Numerical modeling of non-destructive testing of composites

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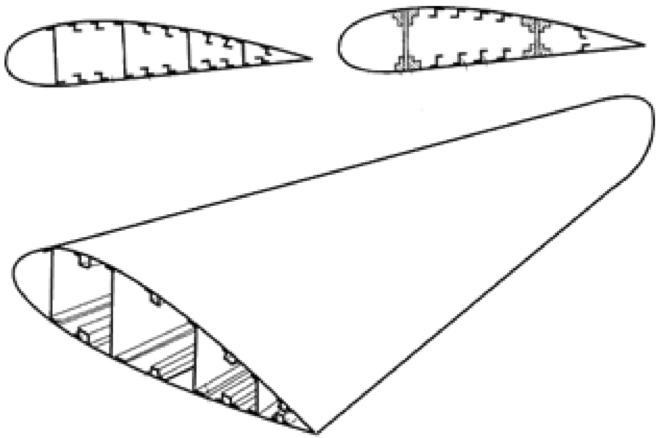
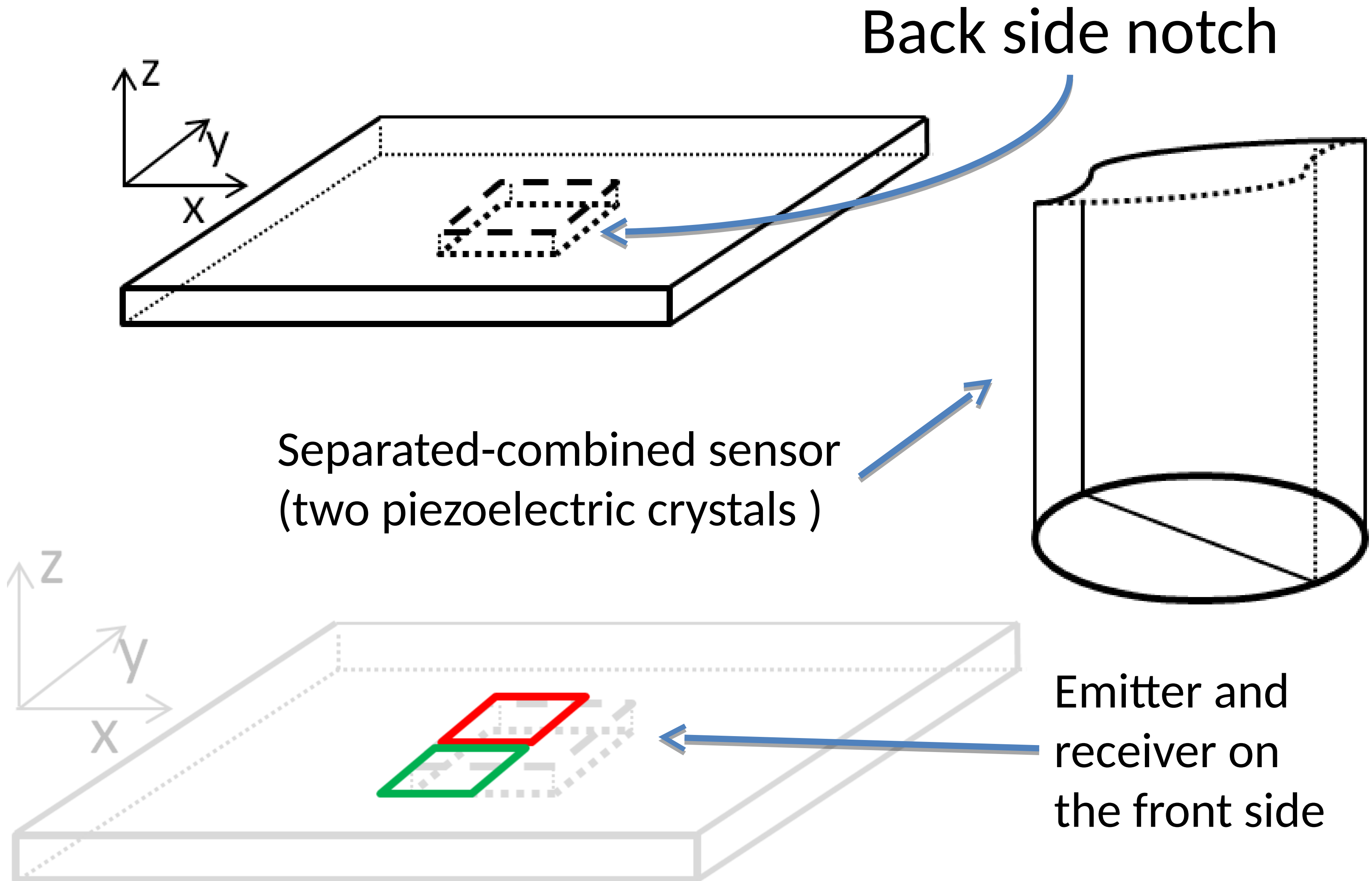
Composites



Low-velocity strike on a polymer composite construction

- Caused by: hail, debris, maintenance failures, etc.
- Internal composite damage – damage is not visible!
- Methods and standards for strength tests, developed for metals, are not effective enough for composites.
- Non-destructive testing devices for composites require a significant amount of time and laboratory equipment.

