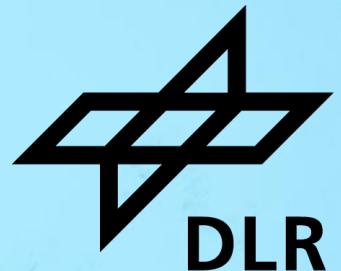


ULTRASONIC GUIDED WAVES SIMULATION IN SHM DESIGN – FINITE ELEMENT MODELING AND MODEL DATA HANDLING

Jean Lefèvre, Christian Willberg, Martin Rädel, Andreas Schuster

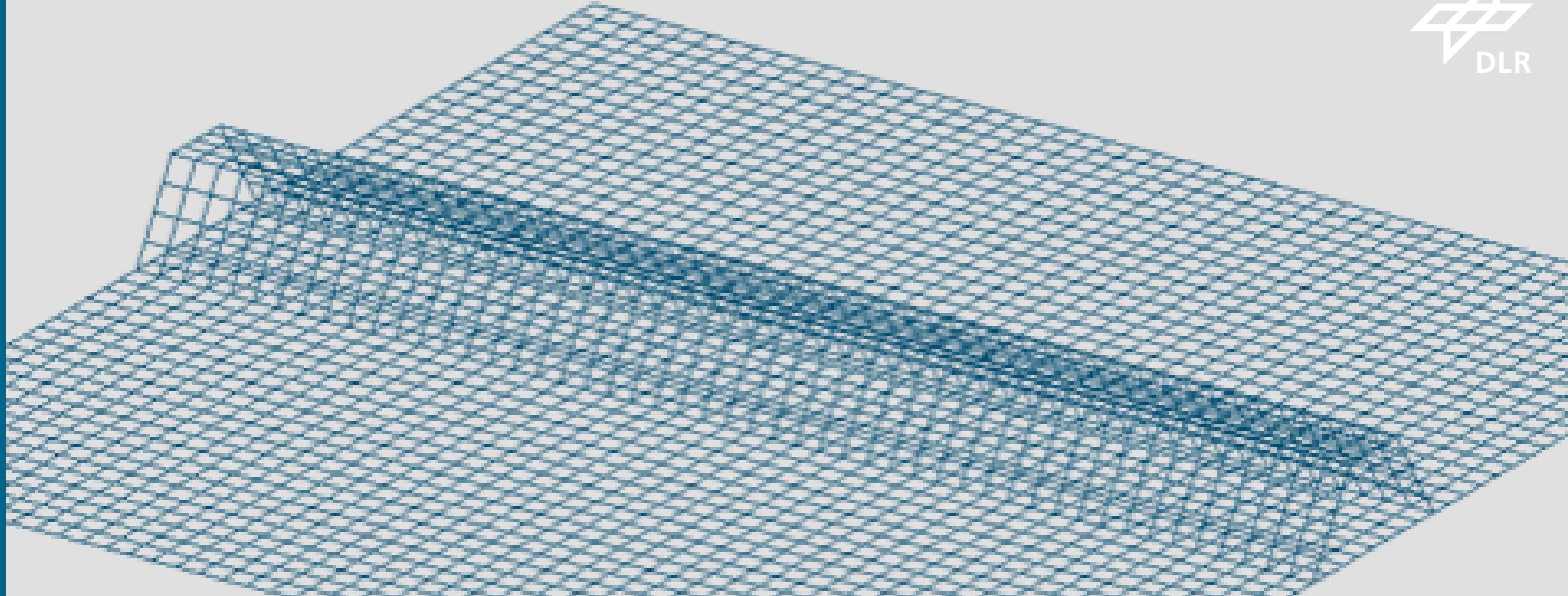
Institute of Composite Structures and Adaptive Systems - German Aerospace Center,
Braunschweig, Germany



Outline

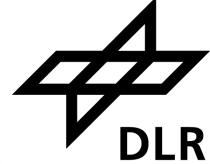


- SHM and Open Guided Waves Project
- Simulations for Ultrasonic Guided Waves propagation analysis
- Solver-independent data handling
- Conclusions and further steps



SHM AND OPEN GUIDED WAVES PROJECT

Guided Waves based Structural Health Monitoring (SHM)



- Guided Waves has become a major topic in research on SHM since ~2000.
- First technical rules and regulations exist.
 - SHM 01 E: Structural Testing with Guided Waves (December 2014, 56 p.)
- Enormous effort in development and adaption cannot be covered by laboratory testing.



- Use of model assisted methods is an alternative to laboratory testing
- **Simulation strategies for UGW propagation in complex composite structures are still challenging**

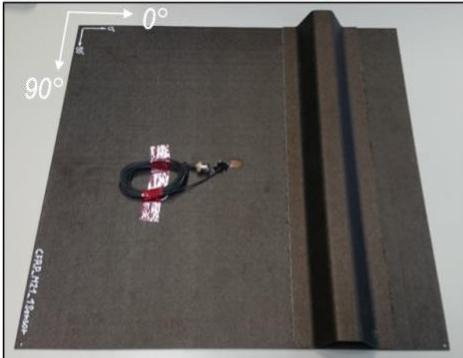
Open Guided Waves Project [Moll2020]



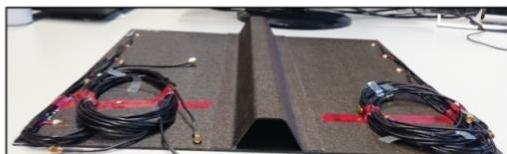
“Rely on Collective Data, Emphasize Your Work!”

- Provides data sets of wide-range measurements that is freely available
- Focused on carbon fiber reinforced polymers

(a) Wave field plate (with stringer)



(b) SHM plate (with stringer)



- <http://openguidedwaves.de>
- 500 mm x 500 mm
- Piezoelectric transducers
- 3D Laser Doppler vibrometer

SIMULATIONS FOR ULTRASONIC GUIDED WAVE PROPAGATION ANALYSIS

Guided waves in thin structures [WILLBERG2013, WILLBERG2015]

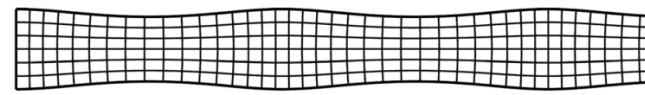
- Appearance of Lamb waves in thin elastic shells and plates
- Dispersion of Lamb wave modes

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

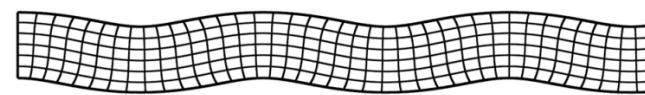
$$\frac{\tan(\tilde{q}h)}{\tan(\tilde{p}h)} + \frac{(k^2 - \tilde{p}^2)^2}{4\tilde{p}\tilde{q}k^2} = 0$$

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

c_L, c_T ...longitudinal, transversal wave velocity

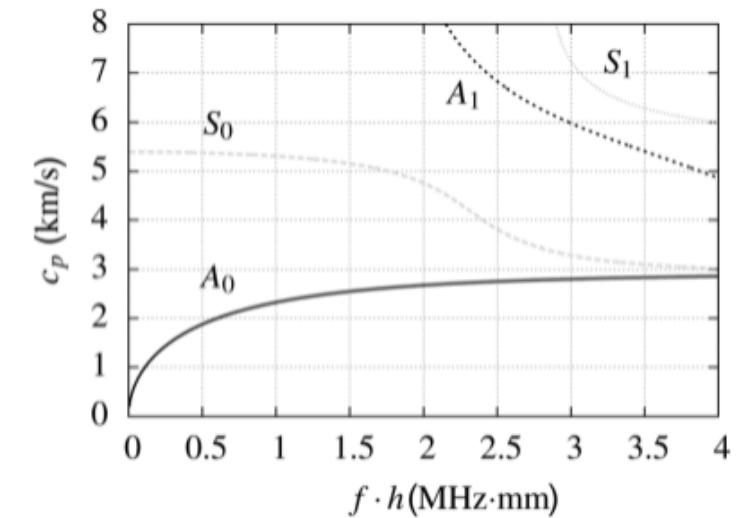


(a) S_0 -mode



(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/m², $\nu = 0.33$)

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

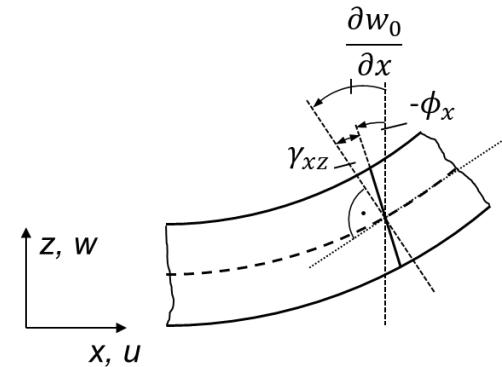
Finite element simulation using b2000++pro



b2000 *pro* Finite Element Analysis Environment

SMR
Engineering & Development

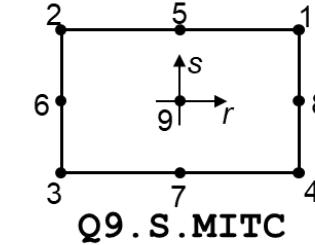
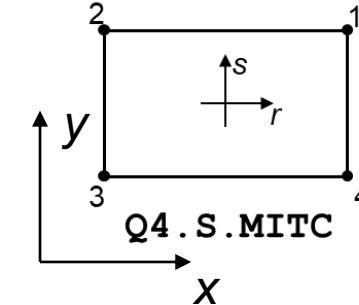
(www.smr.ch)



$$u(x, y, t) = u_0(x, y, t) + z\phi_x(x, y, t)$$

$$v(x, y, t) = v_0(x, y, t) + z\phi_y(x, y, t)$$

$$w(x, y, t) = w_0(x, y, t)$$



- 4-node and 9-node shell elements following First Order Shear Deformation Theory (FSDT) [Reddy1999]
- MITC – Mixed Interpolation of Tensorial Components [Bathe1996]

