

The Dispersion Calculator: a free software for calculating dispersion curves of guided waves

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EVIDENT

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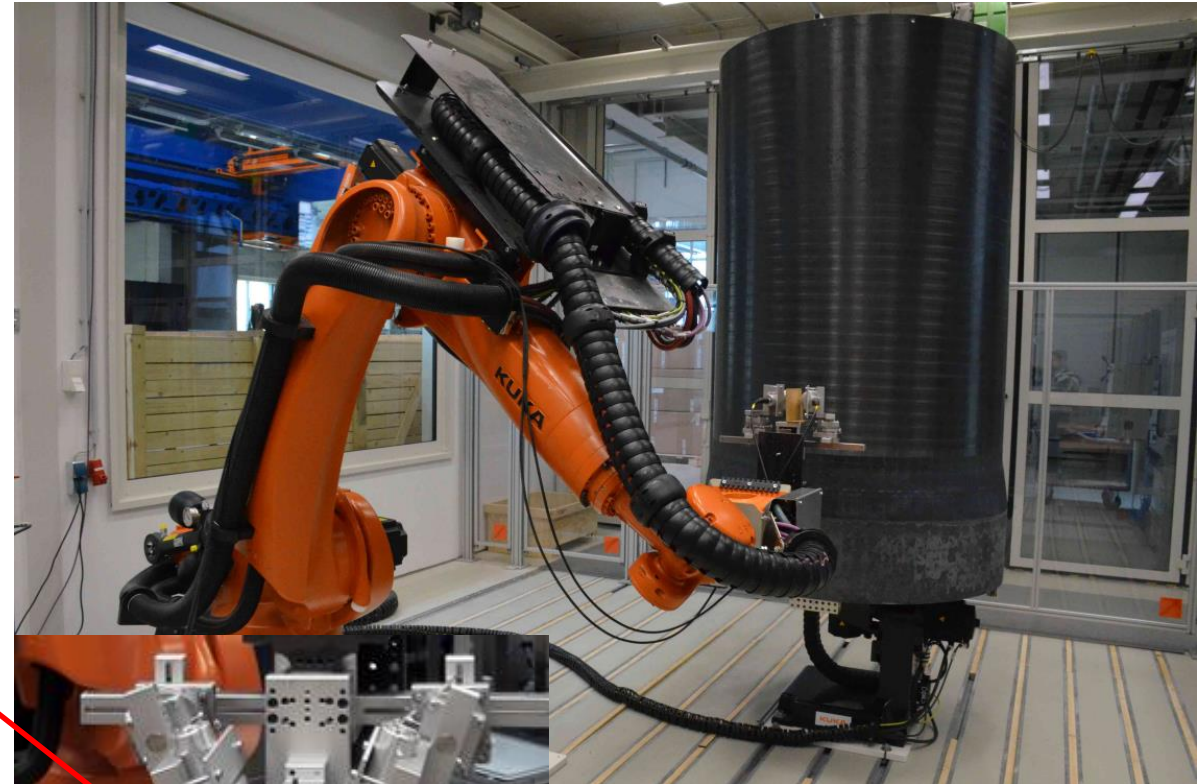
27-31 May 2024



Why developing the Dispersion Calculator (DC)?

2016

- Air-coupled ultrasonic inspection of composite rocket booster pressure vessels
- Excitation of Lamb waves by slanted incidence
- Lamb waves are dispersive → Incidence angle is too
- No free software for calculating dispersion diagrams available (except GUIGUW) → Purchase DISPERSE



$d = 48 \text{ mm}$
360 layers

Why developing the Dispersion Calculator (DC)?



2016

- DISPERSE cannot handle so many layers
- Starting with small MATLAB scripts:
 - Rayleigh-Lamb equations for isotropic single layers
 - Transfer Matrix Method (TMM) for isotropic and anisotropic multilayers
 - encountering the numerical instability in TMM
 - Came across the Stiffness Matrix Method (SMM)
 - numerically stable and perfectly suited for many layers

