Overview of activities

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Co-workers

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- Dr. Jan Trnka
- Dr. Robert Cimrman
- Dr. Ladislav Musil
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- Ing. Michal Mračko (FS CVUT)
- Ing. Xavier Arnoult (VŠCHT)
- Ing. et Ing. Radim Dvořák (FD CVUT)
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International collaborations

- Prof. K.C. Park, (Colorado Uni at Boulder, US)
- Prof. Jose Gonzalez (Uni of Seville, Spain)
- Prof. Michel Arrigoni (ENSTA Bretagne, Brest, France)
- Dr. A. Berezovski (Tallinn University of Technology, Estonia)
- Prof. S. Sorokin (University of Aalborg, Denmark)
- Dr. A. Tkachuk (University of Stuttgart, Germany / Karlstad University, Sweden)
- Prof. A. Popp (Bundeswehr University Munich, Germany).
- Dr. M. Geiß (OHB System AG, Munchen, Germany)
- Prof. Jin-Gyun Kim (Kyung Hee University, Suwon, Korea)
- Prof. Hoon Huh (KAIST, Daejeon, Korea)
- Dr. Ruben Acevedo (Centro Tecnológico – Universidade Federal de Santa Catarina, Brasil)

Introduction of the Laboratory of computational mechanics

- Numerical methods in thermomechanics, material models, dynamic plasticity model identification via Taylor test
- Impact-contact problems, domain decomposition techniques
- Surface treatment - plasma shock peening
- Isogeometric analysis and coupling with FEM (geometry preserving simulations)
- Shock and wave propagation in solids
- Metamaterials and band gap problems
- Experimental study on impact mechanics
- Smart materials and structures, soft robotics, electroactive materials.
- Consultations for industry and summer short courses on numerical methods

Important projects: ESA LISA (gravity waves), OHB System AG (3D printed structures in aerospace objects), GAČR, TAČR. Computations of seismic risk on Mochovce power station.

Patents: Brno University of Technology (3D printing)

Governing equations for elastodynamic problem

Strong form:

$$\begin{aligned} \operatorname{div} \boldsymbol{\sigma} + \mathrm{b} &= \rho \ddot{\mathrm{u}} && \text{in} && \Omega \times [t^0, T] \\ \mathrm{u} &= \hat{\mathrm{u}} && \text{on} && \Gamma_D \times [t^0, T] \\ \mathrm{n} \cdot \boldsymbol{\sigma} &= \hat{\mathrm{t}} && \text{on} && \Gamma_N \times [t^0, T] \\ \mathrm{u}\left(\mathrm{x}, t^0\right) &= \mathrm{u}_0\left(\mathrm{x}\right) && \text{for} && \mathrm{x} \in \Omega \\ \dot{\mathrm{u}}\left(\mathrm{x}, t^0\right) &= \dot{\mathrm{u}}_0\left(\mathrm{x}\right) && \text{for} && \mathrm{x} \in \Omega \end{aligned}$$

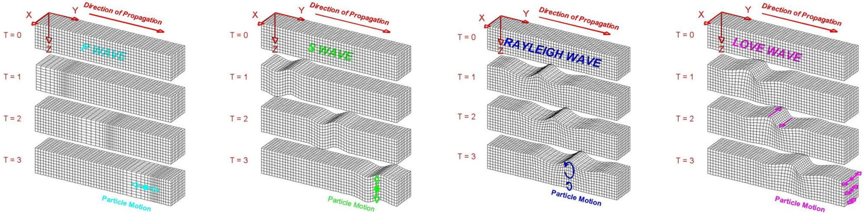
the Hooke's law and the infinitesimal strain tensor:

$$\boldsymbol{\sigma} = \mathbb{C} : \boldsymbol{\varepsilon}, \quad \boldsymbol{\varepsilon} = \frac{1}{2}\left[(\operatorname{grad} \boldsymbol{u})^{\mathsf{T}} + \operatorname{grad} \boldsymbol{u}\right]$$

u_i - the component of displacement vector $\mathrm{u}(\mathrm{x}, t)$; $\mathrm{x} \in \Omega$ - the position vector; Ω - the domain of interest with the boundary Γ; σ_{ij} - the Cauchy stress tensor (symmetric tensor); ε_{kl} - the infinitesimal strain tensor; ρ - mass density; b_i - the component of volume (body) intensity vector b; n_i - the component of the outward normal vector n on Γ; $\hat{u}_i$ - the component of prescribed boundary displacement vector g; $\hat{t}_i$ - the component of prescribed traction vector t; u_{0i} and $\dot{u}_{0i}$ - the components of the initial displacement and velocity fields. **System of 15 linear hyperbolic PDEs.**