- Lamb wave A_0 -mode → shell bending mode
- Lamb wave S_0 -mode → shell membrane mode
- Shear horizontal SH_0 -mode → shell in plane shear mode

Plate with stringer model – material and composite lay-up

[MOLL2020]



- Lay-up plate

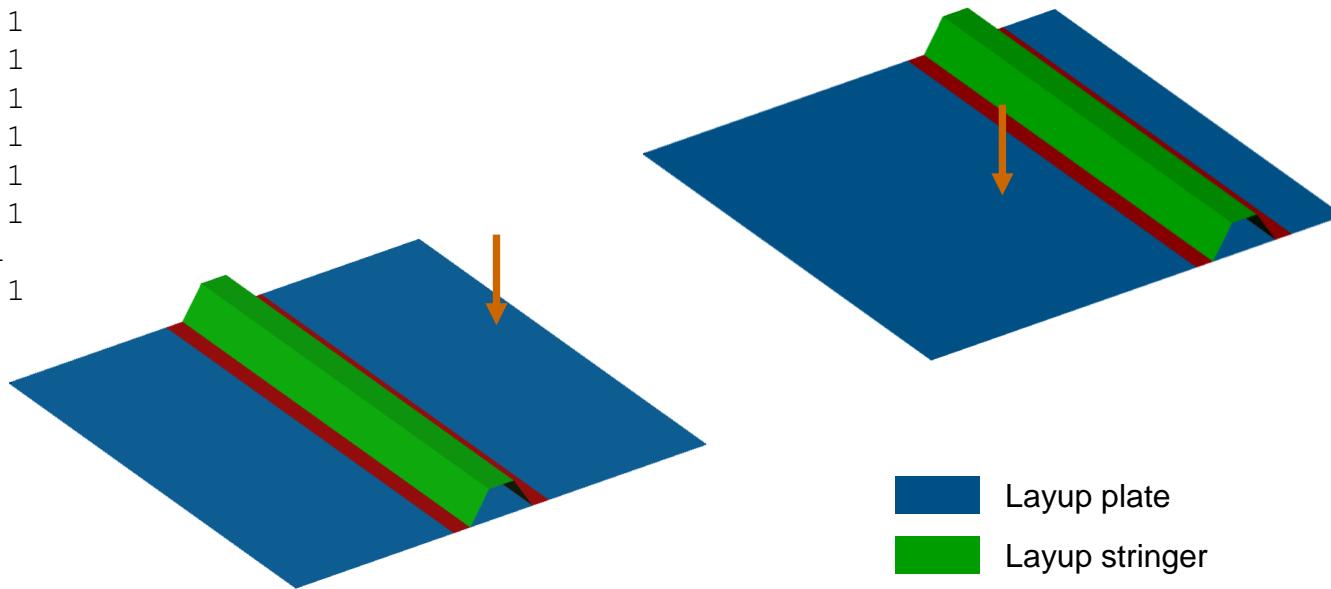
```
material 3 type
lamine
 0.125 +45 2
 0.125 +0 2
 0.125 -45 2
 0.125 +90 2
 0.125 -45 2
 0.125 +0 2
 0.125 +45 2
 0.125 +90 2
 0.125 +90 2
 0.125 +45 2
 0.125 +0 2
 0.125 -45 2
 0.125 +90 2
 0.125 -45 2
 0.125 +0 2
 0.125 +45 2
end
```

- Lay-up stringer

```
material 5 type
lamine
 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
```

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

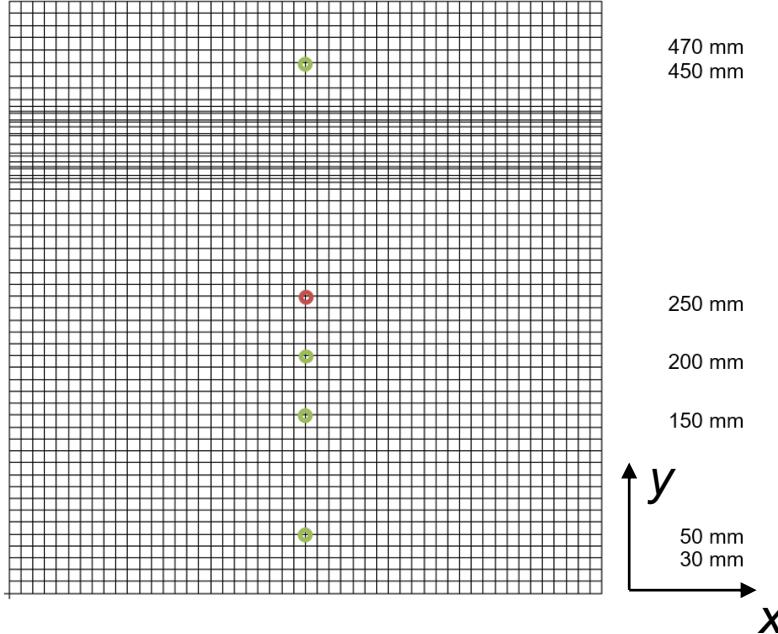
- Material stringer: Hexply ® M21/34%/UD194/IMA-12K



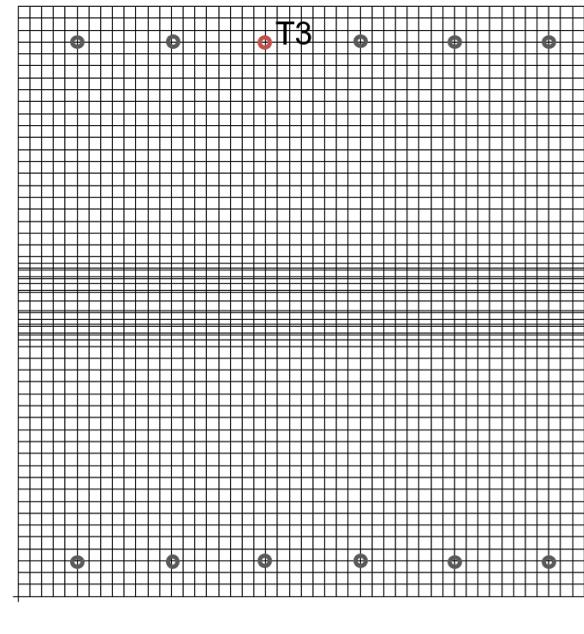
- Layup plate
- Layup stringer
- Layup plate + stringer

Excitation and evaluation

Wave field plate

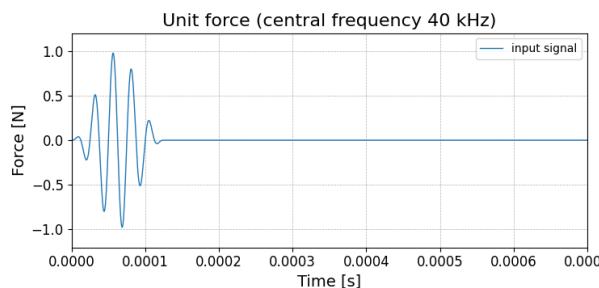


SHM plate

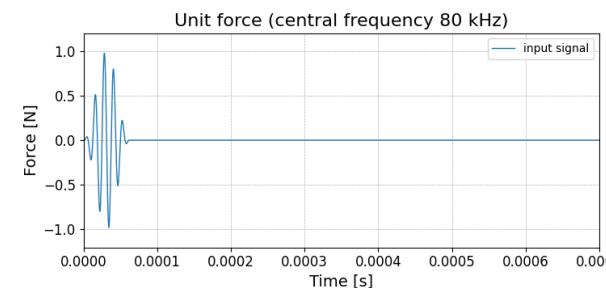


- Excitation
 - Transducer positions
 - Evaluation
-
- modulated out-of-plane unit force

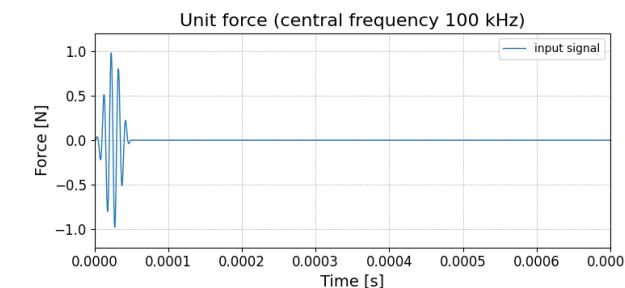
$$F(t) = \hat{F} \sin^2\left(\frac{2\pi f_c t}{2n}\right) \sin(2\pi f_c t),$$
$$n = 5$$