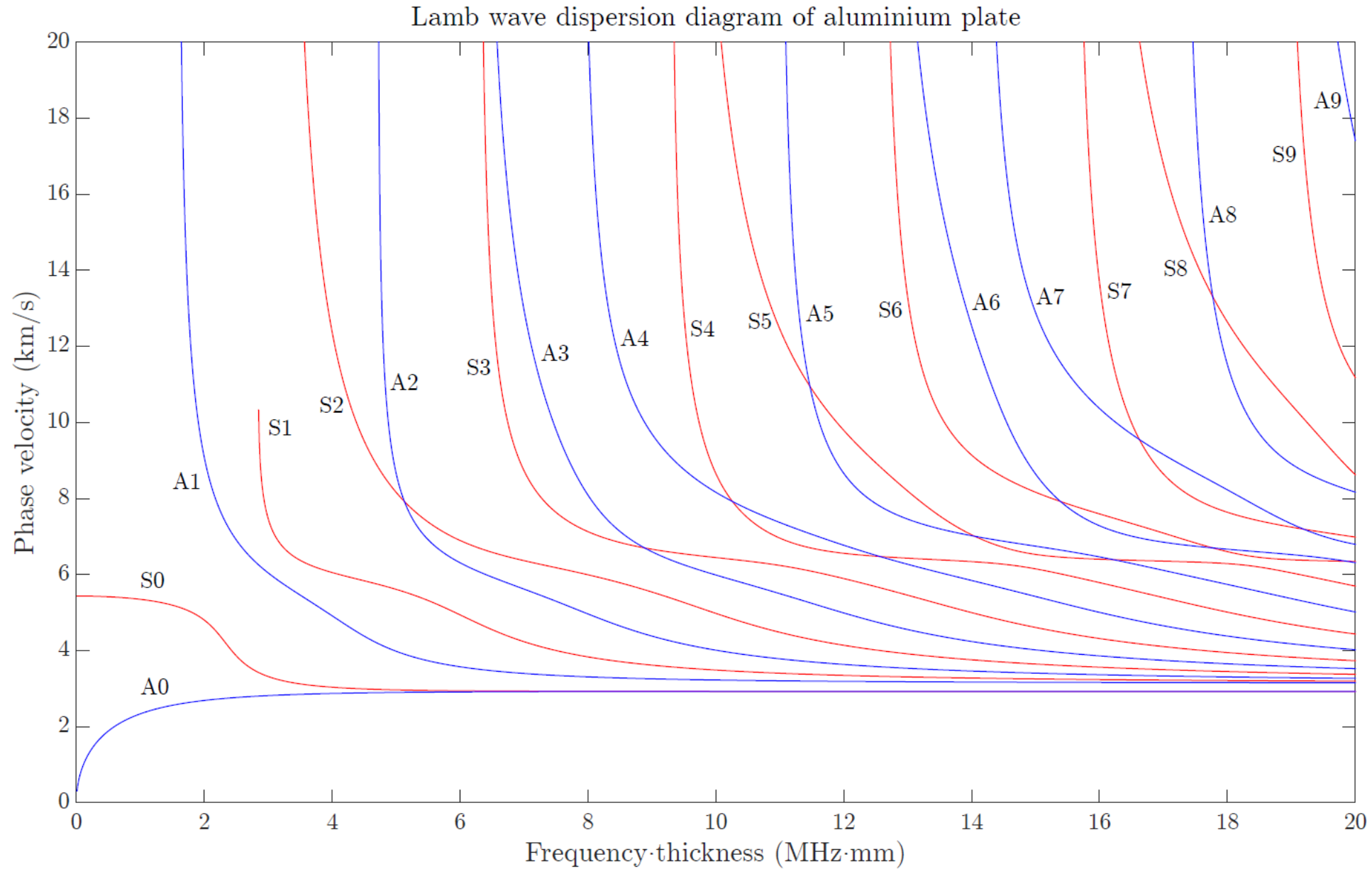


Phase velocity

$$c_p = \frac{\omega}{k}$$

ω angular frequency

k wavenumber

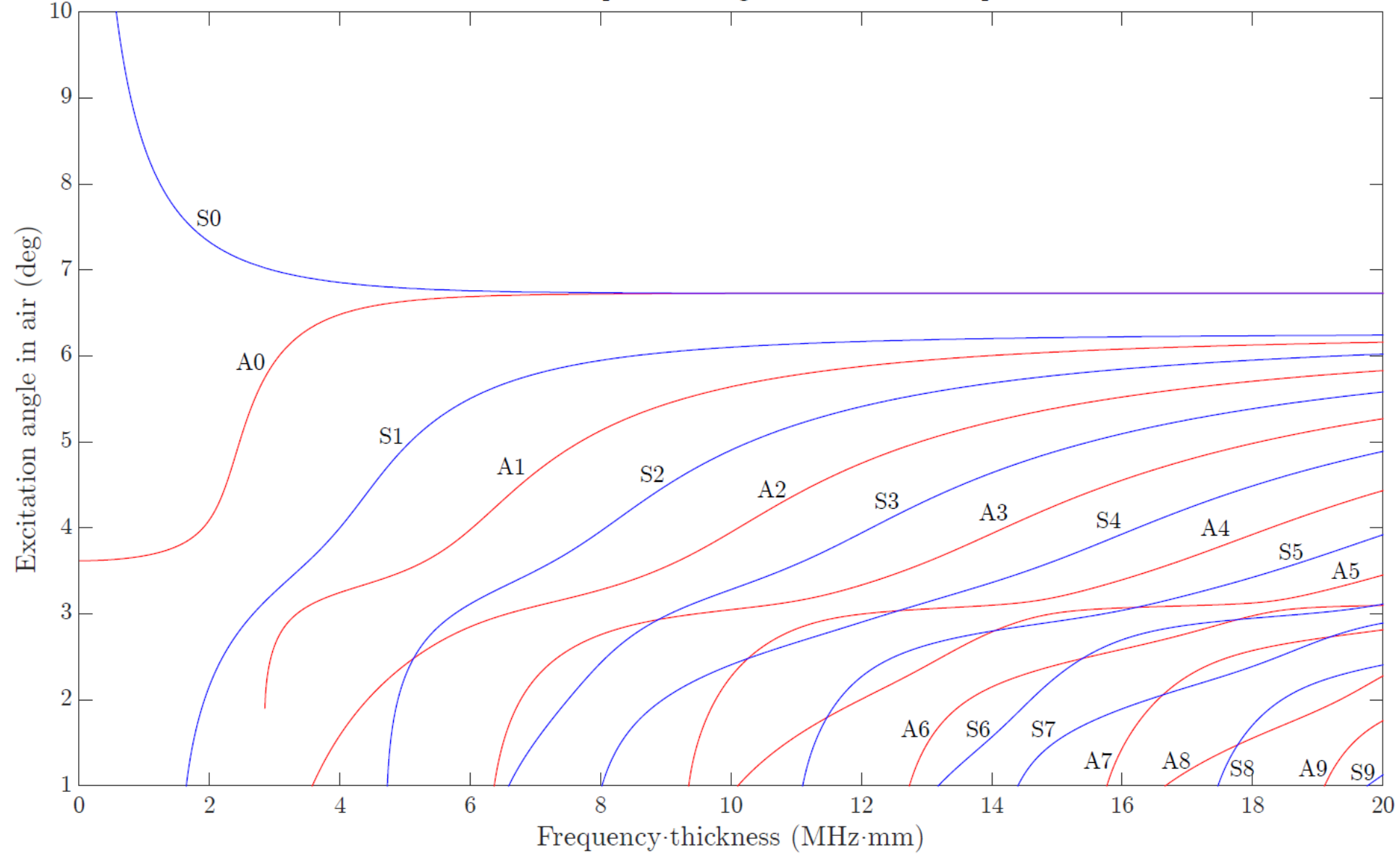




Incidence angle

$$\theta = \sin^{-1} \left(\frac{c_{pAir}}{c_{pLamb}} \right)$$

Lamb wave dispersion diagram of aluminium plate

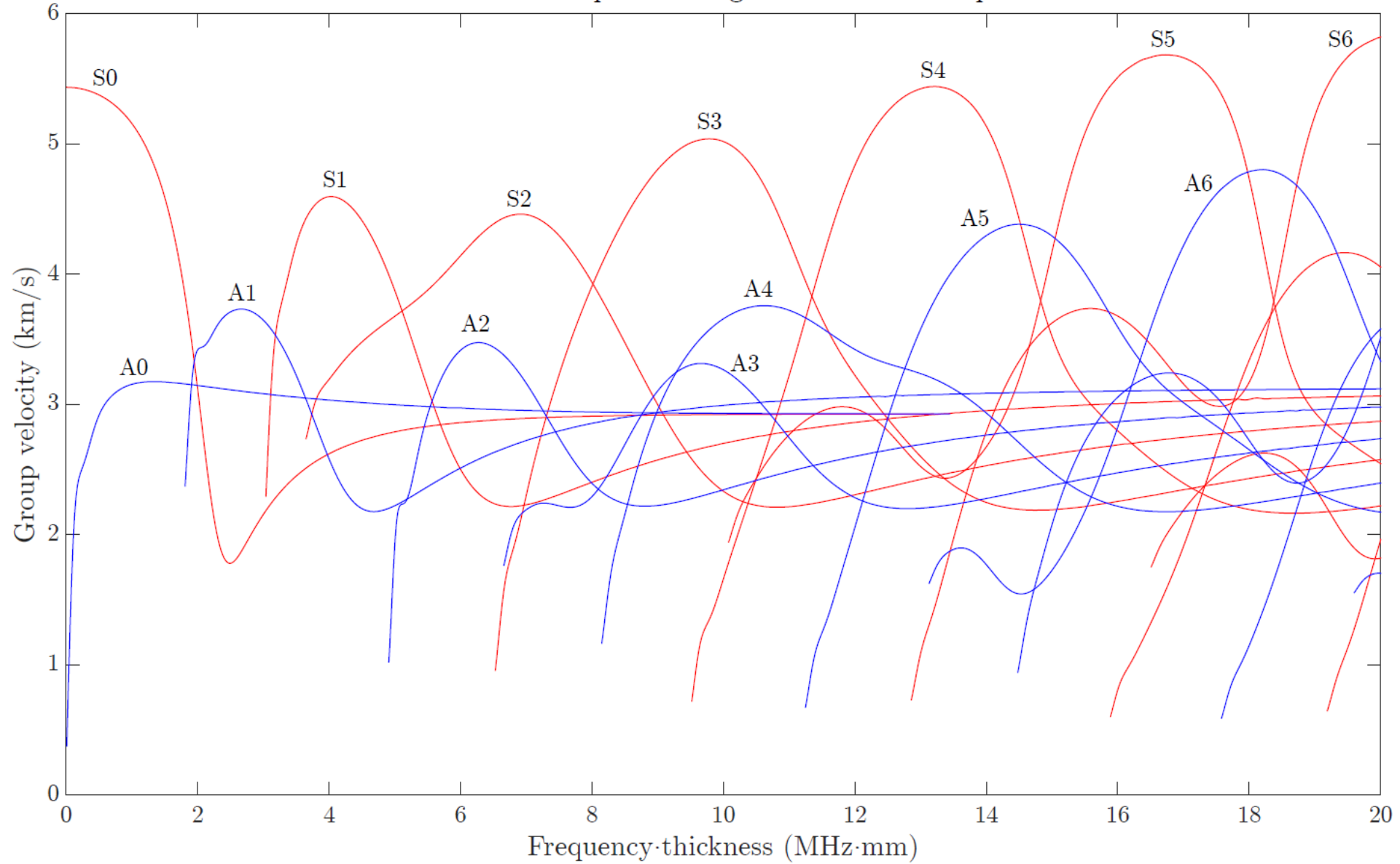




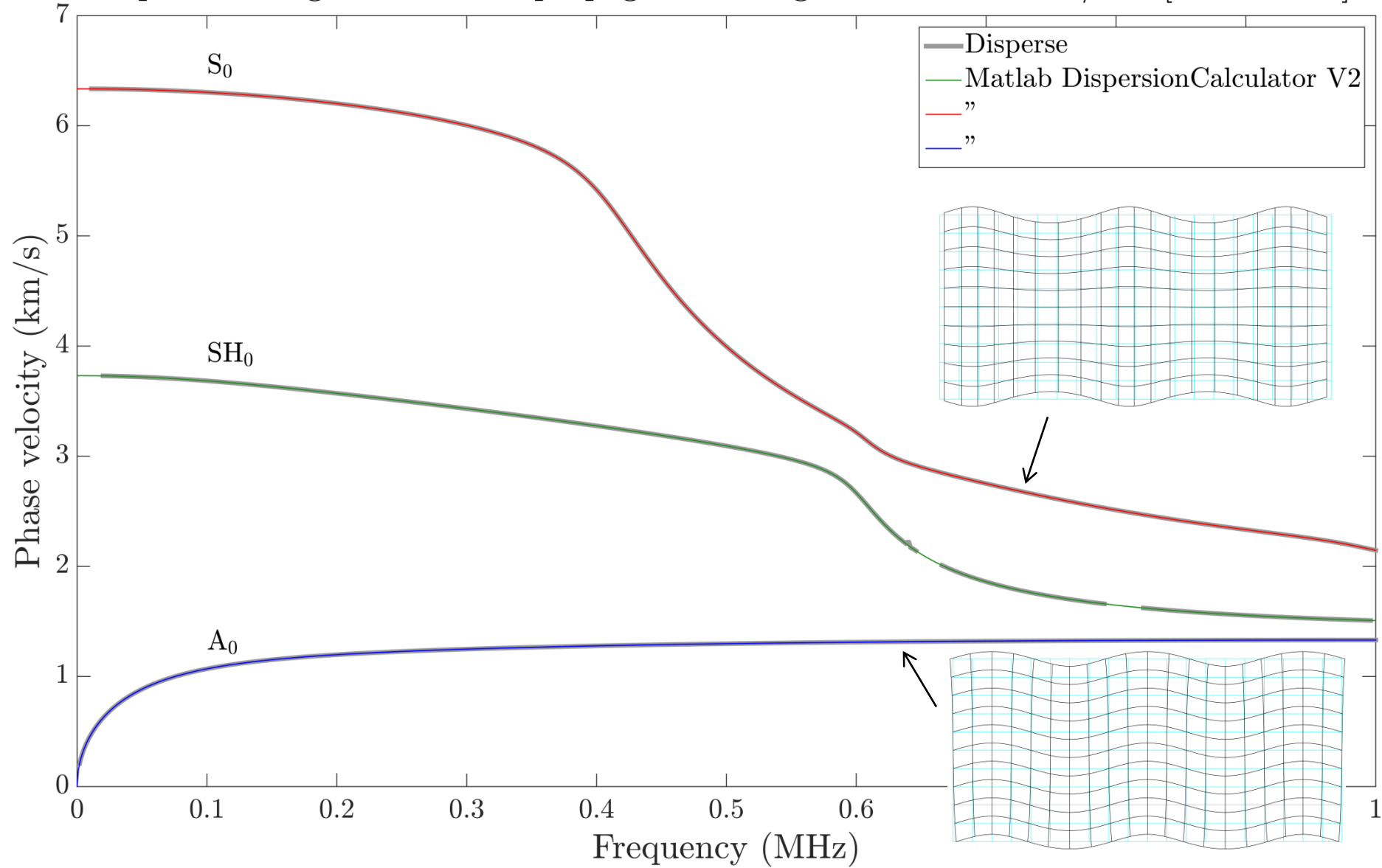
Lamb wave dispersion diagram of aluminium plate

Group velocity

$$c_{\text{gr}} = \frac{d\omega}{dk}$$



Dispersion diagram for wave propagation along 5° in 2 mm T800/913 $[0\ 45\ 90\ -45]_2$



- Early 2018: Decision to create a software → work on GUI
- November 2018: DC v1.0
 - Dispersion diagrams and mode shapes for Lamb and SH waves in isotropic and multilayered anisotropic plates
 - Versions 1.0 through 1.11
- April 2022: DC v2.0
 - Damping through fluid-loading (leaky waves) and viscoelasticity
 - Current version is 2.4



Most important tools currently available



Tool	Authors	Initial release	Computation method	GUI	Free
DISPERSE	Lowe, Pavlakovic	Early 1990s	Global Matrix Method (currently upgraded to Spectral Collocation Method)	Yes	No
GUIGUW	Marzani, Bocchini	2011	Semi-analytical Finite Element Method	Yes	Yes
DC	Huber	2018	Stiffness Matrix Method	Yes	Yes
