Numerical Simulations in Ultrasonic Guided Waves Analysis for the Design of SHM Systems – Benchmark Study based on the Open Guided Waves Online Platform Dataset

Jean Lefèvre *, Enes Savli **
Christian Willberg *, Kilian Tschöke **

* Institute of Composite Structures and Adaptive Systems,
German Aerospace Center (DLR), Braunschweig, Germany

** Fraunhofer Institute for Ceramic Technologies and Systems IKTS,
Systems for Condition Monitoring, Dresden, Germany

Outline

- Guided Waves based Structural Health Monitoring (SHM)
- Guided Waves in thin structures
- Simulation methods for ultrasonic wave propagation analysis
- Open Guided Waves Project
- Simulation results
- Conclusions and further steps

Guided Waves based Structural Health Monitoring (SHM)

- GW has become a major topic in research on SHM since ~2000
  - ✓Knowledge about underlying physics in isotropic and anisotropic materials
  - ✓Simulations
  - ✓Measurement equipment
  - ✓Demonstrators
- First technical rules and regulations exist
  - ✓SAE-ARP6461: Guidelines for Implementation of Structural Health Monitoring on Fixed Wing Aircraft (September 2013)
  - ✓SHM 01 E: Structural Testing with Guided Waves (December 2014, 56 p.)
  - ✓SAE-AIR6245: Perspectives on Integrating Structural Health Monitoring Systems into Fixed-Wing Military Aircraft (September 2019)

DGZIP

DEUTSCHE
GESELLSCHAFT FÜR
ZERSTÖRUNGSFREIE
PRÜFUNG E.V.

Fachausschuss Zustandsüberwachung (FA SHM)

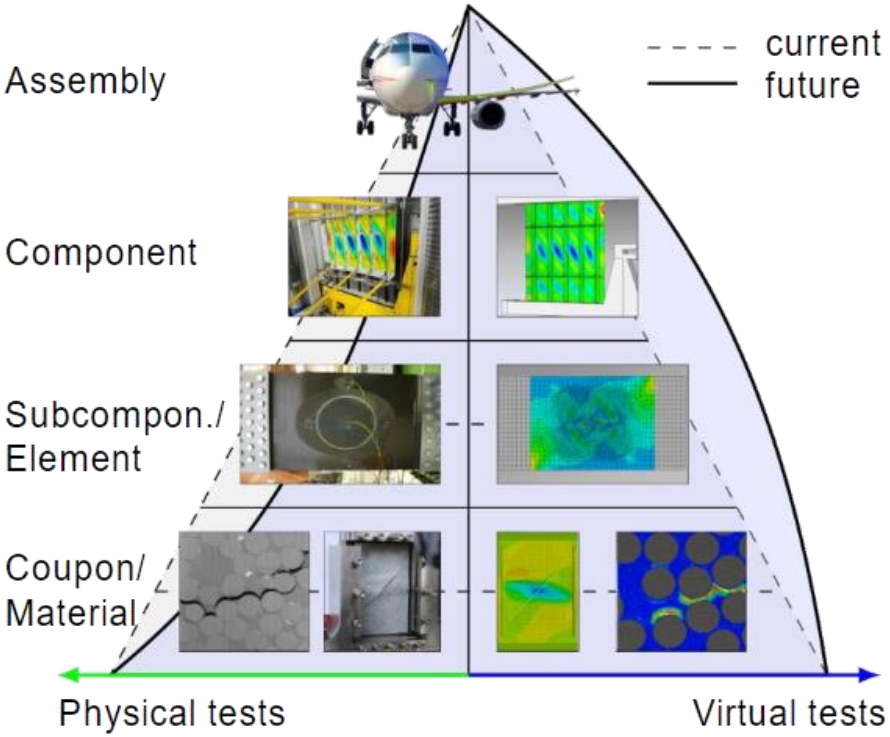
Merkblatt SHM 01

Strukturprüfung mit geführten Wellen als Sonderform des Ultraschalls

Dezember 2014

Need for efficient simulation methods in SHM

- For the approval of SHM systems, proof of damage detection is required
- Enormous effort in development and adaption cannot be covered by laboratory testing
- Use of model assisted methods is an alternative to laboratory testing
- Development of numerical methods to analyze ultrasonic wave propagation is still a challenge
- Detection of typical defects and damages occurring in fiber reinforced composites by ultrasonic guided waves (UGW)



→ **Aim: Simulation strategies for UGW propagation in complex composite structures**

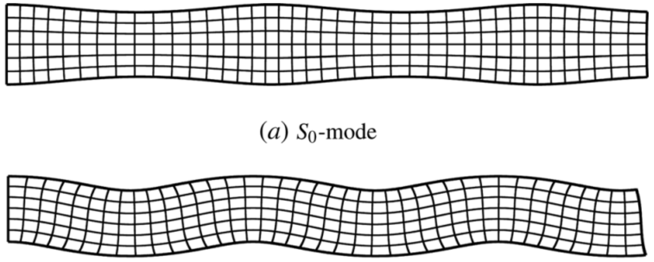
Guided waves in thin structures [WILLBERG2013, WILLBERG2015]

- Appearance of Lamb waves in thin elastic shells and plates
- Dispersive properties of Lamb wave modes

$$\frac{\tan(\tilde{p}h)}{\tan(\tilde{q}h)} + \frac{4\tilde{p}\tilde{q}k^2}{(k^2-\tilde{p}^2)^2} = 0$$

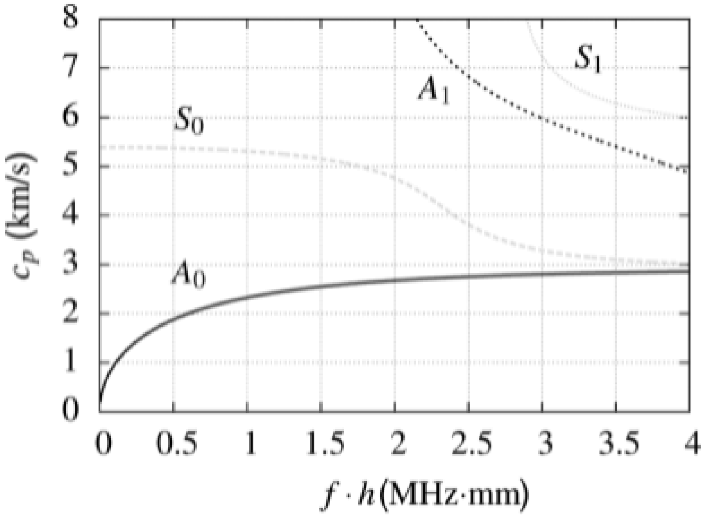
$$\frac{\tan(\tilde{q}h)}{\tan(\tilde{p}h)} + \frac{(k^2-\tilde{p}^2)^2}{4\tilde{p}\tilde{q}k^2} = 0$$

$$\tilde{p}^2 = \frac{\omega^2}{c_L^2} - k^2, \quad \tilde{q}^2 = \frac{\omega^2}{c_T^2} - k^2$$


(*a*) S_0-mode

(*b*) A_0-mode

Fig. 1 Lamb wave mode shapes



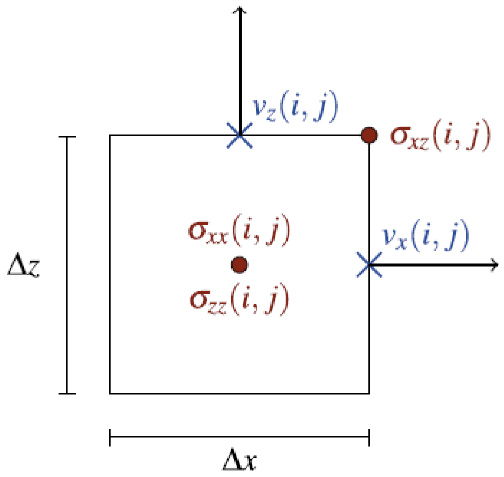
(*a*) Phase velocity dispersion curves

Fig. 2 Dispersion curves for the first two symmetric and anti-symmetric Lamb modes in an aluminum plate ($E = 7 \cdot 10^{10}$ N/m^2, $\nu = 0.33$)

c_L, c_T…longitudinal, transversal wave velocity

$$c_p = \frac{\omega}{k}, \quad k = \frac{2\pi}{\lambda}$$

Elastodynamic Finite Integration Technique (EFIT) [SCHUBERT2004, TSCHÖKE2018]



