Polish Academy of Sciences
Institute of Fluid Flow Machinery
Gdańsk, Poland

Structural Health Monitoring by Based on Piezoelectric Sensors

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OUTLINE FOR THE FIRST LECTURE

General Overview on SHM and NDT Methods

- NDT methods
- Extended NDT methods
- SHM methods
- General definitions

General Overview on SHM and NDT Methods

NDT methods

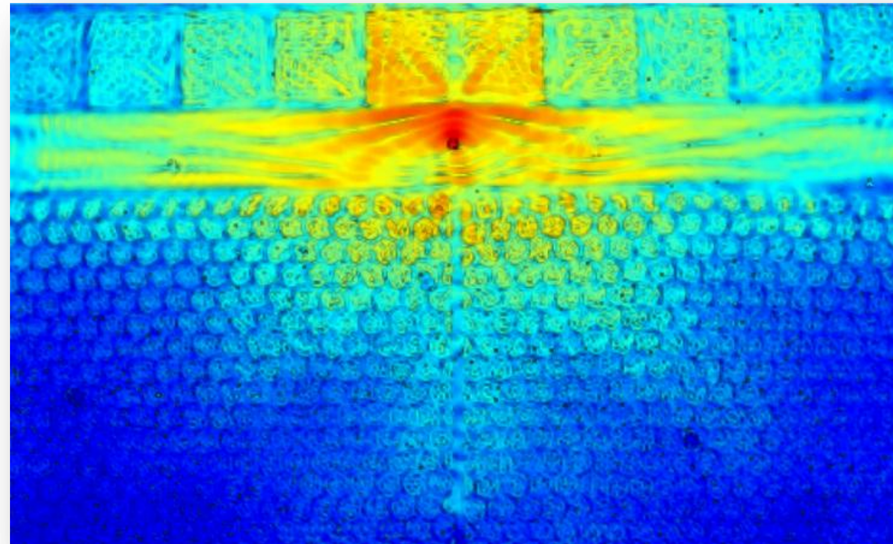
- *Conventional ultrasounds with frequency analysis*
- *Nonlinear ultrasounds*
- *Laser excited ultrasounds*
- *Eddy current*
- *Strain gauges*
- *………………………………*

General Overview on SHM and NDT Methods

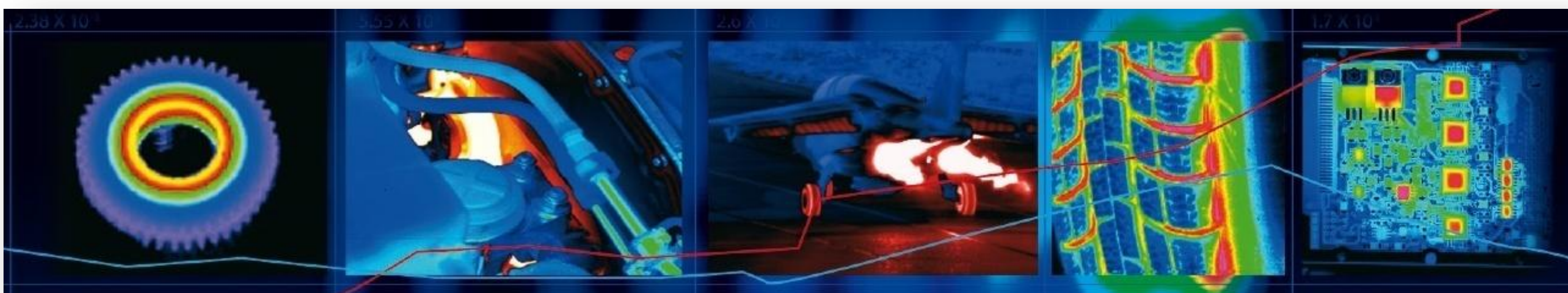
Extended NDT methods

- *Active thermography using optical excitation*
- *Active thermography using ultrasound excitation*
- *THz technology*
- *Electro–mechanical impedance*
- *………………………………………………………..*