Problem statement



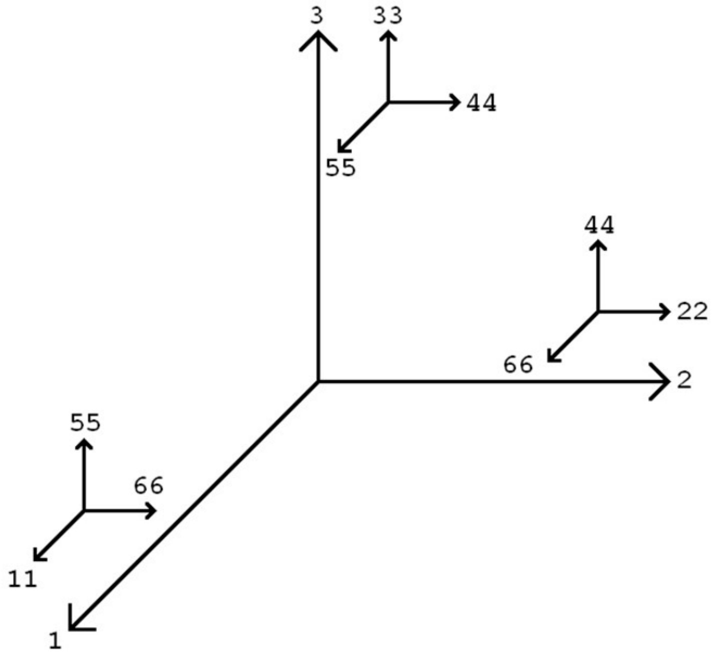
Anisotropic material

$$C_{ij,kl} = c_{i,k}\delta_{ij}\delta_{kl} + \sum_{m=1}^{3} c_{i,m+3}\delta_{ij}\left|\varepsilon_{mkl}\right| + \sum_{m=1}^{3} c_{m+3,k}\left|\varepsilon_{mij}\right|\delta_{kl} + \sum_{m=1}^{3}\sum_{n=1}^{3} c_{m+3,n+3}\left|\varepsilon_{mij}\right|\left|\varepsilon_{nkl}\right|$$

$$\rho\partial_t v_i = \sum_j \partial_j \sigma_{ij} ,$$

$$\partial_t \sigma_{ij} = \sum_k \sum_l C_{ij,kl}\left(\partial_k v_l + \partial_l v_k\right) .$$

$$\begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix}$$



$$\left\{\sqrt{\frac{c_{11}}{\rho}}, -\sqrt{\frac{c_{11}}{\rho}}, \sqrt{\frac{c_{55}}{\rho}}, -\sqrt{\frac{c_{55}}{\rho}}, \sqrt{\frac{c_{66}}{\rho}}, -\sqrt{\frac{c_{66}}{\rho}}, 0, 0, 0\right\}$$

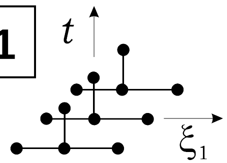
$$\left\{\sqrt{\frac{c_{22}}{\rho}}, -\sqrt{\frac{c_{22}}{\rho}}, \sqrt{\frac{c_{44}}{\rho}}, -\sqrt{\frac{c_{44}}{\rho}}, \sqrt{\frac{c_{66}}{\rho}}, -\sqrt{\frac{c_{66}}{\rho}}, 0, 0, 0\right\}$$

$$\left\{\sqrt{\frac{c_{33}}{\rho}}, -\sqrt{\frac{c_{33}}{\rho}}, \sqrt{\frac{c_{44}}{\rho}}, -\sqrt{\frac{c_{44}}{\rho}}, \sqrt{\frac{c_{55}}{\rho}}, -\sqrt{\frac{c_{55}}{\rho}}, 0, 0, 0\right\}$$

Grid-characteristic method

- Split by space variables

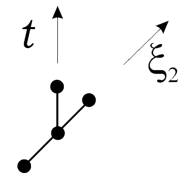
Этап 1



$$\frac{\partial \vec{u}}{\partial t} + \mathbf{A}_1 \frac{\partial \vec{u}}{\partial \xi_1} = 0$$

$$\vec{u}' = \vec{u}^n - \tau \mathbf{A}_1 \Delta_1 \vec{u}^n$$

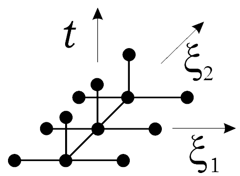
Этап 2



$$\frac{\partial \vec{u}}{\partial t} + \mathbf{A}_2 \frac{\partial \vec{u}}{\partial \xi_2} = 0$$

$$\vec{u}^{n+1} = \vec{u}' - \tau \mathbf{A}_2 \Delta_2 \vec{u}'$$

Итог (2D)



$$\vec{u}^{n+1} = \vec{u}^n - \tau \left(A_1 \Delta_1 + A_2 \Delta_2 \right) \vec{u}^n + O\left(\tau^2\right)$$

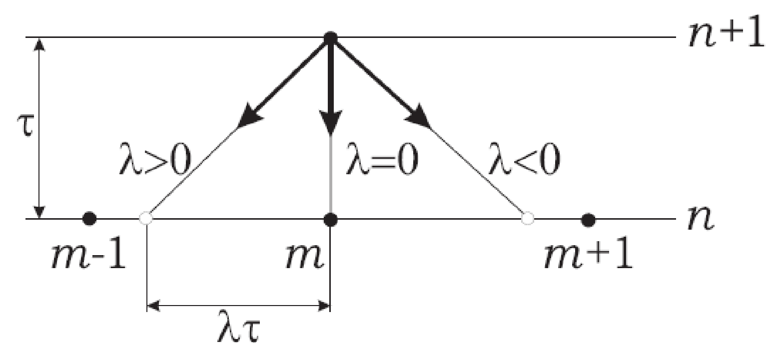
- Hyperbolic equations in plane (ξ, t)

$$\mathbf{A} = \mathbf{\Omega}^{-1} \mathbf{\Lambda} \mathbf{\Omega}$$

$$\frac{\partial \vec{u}}{\partial t} + \mathbf{\Omega}^{-1} \mathbf{\Lambda} \mathbf{\Omega} \frac{\partial \vec{u}}{\partial \xi} = 0$$

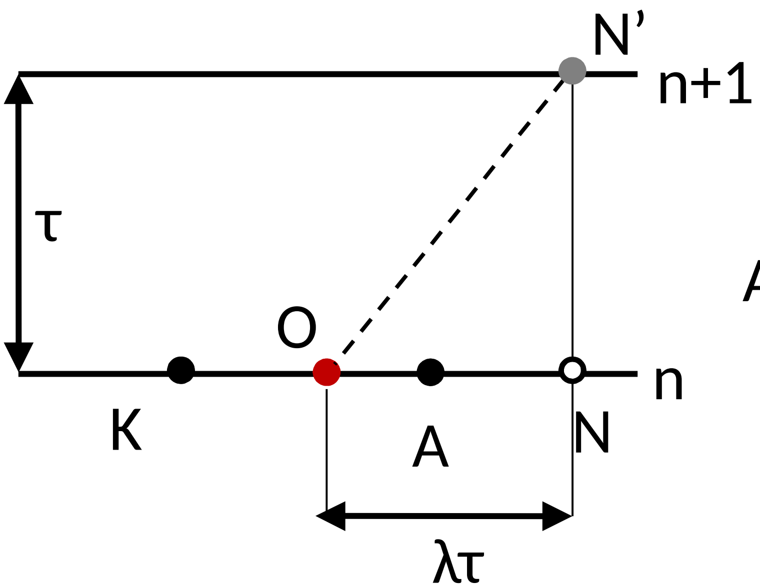
$$\frac{\partial \vec{v}}{\partial t} + \mathbf{\Lambda} \frac{\partial \vec{v}}{\partial \xi} = 0 \quad (\vec{v} \equiv \mathbf{\Omega} \vec{u})$$

