Metamaterials with tunable dynamic properties

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Mechanics of Materials

Project aim

development of new generation
mechanical metamaterials
with adaptive, tunable or superb dynamical properties

by systematically exploiting the combination of material and geometrical non-linearities

potential applications:

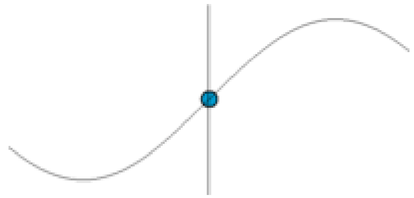
tunable wave guides
adaptive passive vibration control
superdumping
acoustic diodes
acoustic cloaking
noise insulation

Outline

- Background
- Locally resonant metamaterials
- State of the art and challenges
- Towards addressing the challenges
- Plan of work
- International collaborations

Background: wave propagation

- **Wave** - disturbance or oscillation that travels through matter or space, accompanied by a transfer of energy without mass transfer

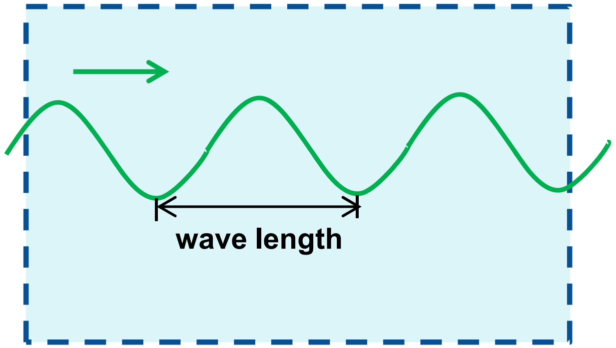


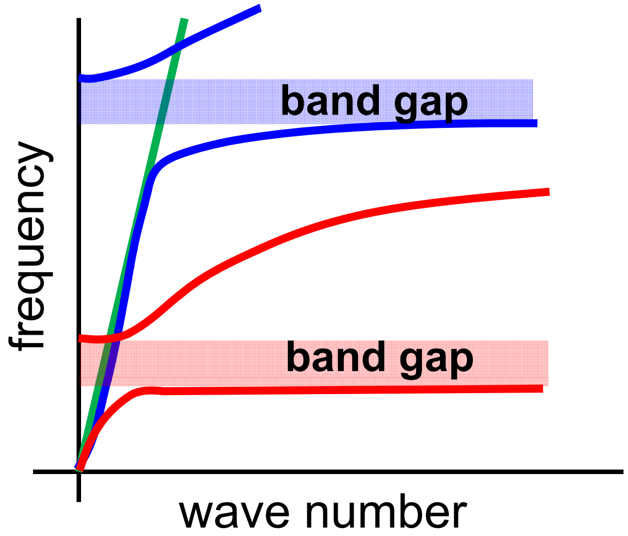
- Electromagnetic waves
  - do not require medium
- **Mechanical waves**
  - **propagate by local deformation of a medium**

  → dynamic properties of materials

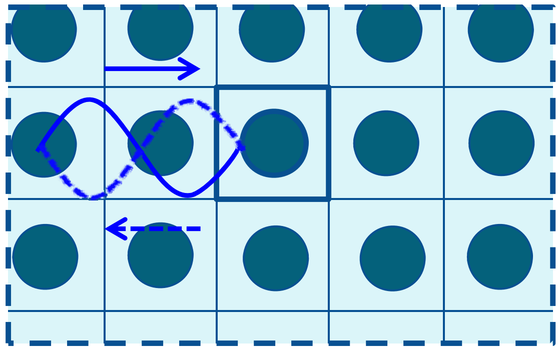
Background: dispersion properties

- infinite homogeneous material



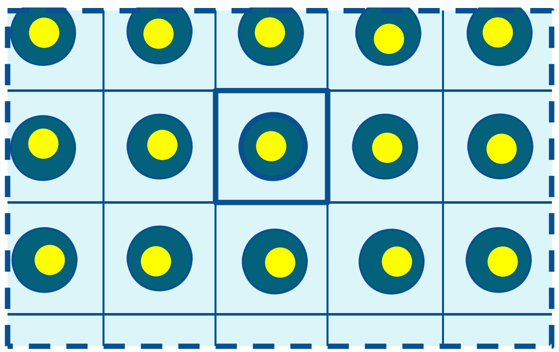


- infinite periodic material



Bragg scattering, phononic crystal (PC)

- infinite material with local resonators

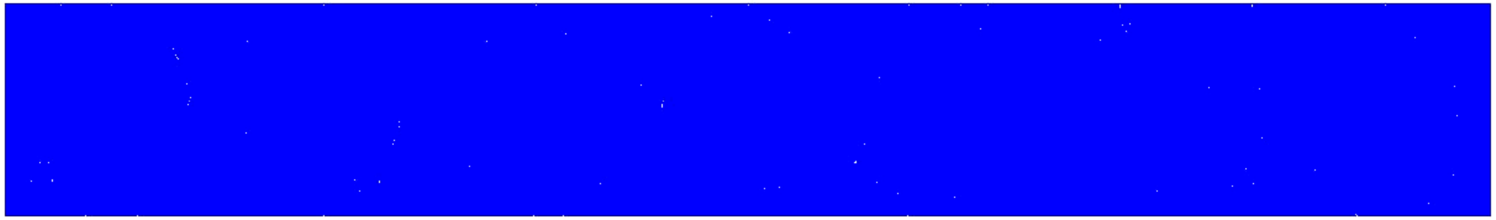


locally resonant acoustic metamaterials (LRAM)

frequency: number of ‘oscillations’ per second
wave number: number of ‘oscillations’ over specified distance
wave number: **1/wave length**