Extended NDT Methods

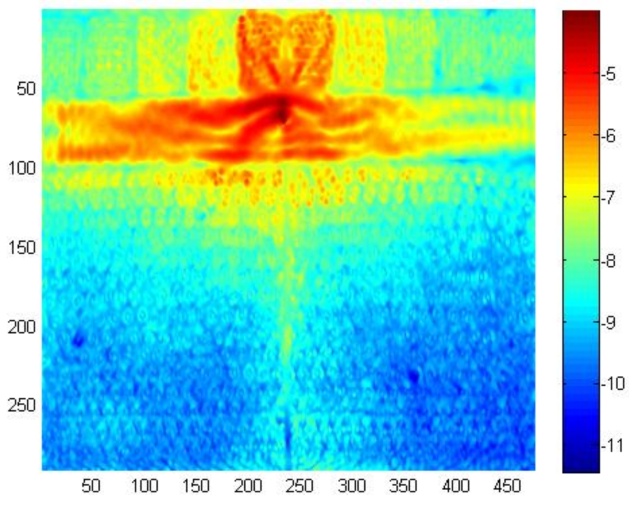


Guided waves monitoring by 3D laser scanning vibrometry

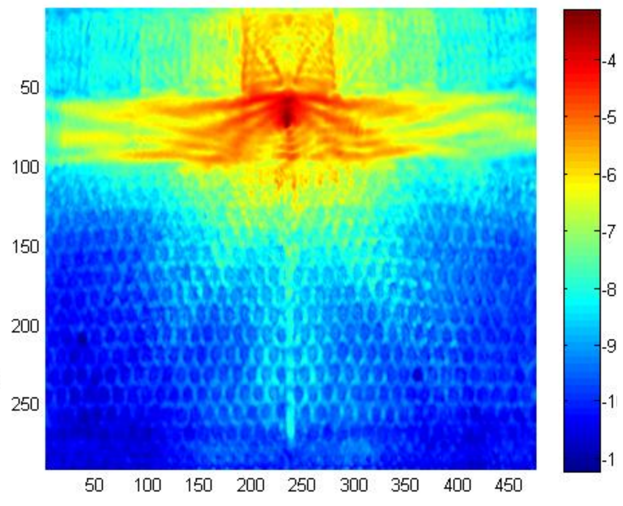


Active thermography

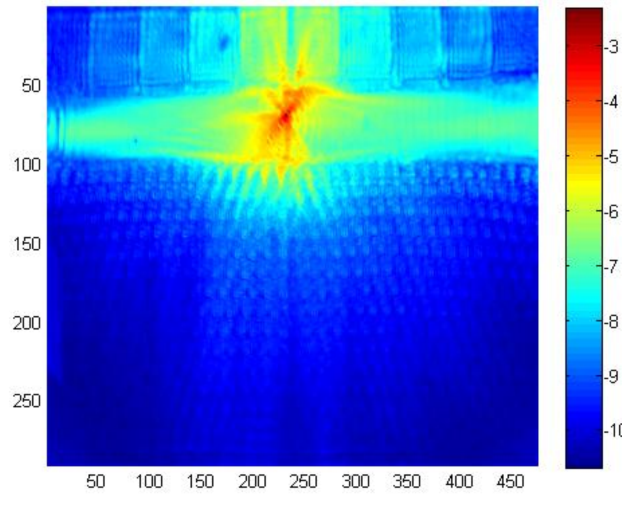
Damage detection



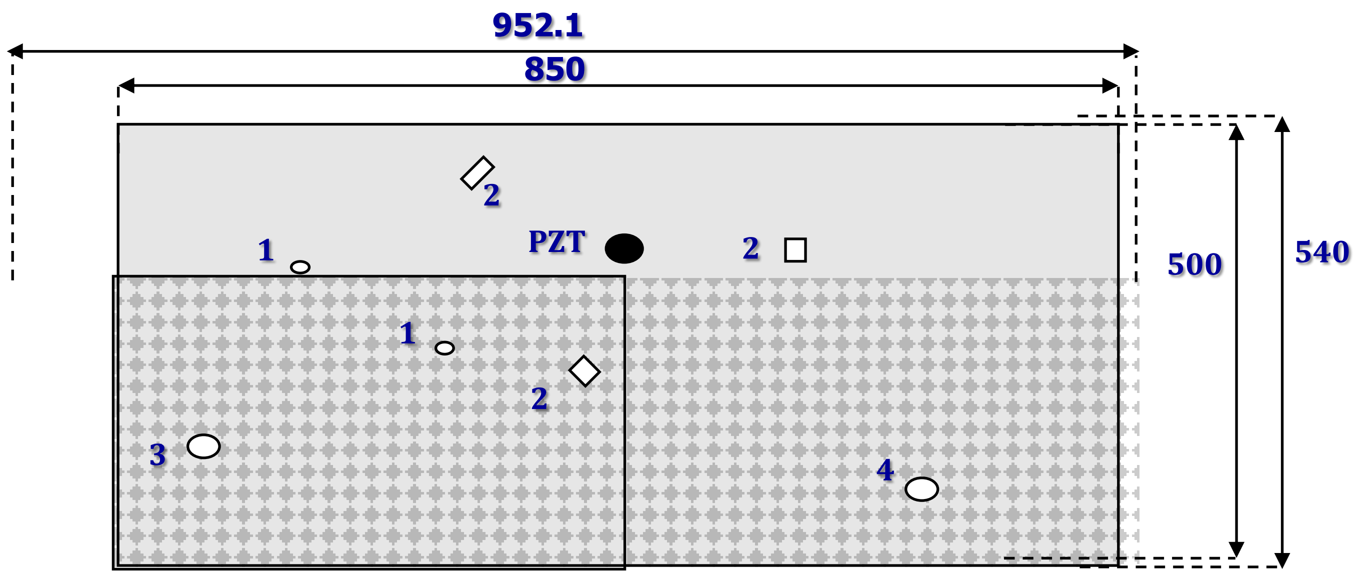
16.5 kHz



35 kHz



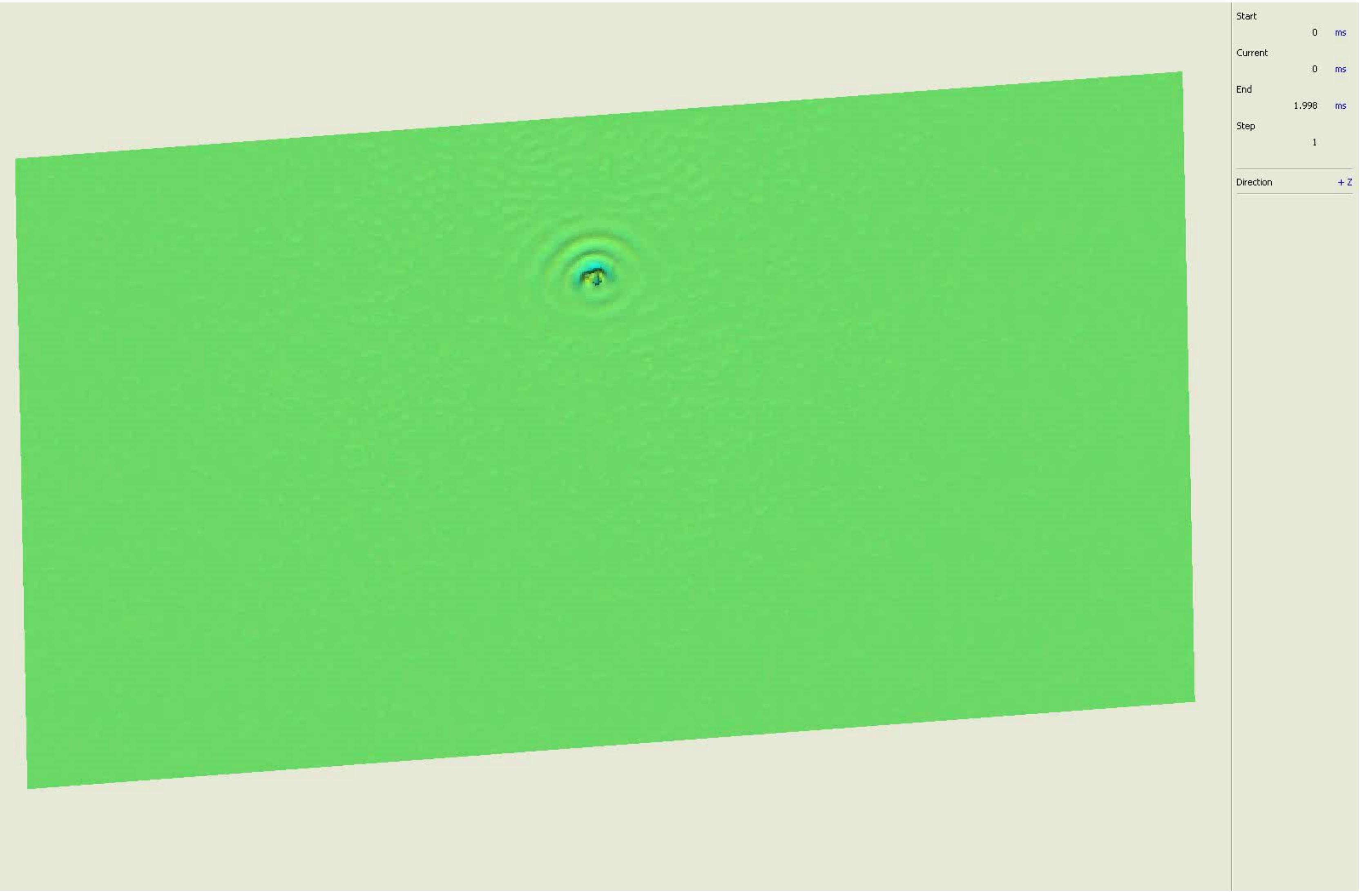
100 kHz



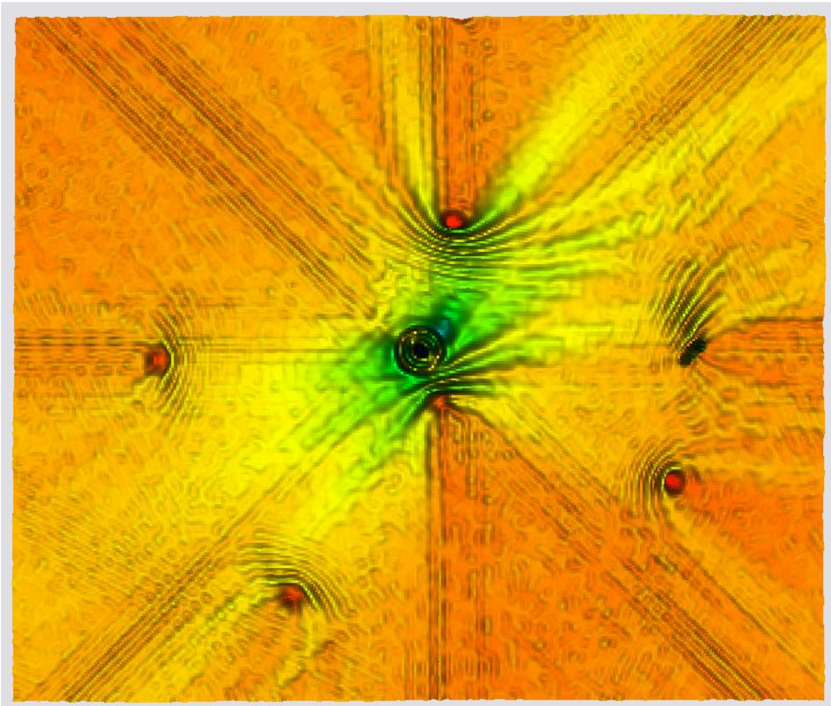
Energy distribution

PZL – WA Stabilizer

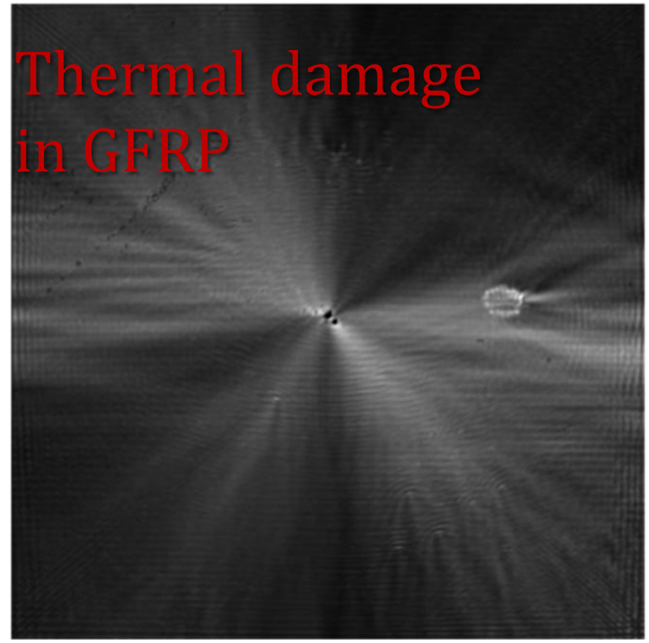
A0 Wave   35 kHz

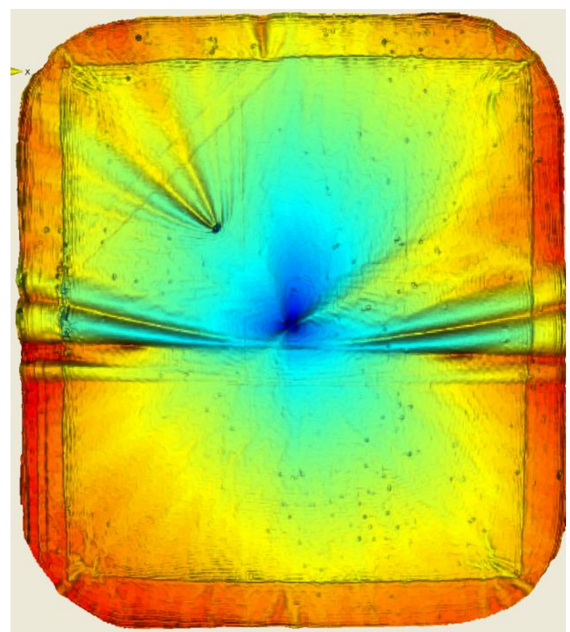


Damage detection



Additional masses detection

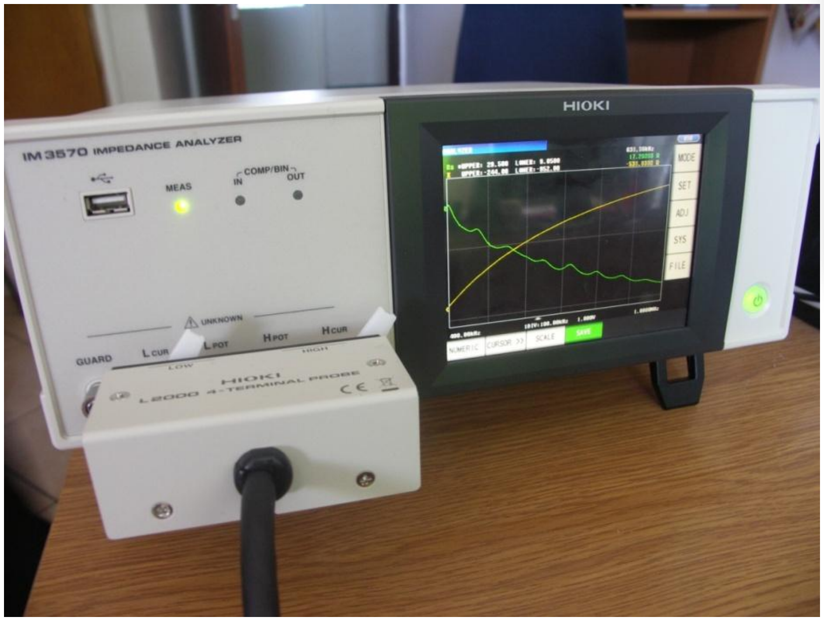


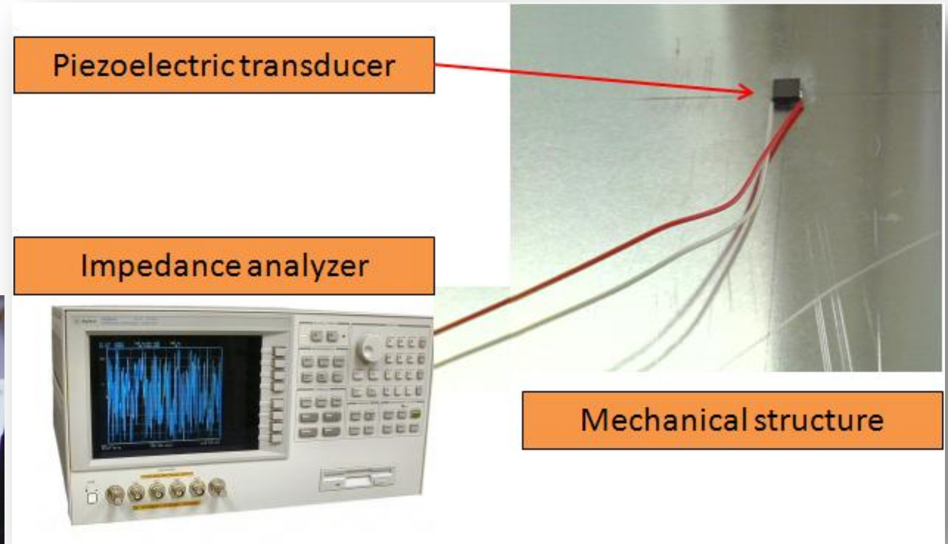


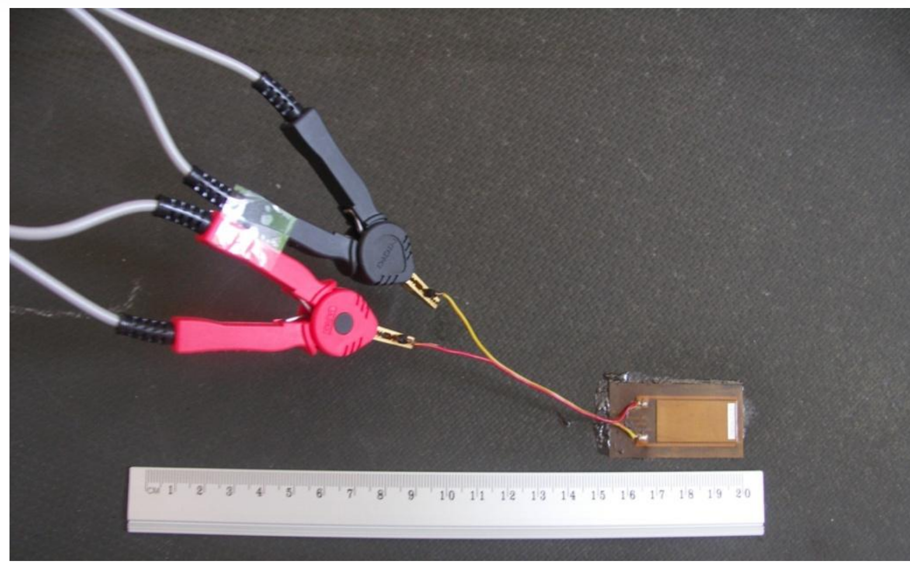
Notch detection

Extended NDT Methods

Electro-mechanical impedance

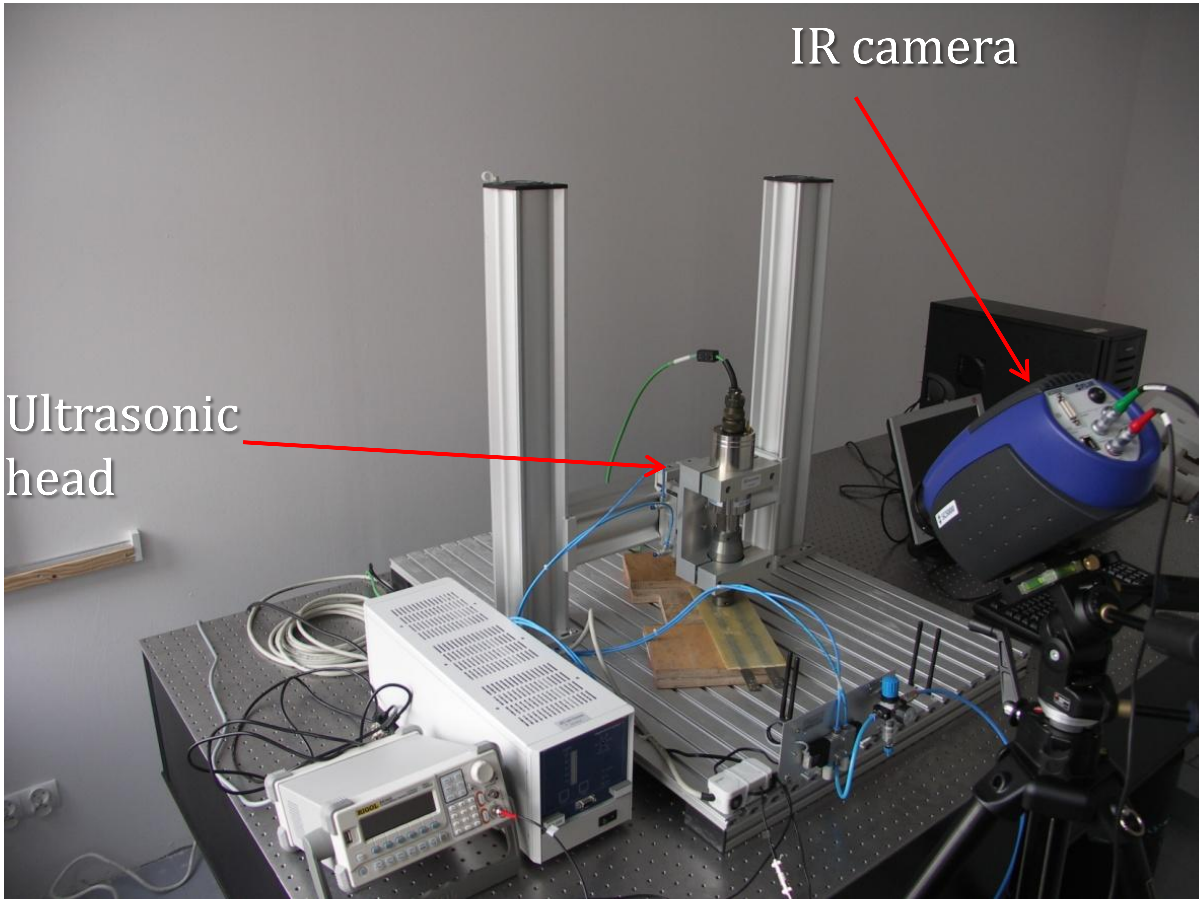




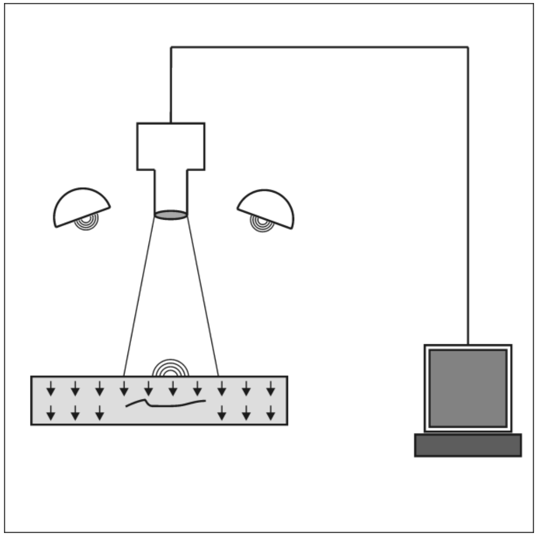


Extended NDT Methods

Vibrothermography



Other applications:



Pulse thermography

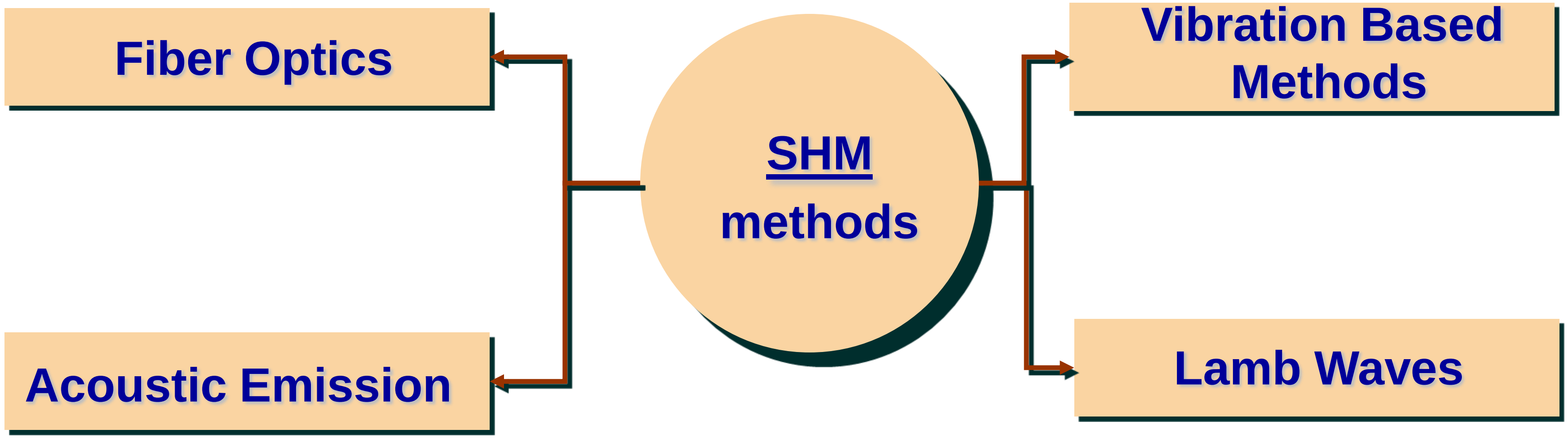
General Overview on SHM and NDT Methods

SHM methods

- *Vibration based methods*
- *Guided wave methods*
- *Fiber Optics Techniques*
- *Acoustic Emission*
- *Comparative Vacuum Monitoring*
- *Electromagnetic layer*
- **……………………………………………………………………**

