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Higher-Order Finite-Element Analysis for Fuzes Subjected to High-Frequency Environments

Stephen Beissel
Southwest Research Institute
sbeissel@swri.org; (210)522-5631

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Outline

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- Background
- Comparison of first-order and higher-order elements in explicit solid dynamics
  - Finite-deformation plasticity
  - Wave propagation
- Summary and Conclusions

Background

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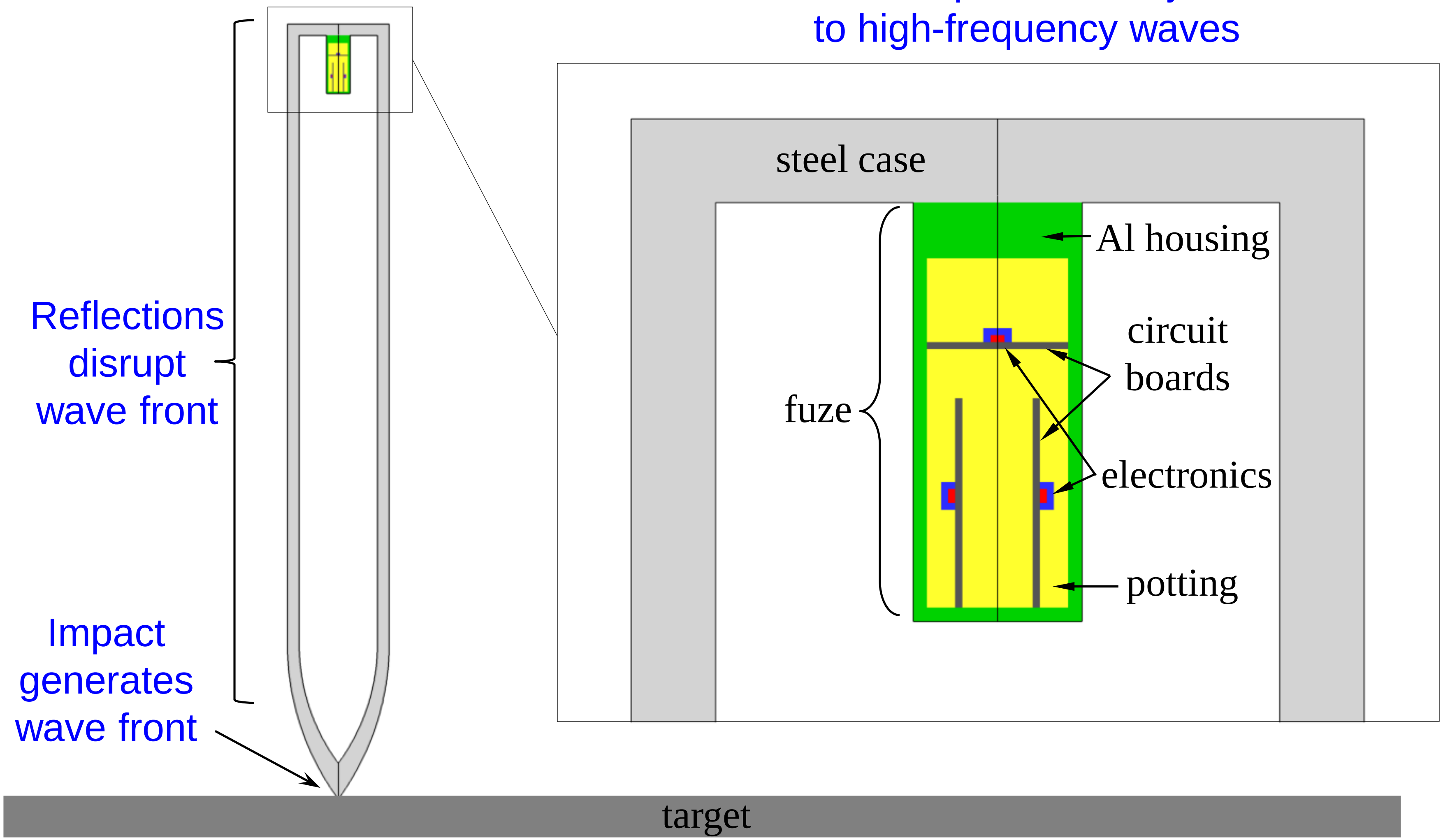
Fuze components subjected to high-frequency waves

Reflections disrupt wave front

Impact generates wave front



Background

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- Lagrangian finite-element codes are industry standard for analysis of wave propagation
  - Explicit time integration by central differences
  - First-order elements
  - Computations often can’t resolve high-frequency modes, resulting in spurious oscillations (Gibbs’ phenomenon)
  - Artificial viscosity damps oscillations *and* high-frequency modes
- Objective is to improve the accuracy of Lagrangian computations of wave propagation
  - Systematic survey of numerical methods uncovered advantages of higher-order (> 2nd order) elements
  - Higher-Order elements formulated and added to the EPIC code

Background

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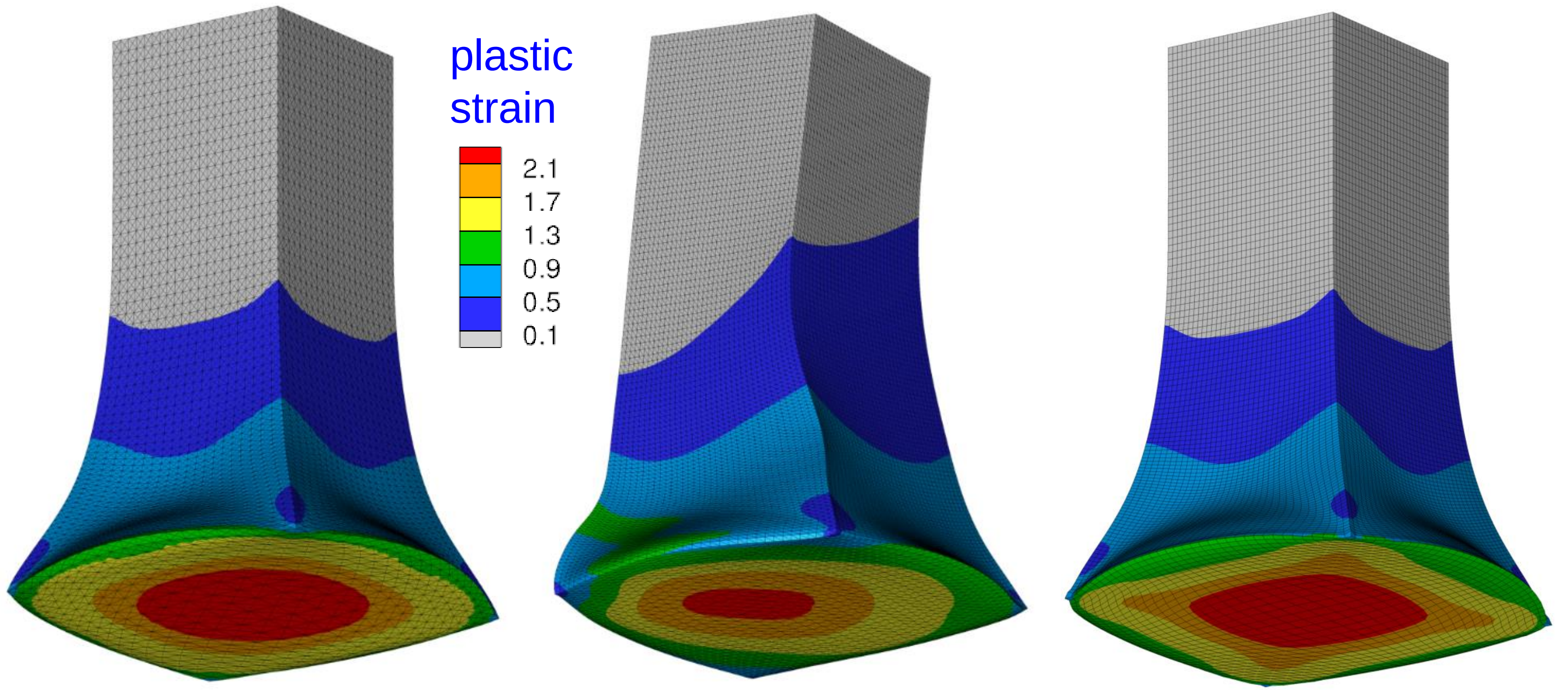
- Higher-order elements used successfully for years in CFD
- Higher-order elements not used for solid mechanics because:
  - Computational efficiency of explicit schemes historically equated to minimizing the floating-point operations (FLOPS) in evaluation of internal-force term, and FLOPs increase with element order.
  - Greater complexity of curved-surface contact algorithms
  - Decades of research invested in various formulaic tradeoffs between locking and zero-energy modes of first-order elements
  - Mass lumping of 2^{nd}-order serendipity elements yields vertex nodes with zero or negative:
    - Masses
    - Nodal forces due to uniform external traction
  - Lack of meshing and visualization software for higher orders

Finite-deformation plasticity

Square copper rod impacting a rigid surface at 200 m/s



symmetric
order-1 tetrahedra

non-symmetric
order-1 tetrahedra

order-1 hexahedra
(Flanagan-Belytschko)

Finite-deformation plasticity

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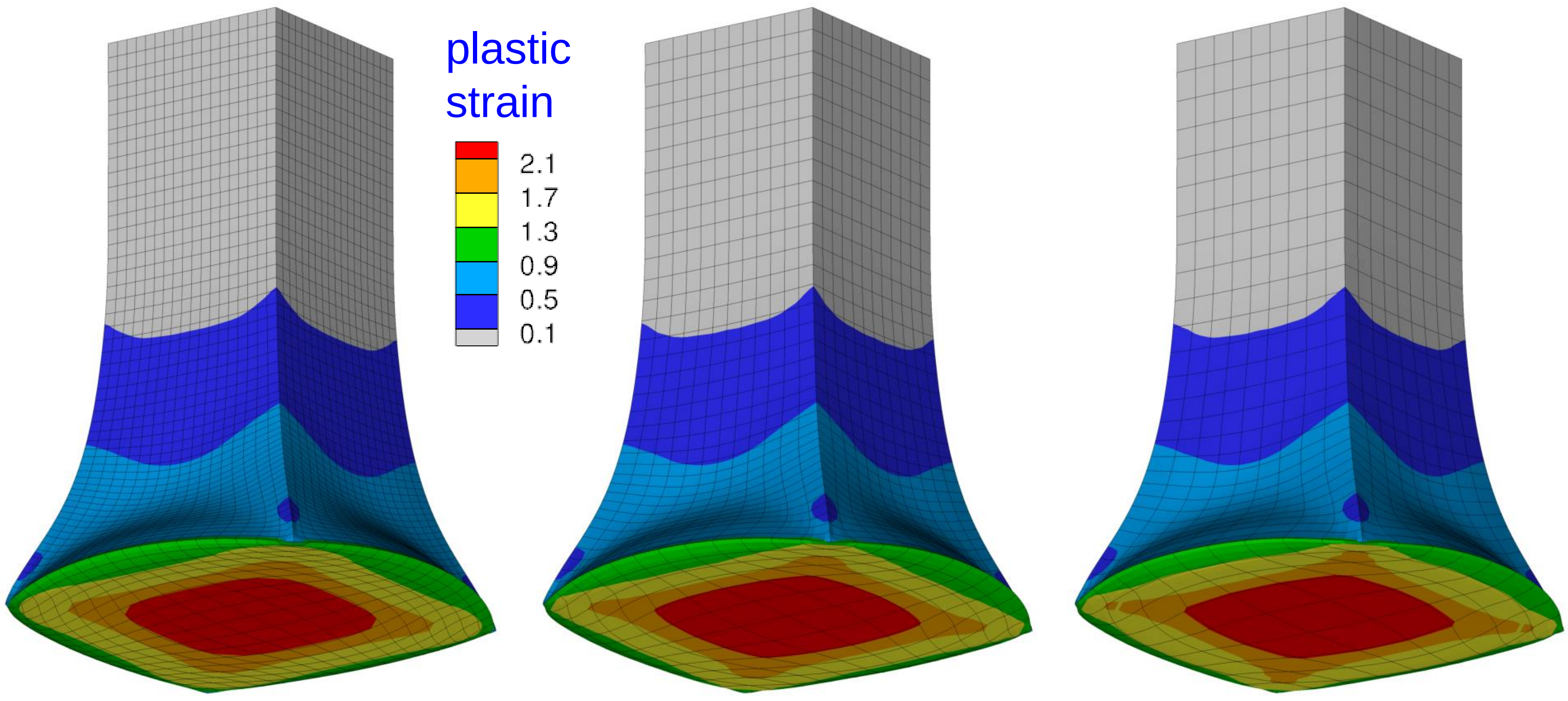
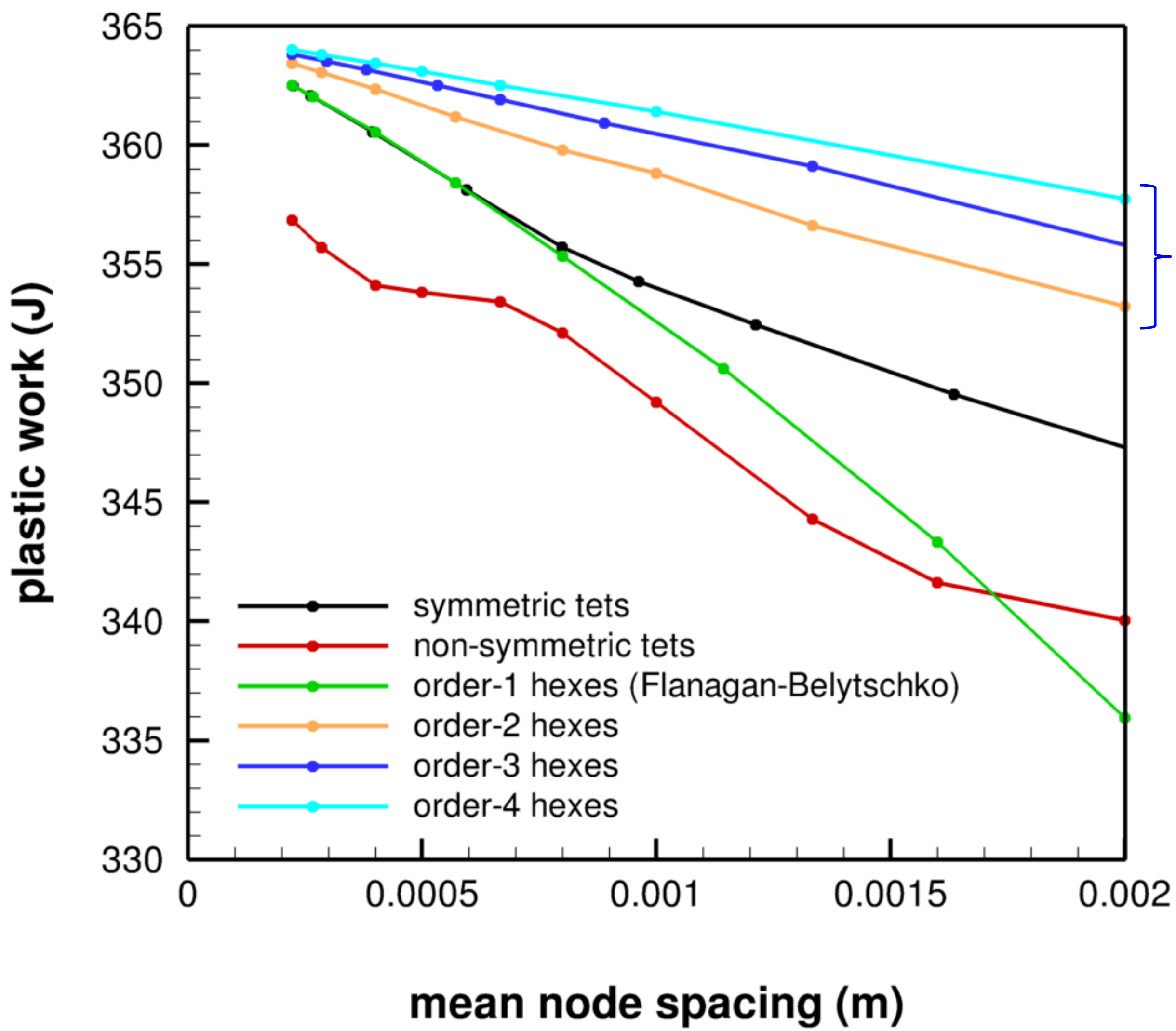
Square copper rod impacting a rigid surface at 200 m/s



order-2 hexahedra order-3 hexahedra order-4 hexahedra

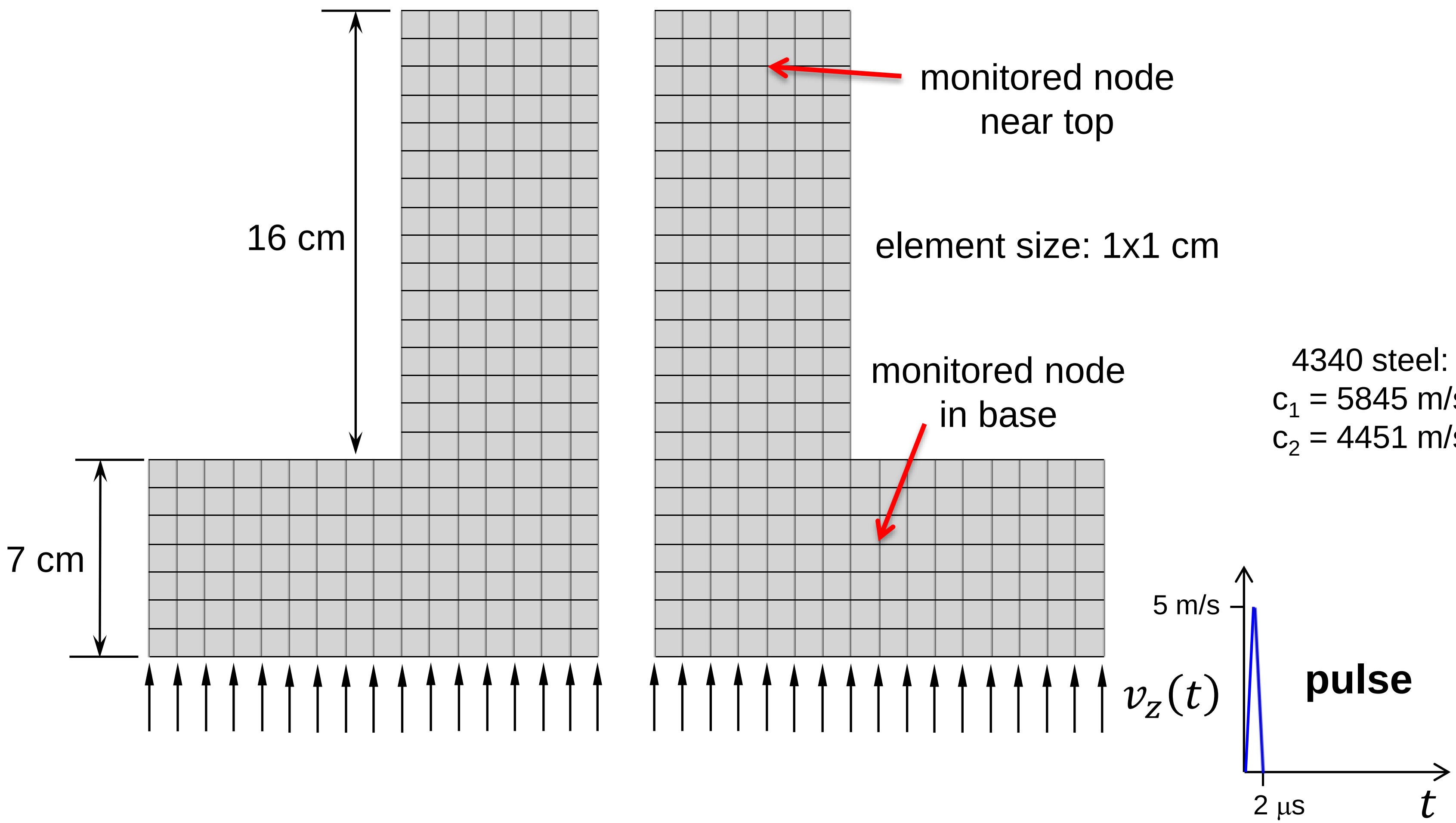
Finite-deformation plasticity



No volumetric locking

Wave propagation in 2-D axisymmetry

Baseline mesh of simple part loaded by a pulse



4340 steel:
c_1 = 5845 m/s
c_2 = 4451 m/s

Wave propagation in 2-D axisymmetry

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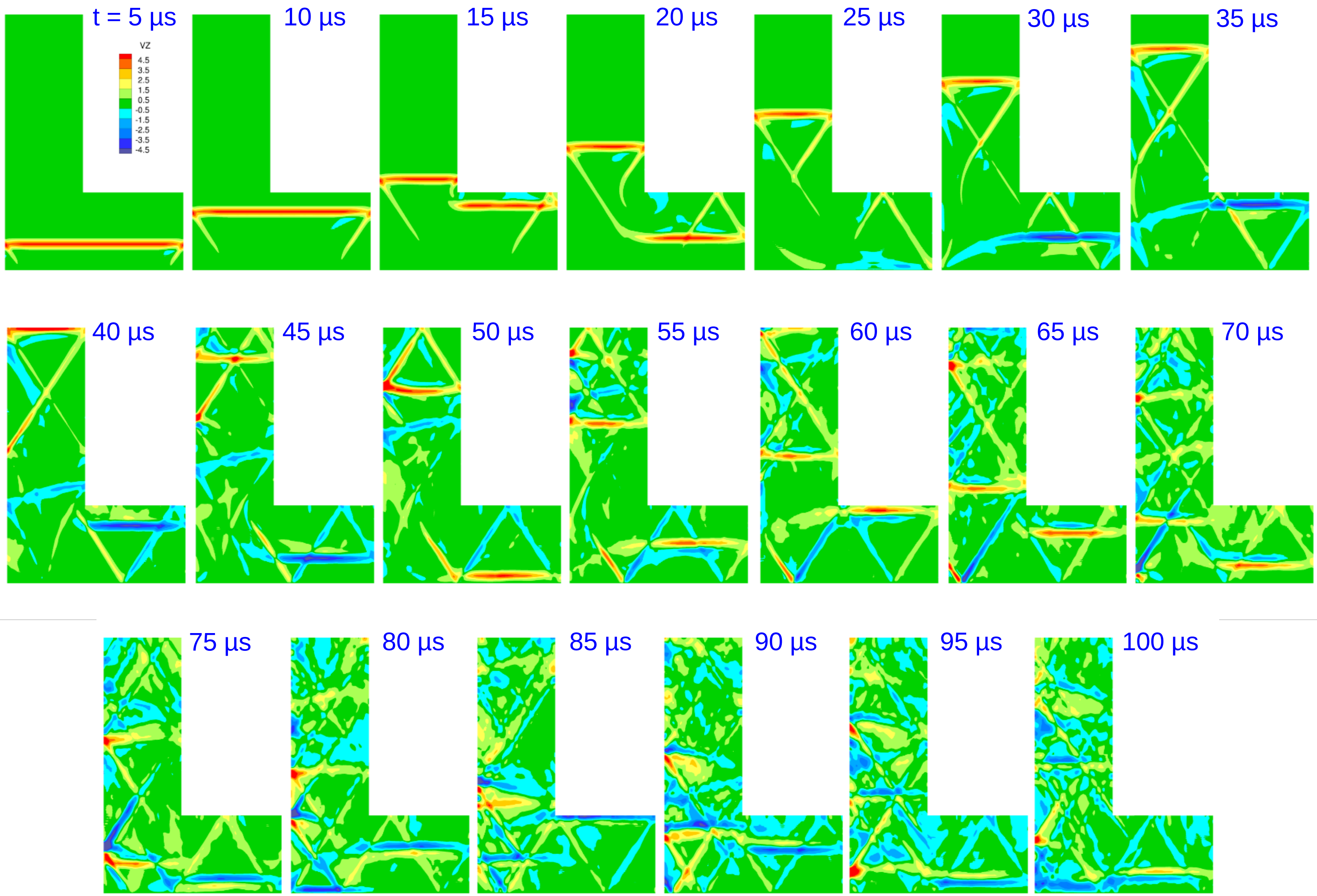