- Discretization scheme to model elastic waves (Finite Volume Method)
- EFIT uses a velocity-stress formalism on a staggered grid
- The time integration scheme is an explicit Leapfrog scheme

Cauchy‘s equation of motion

1. Calculate $\dot{v}$ in space
2. Update v in time using $\dot{v}$

$$\rho \dot{v}_h^{k-\frac{1}{2}} = F\left(\sigma_h^{k-\frac{1}{2}}, f_h^{k-\frac{1}{2}}\right)$$

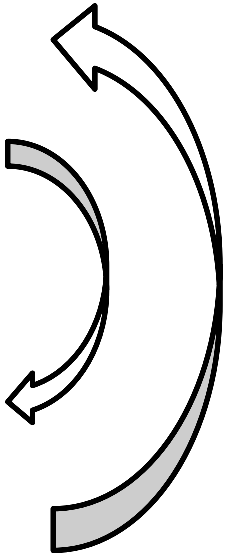
$$v_h^k = v_h^{k-1} + \Delta t \cdot \dot{v}_h^{k-\frac{1}{2}}$$

Hooke‘s law

3. Calculate $\dot{\sigma}$ in space
4. Update σ in time using $\dot{\sigma}$

$$\dot{\sigma}_h^k = \tilde{F}\left(v_h^k\right)$$

$$\sigma_h^{k+\frac{1}{2}} = \sigma_h^{k-\frac{1}{2}} + \Delta t \cdot \dot{\sigma}_h^k$$



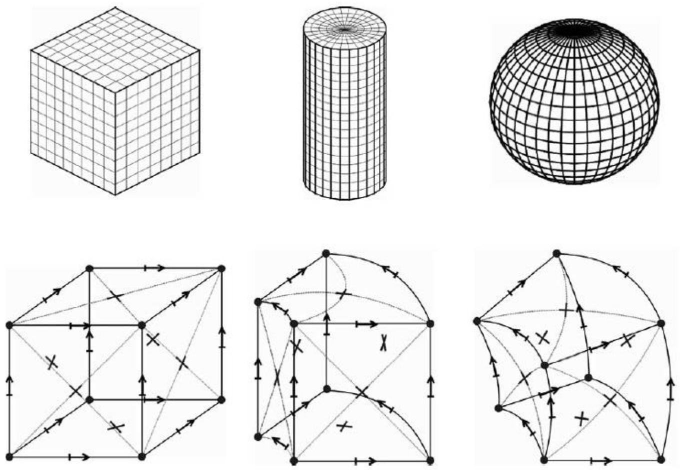
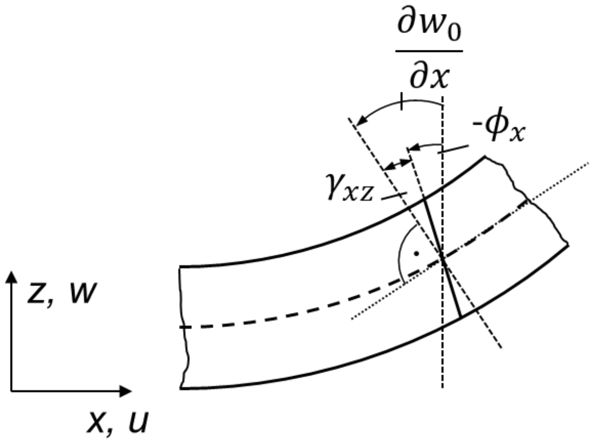


Figure: Staggered grid in 3D.

Finite shell elements in b2000++pro

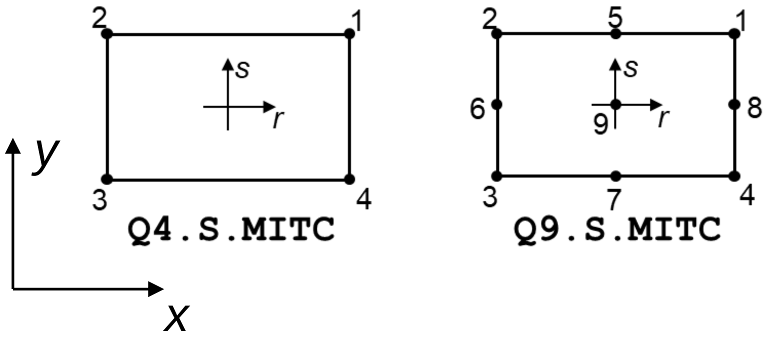
Finite Element Analysis Environment

(https://www.smr.ch)



- 4-node and 9-node shell elements following First Order Shear Deformation Theory (FSDT) [Reddy1999]
- MITC – Mixed Interpolation of Tensorial Components [Bathe2002]

$$u(x,y,t) = u_0(x,y,t) + z\phi_x(x,y,t)$$
$$v(x,y,t) = v_0(x,y,t) + z\phi_y(x,y,t)$$
$$w(x,y,t) = w_0(x,y,t)$$

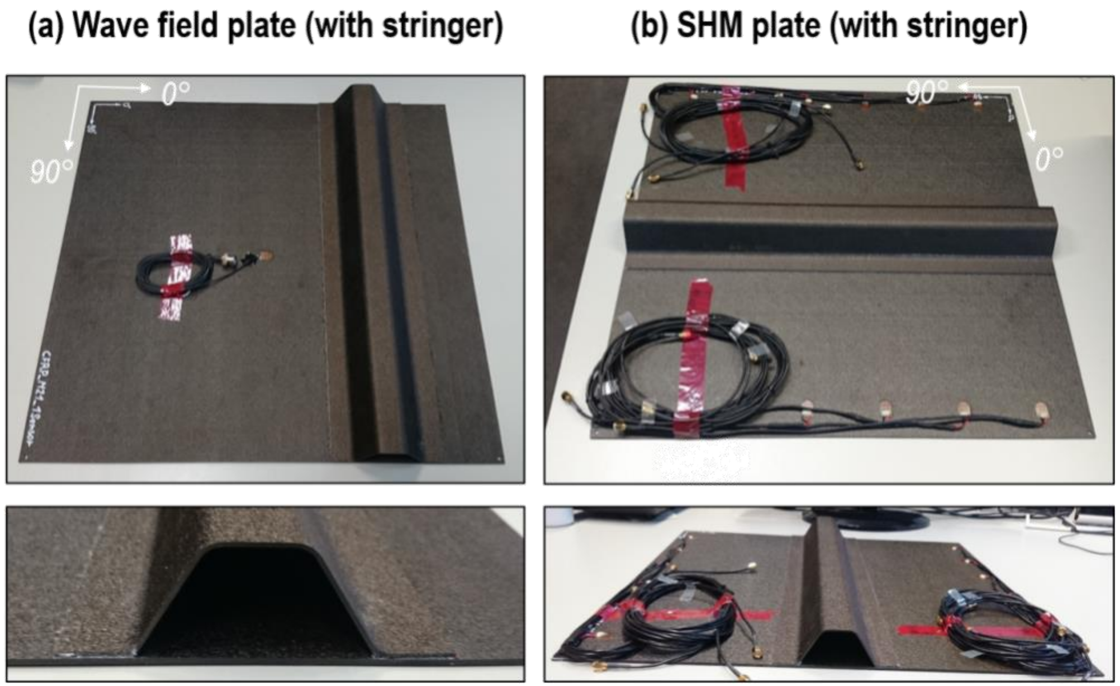


- Lamb wave A_0-mode → shell bending mode
- Lamb wave S_0-mode → shell membrane mode

Open Guided Waves Project [Moll2020]

“Rely on Collective Data, Emphasize Your Work!”

