm{mm}$$

- **This represents a starting point**
- **Then: Grid refinement study (as for CFD)**

Case 1

2D calculation of a beam

Case 1 2D beam
Boundary conditions



- Spatial and temporal convergence
- Estimation of numerical errors and order of convergence
- Validation against 4th order FD code

Case 1 2D beam
Parallel performance

- **Variations of grid size and their simulation time**

Name	No. Cells	No. CPUs	Time step [mus]	Calculation time [h]
10 mm grid	40000	1	0.4	0.5
5 mm grid	160000	1	0.2	4
2.5 mm grid	640000	1	0.1	36

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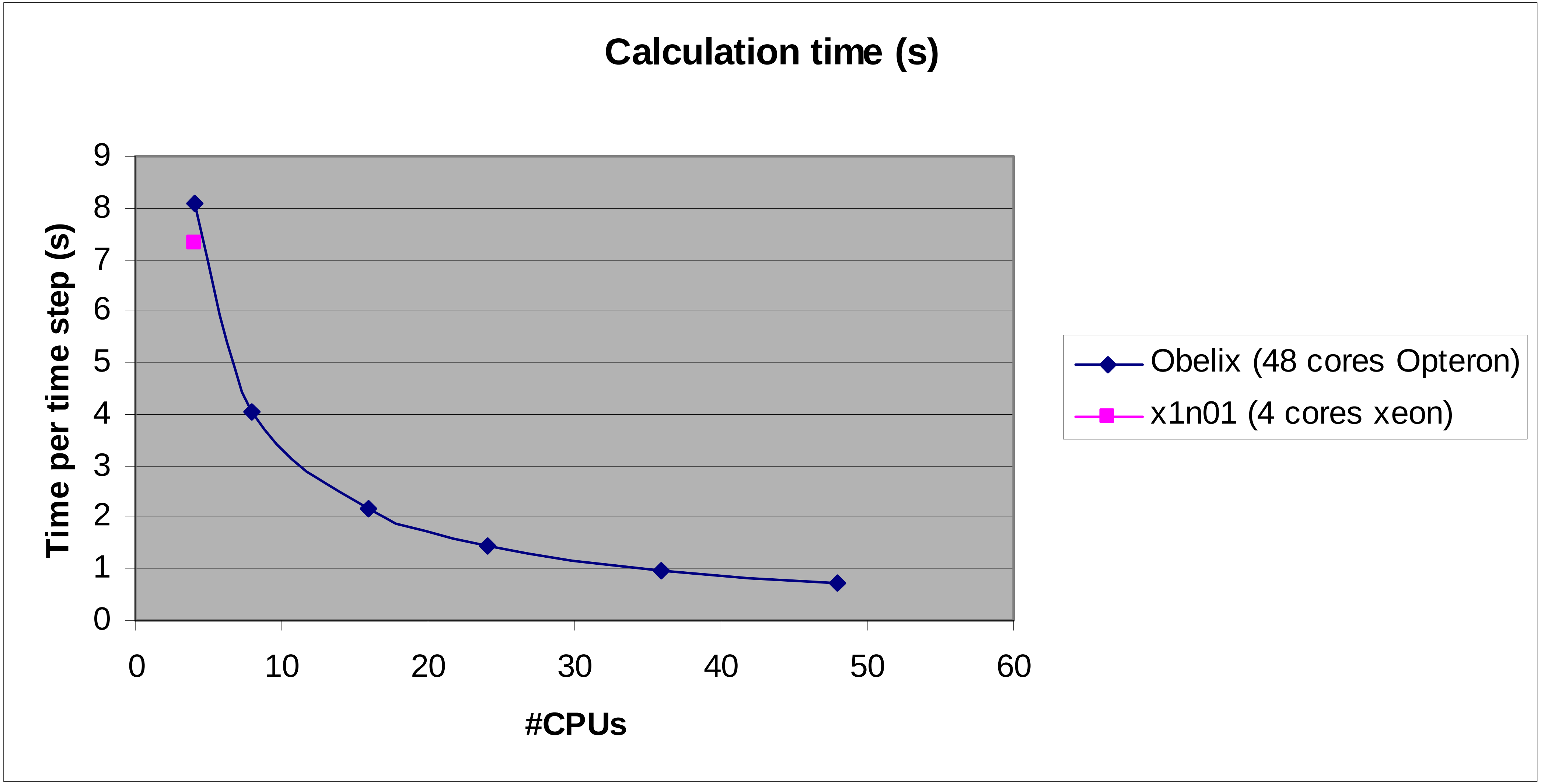
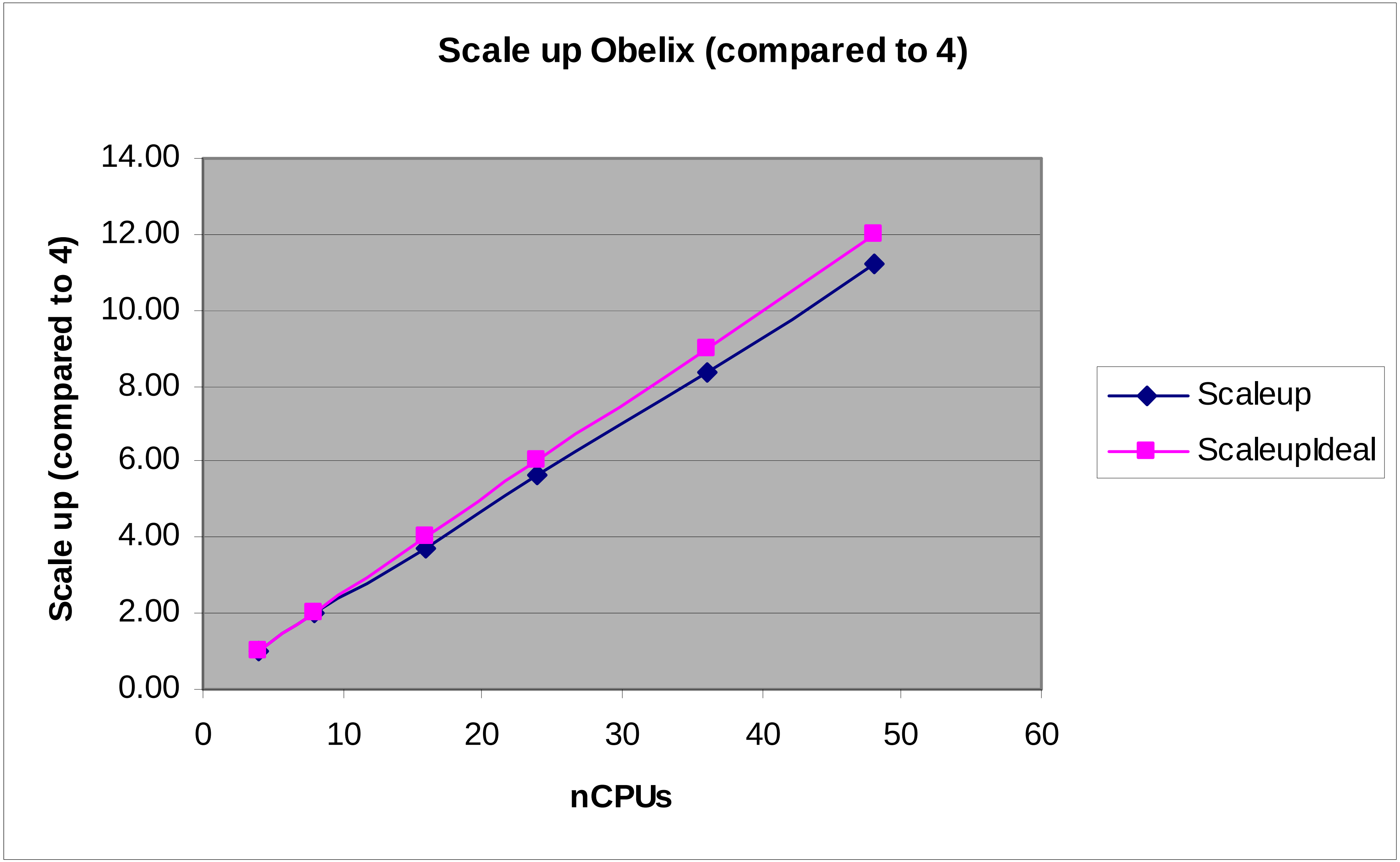
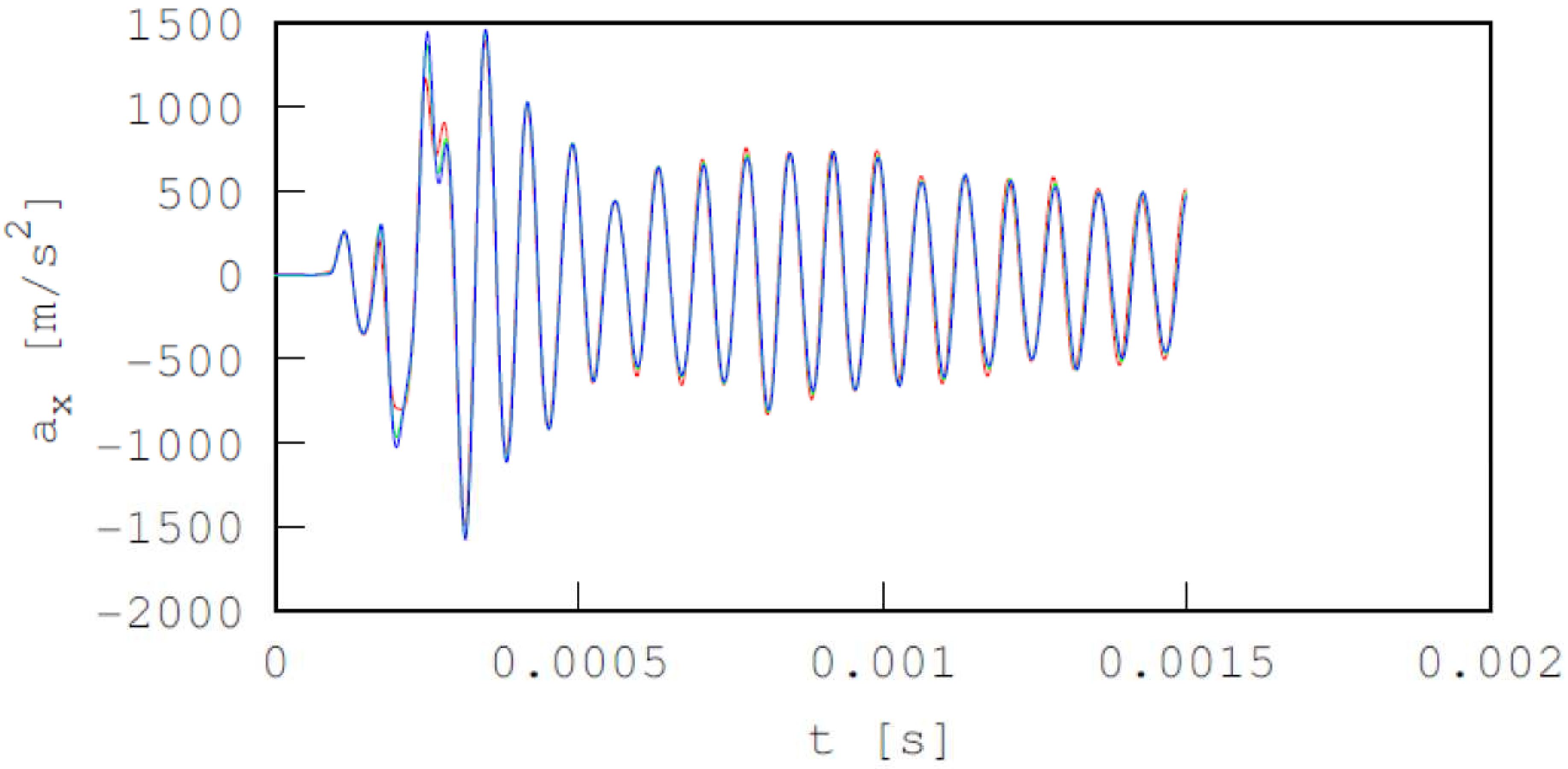
Case 1 2D beam
Parallel performance