$f_c = 40 \text{ kHz}$



$f_c = 80 \text{ kHz}$



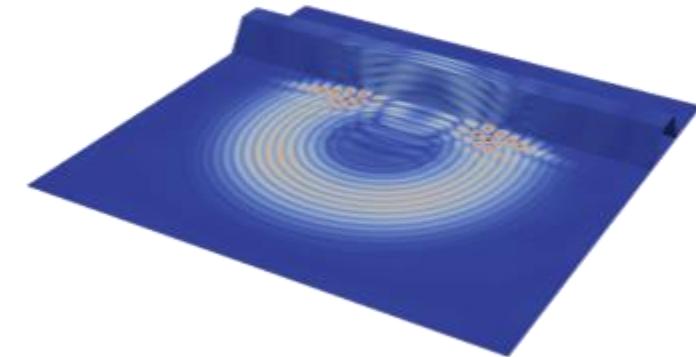
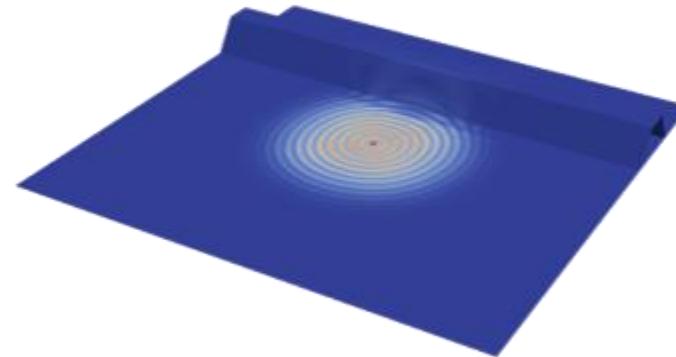
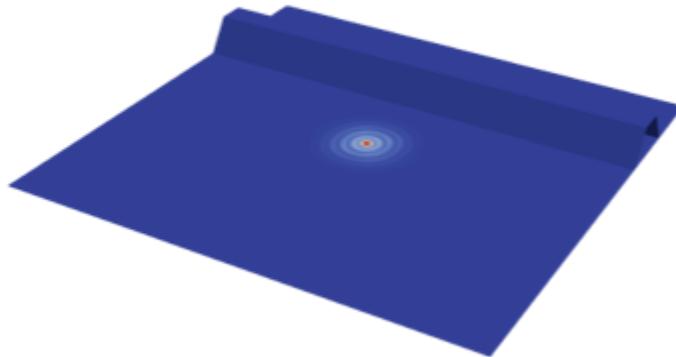
$f_c = 100 \text{ kHz}$

Wave field plate – $f_c = 40$ kHz, Total displacement amplitudes (normalized)

t = 50 μ s

t = 100 μ s

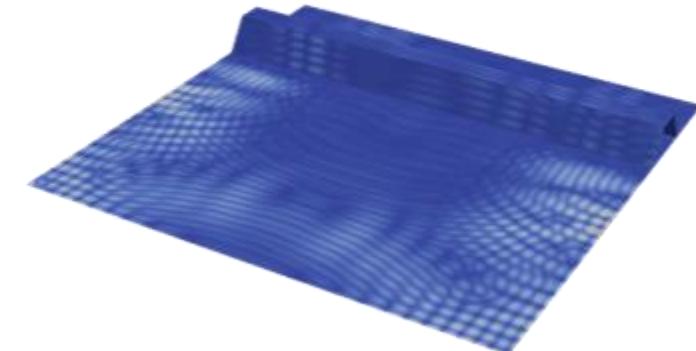
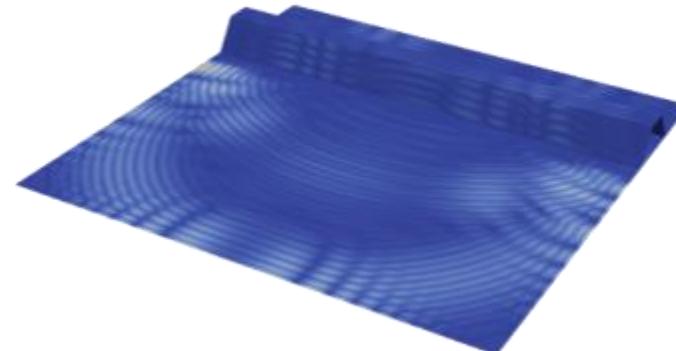
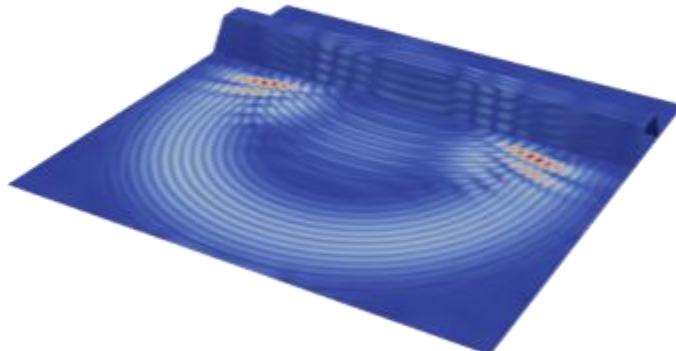
t = 150 μ s



t = 200 μ s

t = 250 μ s

t = 300 μ s

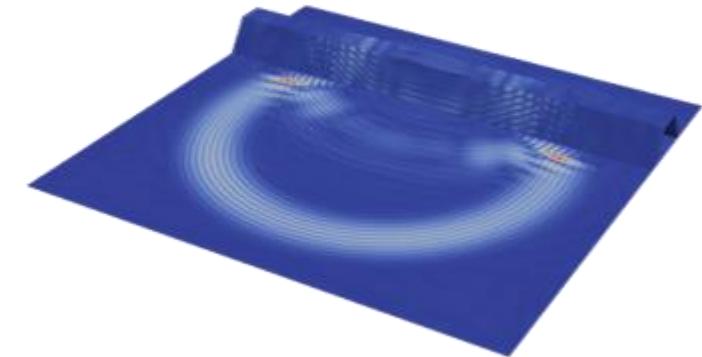
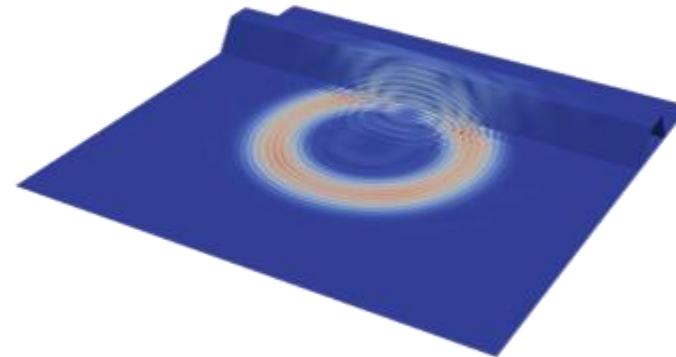
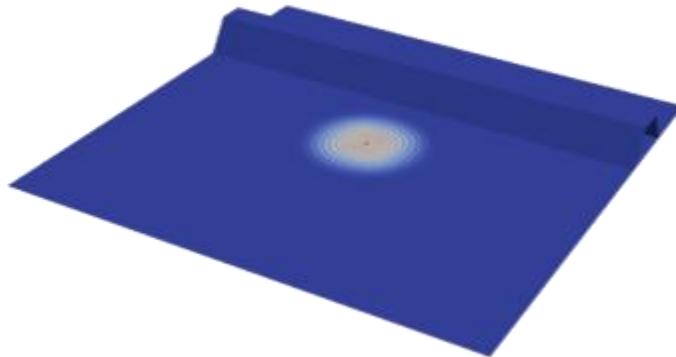


Wave field plate – $f_c = 80$ kHz, Total displacement amplitudes (normalized)

t = 50 μ s

t = 100 μ s

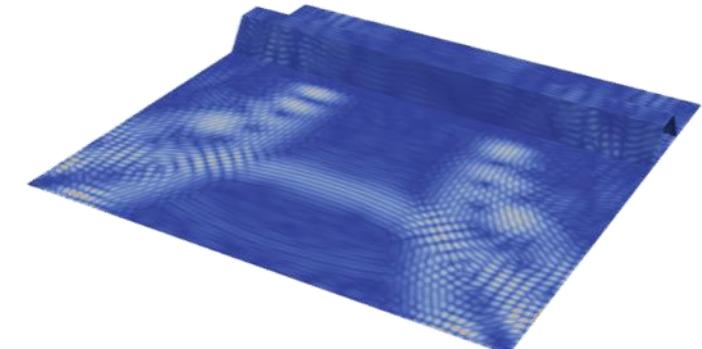
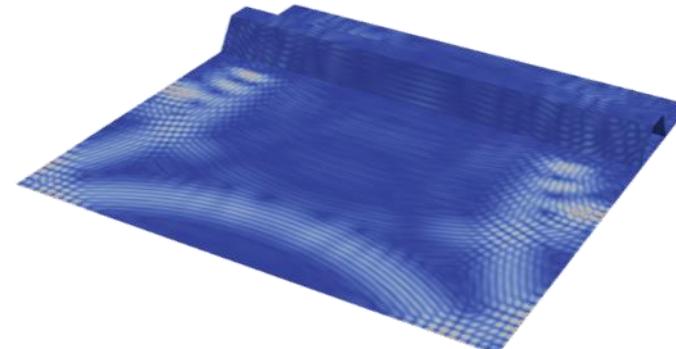
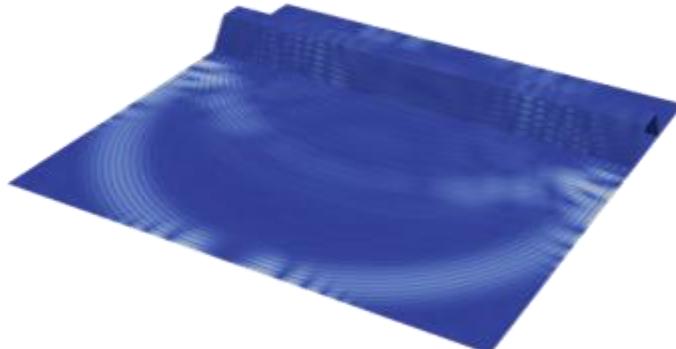
t = 150 μ s