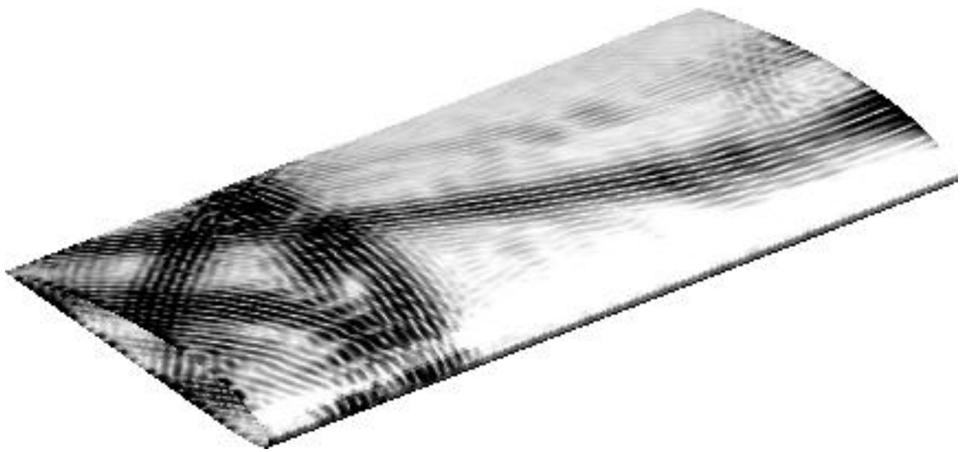
SHM METHODS

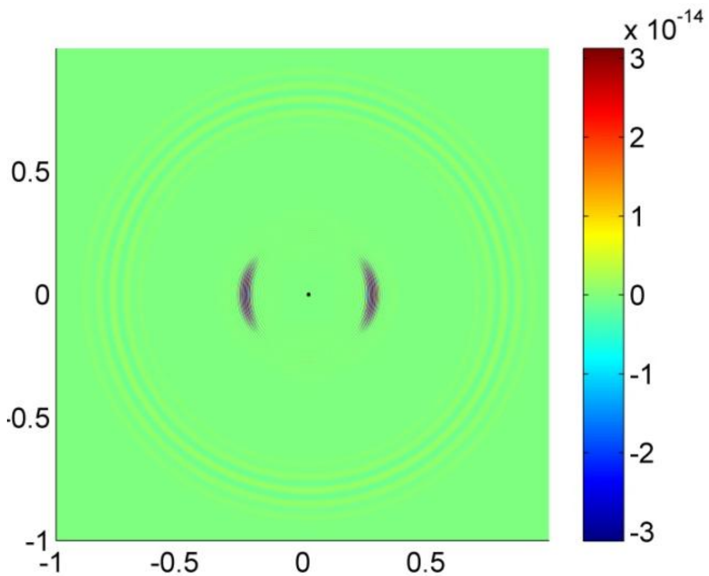
There is a need for SHM methods capable of comprehensive, real-time condition monitoring