Case 1 2D beam
Parallel performance



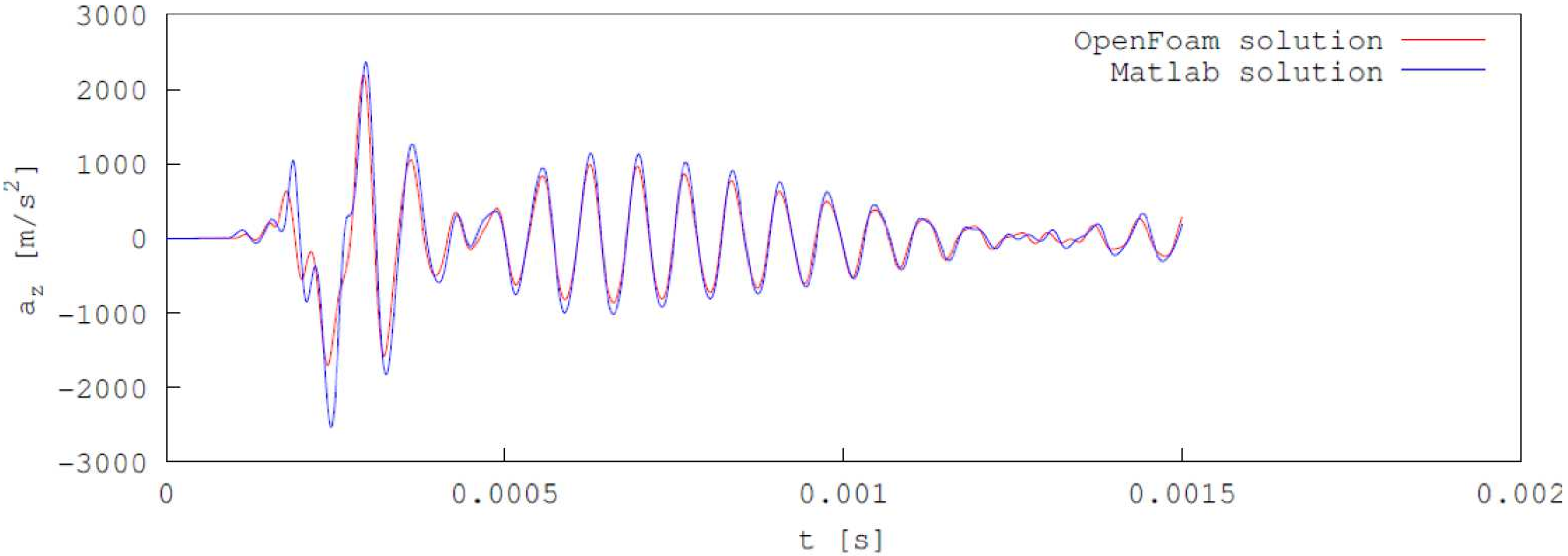
Case 1 2D beam Convergence



a_x at P for a coarse (green), medium (red) and fine (blue) grids

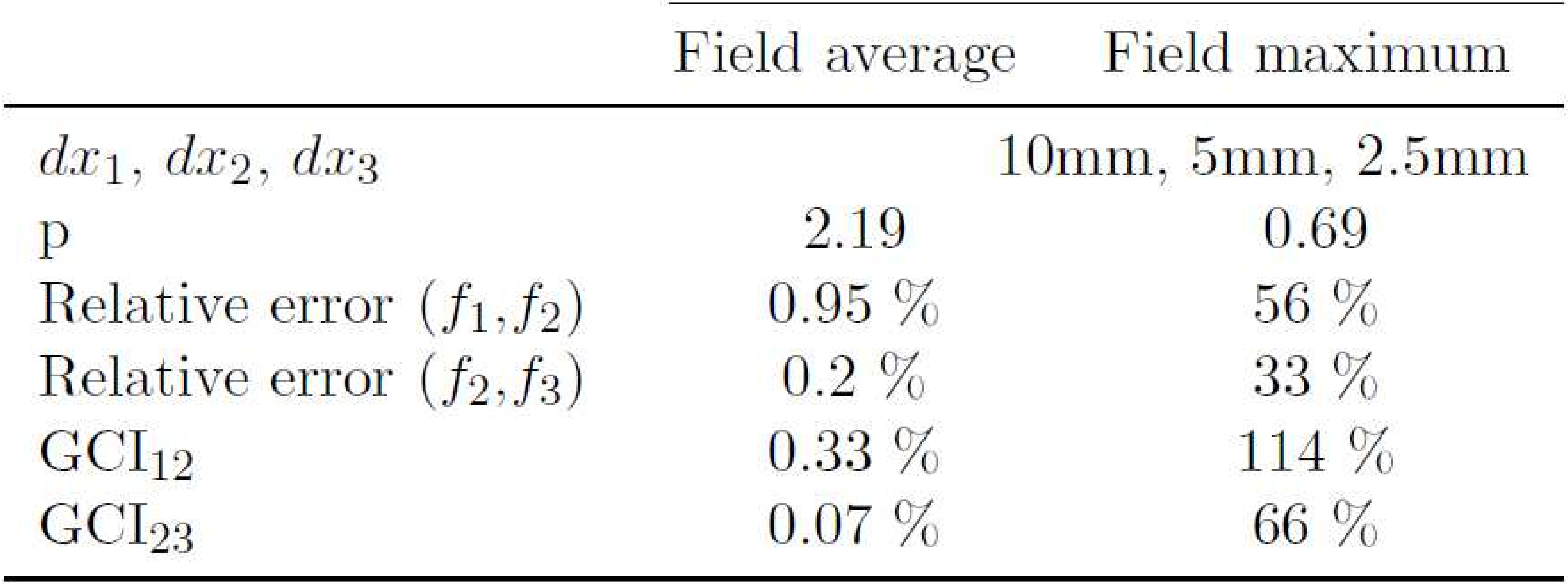
➡ Spatial and temporal convergence achieved.