t = 200 μ s

t = 250 μ s

t = 300 μ s



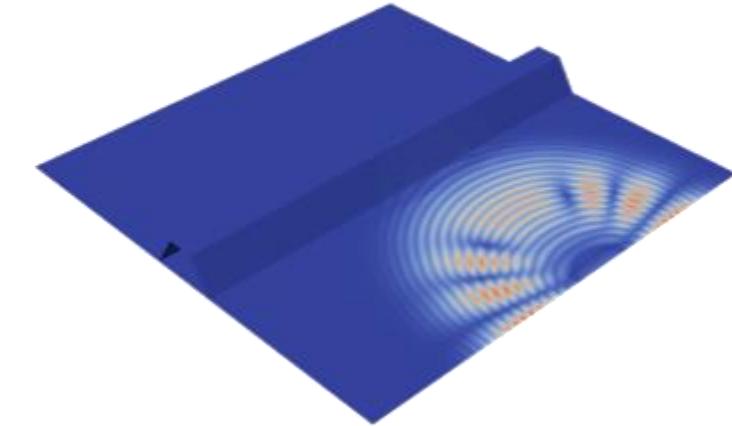
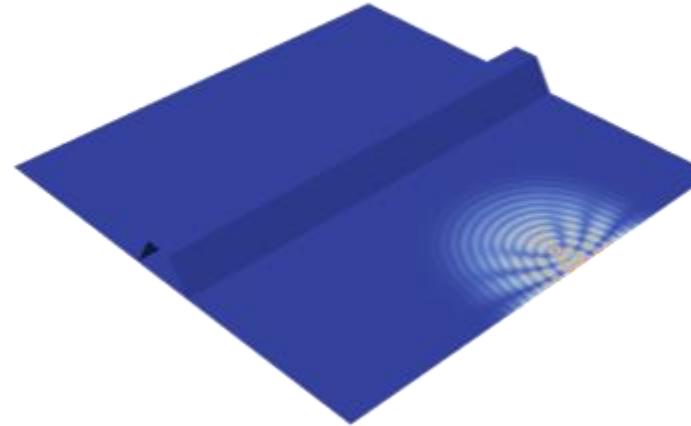
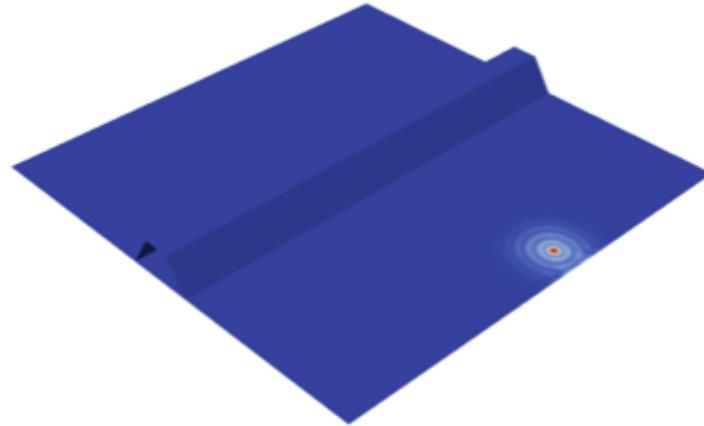
SHM plate – $f_c = 40$ kHz, Total displacement amplitudes (normalized)



$t = 50 \mu\text{s}$

$t = 100 \mu\text{s}$

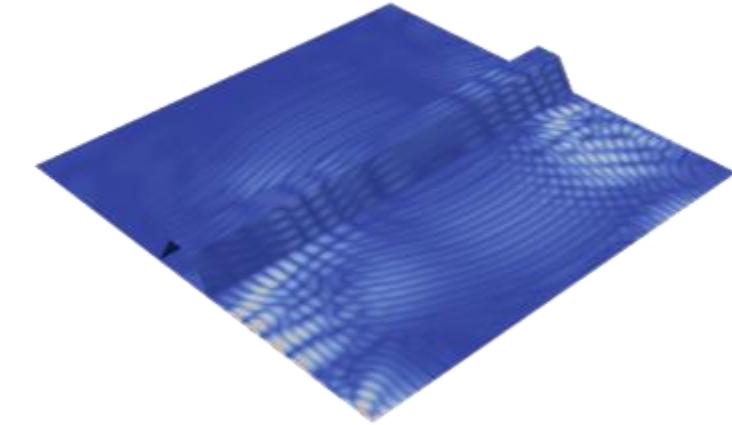
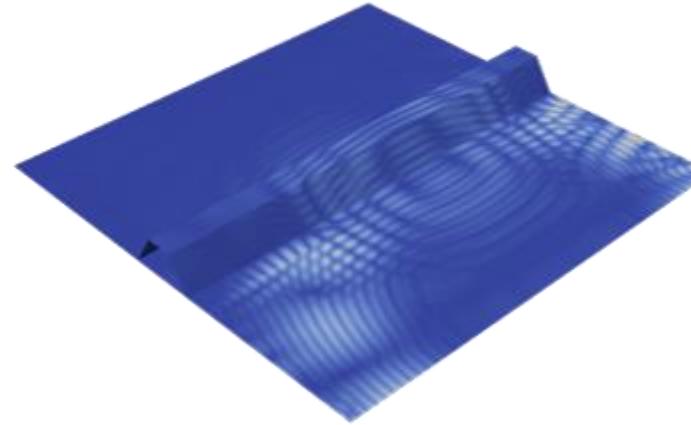
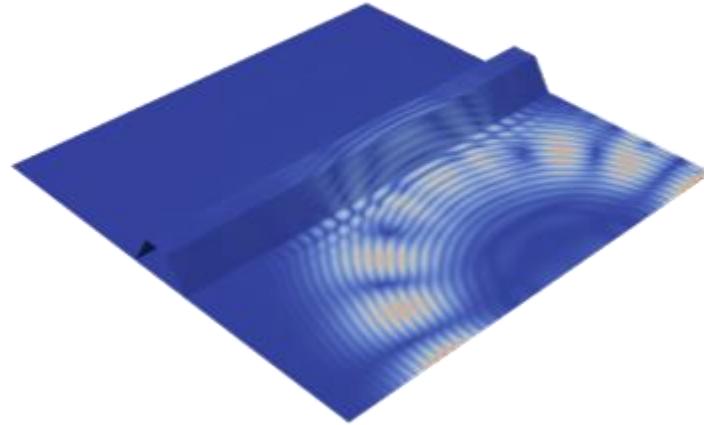
$t = 150 \mu\text{s}$



$t = 200 \mu\text{s}$

$t = 250 \mu\text{s}$

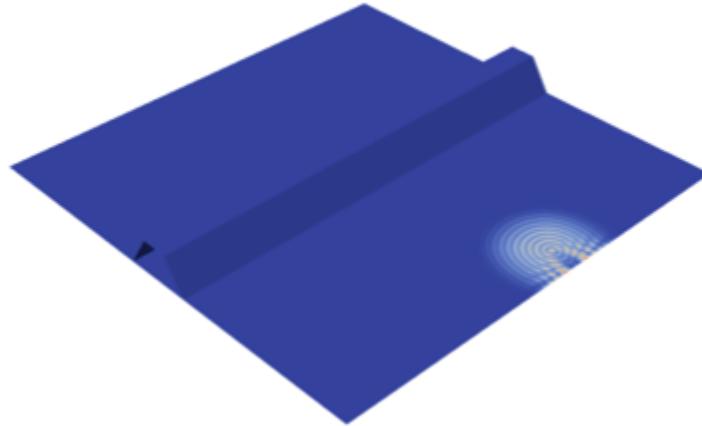
$t = 300 \mu\text{s}$



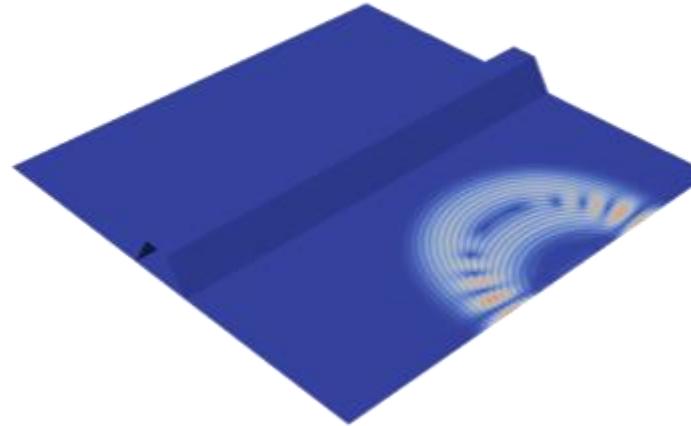
SHM plate – $f_c = 80$ kHz, Total displacement amplitudes (normalized)