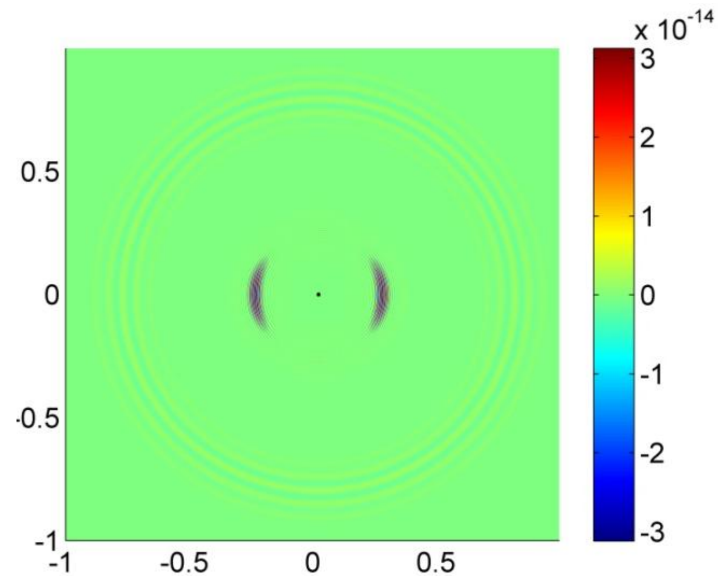


SHM METHODS

Guided waves propagation

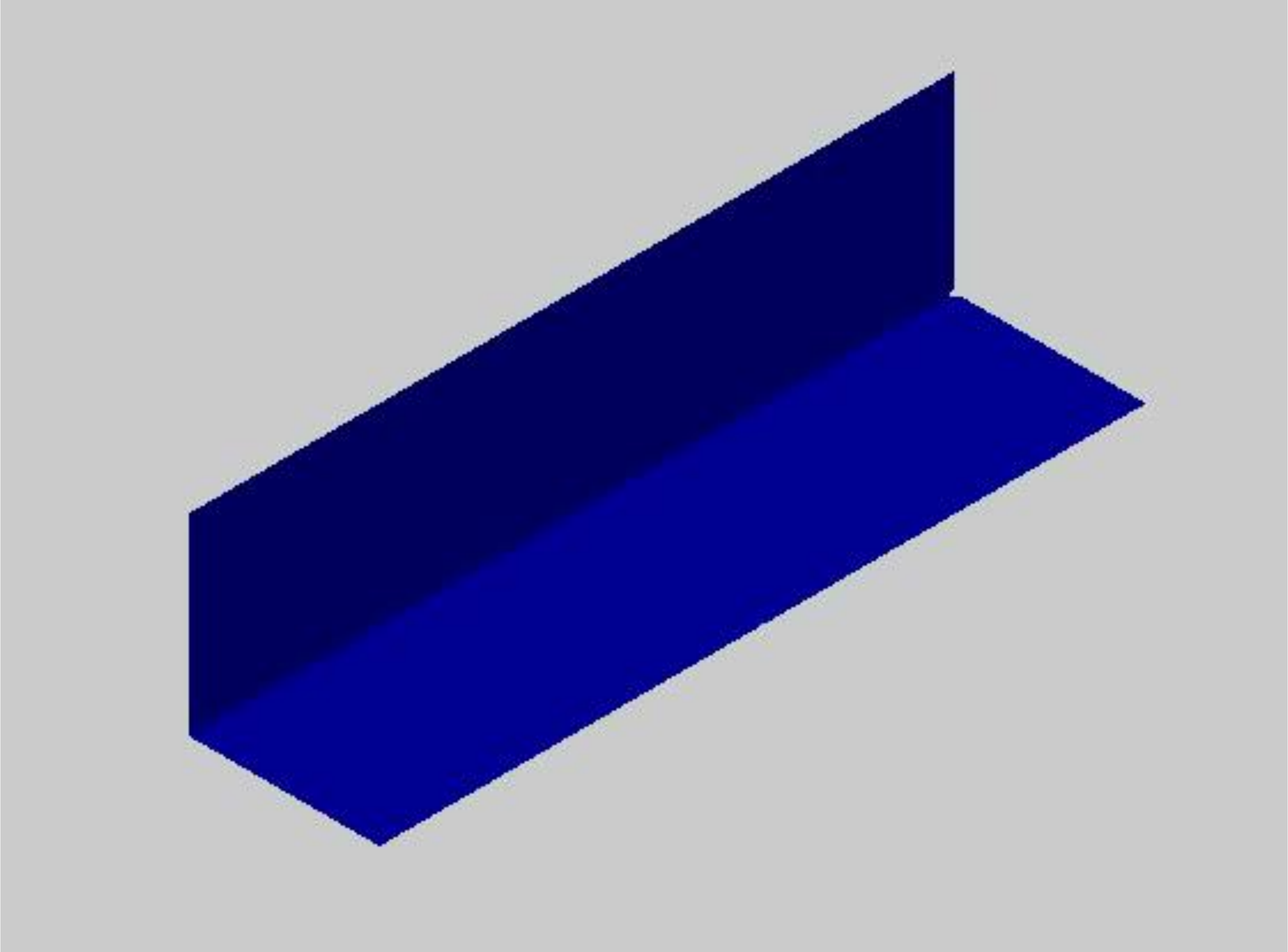






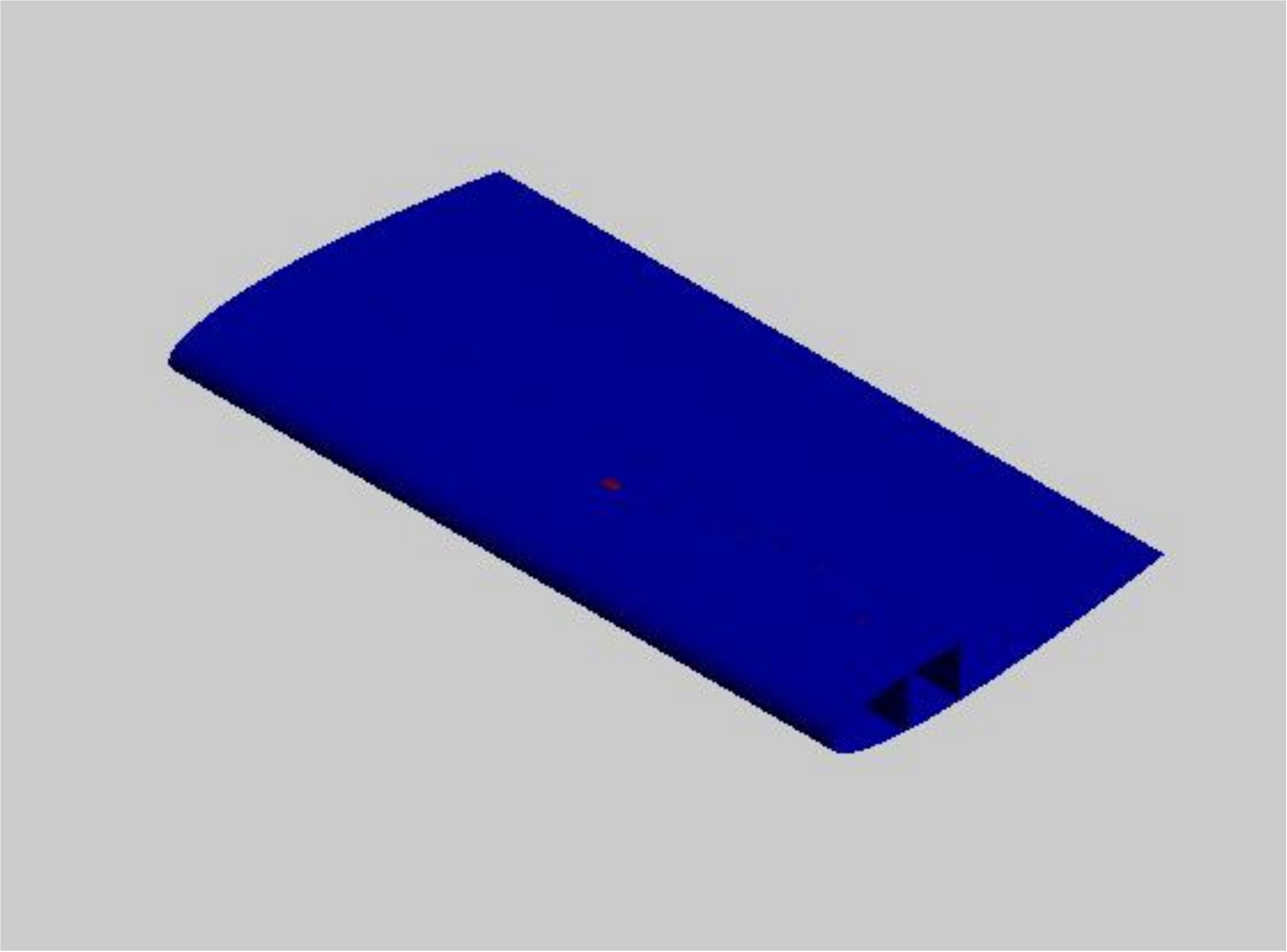
L – Shape

A0 Wave   75 kHz

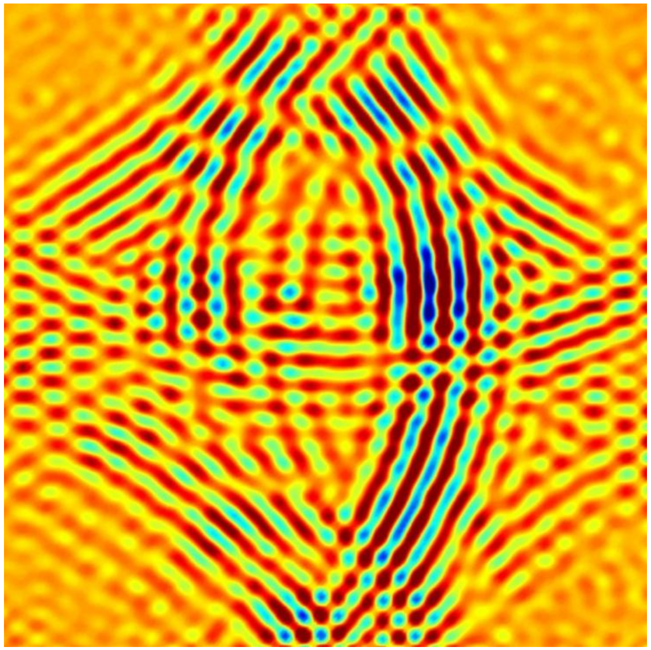


Wing Section

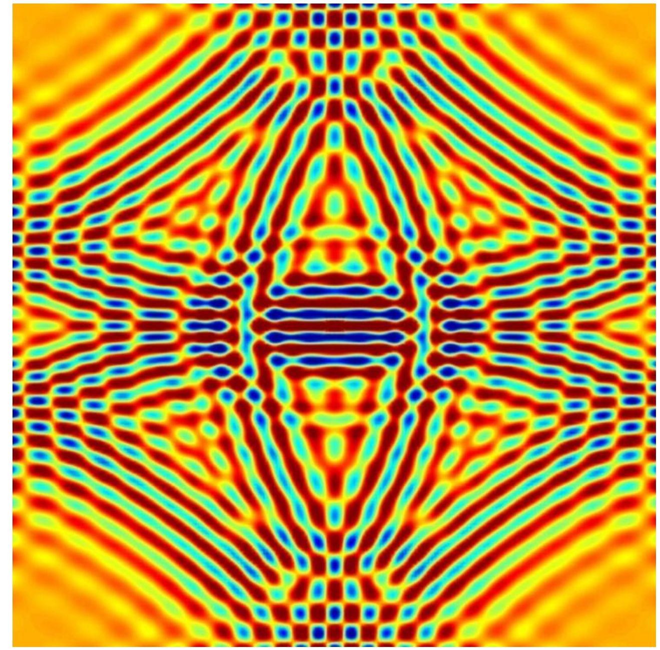
A0 Wave 75 kHz



Experimental vs. numerical results



Laser vibrometry



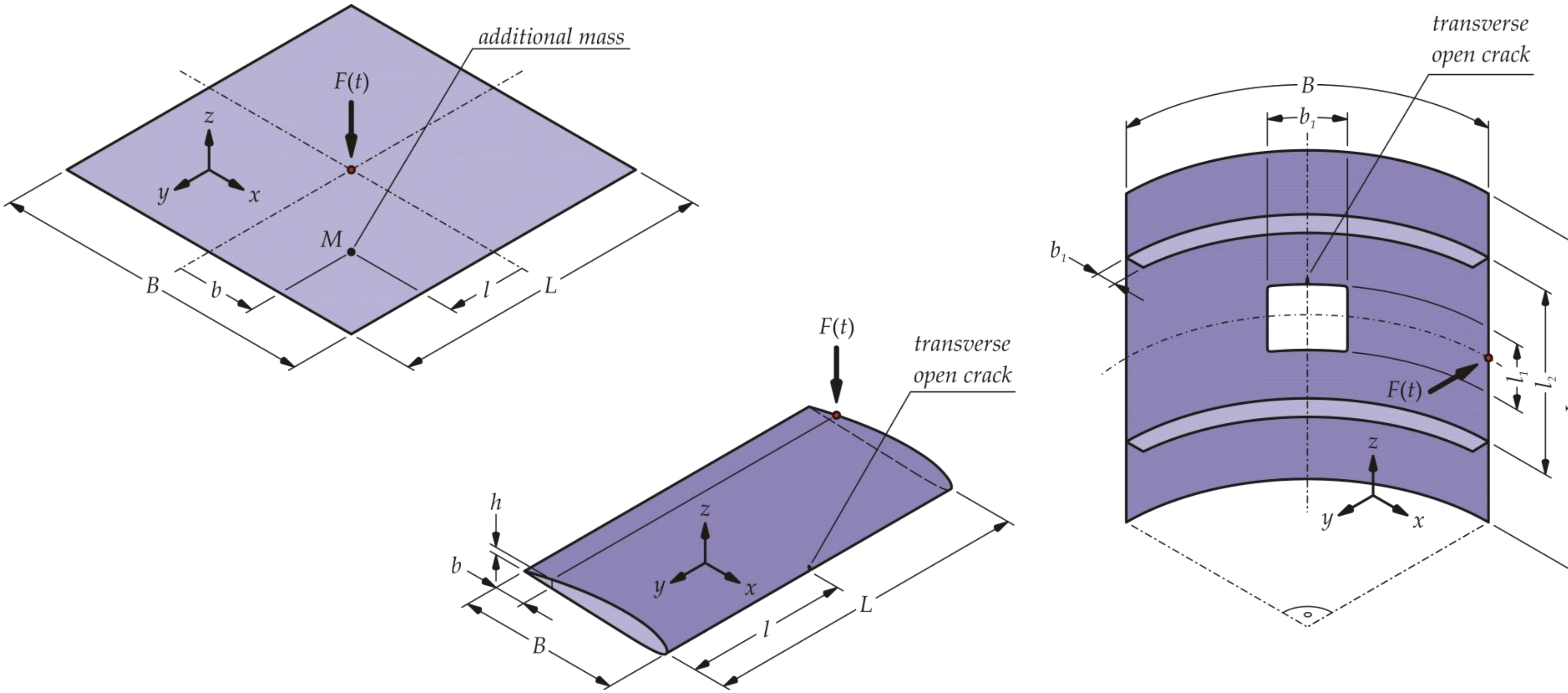
Spectral Finite Element Method
(numerical calcilations)

Lateral Velocities

Glass fibers/epoxy, laminate [0/90/0/90]

Spectral Finite Element Method

– Damage Detection and Localization

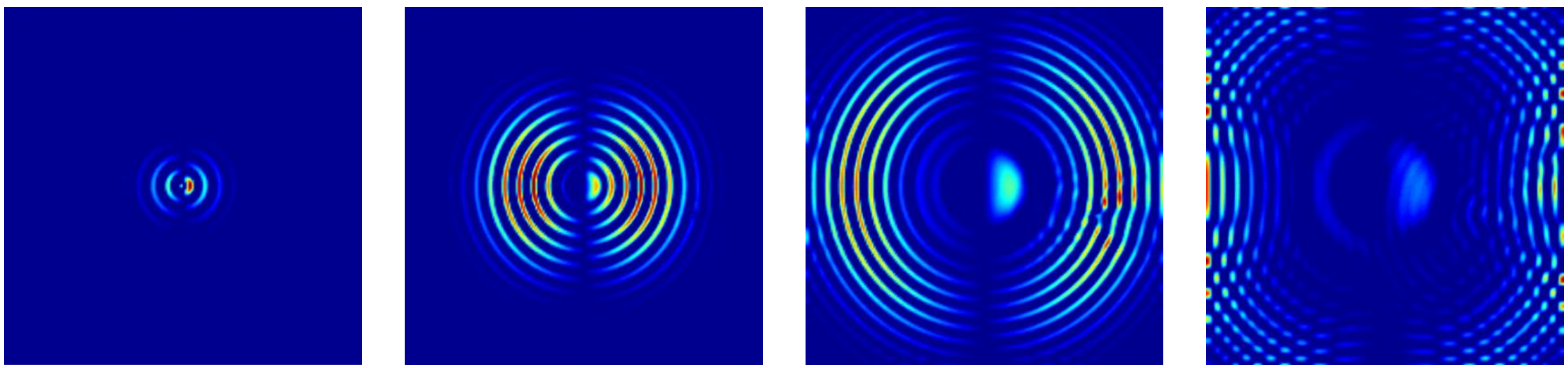


Numerical Simulations – Geometry

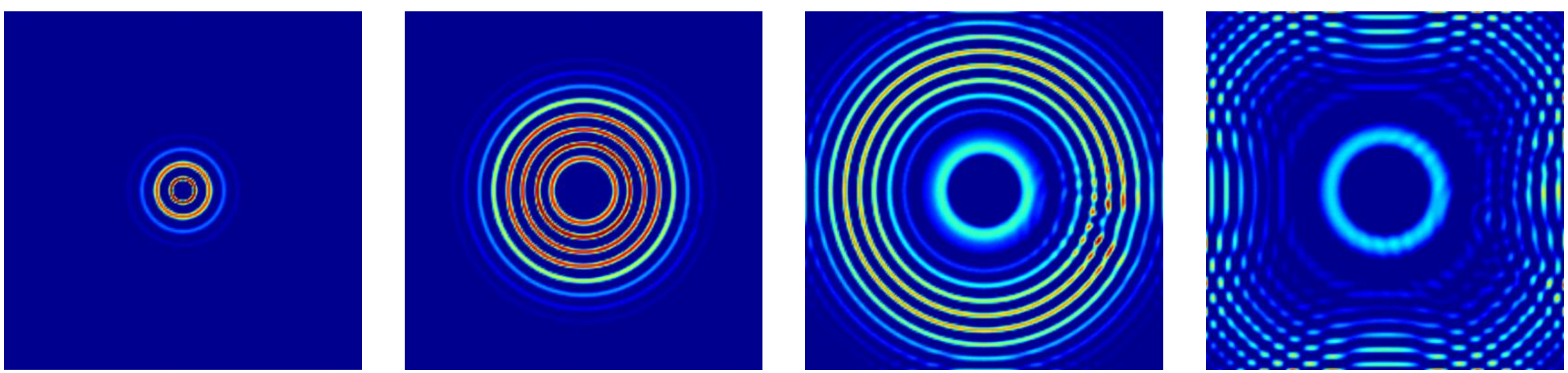
Spectral Finite Element Method

– Damage Detection and Localization

Aluminium plate, detection and localization of additional mass– IMV (*Integral Mean Value*) Maps



IMV Maps for displacements *u*, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms

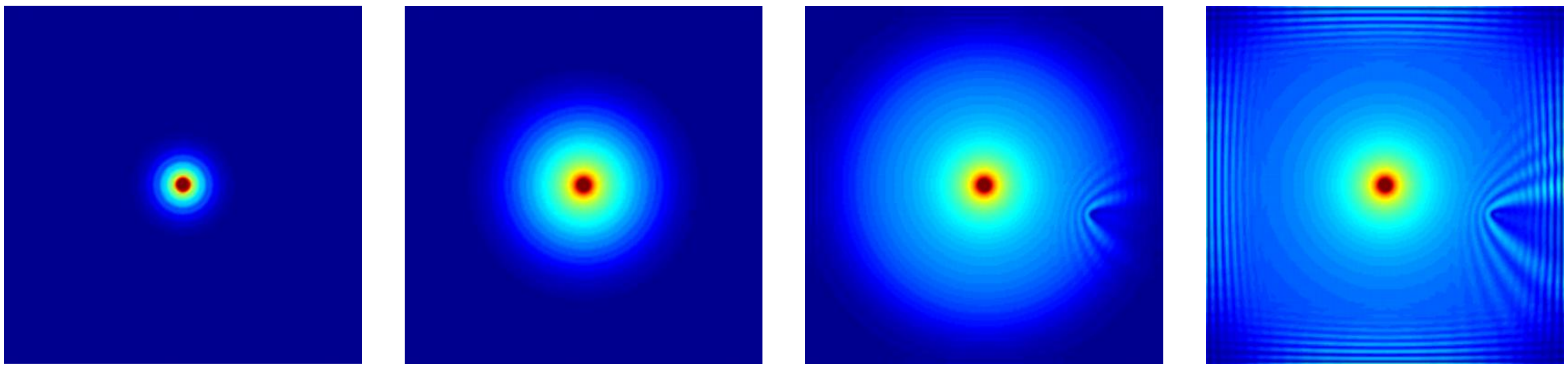


IMV Maps for displacements *w*, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms

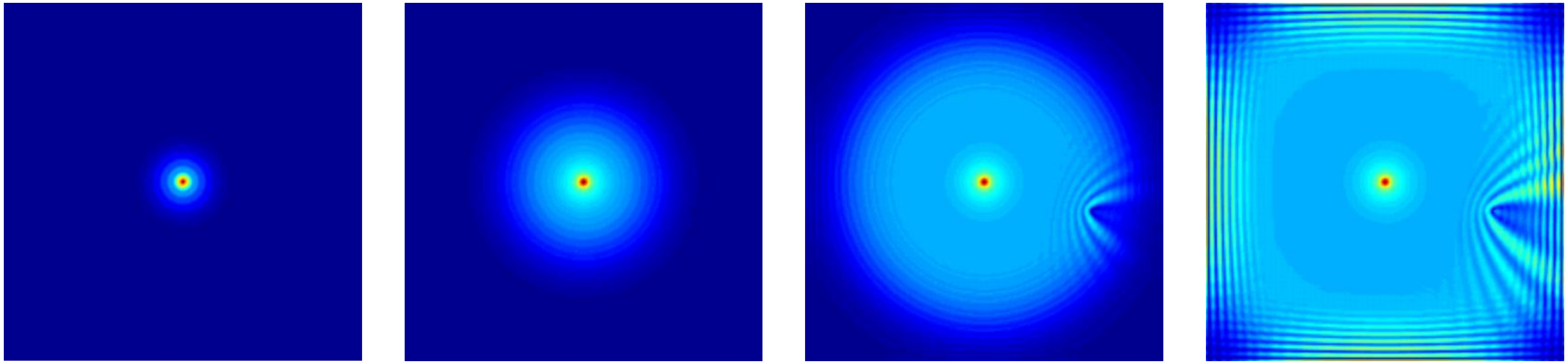
Spectral Finite Element Method

– Damage Detection and Localization

Aluminium plate, detection and localization of additional mass– RMS (*Root Mean Square*) Maps



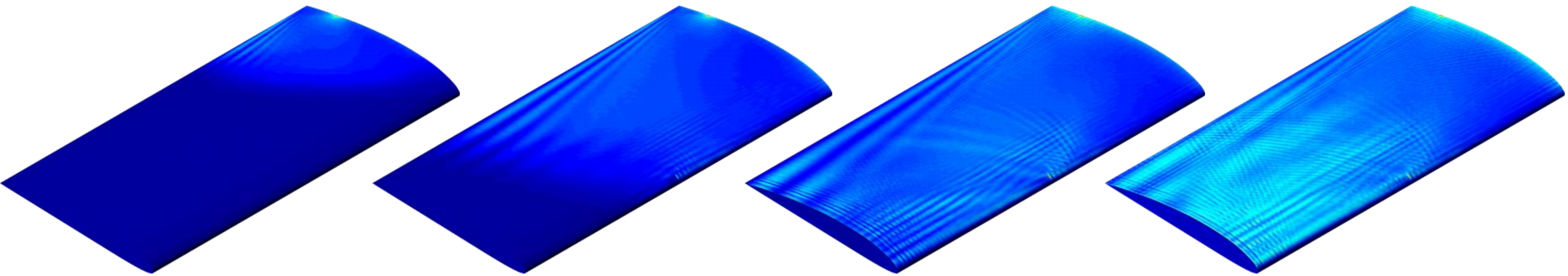
RMS Maps for displacements *u*, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms



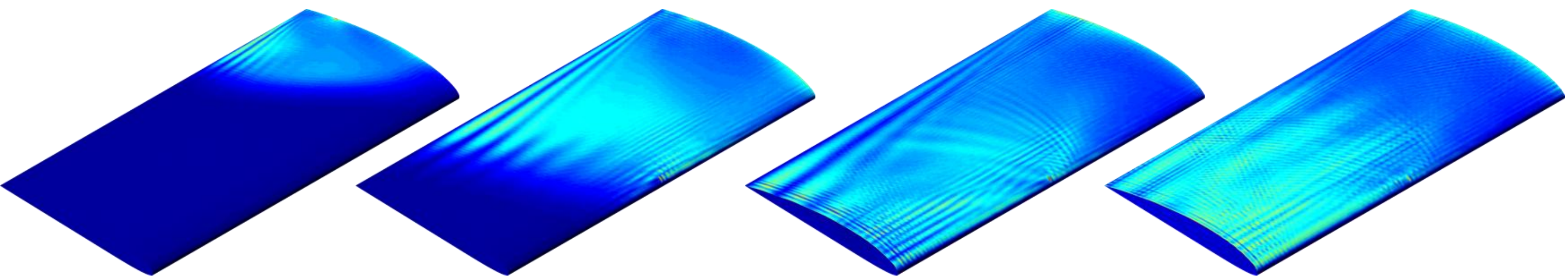
IMV Maps for displacements *w*, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0.5 ms