Wave propagation in 2-D axisymmetry

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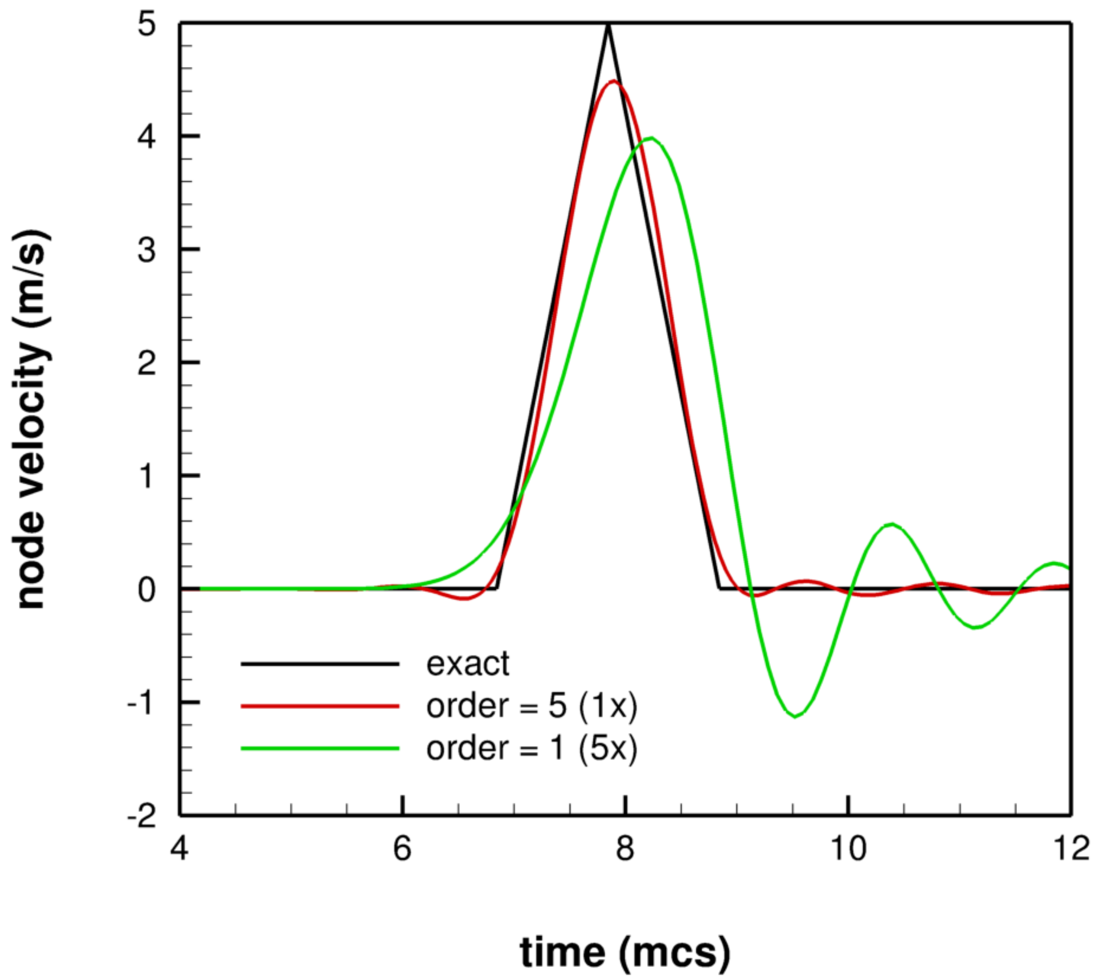
Velocities of node in base at equal mesh refinement



Wave propagation in 2-D axisymmetry

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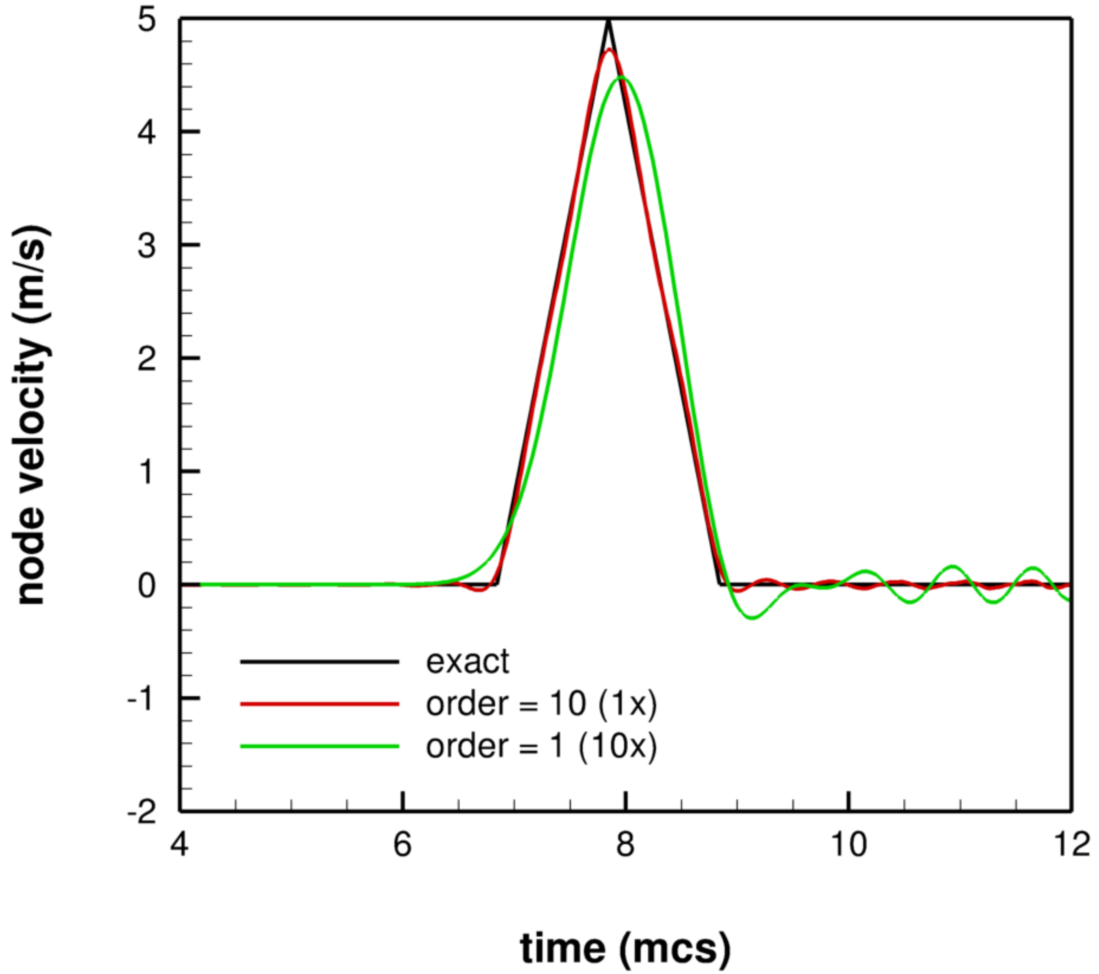

Wave propagation in 2-D axisymmetry

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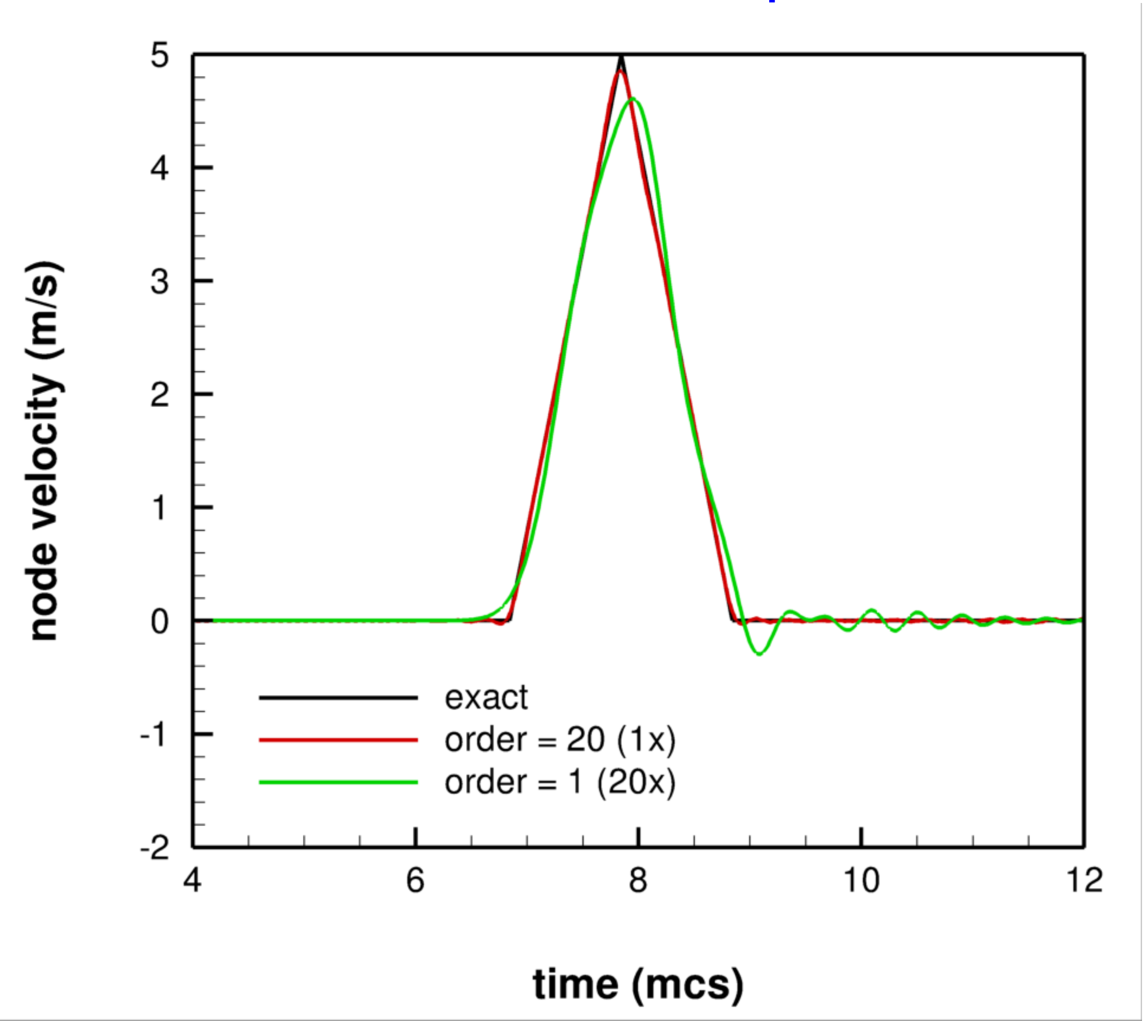

Wave propagation in 2-D axisymmetry

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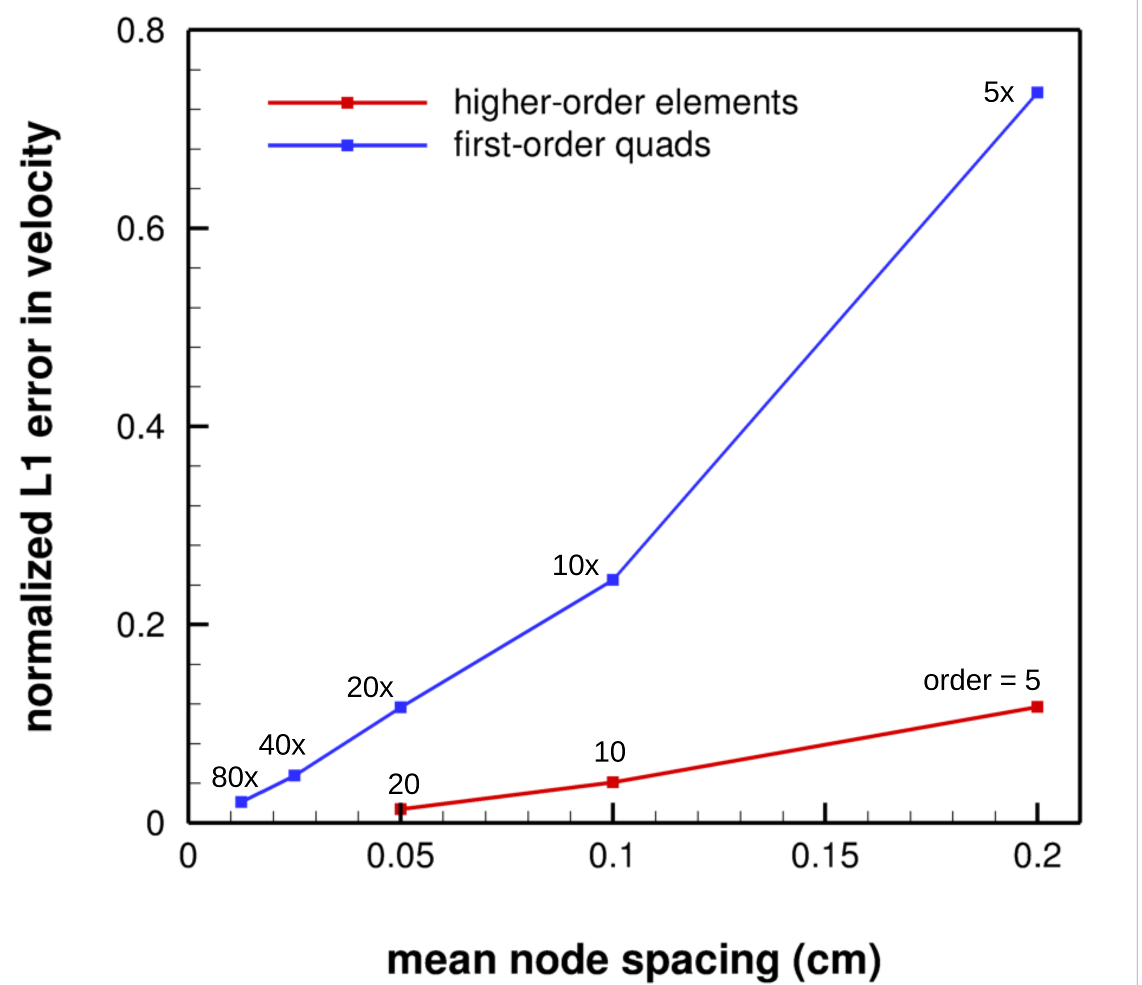
Summary of errors at node in base (0 -12 μs)



Wave propagation in 2-D axisymmetry

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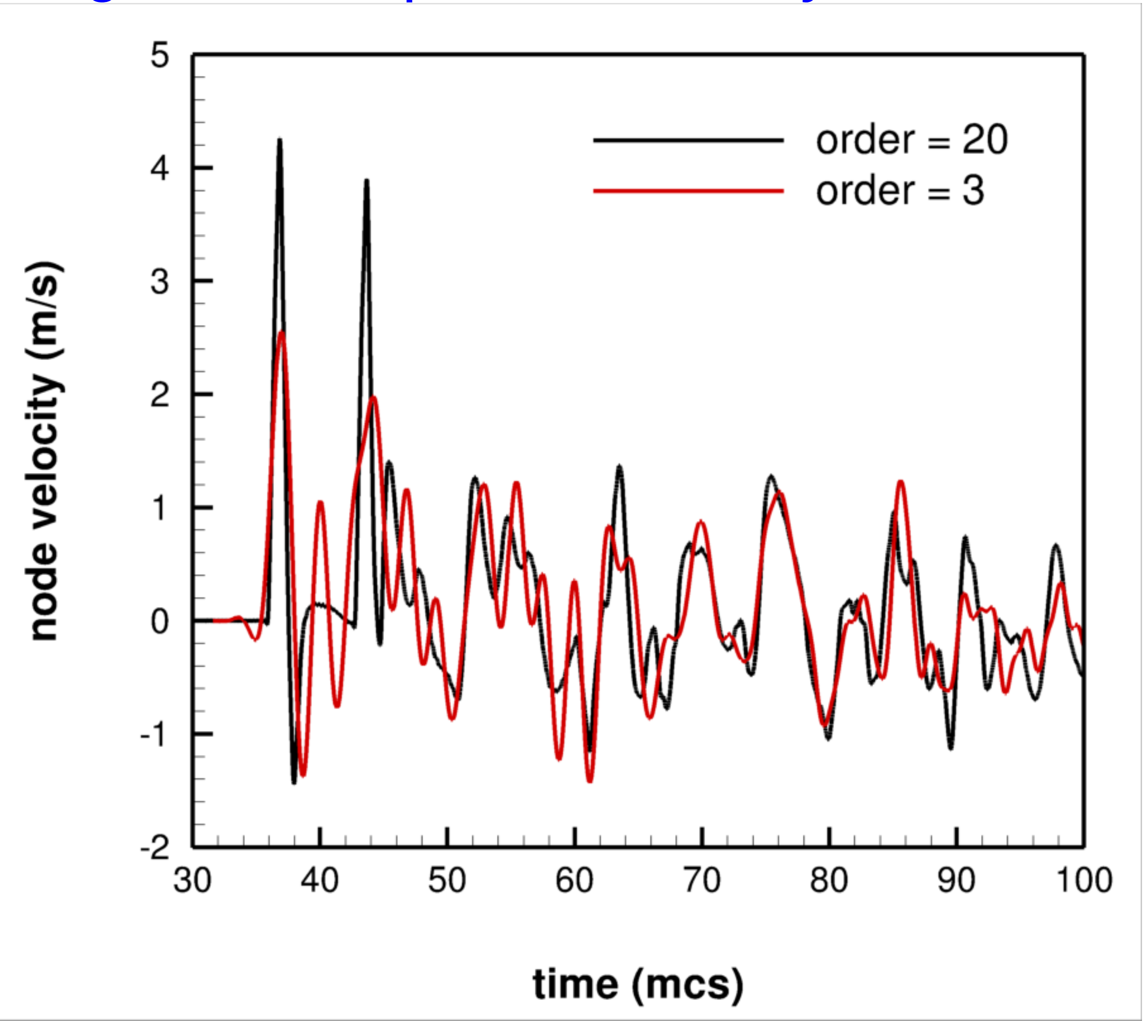
Convergence of top-node velocity with element order



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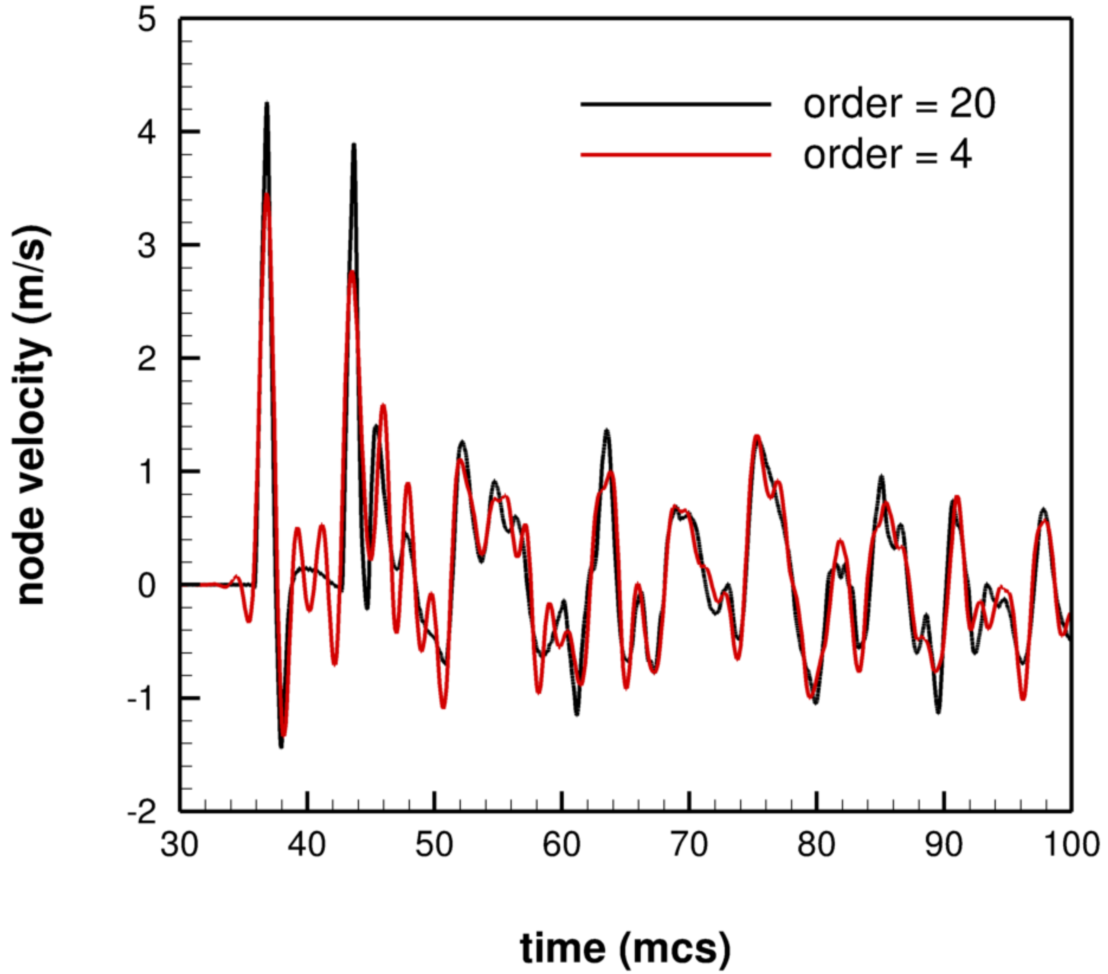

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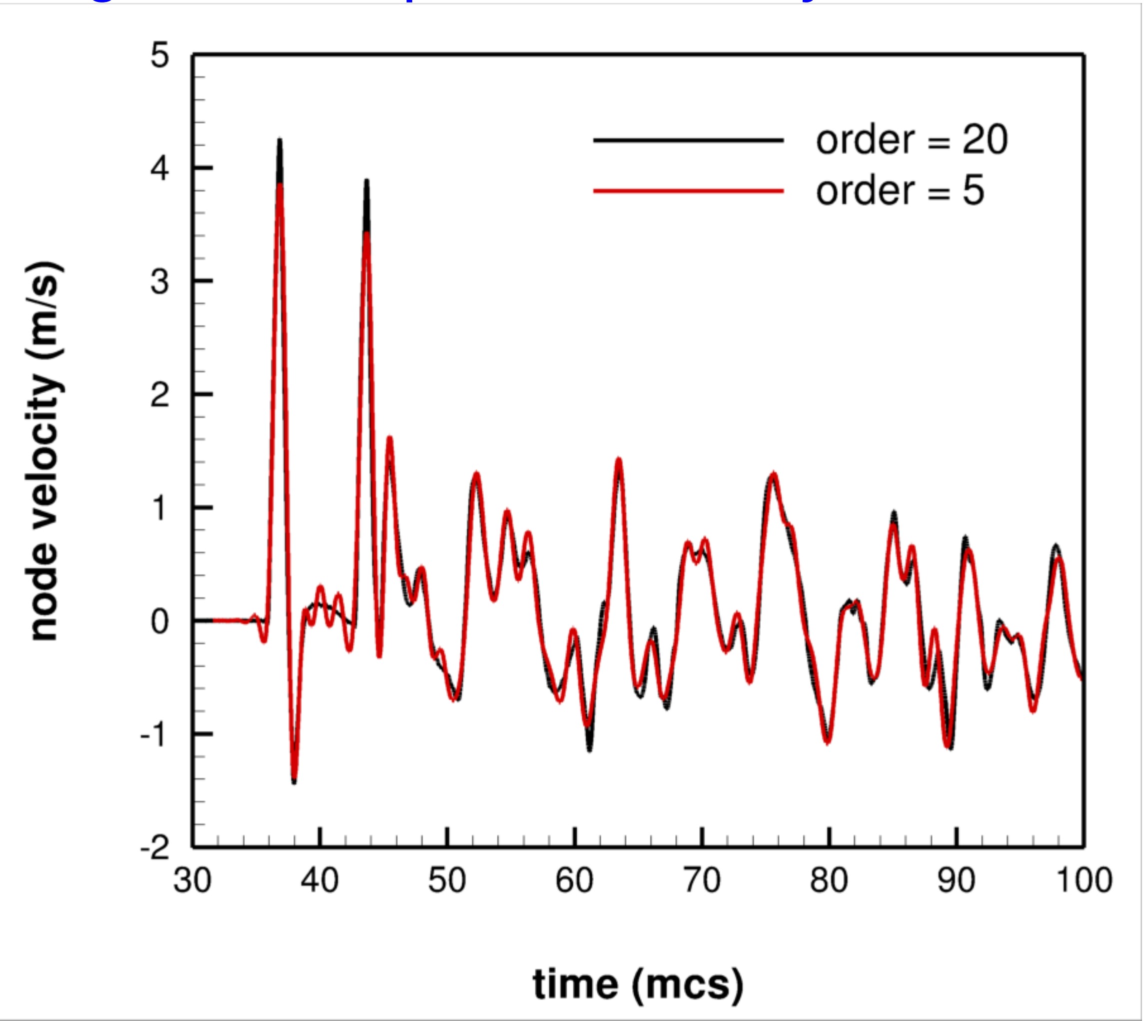

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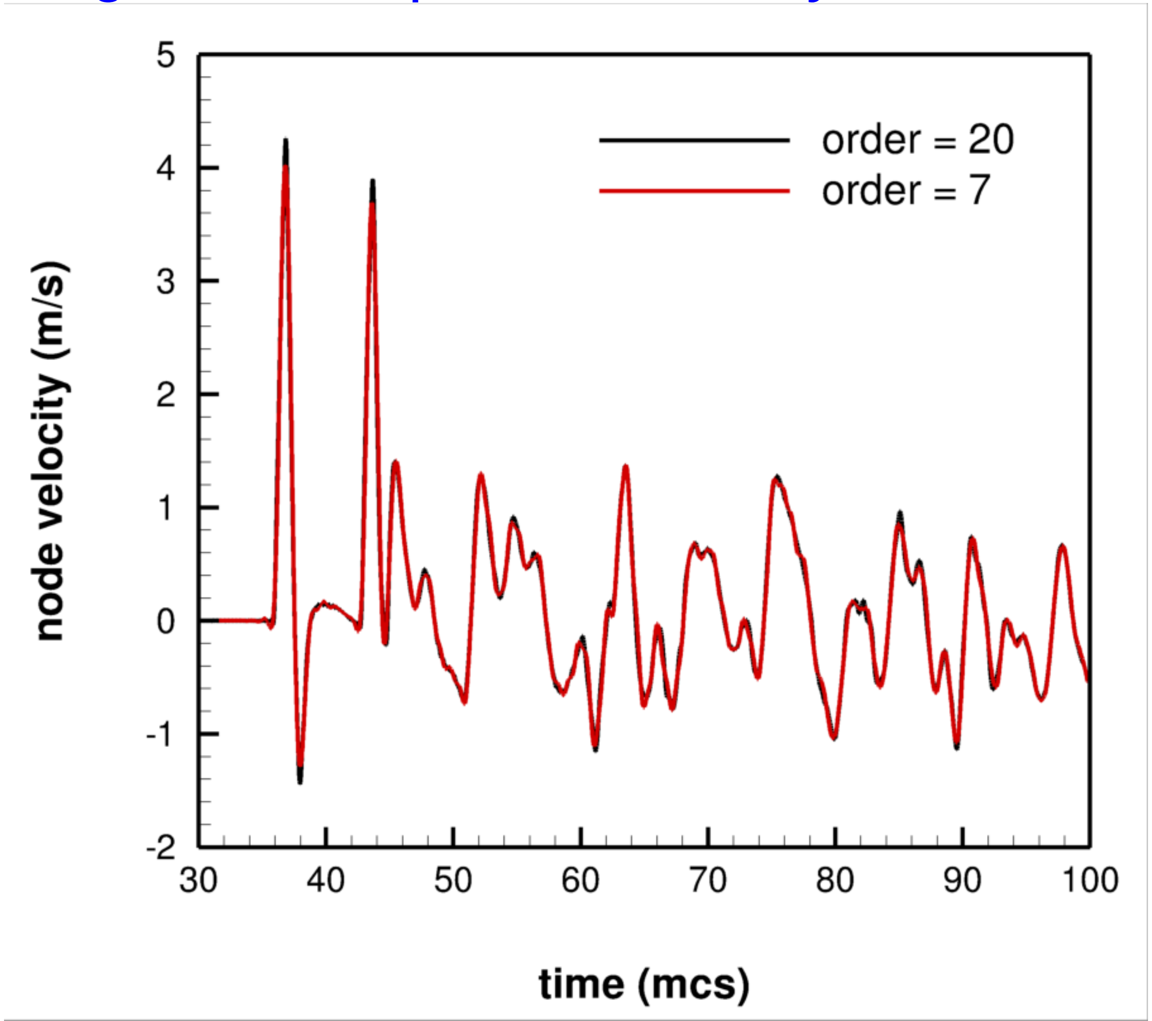