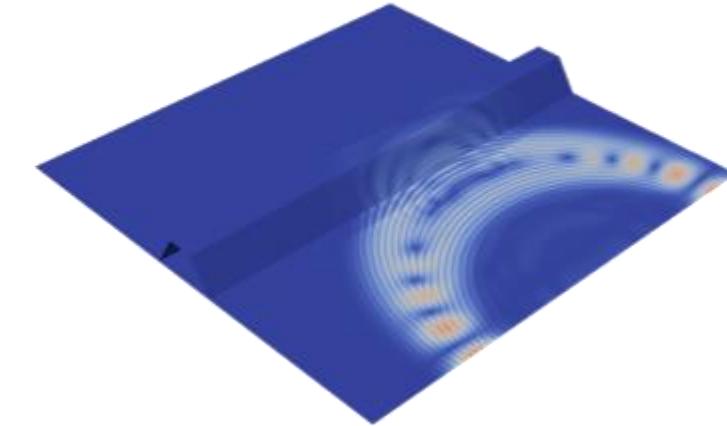
$t = 50 \mu\text{s}$



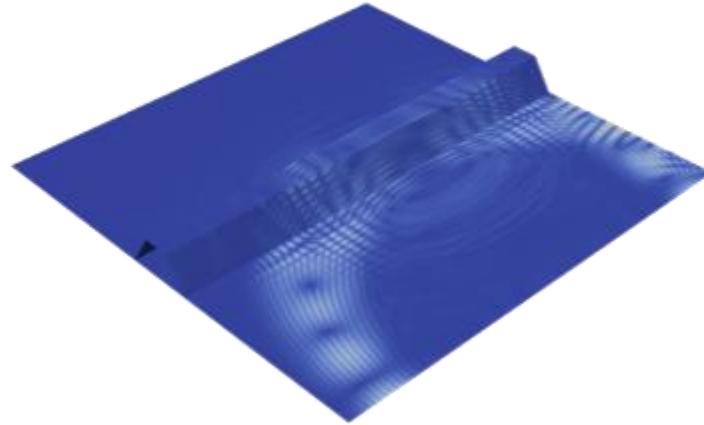
$t = 100 \mu\text{s}$



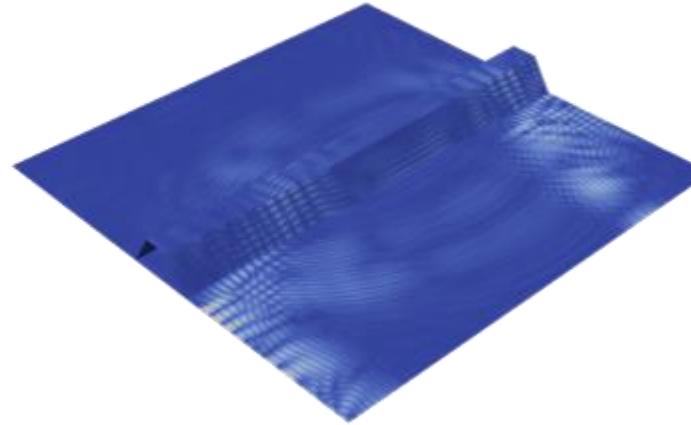
$t = 150 \mu\text{s}$



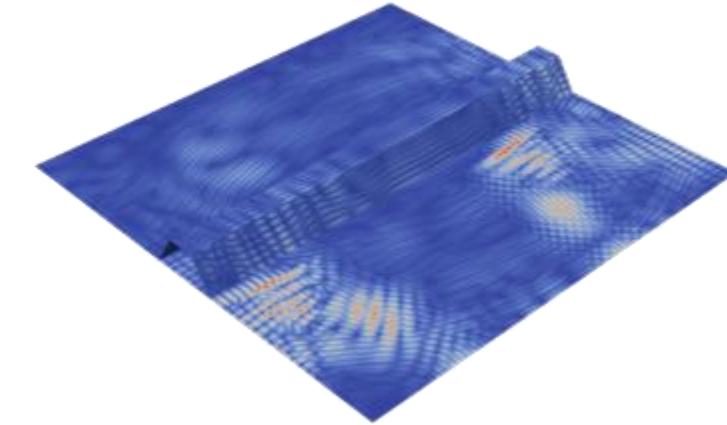
$t = 200 \mu\text{s}$



$t = 250 \mu\text{s}$



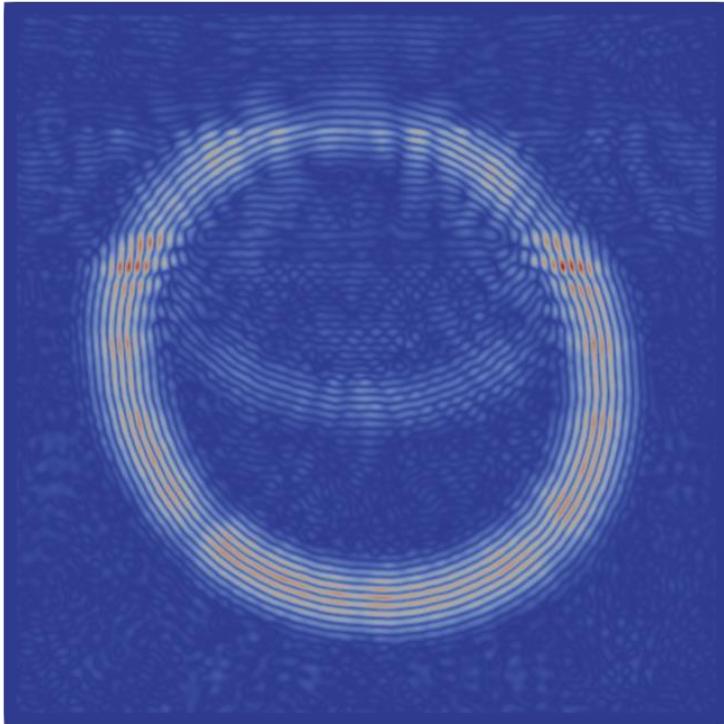
$t = 300 \mu\text{s}$



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



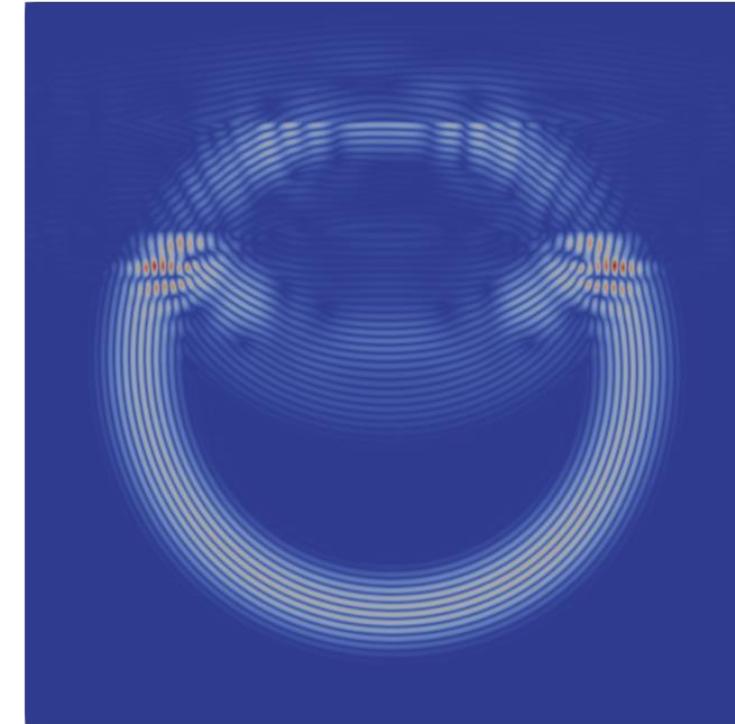
Scanning laser doppler vibrometry [KUDELA2022]