- Provides a transparent data set of wide-range measurements that is freely available
- Focused on guided wave inspection techniques for carbon fiber reinforced polymers
- http://openguidedwaves.de
- https://doi.org/10.5281/zenodo.5105861


(a) Wave field plate (with stringer)

(b) SHM plate (with stringer)

- 500 mm x 500 mm
- Piezoelectric transducers
- 3D Laser Doppler vibrometer

Plate with stringer – material and composite lay-up [Moll2020]

- Material stringer:
  Hexply ® M21/34%/UD194/IMA-12K

```
material 1  type orthotropic
  e1 171500.
  e2 8659.
  nu12 0.324
  g12 5882.
  g13 5882.
  g23 3331.
  density 1.58e-09
end
```

- Material plate:
  Hexply ® M21/34%/UD134/T700/300

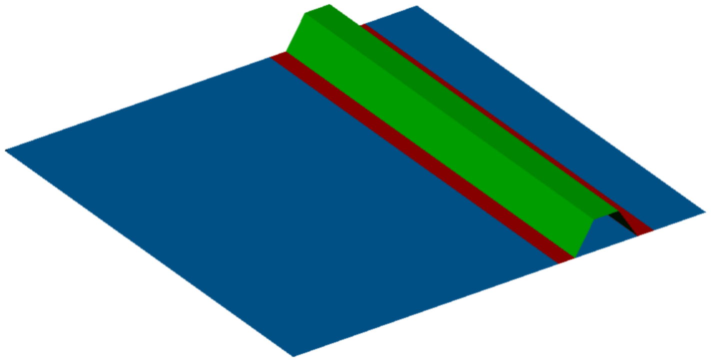
```
material 2  type orthotropic
  e1 125462.
  e2 8701.
  nu12 0.372
  g12 4200.
  g13 4200.
  g23 3000.
  density 1.571e-09
end
```

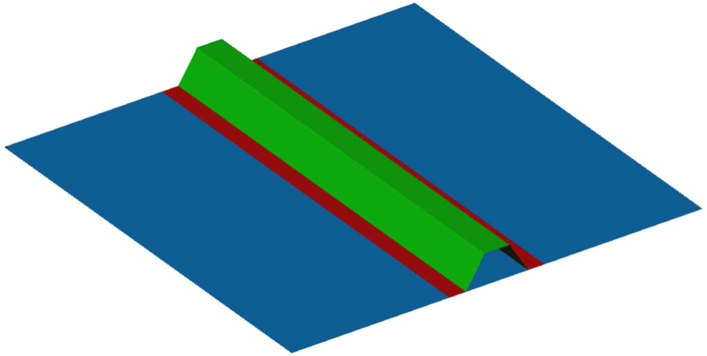
- Lay-up plate

```
material 3 type laminate
  0.125 +45 2
  0.125 +0 2
  0.125 -45 2
  0.125 +90 2
  0.125 -45 2
  0.125 +0 2
  0.125 +45 2
  0.125 +90 2
  0.125 +90 2
  0.125 +45 2
  0.125 +0 2
  0.125 -45 2
  0.125 +90 2
  0.125 -45 2
  0.125 +0 2
  0.125 +45 2
end
```

- Lay-up stringer

```
material 5 type laminate
  0.125 -45 1
  0.125 +0 1
  0.125 +90 1
  0.125 +45 1
  0.125 +90 1
  0.125 -45 1
  0.125 -45 1
  0.125 +90 1
  0.125 +45 1
  0.125 +90 1
  0.125 +0 1
  0.125 -45 1
end
```