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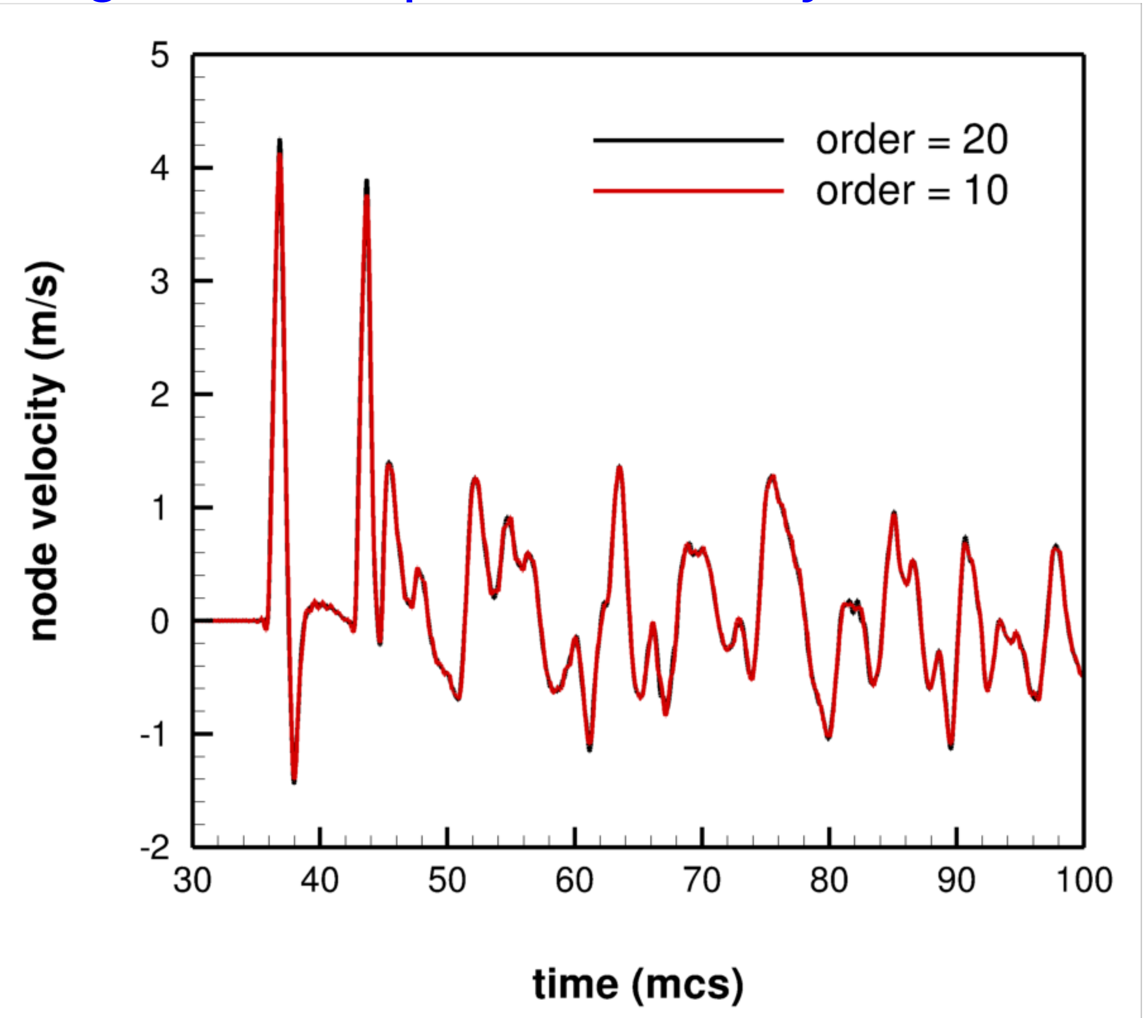

Wave propagation in 2-D axisymmetry

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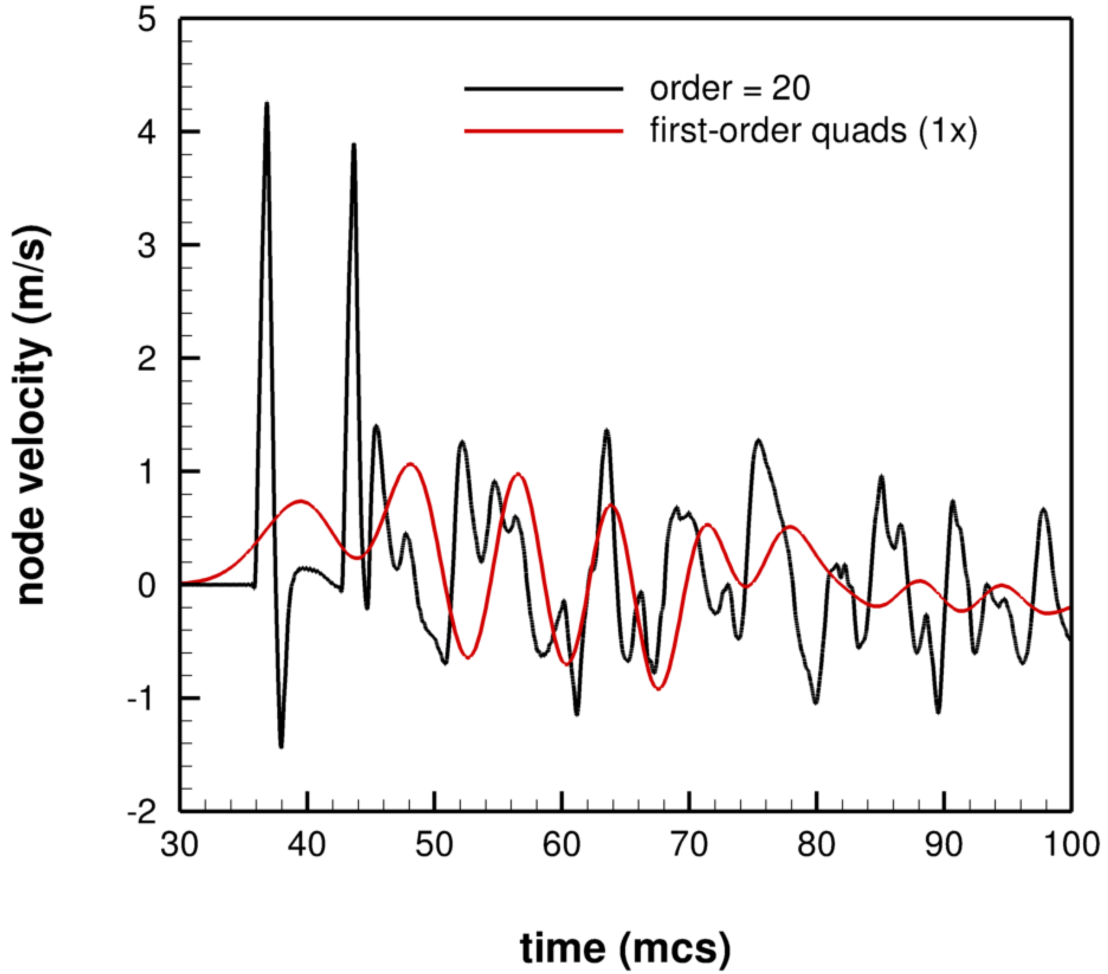
Convergence of top-node velocity with refinement of first-order quads



Wave propagation in 2-D axisymmetry

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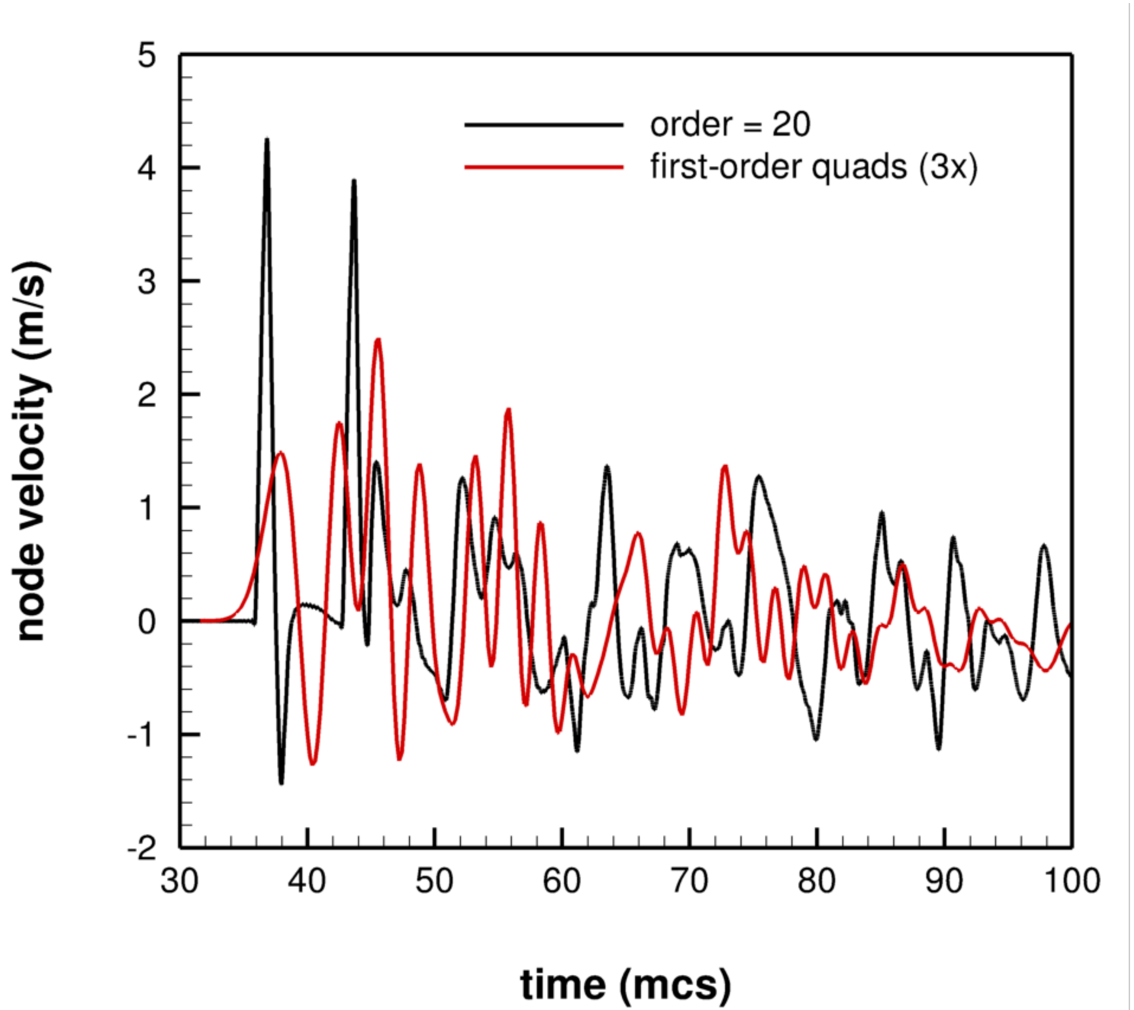

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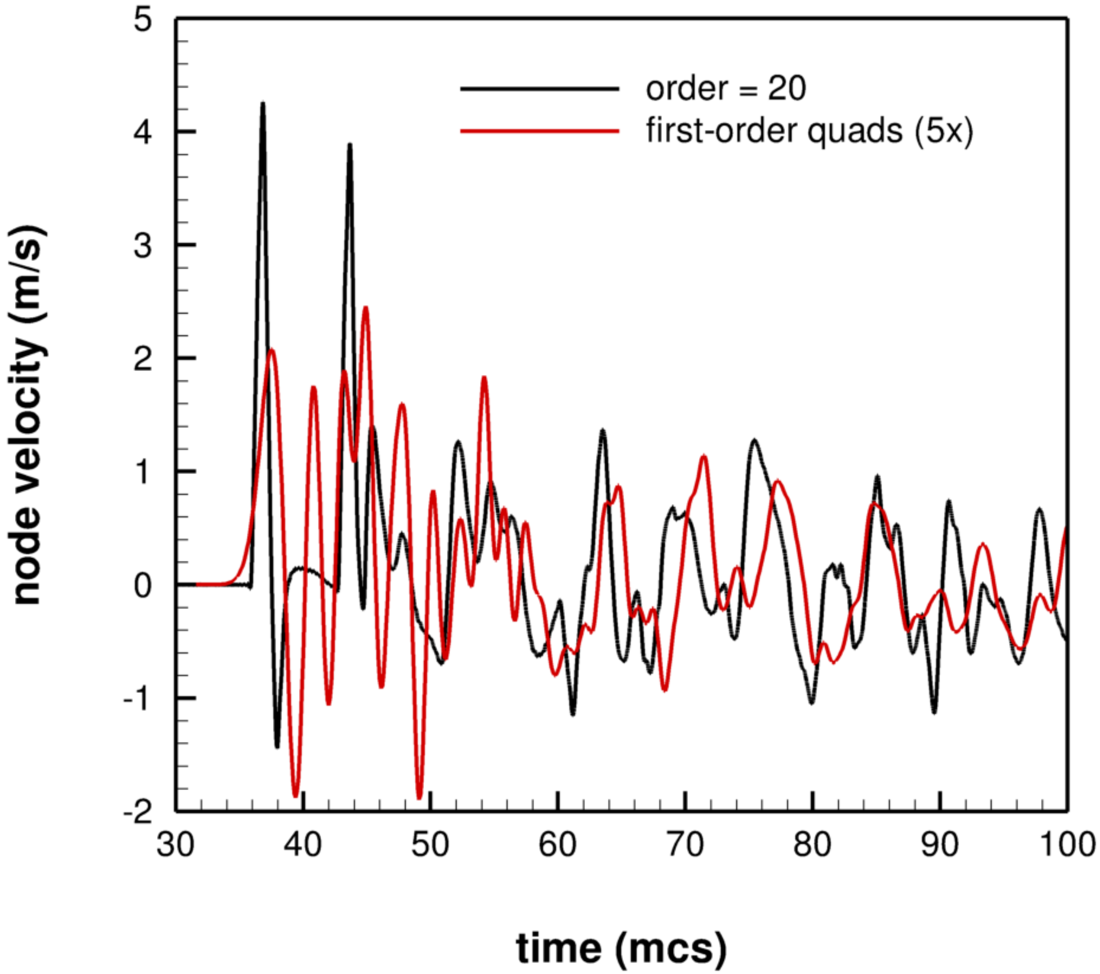

Wave propagation in 2-D axisymmetry

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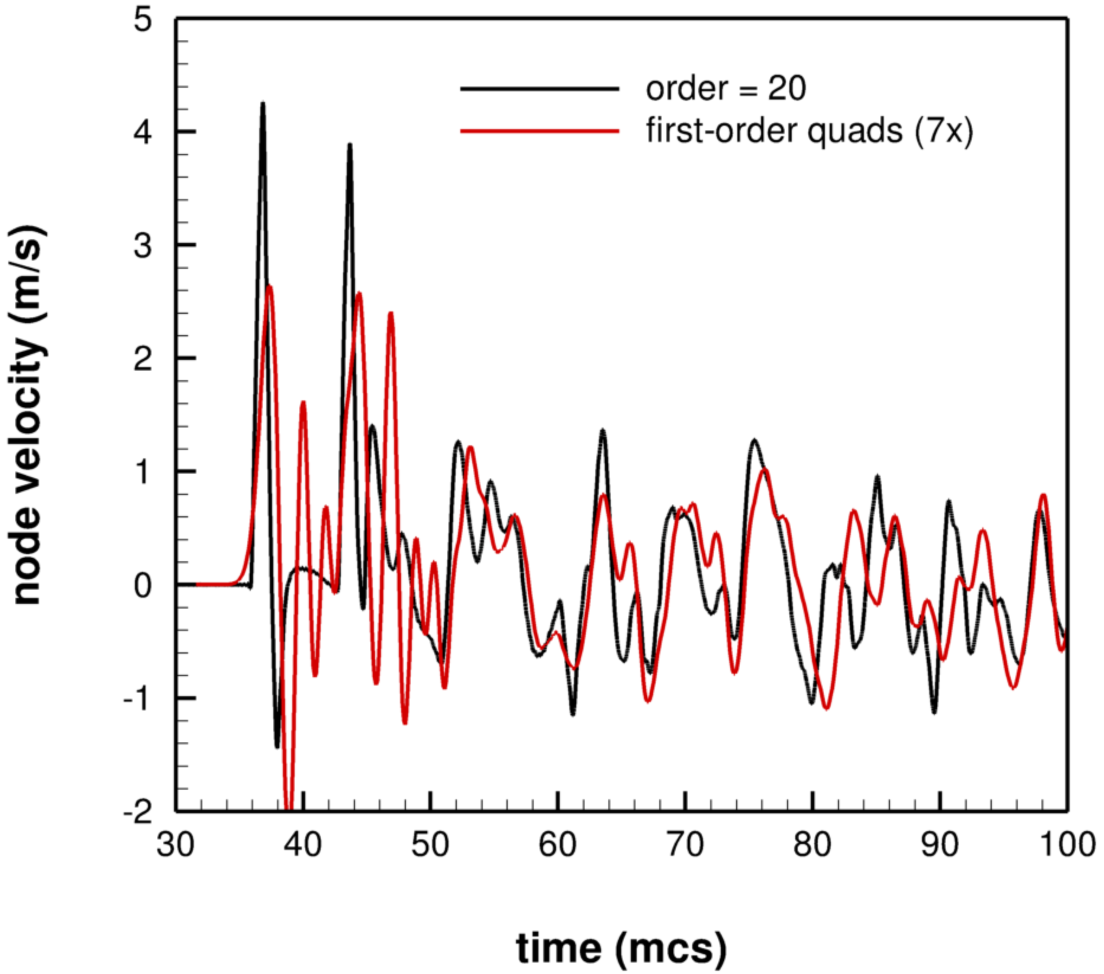

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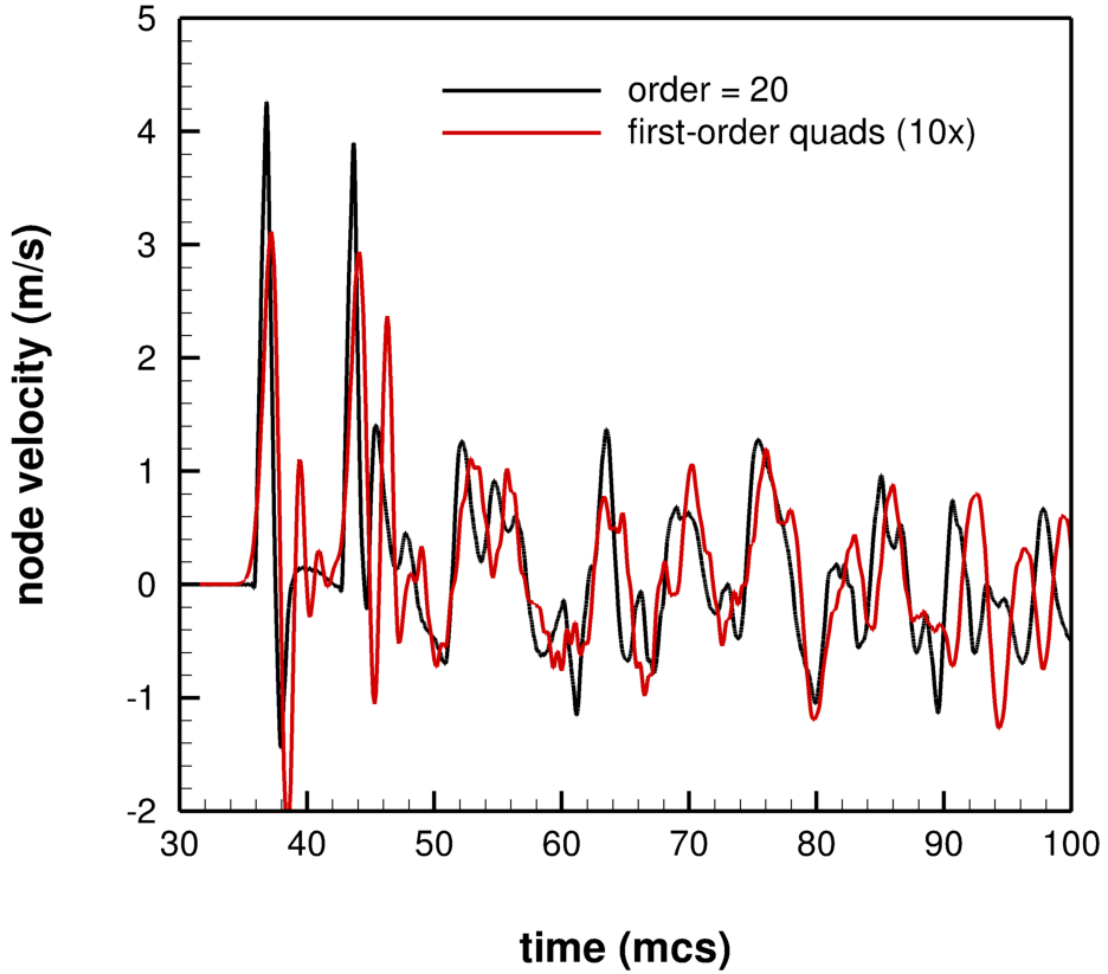

Wave propagation in 2-D axisymmetry

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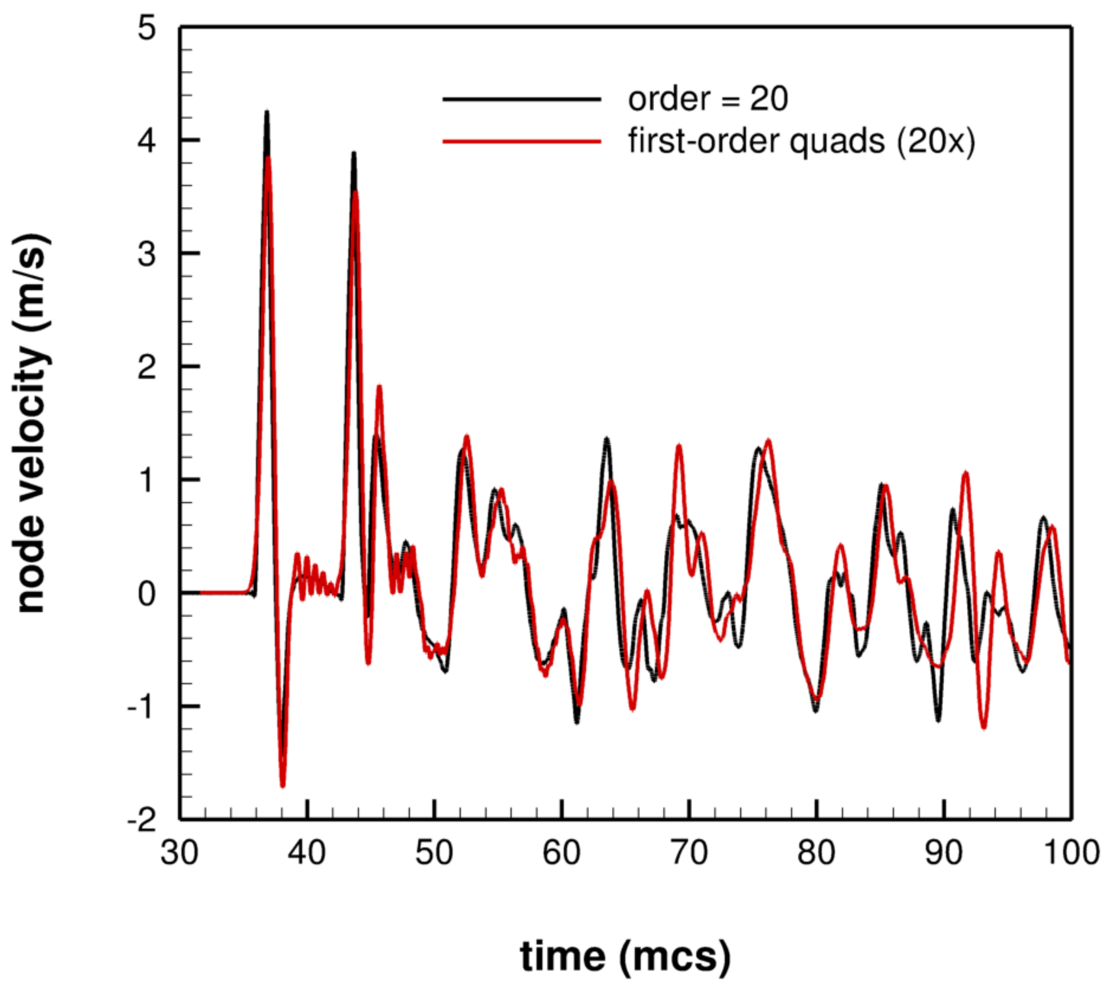