Sheathing of a small aircraft wing – detection and location of a failure

RMS (*Root Mean Square*) maps



RMS maps for displacements *w* | time: 0,125 ms; 0,25 ms; 0,375 ms; 0,5 ms



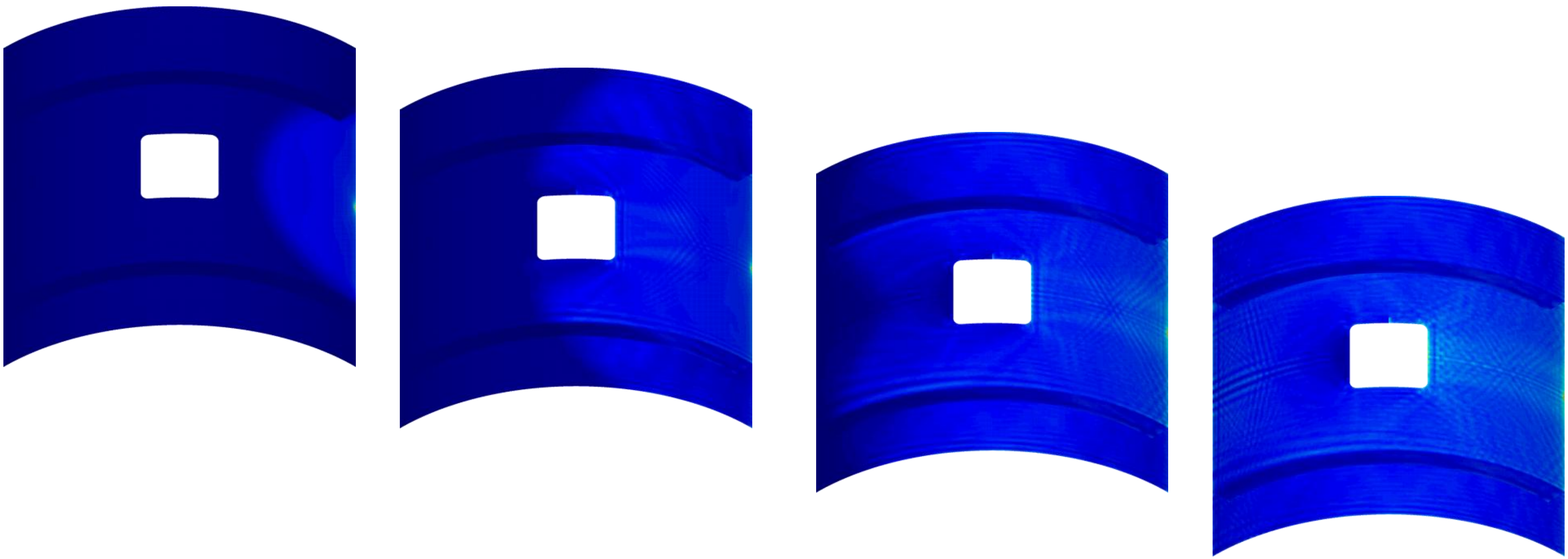
Weighted RMS maps for displacements *w* | time: 0,125 ms; 0,25 ms; 0,375 ms; 0,5 ms

Spectral Finite Element Method

– Damage Detection and Localization

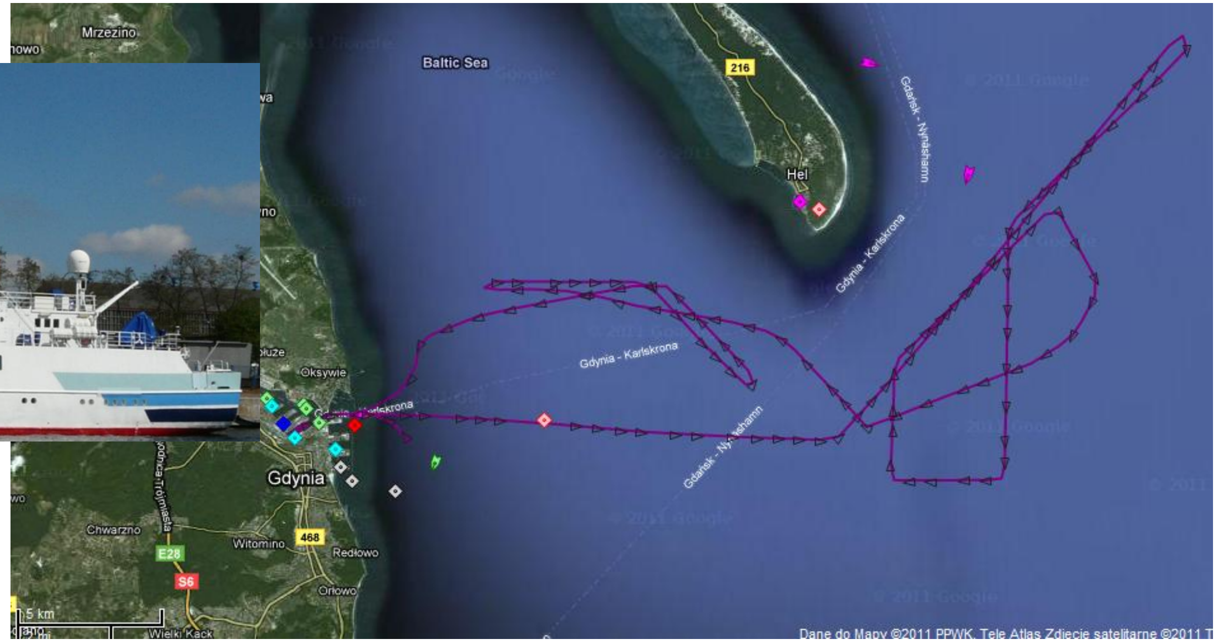
Part of the fuselage shell, detection and localization of fatique cracks

RMS (z ang. *Root Mean Square*) Maps

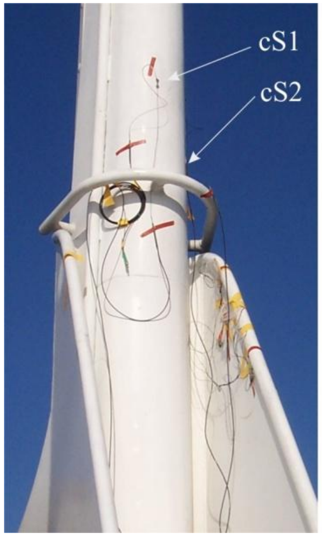


RMS Maps for amplitudes of displacement *a*, for the following periods: 0,125 ms; 0,25 ms; 0,375 ms; 0,5 ms

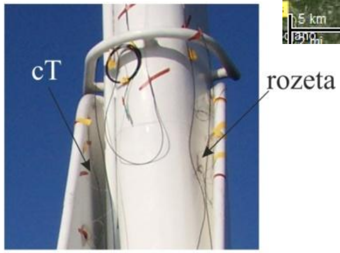
SHM METHODS



Mrzezino
Baltic Sea
216
Hel
Gdańsk - Nynäshamn
Gdynia - Karlskrona
Gdynia - Karlskrona
Gdańsk - Nynäshamn
Oksywie
Gdynia
Chwarzno
Witomino
468
Redłowo
Orłowo
E28
S6
5 km
Dane do Mapy ©2011 PPWK, Tele Atlas Zdjęcie satelitarne ©2011 T



cS1
cS2



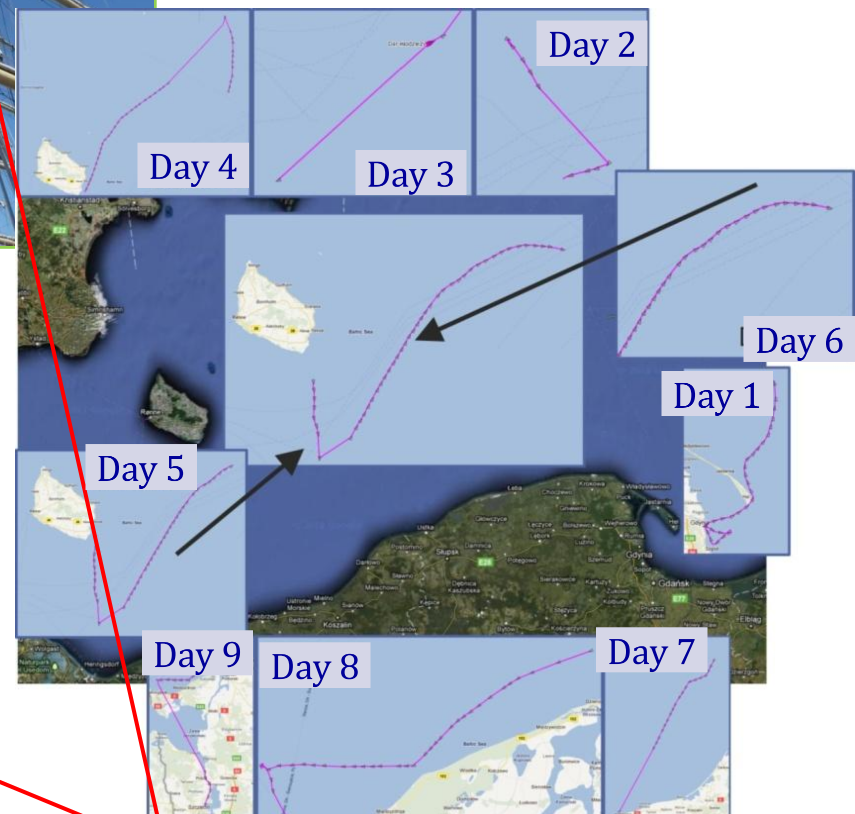
cT
rozeta

1
2
3

Experimental stands located on ship yacht Dar Młodzieży (Maritime University | Gdynia)

The ship's route

29 May – 6 June 2011



Fokmast with FBG sensors

GENERAL DEFINITIONS

Problems:

Sensors cannot measure damage

Size of detectable damage versus sensor size

Size of detectable damage versus sensor power

Levels of health monitoring

GENERAL DEFINITIONS

Sensors cannot measure damage.

Feature extraction though signal analysis and statistical classification are necessary to convert sensor data into damage information.

The size of damage that can be detected from changes in system dynamics is inversely proportional to the frequency range of excitation.

See K. Worden, C. R. Farrar, G. Manson and G. Park "The Fundamental Axioms of Structural Health Monitoring," Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences Issue **463 (2082) June, 2007.**

GENERAL DEFINITIONS

Levels of Health Monitoring

- ❑ Level 1: Detect the existence of damage.
- ❑ Level 2: Detect and locate damage.
- ❑ Level 3: Detect, locate and quantify damage.
- ❑ Level 4: Estimate remaining service life (prognosis).

- ❑ Level 5: Self diagnostics.
- ❑ Level 6: Self healing.

INCREASING DEGREE OF COMPLEXITY.
GREATER NEED FOR ANALYTICAL MODELS

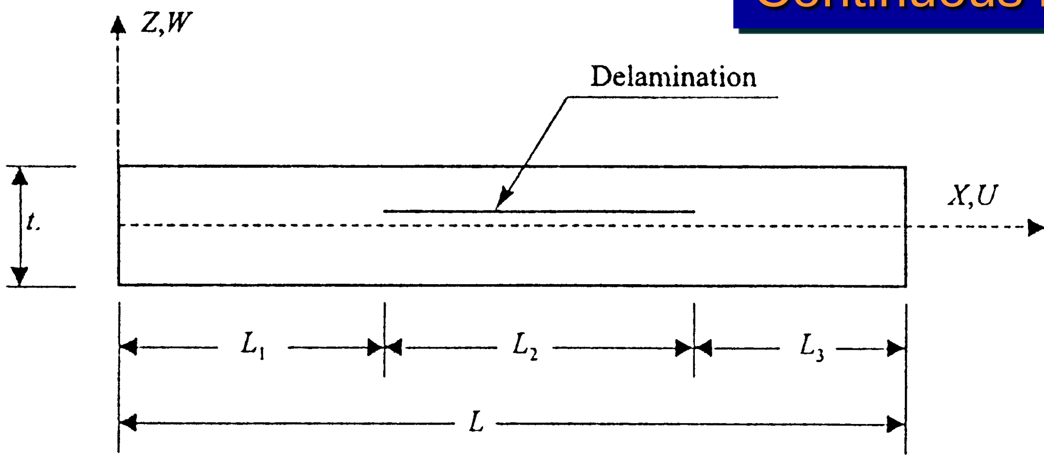
ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

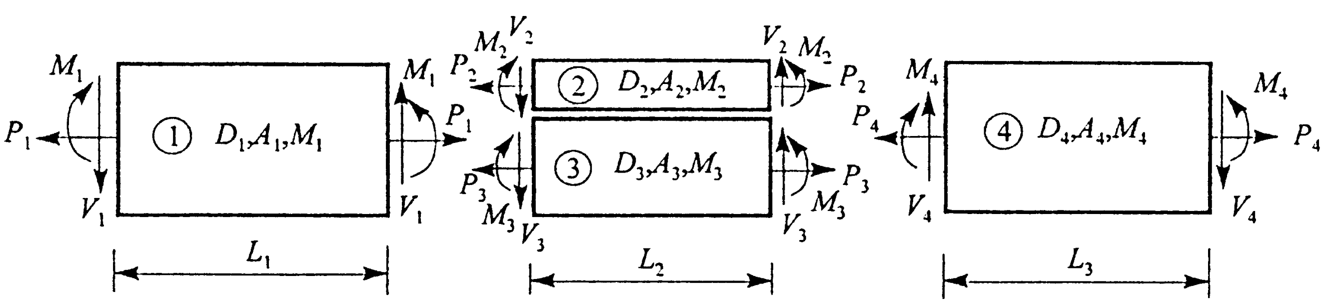
- **Continuous models**
- **Discrete - continuous models**
- **Discrete models**
  - Boundary Element Method
  - Transition Matrix Method
  - Graph Method
  - Analogue Method
  - Finite Element Method

Ostachowicz W., Krawczuk M. (2009). *Modelling for Detection of Degraded Zones in Metallic and Composite Structures*, in Encyclopedia of Structural Health Monitoring, Boller, C., Chang, F. and Fujino, Y. (eds). John Wiley & Sons Ltd, Chichester, UK, pp. 851–866. (ISBN 978–0–470–05822–0)

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

Continuous models



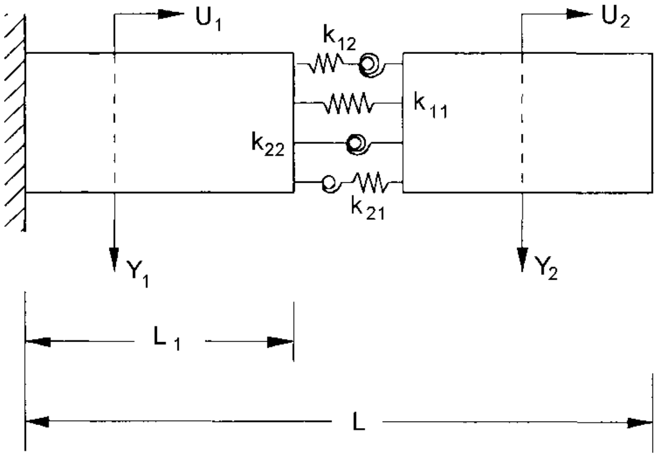


Zou *et al*. (2000)
Tracy & Pardoen (1989)
Chai *et al*. (1981)
Botega & Maewal (1983)
Whitcomb (1986)
Yin *et al*. (1986)
Chen (1992)
Ramkumar *et al*. (1979)
Wang *et al*. (1982)

Ostachowicz W., Krawczuk M. (2009). *Modelling for Detection of Degraded Zones in Metallic and Composite Structures*, in Encyclopedia of Structural Health Monitoring, Boller, C., Chang, F. and Fujino, Y. (eds). John Wiley & Sons Ltd, Chichester, UK, pp. 851–866. (ISBN 978–0–470–05822–0)

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

Discrete - Continuous models



A fatigue crack is represented by additional spring - like elements, compliance of which is calculated according to the laws of fracture.