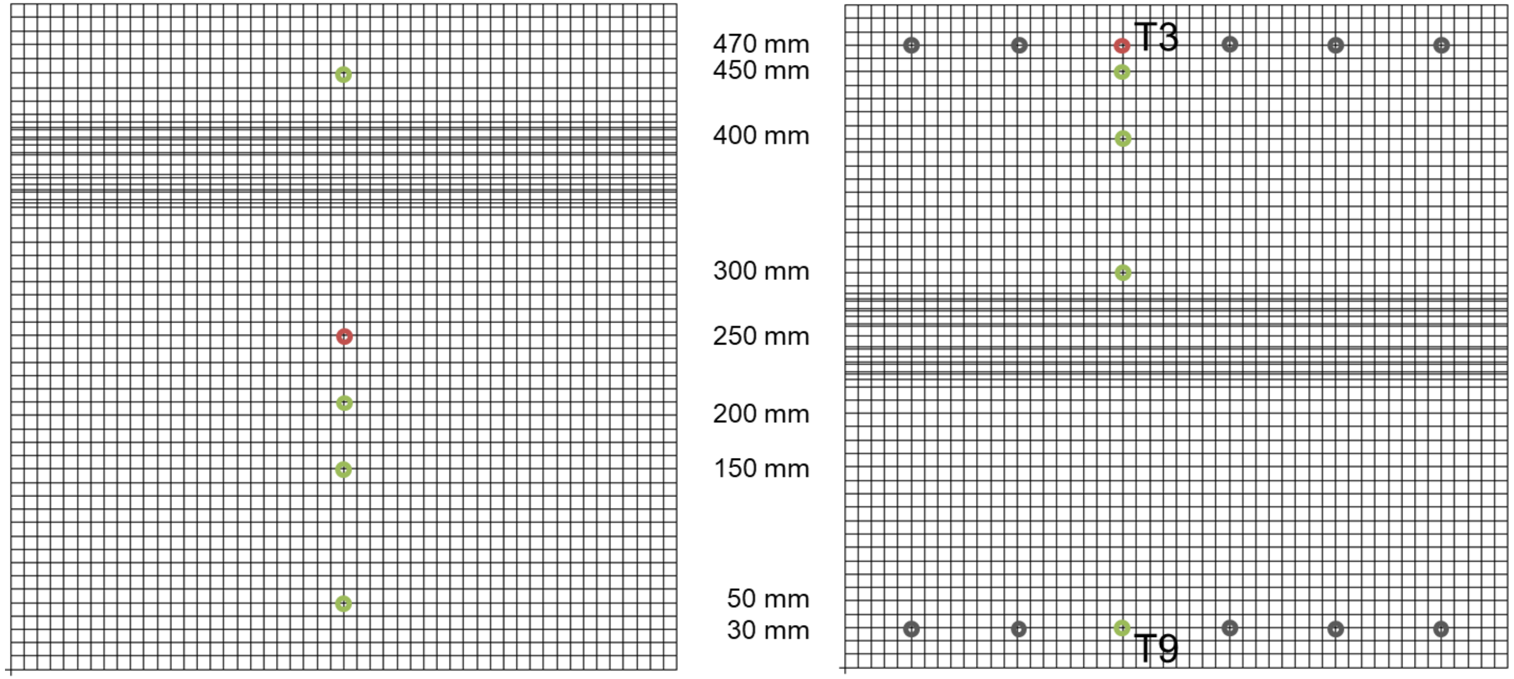




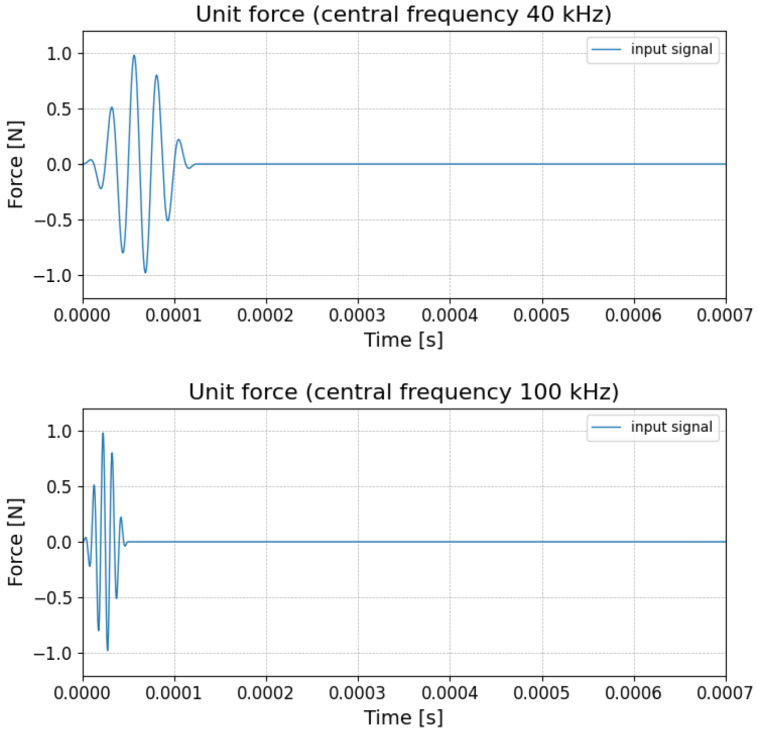
Input/output setup of test plates

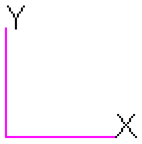
Wave field plate

SHM plate



Excitations (modulated unit force)





○ Transducer/excitation

○ Evaluation

○ Other transducer positions

$$F(t) = \hat{F}\sin^2\left(\frac{2\pi f_c t}{2n}\right)\sin(2\pi f_c t)\,,\ \ n = 5$$

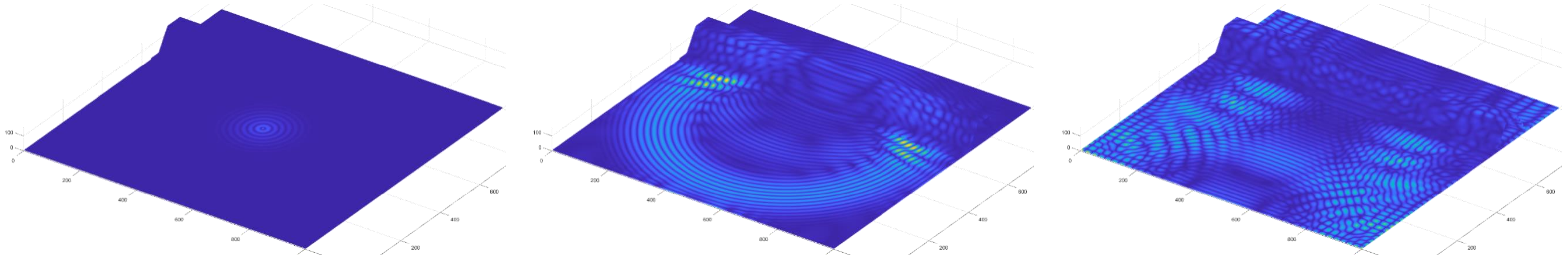
Wave field plate – f_c = 40 kHz, Displacement amplitudes (normalized)

t = 0.7E-4 s

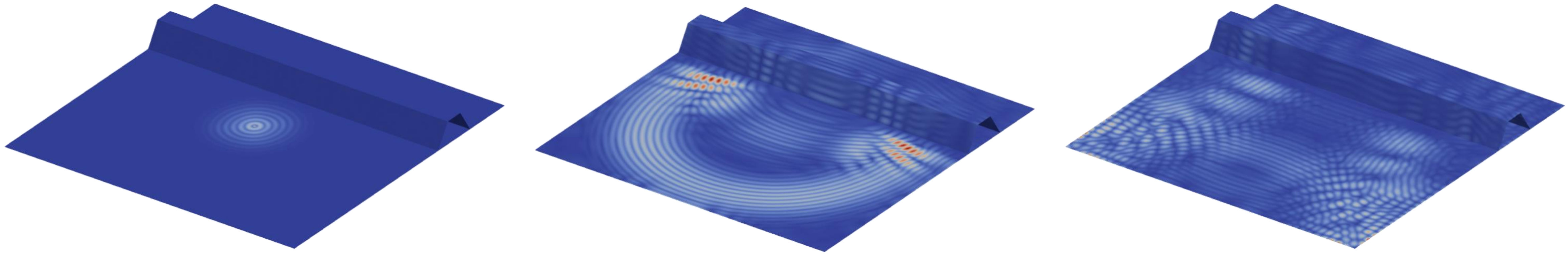
t = 2.1E-4 s

t = 3.5E-4 s

EFIT



FEM



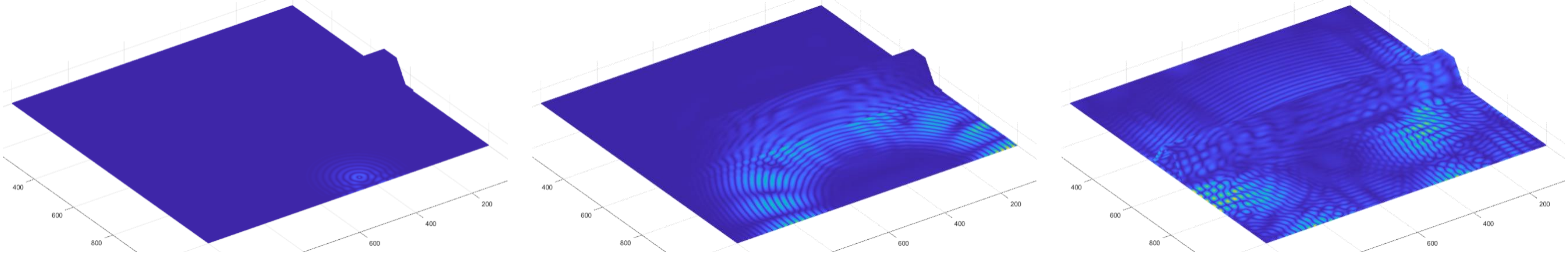
SHM plate – f_c = 40 kHz, Displacement amplitudes (normalized)

