"Structural Health Sensors Benchmarking for space vehicles"

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Why is SHM Important for generic cargo roket

Structural Health Monitoring :

Is responsible for real time detection of faults.

Must identify faults that result from environment as well as intrinsic stress.

Must identify specific location of a fault as well as the specific nature of a fault.

The SHM sensor may result in the scrub of a launch.

The SHM sensor may trigger a launch abort

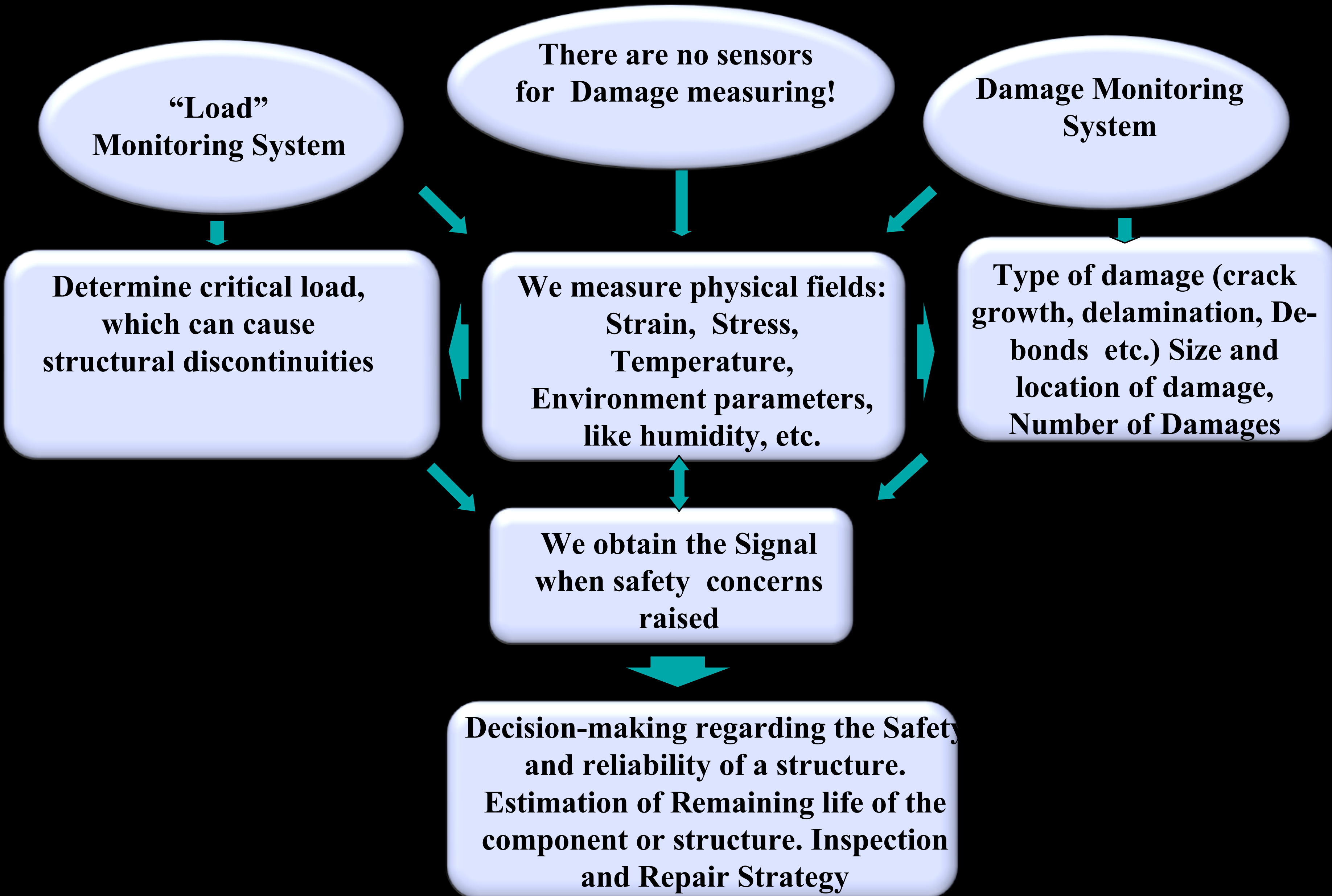
What kinds or loads are of interest?

Compression and stretching due to bending,
stability, static strength,
Joints of High local loads,
Longitudinal stress,
Residual stress

What kinds of faults are of interest?