Wave propagation in 2-D axisymmetry

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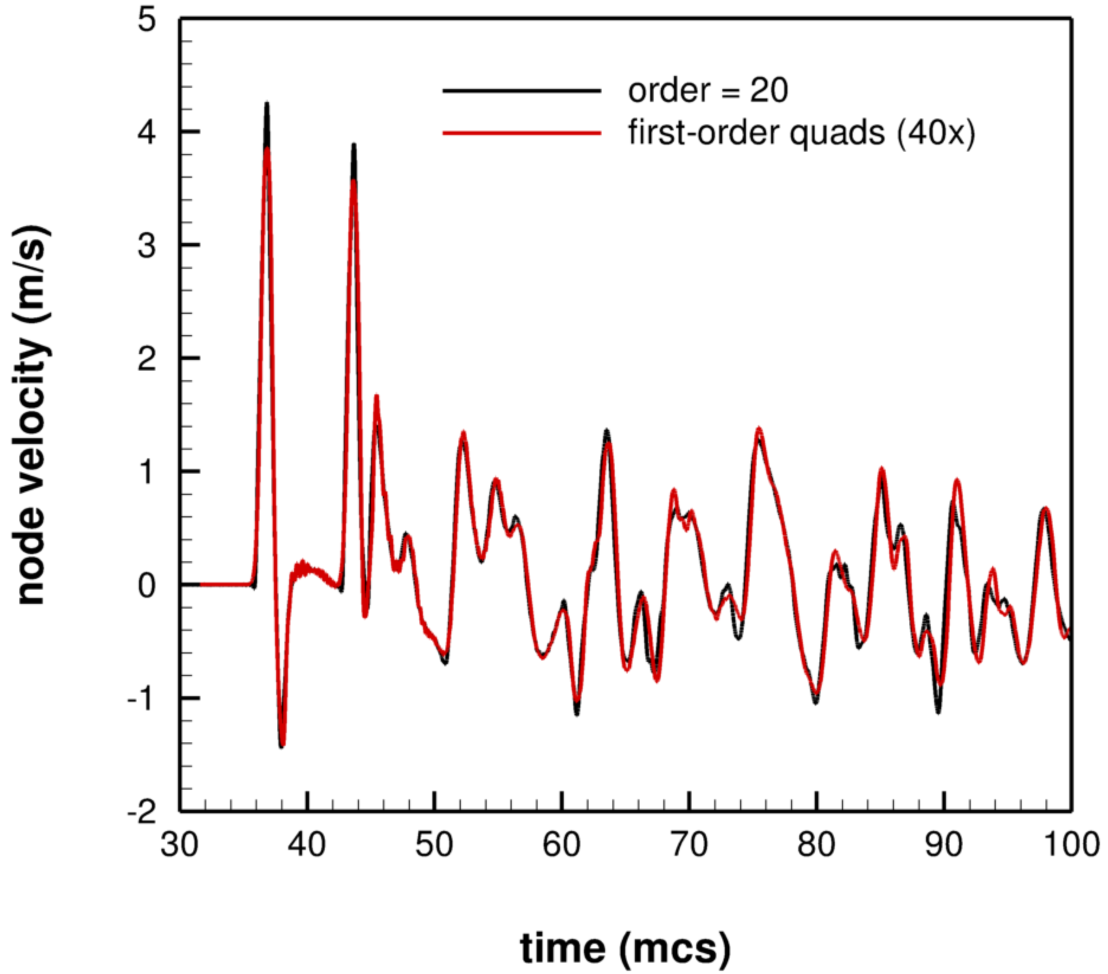

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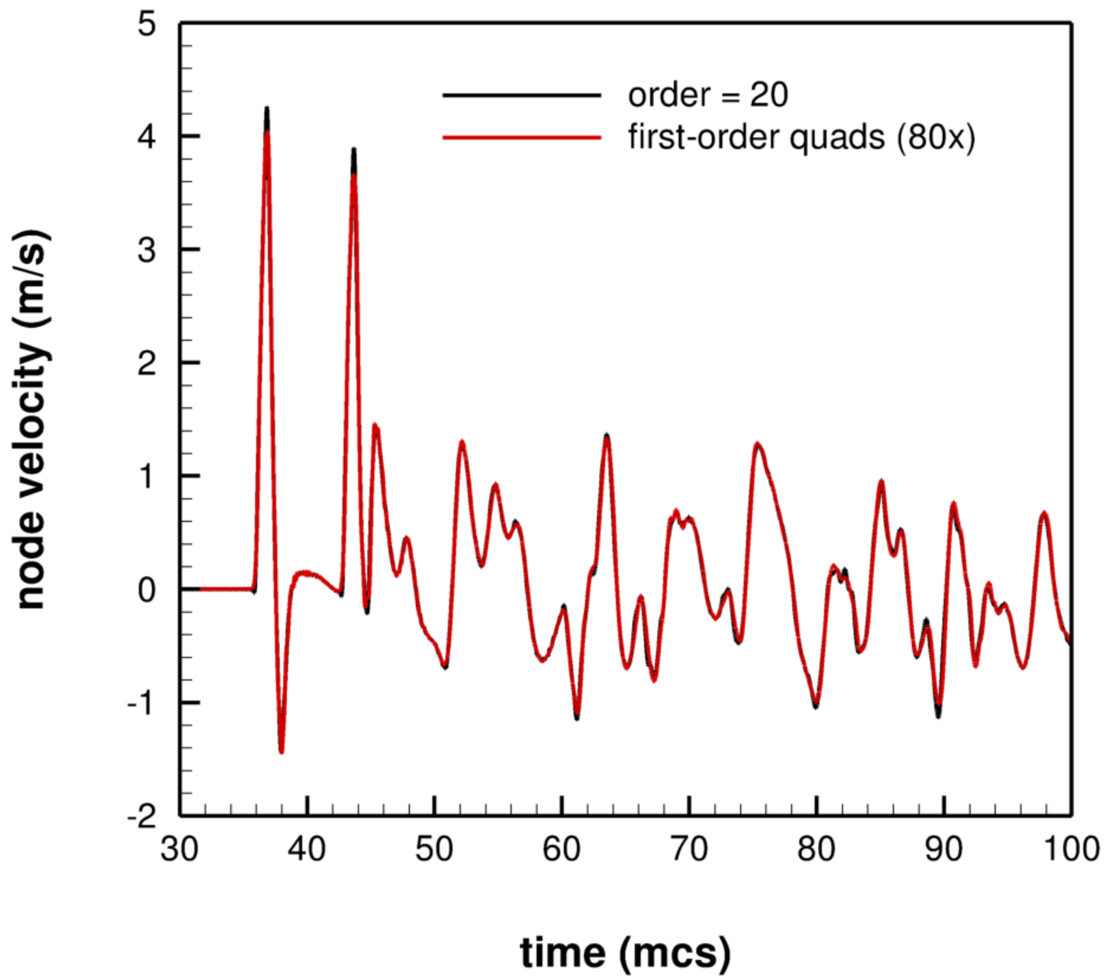
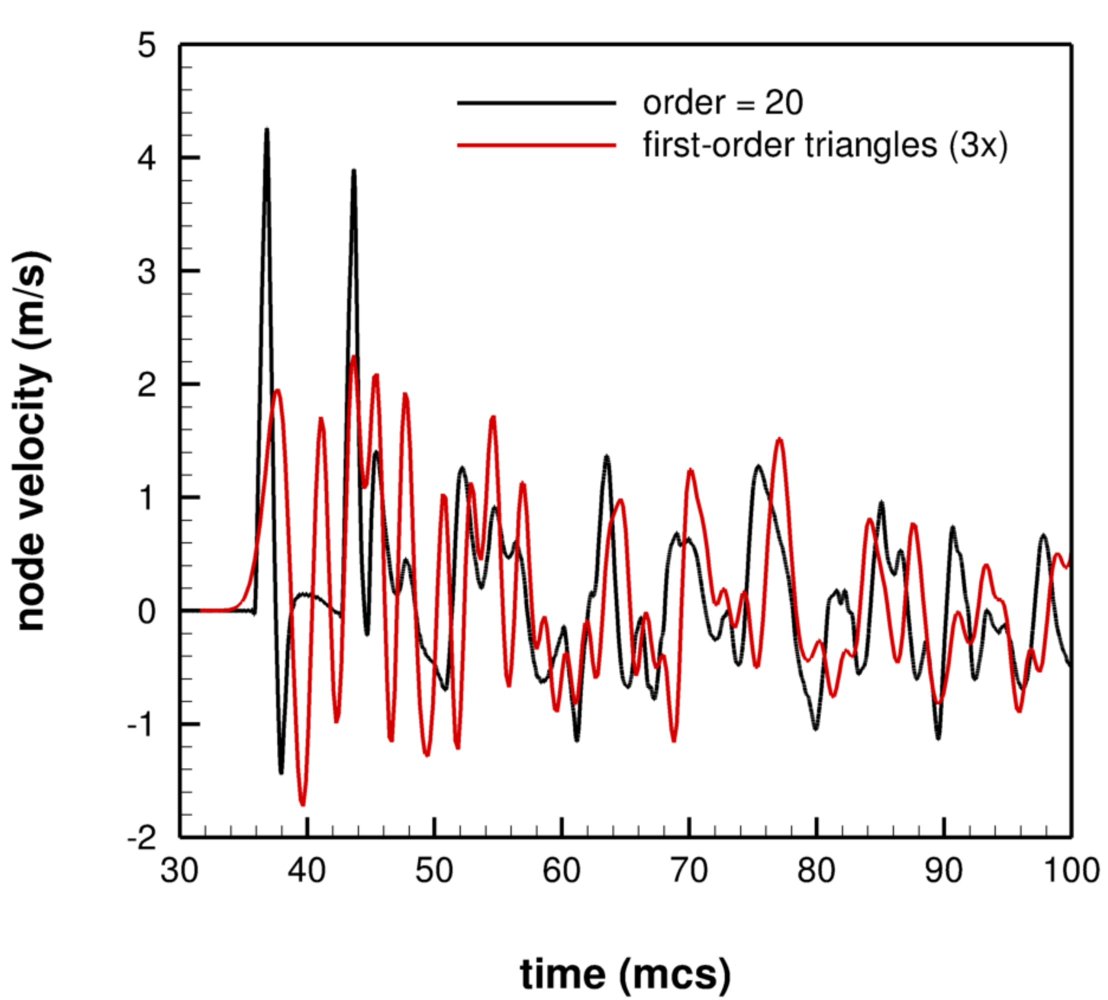


Wave propagation in 2-D axisymmetry

Convergence of top-node velocity with refinement of first-order triangles



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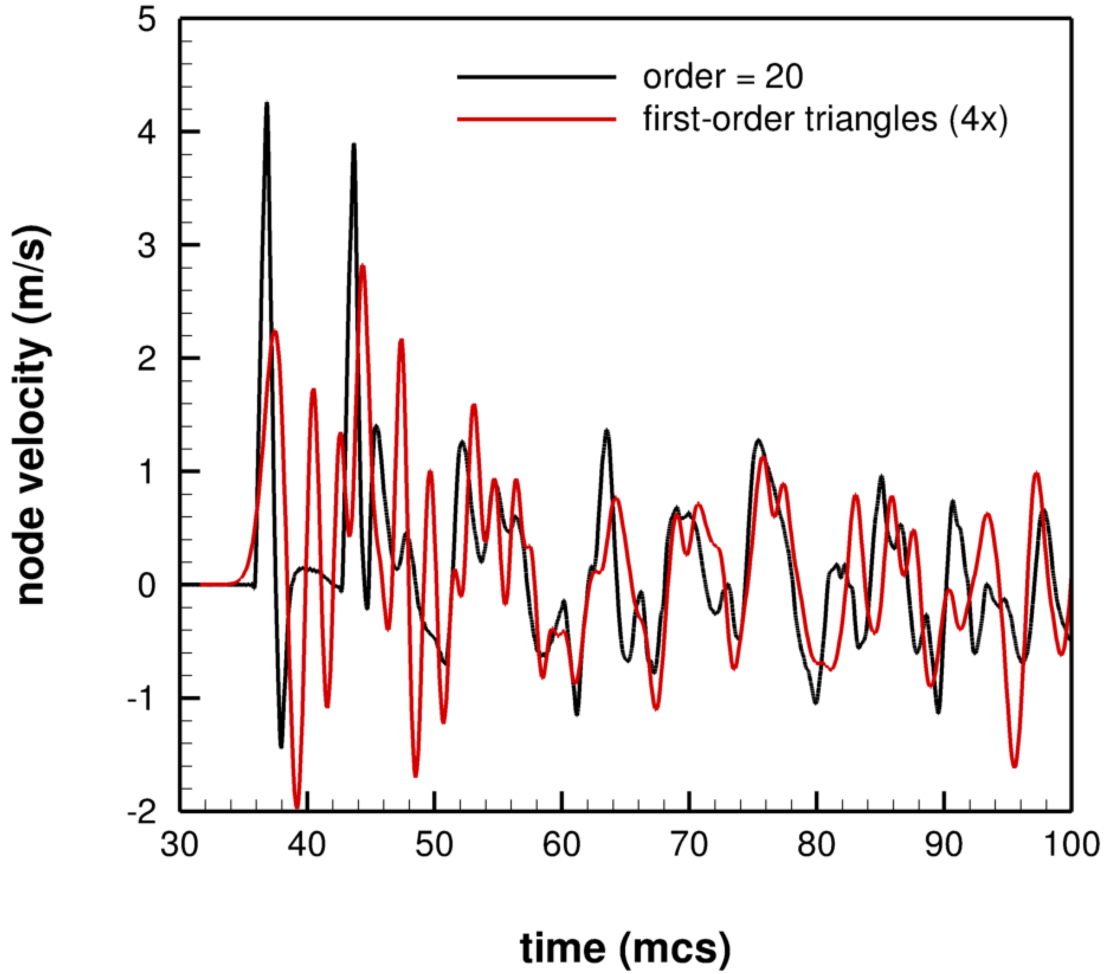

Wave propagation in 2-D axisymmetry

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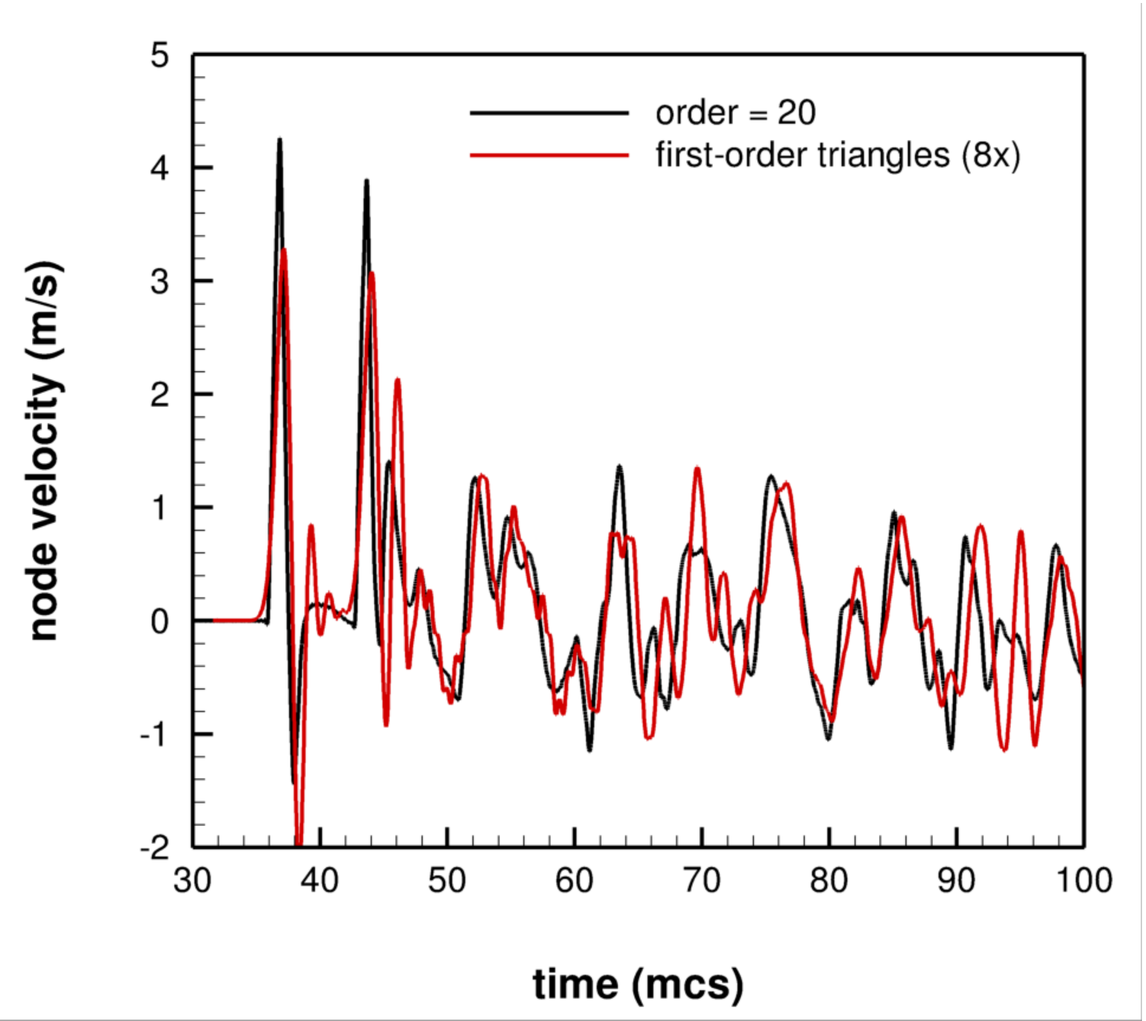

Wave propagation in 2-D axisymmetry

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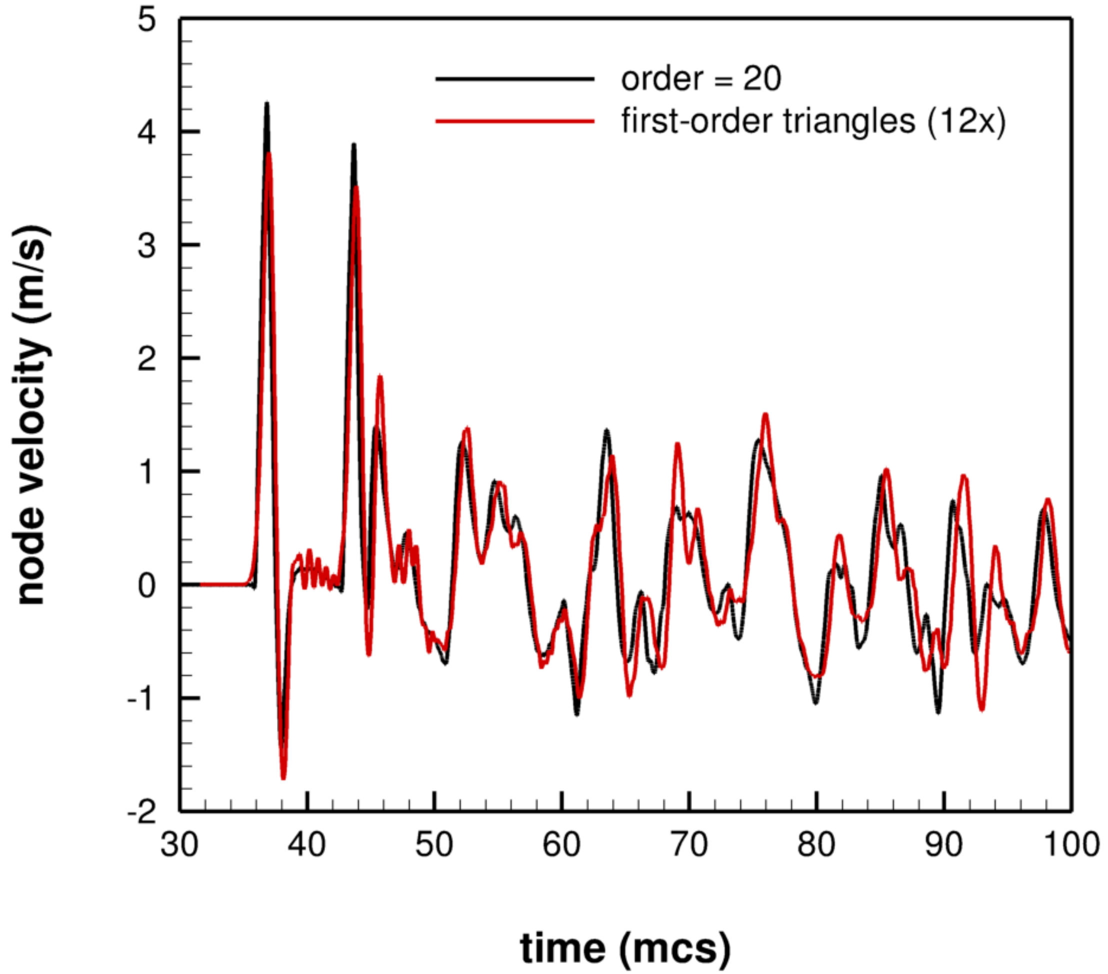

Wave propagation in 2-D axisymmetry

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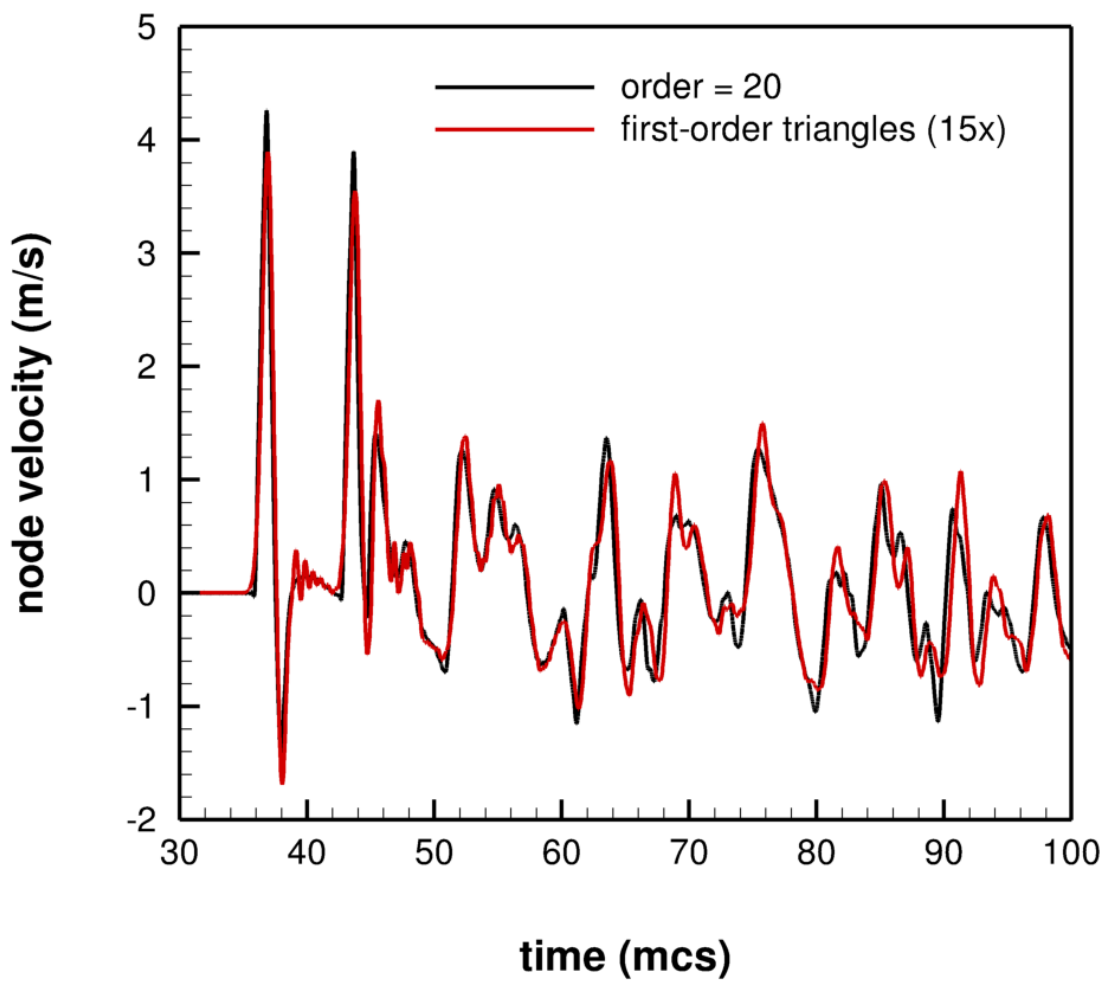