t = 0.7E-4 s

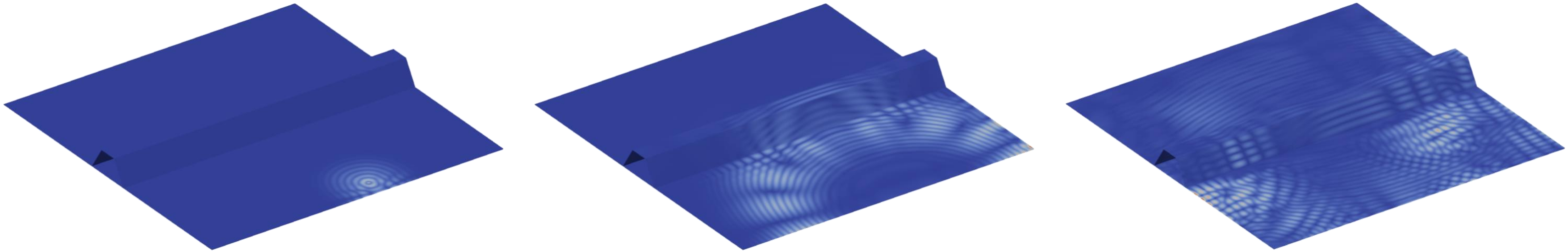
t = 2.1E-4 s

t = 3.5E-4 s

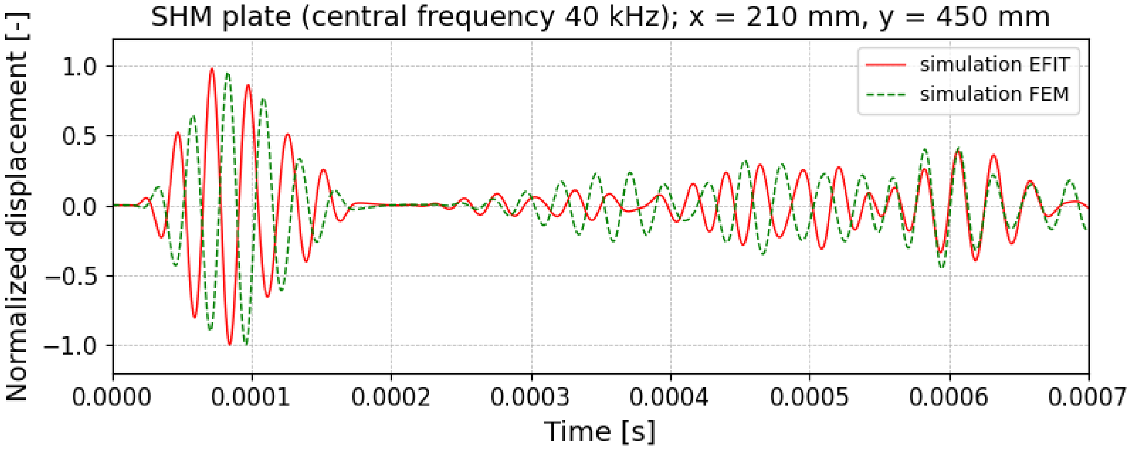
EFIT

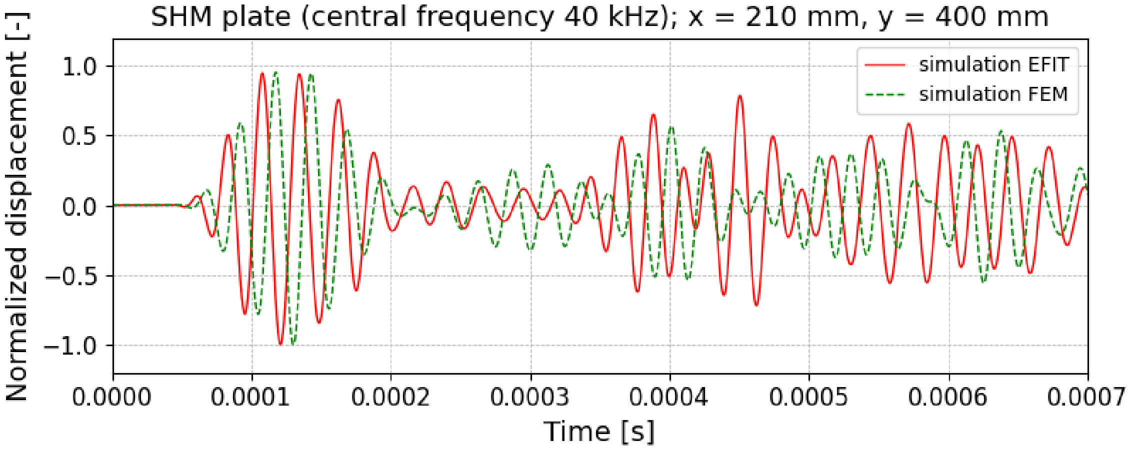


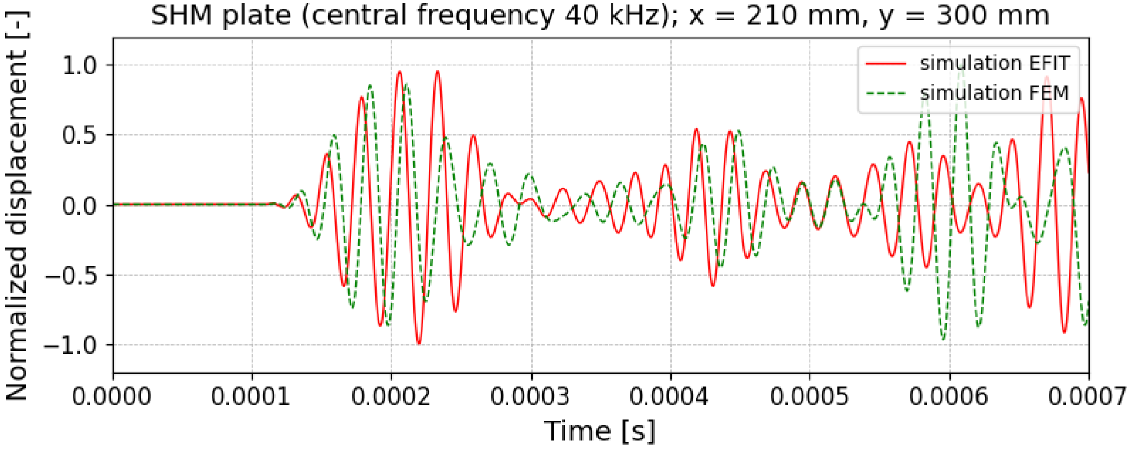
FEM

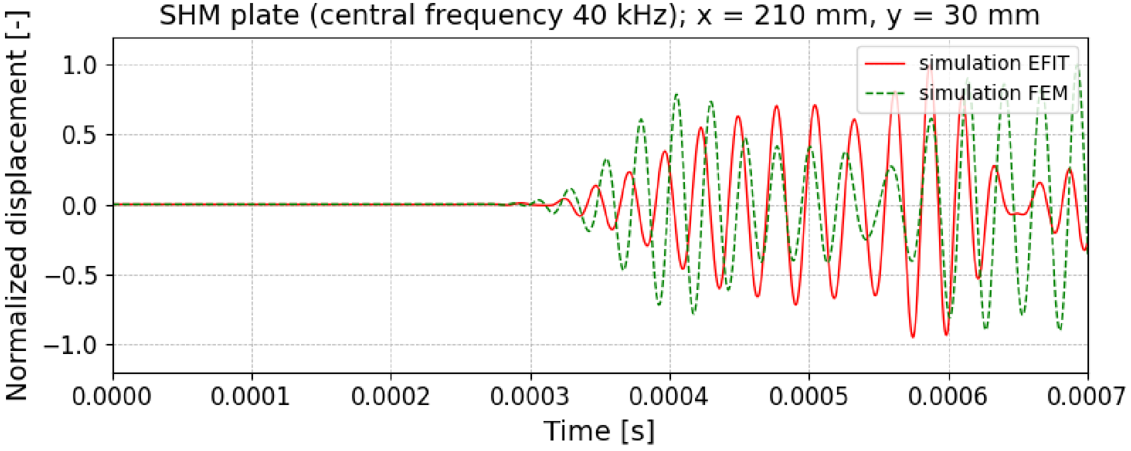


SHM plate – f_c = 40 kHz, Out-of-plane displacement in path T3 – T9



