

Structural Health Monitoring (SHM)
Prof. Srinivasan Chandrasekaran
Department of Ocean Engineering
Indian Institute of Technology, Madras

Lecture - 41
Non - Destructive evaluation - I

Welcome, to the 13th lecture in module 2.

(Refer Slide Time: 00:20)

NPTEL

Module 2
 Lecture 13: Non-Destructive Evaluation
 (Embedded sensors)

- plane-strain condition,

$$f'' - \zeta^2 f = -\frac{\omega^2 f}{C_p^2}$$

$$h_x'' - \zeta^2 h_x = -\omega^2 h_x / C_s^2$$

$$h_y'' - \zeta^2 h_y = -\omega^2 h_y / C_s^2$$

$$h_z'' - \zeta^2 h_z = -\omega^2 h_z / C_s^2$$

$$C_p^2 = \frac{\lambda + 2\mu}{\rho}$$

$$C_s^2 = \frac{\mu}{\rho}$$

(Note: The handwritten equations in the image contain some typos compared to the typed transcription below.)

In this lecture, we will continue with Non-Destructive Evaluation techniques, but we will talk about embedded sensors. So, in the last lecture, we are discussing about a plane-strain condition we have equations $f'' - \zeta^2 f = -\frac{\omega^2 f}{C_p^2}$, $h_x'' - \zeta^2 h_x = -\omega^2 h_x / C_s^2$, $h_y'' - \zeta^2 h_y = -\omega^2 h_y / C_s^2$, $h_z'' - \zeta^2 h_z = -\omega^2 h_z / C_s^2$ or $h_x'' - \zeta^2 h_x = -\omega^2 h_x / C_s^2$, $h_y'' - \zeta^2 h_y = -\omega^2 h_y / C_s^2$, $h_z'' - \zeta^2 h_z = -\omega^2 h_z / C_s^2$; where C_s is given by $\lambda + 2\mu$ by ρ and C_p^2 is given by μ by ρ .

(Refer Slide Time: 02:00)

Solution of the above Eqn will lead to:

$$\bar{\phi} = (A \cos \alpha y + B \sin \alpha y) e^{i(\beta x - \omega t)}$$

$$H_x = (C \cos \beta y + D \sin \beta y) e^{i(\beta x - \omega t)}$$

$$H_y = (E \cos \beta y + F \sin \beta y) e^{i(\beta x - \omega t)}$$

$$H_z = (G \cos \beta y + H \sin \beta y) e^{i(\beta x - \omega t)}$$

Now, the solution of this equation will lead to solution on phi H x H y and H z, which will be A cos alpha y plus B sine alpha y of e i minus omega t. Similarly, C cos beta y plus D sine beta y e i minus omega t: similarly, E cos beta y plus B sine beta y e i minus omega t and G cos beta y plus H sine beta y e i z x minus omega t.

(Refer Slide Time: 03:30)

where

$$\alpha^2 = \frac{\omega^2}{C_p^2} - \beta^2$$

$$\beta^2 = \frac{\omega^2}{C_s^2} - \delta^2$$

(A-H) are constants, which can be determined from the stress-free boundary conditions - @ both upper & lower surface of the plate

Alpha square is omega square by C p square minus zeta square and beta square is omega square by C s square minus delta square, ok. Look at this equation there are pairs A to H

are actually constants which can be determined from the stress free boundary conditions at both upper and lower surface of the plate.

(Refer Slide Time: 04:30)

Let us write down those equations $A C_3 \sin \alpha d + H C_4 \sin \beta d = 0$, $A C_1 \cos \alpha d + H C_2 \cos \beta d = 0$, these are the characteristic equations we are writing. $B C_1 \sin \alpha d - G C_2 \sin \beta d = 0$, and $B C_3 \cos \alpha d + G C_4 \cos \beta d = 0$, $-E C_5 \sin \beta d + D \beta^2 \sin \beta d = 0$, $-E \beta \sin \beta d + D i \psi \sin \beta d = 0$, $C \beta^2 \cos \beta d + F C \phi \cos \beta d = 0$ and $C i \psi \cos \beta d + F \beta \cos \beta d = 0$; where C_1 is $\alpha^2 + 2 \mu \psi^2$, C_2 is $2 i \mu \zeta \beta$, C_3 is $2 i \alpha$, C_4 and C_5 are $\zeta^2 - \beta^2$ and $i \zeta \beta$ respectively.

You can wonderfully see here there are pairs which have been formed which are called coefficient pairs of this characteristic equation. These pairs are namely A, H B, G E, D and C, F. These two correspond to symmetric and non symmetric of Lamb waves, these two pairs correspond to symmetric and non symmetric of shear horizontal way. For each of the characteristic equation one can find the specific value of wave number and wave period wave speed and that gives a solution for these equations.

(Refer Slide Time: 08:39)

The slide is titled "Embedded sensors" in green. The text is handwritten in black and green ink. It discusses methods to excite guided waves on a surface. The NPTEL logo is in the top right corner. A video inset in the bottom right shows a man in a purple striped shirt speaking.

