Transducers For Instrumentation
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Lecture - 21
Acoustic Sensors: Piezoelectric Materials

Hello, welcome to the course transducers for instrumentation. Last lecture we discussed about acoustic sensors these are the sensors which use the acoustic waves for measurements and acoustic wave as we know these are mechanical waves and there is a physical motion involved of the media, the media is composed of let us say the atoms and there is a physical motion of these atoms which carry this kind of waves which are acoustic waves. In that we saw some practical applications where all these acoustic sensors are useful and then we started discussing about the piezoelectricity and the piezoelectric effect. So, in piezoelectric effect what we discussed last lecture that there are certain materials if you apply a mechanical stress across those materials they develop a potential difference across it and this develop potential is proportional to how much stress we apply. So, here in this slide we see there is a piezoelectric material and we are applying the force from top and bottom and this piezoelectric material is developing some electric charge which we can measure through some measuring instruments let us say multimeter or some voltmeter. So, this property is called piezoelectric effect and the materials are called piezoelectric materials.

These materials are very much useful for making these acoustic devices or acoustic sensors and we use this property primarily in this kind of devices. So, this we discussed last lecture. Now let us see how this property is actually shown by this piezoelectric material how a mechanical stress give rise to a electric property which is potential. So, we have let us say we consider silicon oxide which is a piezoelectric material and the silicon oxide material if we see the configuration of the crystal is something like this.

Let us say we have a crystal in uniform state when we are not applying any force. So, at that point we have silicon and oxygen atoms in this structure. This is let us say silicon and we have oxygen atom. This is bounded to another silicon atom and we have another oxygen atom and we have again an another silicon atom. So, this is let us say the structure of silicon oxide crystal and this silicon is let us say positively charged and oxygen has negatively charged and this is how they are connected. Silicon is positively charged and oxygen is negative and they are giving rise to silicon oxide crystal. So, this is the state when we do not apply any mechanical stress means no mechanical stress. Now at this material we apply a mechanical stress for example, we apply a compressive stress we are applying a force which is compressing this crystal lattice from both the sides. Let us say from left and right we are applying some force. So, the crystal will become something like in x direction it will squeeze and in y direction it will kind of come out it will expand. So, silicon atoms which are positively charged they will go up and negative oxygen atoms they will kind of compress. So, this will be a typical structure if we apply a physical stress in x direction. So, here we see if we look at this complete material the positive silicon atom this has come out in y direction relatively what it was earlier with no mechanical stress and the negative which is this oxygen atom on the bottom this has come down in y direction compared to what it was earlier. So, there is a net potential build up by in this inside this material the positive has gone in the positive y direction and negative oxygen atoms has gone in the negative y direction. So, if we see the effectively there is a net charge positive charge build up in the top portion of this material and negative charge build up in then in the bottom in the lower portion of this material.

So, effectively a potential positive potential will build up in positive x direction positive y direction and in negative charge will build up in negative y direction. So, this is the case when compressive mechanical stress is applied or we can say the positive mechanical stress is compressing. So, when we are compressing this material there is a positive charge on the top and negative charge on the bottom. Now let us see the reverse case when instead of compressing the material we are trying to expand the material we are applying a expanding force from both the sides. So, what happens to the charge? So, this is case C where the force is expanding this material in x direction. So, what will happen the positive charge will go inside which is silicon atom and negative charge will be dominating compared to the normal case. So, this is what happen when we apply a expanded force and if we see this configuration compared to the case A where no mechanical stress is applied relatively the upper portion of this material is relatively negatively charged because earlier in the neutral case positive was on the very top and negative was compensating that positive charge and there was no charge because of that. When we apply this expanding force this positive comes down and negative both the atoms goes up. So, it means there is a net negative charge build up on the top of the material. So, now we have a negative charge build up overall and positive on the bottom. So, if we see now in case A when there was no mechanical stress applied there was no overall charge on the material when we apply mechanical compressive strength stress on case B top side is positively charged and when we apply a case in case C a expanding force the top layer is negatively charged. So, that depending upon its compressive or expanded force the top layer is changing its polarity from positive to negative. So, it is changing the polarity of voltage build up. So, this is case C where the mechanical stress is applied which is expanded. So, this is the process happens in the materials which shows this piezoelectric property based on the applied force they develop this electric potential. So, next these piezoelectric devices let us write down their properties these piezoelectric devices can operate at fairly high frequencies. So, let us write down their properties. These piezoelectric devices can operate at quite high frequencies and these are often used in ultrasonic sensors. These piezoelectric microphones can be used as piezoelectric actuators. And, usually these the same device actually can be used in either mode.