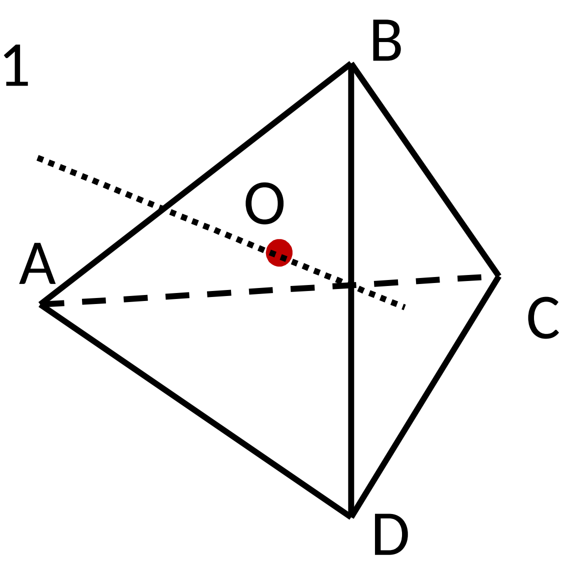
$$v^{n+1}(\xi) = v^n(\xi - \lambda \tau)$$

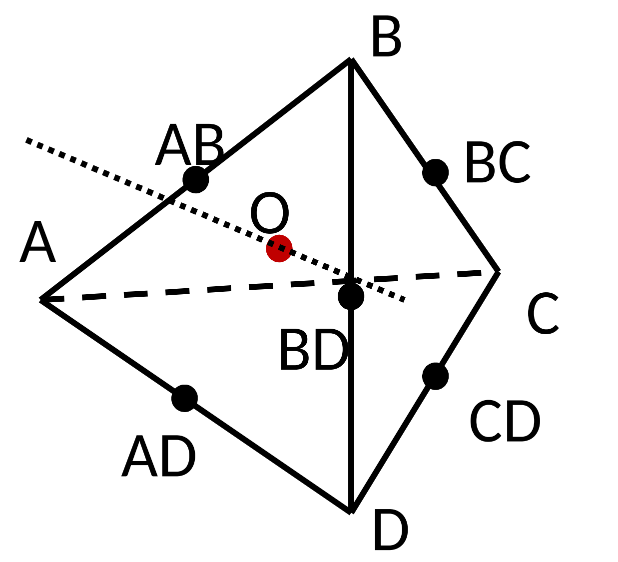


GCM on unstructured grid

- Tetrahedral interpolation of a Riemann's invariant :
  - linear – first order of approximation;
  - quadratic – second order of approximation;
  - scheme hybridization depending on a solution "smoothness".