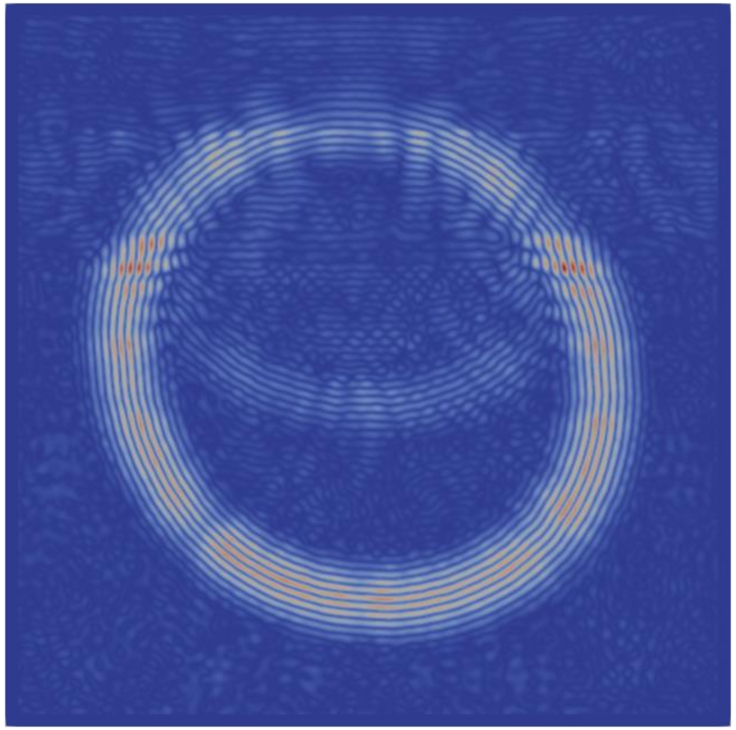




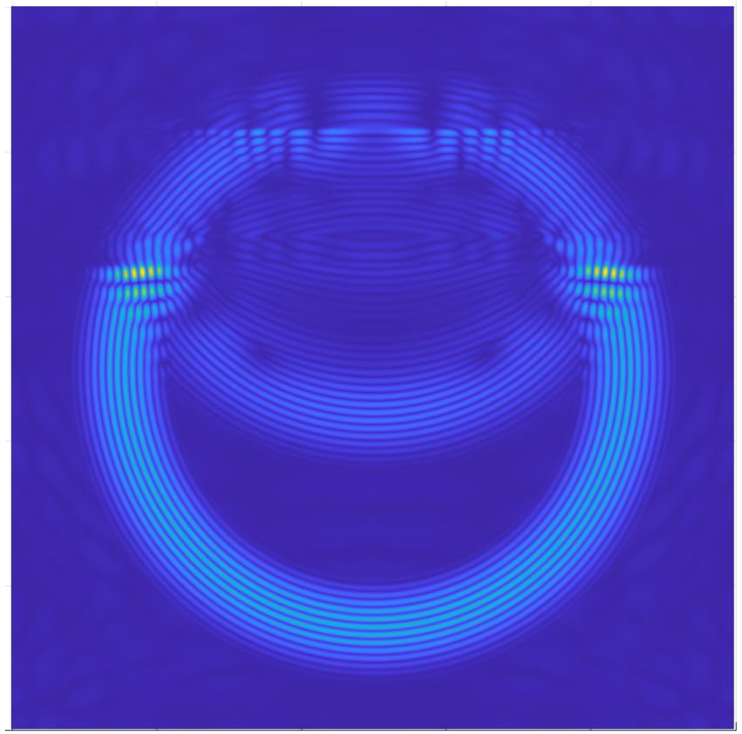


Wave field plate – f_c = 100 kHz, Out-of-plane velocity amplitudes

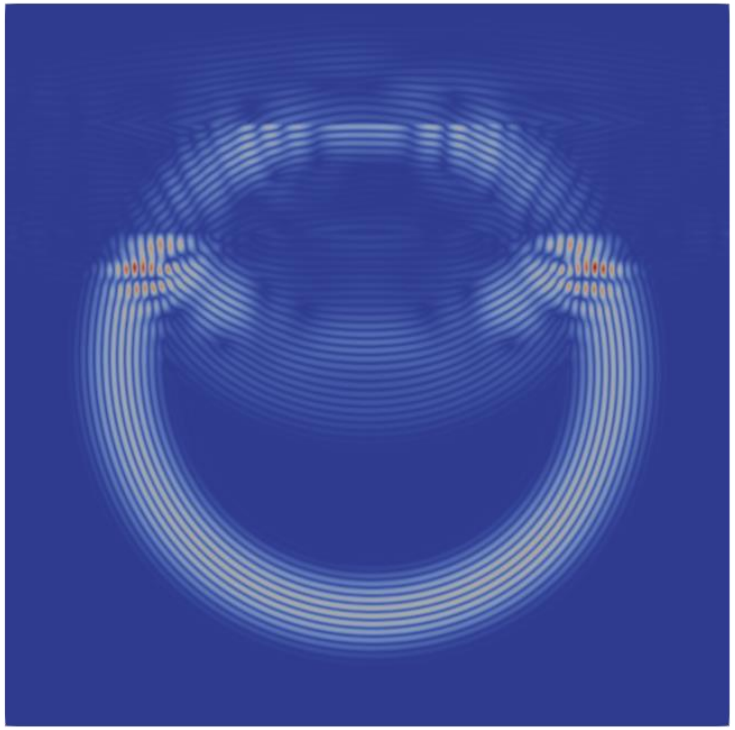
Scanning laser doppler vibrometry [KUDELA2022]



Simulation (EFIT)

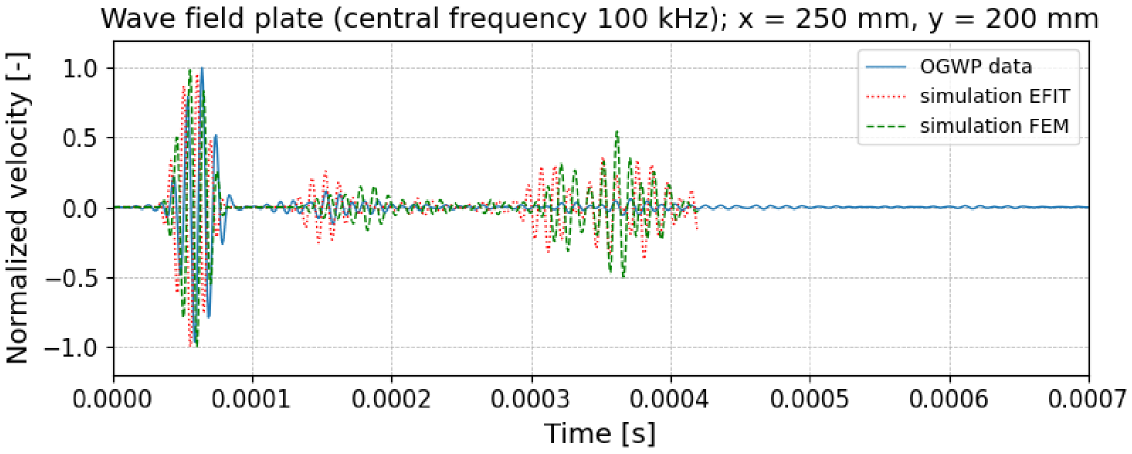


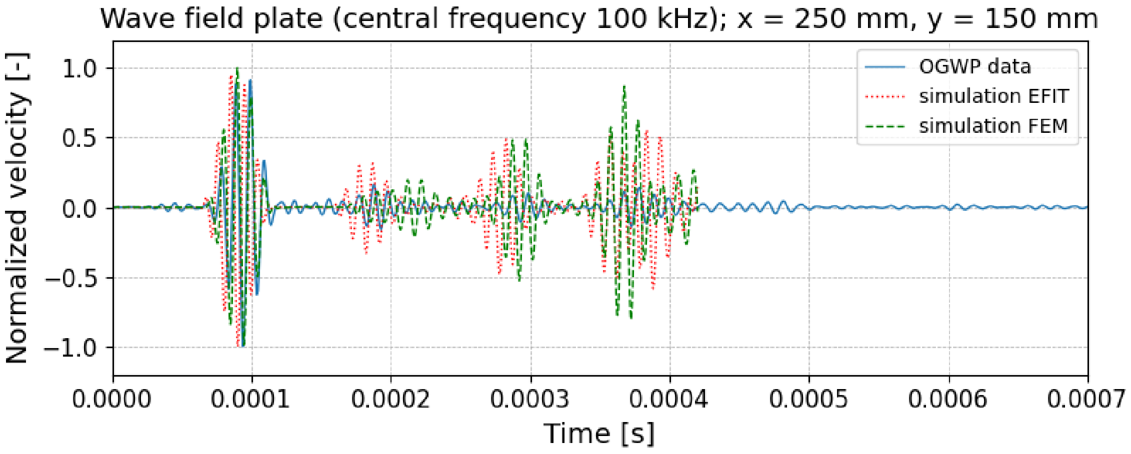
Simulation (FEM)