ElasticMatrix	Ramasawmy et al.	2020	Global Matrix Method	No	Yes
Dispersion Box	Orta et al.	2022	GMM, SMM, HCSMM, SAFE, LPM, 5-SDT	Yes	Yes
SAFEDC	Liu et al.	2022	Semi-analytical Finite Element Method	Yes	Yes
GEWtool	Kiefer	2023	Spectral Element Method	No	Yes

Isotropic materials

Material: AluminumAlloy1100

Mass density (kg/m3): 2710

Engineering constants		Stiffness components (GPa)	
	Real part	Imaginary part	
E (GPa)	69	0	C11
v	0.33	0	C66

Bulk waves

Longitudinal velocity (m/s): 6142.03

Shear velocity (m/s): 3093.85

Attenuation unit: Np/λ

Longitudinal attenuation (Np/λ): 0

Shear attenuation (Np/λ): 0

At frequency (kHz): 1000

New material's name: AluminumAlloy1100

Save material Delete material

Fluids

Fluid: air

Mass density (kg/m3): 1.2

Velocity (m/s): 343

New fluid's name: air

Save fluid Delete fluid

Anisotropic materials

Class: Orthotropic

Material: CarbonEpoxy2_Rokhlin_2011

Mass density (kg/m3): 1610

Engineering constants		Stiffness components (GPa)						
	Real part	Imaginary part	Real part			Imaginary part		
E1 (GPa)	150.912	0	162	10.6	13	0	0	0
E2 (GPa)	11.5473	0		15.3	8.2	0	0	0
E3 (GPa)	13.9589	0			18.7	0	0	0
G12 (GPa)	7.2	0				4.4	0	0
G13 (GPa)	8.8	0					8.8	0
G23 (GPa)	4.4	0						7.2
v12	0.418605	0	0	0	0	0	0	0
v13	0.511628	0		0	0	0	0	0
v23	0.416235	0			0	0	0	0