Type of waves in continuum

P-wave S-wave Rayleigh's wave Love's wave



source:©2007 Michigan Technological University; http://www.geo.mtu.edu/UPSeis/waves.html **Other wave types**:

- waves in rods, flexural (bending) and torsional waves, guided waves
- Lamb's waves (waves in plates, dispersive, application in NDT)
- surface Rayleigh's waves (waves in a half-space)
- Love's waves (waves in a half-space covered by a layer with different elastic properties)
- von Schmidt's waves (reflected waves from boundaries)
- inter-facial Stoneley's (Leaky Rayleigh's) waves
- Scholte's waves (solid-liquid interface)

Finite element method - recapitulation

Principle of virtual work in continuum mechanics:

$$\int_\Omega \delta \mathsf{u}^T \varrho \ddot{\mathsf{u}} \, \mathrm{d}\Omega + \int_\Omega \delta \boldsymbol{\varepsilon}^T \boldsymbol{\sigma} \, \mathrm{d}\Omega = \int_\Omega \delta \mathsf{u}^T \mathsf{b} \, \mathrm{d}\Omega + \int_{\Gamma_N} \delta \mathsf{u}^T \mathsf{t} \, \mathrm{d}\Gamma$$

Using discretization of kinematic quantities we have

$$\delta \mathbf{q}^T \left[\int_\Omega \varrho \mathbf{N}^T \mathbf{N} \ddot{\mathbf{q}} \, \mathrm{d}\Omega + \int_\Omega \mathbf{B}^T \boldsymbol{\sigma} \, \mathrm{d}\Omega - \int_\Omega \mathbf{N}^T \mathbf{b} \, \mathrm{d}\Omega - \int_{\Gamma_N} \mathbf{N}^T \mathbf{t} \, \mathrm{d}\Gamma \right] = 0.$$

The previous equation should be valid for an arbitrary $\delta \mathbf{q}$ respecting Dirichlet boundary conditions and, then the discretized equations of motion have the form

$$\mathsf{M}\ddot{\mathsf{q}} = \mathsf{f}^{ext} - \mathsf{f}^{int}$$

Other possibility is to use the Hamilton's principle of least action.

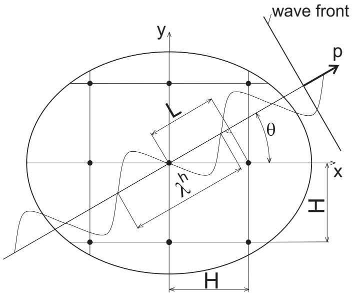
Dispersion properties of finite element method

Characteristic equations of motion for patch

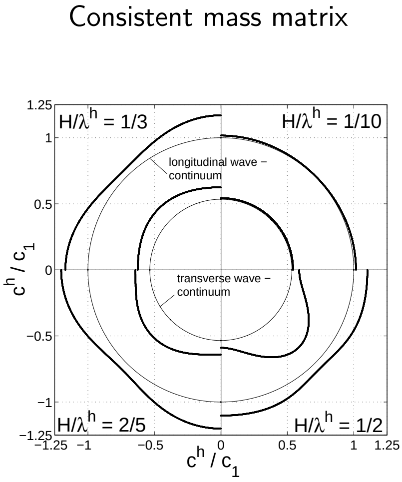
$$\mathrm{M}_c\ddot{\mathrm{u}}^h + \mathrm{K}_c\mathrm{u}^h = 0, \qquad \mathrm{M} = \int_V \varrho \mathrm{H}^T\mathrm{H}\, dV, \qquad \mathrm{K} = \int_V \mathrm{B}^T\mathrm{C}\mathrm{B}\, dV$$