So, these piezoelectric materials these materials can operate at fairly high frequencies. Of course, not in microwave regime or so, but they can operate at fairly high frequencies. Often these are used in ultrasonic sensors in making these ultrasonic kind of sensors even in underwater monitoring. These piezoelectric microphones or these piezoelectric devices they can be used in either mode you can use that as a receiver as well as a transmitter. So, this is because the piezoelectric property is reversible means when we are applying a physical stress on the material it develops voltage or in reverse case if we apply a time changing electric field across that across this material it can generate this mechanical stress or mechanical expansion and contraction. So, this property is reversible we can either apply electrical signal and generate a mechanical wave or we can apply a mechanical wave on these materials and they develop a electric potential across it. So, this property is reversible and some of the materials which show this property one we saw is silicon oxide or we call it quartz crystal. The other material is lithium niobate which is very common material for these acoustic sensors and the other one is lithium tantalate that is also used as a caustic material or piezoelectric material. So, the common materials used for acoustic sensors are the first one is quartz. Or we call it silicon oxide. The second one is lithium niobate O3 and the other material is lithium tantalate. So, these are few materials which we can use as a piezoelectric material to fabricate acoustic sensor. Let us discuss a little bit about the acoustic waves which we use generally for these sensors. These acoustic waves are described by the mood of their propagation. Acoustic wave devices are described by the mood of wave propagation.

Through the piezoelectric substrate. And the first one to this is longitudinal waves. So, these acoustic wave devices actually we characterize them in terms of mood in what mode this wave is propagating through those materials and the first one to consider the mode of wave is the first is longitudinal waves. This is the wave this is the longitudinal waves are the waves when a wave is travelling in a material and the atoms of the material are oscillating in the direction of wave propagation. So, that is a longitudinal wave.

In the longitudinal direction. Or the direction of wave propagation. So, let us say the wave is travelling in the x direction. And the atoms of the material they are oscillating in the same direction. So, these atoms they are actually oscillating in the same direction. So, when this is happening these atoms sometime they come close to each other and sometime they go far away than each other it means there is a compression and expansion happening in the material because of that this wave travels the atoms are actually transferring this energy from one atom to other and this is how this wave propagates in the material. This can be generated in solid as well as liquid and even gaseous. So, these in this kind of wave the particle density fluctuates and they can be generated in solids as well as liquid. So, these are longitudinal waves. The next is transverse or shear waves.

These are the waves when the wave travel in x direction the atoms of the material they do not oscillate in x direction, but they oscillate in perpendicular to the wave direction. So, the example of this wave is when we throw a stone in the water. So, the wave generated in between and it expands towards all the direction in that case the water particles they are not moving in the direction of wave the direction of wave is tangentially outward from the center of impact and the atoms are moving in perpendicular direction up and down which is perpendicular to wave direction. So, in this transverse or shear wave the particle oscillates at a right angle or transverse to the direction of propagation. So, in transverse wave this motion is happening in the perpendicular direction compared to the wave motion the wave direction.

This kind of mode travelling of these waves they require an acoustically solid material compared to the other cases. So, this is not very effectively done in case of for example, liquids or gases it is not very effective way of wave propagation. This mode requires an acoustically solid material. So, in transverse waves we have a direction of wave propagation and the atoms oscillate perpendicular to this motion. So, this is how this wave actually travels. The third one which we are going to discuss now is the surface waves. The surface wave is something which is different than both the two in longitudinal we have motion in direction of wave propagation, in other we have a motion perpendicular to the wave propagation. In this surface wave this motion is neither in the direction and nor a completely tangential or 90 degree to the wave propagation. This is some sort of a elliptical motion when these atoms are not even in the direction not completely in the right angle they are the motion is in a certain angle and they oscillate at certain angle compared to the wave propagation. So, that is a shear wave or the surface wave we call it. So, the third one is the surface waves. This surface wave combine both the longitudinal and transverse motion to create a elliptical kind of orbit. These surface waves combine both a longitudinal and transverse wave to create an elliptical orbit motion. So, in this case it is neither a longitudinal wave nor a transverse wave this is somewhere in between and combination of this longitudinal and transverse is such that it takes a elliptical sort of motion. So, this is elliptical orbit and the major axis of this ellipse is perpendicular to the surface of the solid.