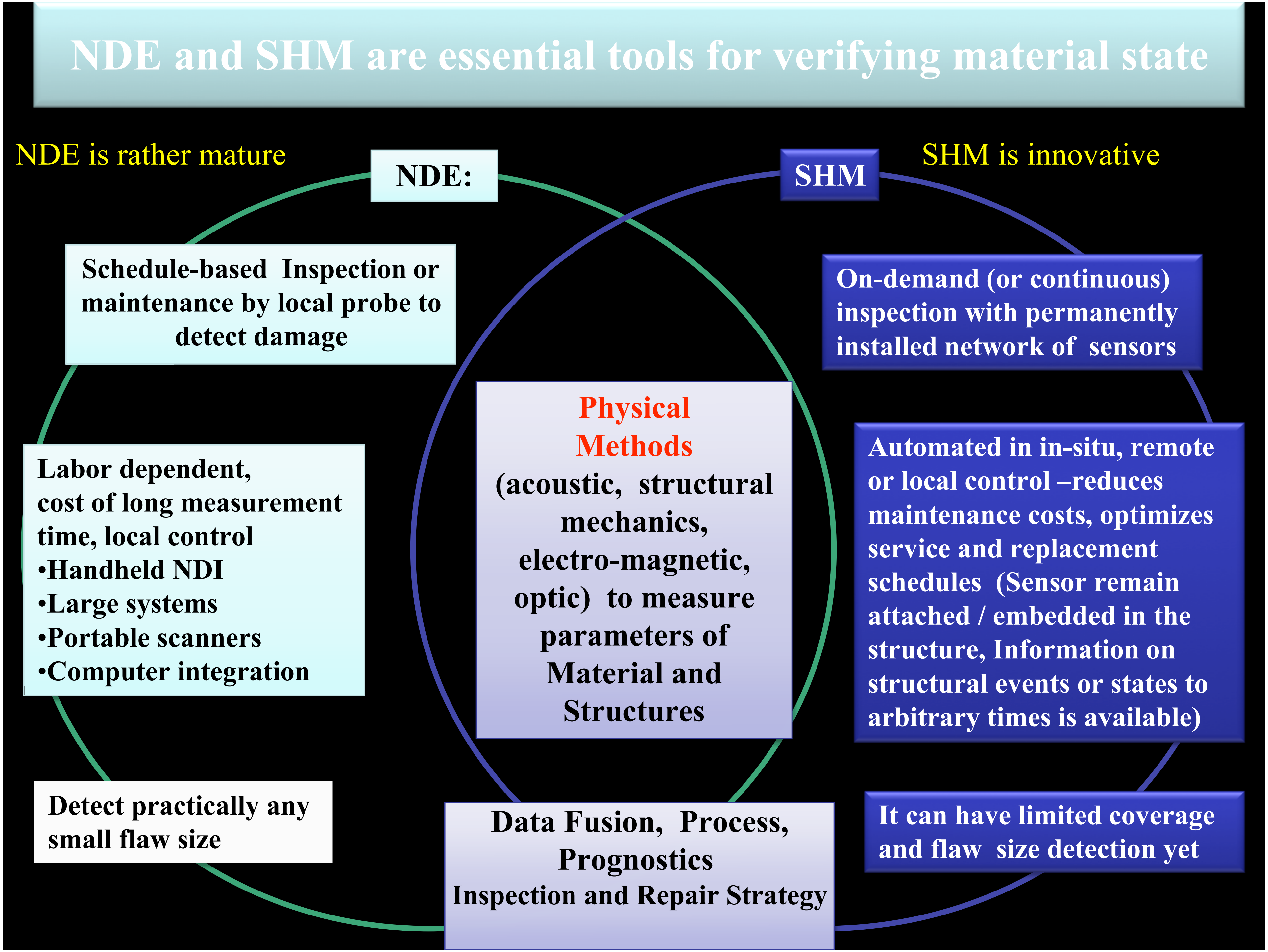
De-bonds
De-laminations
Cracks
Crunching