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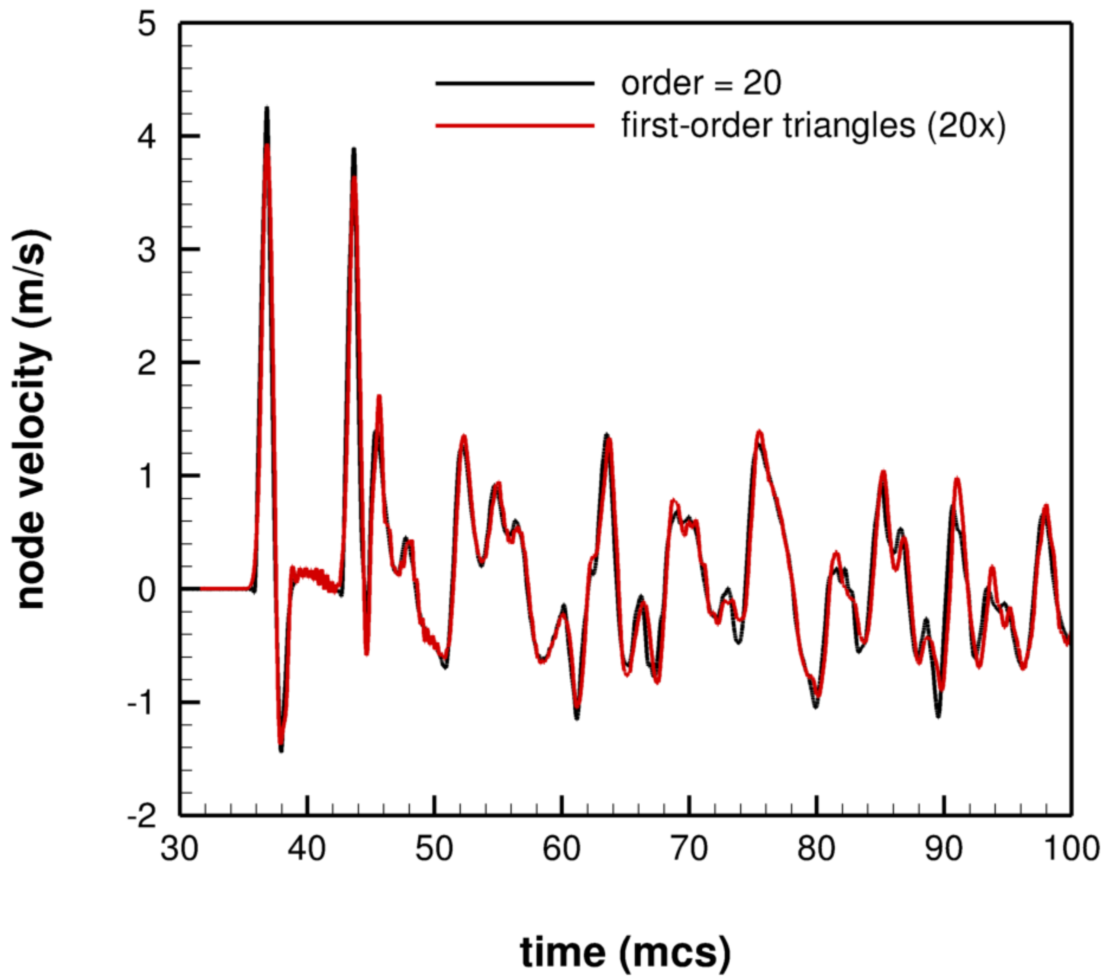

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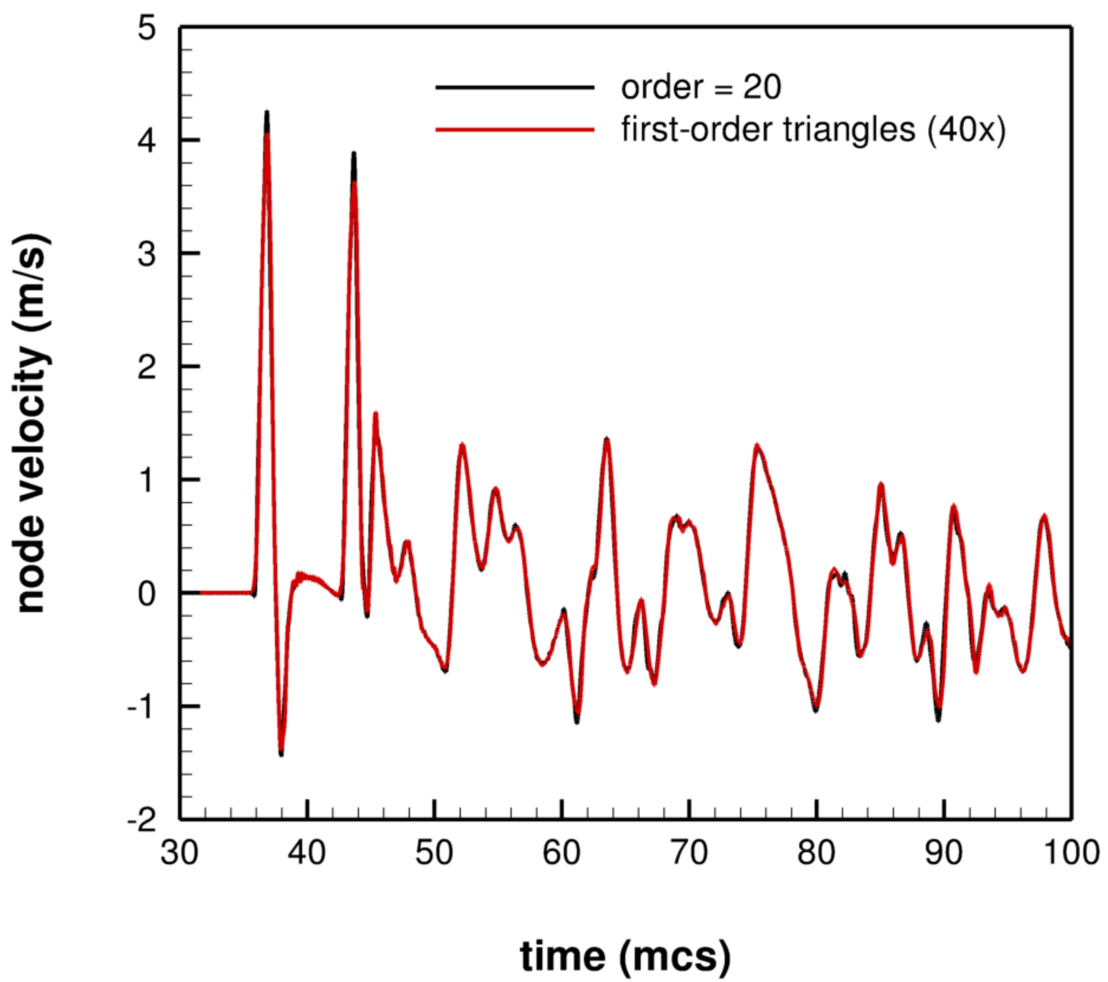

Wave propagation in 2-D axisymmetry

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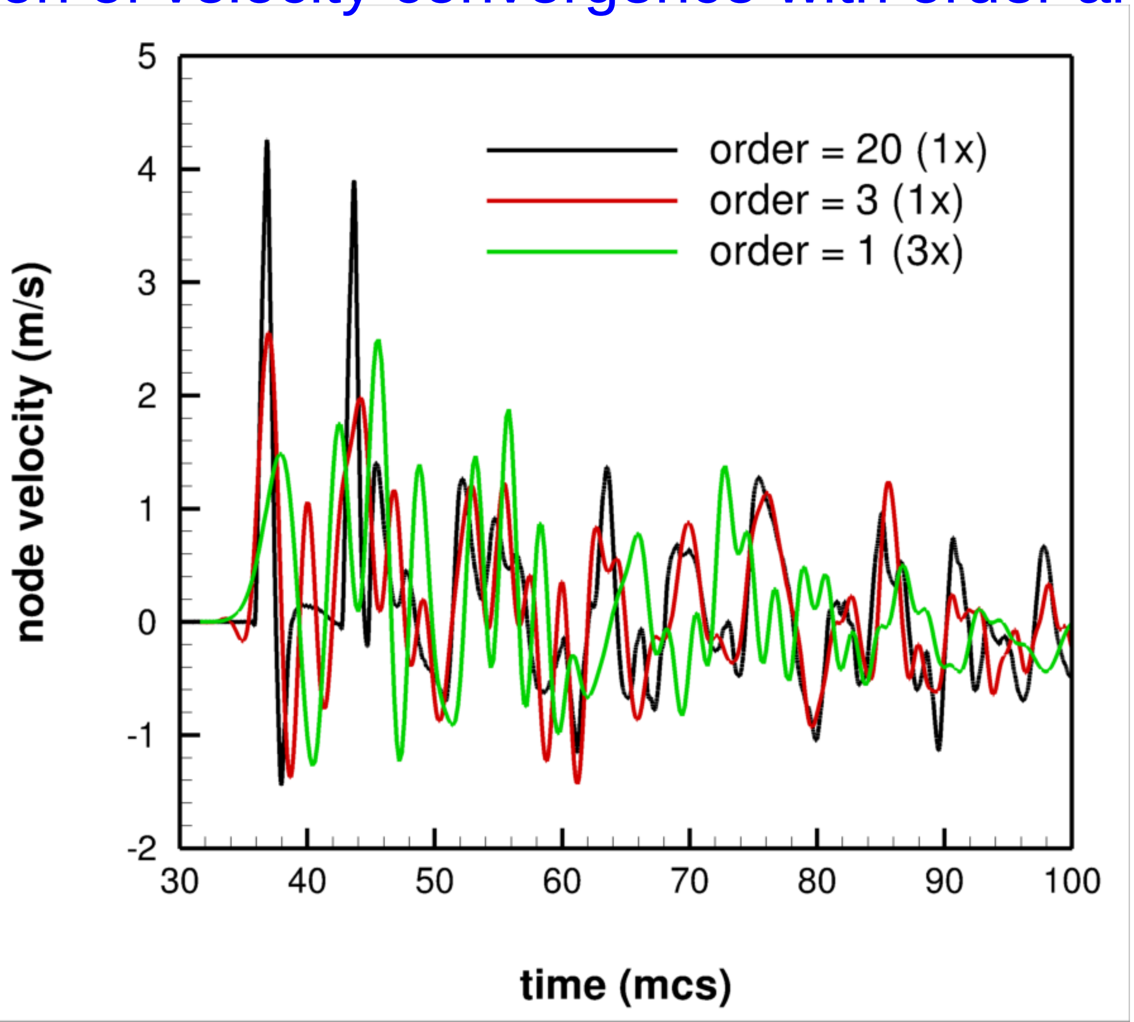
Comparison of velocity convergence with order and refinement



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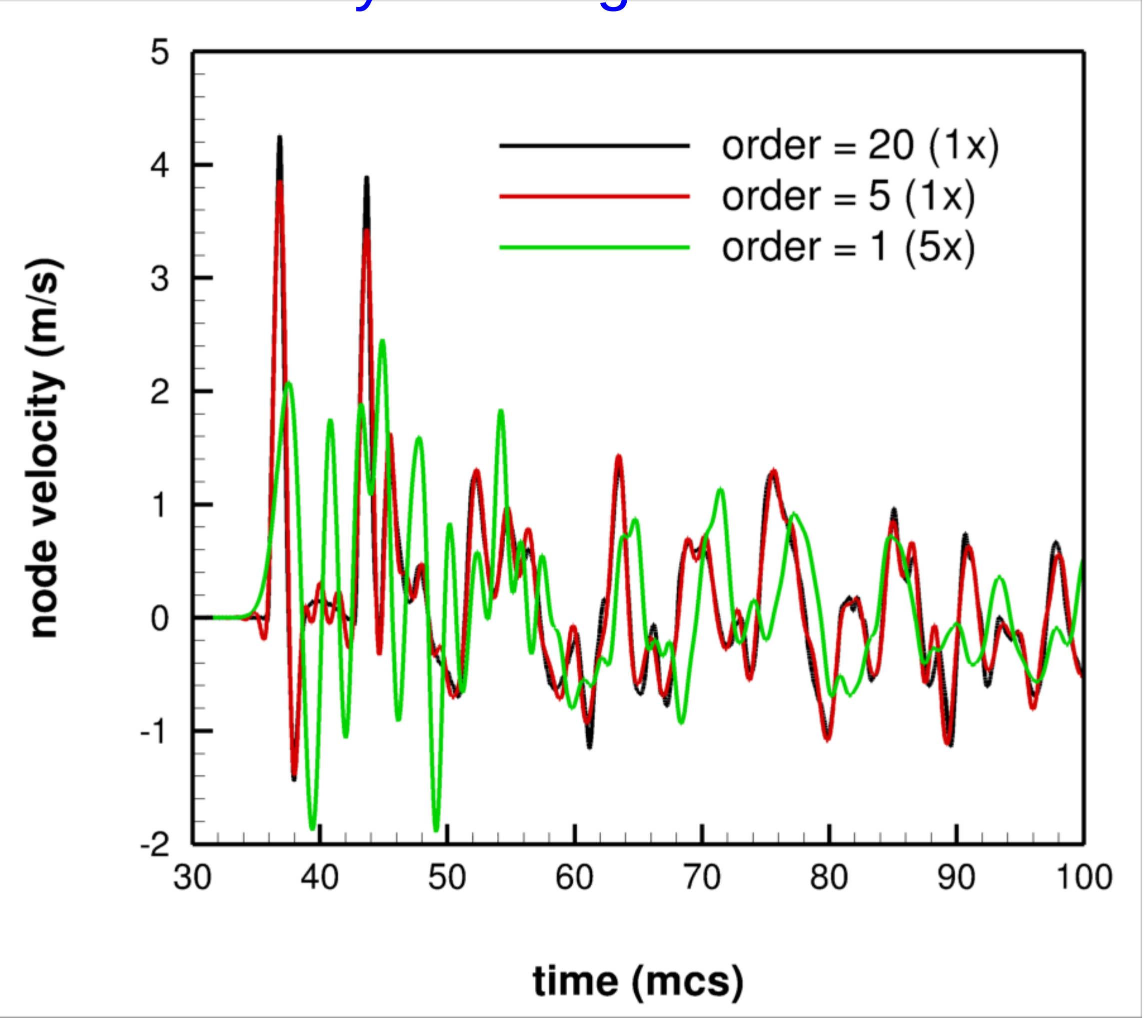

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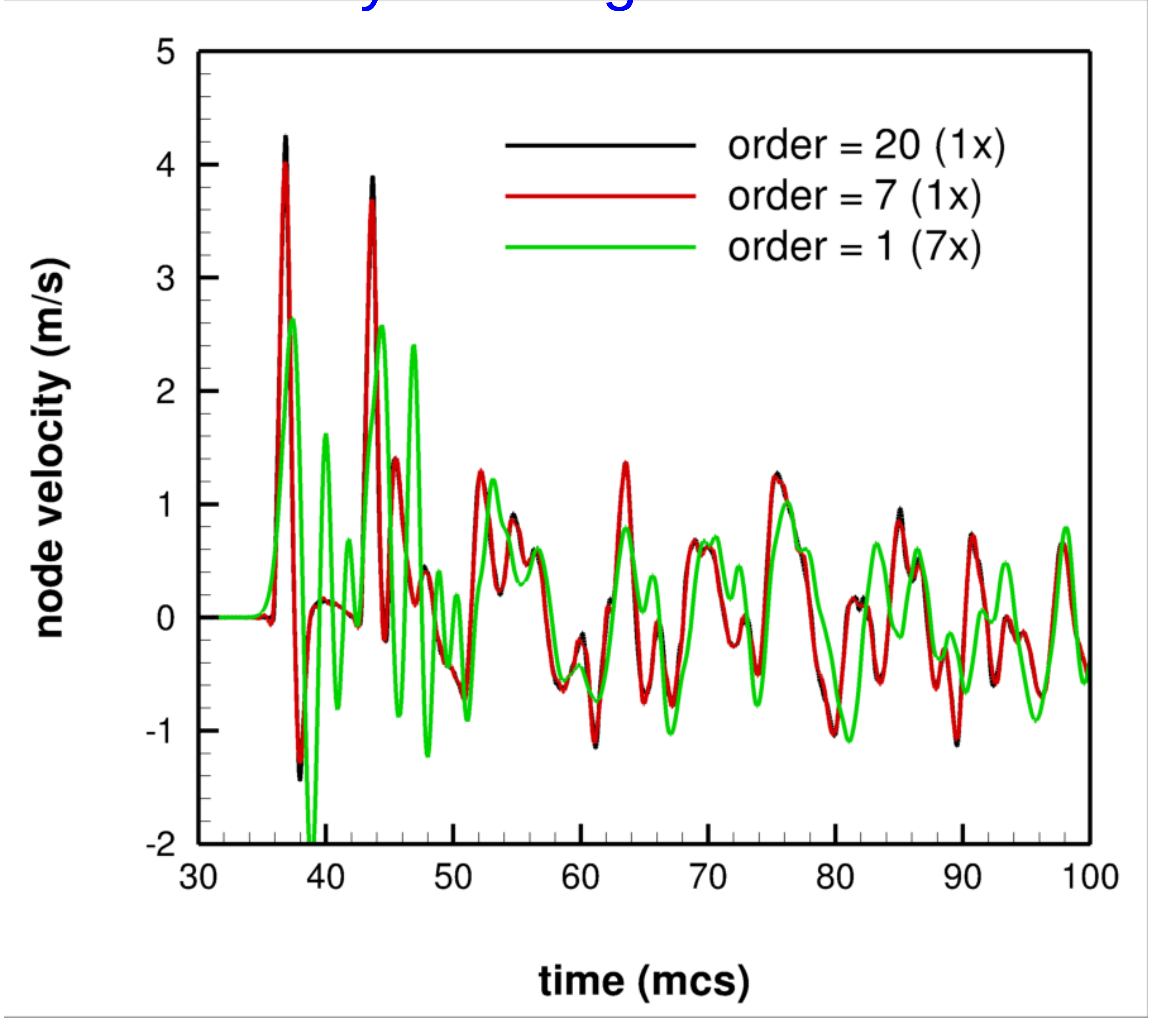

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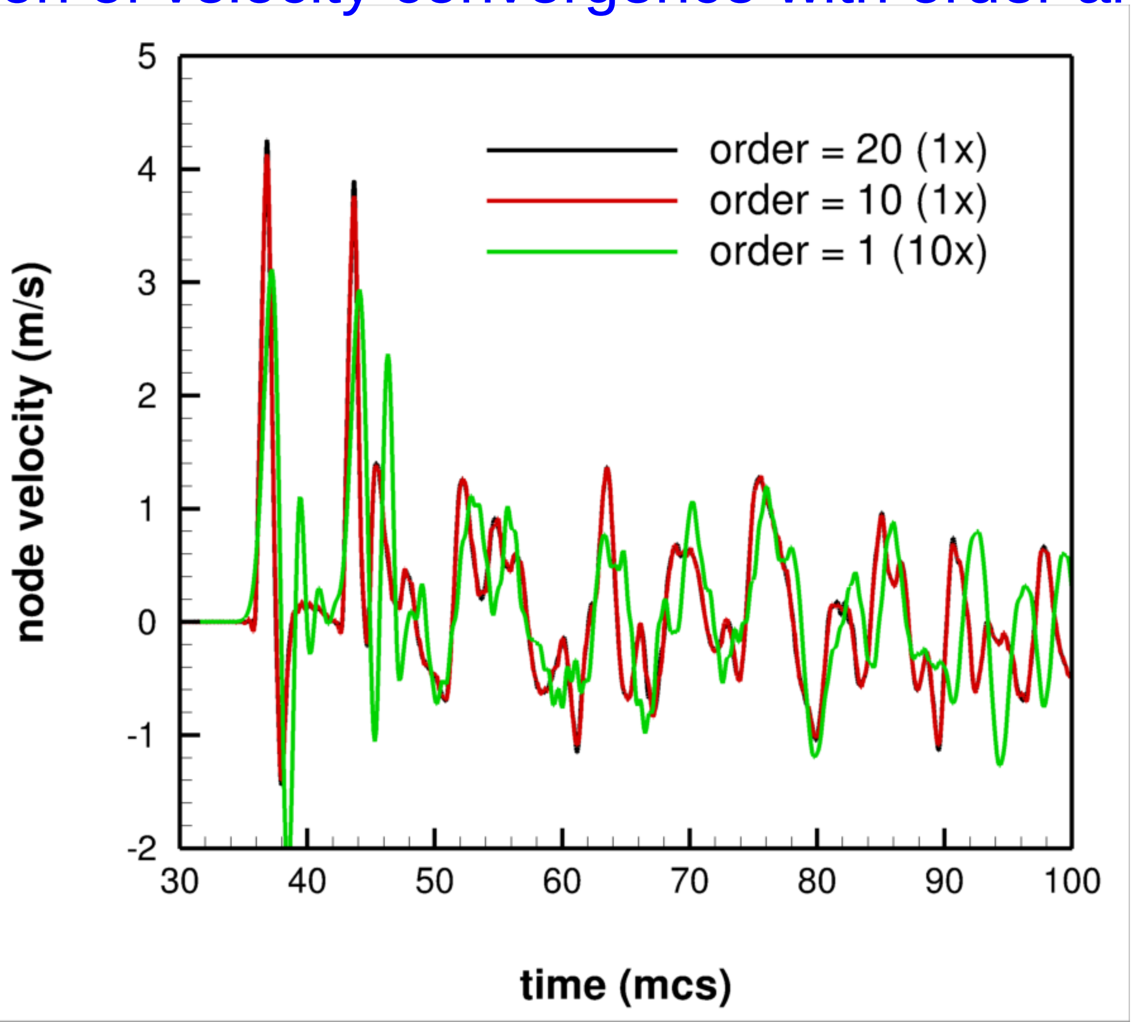

Wave propagation in 2-D axisymmetry

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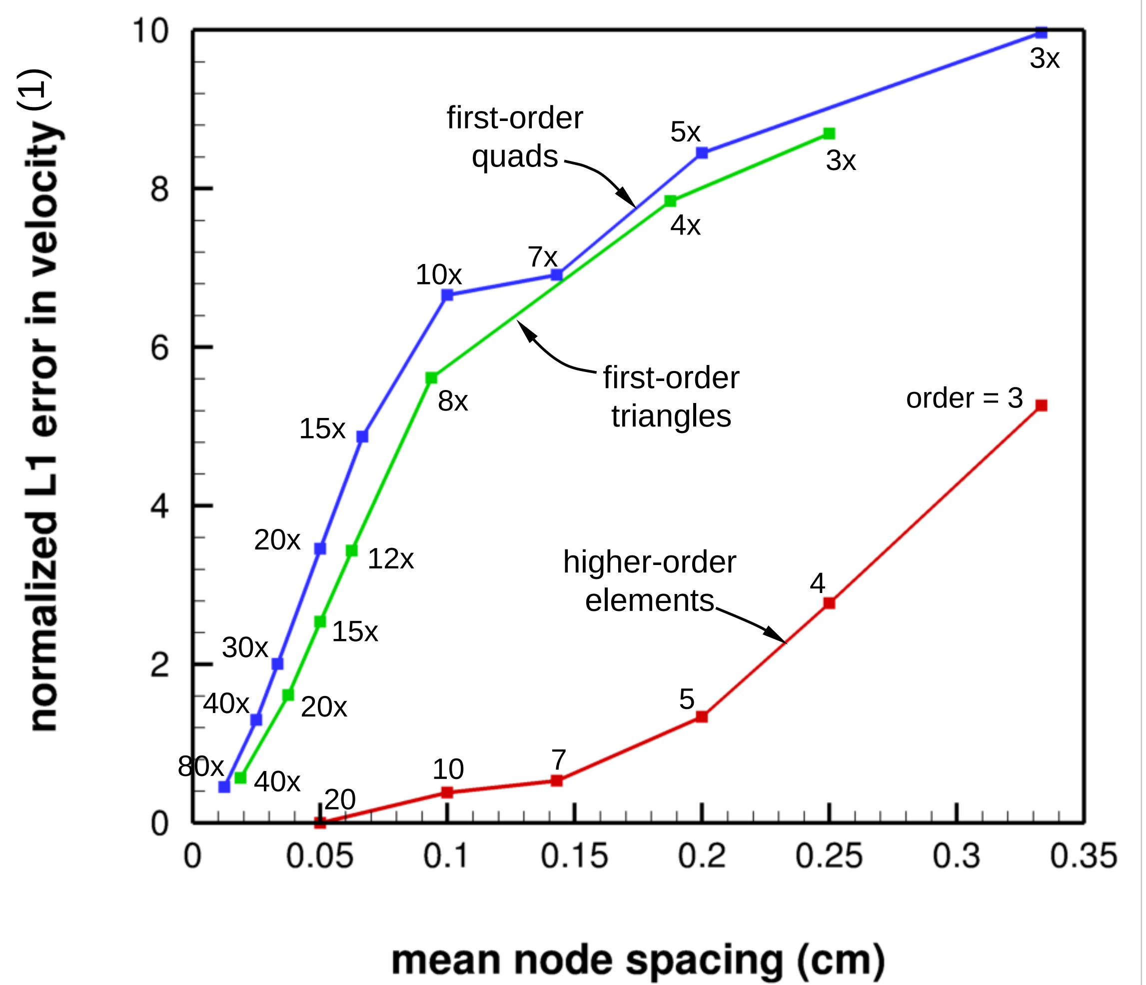
Summary of errors in velocity at node near top