Background: working principle of LRAM

incident wave

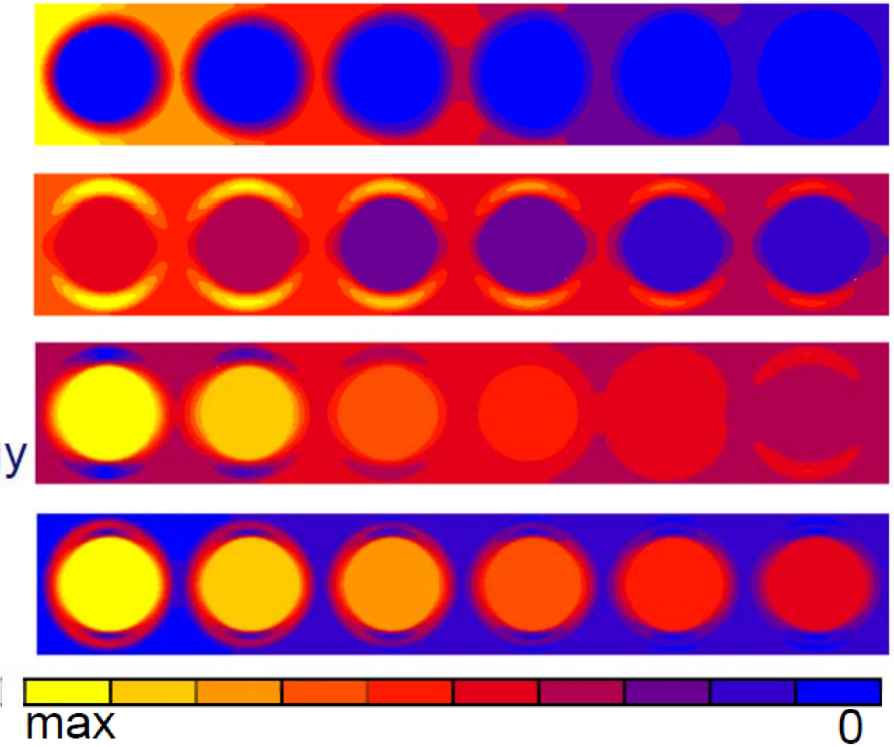


$t=t_1$; wave propagates in matrix

$t=t_2$; inclusions start to vibrate

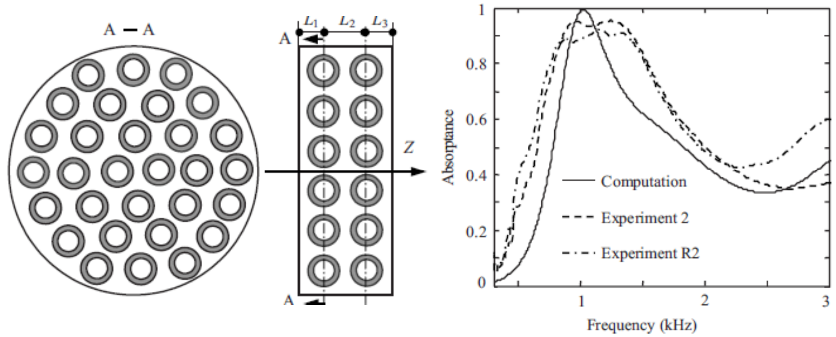
$t=t_3$; inclusions grab the wave energy

$t=t_4$; wave in matrix disappears



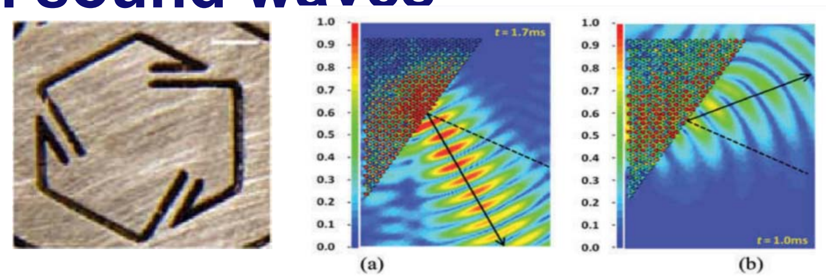
Potential applications of LRAM

- **low frequency absorbers**
  - **noise reduction**



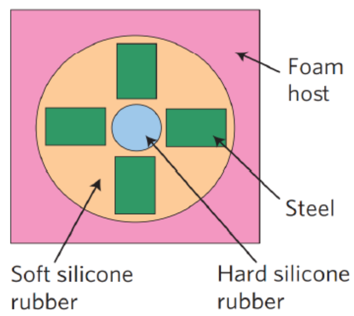
[Zhao et al. J. App. Phys. (2010)]

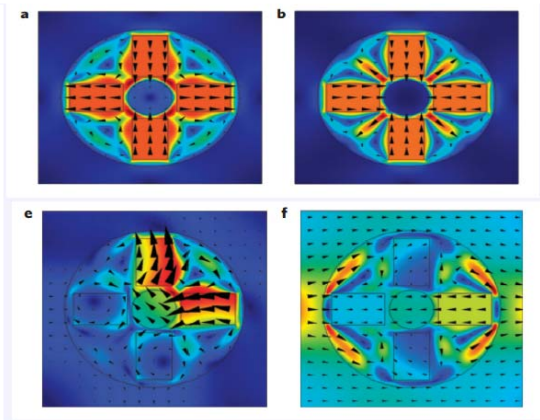
- **negative refractive index w.r.t. sound waves**
  - **super lenses**
  - **cloaking**



[Zhu et al. Nature Comm. (2014)]