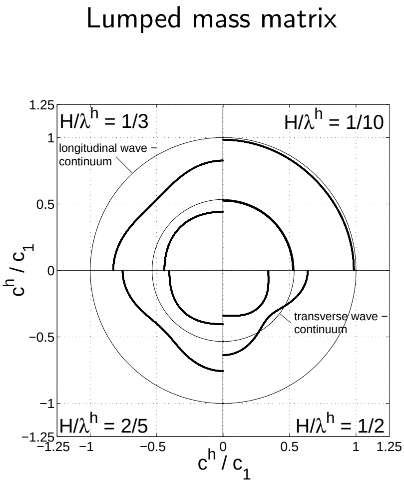
Fourier analysis - prescriebed time nodal displacements

$$\begin{aligned} u^h_{mn} &= U_{mn} \exp\left[\mathrm{i}\left(k^h x_m p_x + k^h y_n p_y - \omega t\right)\right] \\ v^h_{mn} &= V_{mn} \exp\left[\mathrm{i}\left(k^h x_m p_x + k^h y_n p_y - \omega t\right)\right] \end{aligned}$$



Dispersion properties of finite element method

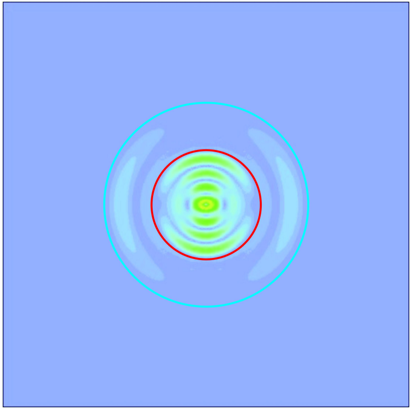




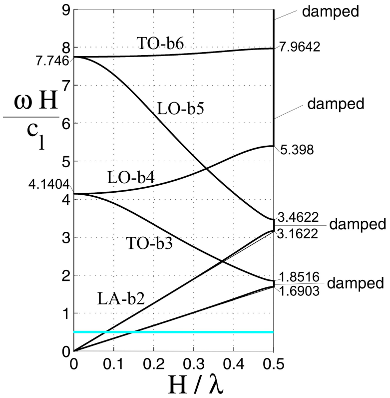
Anisotropic effect of FE discretization.

Dispersion properties of finite element method

Wave field for frequency $\omega H / c_1 = 0.5$



Dispersion spectrum



LA - longitudinal acoustic

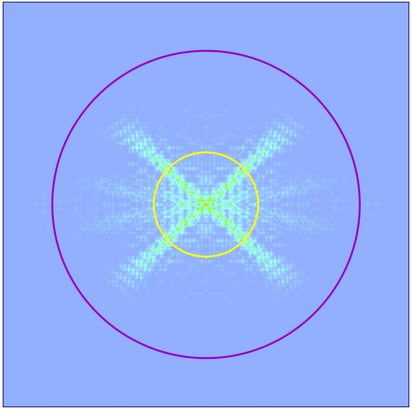
TA - transverse acoustic

LO - longitudinal optical

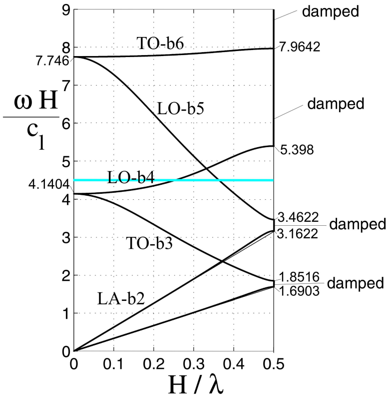
TO - transverse optical

Dispersion properties of finite element method

Wave field for frequency $\omega H / c_1 = 4.5$



Dispersion spectrum



LA - longitudinal acoustic

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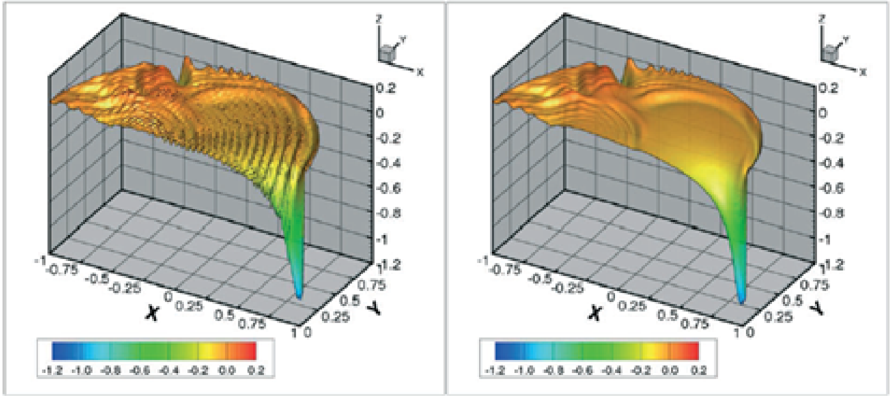
Time stepping methods

the second-order system

$$\ddot{\mathrm{u}} = f(\mathrm{u}, \dot{\mathrm{u}}, t)\text{or} \qquad \mathrm{M}\ddot{\mathrm{u}}(t)+\mathrm{D}\dot{\mathrm{u}}(t)+\mathrm{K}\mathrm{u}(t) = \mathrm{f}^{ext}(t)-\mathrm{f}^{contact}(t)$$