So, this is a solid so the major axis of this ellipse is perpendicular to this surface. The major axis of the ellipse is perpendicular to the surface of the solid. And these surface waves are generated. When a longitudinal wave generates a surface near the something we call it second critical angle. And they travel at a velocity between 0.87 and 0. 0.87 and 0.95 depending upon the material of a shear wave. So, here we have the surface waves which are neither longitudinal nor traverse they are somewhere in between and the motion of these particles are elliptical and the major axis of this ellipse is perpendicular to the surface. Now how these surface waves are generated? So, these are generated when a longitudinal wave hits the surface of piezoelectric material at second critical angle. So, this second critical angle we will come to know in the next slide what is a second critical angle. But when this longitudinal wave hits the piezoelectric material at second critical angle then these surface waves are generated and their velocity is somewhere in between 0.87 and 0.95 of the shear wave they are little bit slower than the shear wave. So, when so this surface wave if we draw the cartoon for this let us say this is the wave propagation and now the motion of atoms are neither in the direction nor perpendicular it is some kind of ellipse. This kind of motion is kind of rotating motion with a it is not a complete circle it is a ellipse kind of motion. This is how these surface waves are formed and this is how they propagate. These surface waves they travel on the surface of the material.

So, we have a material piezoelectric material and these are the waves which travel on the surface of this material and these surface waves are very sensitive to any surface defects. For example we have a material and on the surface there is some abnormality or something other some other material is there these surface waves are very much sensitive to that impurity. So, if when they travel they are generally reflected or their properties changes based on what is there on the surface. So, these surface waves are very sensitive to surface defects and this is one of the application of these surface waves that if we want to check the purity of the surface whether it is very clean or there is no impurity on that we can use this surface wave we can send this surface wave and if there is a change in the characteristic we know that there is some impurity or something is there on the surface. Moreover these surface waves can even bend along the material let us say the material is not a straight slab it is a kind of a angle in that.

So, these surface waves they can even bend in the as per the material shape. So, in that way also these are very useful for checking the surface defects. Therefore, these waves are useful because they are sensitive to surface defects. So, these are very sensitive to surface defects. So, next we just considered that these surface waves are generated by longitudinal waves only and in a special case when this longitudinal wave hit the surface at second critical angle. Now let us see what the second critical angle is. So, we know that when a wave hits a material then we have a boundary between the first material and the second material let us say in this case first material is air or something the second material is this piezoelectric material and this longitudinal wave is hitting the interface between material 1 and material 2. So, when it hits the surface there will be some part which will be reflected back in the same material and some part will be refracted into the other material just like our optical wave propagation. Longitudinal waves when they hit the another material because of the refractive index difference some part is reflected some part is refracted and that process is governed by Snell's law in optical. So, the same thing happens here as well when this longitudinal waves hits the surface some part is reflected and some part is refracted and this angle of reflection and refraction that is determined by Snell's law.

So, let us draw that Snell's law first. So, what is a second critical angle let us say this what we are defining. So, in normal case when a longitudinal wave is hitting this surface this is the perpendicular direction and longitudinal wave is hitting here and the velocity is let us say VL1, V is the velocity, L is for the longitudinal waves, L1 is the medium 1 this is medium 1 let us say and this is medium 2. So, VL1 is the velocity in medium 1 of longitudinal wave this is hitting the surface at an angle theta 1. So, some part will be reflected back that will be at theta 1 itself VL1 let us say dash this angle will be theta 1 and some part will be going to the material 2 which is refracted part and that is let us say here. This angle will be theta 2 and the velocity in this medium will be VL2 velocity of longitudinal wave in material 2. And we can write the Snell's law as sin theta 1 upon VL1 is equal to sin theta 2 upon VL2. So, we can write that VL1 is longitudinal wave velocity in material 1 and VL2 is longitudinal wave velocity in material 2. So, this is the case when a longitudinal wave is hitting on the surface of piezoelectric material some part is reflected and some part is refractive and the Snell's law is given by sin theta 1 theta is the angle of incidence sin theta 1 upon VL1 is equal to sin theta 2 upon VL2. So, this is a normal case of like optics but what happens in case of which is different than these for these acoustic materials when a longitudinal wave hits the surface when it goes into the piezoelectric material it does not only generate VL2 the longitudinal wave but it also generates a shear it a different wave which is at a different angle than theta 2 and one longitudinal wave generate two waves inside this piezoelectric material. So, the actual case what happens which is different than optics is we can draw that here we get two waves in the material 2.