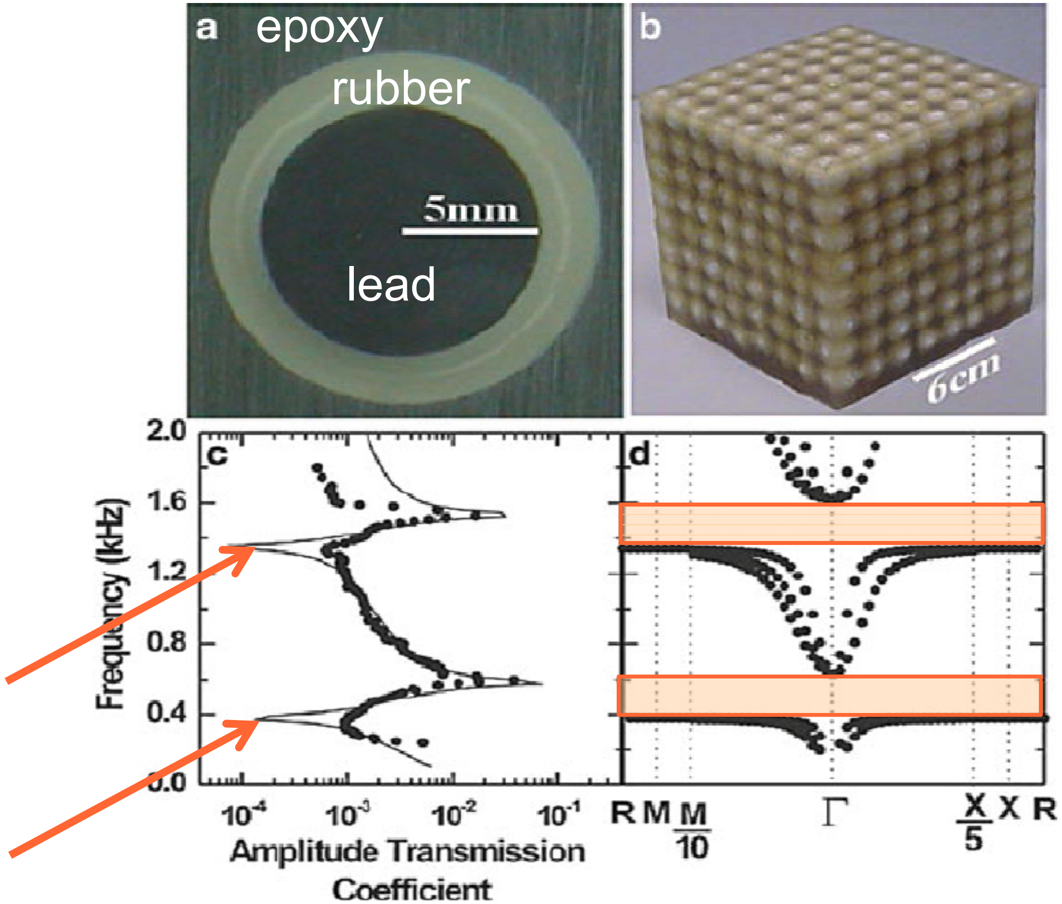
- **exotic dynamic effective properties**
  - **fluid-like behaviour (zero shear stiffness)**
  - **compressive and shear wave filters**





[Lai et al. Nature Mat. (2011)]

Example of LRAM



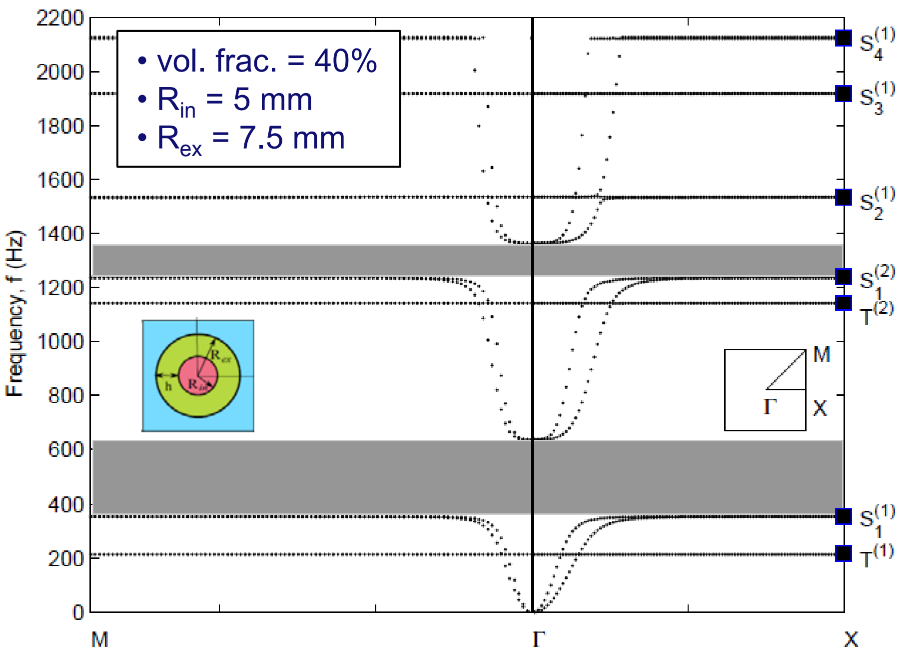
[**Liu, Z., et al.** Science (2000)]

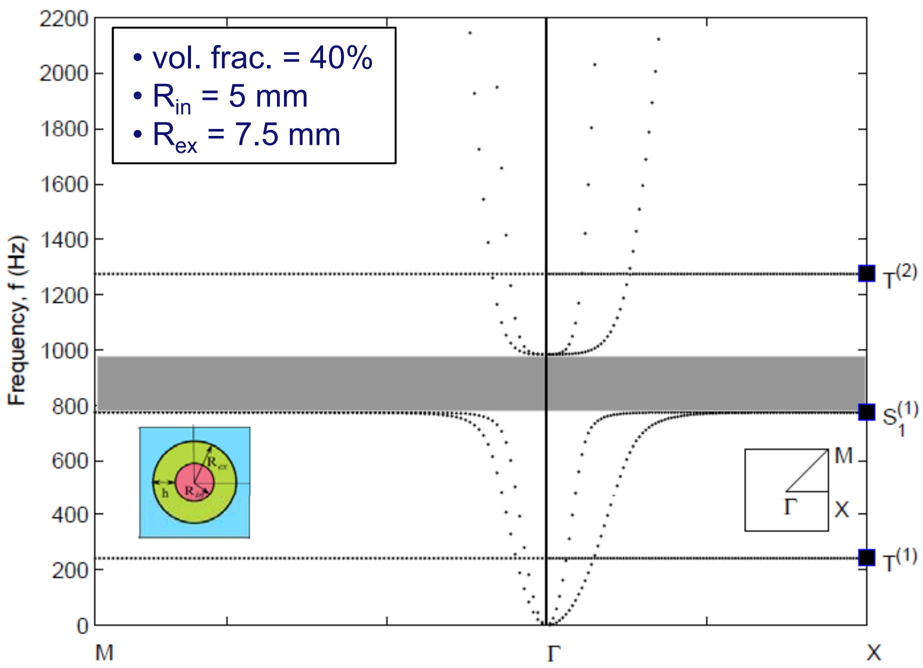
Frequency band gaps

lattice constant =15.5mm
band gap freq. 380 Hz ->
approx. 300x lattice const.