Bulk wave velocities (m/s)

	1	2	3
Longitudinal velocity	10031	3082.71	3408.06
Fast shear velocity	2337.91	2114.72	2337.91
Slow shear velocity	2114.72	1653.15	1653.15

New material's name: CarbonEpoxy2_Rokhlin_2011

Save material Delete material



Specimen

Edit

Fluids vacuum vacuum

Material CarbonEpoxy2_Rokhlin_2011

Layup [0/90]2s

Effective [0/90]2s

Layers, d (mm) 8 1

Computational settings

Propagation angle (°) 0

Phase velocity limit (m/ms) 20

Frequency limit (kHz) 4000

Frequency step (kHz) 10

Mode selection

Higher order modes

Symmetric modes

Antisymmetric modes

Lamb modes

Shear horizontal modes

Scholte modes

Manually detect higher order modes

Step (kHz) 1 Detect

Frq. @ 20 m/ms:		Frq. @ 20 m/ms:	
Mode	Frq.(kHz)	Mode	Frq.(kHz)
A1	996.257	S1	1684.950
A2	2864.495	S2	2073.255
A3	3486.955	S3	3969.649
ASH1	1003.201	SSH1	1912.474
ASH2	3148.374	SSH2	3788.795

Calculate Stop calculation

Dispersion diagrams

Quantity Phase velocity (m/ms)

Bulk velocities

X-axis mode Frequency (kHz)

X-axis (kHz) [0 4000]

Y-axis (m/ms) [0 20]

Plot

Through-thickness profiles

Quantity Displacement

Mode A0

Frequency (kHz) 4000

Samples per layer 63

Half-spaces 1

Phase

11 12 1

22 2

3

Plot

Mode shape

Mode A0

Frequency (kHz) 4000

Wavelengths 2.5

Samples x1 80

Samples per layer 5

Scale 1

Grid line 2 Half-spaces 1

Undistorted

Animation settings

Cycles 1

Cycle duration (s) 1.5

Frame rate (Hz) 30

Movie quality (0-100) 75

Animate

Plot

Export settings

Export plots PDF Dispersion curves Frequency (kHz)

Crop plots PNG Through-thickness

PNG resolution (dpi) 150 *.mat *.xlsx *.txt Horizontal arran...

File name File name

Directory C:\

Plot layout settings

Title with layout

Mode labels

Legend location outside

Box line width 0.5

Curve line width 1

Dispersion curve colors [R G B]

S [1 0 0]

A [0 0 1]

B [5 0 1]

Mode labels x-position (0-1)

S0/B1 0.05

SSH0/BSH0 0.05

A0/B0 0.05

Font size

Title 30

Axes labels 30

Axes ticks 24

Mode labels 24

Legend 24

Default

A: 3 S: 3
ASH: 2 SSH: 2



DC Specimen_Anisotropic

Open Save Reset

Upper fluid water

Lower fluid water

Hybrid

Class Transversely isotropic

Material T800M913

Uniform layer thickness

Total thickness (mm) 4

Unit cell repetitions 1

Symmetric system

OK Cancel

Unit cell

	Phi (°)	d (mm)	Orthotropic	Trans. iso.	Cubic	Isotropic	Delete
1	0	0.5000	▼	▼	▼	AluminumAlloy6l ▼	<input type="checkbox"/>
2	25	0.2500	▼	TVR380M12R_G ▼	▼	▼	<input type="checkbox"/>
3	-25	0.2500	▼	TVR380M12R_G ▼	▼	▼	<input type="checkbox"/>
4	25	0.2500	▼	TVR380M12R_G ▼	▼	▼	<input type="checkbox"/>
5	-25	0.2500	▼	TVR380M12R_G ▼	▼	▼	<input type="checkbox"/>
6	25	0.2500	▼	TVR380M12R_G ▼	▼	▼	<input type="checkbox"/>
7	0	0.2500	▼	▼	▼	AluminumAlloy6l ▼	<input type="checkbox"/>
8			▼	▼	▼	▼	<input type="checkbox"/>
9			▼	▼	▼	▼	<input type="checkbox"/>
10			▼	▼	▼	▼	<input type="checkbox"/>
11			▼	▼	▼	▼	<input type="checkbox"/>
12			▼	▼	▼	▼	<input type="checkbox"/>
13			▼	▼	▼	▼	<input type="checkbox"/>
14			▼	▼	▼	▼	<input type="checkbox"/>
15			▼	▼	▼	▼	<input type="checkbox"/>

Specimen

Edit

Fluids vacuum vacuum

Material CarbonEpoxy2_Rokhlin_2011

Layup [0/90]2s

Effective [0/90]2s

Layers, d (mm) 8 1

Computational settings

Propagation angle (°) 0

Phase velocity limit (m/ms) 20

Frequency limit (kHz) 4000

Frequency step (kHz) 10

Mode selection

Higher order modes

Symmetric modes

Antisymmetric modes

Lamb modes

Shear horizontal modes

Scholte modes

Manually detect higher order modes

Step (kHz) 1 Detect

Frq. @ 20 m/ms:		Frq. @ 20 m/ms:	
Mode	Frq.(kHz)	Mode	Frq.(kHz)
A1	996.257	S1	1684.950
A2	2864.495	S2	2073.255
A3	3486.955	S3	3969.649
ASH1	1003.201		
ASH2	3148.374		

Calculate Stop calculation

Dispersion diagrams

Quantity Phase velocity (m/ms)

Bulk velocities

X-axis mode Frequency (kHz)

Through-thickness profiles

Quantity Displacement

Mode A0

Frequency (kHz) 4000

Samples per layer 63

Half-spaces 1

Plot layout settings

Title with layout

Mode labels

Legend location outside

Box line width 0.5

Curve line width 1

Dispersion curve colors [R G B]

S [1 0 0]

A [0 0 1]

B [5 0 1]

Mode labels x-position (0-1)