- The Newmark method
- The Houbolt method
- The Wilson θ method
- The Midpoint method
- The Central difference method
- The HHT method
- The Generalized-α method
- Other methods

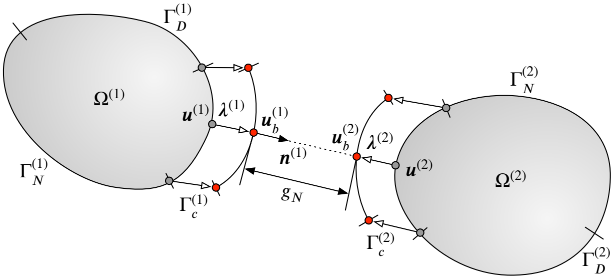
Special time integration for spurious-stress-free oscillations



(a) (b)

Figure 14. Distributions of dimensionless stress σ_{XX}/σ_0 at the disc at the time $4\,R/c_L$: (a) the central difference method and (b) the proposed method. A half of a disc is shown.

Partitioned formulation of contact-impact problems

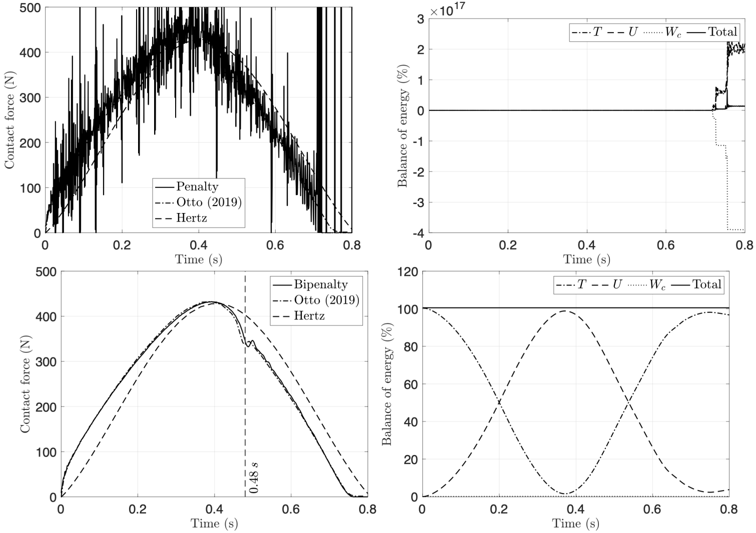


Partitioned formulation of impact problems

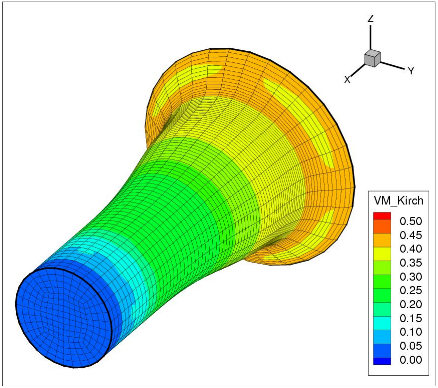
$$\begin{bmatrix} \mathsf{M} & \mathsf{B} & 0 \\ \mathsf{B}^{\mathsf{T}} & 0 & -\mathsf{L}_c \\ 0 & -\mathsf{L}_c^{\mathsf{T}} & \mathsf{M}_p \end{bmatrix} \begin{Bmatrix} \ddot{\mathsf{u}} \\ \boldsymbol{\lambda} \\ \ddot{\mathsf{u}}_c \end{Bmatrix} = \begin{Bmatrix} \mathsf{r}_u \\ 0 \\ -\mathsf{r}_p \end{Bmatrix}$$