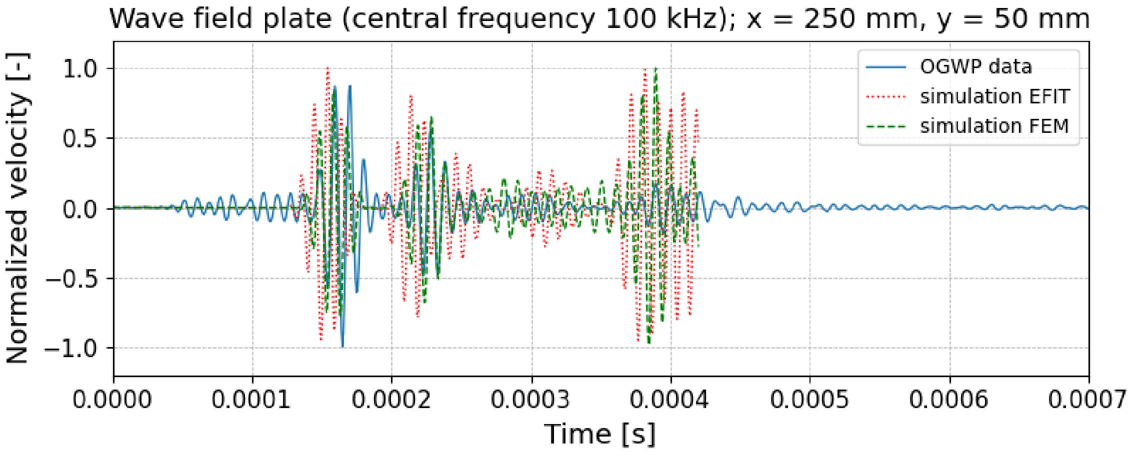


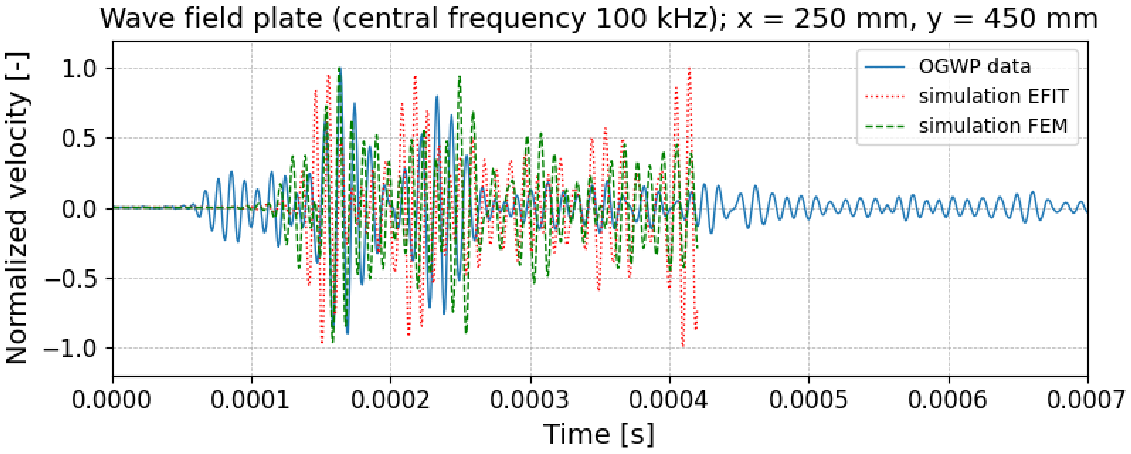
Normalized magnitudes of velocity at t = 1.4E-4 s

Wave field plate – f_c = 100 kHz, out-of-plane velocity


Wave field plate (central frequency 100 kHz); x = 250 mm, y = 200 mm


Wave field plate (central frequency 100 kHz); x = 250 mm, y = 150 mm

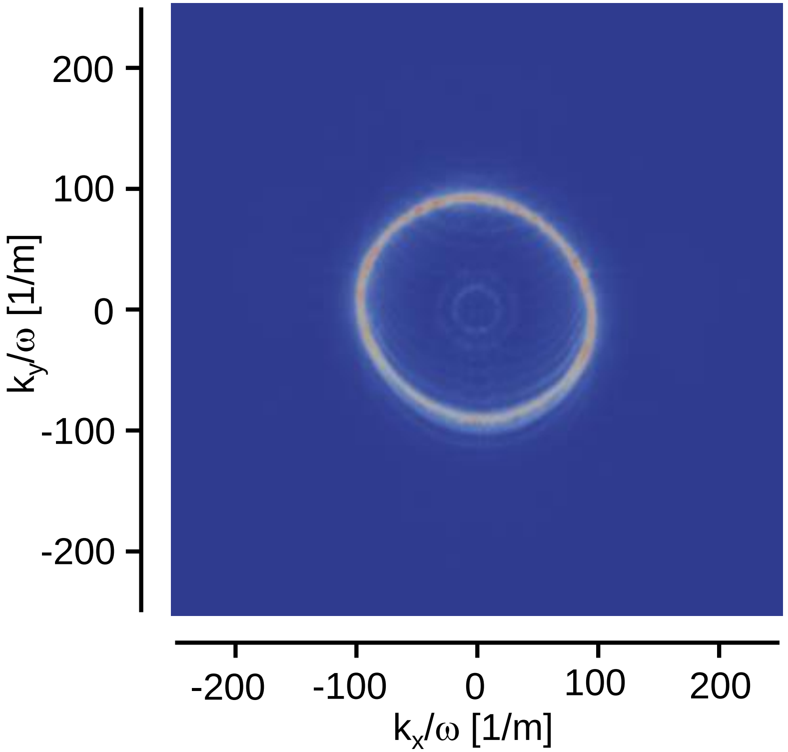

Wave field plate (central frequency 100 kHz); x = 250 mm, y = 50 mm


Wave field plate (central frequency 100 kHz); x = 250 mm, y = 450 mm

Wave field plate – f_c = 100 kHz, Experimental out-of-plane vs. simulation radial in-plane wavenumber profiles

- Transformation from time-space domain to frequency-wavenumber domain by applying 3DFFT

Data from scanning laser doppler vibrometry [Kudela2022]