S0/B1 0.05

SSH0/BSH0 0.05

A0/B0 0.05

Font size

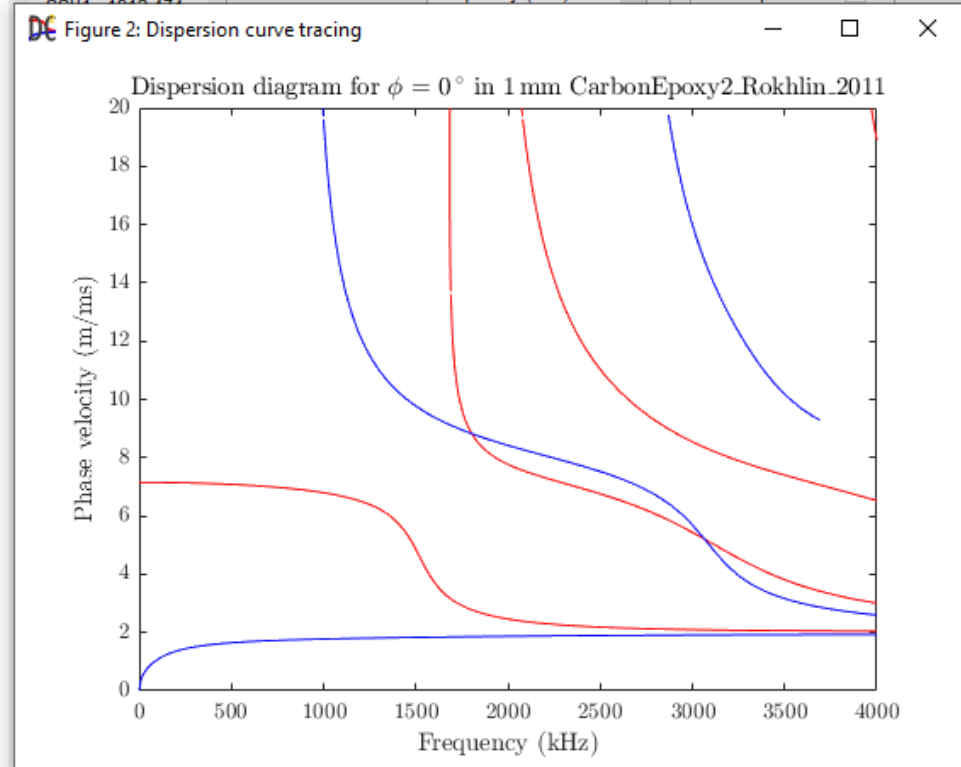
Title 30

Axes labels 30

Axes ticks 24

Mode labels 24

Legend 24



Crop plots PNG Through-thickness

PNG resolution (dpi) 150

*.mat *.xlsx *.txt Horizontal arran...