Embedded sensors

Guided waves can be excited by impinging the surface with ultrasonic beam in oblique angle.

- This can be induced by a large ultrasonic transducer, fixed @ the wedge.
- This can generate a combination of pressure & shear waves into the structure.
- Alternatively created by Comb-Transducers
 - Comb-spacing tunes the guided waves to its half wave-lengths

Now, the guided waves can be excited by impinging the surface with ultrasonic beam in oblique angle. This can happen or this can be induced by a large ultrasonic sensor or ultrasonic transducer fixed at the wedge. So, this can generate a combination of pressure waves and shear waves into the structure. They can also be alternatively created by comb-transducers, comb-spacing tunes the guided waves to its half wavelength.

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The slide contains handwritten text in black ink. It states that researchers use piezoelectric wafer sensors (PWAS) to generate guided waves. It lists four advantages of PWAS. The NPTEL logo is in the top right corner. A video inset in the bottom right shows the same man in a purple striped shirt speaking.

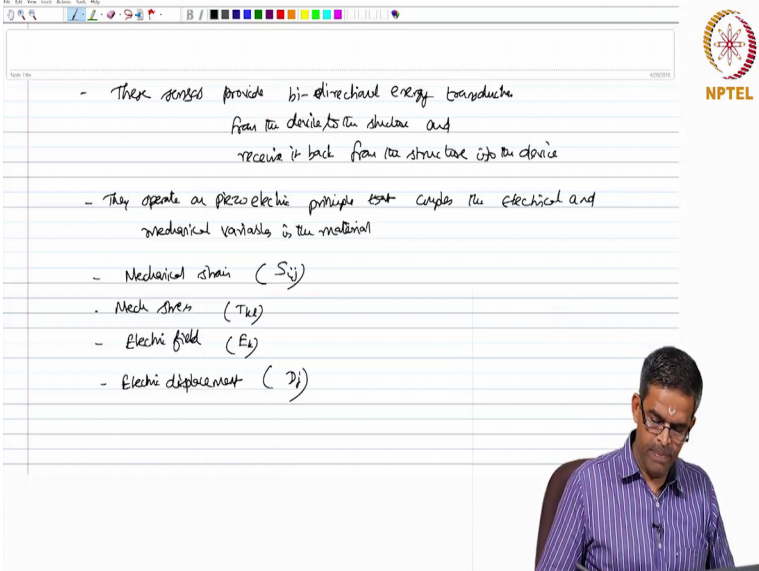
Researchers used piezo electric wafer sensors (PWAS) to generate guided waves.

- Advantages | PWAS
 - 1) Light in weight (60mg)
 - 2) Cheap (~\$45 each)
 - 3) Single and thin (0.2mm thick)
 - 4) Unobtrusive to the surface

In the recent past researchers have also used piezoelectric wafer sensors, ok, these are called as piezoelectric wafer active sensors to generate guided waves.

There are some advantages of these sensors. They are very light in weight, it is only about 68 milligram, they are very cheap approximately about let us say 45 dollars each, they are very simple and thin essentially they are about 0.2 millimeter thick and they are on obstructive to the surface where they are embedded.

(Refer Slide Time: 12:20)



The image shows a digital whiteboard interface with a toolbar at the top. The whiteboard contains the following handwritten text:

- These sensors provide bi-directional energy transduction from the device to the structure and receive it back from the structure into the device
- They operate on piezoelectric principle that couples the electrical and mechanical variables in the material
- Mechanical strain (S_{ij})
- Mech stress (T_{kl})
- Electric field (E_k)
- Electric displacement (D_j)

In the bottom right corner of the whiteboard, there is a small inset video of a man with glasses and a purple shirt, who appears to be the presenter.

These sensors provide bi-directional energy transduction, that is, from the device to the structure and receive it back from the structure into the device. They operate on piezoelectric principle that couples the electrical and mechanical variables in the material.

Let us say mechanical strain is given by S_{ij} and mechanical stress is given by T_{kl} and electric field is indicated by E_k and electric displacement is indicated by D_j .

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$$S_{ij} = S_{ijl}^E T_{kl} + d_{kij} E_k$$

$$D_j = d_{jkl} T_{kl} + \epsilon_{jk}^T E_k$$

where S_{ijl}^E - Mechanical compliance of material, measured @ zero the electric field $E=0$

ϵ_{jk}^T - dielectric permittivity, measured @ mechanical stress $T=0$

d_{jkl} - piezoelectric coupling effort

Then following equation holds good, S_{ij} is S_{ijkl} of E , T_{kl} plus $d_{kij} E_k$. Similarly, D_j is $d_{jkl} T_{kl}$ plus $\epsilon_{jk}^T E_k$, where S_{ijkl} is the mechanical compliance of material measured at E equals 0. Whereas, ϵ_{jk}^T is dielectric permittivity measured at mechanical stress T equals 0, d_{jkl} is piezoelectric coupling effort.