- coating material ?
- core material?
- volume fraction?
- size variations?

Coating properties



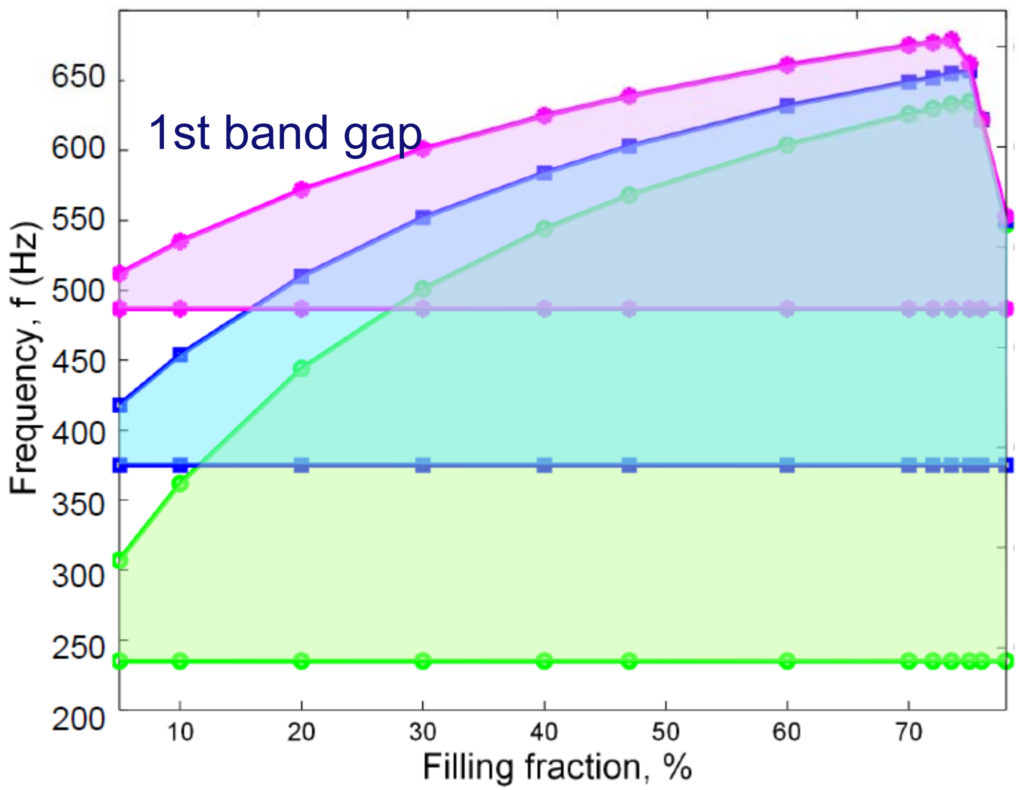


- coating Poisson's ratio: ν = 0.469 (longitudinal wave velocity c_l=23 m/s)
- coating Poisson's ratio: ν = 0.49998 (longitudinal wave velocity c_l >1000 m/s)

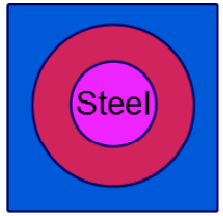
- (in)compressibility of coating changes the band gap structure

[Krushynska, Kouznetsova, Geers, JMPS (2014)]

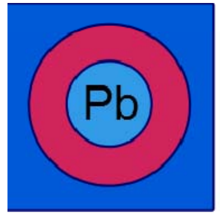
Inclusion volume fraction & core material



(inclusion and coating sizes fixed)