File name File name

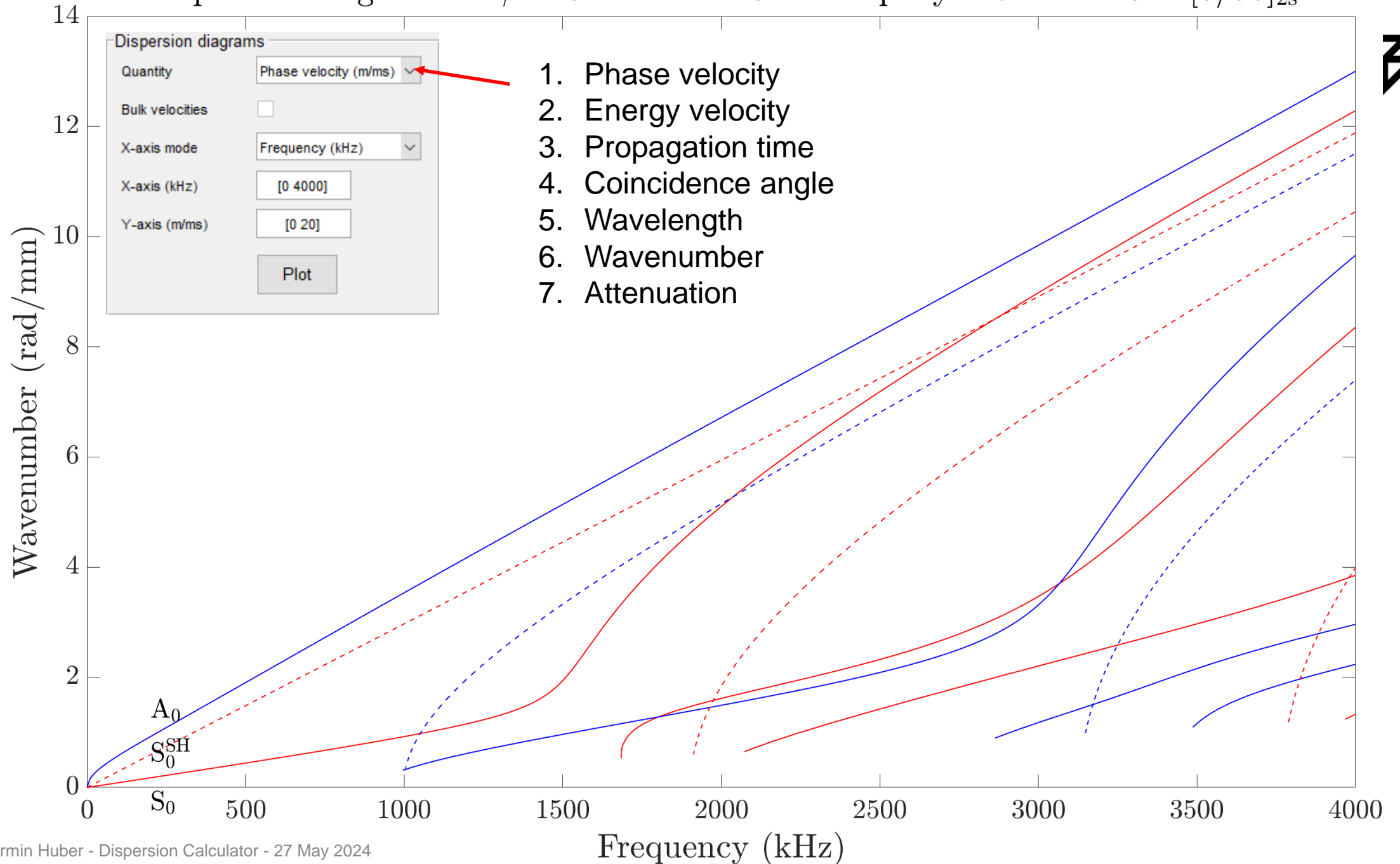
Directory C:\

A: 3 S: 3

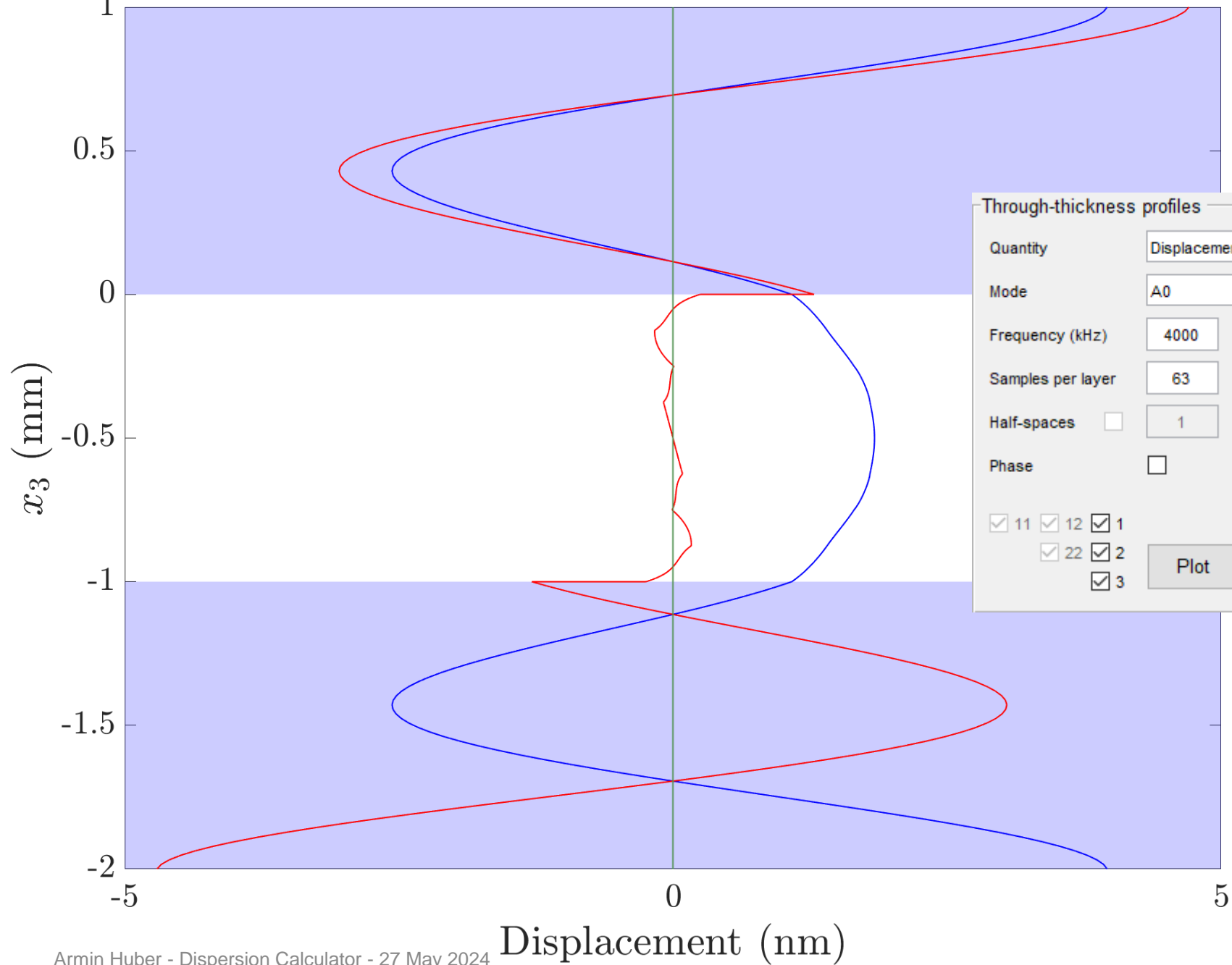
ASH: 2 SSH: 2



Dispersion diagram for $\phi = 0^\circ$ in 1 mm CarbonEpoxy2_Rokhlin_2011 $[0/90]_{2s}$



A_0 @ 2000 kHz for $\phi = 0^\circ$ in 1 mm CarbonEpoxy2_Rokhlin_2011 $[0/90]_{2s}$ in water/water



— Out-of-plane (u_3)
— In-plane (u_1)
— Shear horizontal (u_2)

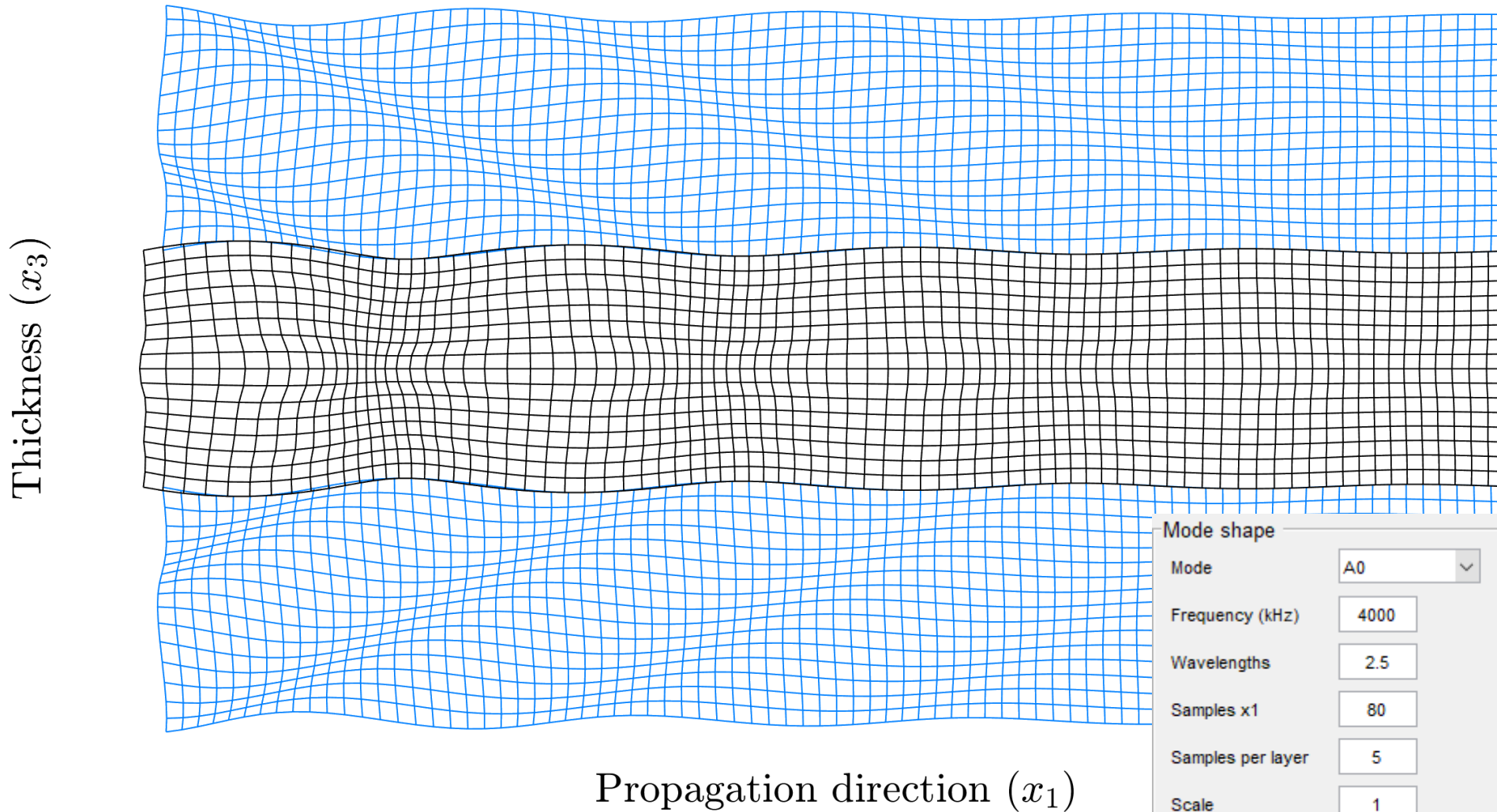
Through-thickness profiles

Quantity: Displacement
Mode: A0
Frequency (kHz): 4000
Samples per layer: 63
Half-spaces: 1
Phase:

11 12 1
 22 2
 3

Plot

1. Displacement
2. Stress
3. Strain
4. Energy density
5. Power flow density



Mode shape

Mode	A0	
Frequency (kHz)	4000	
Wavelengths	2.5	
Samples x1	80	
Samples per layer	5	
Scale	1	
Grid line	2	Half-spaces 1
Undistorted	<input type="checkbox"/>	<input type="checkbox"/>

Animation settings

Cycles	1
Cycle duration (s)	1.5
Frame rate (Hz)	30
Movie quality (0-100)	75
Animate	<input type="checkbox"/>

Plot

AluminumAlloy1100

Computational settings

Frequency (kHz)

Cycles, Samples/cycle

Window

Distance (mm)

n-Distance/ce

Spectral threshold (%)

Displacement component

Gate (μs)