Case 1 2D beam
Comparison to FD code



➡ Good agreement between the two simulations.

Case 1 2D beam
GCI Index



	Field average	Field maximum
dx_1, dx_2, dx_3	10mm, 5mm, 2.5mm	
p	2.19	0.69
Relative error (f_1,f_2)	0.95 %	56 %
Relative error (f_2,f_3)	0.2 %	33 %
GCI_{12}	0.33 %	114 %
GCI_{23}	0.07 %	66 %

Case 2

3D simulation of a small tube

Case 2 small tube
Boundary conditions

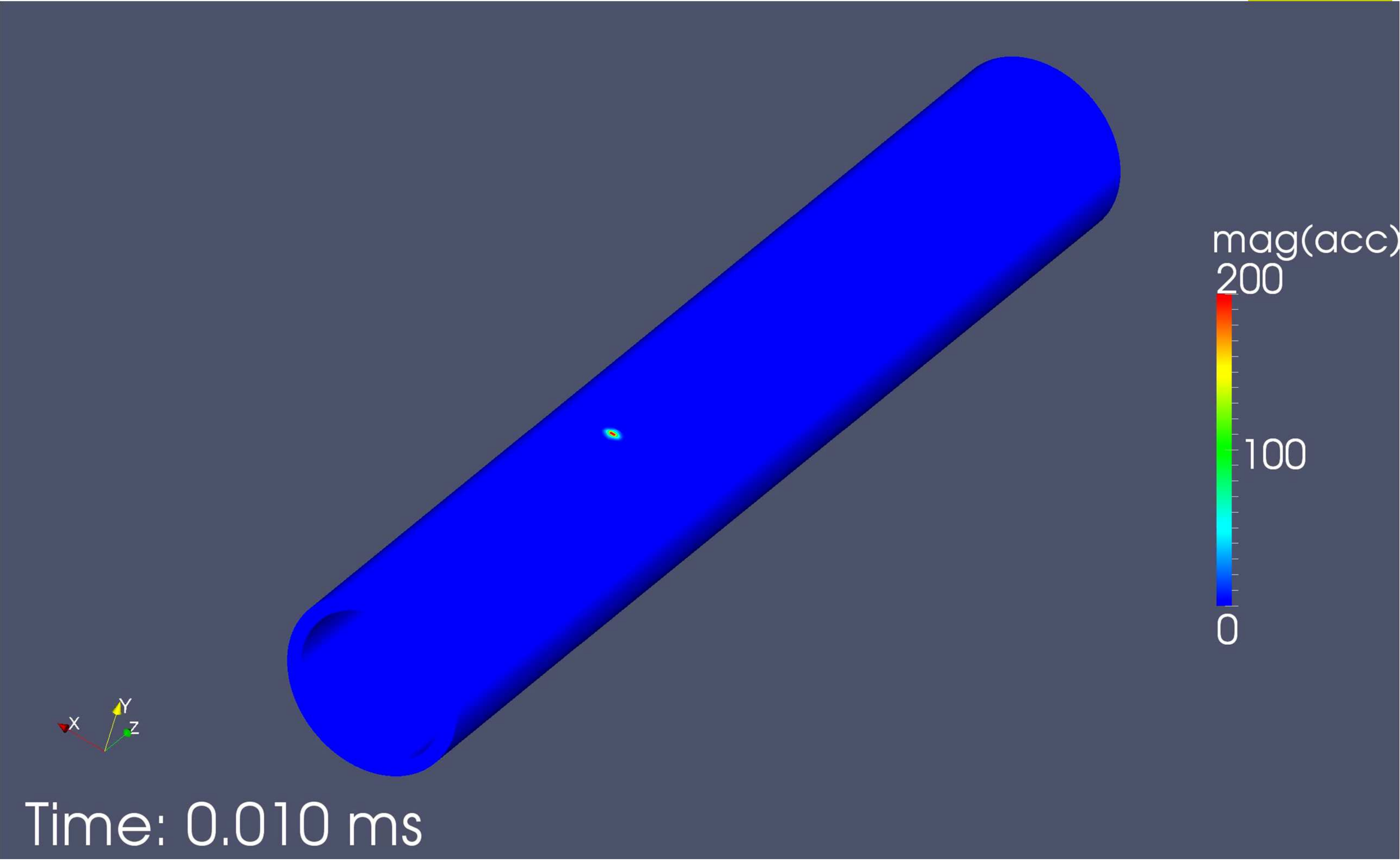
- **Mesh generation with blockMesh**
- **Half tube calculated**
- **l=2.46 m, Di=160 mm; Da=190 mm**
- **Excitation at l=0.8 m, measurement at 1.6 m**
- **See also [3]**

