

Acoustic Instabilities in Aerospace Propulsion
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Module - 01
Lecture - 07
Power Flow and Acoustic Admittance

Good morning, we will start with questions if you have any on last class or any of classes before that.

Student: From transport phenomena and acoustics there is both, helping transporting information within the source and how does they differ molecular ((Refer time: 00:31))

Yes, so there are this transport by diffusion where you have, let us say, we are thinking about transport of heat or concentration or any such quantities, so the molecular motion is random. So, if you have a molecule and if you think one-dimensional, just for convenience, the molecule has the same chance of going to the left or right, you can go anywhere. But then, if you are talking about diffusion of heat or material, on one side we have, let us say more number of particles than let say on the other side. So, although a particle can move left or right, there are more particles moving from left to right and right to left if there are more particles on the right side. So, because of that some kind of transport happens. So, this is like a crude explanation to diffusion.

Now, you can also transport properties, temperature or concentration or any kind of thing by convection. That would mean, that although molecules are moving in random fashion, on an average there is a bulk motion, which is moving from one place to another place. So, simply because physically something is moving from somewhere to other, it carries the properties along with it, that would be like a convective transport. Now, when you speak about waste/various transporting energy or momentum and so on, what it does is you do not have to physically move, the particle does not have to physically move from one place to another place.

Particles are moving, but you can actually transport the properties over much larger distances than the amount of particle displacements a particle is undergoing. This is because you can have collisional process and you have one molecule hitting another molecule that hitting another one, that hitting another one and this process can happen,

and over very large distance can have the properties being propagated without really having the physical mass moving in that sense and so, this is another kind of transport.

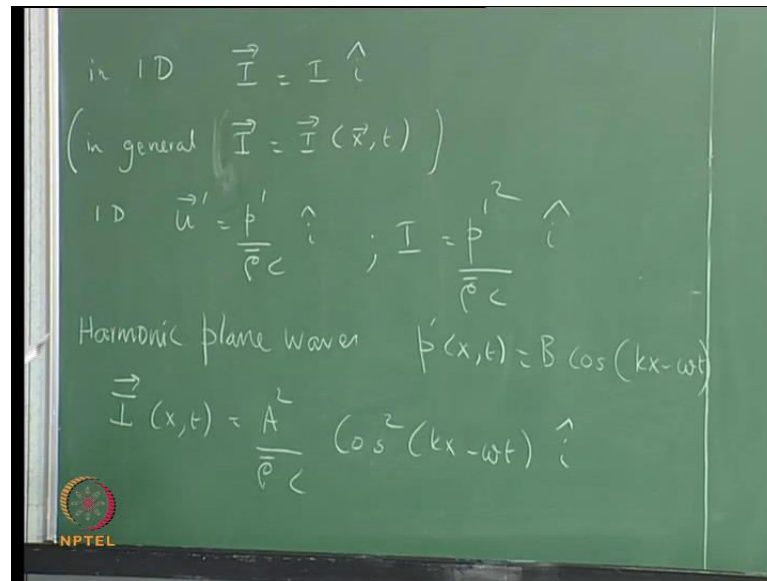
Now, this happens with the speed of sound and if you, if you want to think in terms of our Euler equations, Navier-Stokes equations and so on. They represent some kind of elasticity and the medium, the Euler equations or compressibility. So, because of the compressibility of the medium, it is like a spring. If you compress a spring and the spring is compressible, the compression or the reflection can propagate. So, that kind of motion is supported by our Euler equation. So, acoustic goes, along with that convection is also supported with that. So, if you have flow going, flow will transport equation.

So, if you have Navier-Stokes equation and you have, if you have diffusion in them, not in Euler, but in Navier-Stokes that supports transport when there is a gradient end properties. So, those are the three different things you either from a molecular view or a, or a from a microscopic Navier-Stokes Euler equation kind of framework. That answers your question. Anything else? Anybody else have any questions? Ok.

So, in the last class we stopped by looking at the acoustic energy corollary. So, that means, we, a corollary implies the fact, that we did not really start from new governing equations, new governing equations. We actually started with the same conservation equation, but we massage them in some way that we got some acoustic energy.

So, we said, that the rate of acoustic energy, the rate of growth of acoustic energy growth or decay, it is equal, equal to whatever is coming in minus, whatever is coming out and whatever is coming in or going out, that we said represented in terms of acoustic intensity. So, that is where we stopped and we will continue from thereon today.