SHM - a system that monitors structure to detect damage



SHM methods

Method	Sensors	Physics	Type of damage	Mode
Acoustic Emission	PZT, Fibre Bragg Gratings (FBG)	Acoustic waves are generated by impacts, crack initiation, crack growth, Delamination	Impacts, Cracks, Delaminations	Global
Acousto-Ultrasonics	PZT, FBG	Acoustic waves are sent through the material. A change in the material local behavior (and hence a damage) can be picked up and localized by an array of such sensors	Cracks, Delaminations	Global
Load monitoring	Strain gages, FBG, PZT	Strain gages are subjected to variation in length, which are caused by load	Measuring pre-crack conditions	Local
Comparative Vacuum Monitoring	CVM device	Open cracks generate leaks and we can tracks the pressure drop	Cracks Corrosion Debondings	Local
Foil Eddy Current	Foil Eddy Current sensors	Eddy currents varies according to the presence of crack or other damages	Cracks, Corrosion	Local


NDE and SHM are essential tools for verifying material state
NDE is rather mature
NDE:
SHM
SHM is innovative
Schedule-based Inspection or maintenance by local probe to detect damage
Labor dependent, cost of long measurement time, local control
•Handheld NDI
•Large systems
•Portable scanners
•Computer integration
Detect practically any small flaw size
Physical Methods
(acoustic, structural mechanics, electro-magnetic, optic) to measure parameters of Material and Structures
Data Fusion, Process, Prognostics
Inspection and Repair Strategy
On-demand (or continuous) inspection with permanently installed network of sensors
Automated in in-situ, remote or local control –reduces maintenance costs, optimizes service and replacement schedules (Sensor remain attached / embedded in the structure, Information on structural events or states to arbitrary times is available)
It can have limited coverage and flaw size detection yet

General requirement s to SHM system

Goal: To make non-destructive testing to become an part of the spacecraft structure itself. In this case
✓Unlike NDE systems, SHM systems can not be independent of the space vehicle,
✓The sensors must be placed in the locations where an area is to be monitored.

Possible approaches for Damage indication in which the SHM System checks the structure and makes Decision about the Safety and reliability of a structure.

We can single out active and passive types of sensors

- **Sensors can be used as both receiver and actuator (Location and magnitude of damage are determined by means of signals (systems based on ultrasonic pitch catch or pulsed echo techniques)**
- **Sensors are used only as receivers (Detection of damage from external sources (e.g. in-flight loads)**

Online and Offline Systems

- **Equipment on-board • Measuring parameters during flight (under load) • Data are sent to a storage device or evaluation computer for further processing**
- **Equipment off-board• Monitoring faults on unloaded structures**
- **Activation on demand • Producing data when necessary (mostly during scheduled testing) • No data storage during flight**

Plans for Benchmarking

Develop combinations between;

Modeling of structural response to energy

Modeling of sensor response to structural faults

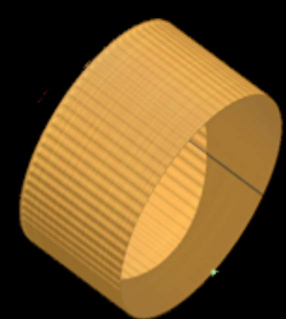
Perform empirical testing;

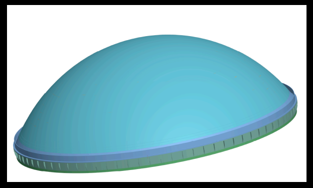
Undamaged structures

Failed structural specimen

Elements of large cargo vehicle Considering Dry Composites

Payload Shroud, Interstage, Nose cone, Forward skirt,Forward skirt of core stage, Inter Tank, Aft Skirt of core stage, Thrust structure, Engine compartment





Sensor system benchmarking attributes

Sensitivity

Repeatability

Accuracy

Reliability of the system

Complexity of the sensor and system (ease of installation)

Sensor system weight and power consumption

Sensor systems environmental susceptibility

Technology readiness level (TRL)