Bi-penalty stabilized contact constraints

Comparison of the conventional penalty method and our proposed approaching



Modelling of Taylor test



Reciprocal mass matrices

Partitioned mixed formulation

$$\mathsf{A}\dot{\mathsf{p}} + \mathsf{B}\boldsymbol{\lambda} = \mathsf{r} \qquad \textit{Equation of motion} \tag{1}$$

$$\mathsf{A}^{\mathsf{T}}\dot{\mathsf{u}} - \mathsf{C}\mathsf{p} = 0 \qquad \textit{Momentum equation} \tag{2}$$

$$\mathsf{B}^{\mathsf{T}}\mathsf{u} - \mathsf{L}_b\mathsf{u}_b = 0 \qquad \textit{Boundary (and interface) constraints} \tag{3}$$

$$-\mathsf{L}_b^{\mathsf{T}}\boldsymbol{\lambda} = 0 \qquad \textit{Newton's 3rd law on the boundaries} \tag{4}$$

Direct building of the inversion of mass matrix as

$$\mathsf{M}^{-1} = \mathsf{A}^{-\mathsf{T}}\mathsf{C}\mathsf{A}^{-1} \tag{5}$$

Mass scaling/tailoring

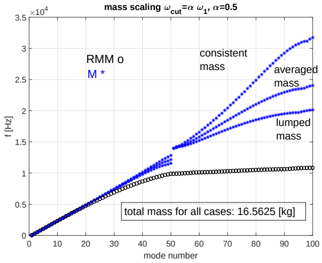
Modifying of the mass matrix so that the total mass is preserved and the higher frequency spectrum is improved.
Mass scaled matrix:

$$\mathsf{M}_{scaled} = \mathsf{M} + \boldsymbol{\lambda} \tag{6}$$

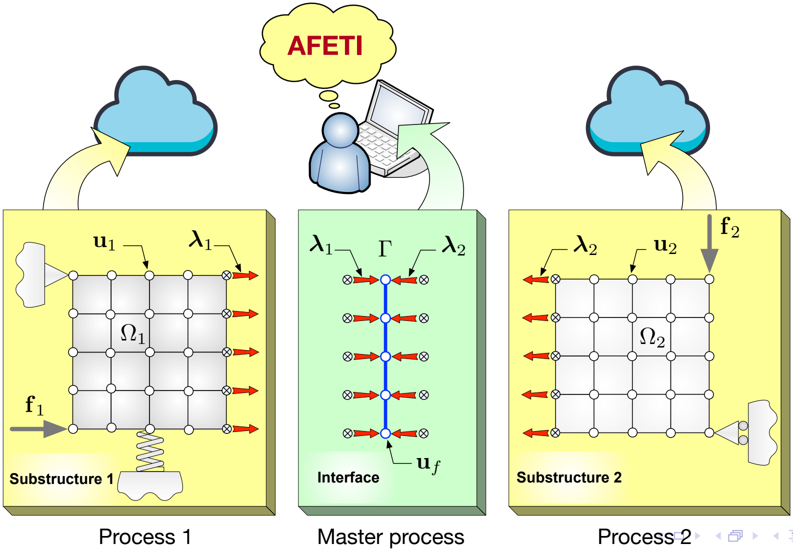
where

$$\boldsymbol{\lambda} = \mathsf{M}\boldsymbol{\Phi}_h \mathsf{S} \boldsymbol{\Phi}_h^{\mathsf{T}} \mathsf{M}^{\mathsf{T}} \tag{7}$$

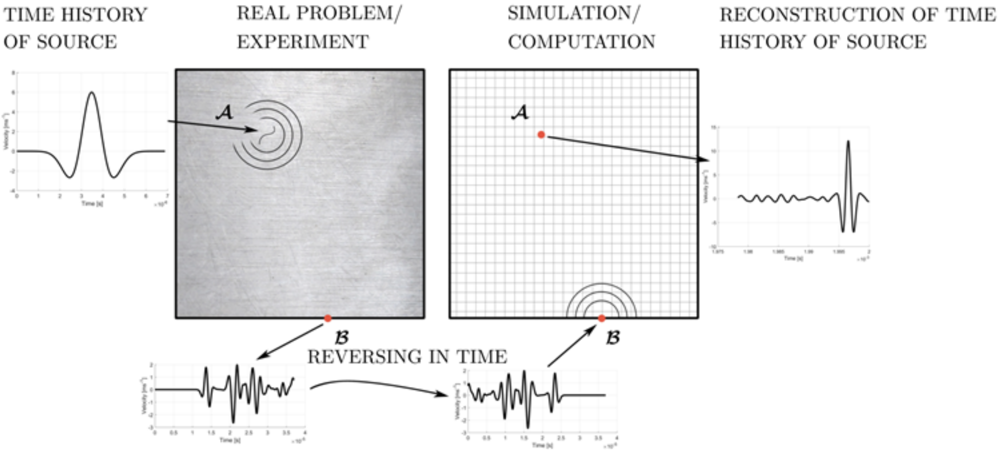
where $\boldsymbol{\Phi}$ contents the higher mode shapes corresponding to eigen-modes for improving, S is the diagonal matrix with coefficients for cutting of value of higher eigen-frequencies.