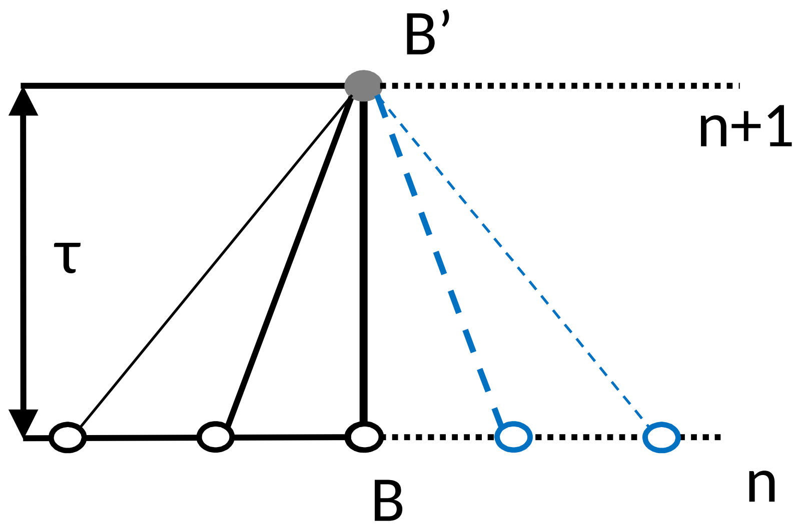






Borders and contacts

External surface



- External force

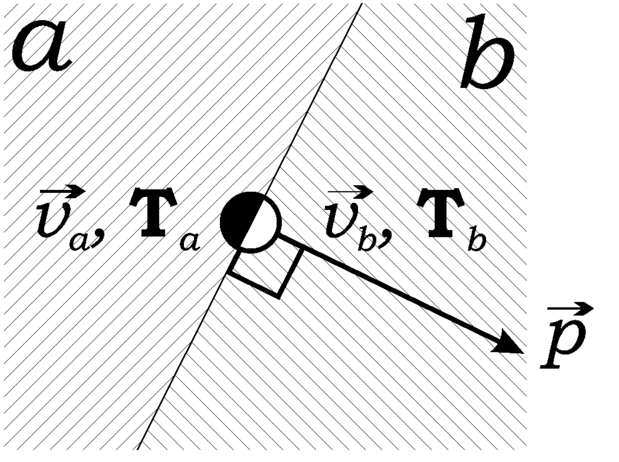
$$\mathbf{T}\vec{p} = \vec{f}$$

- External velocity

$$\vec{v} = \vec{V}$$

- Mixed conditions

Surface between media



A – real node
B – virtual node

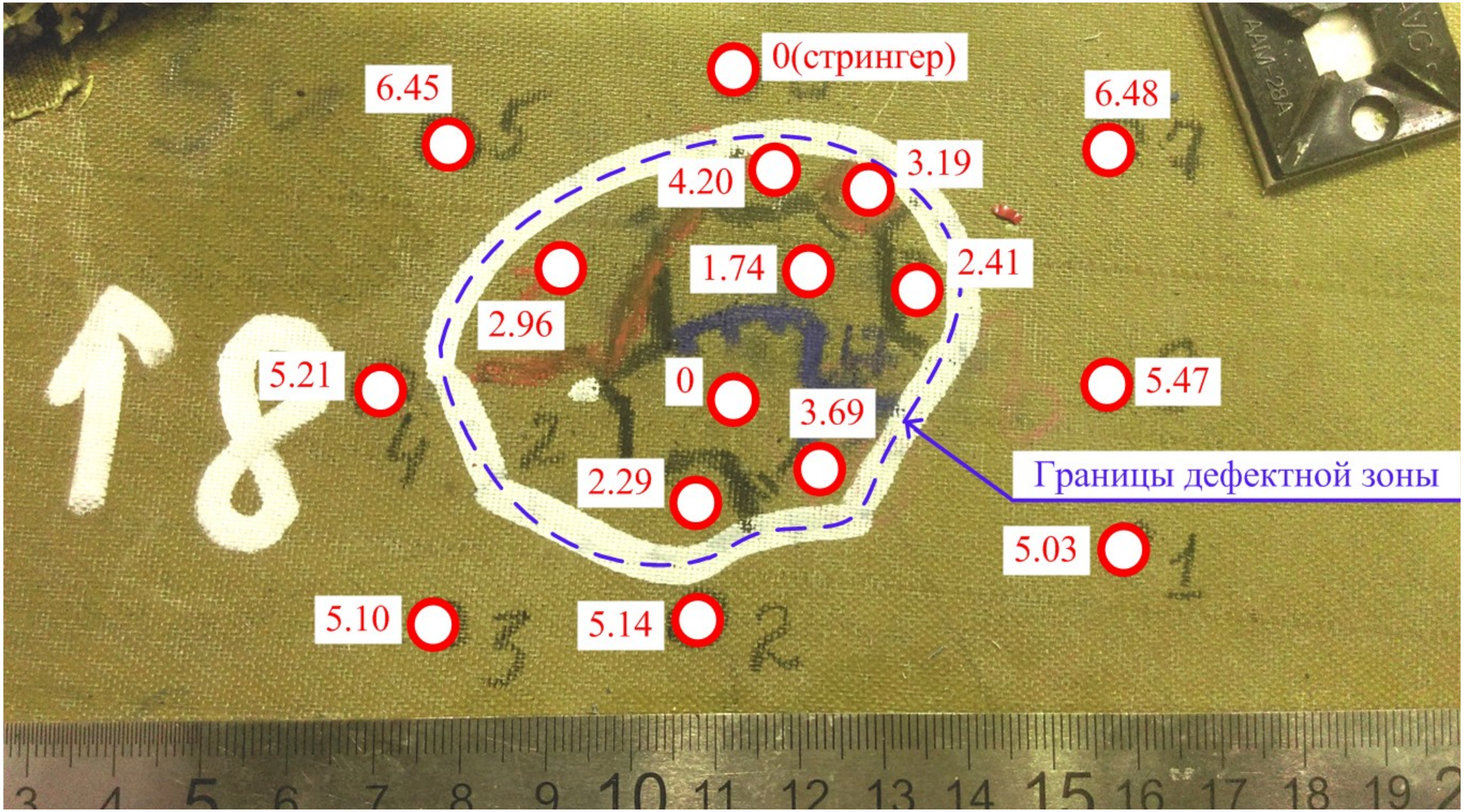
- Adhesion

$$\vec{v}_a = \vec{v}_b = \vec{V}, \quad \vec{f}_a = -\vec{f}_b$$

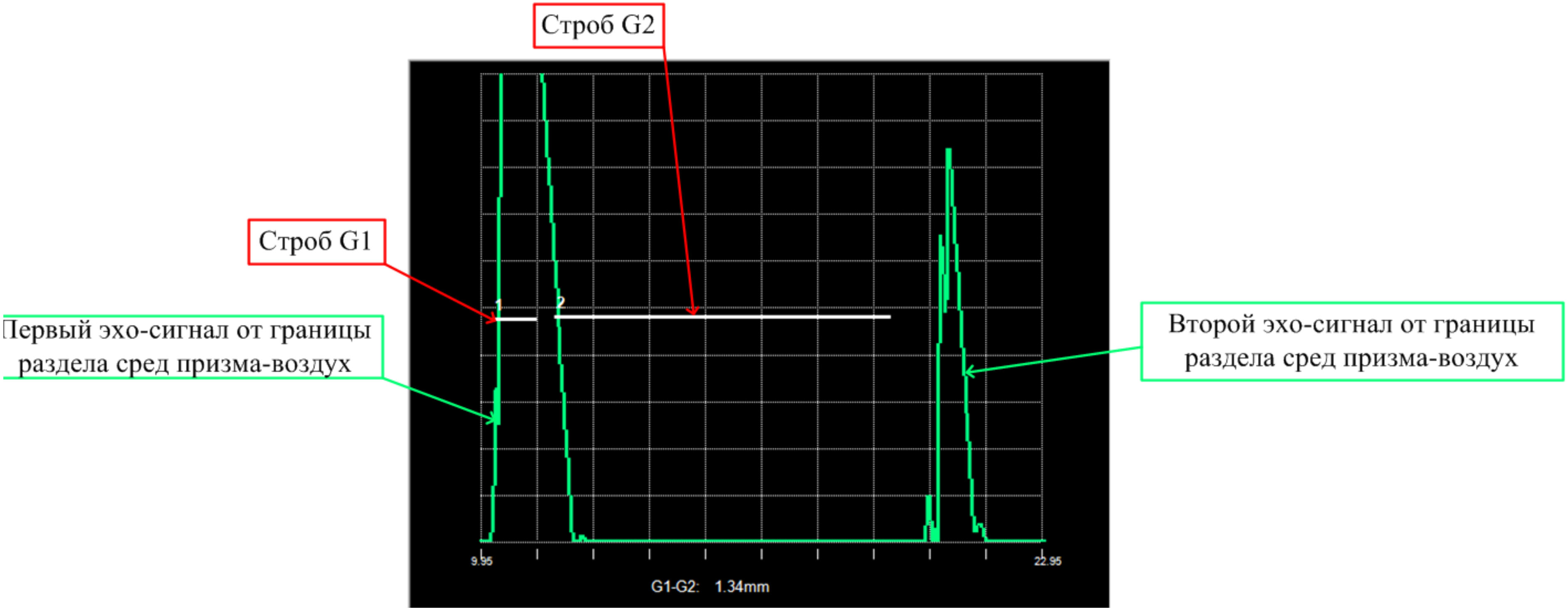
- Sliding
- Friction
- Destructible adhesion