$\rho = 7784 \quad kg/m^3$



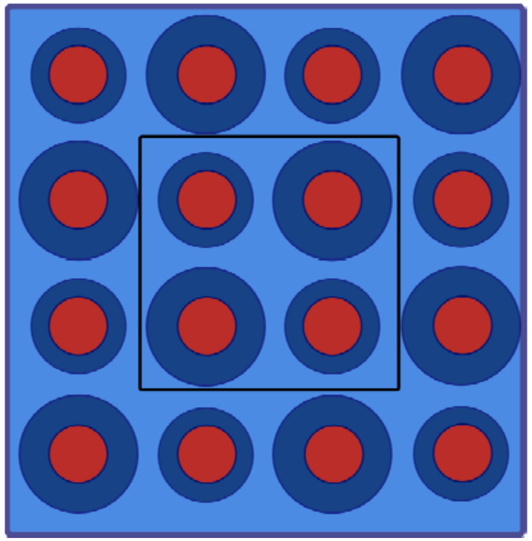
$\rho = 11600\ kg/m^3$

$\rho = 19250\ kg/m^3$

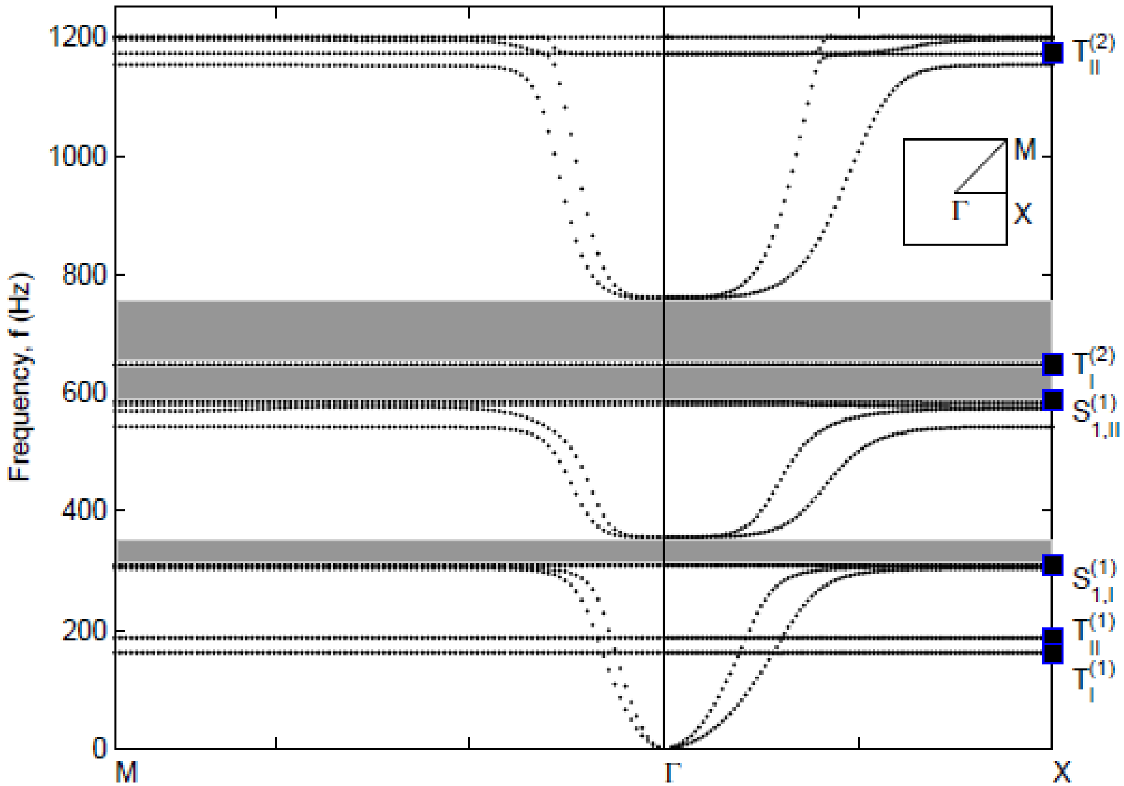
- lowest bound is independent of volume fraction (local resonance)
- band gap width depends on the volume fraction with a maximum around 70%
- heavier inclusions result in lower and wider band gap
- tungsten (W) is a good option instead of lead

[Krushynska, Kouznetsova, Geers, JMPS (2014)]

Two inclusion sizes combined



- same core radius
- different coating thickness



- presence of different inclusion sizes increases the number of band gaps
- <u>but</u> the width of band gaps is decreased
- due to the localized nature of in-plane modes, overlapping band cannot be created
- dispersion properties can be fine-tuned for a specific application

[Krushynska, Kouznetsova, Geers, JMPS (2014)]

State of the art and Challenges

State of the art:

- linear elastic materials
- (mostly) infinite medium
- or specific geometries only (e.g. spheres)

Challenges:

- non-linear materials?
- finite structures (i.e. real applications)?
  - boundaries/constraints? complex loading?
- tunable dynamic behaviour?

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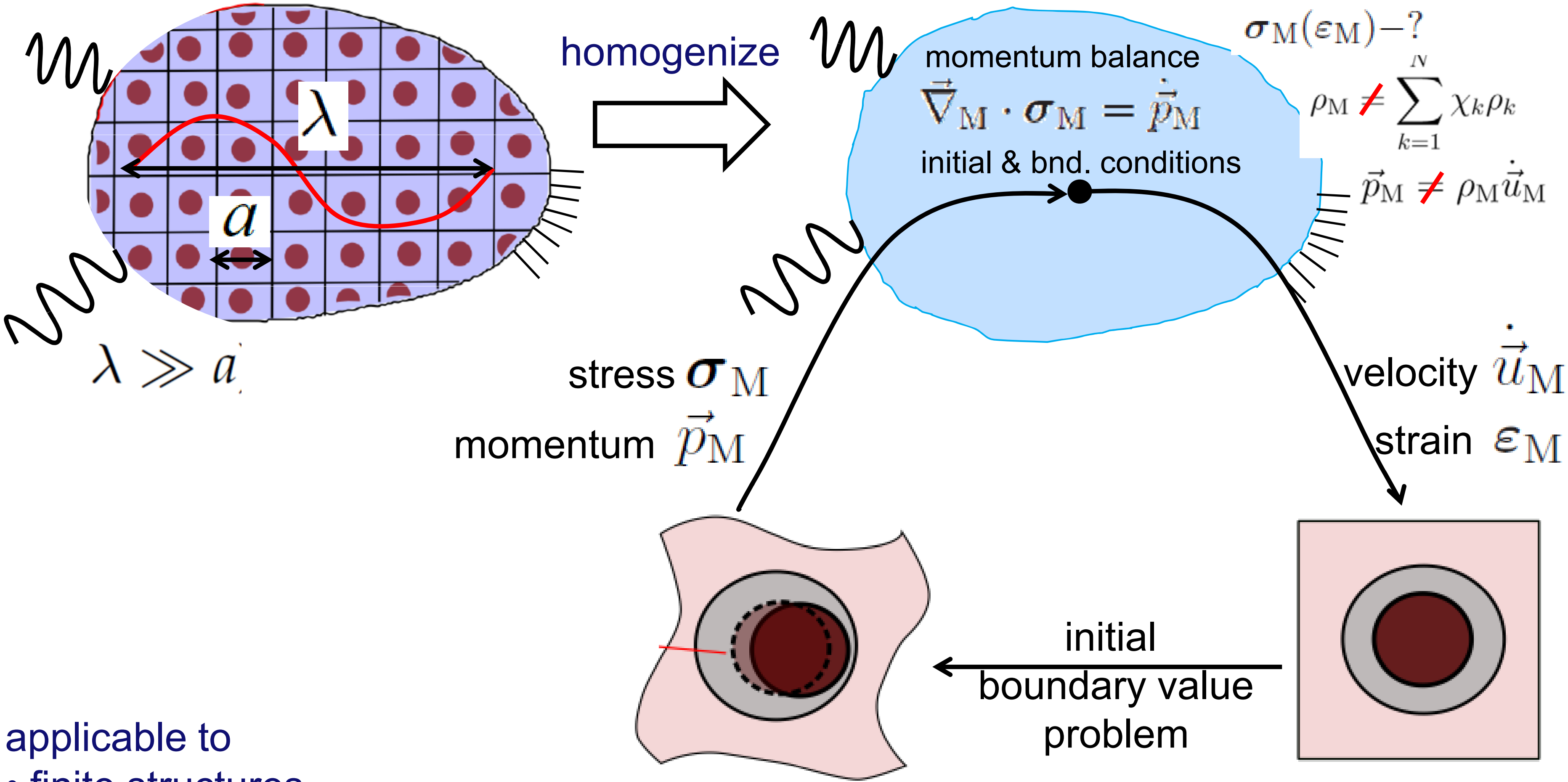
Computational Homogenization