This method can successfully be used for modelling fatigue cracks in one-dimensional constructional elements (rods, beams, shafts, columns and pipes) or in constructions made of such elements (frames and trusses).

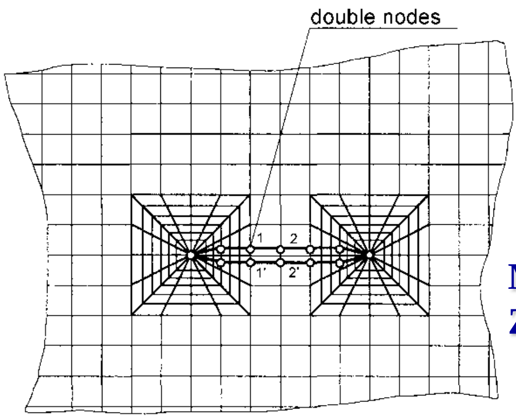
Ostachowicz W., Krawczuk M. (2009). *Modelling for Detection of Degraded Zones in Metallic and Composite Structures*, in Encyclopedia of Structural Health Monitoring, Boller, C., Chang, F. and Fujino, Y. (eds). John Wiley & Sons Ltd, Chichester, UK, pp. 851–866. (ISBN 978–0–470–05822–0)

Papadopoulos & Dimarogonas (1987)
Liebowitz *et al.* (1967)
Okamura *et al. (1969)*
Rice & Levy (1972)
Dimarogonas & Massouros (1980)
Anifantis & Dimarogonas (1983)
Dimarogonas & Papadopoulos (1983)
Krawczuk (1992)
Nikpour & Dimarogonas (1988)
Nikpour (1990)
Gudmudson (1982)
Adams et al. (1978)
Ju *et al*. (1982)
Springer *et al*. (1987)
Liang *et al*. (1988)
Ostachowicz & Krawczuk (1991)
Rajab & Al-Sabeeh (1991)
Rytter *et al.* (1991)
Cuntze & Hajek (1985)
Papaeconomu & Dimarogonas (1989)
Kikidis & Papadopoulos (1992)
Krawczuk & Ostachowicz (1992)

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE

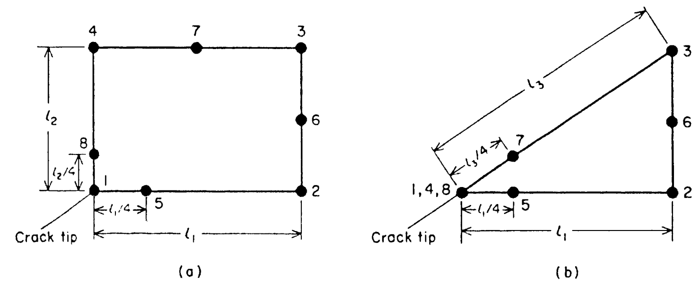
Discrete models

Finite Element Method

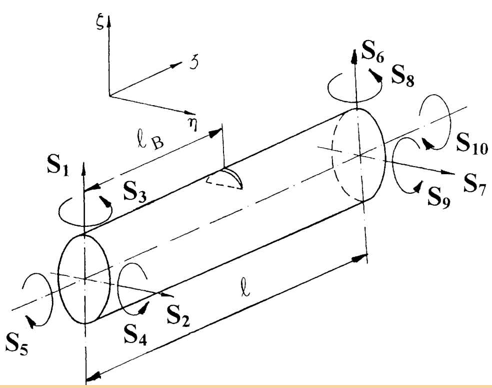


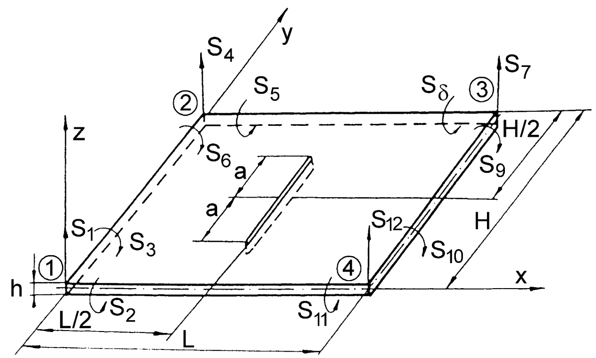
Markstrom & Storakers, (1980)
Zastrau, (1985)

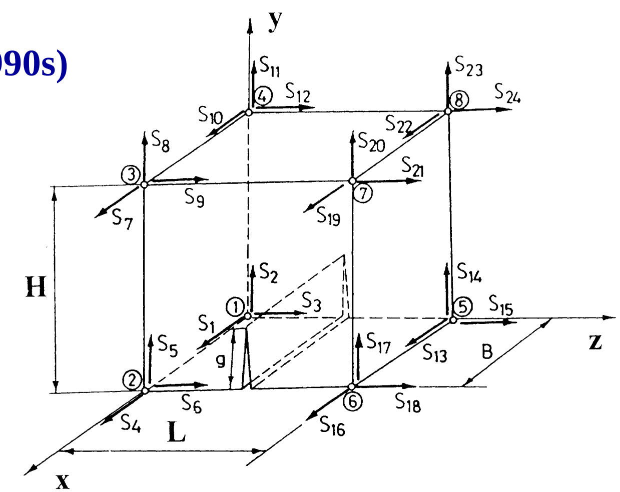
Shen & Pierre, (1990)



Krawczuk & Ostachowicz, (1990s)

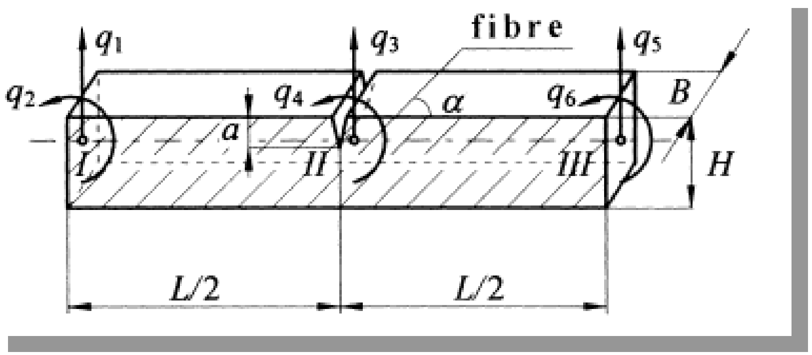




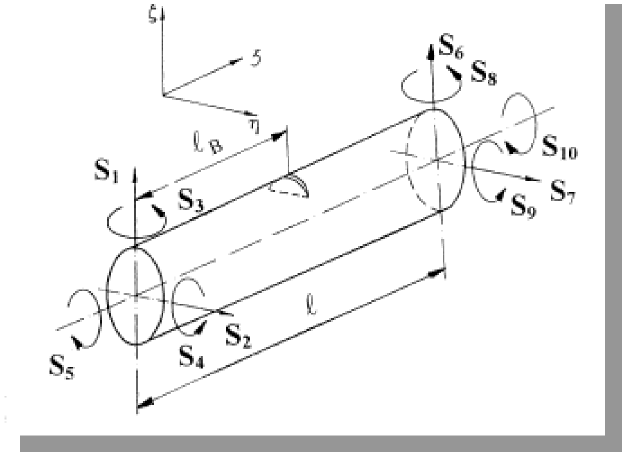


Ostachowicz W., Krawczuk M. (2009). *Modelling for Detection of Degraded Zones in Metallic and Composite Structures*, in Encyclopedia of Structural Health Monitoring, Boller, C., Chang, F. and Fujino, Y. (eds). John Wiley & Sons Ltd, Chichester, UK, pp. 851–866. (ISBN 978–0–470–05822–0)

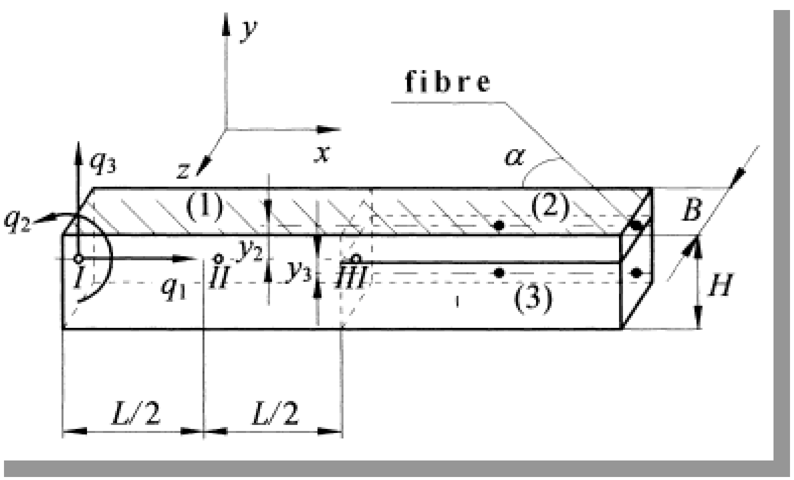
ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE



Composite beam finite element with a crack



Shaft beam finite element with a crack



Composite beam finite element with a delamination

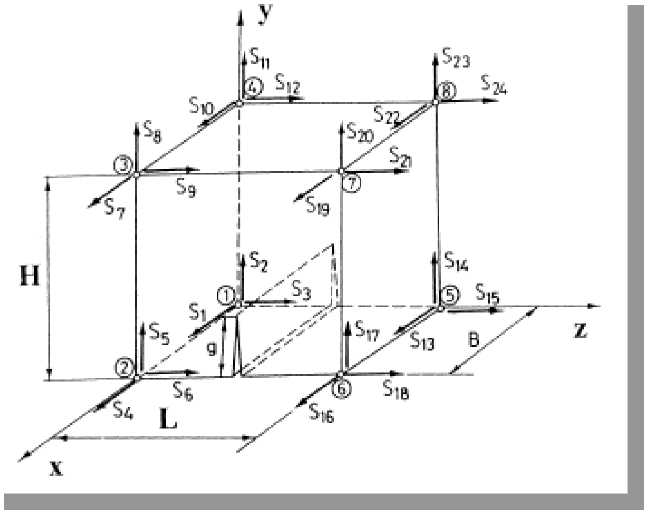
US Army Grant

No N68171-94-C-9108

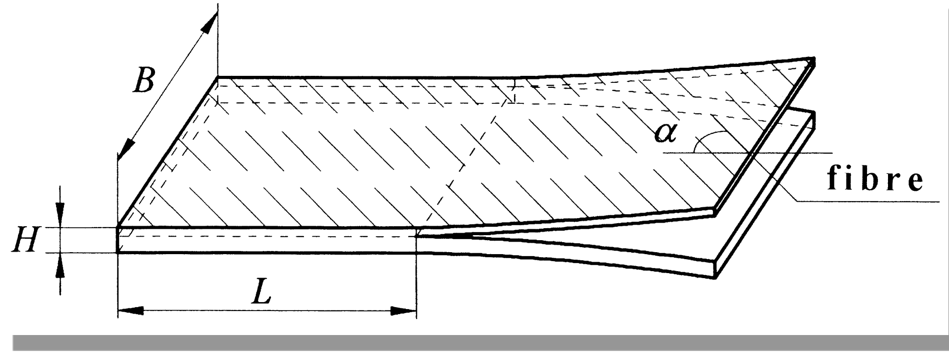
Duration: 1994 – 1996

Title: Dynamics of cracked Composite Material Structures

ON MODELLING OF STRUCTURAL STIFFNESS LOSS DUE TO DAMAGE



Solid finite element with a crack



Composite plate finite element with a delamination

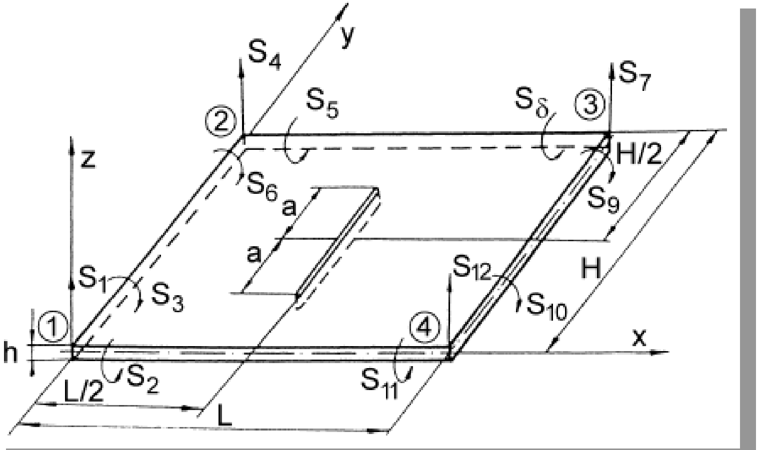


Plate finite elements with a crack

US Army Grant

No N68171-94-C-9108

Duration: 1994 – 1996

Title: Dynamics of cracked Composite Material Structures

Ostachowicz W., Krawczuk M. (2009).

Modelling for Detection of Degraded Zones in Metallic and Composite Structures,

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Boller, C., Chang, F. and Fujino, Y. (eds).