Verification

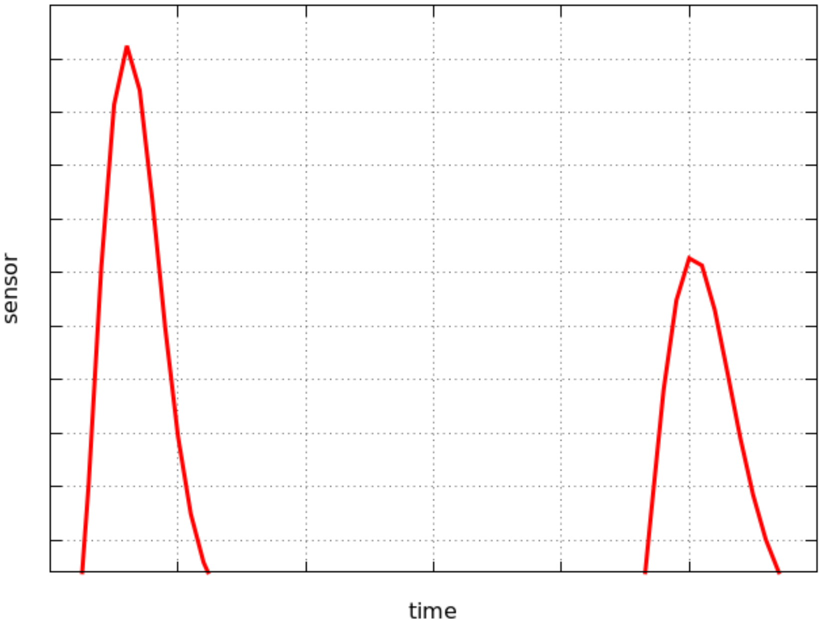
- SiteScan D-20 с преобразователем RDT2550