$t = 150 \mu\text{s}$

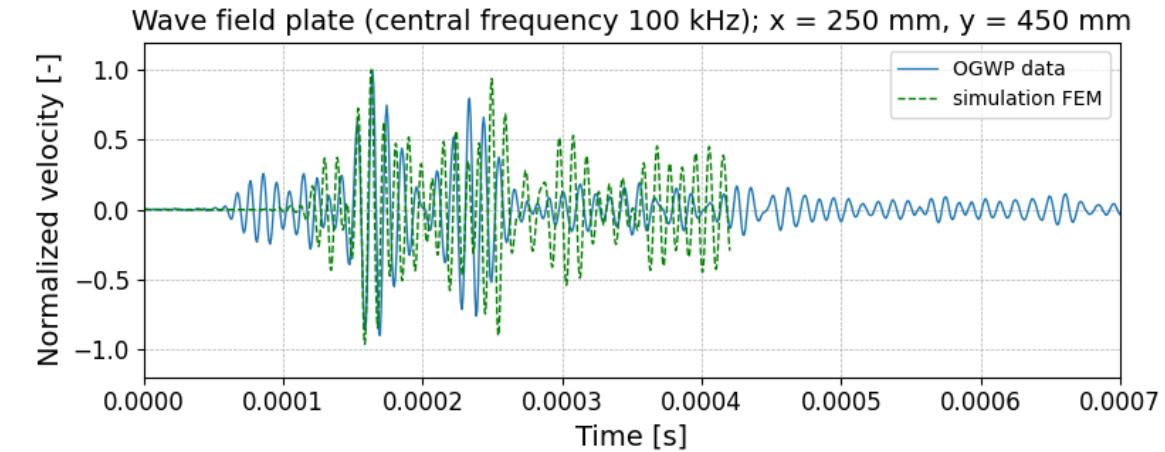
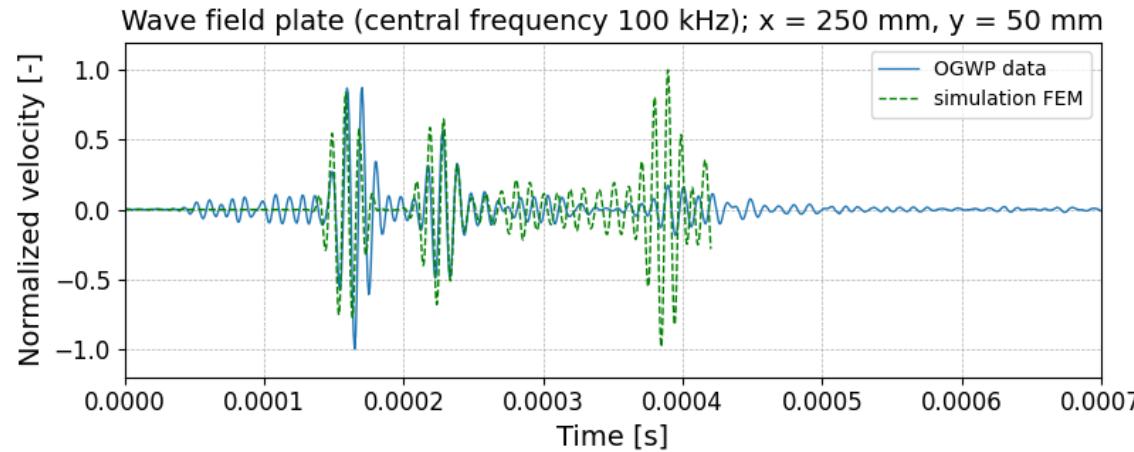
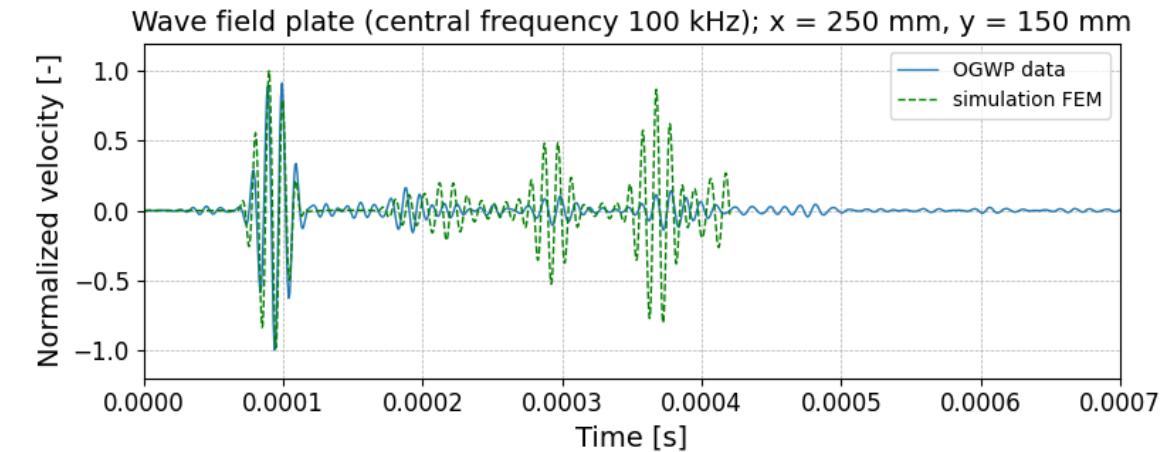
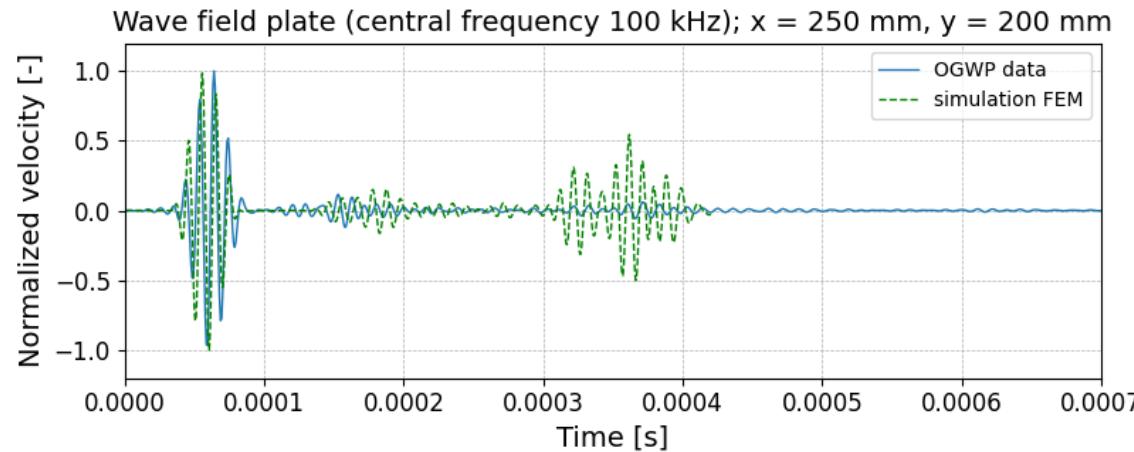
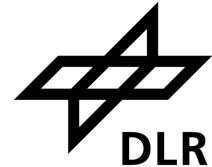
Normalized magnitudes

Simulation (FEM)



- Need for handling simulated as well as measured data

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

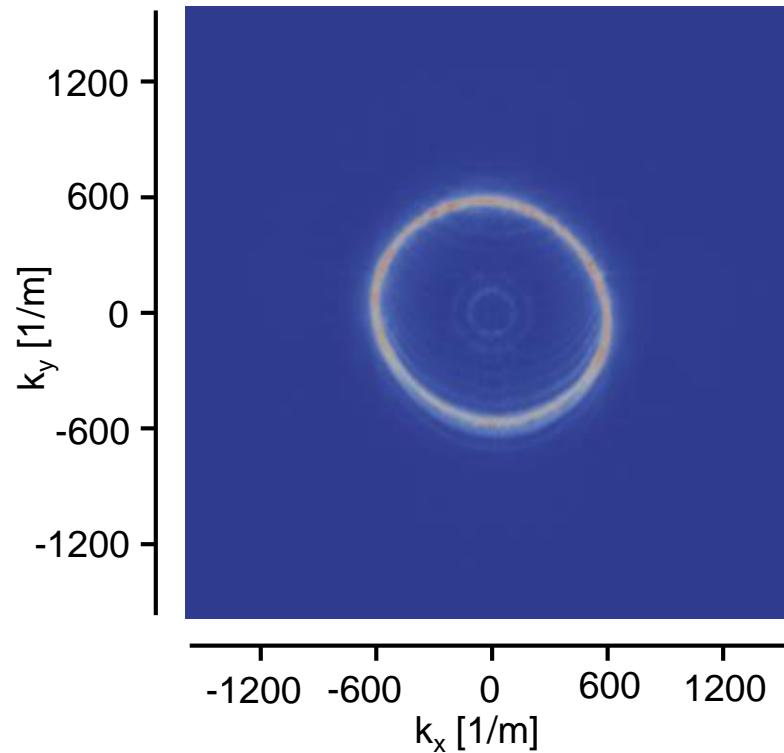


- Time-domain data recording at particular points

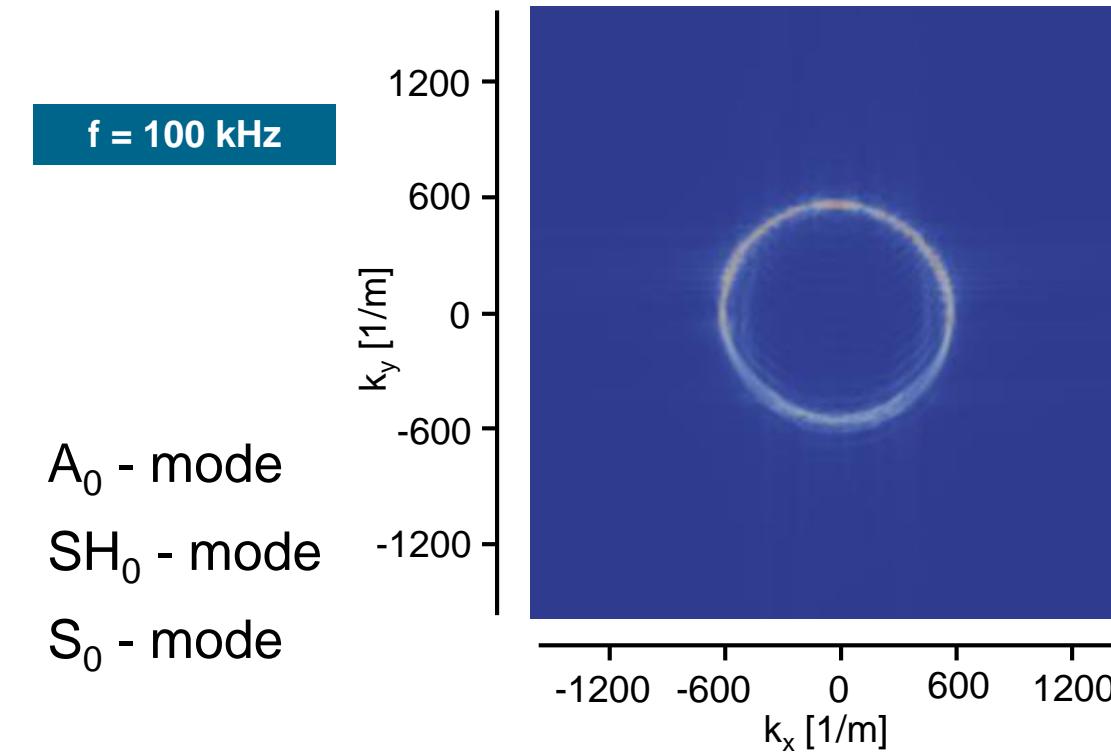
Wave field plate – $f_c = 100$ kHz, Out-of-plane wavenumber profiles