(1) Errors relative to data from 20th-order elements for t = 0-100 μs

Wave propagation in 2-D axisymmetry

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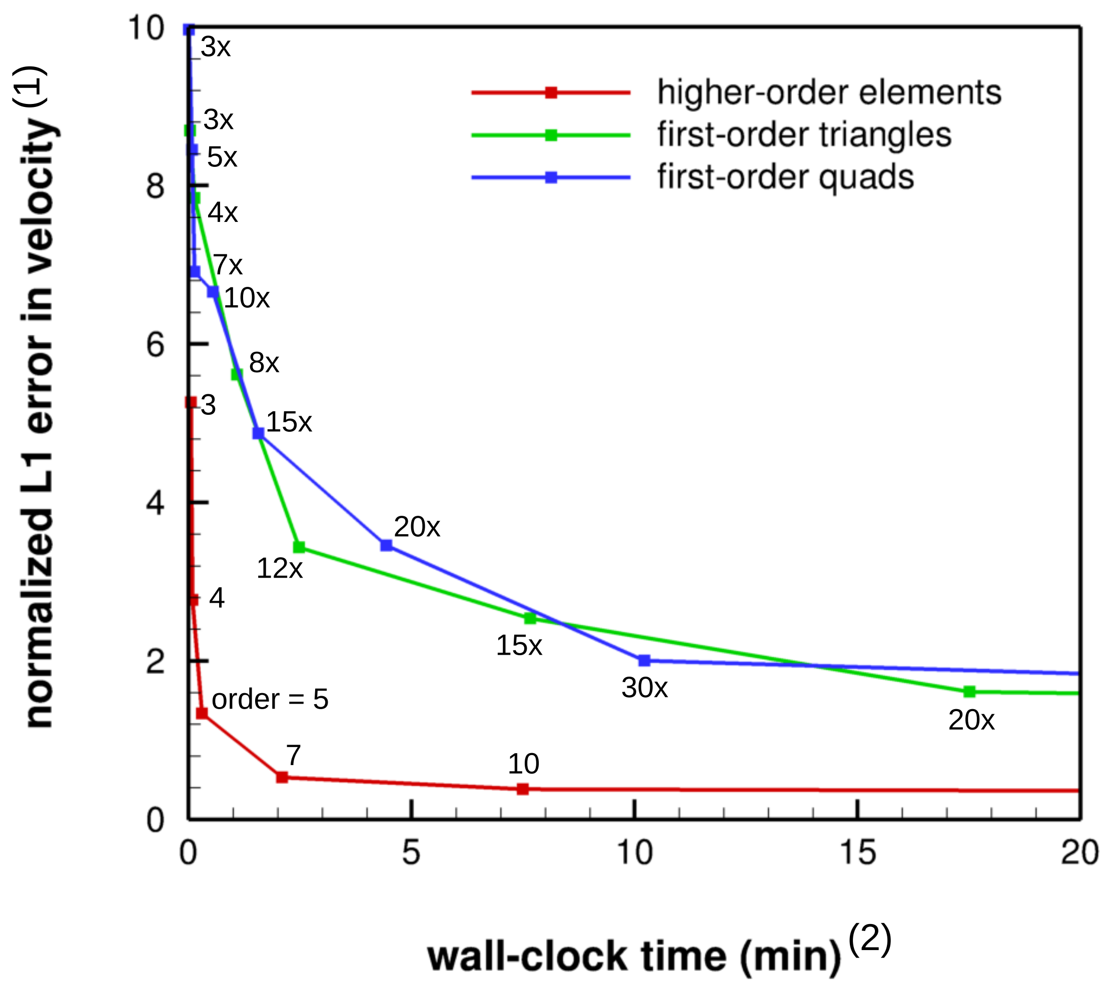

(1) Errors relative to data from 20th-order elements for t = 0-100 μs

(2) Intel Core i7: 2.93 GHz 15 GB RAM

Wave propagation in 2-D axisymmetry

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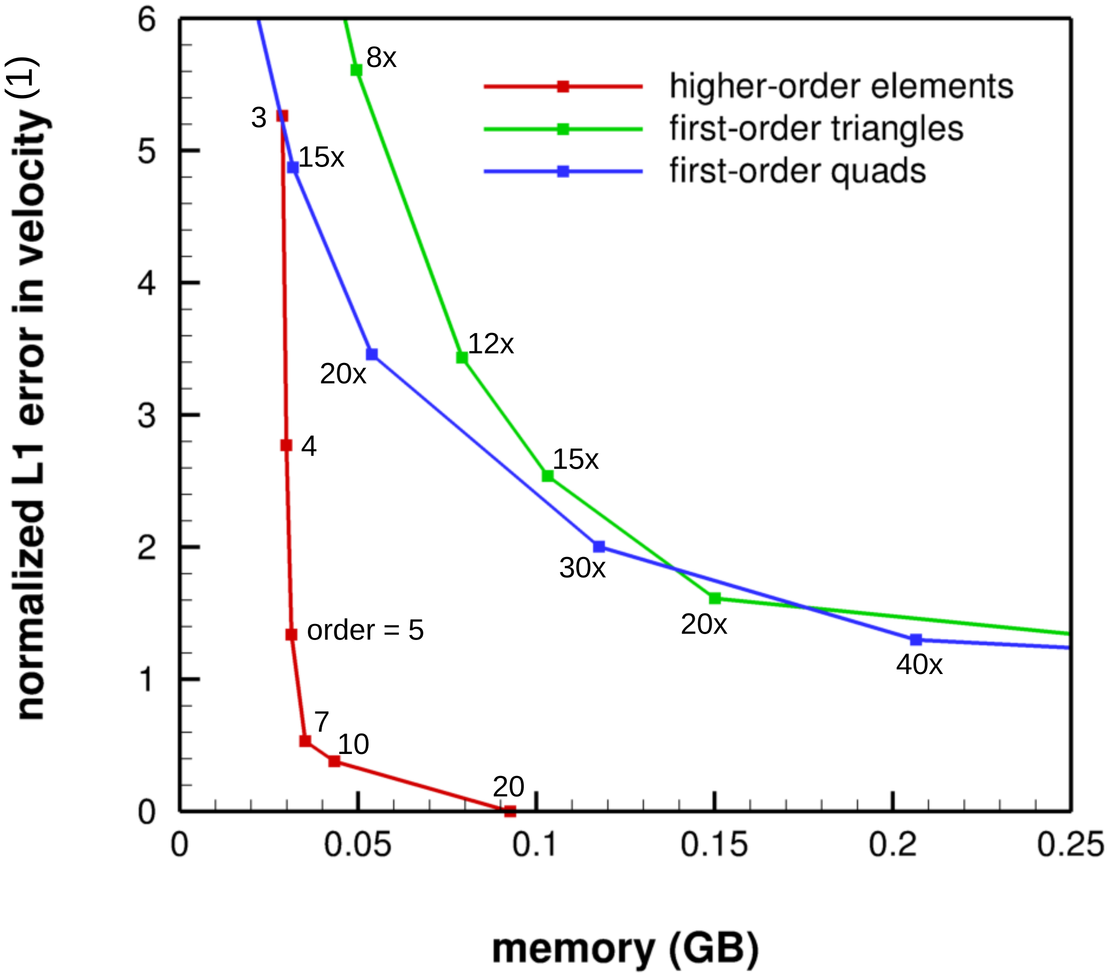
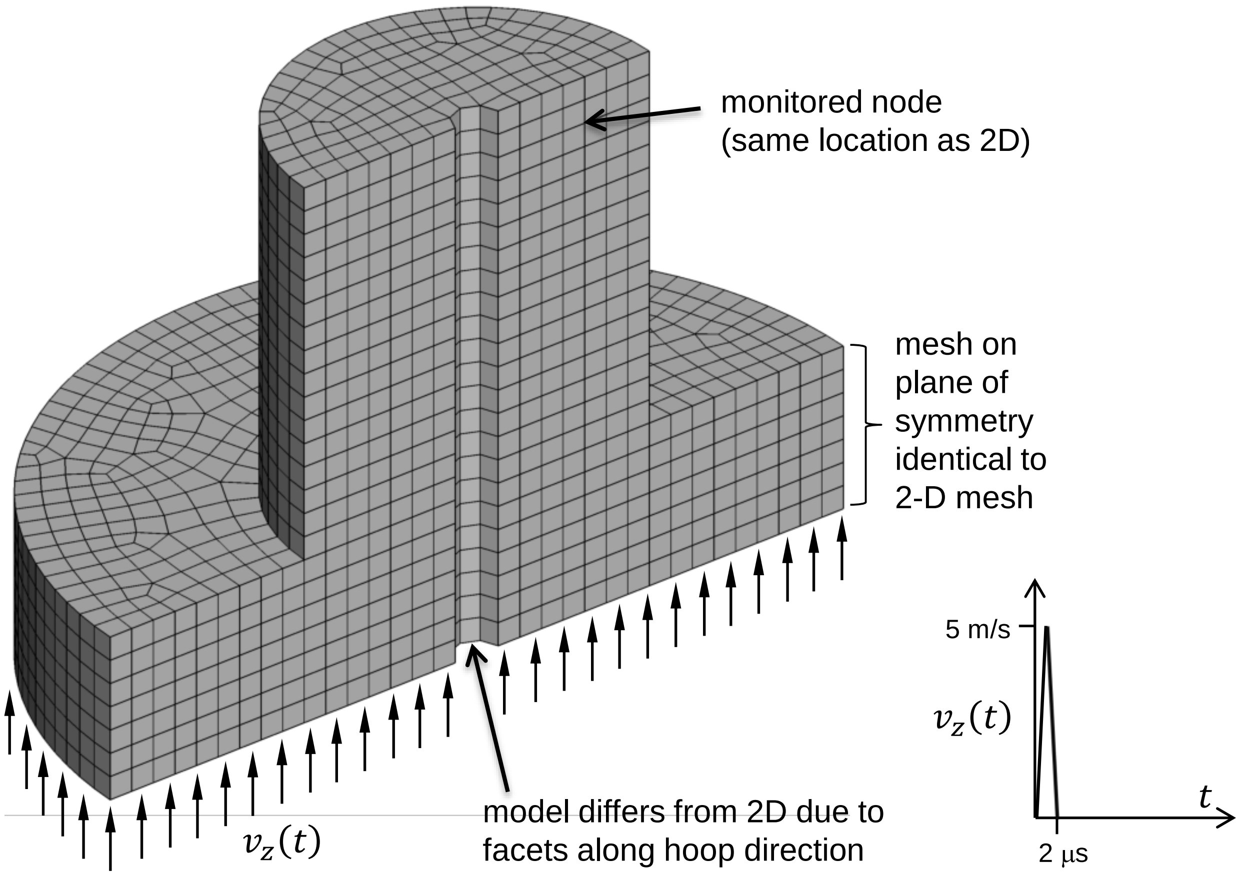


(1) Errors relative to data from 20th-order elements for t = 0-100 μs

Wave propagation in 3D

Baseline mesh of simple part loaded by a pulse



Wave propagation in 3D

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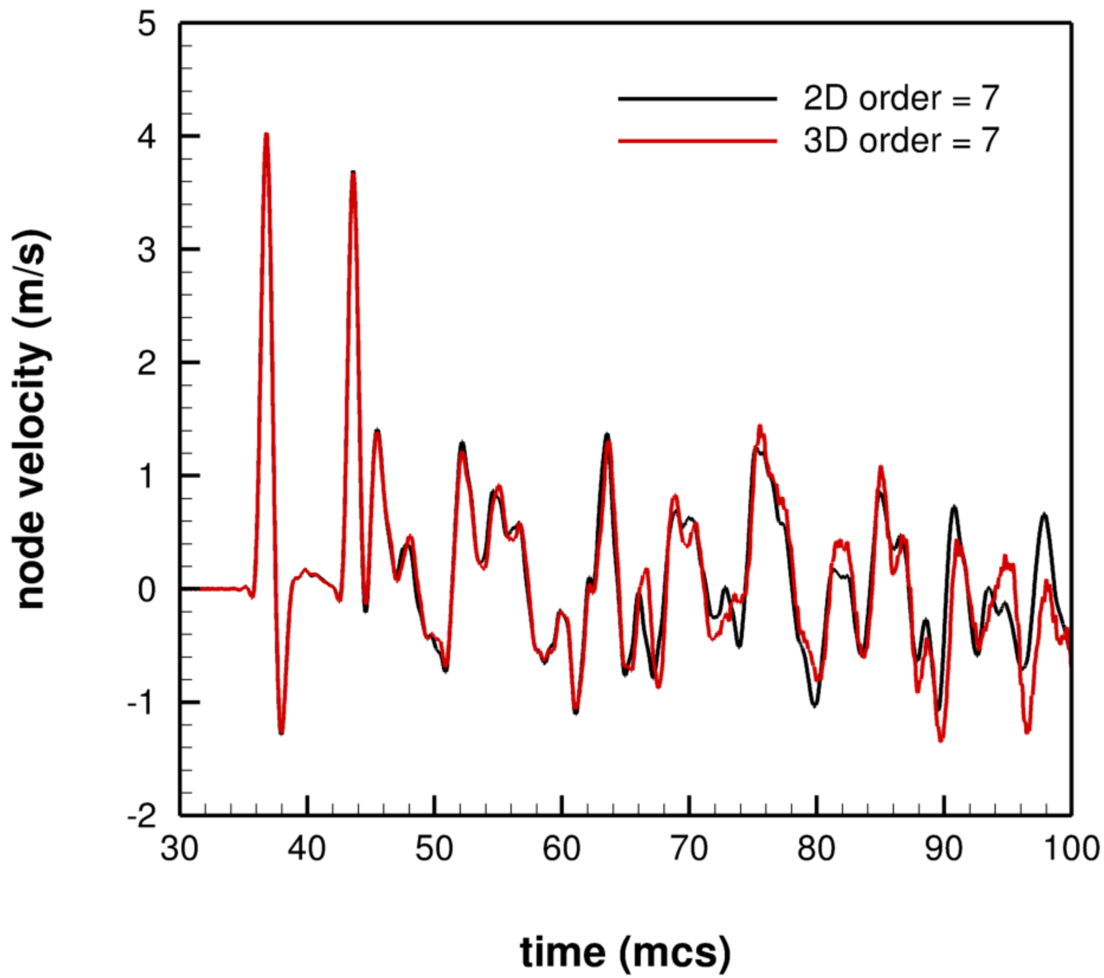
Comparison of 2-D and 3-D node velocities



Wave propagation in 3D

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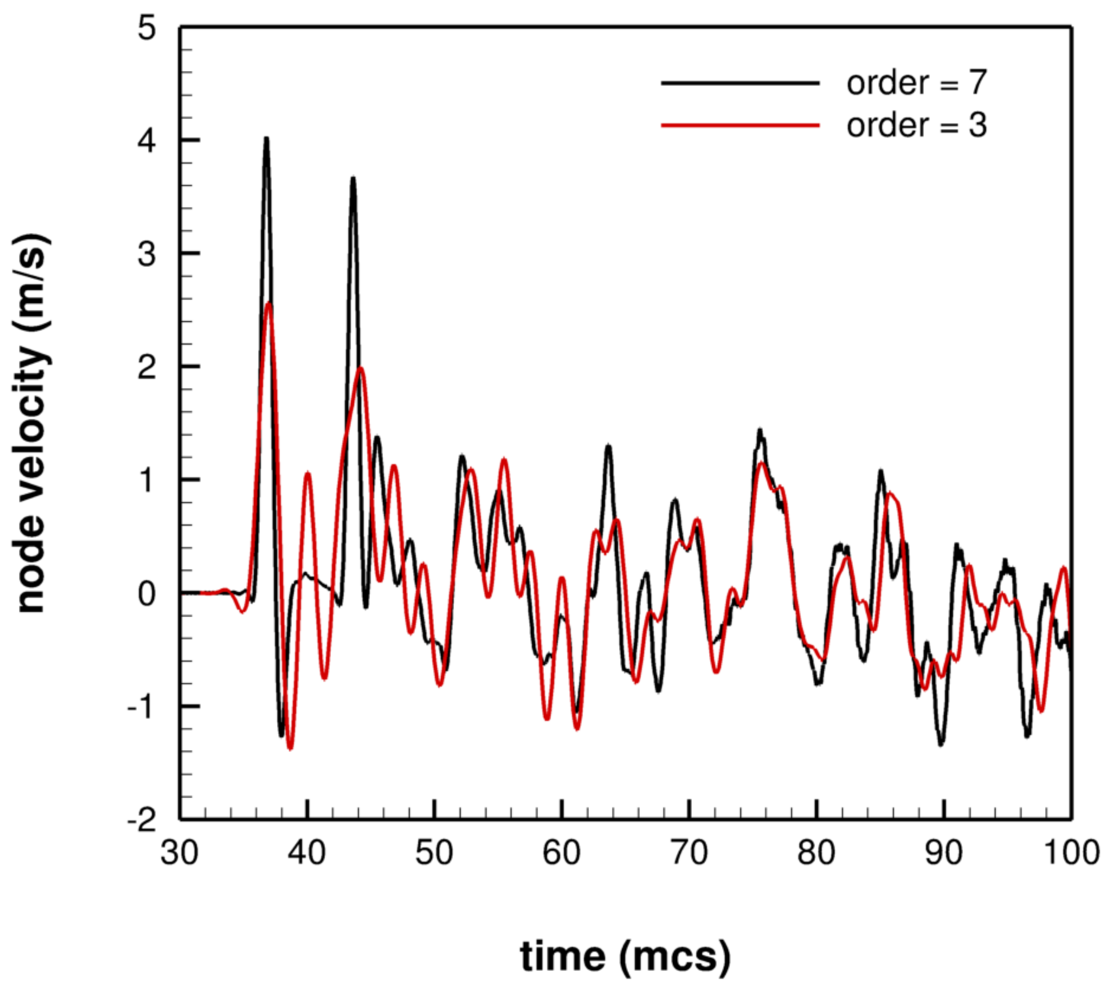
Convergence of top-node velocity with element order



Wave propagation in 3D

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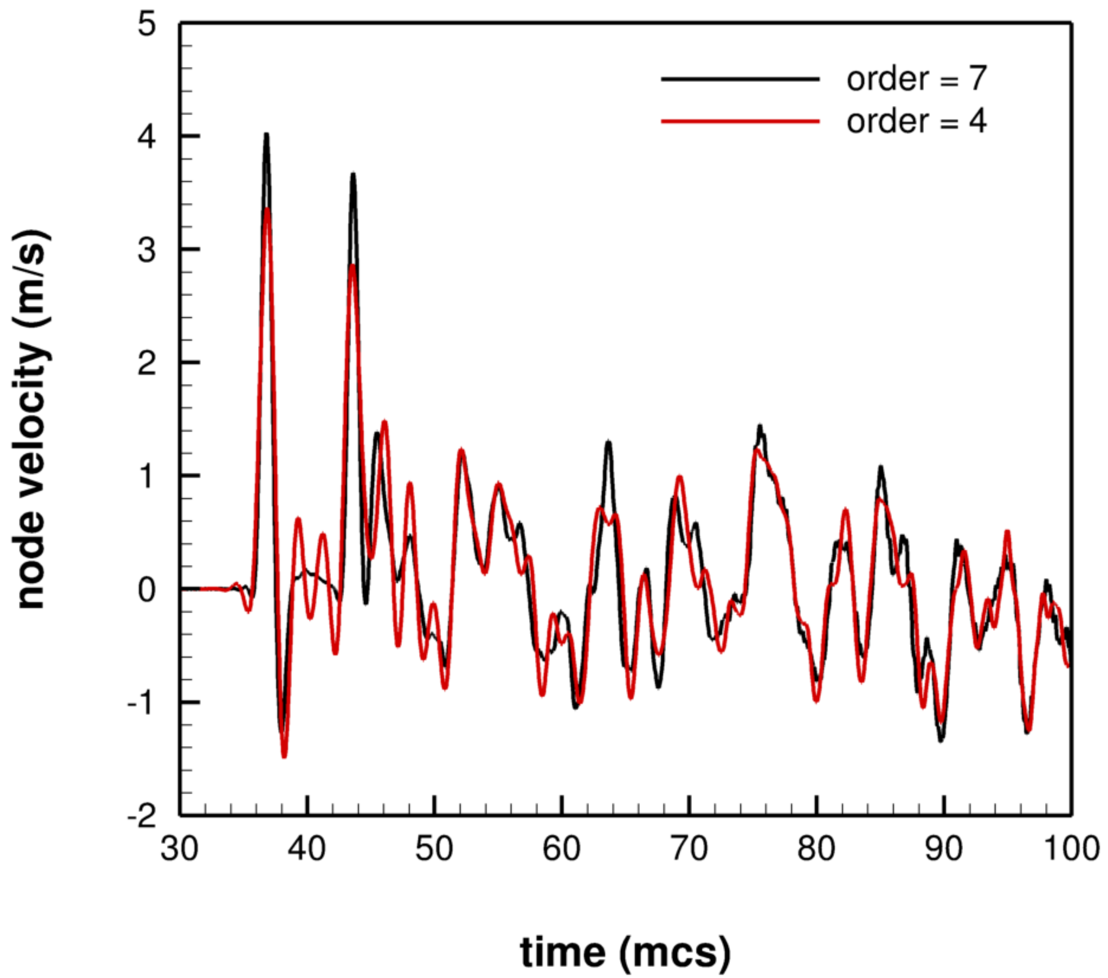

Wave propagation in 3D

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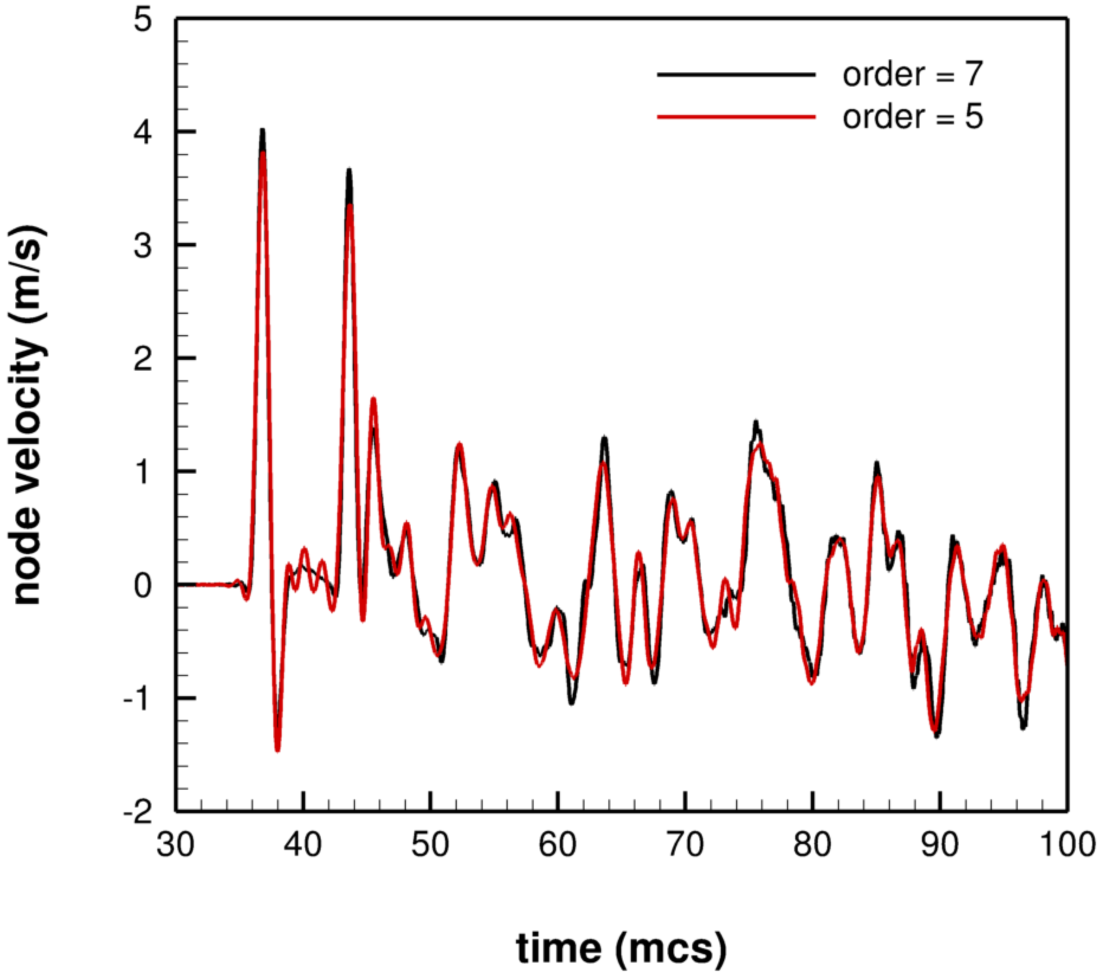