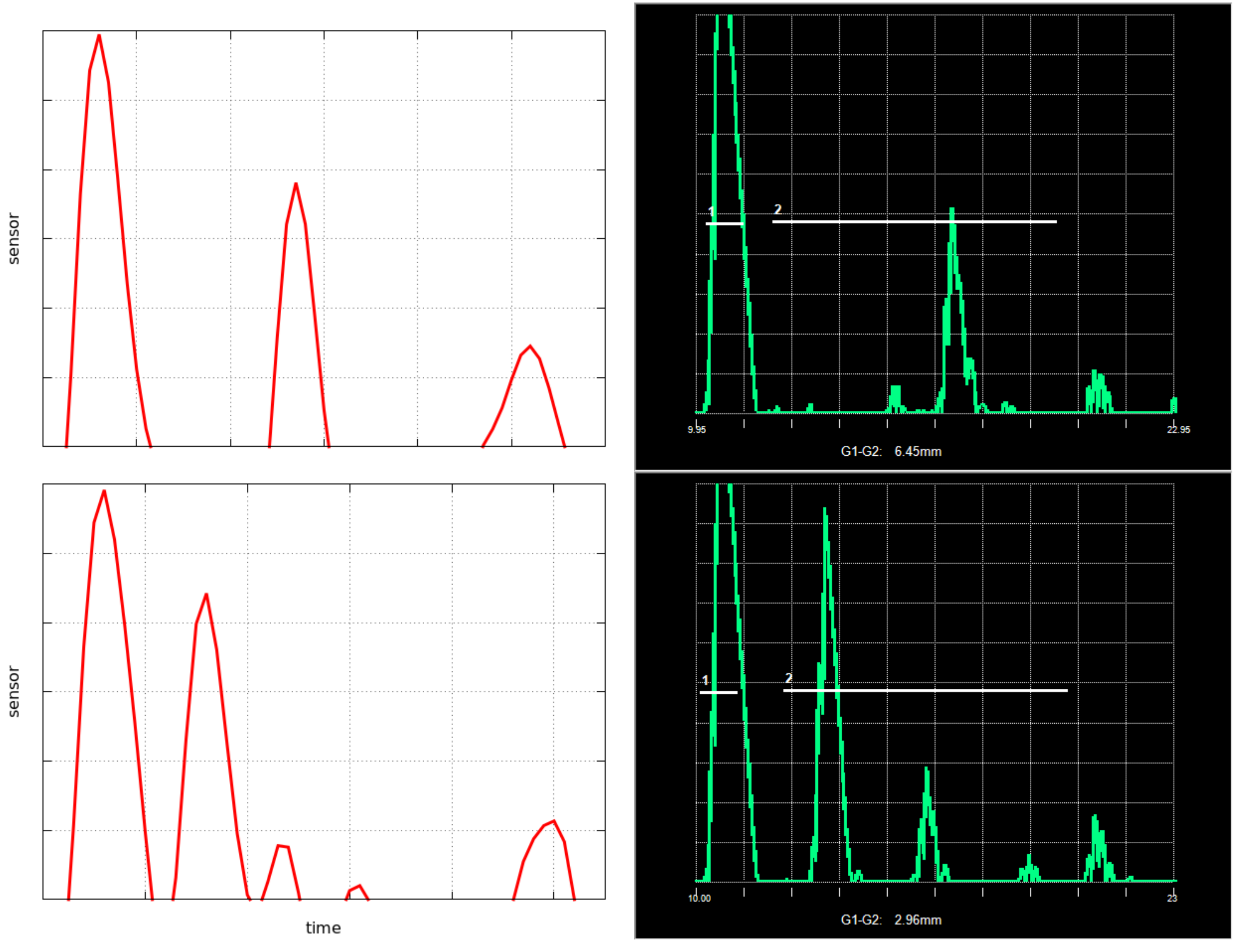
A-scan comparison



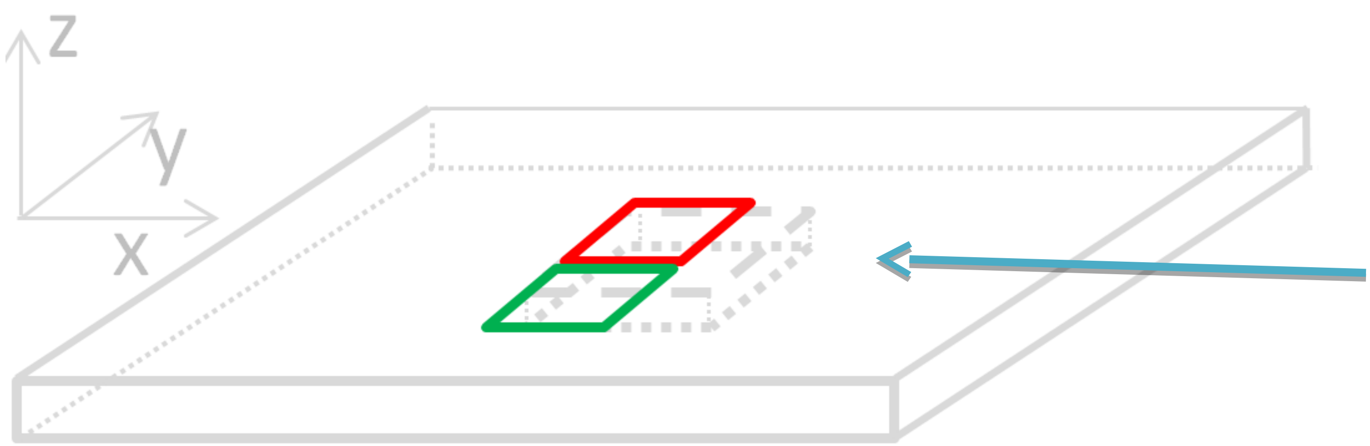
A-scan comparison



A-scan comparison



Serial calculations



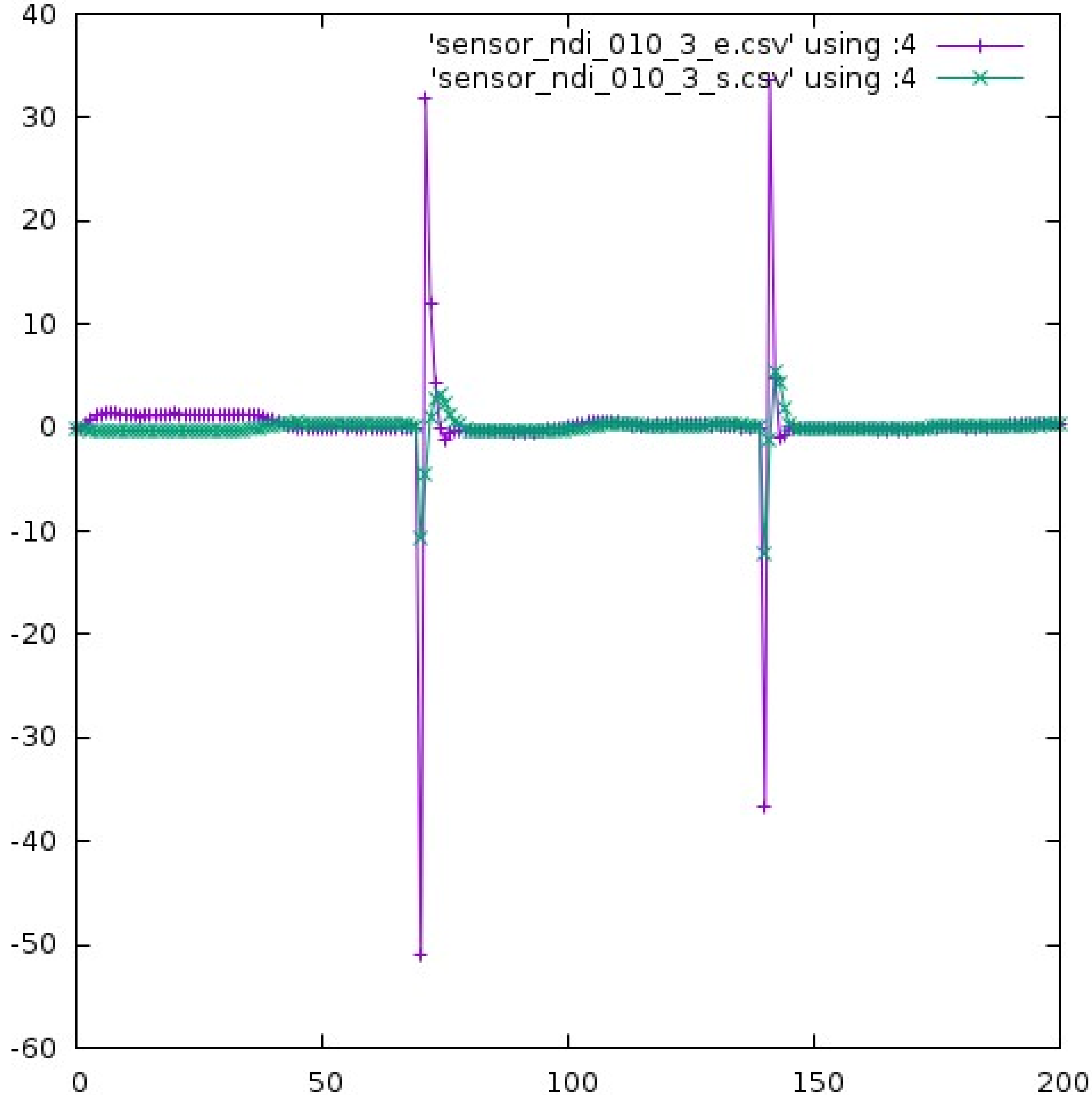
Emitter and receiver on the front side

Calculation number	1	2	3	4	5
Notch depth, mm	0.000	1.875	3.750	5.625	7.500
Distance from plate center to the sensor by x axis, mm	0.0	2.5	5.0	7.5	10.0
Diagnostic impulse length, s	0.0007	0.0021	0.0035	0.0049	0.0063
Sensor size, mm	0.6	1.2	2.2	3.2	4.2

Data representation

Green – separated-combined sensor.
Purple – combined sensor.

X axis – time step,
Y axis – velocity amplitude, averaged by receiver area:
z component for longitudinal wave,
x or y – transverse.