Multi-mode

Mode selection and magnification

A0 1 S0 1 ASH1 1 SSH0 1

A1 1 S1 1 ASH2 1 SSH1 1

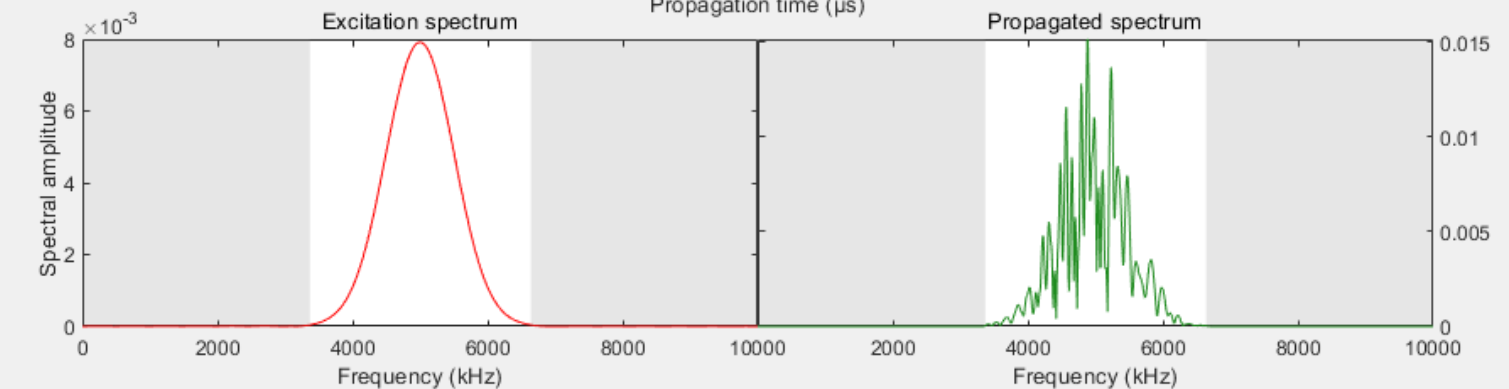
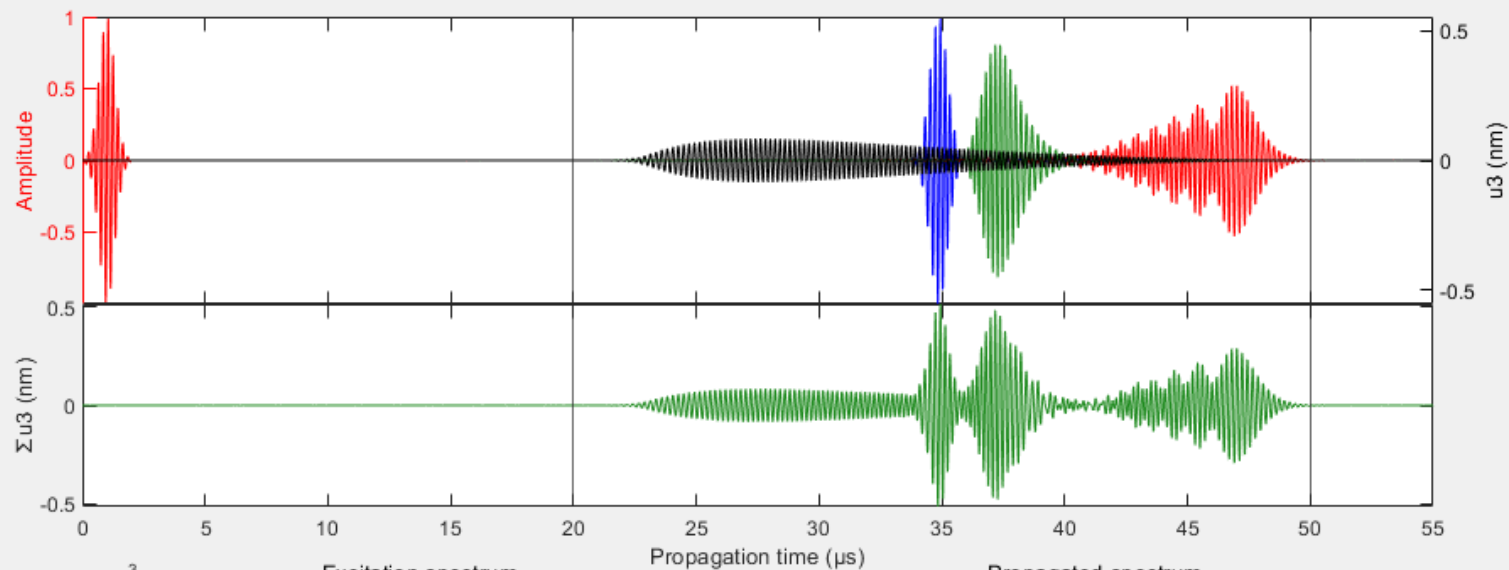
A2 1 S2 1

TIME DOMAIN:
 Time limit: 174 micsec
 Coh. time (original): 100 micsec
 Coh. time (interp.): 167 micsec
 Sample rate: 100 MHz
 Samples: 17401

FREQUENCY DOMAIN:
 Spectral range: 3370 - 6640 kHz
 Res. (original): 10 kHz
 Res. (interp.): 6 kHz
 Frequencies: 546

X-axis (μs)

Y-axis (nm)



Export settings

Export plots PDF

Crop plots PNG

PNG resolution (dpi)