(Refer Slide Time: 16:22)

procedure

piezoelectric effect converts stress applied to the sensor into electric charge

III, converse piezoelectric effect produces strain, when voltage is applied to the sensor

PZTs - can act both as sensors and detectors of elastic waves, based on the material

- They can be used as both active & passive probes

Let us see what is a procedure on which the piezoelectric wave active sensors works. The piezoelectric effect converts stress applied to the sensor into an electric charge. Similarly, the converse piezoelectric effect produces strain, when voltage is applied to the sensor.

So, interestingly these piezoelectric wave active sensors can act both as executors, sorry exciters, and detectors of elastic lamb waves traveling in the material. They can be used as both active and passive probes.

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The slide content is as follows:

Application of PWAS

- (1) Active sensing of far-field damage via pulse-echo, pitch-catch, & Phased-Array method
- (2) Active sensing of near-field damage via high-frequency impedance method
- (3) Passive sensing of crack initiation and location by acoustic emission method
- (4) Passive sensing of damage through low-velocity impact detection technique

Let us see the applications of piezoelectric wave active sensors. One, they can be useful in active sensing of far field damage using pulse-echo precision, pitch catch method and phased array method. They can also be useful in active sensing of near field damage with high frequency impedance method. Further, they can be useful in passive sensing of crack initiating and location by acoustic emission method. They can also be useful for passive sensing of damage through low velocity impact detection technique.

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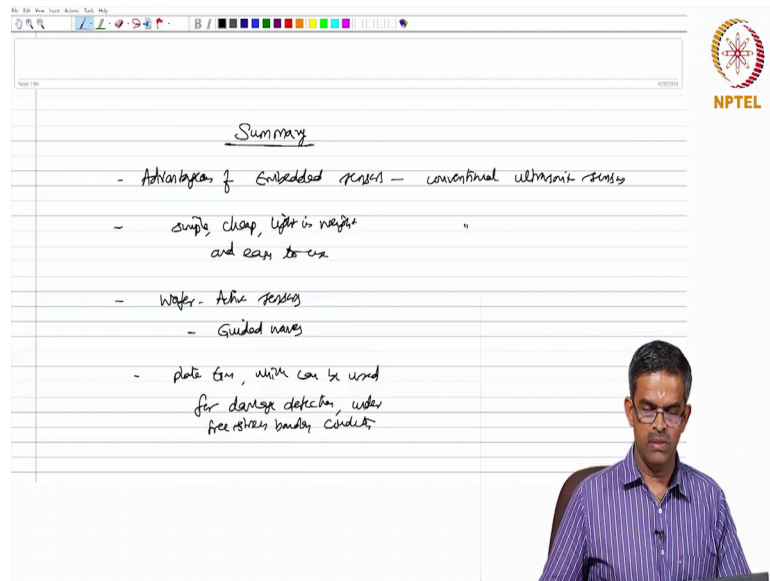
Exclusive advantages of Embedded sensors (Conventional ultrasonic sensors)

Conventional ultrasonic sensors	Embedded sensors
are weakly coupled	are connected to the structure permanently
- they are connected to the structure through gels	- because they are embedded inside the structure
These sensors are resonant, narrow-banded type	These sensors are non-resonant broadband type.
These sensors sense Lamb waves indirectly through acoustic waves, impinging them on the surface.	- They can be tuned for a wide range of frequency of certain Lamb waves
	These sensors excite Lamb waves directly through in-plane coupling.

Of embedded sensors, in comparison to conventional ultrasonic sensors, let us see what are they. The conventional ultrasonic sensors are weakly coupled because they are connected to the structure through gels. Whereas, embedded sensors are connected to the structure permanently because they are embedded inside the structure.

Conventional sensors are these sensors are resonant, narrow-banded type, whereas these sensors are non-resonant broadband type. They can be tuned for a wide range of frequency of certain lamb waves. Conventional sensors sense lamb waves indirectly through acoustic waves by impinging them on the surface whereas, these sensors measure sorry, excite lamb waves directly through in-plane coupling.

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The image shows a digital whiteboard interface with a toolbar at the top. The whiteboard contains the following handwritten text:

Summary

- Advantages of Embedded sensors - conventional ultrasonic sensors
- simple, cheap, light in weight and easy to use
- Wafer active sensors
 - Guided waves
- plate Eqn, which can be used for damage detection under free stress boundary condition.

In the bottom right corner, there is a video feed of a man with glasses wearing a purple striped shirt. The NPTEL logo is visible in the top right corner of the whiteboard area.

So friends, we have seen the advantages of in comparison to the conventional ultrasonic sensors. We have also said they are very simple, cheap, light in weight and easy to use comparison to these sensors. Wafer active sensors which are useful for guided waves application; the plate equation, which can be used for damage detection under free stress boundary condition.

In the next lecture, we will discuss further about the NDE methods, different kinds of sensors applicable to NDE and their usefulness in structural health monitoring processes.

Thank you very much.