Wave propagation in 3D

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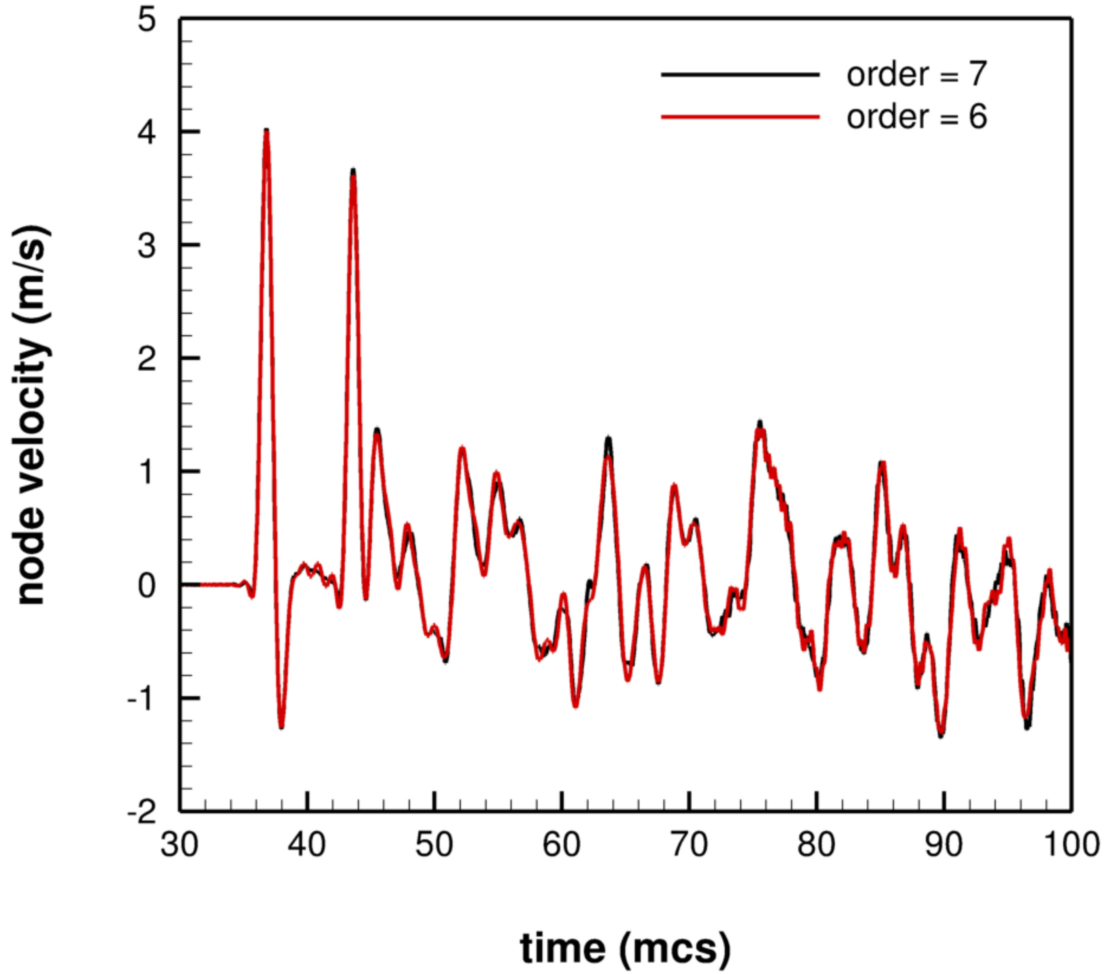

Wave propagation in 3D

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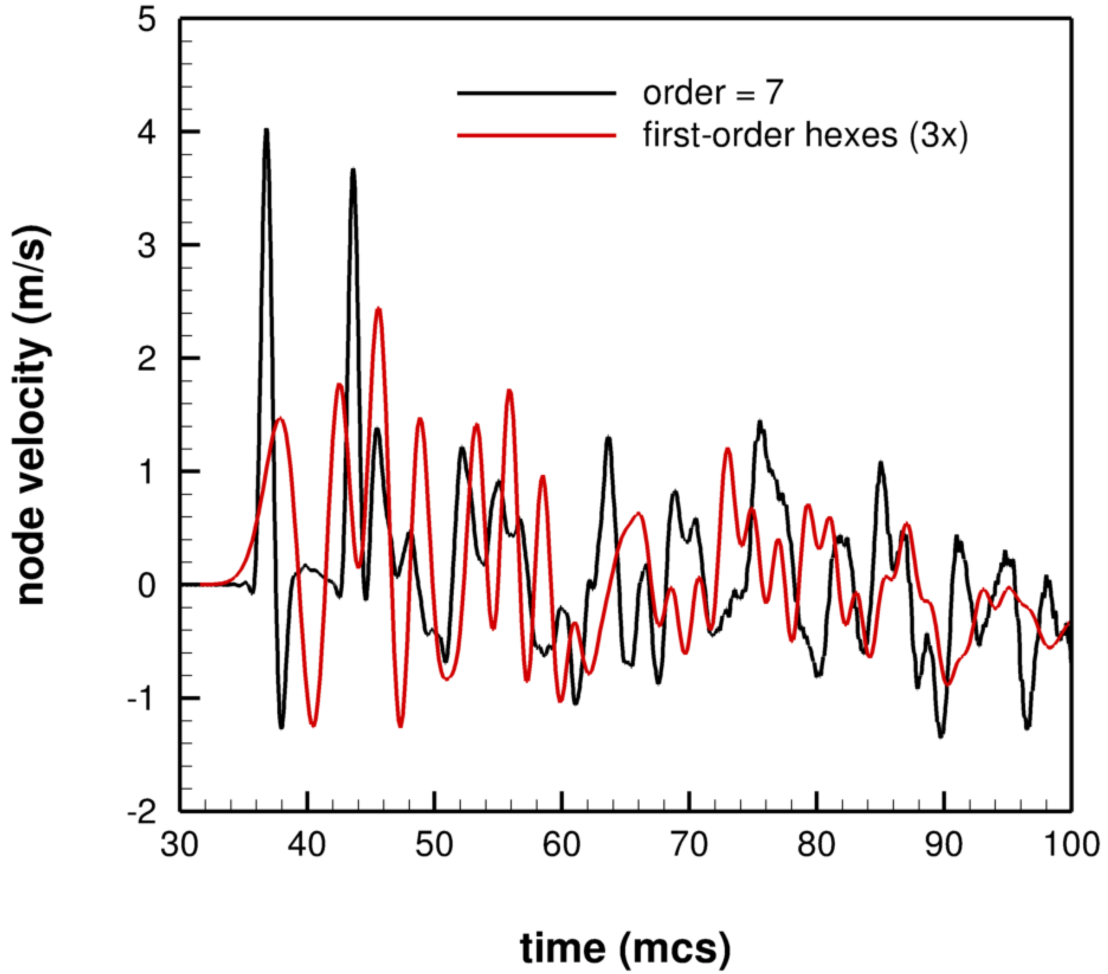
Convergence of top-node velocity with refinement of first-order hexes



Wave propagation in 3D

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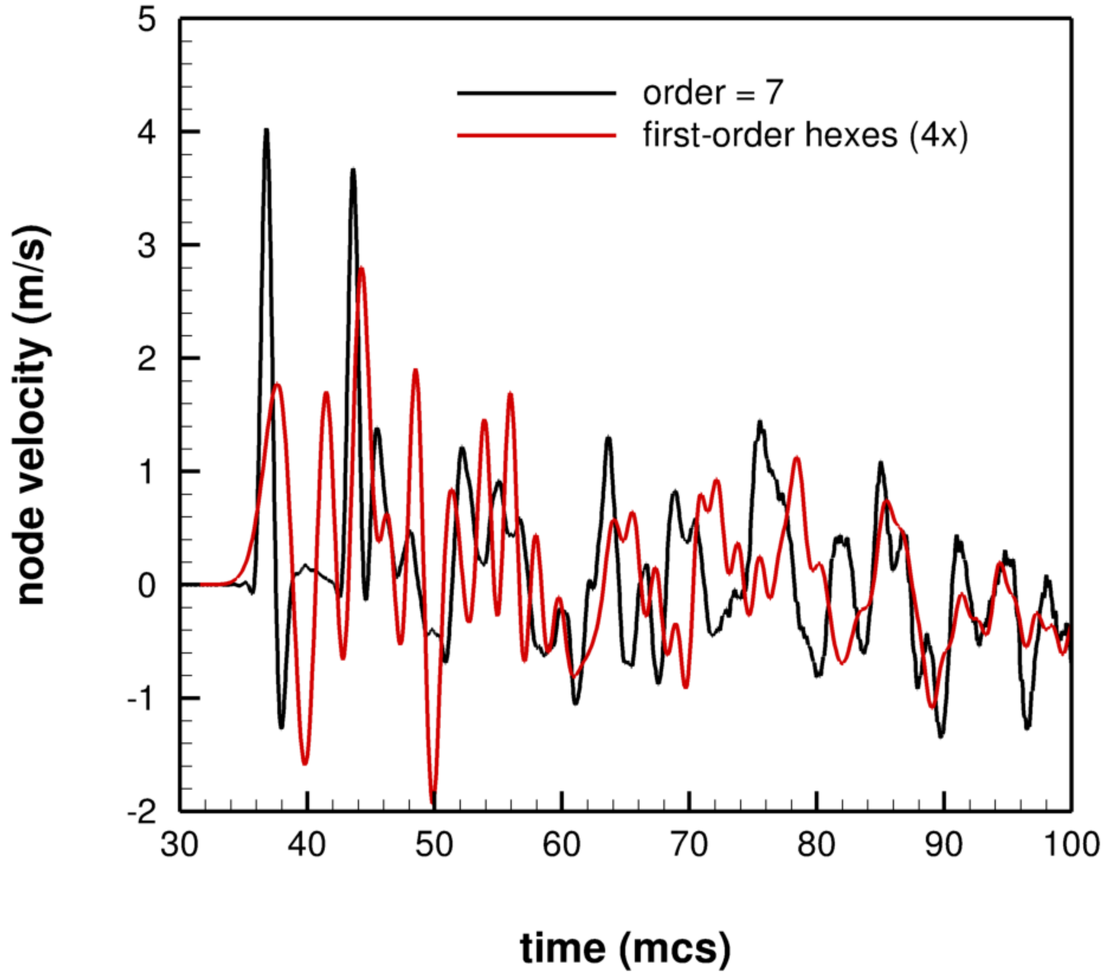

Wave propagation in 3D

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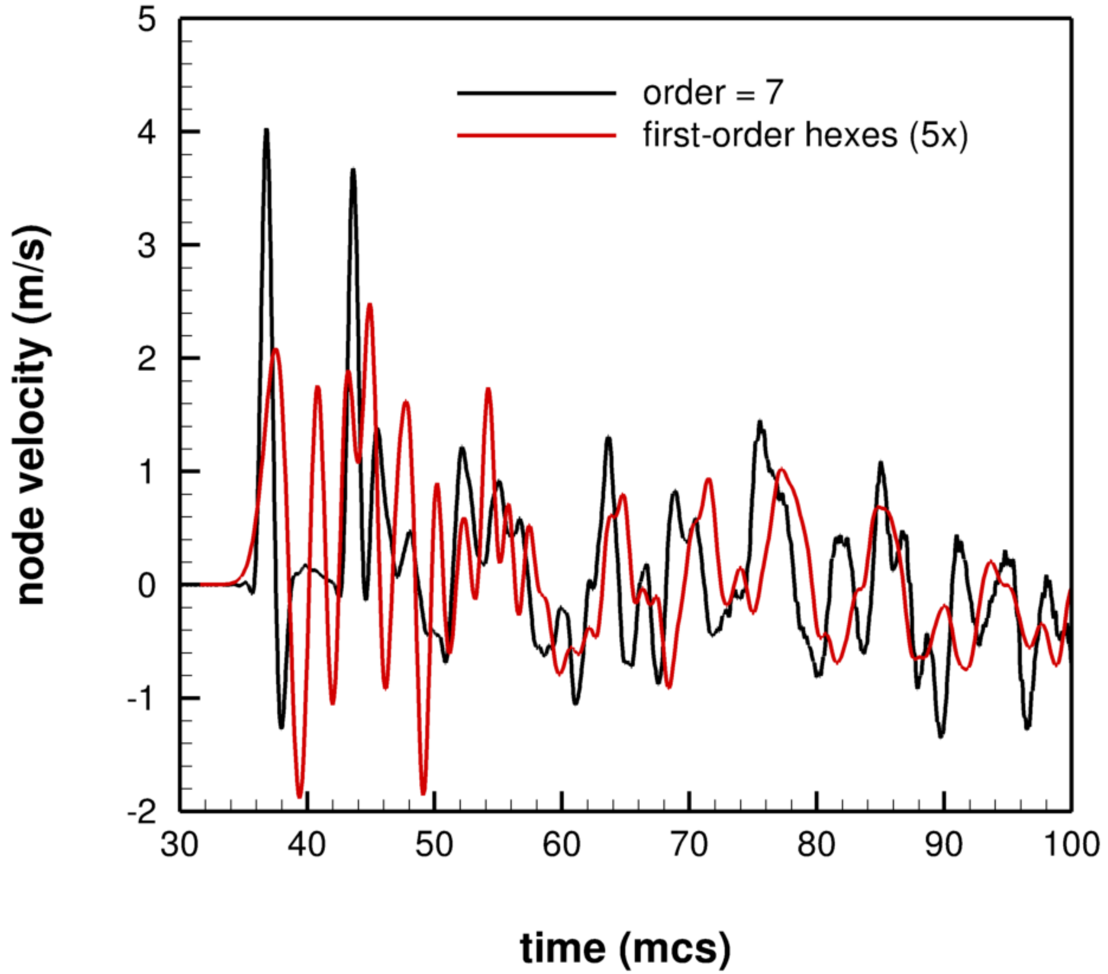

Wave propagation in 3D

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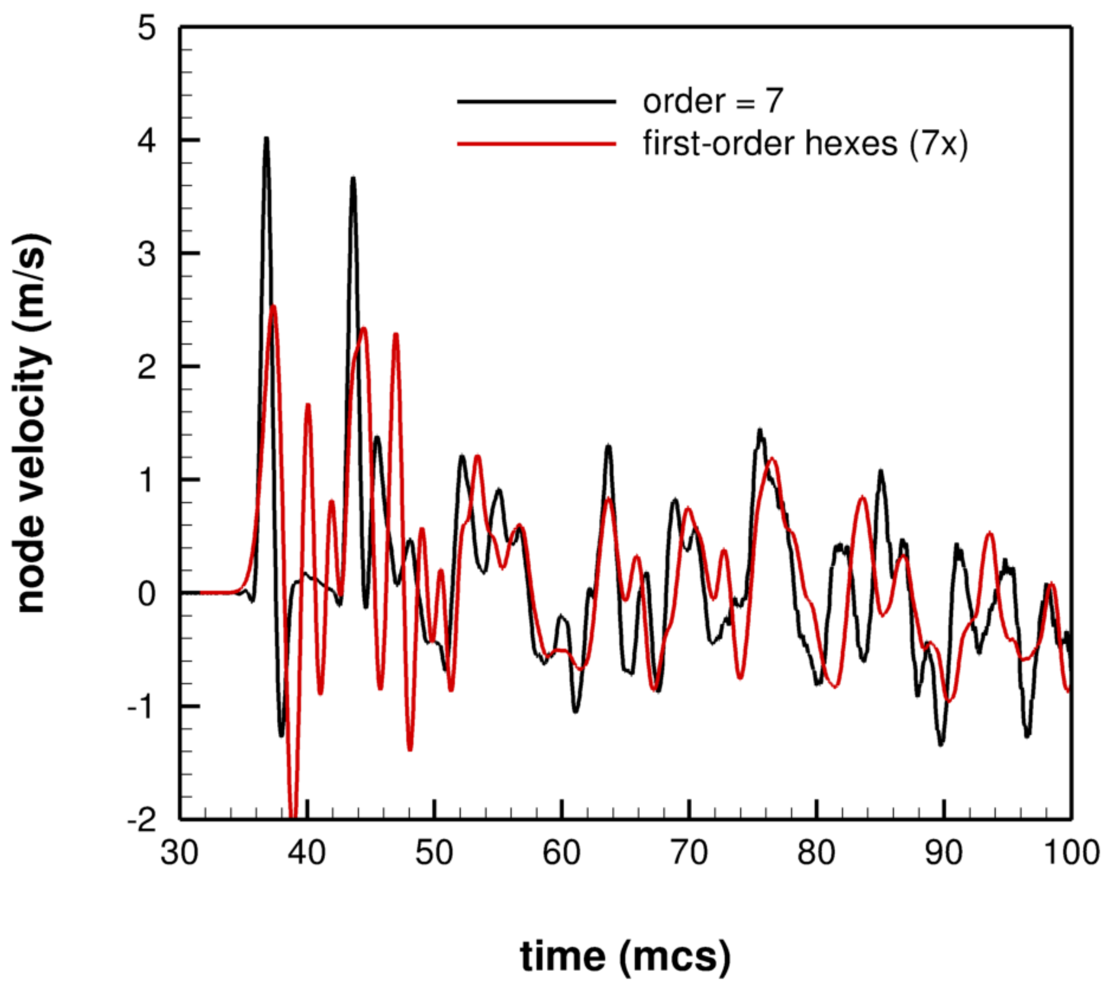

Wave propagation in 3D

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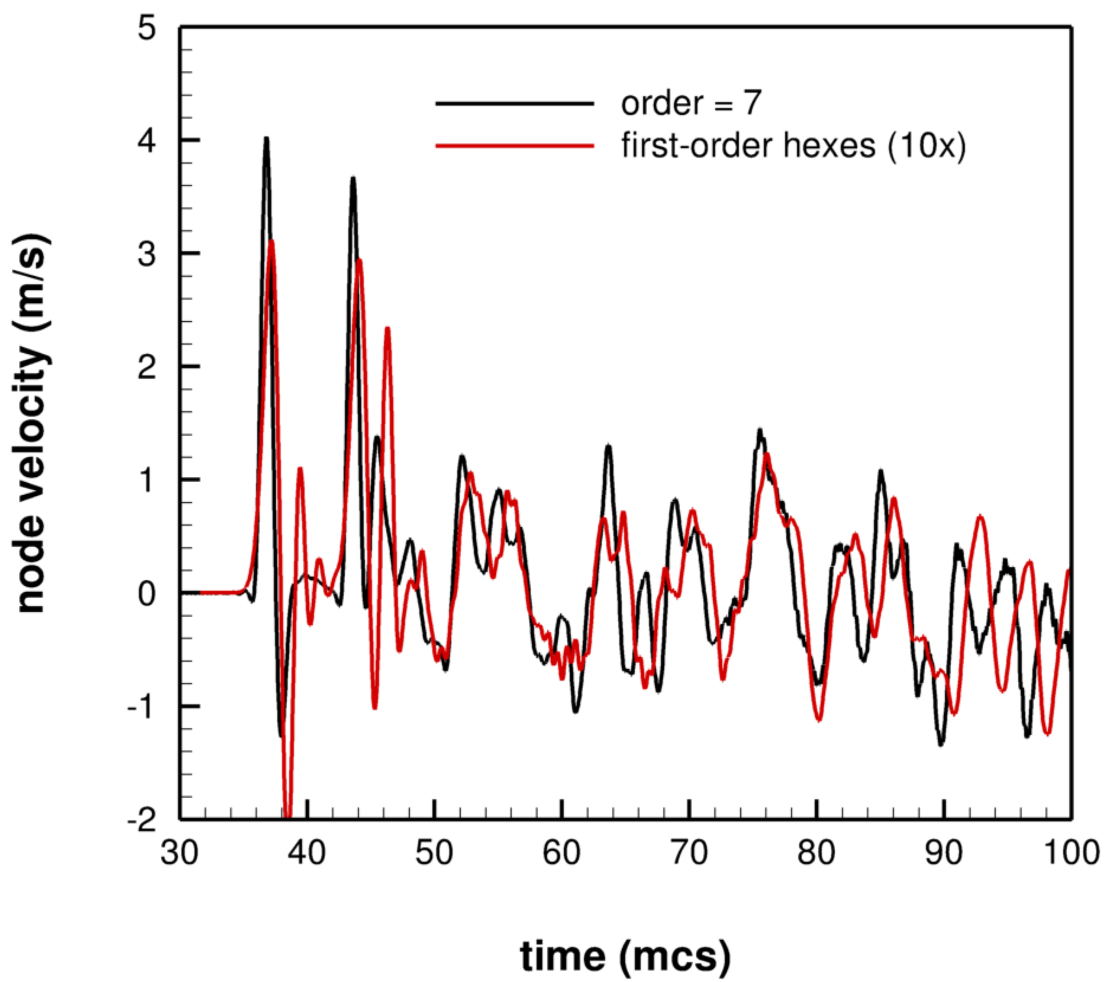

Wave propagation in 3D

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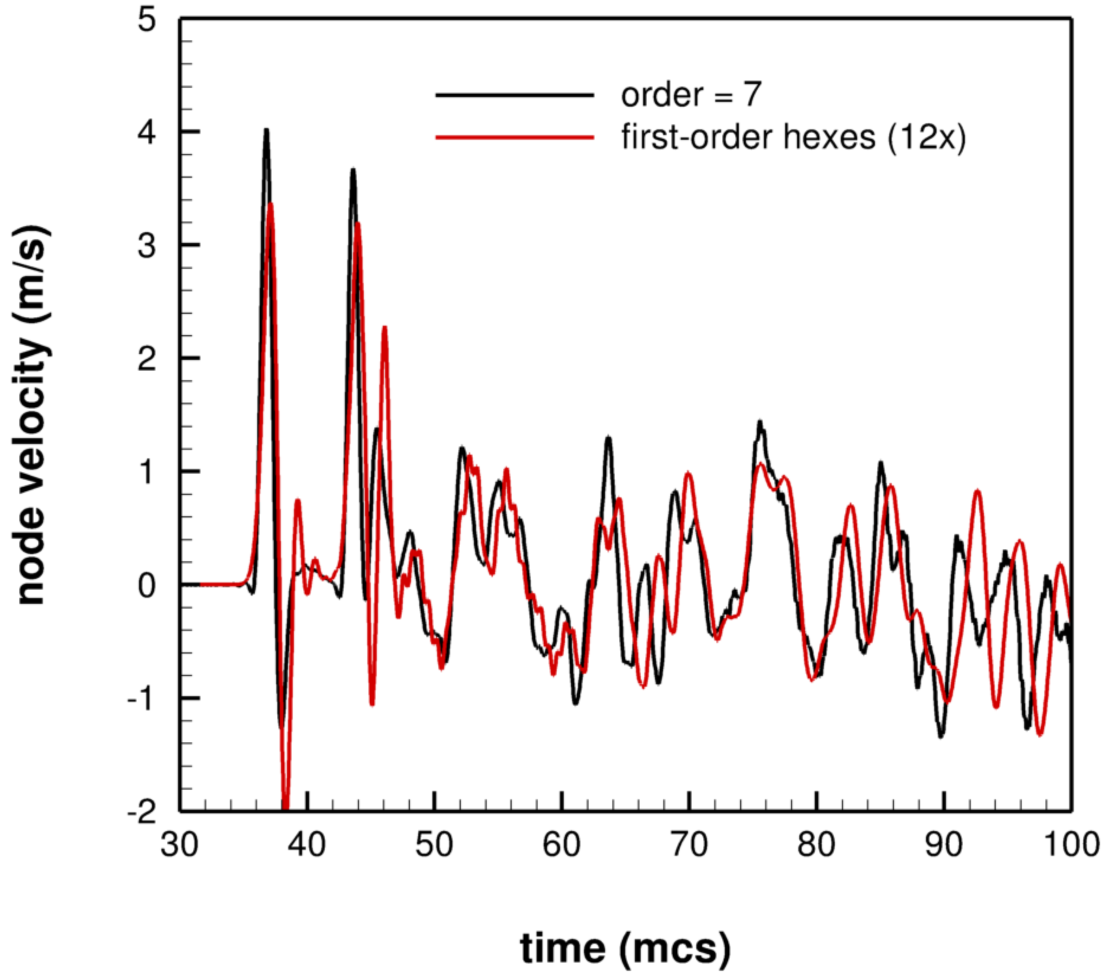

Wave propagation in 3D

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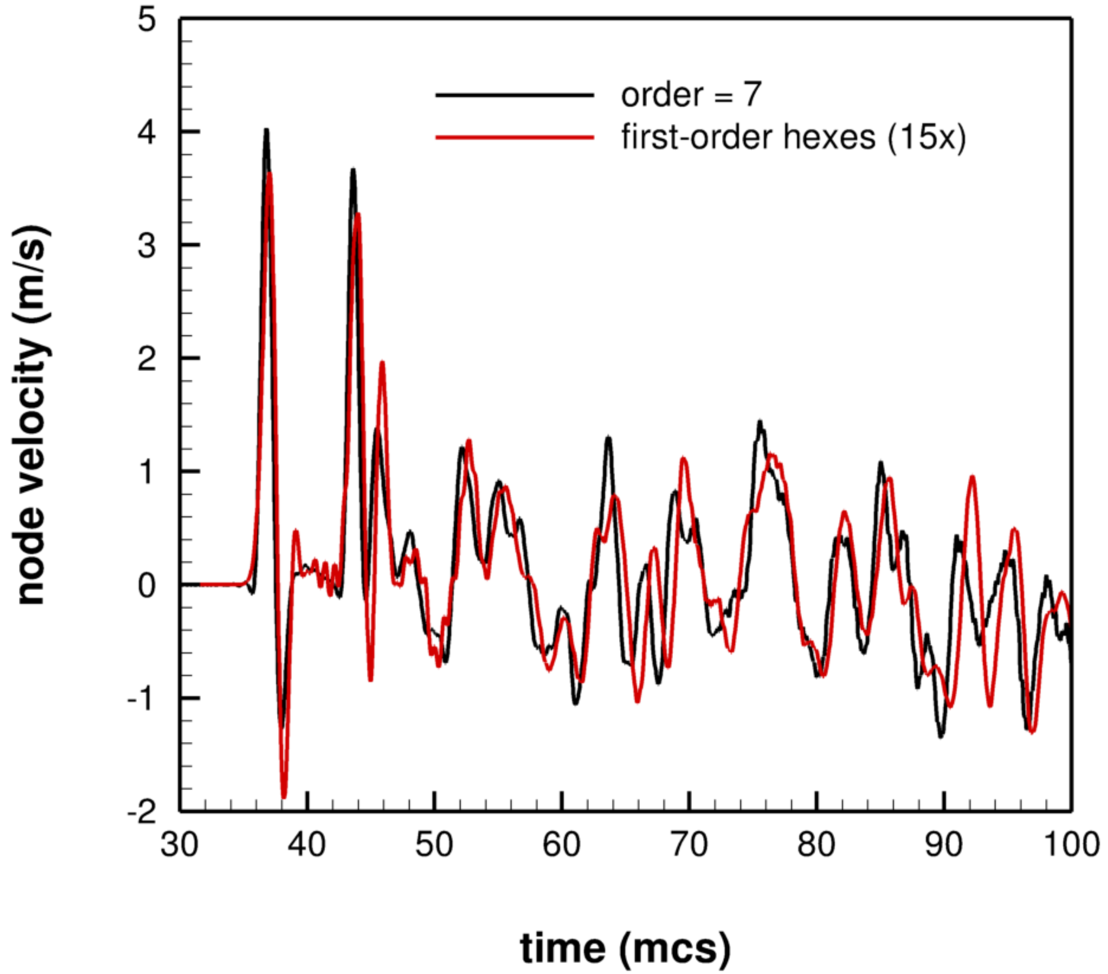