Data from scanning laser doppler vibrometry [Kudela2022]



Data from simulation (FEM)



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

GEOMETRY

1

ELEMENTS

GEOMETRYSETS

> 000000

> 000001

> 000002

> 000003

> 000004

> 000005

> 000006

> 000007

> 000008

> 000009

POINTS

MATERIAL

SYSTEM

VARIABLES

STATE-1

1

MYVALUES

STRAIN-CAUCHY

STRESS-CAUCH

STATE-10

Object Attribute Info General Object Info

Attribute Creation Order: Creation Order NOT Tracked

Number of attributes = 12

[Add Attribute](#) [Delete Attribute](#)

Name	Type
MYCOORDINATESYSTEM	32-bit integer
MYDIMENSION	32-bit integer
MYENTITY	32-bit integer
MYIDENTIFIER	32-bit integer
MYINCREMENTVALUE	32-bit integer
MYLOCATION	
MYMULTIPLICITY	
MYTIMEVALUE	
MYUNIT	
MYVARIABLEDEPENDENCY	
MYVARIABLEDESCRIPTION	
MYVARIABLENAME	

 MYVALUES at /VMAP/VARIABLES/STATE-1/1/DISPLACEMENT/ [020...][Table](#) [Import/Export Data](#) [Data Display](#)

Int

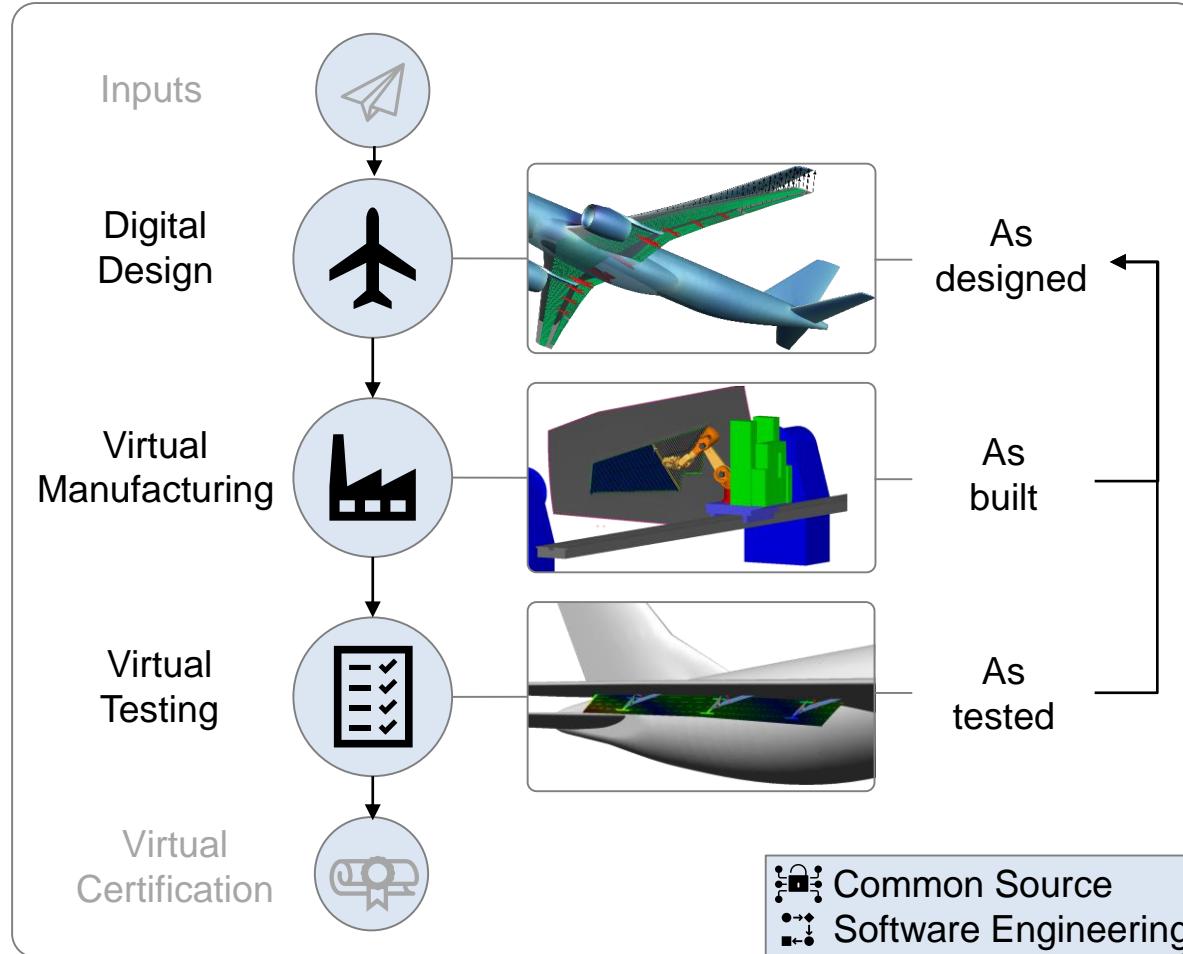
0-based

0	4.267316...	-6.20525...	-2.16256...	2.550222...	2.371430...	0.0
1	5.19959...	5.79099...	-1.86827...	3.987078...	4.527488...	0.0
2	6.297355...	-4.86071...	-1.38085...	6.433515...	7.221899...	0.0
3	6.440499...	0.0	0.0	2.430025...	4.816513...	0.0
4	4.030958...	-6.24994...	-1.96184...	3.940525...	1.536486...	0.0
5	4.000577...	5.93851...	1.48735...	5.999533...	3.812253...	0.0

SOLVER-INDEPENDENT DATA HANDLING



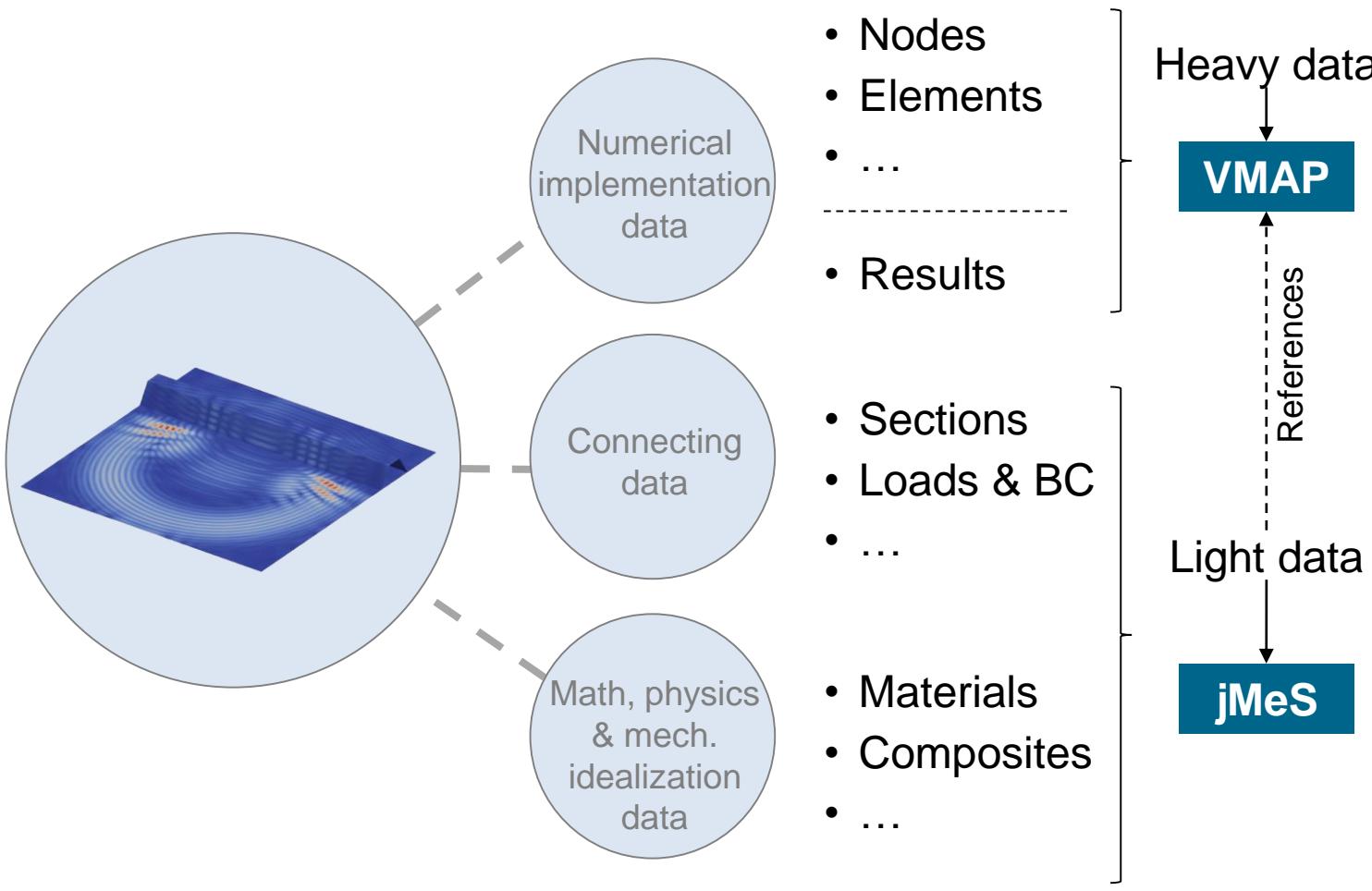
Virtual product development



- Multiple simulation steps
- Using different analysis methods
 - Numerical
 - Semi-analytical
 - Analytical
- Specific model for each step is needed
- Introducing SHM considerations into product development process
- Including experimental data to set-up and validate the process