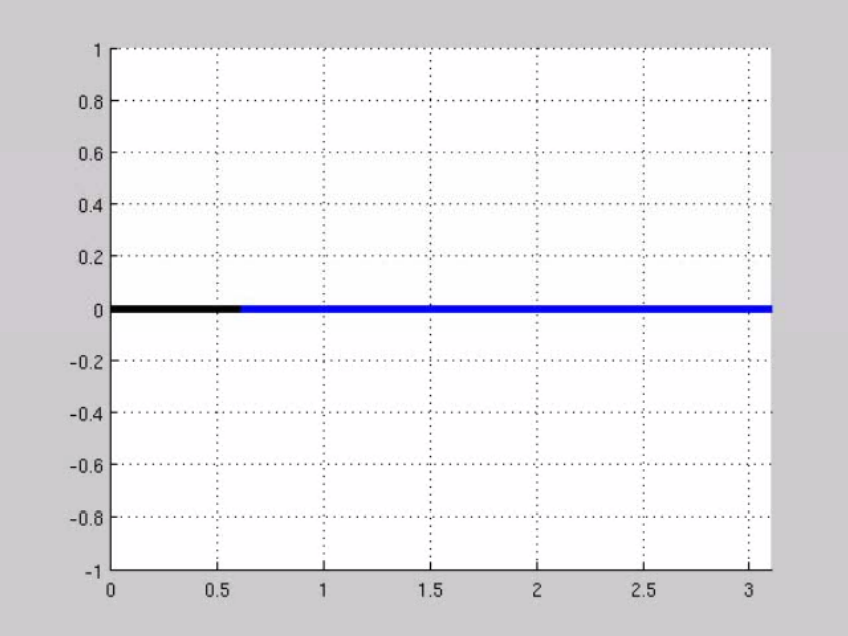


applicable to
- finite structures
- complex loading/constraints
- non-linear material behaviour

[Pham, Kouznetsova, Geers, JMPS (2013)]

Computational homogenization: example

macro
velocity profile



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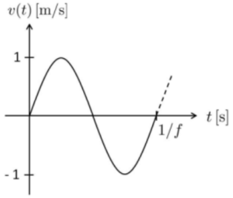
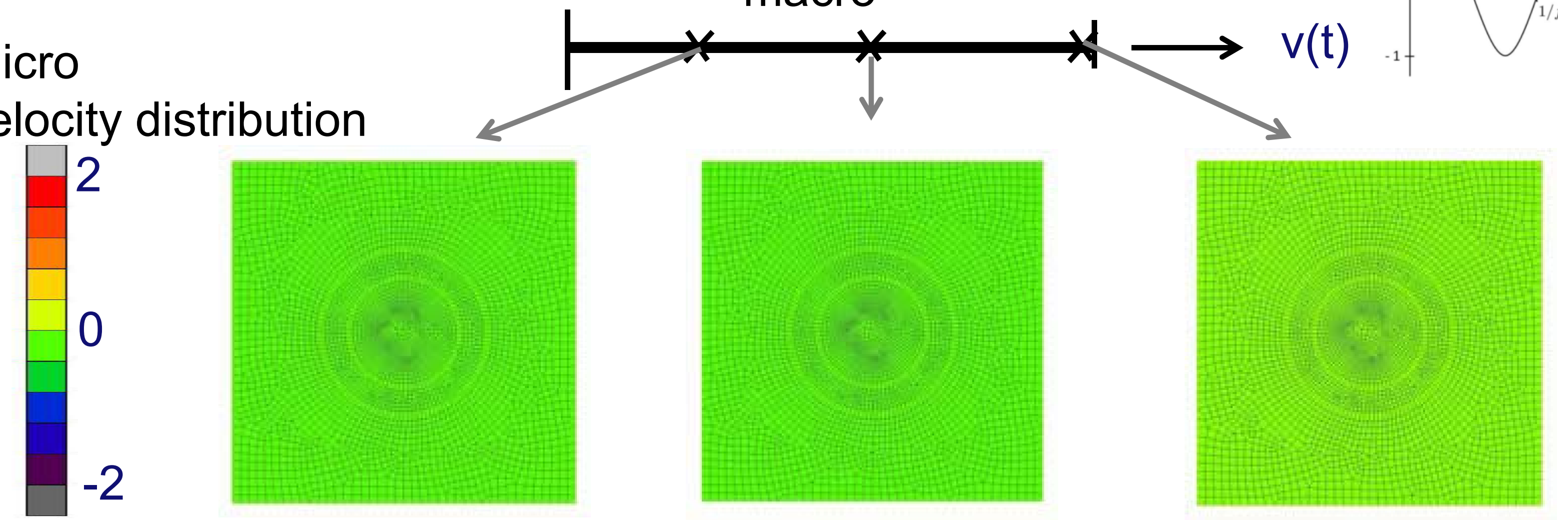