Parallel computing: A-FETI solver including heterogeneous time integration (Radim Dvořák)

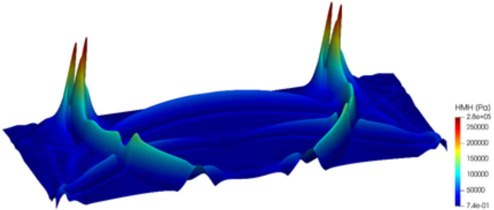


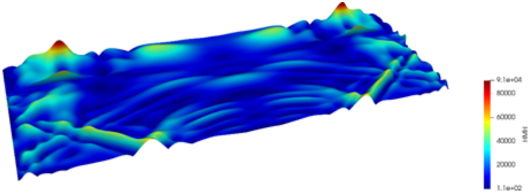
Computational time reversal method for NDT applications



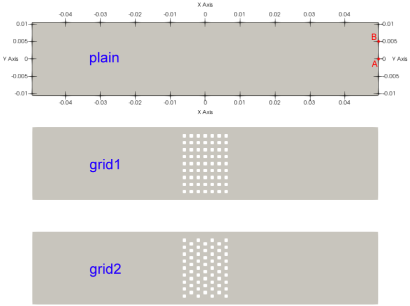
Wave propagation in heterogeneous media

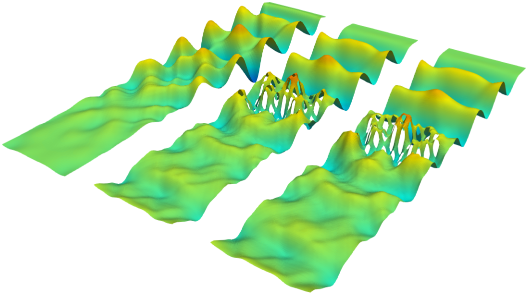
- 3D printed bimaterial problems
- Auxetic structures, Anisotropic media
- Space-time modulated materials
- Connection to topology optimization and material distributions



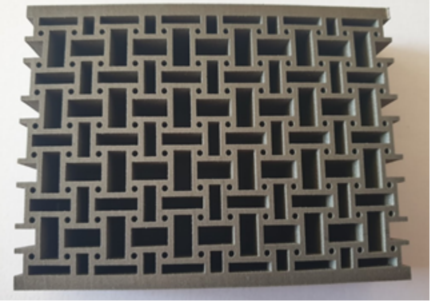


Wave propagation in 3D printed structures (M. Mračko)





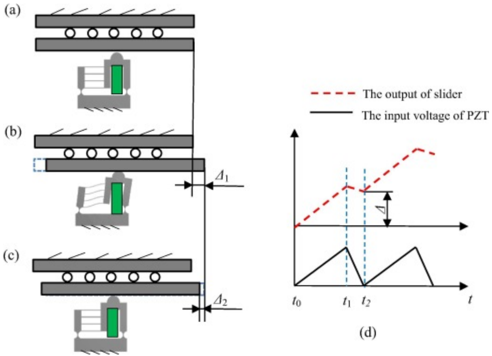
Wave propagation in 3D printed auxetic structures

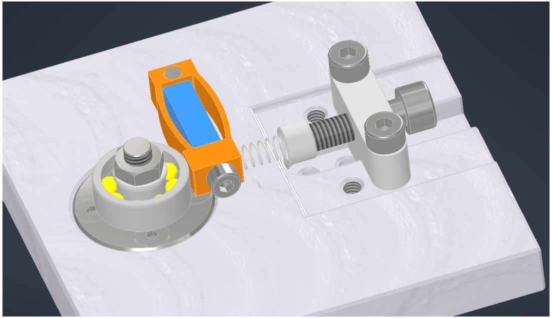


- Controllable metametamaterials - GACR LA project 2022-2024 with Germany. - Controlable metamaterials based on piezoelectric materials - Controable gripping mechanics -Shape morphing for fluid-structure interaction - Energy harvesting - Smart sensing events - Embedded sensors and actuators, adaptronic structures.