Name	No. Cells	No. CPUs	Time step [mus]	Calculation time [h]
Small tube 5mm	350000	12	0.4	5

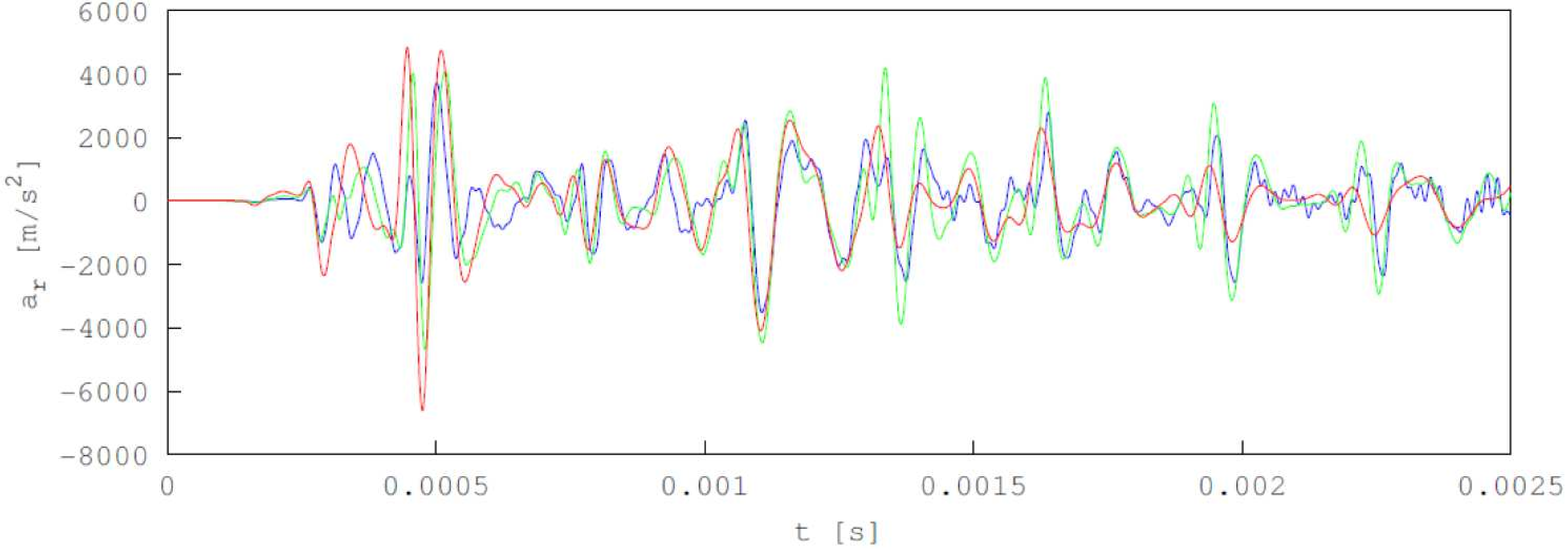
[3] Guided wave propagation simulation using finite-difference time-domain method, Kouty nad Desnou, Czech Republic, June 2010. 9th International Conference PROCESS CONTROL.