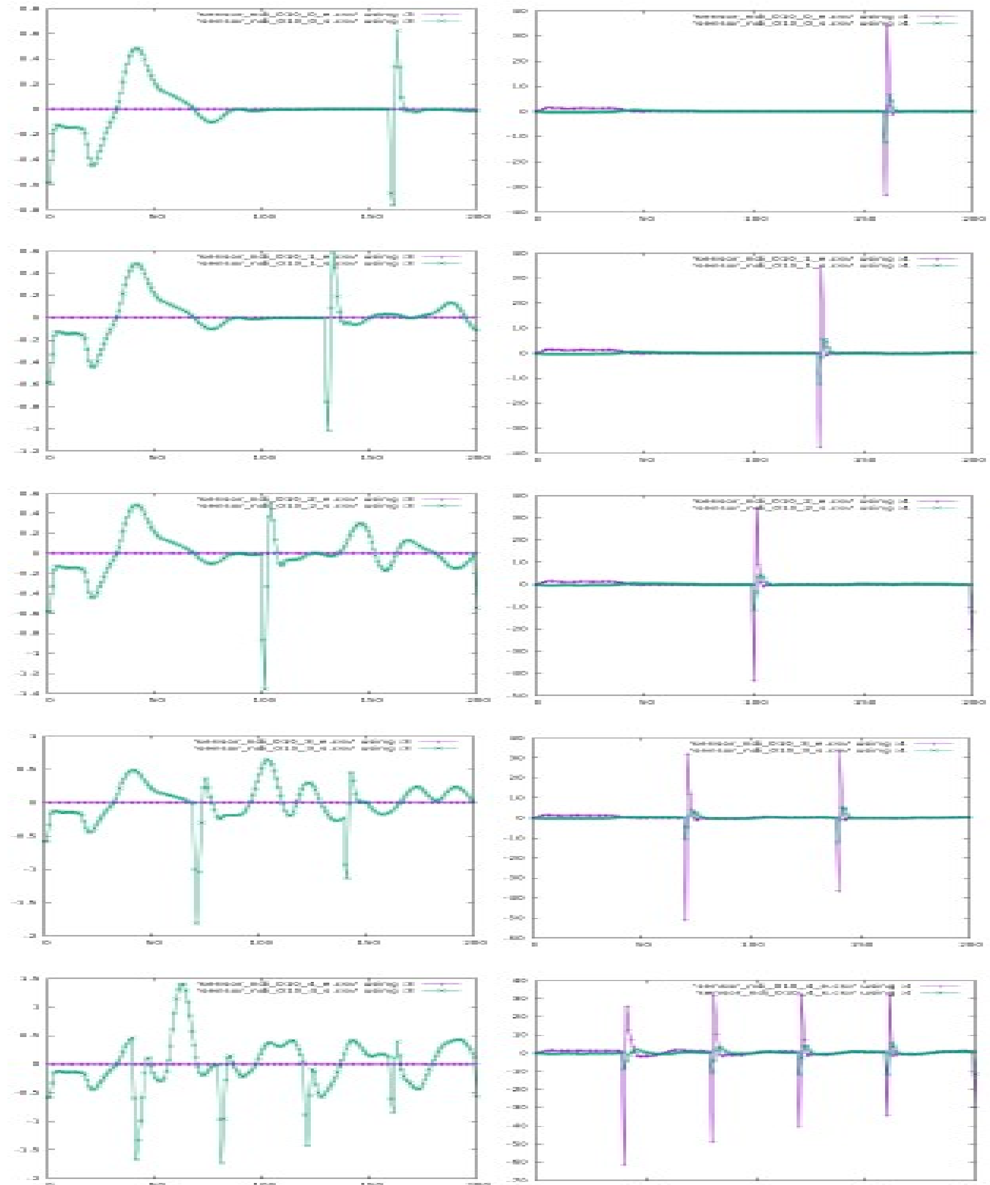


Steel plate: notch depth

Green – separated-combined sensor.
Purple – combined sensor.

- Increasing notch depth => increasing number of responses.
- The initial signal is visible on the transverse wave data.
- Combined sensor is better for processing longitudinal wave response, but can't be used for transverse waves.