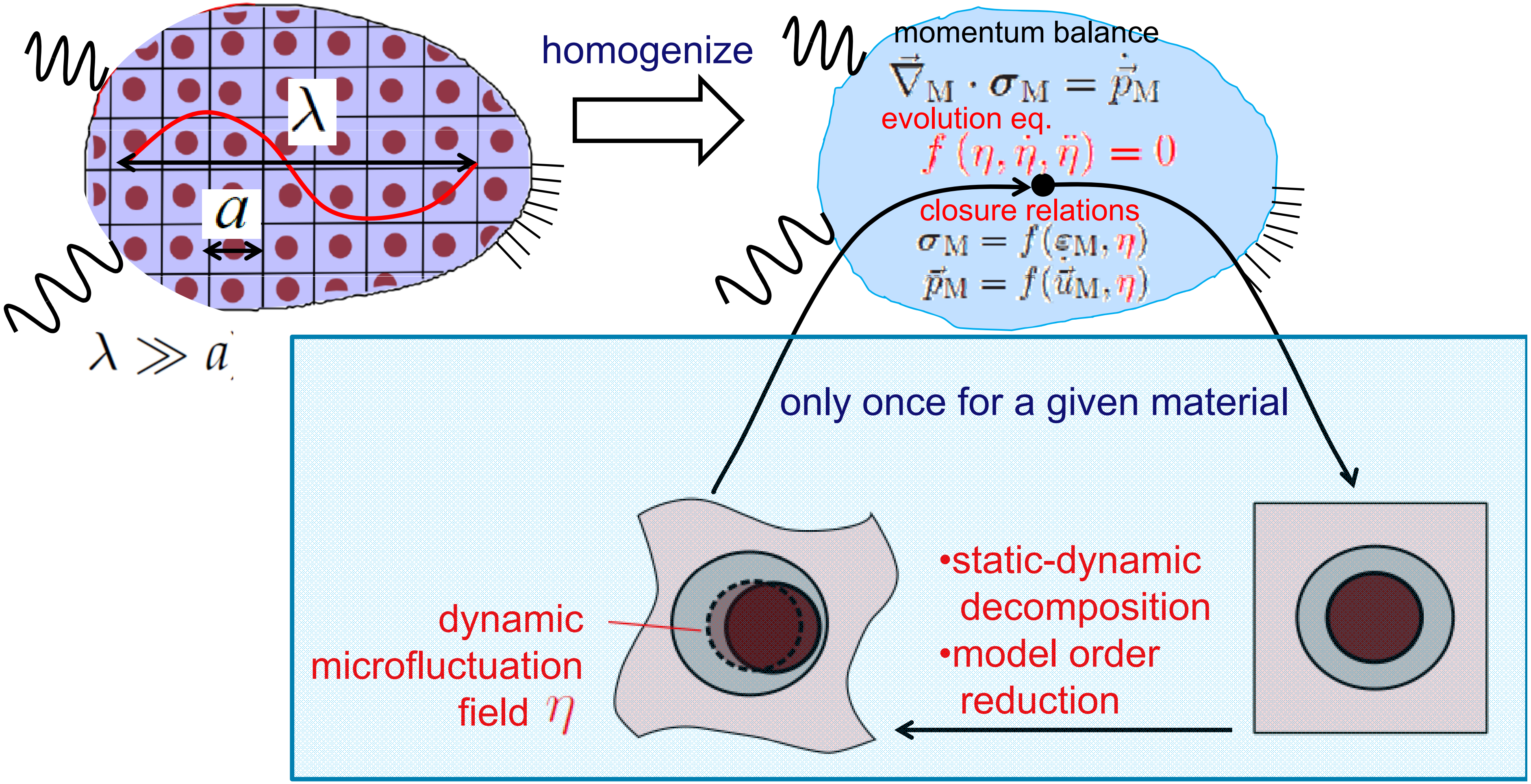
macro

v(t)

micro
velocity distribution



Closed-form Homogenization

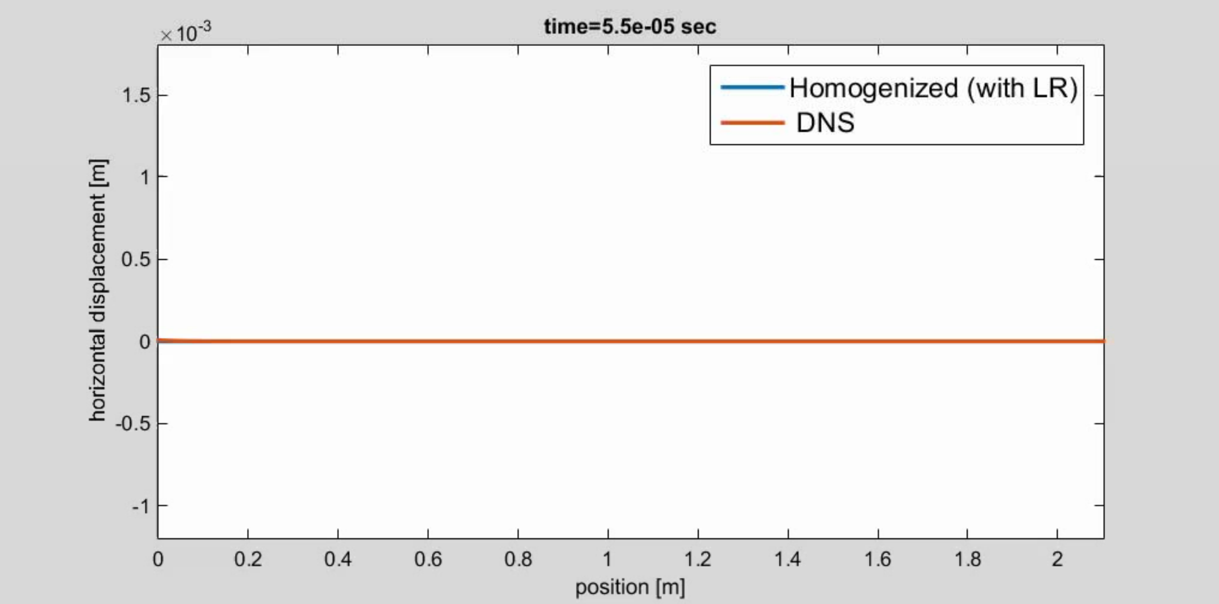


applicable to

- finite structures
- complex loading/constraints
- **linear** material behaviour