Case 2 small tube Experiment

Case 2 small tube



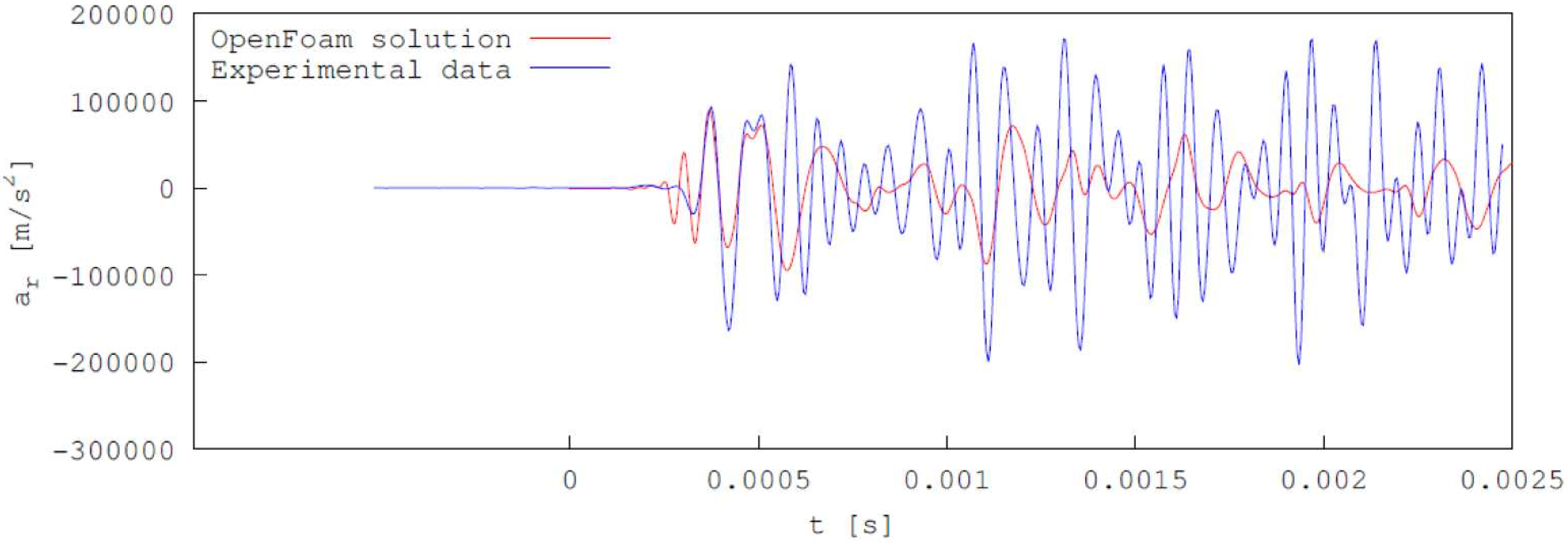
Case 2 small tube
Convergence study



a_r at P for a coarse (red), medium (green) and fine (blue) grids

➡ No convergence.

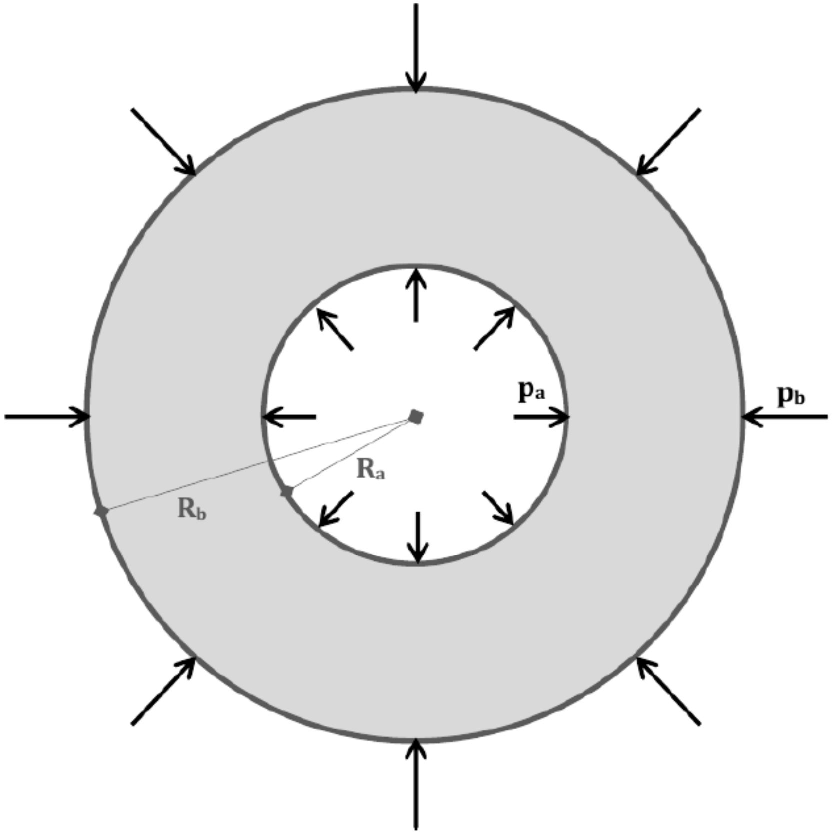
Case 2 small tube
Comparison with measurement