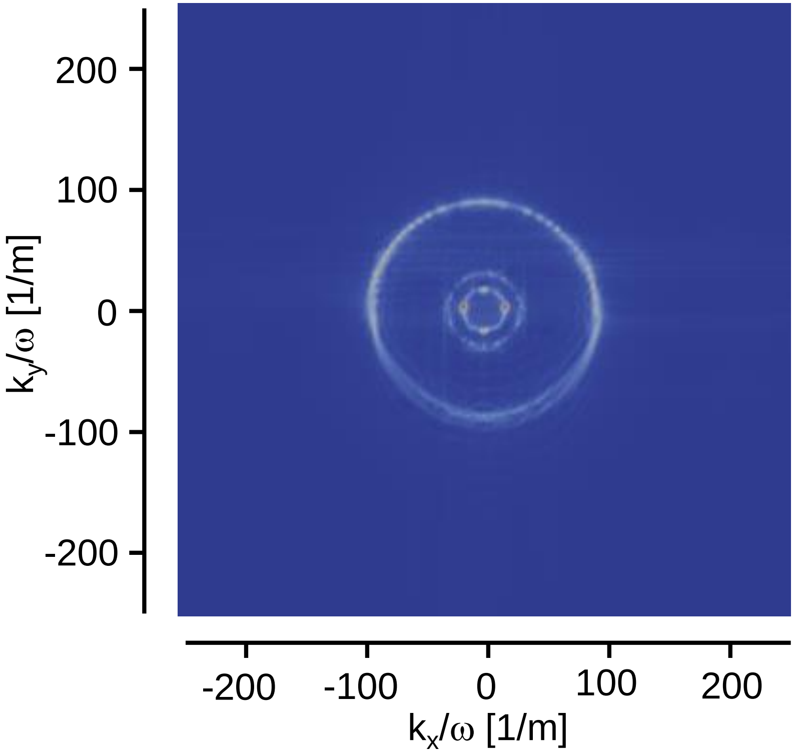
f = 100 kHz

A_0 - mode

SH - mode

S_0 - mode

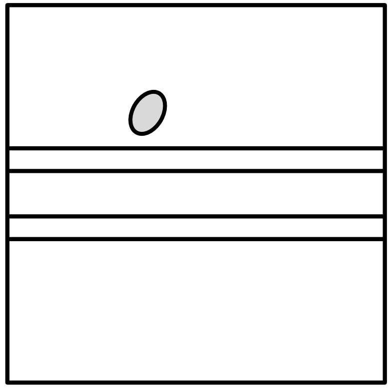
Data from simulation (FEM)



SHM plate – f_c = 40 kHz, Artificial reference damage

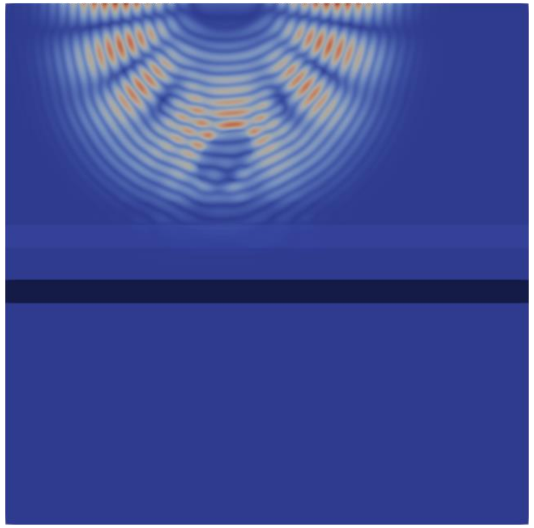
- Elliptical steel disk of 1 mm thickness and different axes sizes fixed on plate's surface
- Elliptical shape corresponds to the characteristics of impact damages on composites

[MOLL2020]

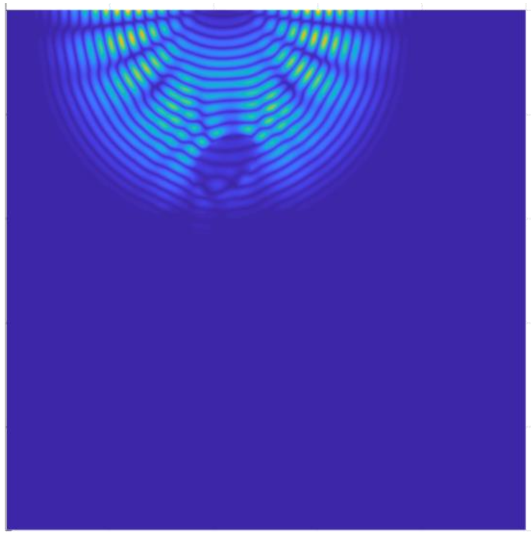


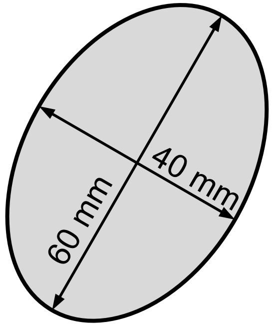
FEM

t = 1.5E-4 s



EFIT





Conclusions

- A concept to simulate the propagation of Ultrasonic Guided Waves in **shell-like composite structures** was developed by introducing the Elastodynamic Finite Integration Technique (EFIT) and finite shell-elements (FEM).
- Time-transient simulations were performed regarding **different excitation frequency levels**.
- Test structures and related data sets coming from the **Open Guided Waves Project** (wave field plate and SHM plate with stringer) were taken into account.
- **3DFFT** was used to transform results from space-time domain to wavenumber-frequency domain.
- For further visualization purposes **Matlab** as well as the DLR-tool **vampire** in combination with ParaView was used.

Vampire – Versatile mesh and postprocessing interface (https://gitlab.dlr.de/fa_sw/vampire)

Further steps

- Improvement of b2000++pro finite shell-elements regarding Lamb waves simulation purposes (linear varying displacement in **out-of-plane direction**)
- Simulation performance improvement by using CARA capabilities in **parallelization** (CARA – Cluster for Advanced Research in Aerospace – TU Dresden / ZIH)
- Augmenting model complexity
    - ✓Geometry and discretization (elements and time steps)
    - ✓Physical phenomena and interactions → **imperfections**, **damages**
- **Model assisted** probability of detection

References

[Bathe2002] Bathe, K. J.: *Finite-Elemente-Methoden.* Springer-Verlag Berlin Heidelberg, (2002).

[Kudela2022] Kudela, P.; Radzienski, M.; Moix-Bonet, M.; Willberg, Ch.; Lugovtsova, Y.; Bulling, J.; Tschöke, K.; Moll, J.: *Dataset on full ultrasonic guided wavefield measurements of a CFRP plate with fully bonded and partially debonded omega stringer.* Data in Brief, (2022).

[Moll2020] Moll, J.; Kexel, Ch.; Kathol, J.; Fritzen, C.-P.; Moix-Bonet, M.; Willberg, Ch.; Rennoch, M.; Koerdt, M.; Herrmann, A.: *Guided Waves for Damage Detection in Complex Composite Structures: The Influence of Omega Stringer and Different Reference Damage Size.* Applied Science, 10, 3068, (2020).

[Reddy1999] Reddy, J. N.: *Theory and Analysis of Elastic Plates.* TAYLOR & FRANCIS, Philadelphia, (1999).

[Schubert2004] Schubert F.: *Numerical time-domain modeling of linear and nonlinear ultrasonic wave propagation using finite integration techniques - theory and applications*, Ultrasonics, 42, (2004).

[Tschöke2018] Tschöke, K.; Gravenkamp, H.: *On the numerical convergence and performance of different spatial discretization techniques for transient elastodynamic wave propagation problems,* Wave Motion, 82, (2018).

[Willberg2013] Willberg, Ch.: *Development of a new isogeometric finite element and its application for Lamb wave based structural health monitoring.* Ph.D. thesis, Otto-von-Guericke-University of Magdeburg, Magdeburg, (2013).

[Willberg2015] Willberg, Ch.; Duczek, S.; Vivar-Perez, J. M.; Ahmad, Z. A. B.: *Simulation Methods for Guided Wave-Based Structural Health Monitoring: A Review.* Applied Mechanics Reviews, 67, (2015).

Thank You!

Jean Lefèvre

DLR
Institute of Composite Structures and Adaptive Systems

Lilienthalplatz 7, 38108 Braunschweig, Germany

Email: jean.lefevre@dlr.de

Enes Savli

Fraunhofer Institute for Ceramic Technologies and Systems IKTS
Systems for Condition Monitoring

Maria-Reiche-Straße 2, 01109 Dresden, Germany

Email: enes.savli@ikts.fraunhofer.de

Christian Willberg

DLR
Institute of Composite Structures and Adaptive Systems

Lilienthalplatz 7, 38108 Braunschweig, Germany

Email: christian.willberg@dlr.de

Kilian Tschöke

Fraunhofer Institute for Ceramic Technologies and Systems IKTS
Systems for Condition Monitoring

Maria-Reiche-Straße 2, 01109 Dresden, Germany

Email: kilian.tschoeke@ikts.fraunhofer.de