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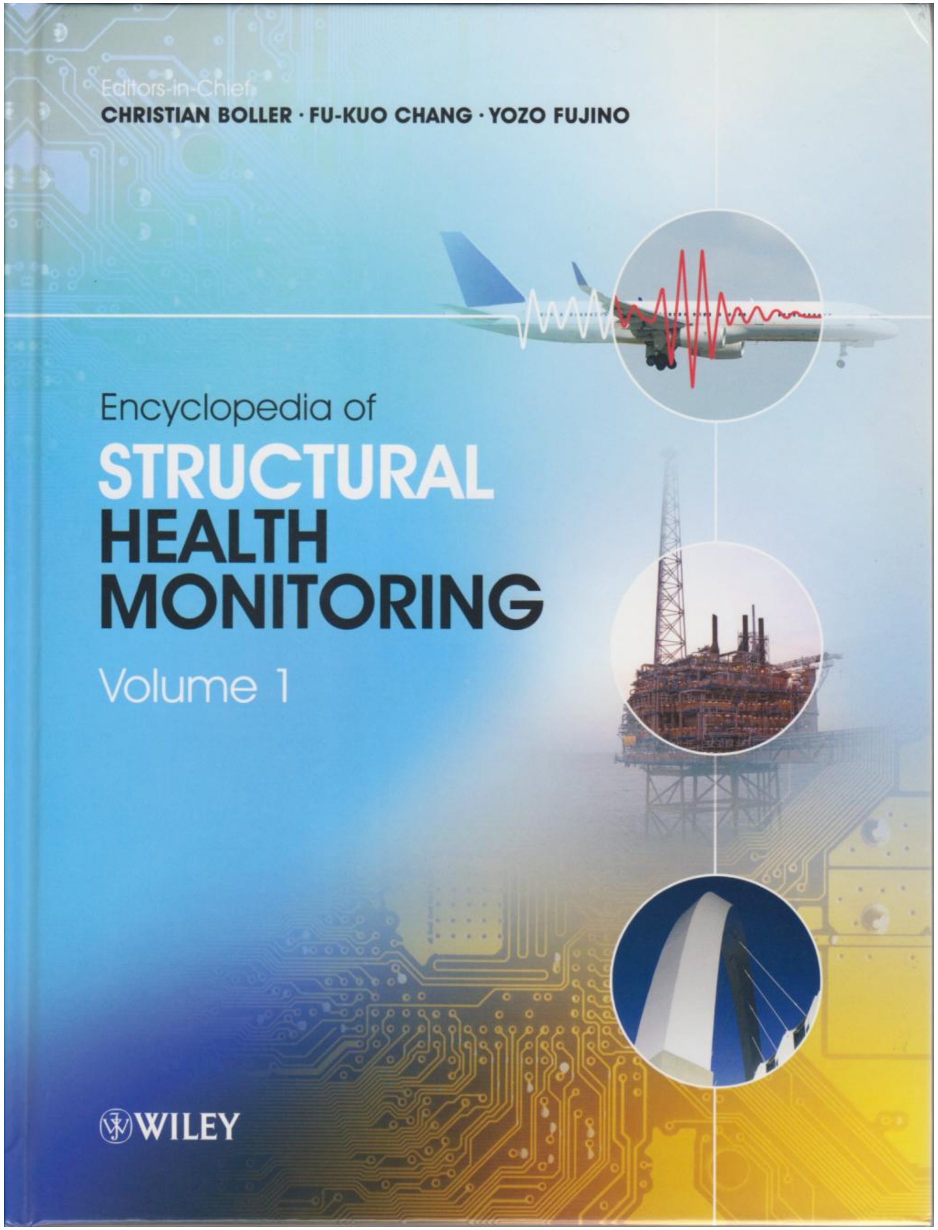


VIBRATION BASED METHODS

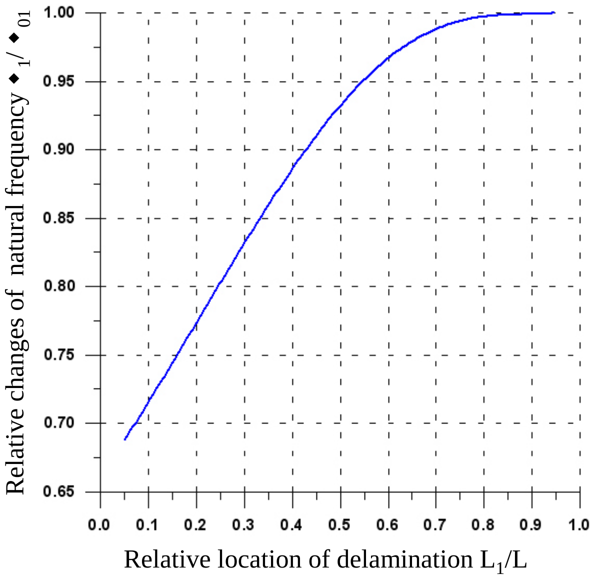
Changes of dynamic properties i.e.:

- **mode shapes,**
- **natural frequencies,**
- **amplitudes of forced vibrations,**
- **damping**
- **..................**

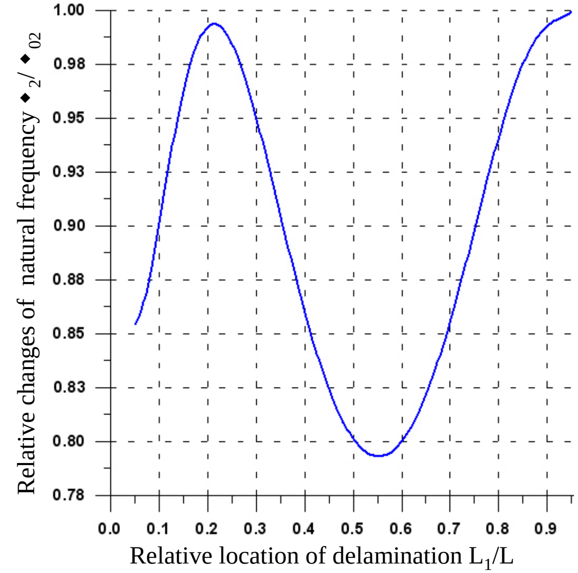
Low frequency method

VIBRATION BASED METHODS

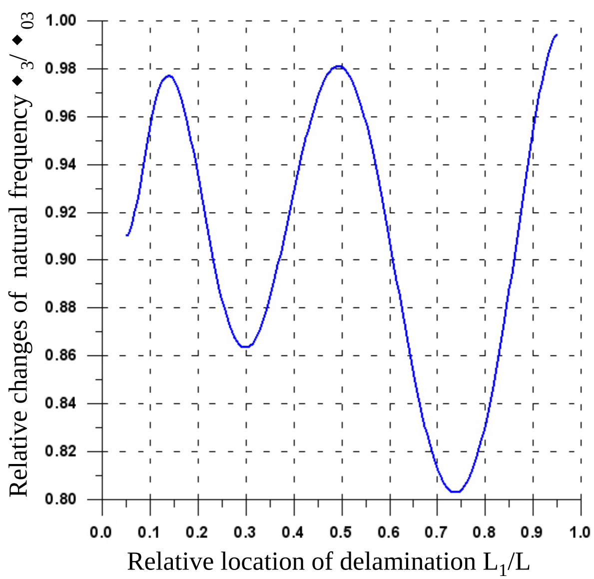
a)



b)



c)



Changes:

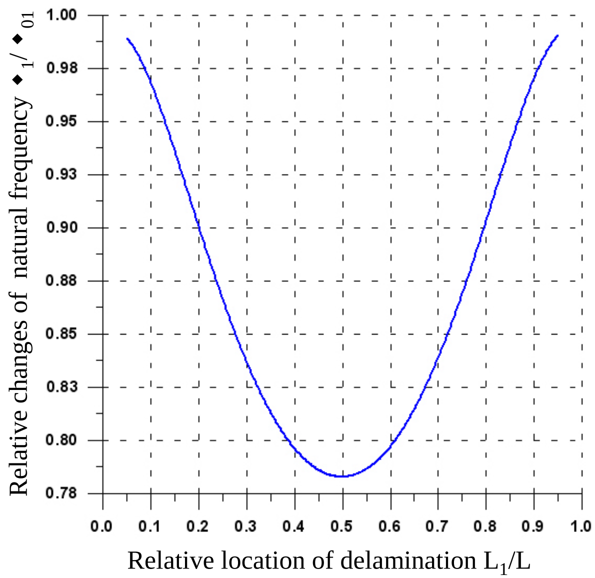
- **first (a)**
- **second (b)**
- **third (c)**

natural frequencies of the cantilever composite beam as a function of damage location (delamination):

beam axis

VIBRATION BASED METHODS

a)



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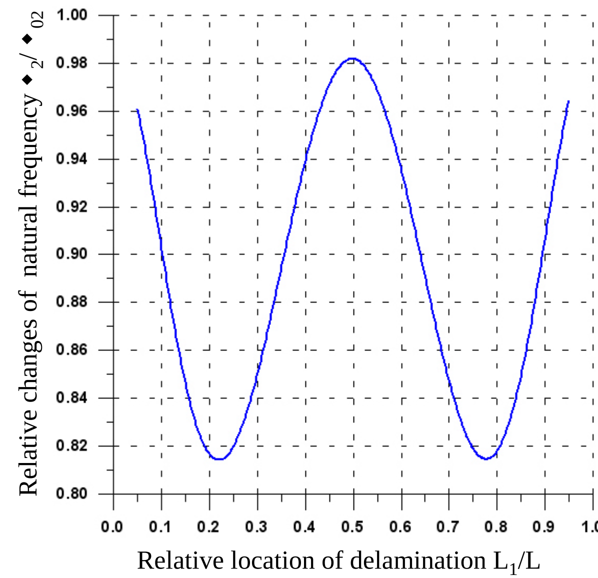

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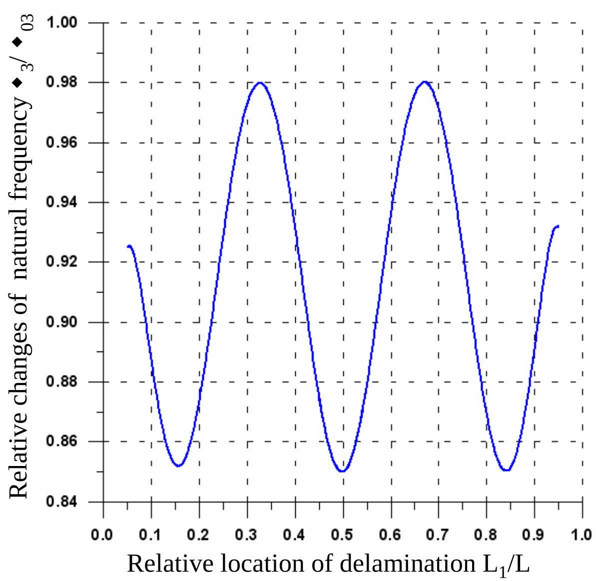


Changes:

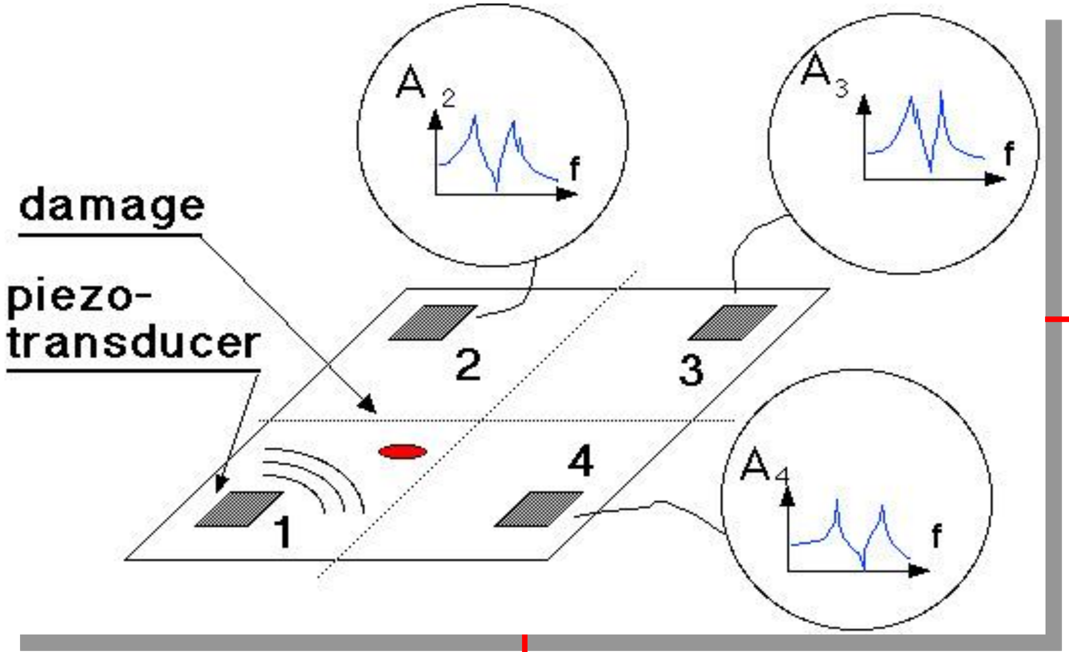
- **first (a)**
- **second (b)**
- **third (c)**

natural frequencies of the simple supported composite beam as a function of damage location (delamination): beam axis

Summary of Detection Methods

Method	Strengths	Limitations	SHM Potential
Optical fibres	Embeddable Simple results Very comfortable	Expensive High data rate Accuracy??	Requires laser localised results
Eddy current	Surface mountable Most sensitive	Expensive Complex results Safety hazard	High power Localised results Damage differentiation
Acoustic emission	Inexpensive Surface mountable Good coverage	Complex results High data rates Event driven	No power Impact detection
Modal analysis	Inexpensive Surface mountable Simple procedure	Complex results High data rates Global results	Low power Complex structures Multiple sensor types
Lamb waves	**Inexpensive** **Surface mountable** **Good coverage**	**Complex results** **High data rates** **Linear scans**	**High power** **Damage differentiation**

Arrays of distributed piezotransducers:



applicable to most structures

can monitor structural condition throughout the life of the structure

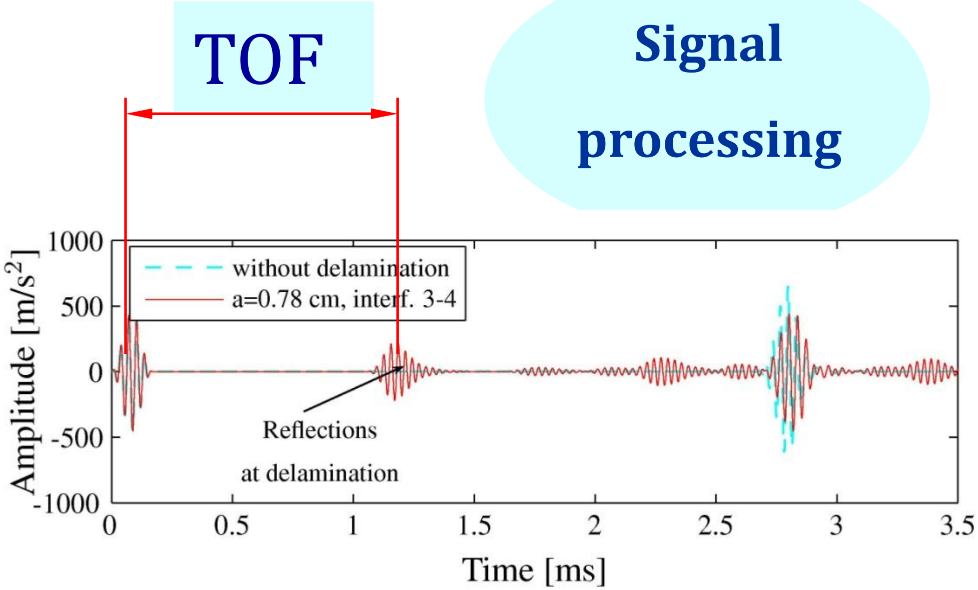
can detect changes in:

- stiffness
- inertial and damping characteristics
- stress levels

can focus on damage

Motivation

Signal processing

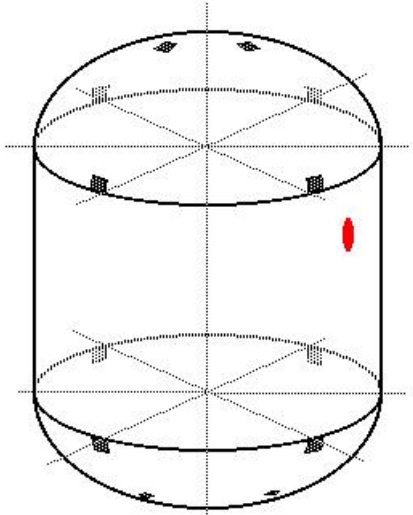


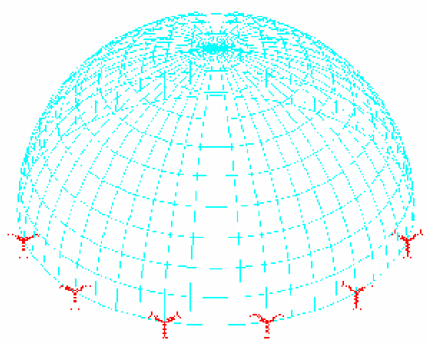
sensors

Damage identification methods:

- Deterministic (based on Time of Flight, amplitude changes)
- Non-deterministic:
  - Neural Networks
  - Evolutionary Algorithms
  - Genetic Algorithms

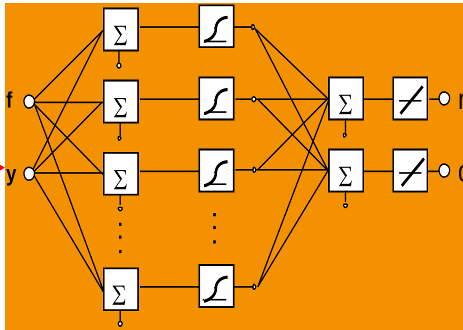
Use theoretical, classical finite element and spectral finite element methods



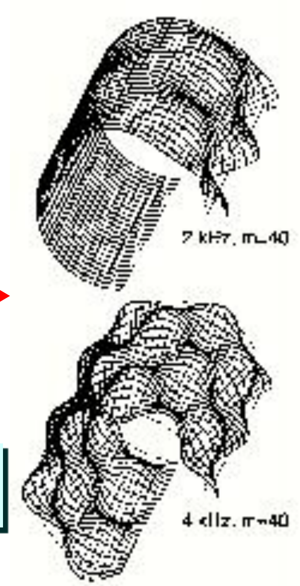


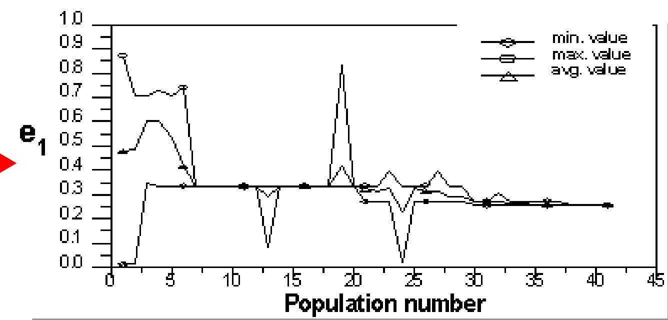
Produce data to train the expert system

Neural Networks



Genetic Algorithms

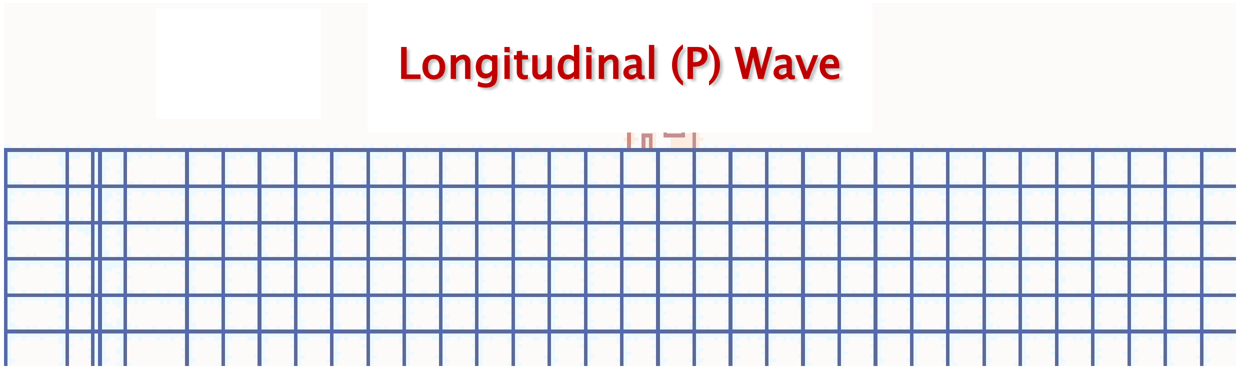




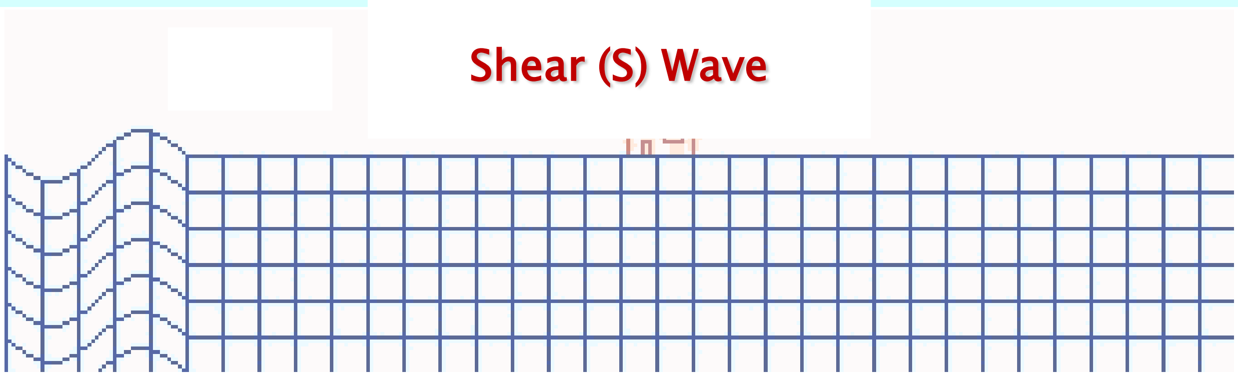
Model of the structure

Elastic Waves

Longitudinal waves – particle motion is in the direction of travel



Shear waves – particle displacement at each point in the material is perpendicular to the direction of wave propagation

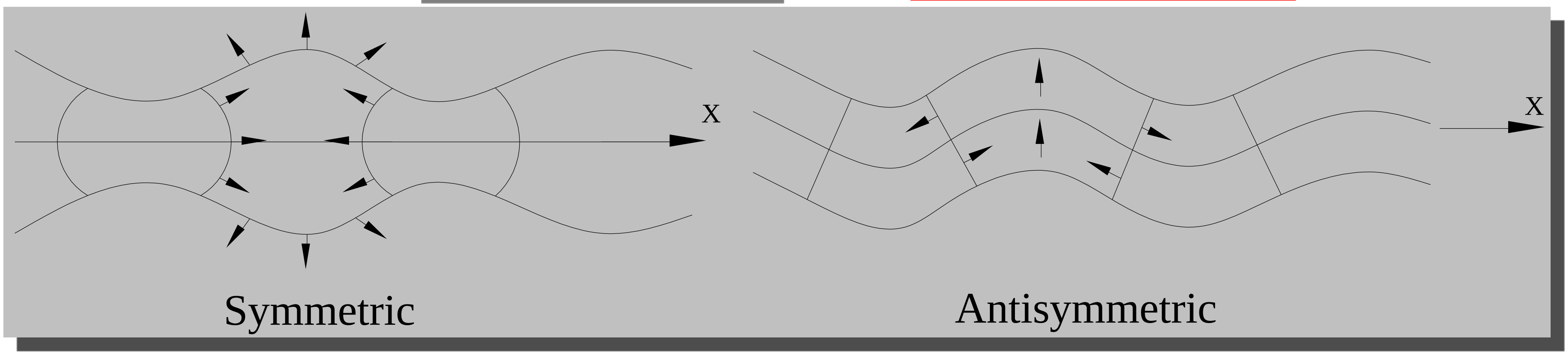


LAMB WAVES

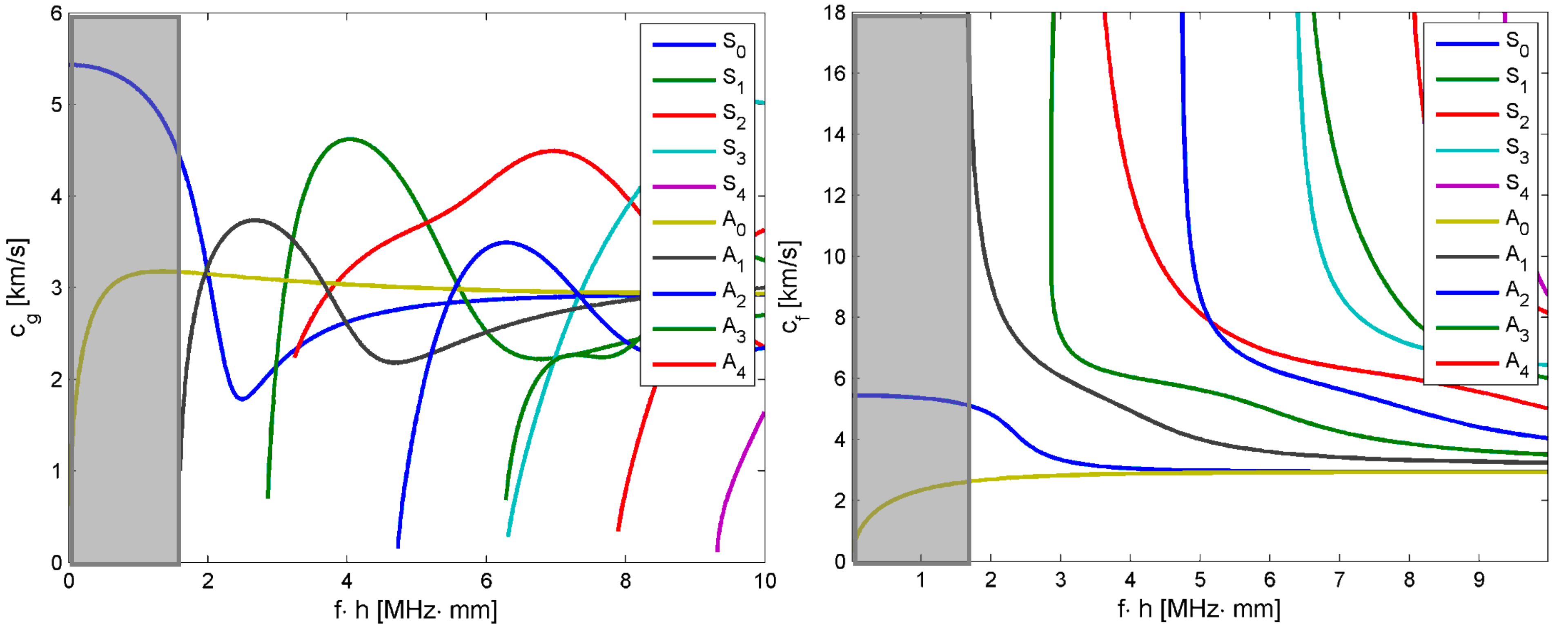
- Lamb waves are waves of plane strain that occurs in a free plate.
- Complex wave mechanism –shear vertical (SV) waves form modes in connections with the longitudinal P wave; these P+SV waves are known as Lamb waves.
- Infinite number of dispersive modes which can propagate in structures.

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2-k^2)^2}$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq}$$



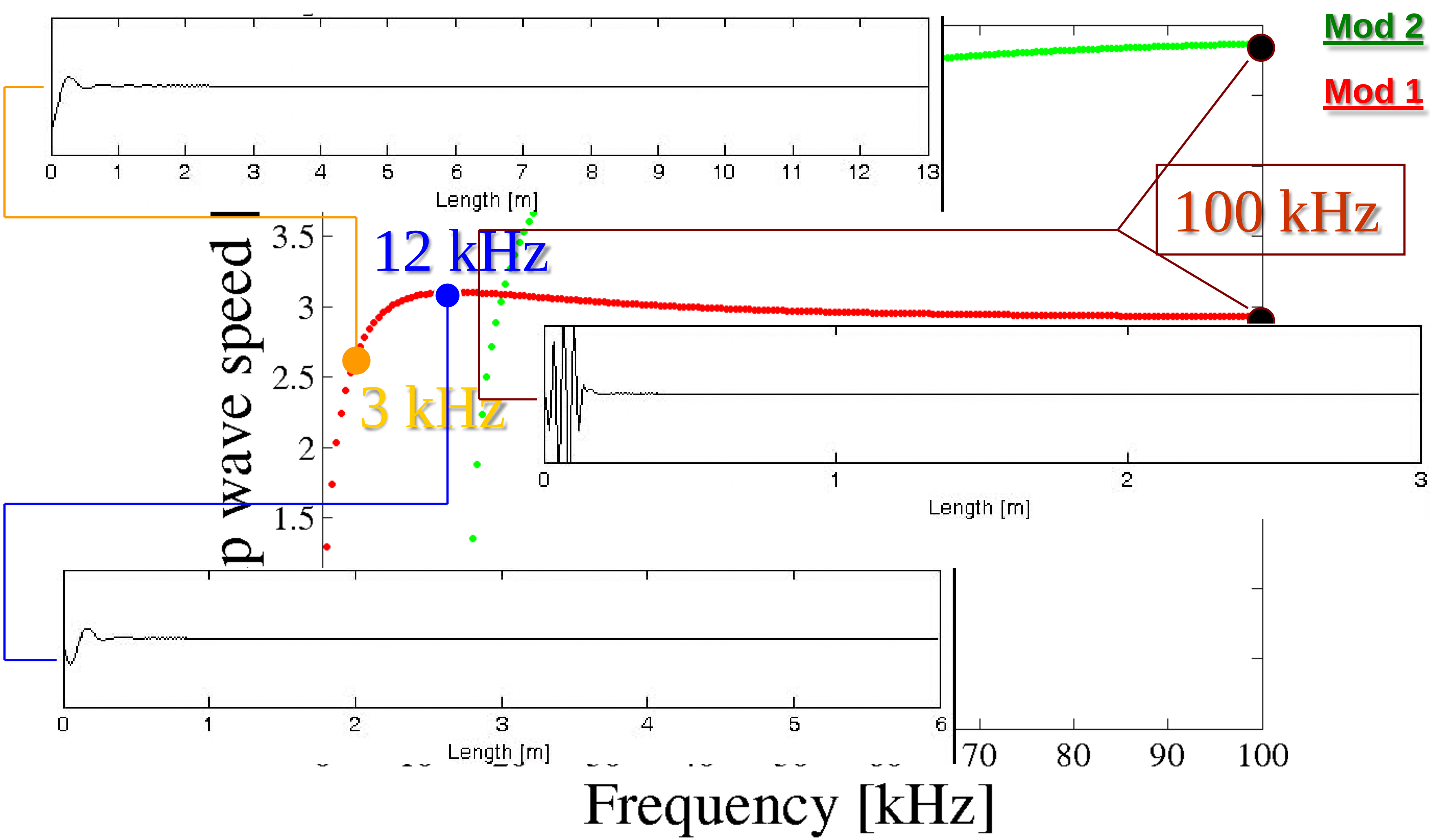
LAMB WAVES



- ❖Dispersion equations are given by Rayleigh-Lamb frequency relations.
- ❖ Lamb wave velocity is a function of the frequency- thickness (f*d) product.
- ❖ Fundamental modes – S_0 and A_0 modes.

J. L. Rose. *Ultrasonic waves in solid media*. Cambridge University Press, 1999.

DISPERSION AND WAVE MODES



Wave propagation modelling

- Finite element Method
- Finite Difference Method (LISA)
- Semi-analytical methods
- FFT-based Spectral Element Method (Doyle)
- Hybrid methods
- Spectral Element Method (Patera 1984)