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So, we defined a quantity called acoustic intensity; my glasses. So, I put this arrow over the letter I because to emphasize that it is a vector, it is $p V$, where V is the direction of the velocity vector. So, in one-dimensions I can be written as I times \hat{i} , where I is the unit vector. So, I is I of (x, t) in general three-dimension. It is a function of not only space, but also time because it is an unsteady quantity and in general, so in one-D we can say. So, if you had a one-D travelling wave, if the travelling wave is, let us say, going to the right, let us say it is p prime over ρc times \hat{i} . And so we could then say, I equal to p prime squared over ρc times \hat{i} . So, that means, it is good intensity, can be, can be reduced from measurements of pressure.

Now, pressure is much cheaper to measure compared to velocity because measurement of pressure involves, what can you do is...

Student: ((Refer Time: 06: 12))

Pit out prop will not measure the expression. Why would it not measure then? The frequency response of pit out measurements is very poor. What would you need to measure sound?

Student: ((Refer time: 06:27))

What kind of transducers that is to measure pressure? You need pressure transducers, that is like a cool statement, but...

Student: Piezo like

Piezo like transducers, what else is available?

Student: Strain gauge

Strain gauge, yeah, those are used for, strain gauge are used for high pressure oscillations. Simple...

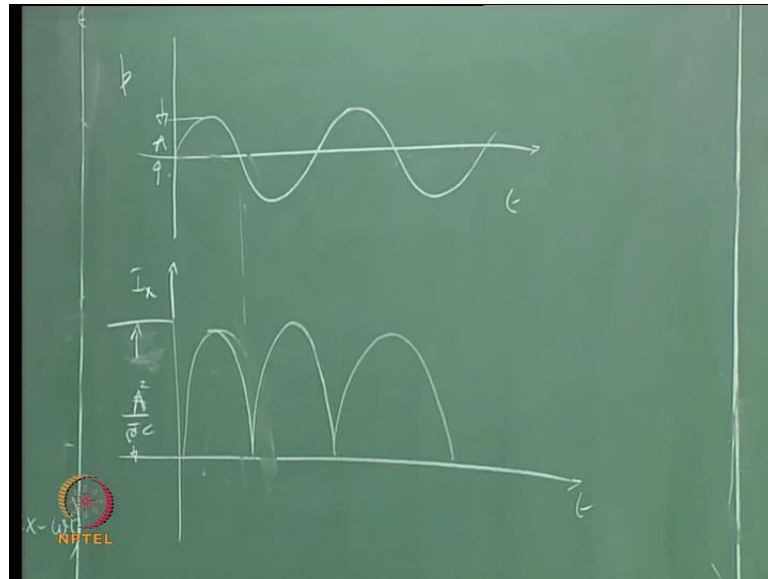
Student: microphones.

Microphones, yeah, if you are musician and you are singing, you sing with that here, there is a microphone here. I think, that is, those are simpler compared to velocity measurements. The cheapest velocity measurement would be like a hardware anemometer, which would be a, in the microphone, very good quality microphone would cost, you know, two lacs or something; cheap one in a music store will cost a few hundred rupees plus the amplifier hardware will cost thirty lacs or something. And then, if you want to do the laser based techniques, I think PIVN, what else is there? LDV, particle image velocimetry and ((Refer Time: 07:27)) velocimetry, they are or the order of crores.

So, I think measuring pressure with a microphone or Piezo electric transducers, they are actually cheaper than the microphones, the good quality ones. So, that is simpler than or cheaper than measuring velocity. So, we are always trying to get techniques where we can measure pressure and estimate the velocity. So, if you want to estimate the acoustic velocity, we actually go for two microphone technique because, why two microphone rather than measuring velocity? It is very expensive to measure velocity, that is the thing and in engineering we want to go as simple and as cheap as possible.

So, now we talked about harmonic plane waves and so, where p prime of (x, t) , let us say, was $B \cos kx - \omega t$. So, therefore, what would I be? I of (x, t) would be equal to $\frac{A^2}{c} \cos^2 kx - \omega t$ times I , which I guess you can recast this as $\frac{A^2}{2\rho c} [1 + \cos 2kx - 2\omega t]$. Now, in practice although we can write this expressions, this quantity I is actually pretty much a useless quantity because you have a quantity, which is oscillating in time.