So, when a longitudinal wave generates the interface form of the energy can cause particle movement in transverse direction. That means we have interface let us say this is the interface this is material 1 this is material 2 and the wave is hitting at this point which is longitudinal wave VL1 at angle theta 1 some part will be VL1 the longitudinal wave at theta 2 and some part some energy will be going into a different kind of wave which is shear wave here at an angle theta 4. So, now the Snell's law applies even in this case as well and the velocity for example, so this wave is Vs2 velocity of shear wave in material 2 and we can write the Snell's law here sin theta 1 upon VL1 is equal to sin theta 2 upon VL2 equal to sin theta 3 upon Vs1. So, some part will be reflected as well this is VL1 dash and Vs1 this angle is theta 3 is equal to sin theta 4 upon Vs4. So, here what we have when a longitudinal wave is hitting the surface of this piezoelectric material some part of this energy goes into the shear wave and some part will be longitudinal wave. Now we have two waves in material 2 which are a different angle theta 2 and theta 4 and theta 2 is generally higher than theta 4. Now in optics what we call a critical angle that angle is when the diffractive wave is at 90 degree for example, this longitudinal wave is coming at theta 1. Now we start increasing the theta 1 it means the theta 2 and theta 4 both will start increasing and at some point this theta 1 is such that the theta 2 becomes 90 degree means the refracted in the material the refracted longitudinal wave reaches on the surface is at a 90 degree then that perpendicular. So, that value of theta 1 is called the critical angle normally, but when this theta 2 becomes 90 degree theta 4 is still lesser than theta 2 that shear wave is still going inside the material this longitudinal wave has come on the surface, but this shear wave is still going in deep into the material because theta 4 is still smaller than 90 degree. So, we do not stop this theta 1 just at that critical angle we further move it we further increase it.

So, that this theta 4 also becomes 90 degree when this theta 4 also becomes 90 degree that angle that theta 1 is called now second critical angle and this is the angle when we get this surface wave generated on the material. So, that value of theta 1 where this shear wave this theta 4 also becomes 90 degree that angle that theta 1 is called the second critical angle and this is the angle when we hit the surface by longitudinal wave a surface wave is generated on the material and this surface wave will now travel on the surface of this piezoelectric material. So, this value is called second critical angle. Let us write down the value values what we used here. V s 1 is the shear wave velocity in material 1 and V s 2 is the shear wave velocity in material 2. Now, let us write down what we just discussed the first critical angle. So, the angle of refraction. So, the longitudinal wave is 90 degree and all of the energy from the refracted longitudinal wave is now converted to surface. So, this is the first critical angle. Following longitudinal wave and there is also an incident angle that makes the angle of reflection of the shear wave 90 degree. This is called second critical angle. We can write here second critical angle. This is called second critical angle and beyond this second critical angle only the surface wave will be generated. So, we saw that there is a first critical angle when longitudinal wave hits the material at first critical angle longitudinal wave the refracted one it comes on the surface and if we further increase this theta 1 beyond this first critical angle then there is a angle at which the shear wave also comes on the surface and that gives rise to the surface wave which travels on the surface of this material. So, it is important to hit the material at theta 1 which is at the second critical angle or more. So, that we can generate the surface wave and this surface wave will travel on piezoelectric material and the surface this will travel on the surface itself and it is very sensitive to any surface defects or if there is a another material which is put on the surface this surface wave is very much sensitive to that material.

So, this is all for today.

Thank you.