- Solver-agnostic CSM model & result data format required

Implementing VMAP-Standard



- Standard for CAE Interoperability
- Coordinated by Fraunhofer SCAI



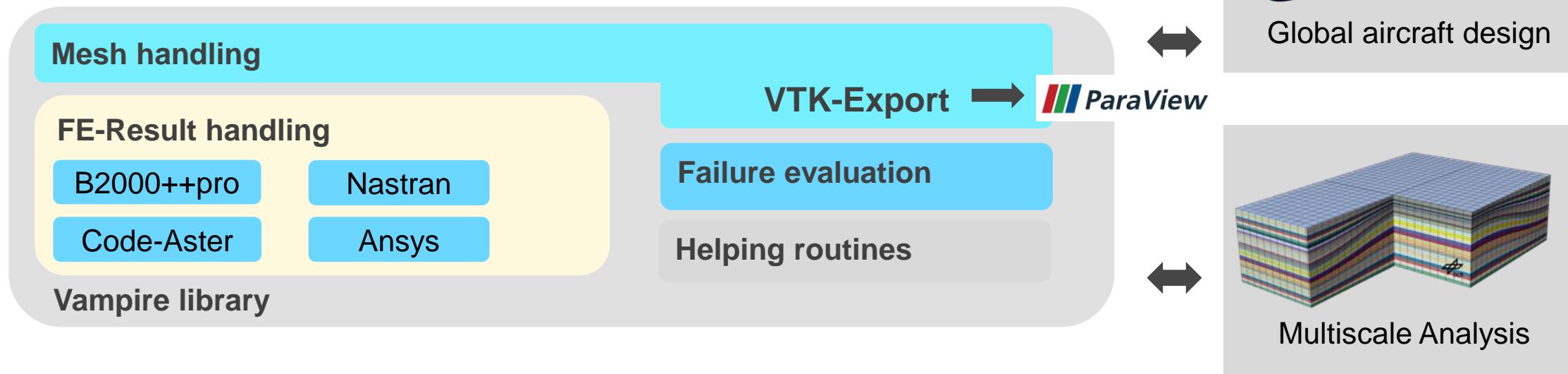
- Java Mechanics Suite (DLR)
- Conversion from & to solver-specific formats using io-plugins

- Virtual Material Modelling in Manufacturing (www.vmap.eu.com)

Vampire library

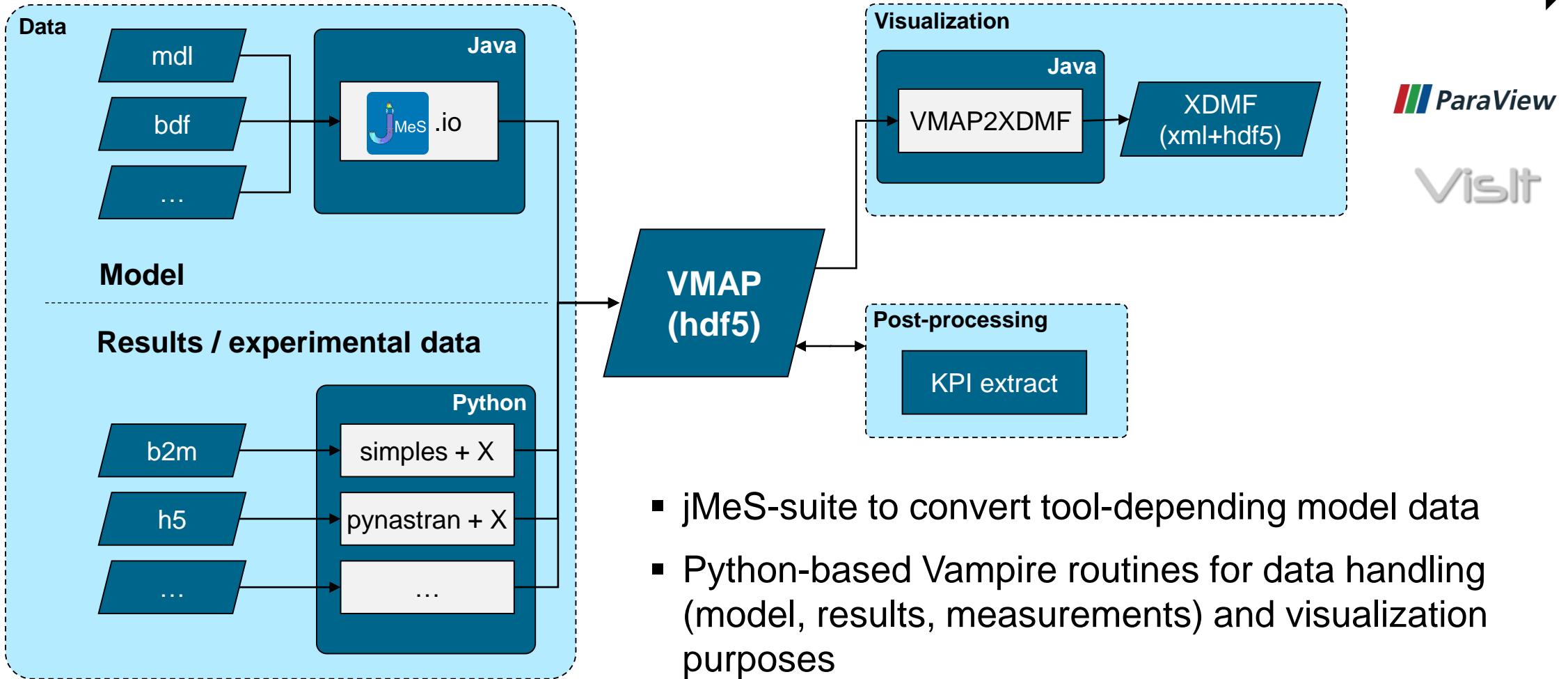


- Versatile mesh and postprocessing interface
- library for convenient mesh handling, FEM result evaluation and post-processing (failure analysis, visualization) written in Python



- Modular approach for particular implementations

Architecture concept



- jMeS-suite to convert tool-depending model data
- Python-based Vampire routines for data handling (model, results, measurements) and visualization purposes
- Usage as input/output for several DLR tools

CONCLUSIONS AND FURTHER STEPS

Conclusions



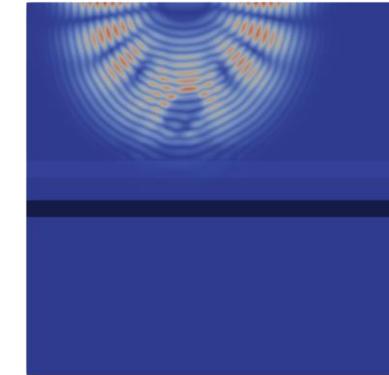
- A concept to simulate the propagation of Ultrasonic Guided Waves in **thin-walled composite structures** was developed by introducing **finite shell-elements** (FEM).
- Experimental data sets from the **Open Guided Waves Project** were taken into account for simulation validation.
- For visualization the DLR-tool **Vampire** in combination with ParaView was used.
- A data handling set-up based on the **VMAP** standard was created incorporating **jMeS** and **Vampire** routines.

Further steps

- Improvement of b2000++pro finite shell-elements regarding **Lamb waves** simulation
- Augmenting model **complexity**
 - Geometry and discretization
 - Physical phenomena and interactions
→ **imperfections, damages**
- **Model assisted** probability of detection
- Straightforward data handling based on **VMAP**-standard and **Vampire** routines



[MOLL2020]



Artificial reference damage

References



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- [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

Email: jean.lefeuvre@dlr.de

Christian Willberg

Email: christian.willberg@dlr.de

Martin Rädel

Email: martin.raedel@dlr.de

Andreas Schuster

Email: andreas.schuster@dlr.de

German Aerospace Center (DLR e.V.)

Institute of Composite Structures and Adaptive Systems

Department of Structural Mechanics

Lilienthalplatz 7, 38108 Braunschweig, Germany

www.dlr.de/fa



Thema: **Ultrasonic Guided Waves Simulation in SHM Design –
Finite Element Modeling and Model Data Handling**
International Conference on NDE 4.0 - Berlin

Datum: 25.10.2022

Autoren: Jean Lefèvre, Christian Willberg, Martin Rädel, Andreas Schuster

Institut: Institut für Faserverbundleichtbau und Adaptronik (DLR FA)

Bildcredits: DLR