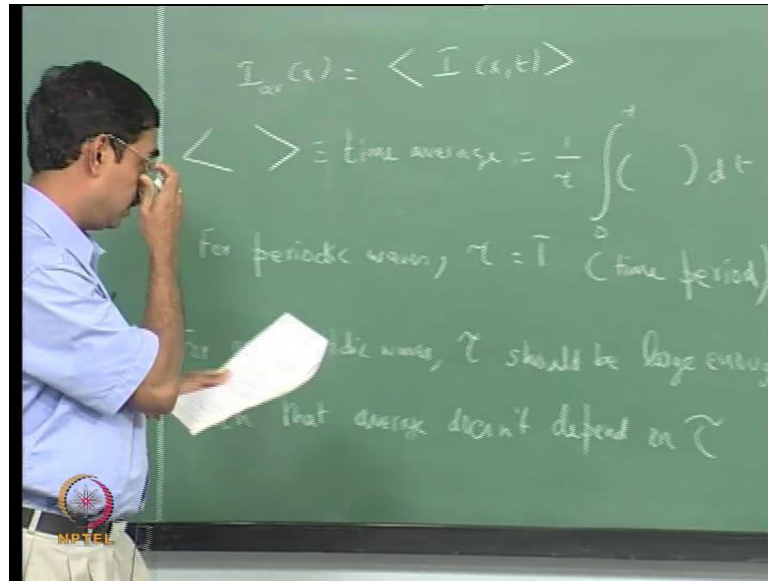
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Now, if you look at a pressure signal of this form, let us say, this is p versus t and this is A and if we look at I_x , this would be..., and so on. So, this is a quantity, which is going up and down every moment and then we will have to evaluate it for each moment and then, we have to figure out, sometimes it is going up, sometime it is coming down. So, this is kind of a useless quantity.

What is much more useful is that time average intensity. Then, we know, that over a time period average, when you say time average, a natural way of averaging would be averaging over acoustic cycle. If there is harmonic oscillations at certain frequency, so then we can know over a cycle by that the power is coming in, going out. So, that way this time average intensity is a much more useful quantity.

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So, if you say I average of x, so typically, time average is denoted by triangle brackets. So, now this could be thought of as 1 over tau integral 0 to tau, whatever is the quantity, times dt. So, for periodic waves time period is very natural quantity to average. Now, for non-periodic waves, that is such an obvious time scale, does not exist. So, what you have to do is we have to average over a time period, which is long enough, so that we can include all the time scales available or that the average does not depend on tau.

So, although with the triangle brackets is, strictly speaking, called the time average acoustic intensity, in practice that is what is referred to as intensity itself. So, we drop the term time average. But when you refer to usually as acoustic intensity, most likely people used this terms would be meaning at time average acoustic intensity as is being used in the engineering parlance.

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The chalkboard shows the following derivation:

$$\langle I \rangle \text{ (often referred to as intensity)}$$

$$1) \text{ wave } \langle \vec{I} \rangle = \left\langle \frac{p'^2}{\rho c} \right\rangle \hat{i} = \frac{1}{\rho c} \langle p'^2 \rangle \hat{i}$$

remove wave

$$= \frac{p_{rms}^2}{\rho c}$$

period) $\frac{1}{T} \int_0^T p'^2 dt$

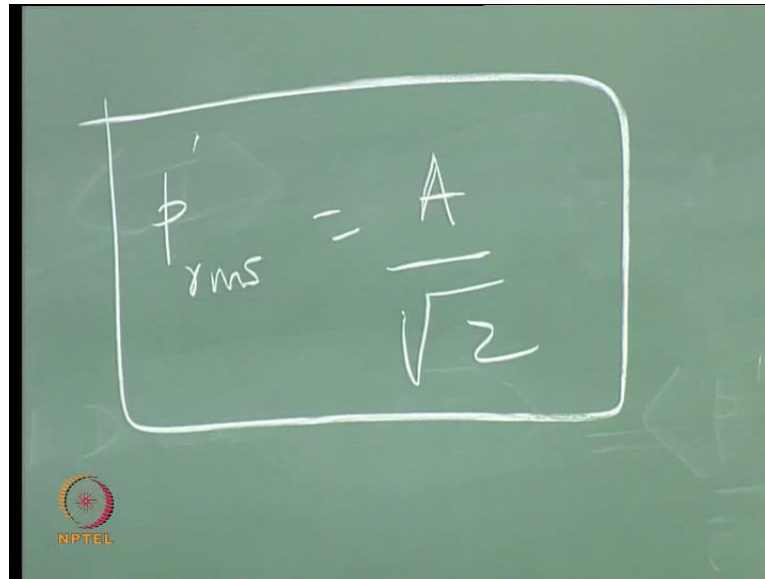
$$= \frac{A^2}{T} \int_0^T \left[\frac{1 - \cos(2kx - 2\omega t)}{2} \right] dt = \frac{A^2}{T} \frac{T}{2} = \frac{A^2}{2}$$

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So, this I often referred to as intensity, but this would actually mean time average intensity. So, if you have a 1-D wave, what would be the acoustic intensity? So, this could be p prime squared over ρ bar c because v is p prime over ρ c . So, this would be this times \hat{i} of course, because it is a vector. So, strictly speaking, so this time average of p prime square would be actually p prime rms squared and there is a ρ c here. So, there is this ρ c here. Now, if you are talking about a harmonic wave we can say, p rms squared equal to $\frac{1}{T} \int_0^T p'^2 dt$ which could be written as $\frac{A^2}{T} \int_0^T \frac{1 - \cos(2kx - 2\omega t)}{2} dt$.