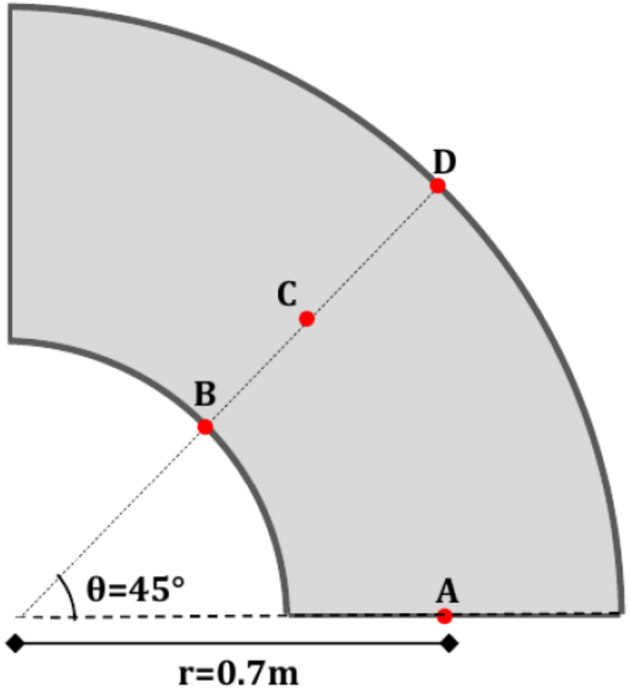


Case 3

2D annulus

Case 3 2D annulus
Boundary conditions



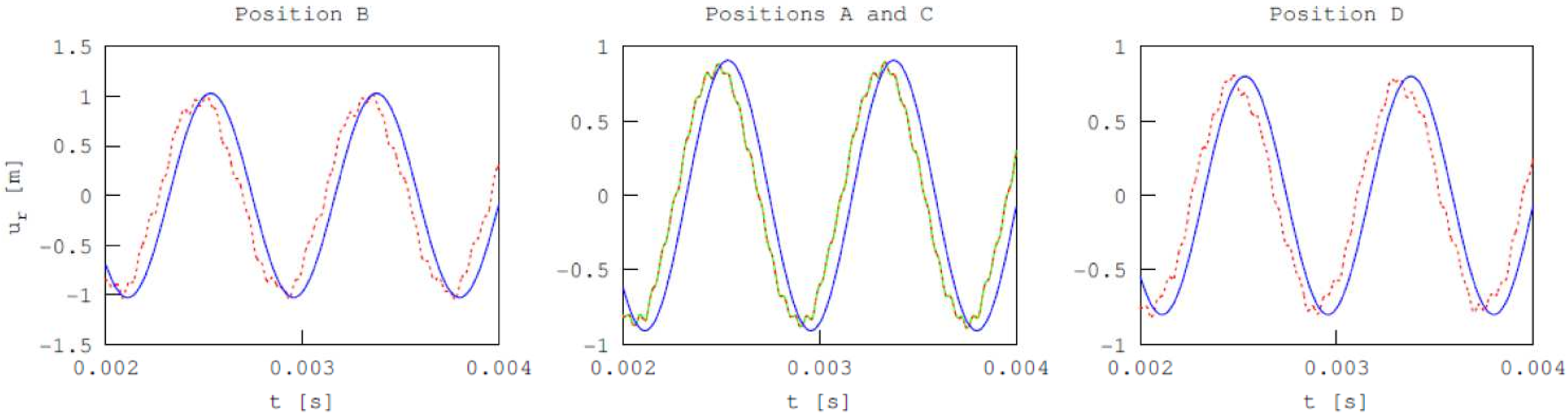


Task

Verify that the simulated signal is the same at the positions A and C, and that it is similar to the analytical one.

[4] W.D. Henshaw D. Appelö, J.W. Banks and D.W. Schwendeman. Numerical methods for solid mechanics on overlapping grids: Linear elasticity. Journal of Computational Physics, 2012.

Case 3 2D annulus Results



Numerical (dashed line) and theoretical (solid line) radial displacements

- ➡ Similar frequencies, no phase shift: analytical solution verifies simulation
- ➡ Similar signals at A and C: no problem with curved geometries

Case 3 2D annulus GCI Error

What level of grid refinement for a certain level of accuracy?

⇨ Grid Convergence Method: relative error bound

Beam		Ring	
GCI_{12}	0.33%		
GCI_{23}	0.07%		
		GCI_{34}	26%
		GCI_{45}	34%
		GCI_{56}	22%
		GCI_{67}	8%

Grid sizes from 10mm (1) to 0.15625mm (7)

Conclusions

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Conclusion

Objective: Verify the accuracy of a 3D finite-volume code for elastic wave propagation in solids

First simulations ➡ Agreement for the beam but not for the tube

Investigation of different parameters ➡ Significant impact of grid resolution

⇨ Refine until satisfying value of GCI is reached

⇨ Develop 4th order accurate code: errors reduced by 16 (4 for 2nd order)

End of presentation: SIMULATION OF THE ACOUSTIC WAVE PROPAGATION IN STEEL COMPONENTS: VALIDATION AND VERIFICATION

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