Transverse wave | Longitudinal wave

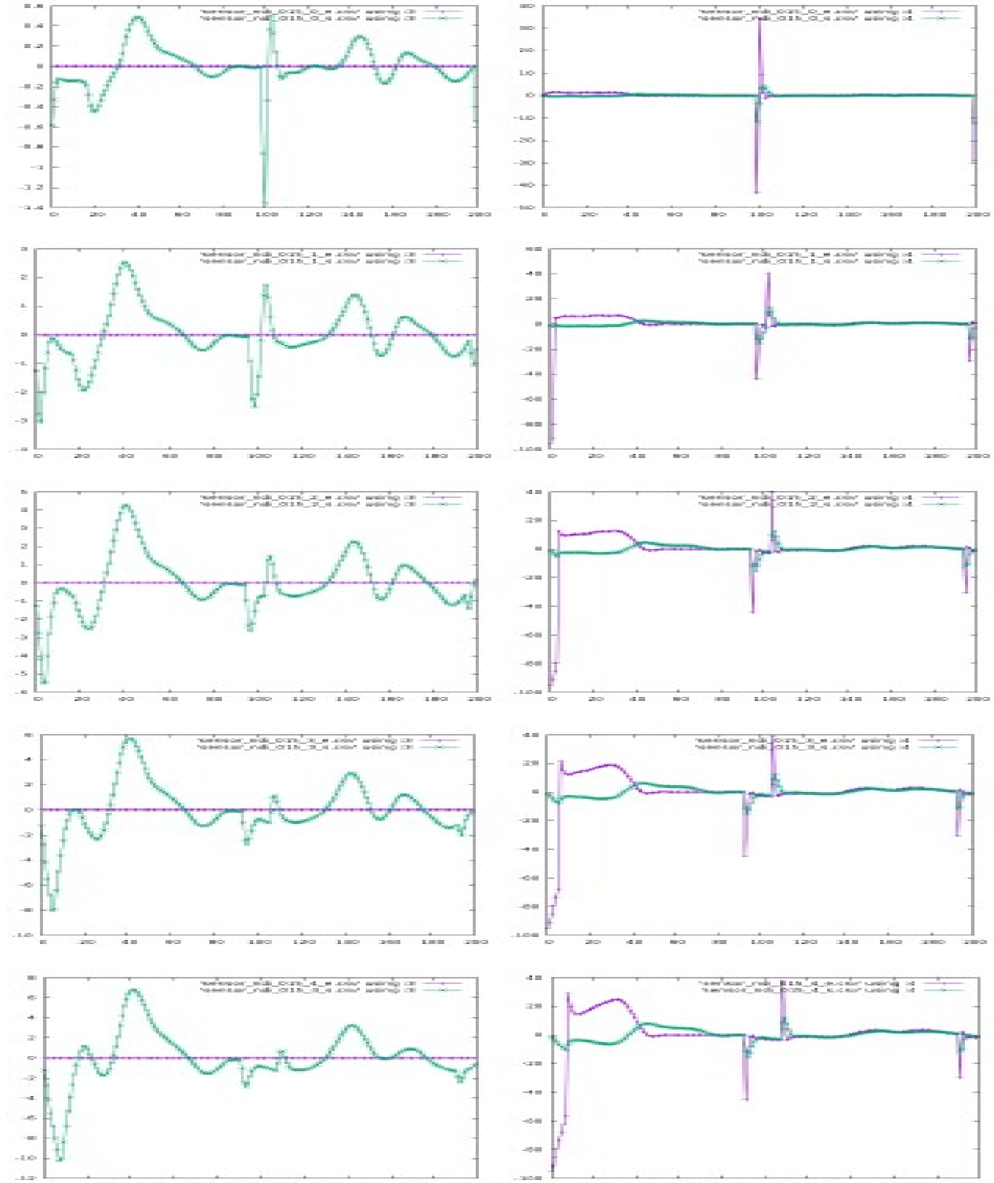


Steel plate: pulse length

Green – separated-combined sensor.
Purple – combined sensor.

- Increasing pulse length => increasing noise amplitude
- The initial signal becomes visible on longitudinal wave data.
- Transverse wave signal from the notch is visible only on low pulse length.

Transverse wave | Longitudinal wave

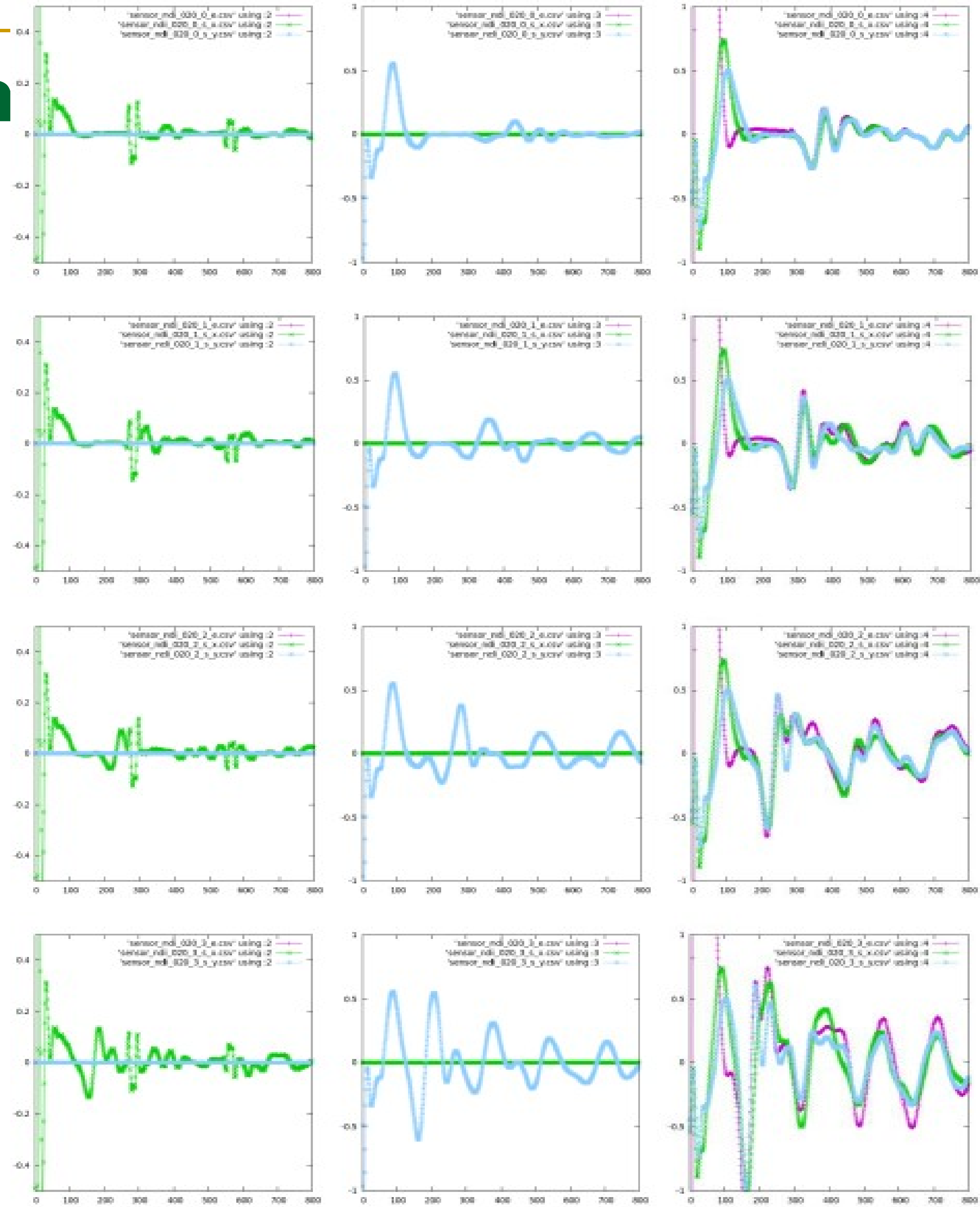


Composite pla
notch depth

Purple – combined sensor, blue – separated-combined sensor, across the fiber direction, green – along.

Left – transverse wave along fiber direction, center – across, right – longitudinal wave.

- High noise on the longitudinal component



Conclusion

- A hybrid grid-characteristic method of 1-2 order on irregular tetrahedral grid is used.
- A carbon fiber polymer matrix of unidirectional composite is modeled as a homogeneous orthotropic media with a single distinguished direction along the fiber.
- A comparison with an isotropic material (steel) was conducted.
- One-dimensional graphics, which correspond to A-scans in real devices, were obtained.
- The detailed analysis of received data is presented.

Application

1. Analysis of complex NDT cases: detail geometry, delaminations, complex destruction types.
2. Development of diagnostic methodology, parameters and modes optimization.
3. Equipment prototyping – research and selection of sensor parameters.
4. Assessment of danger from various destruction types.

Thank you for your time and attention!