Slip-stick mechanism for space applications

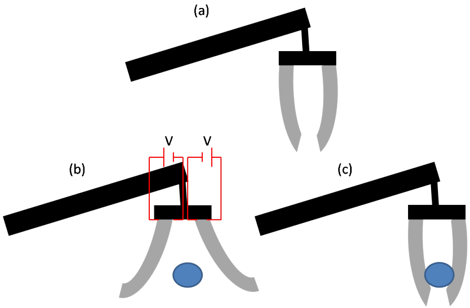
- piezoelectric actuators
- FSUA device for LISA ESA project - The Laser Interferometer Space Antenna. Launch is expected in 2037.





Electro-active materials for controlable gripping

- electro-active polymers and gels
- piezoelectric materials including 3D printing technology
- flexoelectric materials

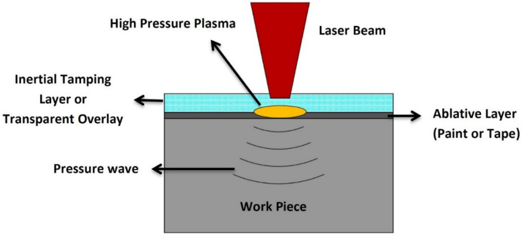


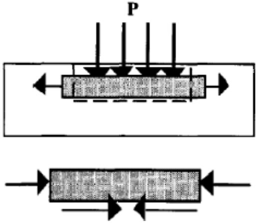
Surface treatment

- Laser shock peening
- Plasma shock peening
- Plastic and shock waves, hardening
- Fatigue
- Corrosion resistance - collaboration with JRC
- Corrosion-Fatigue

Principle of Laser Shock Peening

- The shock wave propagates to the target
- Causes plastic deformation to a depth at which the peak stress no longer exceeds the Hugionot Elastic Limit (HEL) to the metal
- This plastic deformation generate Residual Stress Throughout the affected depth.



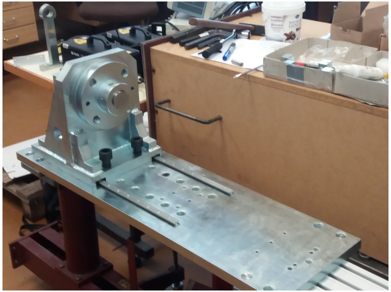


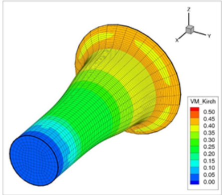
Now, we are working on Plasma shock peeing technology under our patent.

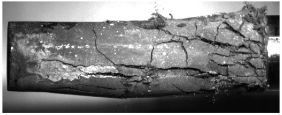
Experiments in impact mechanics, wave propagation and vibration problems

Experimental equipments:

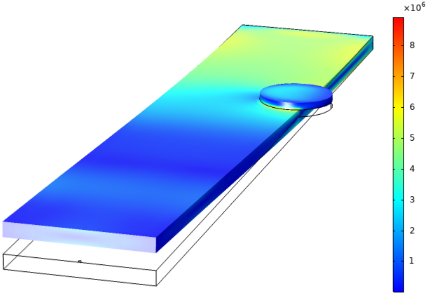
- Taylor test wit air guns
- Split Hopkinson pressure bars
- Vibrometers

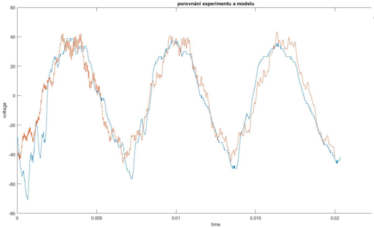


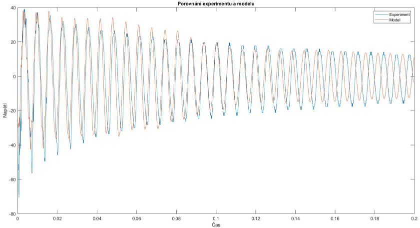




Experiments in vibration problems with sensing by PZ materials







Thanks

Thank you for your attention!!!