Advocacy of peer researchers and users

Availability from an industrial source

Application to other domains

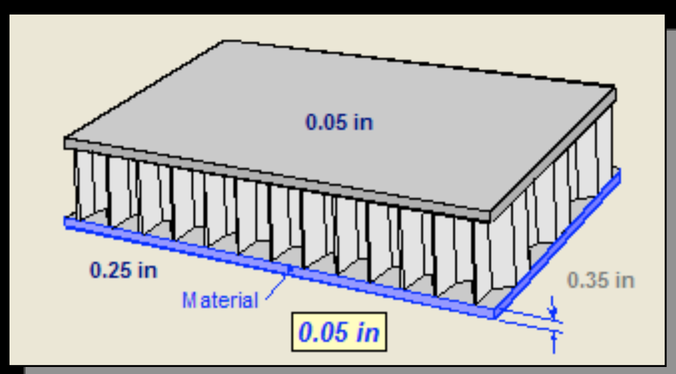
Cost

Modeling Needs and Methods

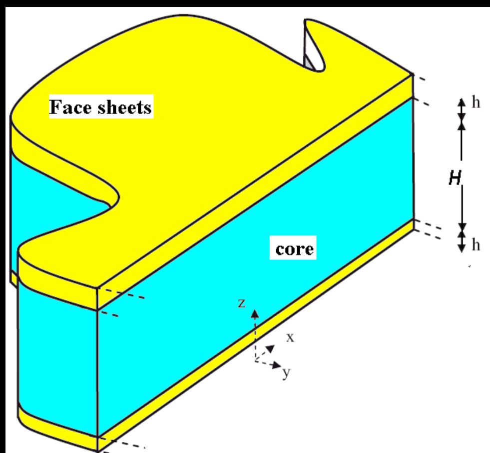
We will consider SHM based on Acoustic technology because an elastic perturbation during propagation carry information changes in stress and velocity.
There are several types of elastic waves which are most promising for using them

- **Balk acoustic waves**
- **Rayleigh surface waves**
- **Lamb waves**

Proprieties of elastic perturbations depend on parameters of materials as well as parameters of waves.
We will consider honeycomb composite structures with aluminum core and FRC face sheets
Let us single out several characteristic limits of frequencies



Honeycomb structure properties at low frequency limit λ>5(H+2h)



Transverse (Bending) waves are dominant a low frequencies (If the wavelength λ>5(H+2h)~15-30cm) f<500Hz the speed of a bending wave of frequency ω is determined by classical beam theory

$$c_{\mathrm{b}} \approx \omega^{1/2}\left[\frac{E_{\mathrm{s}} h H^2}{2(1-\sigma_{\mathrm{s}}^2)(\rho_{\mathrm{s}} h + \rho_{\mathrm{c}} H)}\right]^{1/4}$$

H- core and h skin thickness, bending waves simply stretch or compress the skins, the bending stiffness is $E_{\mathrm{s}} h H^2 / 2(1-\sigma_{\mathrm{s}}^2)$

moving mass per unit area $\rho_{\mathrm{s}} h + \rho_{\mathrm{c}} H$

If **f<5(H+2h)** the speed of bending waves is

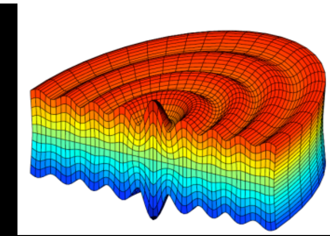
$$c_{\mathrm{b}} \approx \omega^{1/2}\left[\frac{E_{\mathrm{s}} h H^2}{2(1-\sigma_{\mathrm{s}}^2)(\rho_{\mathrm{s}} h + \rho_{\mathrm{c}} H)}\right]^{1/4}$$

And transformation to shear waves is like

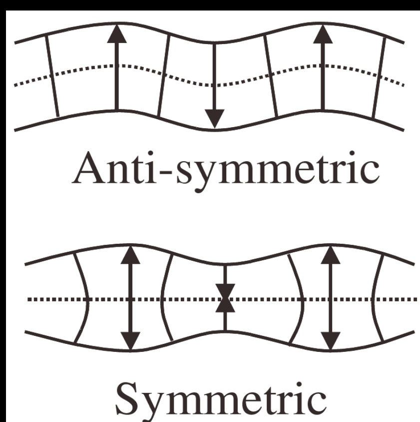
$$c_{\mathrm{s}} \approx \left(\frac{G_{\mathrm{c}} H + 2 G_{\mathrm{s}} h}{\rho_{\mathrm{s}} h + \rho_{\mathrm{c}} H}\right)^{1/2}$$