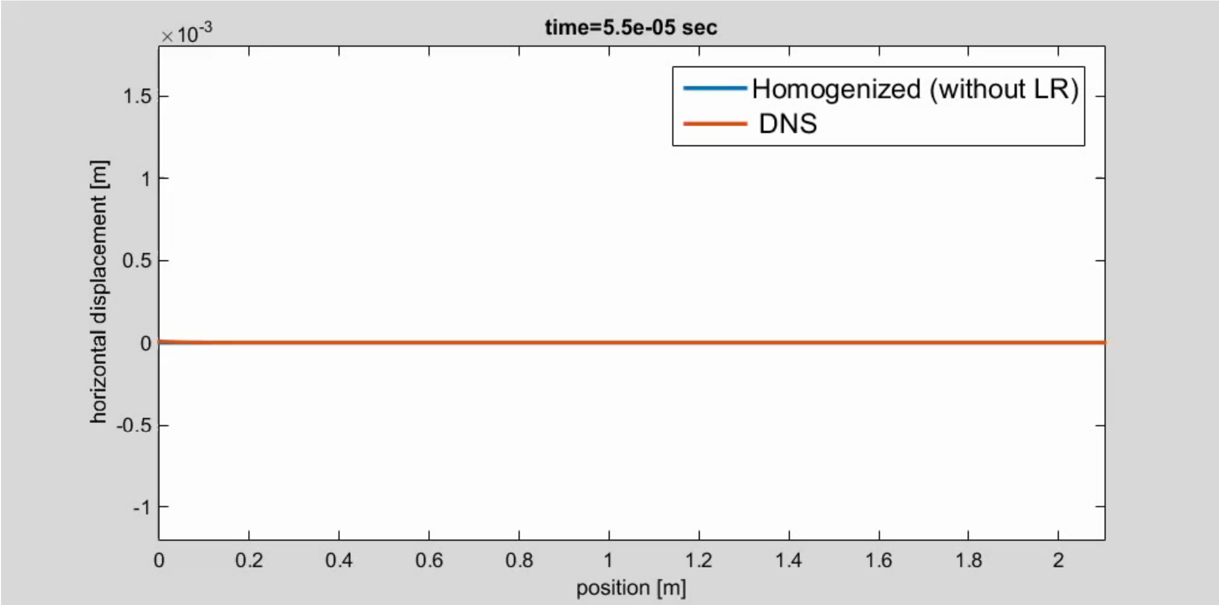
[Sridhar, Kouznetsova, Geers, in preparation]

Closed-form Homogenization: example



homogenized **with** dynamic fluctuations

homogenized **without** dynamic fluctuations



[Sridhar, Kouznetsova, Geers, in preparation]

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Other effects of non-linearities

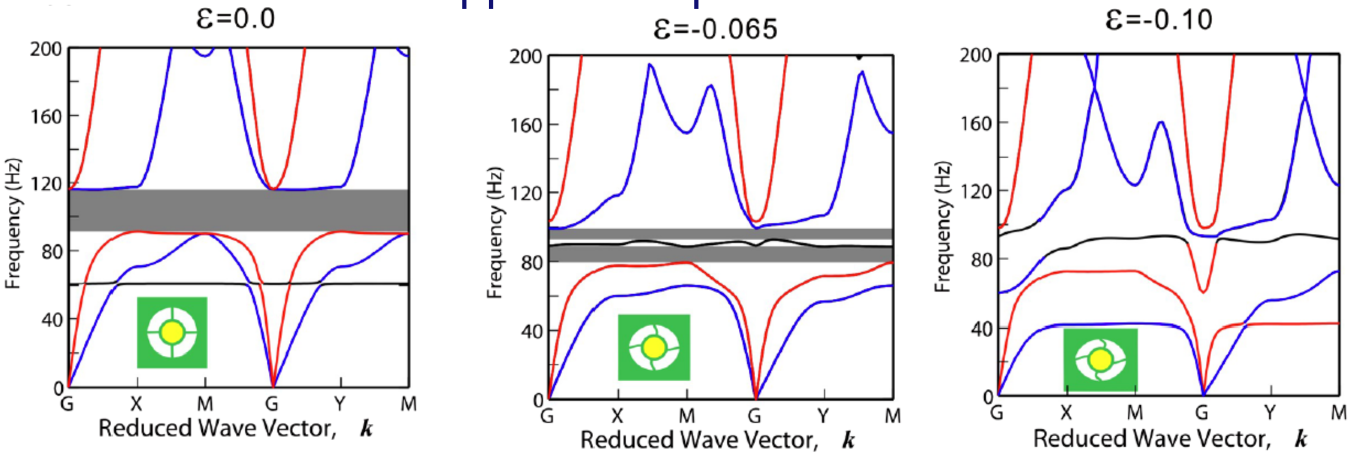
- **material non-linearities lead to amplitude dependent dispersion behaviour**

  Prof. Michael Leamy and co-workers:
  - **spring-mass systems with ‘weak’ non-linearities**

- **geometrical non-linearities can switch-on/off band gaps**

  Prof. Katia Bertoldi and co-workers

different levels of applied compressive strain



[Wang et al. PRL (2014)]

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tunable wave guides

adaptive passive vibration control

superdumping

acoustic diodes

acoustic cloaking

noise insulation

Project plan

- focus on development of analysis and modelling techniques for non-linear metamaterials
- combination of techniques from non-linear vibrations (e.g. harmonic balance, perturbation method etc.) with transient computational homogenization
- LRAMs with continuous phases and realistic non-linear material properties
  - non-linear rubber elasticity
  - visco-elasticty
  - visco-plasticity
  - ….
- LRAMs with geometrically non-linear effects
- identify the most critical material and geometrical properties for tunable systems
- formulate design guidelines

International Collaboration

- Prof. Michael Leamy (Georgia Institute of Technology, USA)
  - non-linear phenomena in dynamics and metamaterials

- Prof. Katia Bertoldi (Harvard University, USA)
  - geometrically non-linear effects in metamaterials

- Prof. John Willis (University of Cambridge, UK)
  - mathematical aspects of dynamics of metamaterials

- Prof. Norman Fleck (University of Cambridge, UK)
  - design, manufacturing and testing of structured materials

Metamaterials with tunable dynamic properties

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