File name

Directory

Plot layout settings

Title

Box line width

Curve line width

Font size

Title

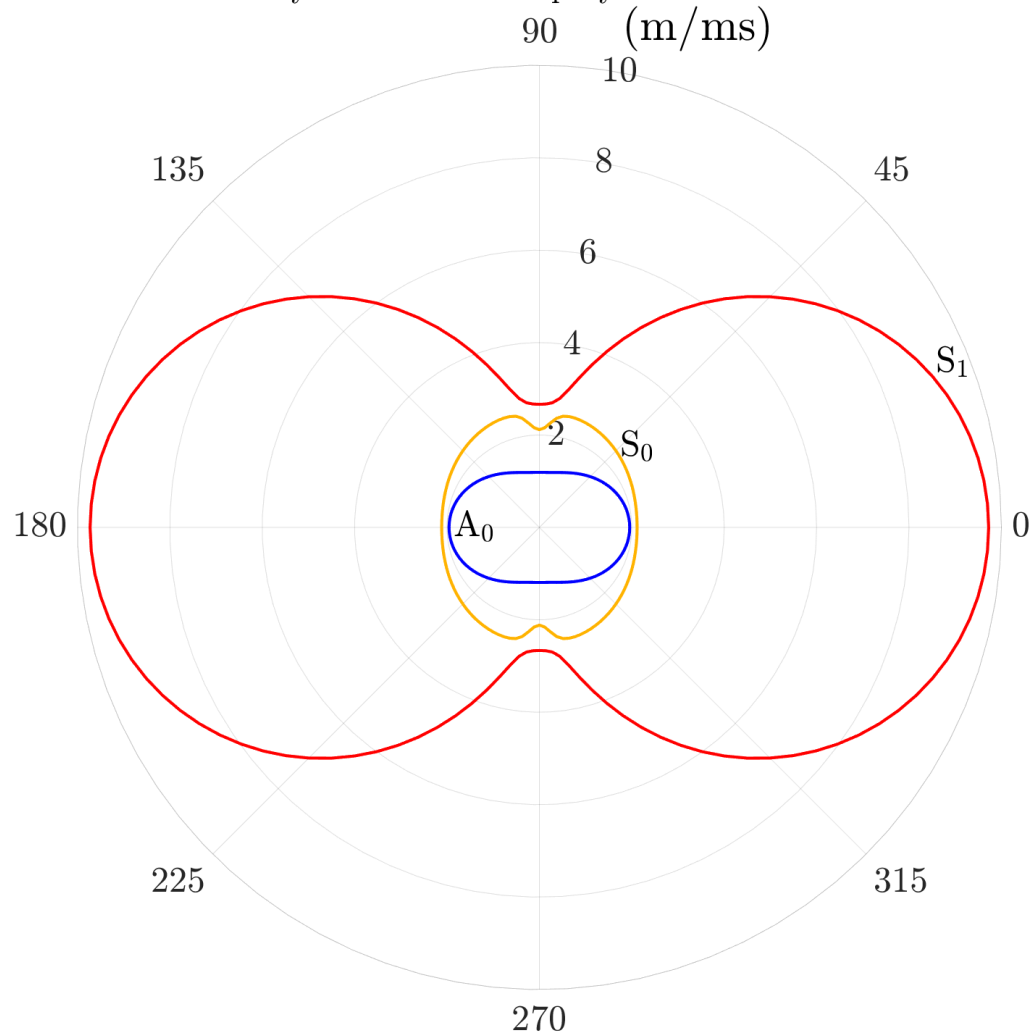
Axes labels

Axes ticks

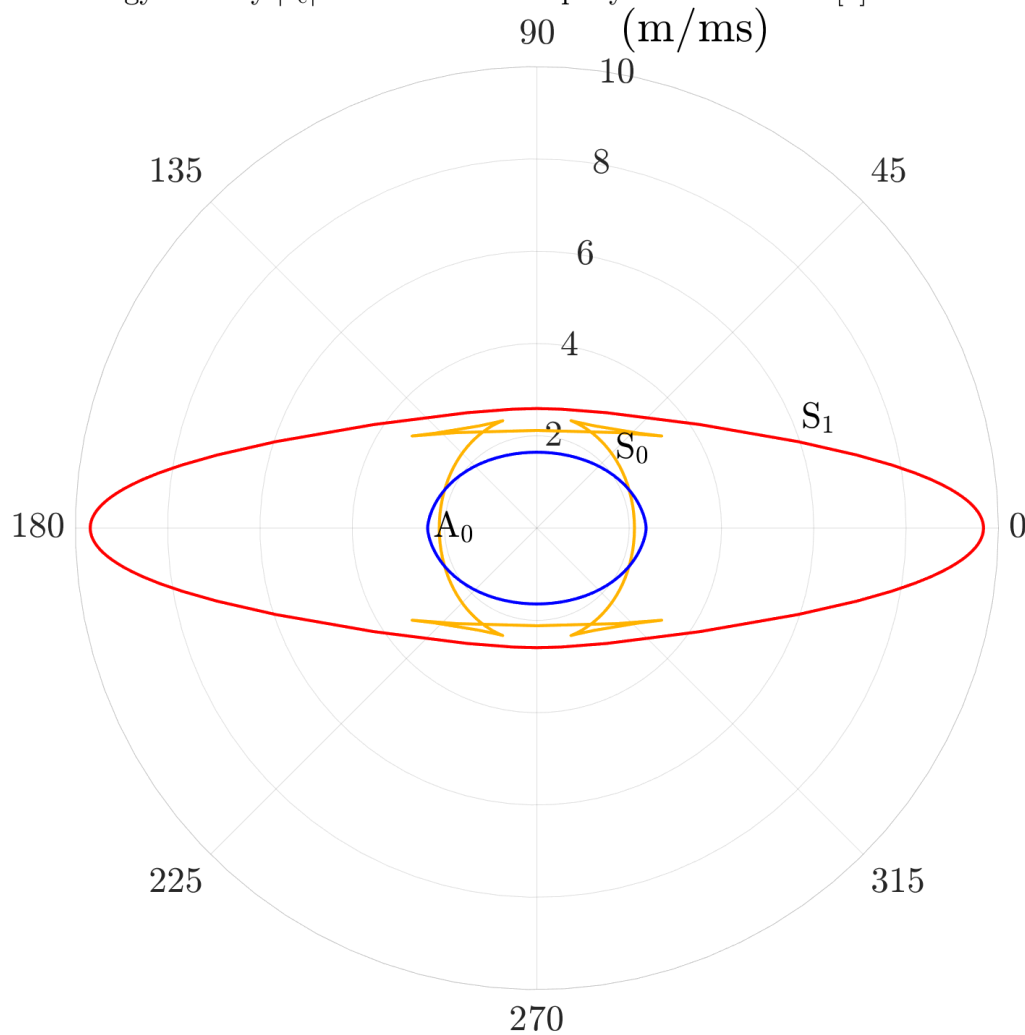


Polar dispersion diagrams

Phase velocity in 1 mm CarbonEpoxy2_Rokhlin_2011 @ 500 kHz

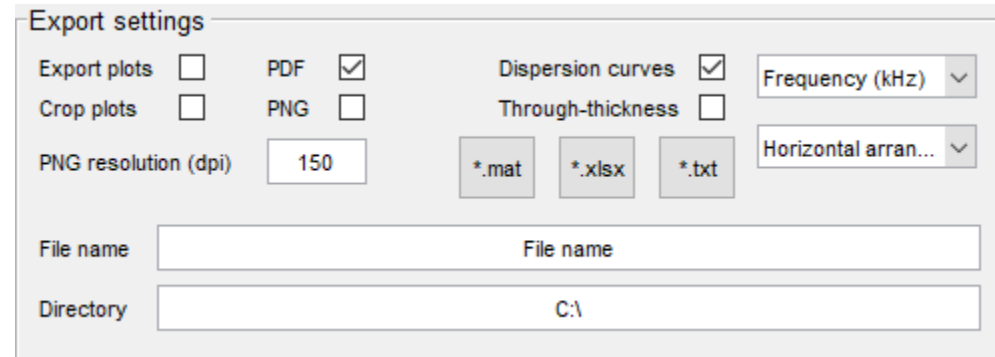


Energy velocity $|\vec{c}_e|$ in 1 mm CarbonEpoxy2_Rokhlin_2011 [0] @ 500 kHz



- Export options

- Plots
- Mode shape animation movies
- Raw data
 - Dispersion curves
 - Through-thickness profiles

A screenshot of the 'Export settings' dialog box. It contains several options: 'Export plots' (checkbox), 'Crop plots' (checkbox), 'PNG resolution (dpi)' (input field with '150'), 'PDF' (checkbox, checked), 'PNG' (checkbox), '*.mat' (button), '*.xlsx' (button), '*.txt' (button), 'Dispersion curves' (checkbox, checked), 'Through-thickness' (checkbox), 'Frequency (kHz)' (dropdown menu), and 'Horizontal arran...' (dropdown menu). At the bottom, there are two text input fields: 'File name' and 'Directory' (containing 'C:\').

Current and future work



- 2025: DC v3.0
 - Guided waves in isotropic rods and pipes including fluid-loading
- DC v3.x
 - ? Guided waves in multilayered anisotropic rods and pipes
 - ? Piezoelectric effects
 - ? Backpropagating modes (c_p and c_e point in opposite directions
→ *negative* damping)



Dispersion Calculator

Thank you!

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