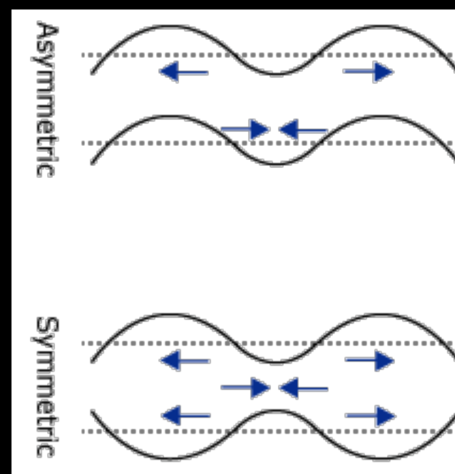
Which are not dispersive

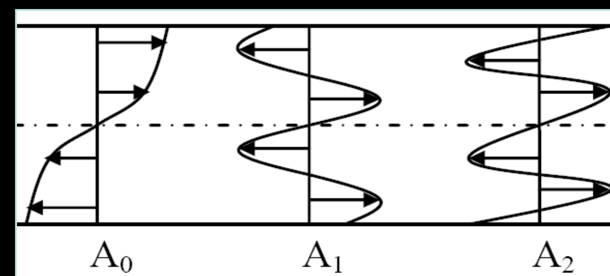
Lamb waves in Honeycomb structures

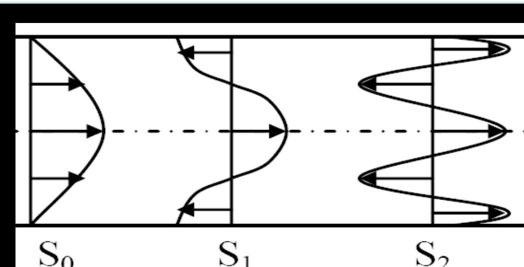


Lamb waves are complex vibrational waves that travels through the entire thickness of a material the wave is "stretching and compressing" the plate in the wave motion direction.









V=2,000-12,000m/s

Mathematical equations of guided waves must satisfy physical boundary conditions; this is in contrast to bulk wave equations.
Both governed by same wave equations but due to boundary conditions there will be an infinite number of guided wave modes.

Rayleigh-Lamb frequency equations

We need to use dispersion equations parameters to get phase velocity and wavelength

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2-k^2)^2}$$ → **Symmetric Lamb modes**

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2-k^2)^2}{4k^2pq}$$ → **Antisymmetric Lamb modes,**

$$p^2 = \frac{\omega^2}{c_L^2} - k^2 , \qquad q^2 = \frac{\omega^2}{c_T^2} - k^2$$

$$\mu = \frac{E}{2(1+\nu)}, \quad \lambda = \frac{E\nu}{(1-2\nu)(1+\nu)}$$

$$c_L^2 = \frac{\lambda + 2\mu}{\rho} , \qquad c_T^2 = \frac{\mu}{\rho}$$

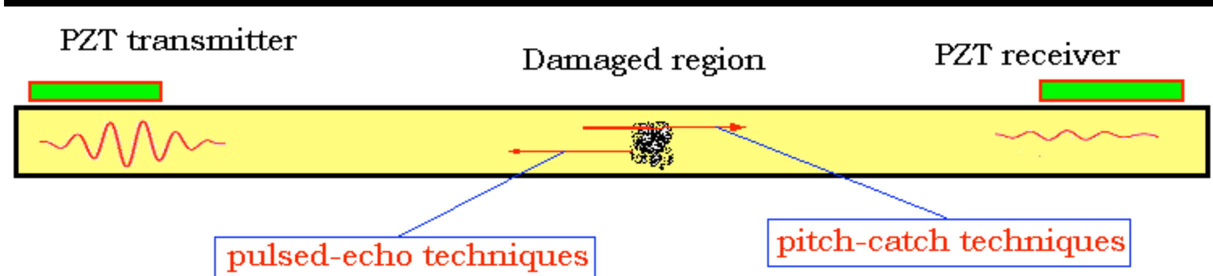
Complex nonlinear dispersion law k=k(ω) !!!

Phase velocity $c_{phase} = \frac{\omega}{k}$

$$c_{group} = c_{phase} + \frac{\partial c_{phase}}{\partial k} k$$

$$\lambda_w = \frac{c_{phase}}{f} \text{ (wavelength)}$$

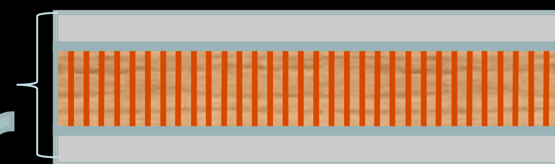
Pulsed echo and pitch catch techniques for Lamb waves
Phase velocity calculation