Wave propagation in 3D

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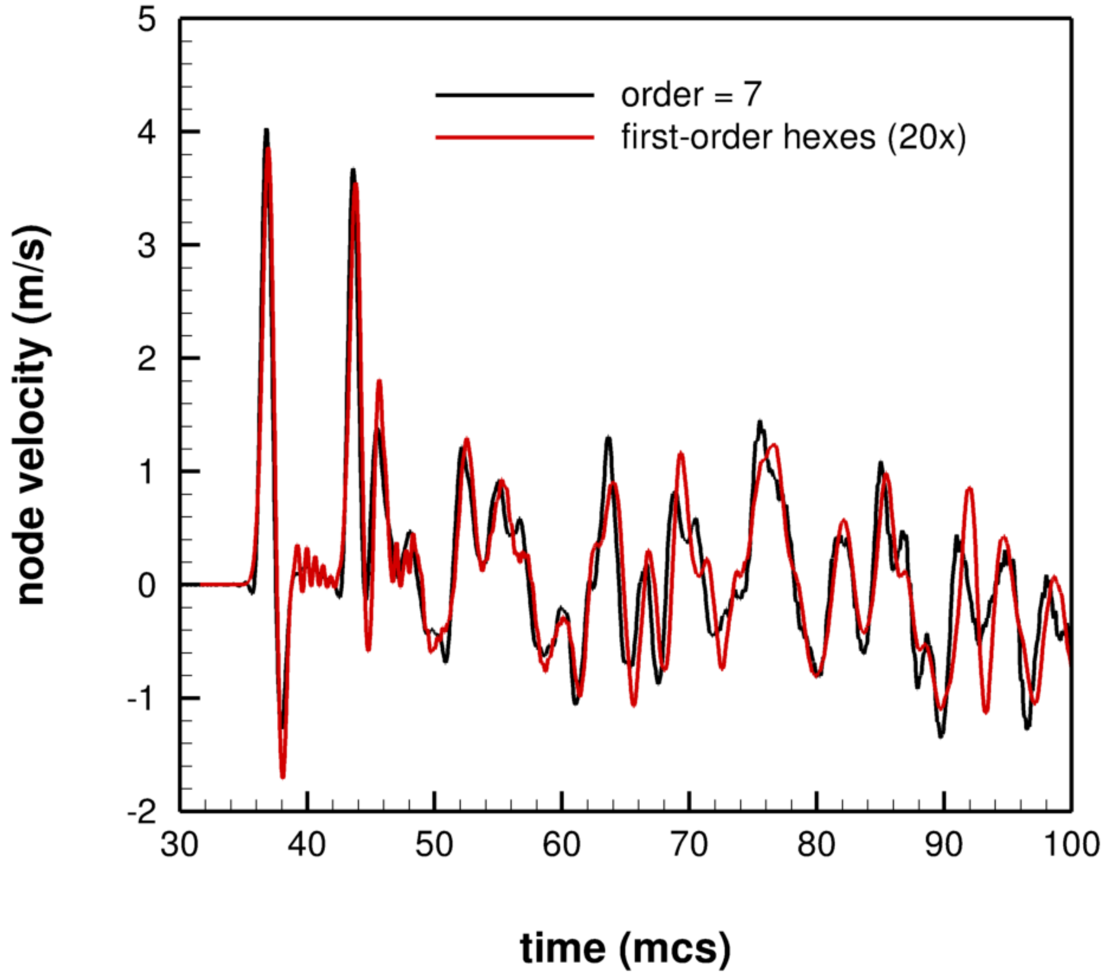

Wave propagation in 3D

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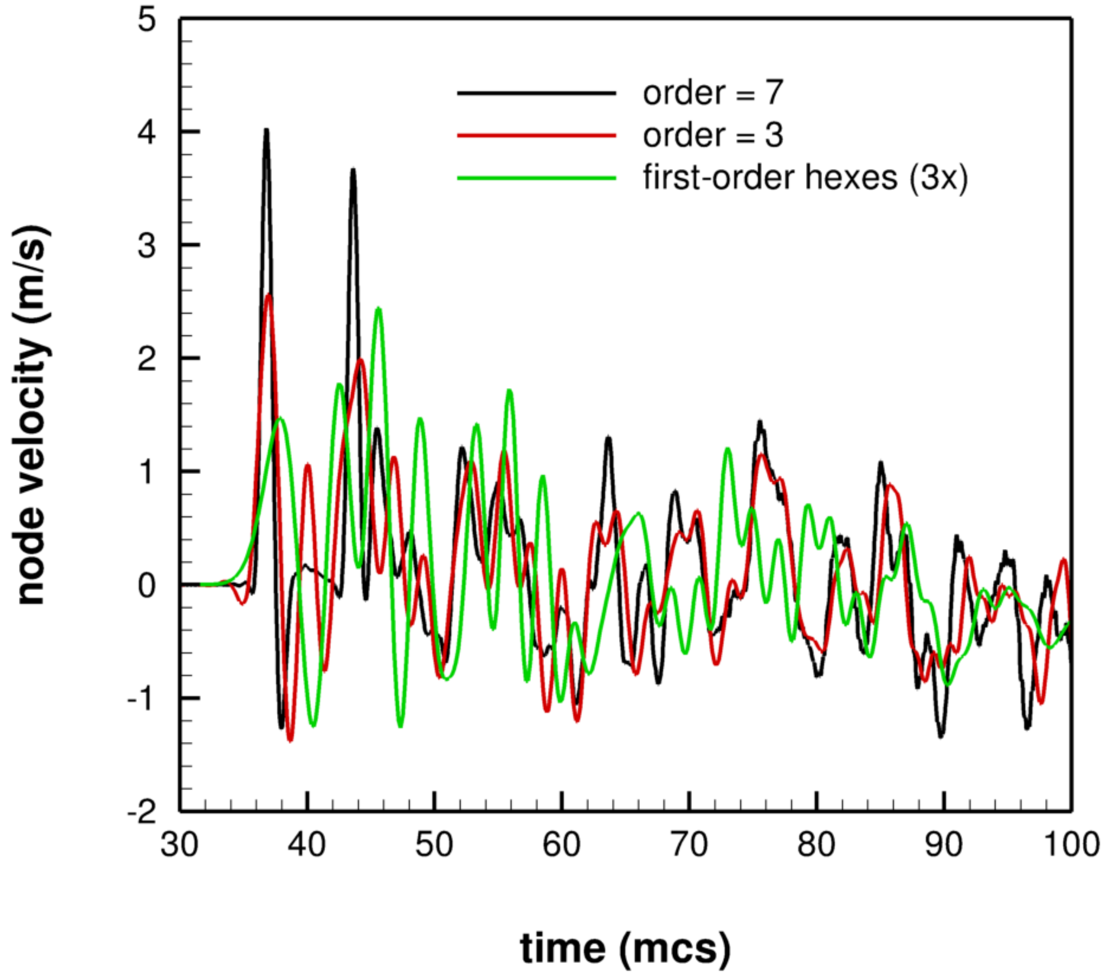

Wave propagation in 3D

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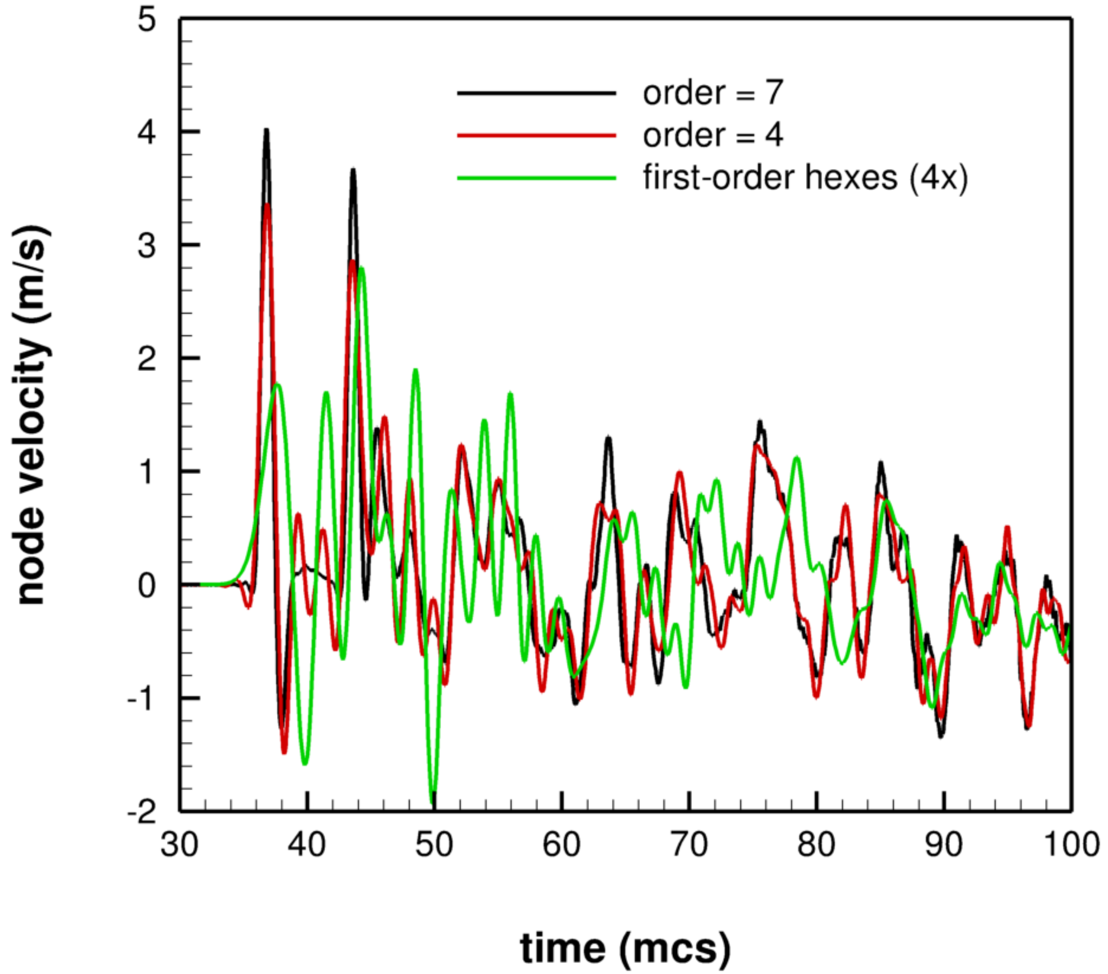

Wave propagation in 3D

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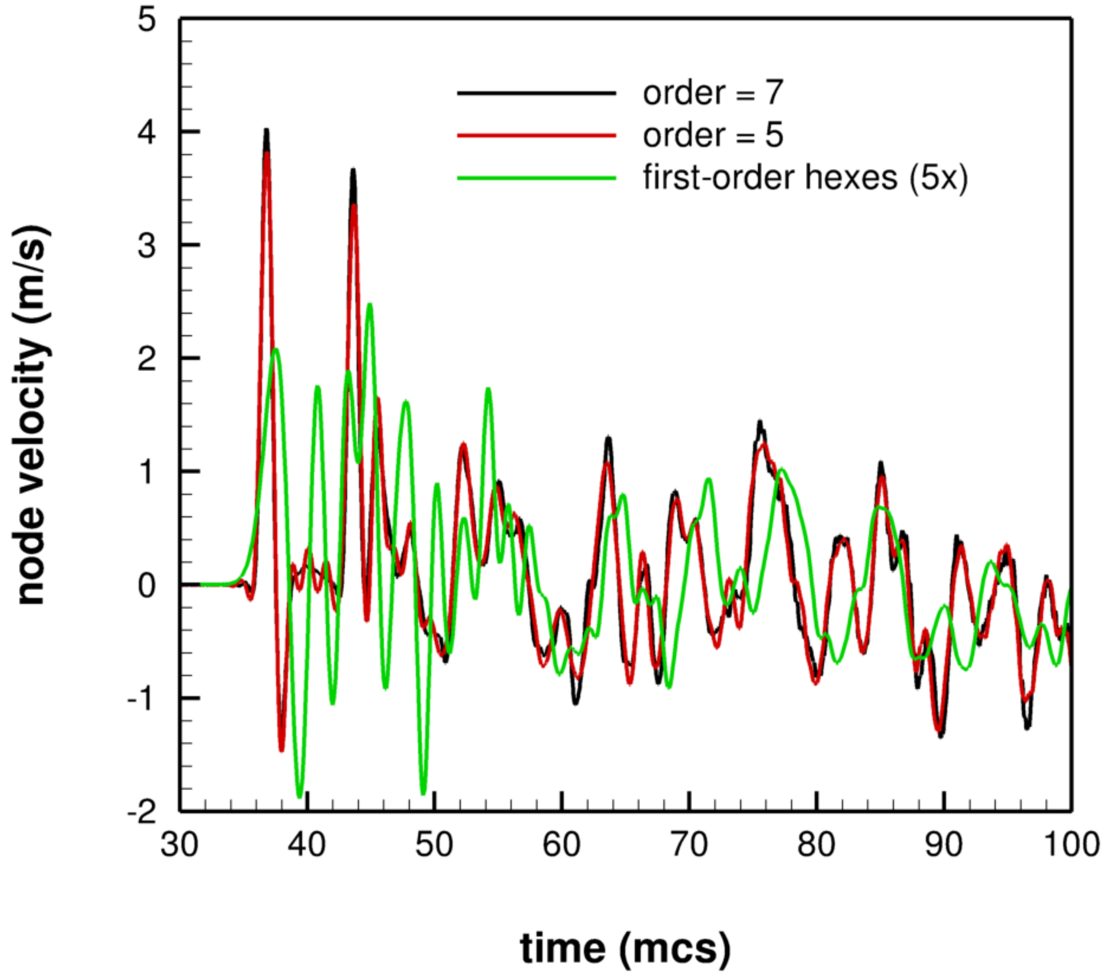
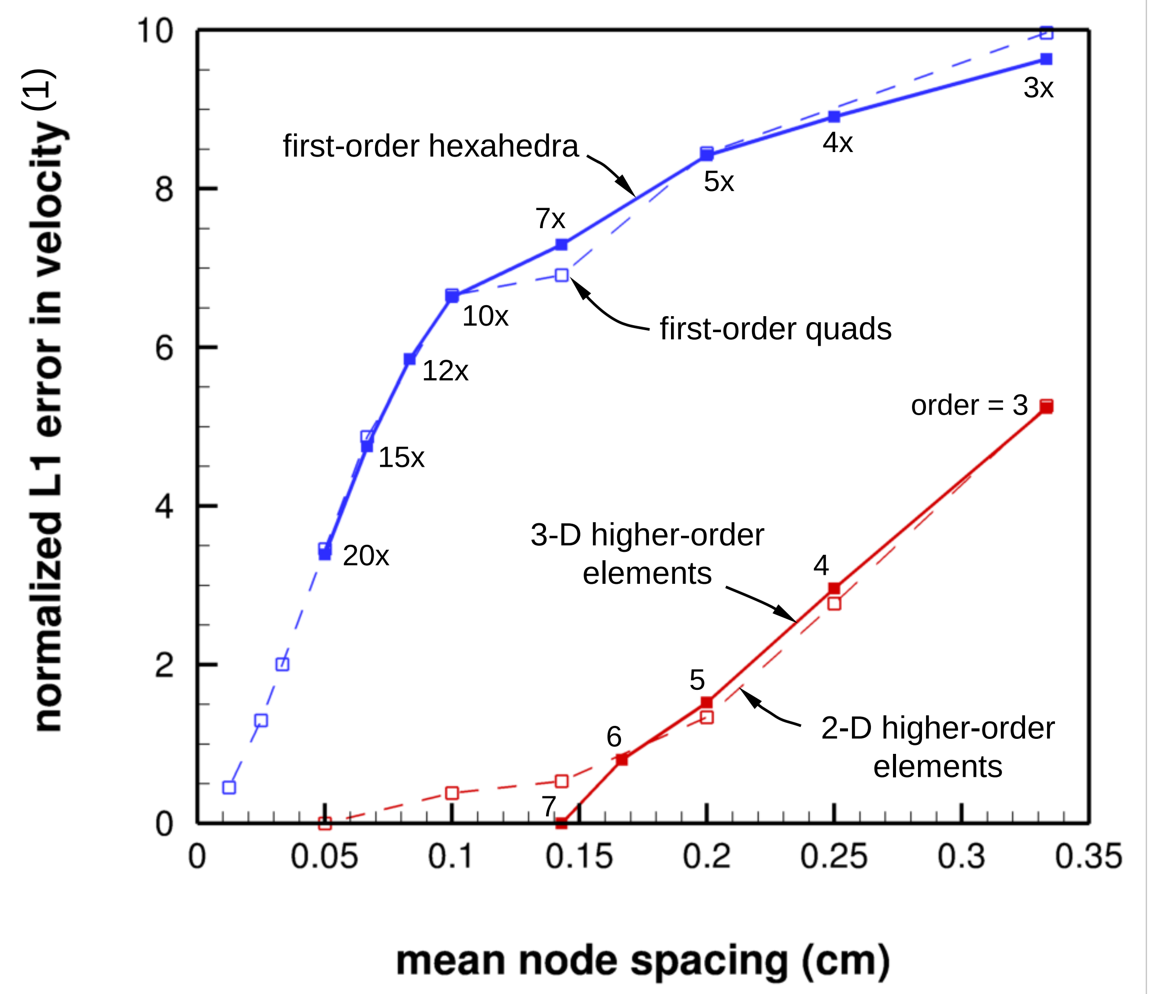


Wave propagation in 3D

Summary of velocity errors at monitored node



(1) Errors relative to data from 7th-order elements for t = 0-100 µs

Wave propagation in 3D

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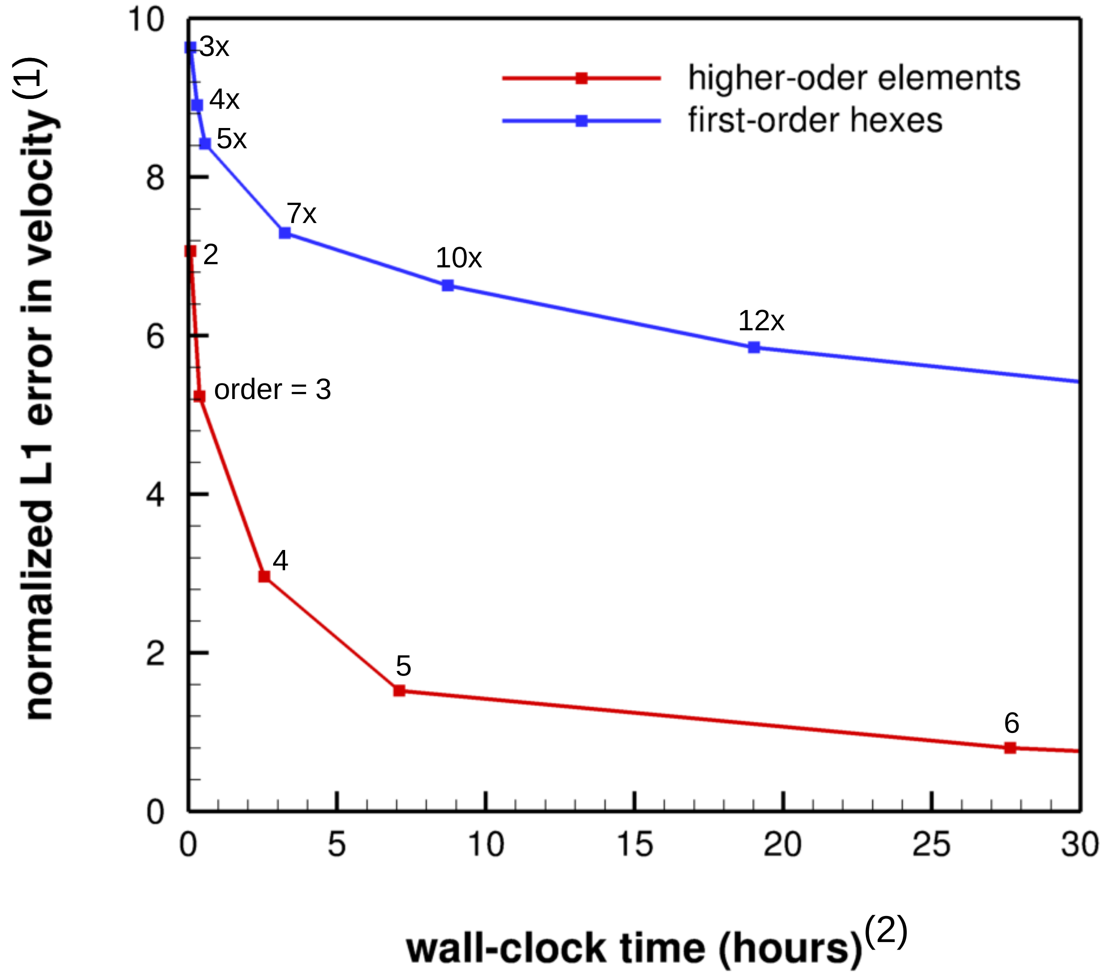
Summary of velocity errors at monitored node

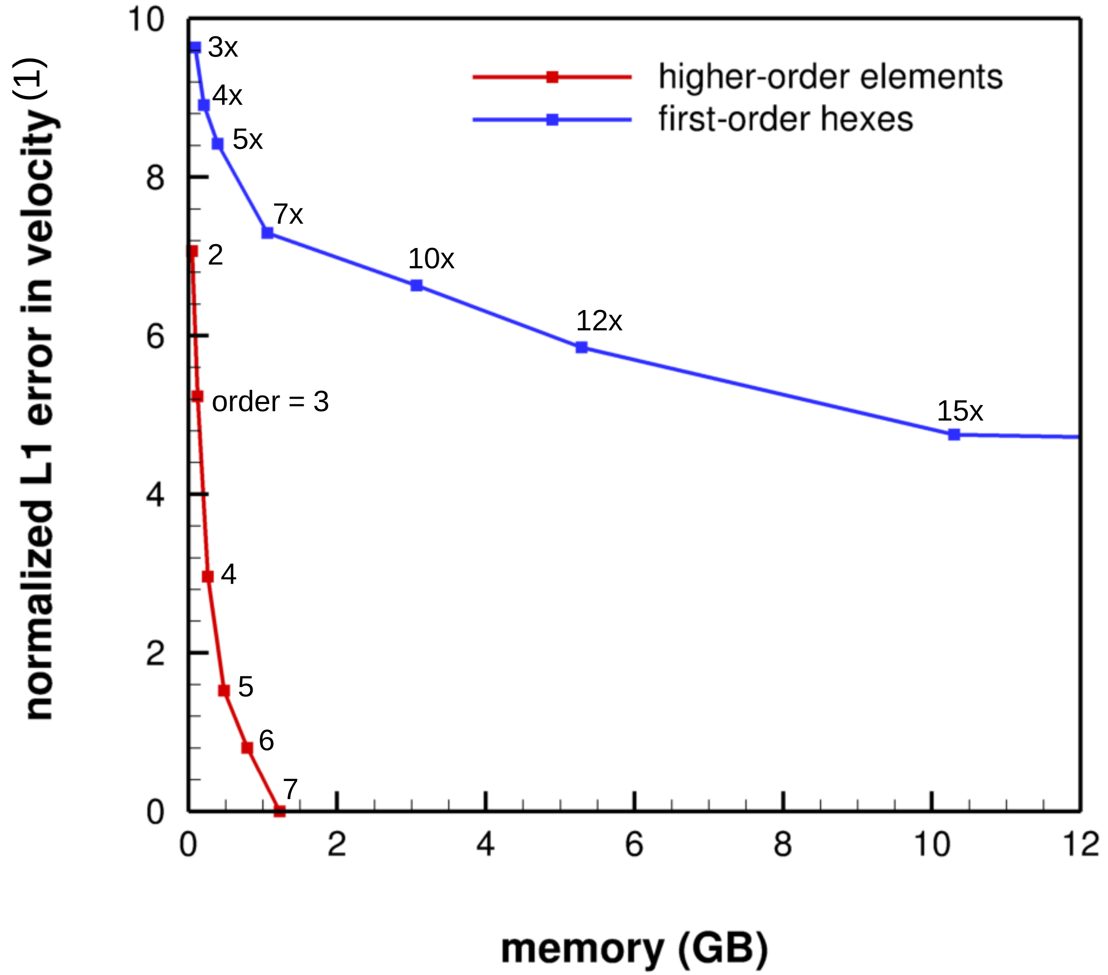


(1) Errors relative to data from 7th-order elements for t = 0-100 µs

(2) AMD Opteron: 2.31 GHz 15.7 GB RAM

Wave propagation in 3D

Summary of velocity errors at monitored node



(1) Errors relative to data from 7th-order elements for t = 0-100 μs

Summary and conclusions

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- Analysis of wave propagation is essential to fuze design
- 1D, 2D and 3D higher-order elements have been formulated and implemented in EPIC
- The higher-order elements show no signs of volumetric locking
- Accuracy of higher-order elements is compared to standard first-order elements in simulations of wave propagation. Higher-order elements provide much greater accuracy at equal:
  - Mesh refinement
  - Computing time
  - Allocated memory

Acknowledgment

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