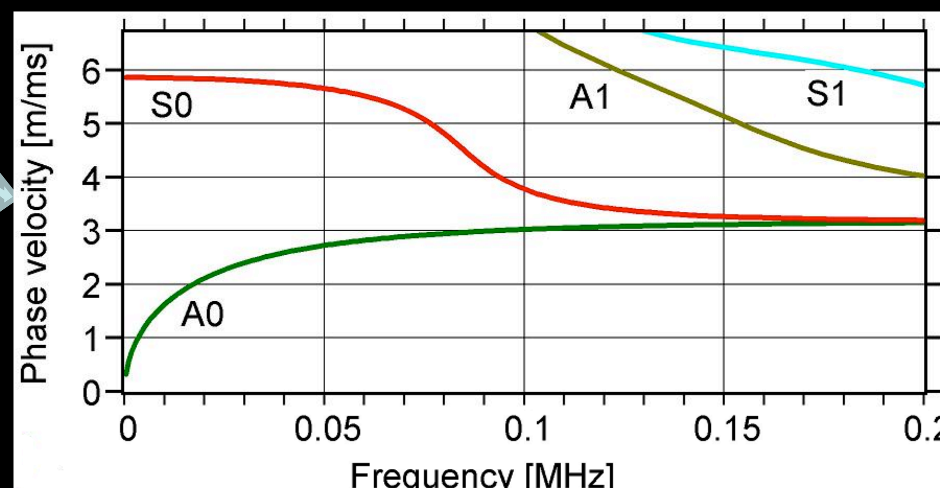


We truncate frequency range to select 2 basic modes that limits wavelength from below

$$\lambda_w = \frac{c_{phase}}{f} \text{ (wavelength)}$$

D=H+2h





Fiber with Epoxy matrix
ρ= 1.57 g/cm^3
E =50 GPa n= 0.33,
c_t=3.4*10^{3}m/s, c_v=6.7*10^{3}m/s
h =0.23cm, D=3.0cm

15 mm ≤ l

Analytical solution

General solution

$$u_z^s(r,t) = \sum_{m,n=1}^{\infty} \frac{u_{mn}(r,z)}{M_{mn}\omega_{mn}} \int_0^t f(t')\sin(\omega_{mn}(t-t'))dt'$$

m, n correspond to normal modes in z, r directions

$$M_{mn} = 2\pi \int_0^R \int_{-h}^{h} u_{mn}u_{mn}(r,z)rdrdz \equiv \langle u_{mn}, u_{mn} \rangle, f(t) = \langle F(r,z,t)u_{mn}(r,z) \rangle$$

$$u_{mn}^{sym}(r,z) = -(k_{mn}a_{mn}\cos p_{mn}z + b_{mn}q_{mn}\cos q_{mn}z)J_1(k_{mn}r)$$

$$u_{mn}^{anti}(r,z) = -(k_{mn}a_{mn}\sin p_{mn}z - b_{mn}q_{mn}\sin q_{mn}z)J_1(k_{mn}r)$$

$$p_{mn} = \sqrt{\omega_{mn}^2 \;/\; c_L^2 - k_{mn}^2}, q_{mn} = \sqrt{\omega_{mn}^2 \;/\; c_t^2 - k_{mn}^2}$$

Amplitudes for symmetric modes are

$$\left.\frac{a_{mn}}{b_{mn}}\right|_{sym} = \frac{2k_{mn}q_{mn}\cos(q_{mn}h)}{(q_{mn}^2 - k_{mn}^2)\cos(p_{mn}h)} = -\frac{(q_{mn}^2 - k_{mn}^2)\sin(q_{mn}h)}{2k_{mn}p_{mn}\sin(p_{mn}h)}$$

And anti-symmetric

$$\left.\frac{a_{mn}}{b_{mn}}\right|_{anti-sym} = -\frac{2k_{mn}q_{mn}\sin(q_{mn}h)}{(q_{mn}^2 - k_{mn}^2)\sin(p_{mn}h)} = \frac{(q_{mn}^2 - k_{mn}^2)\cos(q_{mn}h)}{2k_{mn}p_{mn}\cos(p_{mn}h)}$$

Finite difference and finite element Modeling

Analytical solution for $F = a\delta(r)\delta(z-h)\sin(\omega t)$ and computer simulation makes it possible to determine strain ***e***. Strain at certain point out of the source makes it possible to determine minimum signal detected by the PZT sensor.

In this case charge density of the PZT in transverse direction is ***P~d*$_{31}$¾**, where **¾** is a stress, **¾~*Ee*,** ***E***-Yung's modulus. The capacitance is **C= ""$_0$ *ab/h*,** and output voltage of PZT subject to the strain ***e*** calculated from FEM is **V=Q/C=*d*$_1$*Ehe/*""$_0$,**
", "$_0$ are permittivity of material and vacuum