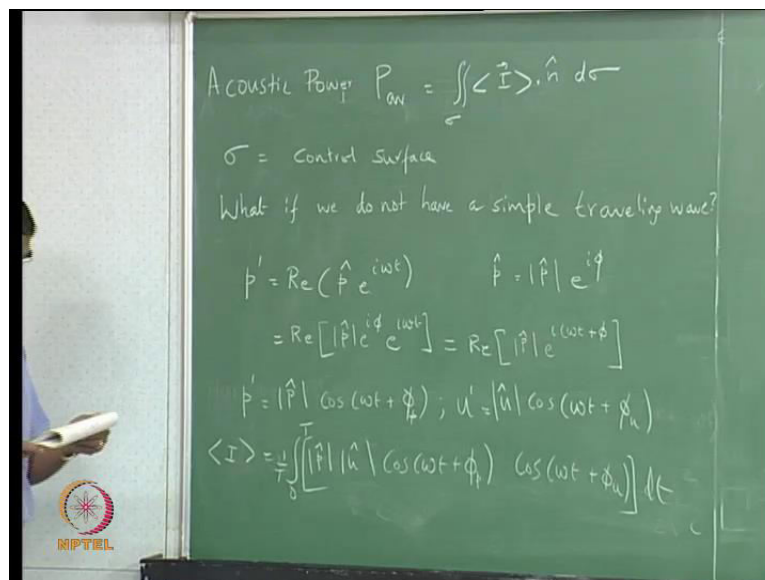
Now, what is the average of, sorry, what is the integral of $\cos(2kx - 2\omega t)$ over time period T , time period t ? This is a periodic function, so if we average over a period or actually there is a 2 here, so it is, double the frequency is oscillating. So, if the average over T , this term will drop it, it would average to 0 because its periodic function and only contribution will be from the first term, which would be $\frac{T}{2}$. So, this would be equal to $\frac{A^2}{T} \frac{T}{2}$, which is $\frac{A^2}{2}$.

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$$p_{rms} = \frac{A}{\sqrt{2}}$$

So, p_{rms} would be A over root 2. So, this is a very simple result we can get for harmonic waves. I think you all knew all of these from high school, but we are just doing it for sake of completeness.

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Acoustic Power $P_{av} = \int_S \langle \vec{I} \rangle \cdot \hat{n} d\sigma$

$\sigma =$ control surface

What if we do not have a simple traveling wave?

$$p' = \text{Re}(\hat{p} e^{i\omega t}) \quad \hat{p} = |\hat{p}| e^{i\phi}$$
$$= \text{Re}[|\hat{p}| e^{i\phi} e^{i\omega t}] = \text{Re}[|\hat{p}| e^{i(\omega t + \phi)}]$$
$$p' = |\hat{p}| \cos(\omega t + \phi_p); \quad u' = |\hat{u}| \cos(\omega t + \phi_u)$$
$$\langle \vec{I} \rangle = \frac{1}{T} \int_0^T [|\hat{p}| |\hat{u}| \cos(\omega t + \phi_p) \cos(\omega t + \phi_u)] dt$$

And now we speak about another quantity, I call acoustic power. Acoustic power is the net acoustic intensity flowing through the entire surface. So, we can write a formal definition as follows. So, if you integrate this intensity over the entire surface, which you are dealing with, then you get the acoustic power and acoustic power is a very useful

quantity because many times in propagating acoustic fields the acoustic power will stay constant at various surfaces. Just to give you an example, if you are talking about acoustic power enclosed in a, let us say, in a sphere or something of radius r and then the waves are propagating, and let us say we are in the middle of the universe, there is no boundaries and so on. And so, it is kind of intuitively obvious, that $4\pi r^2 I$ would be a constant. So, although I is intensity, is flowing, is going as 1 over r^2 and p and v are falling as 1 over r , but the power is staying constant. So, in that sense power is a very useful quantity.

So, now we talked about a travelling waves and then we spoke about acoustic intensity. Now, the next issue comes, we are dealing with combustors and there do we have often travelling waves or standing waves. There are standing waves are more the norm travelling waves. Why do we have standing waves? Yeah, so if you are looking at a flame in the open, middle of nowhere, sound will be radiated out and very likely you can think of sound as just as the radiating field, but in the combustors.

For example, the combustor is for gas ((Refer time: 18:06)), the sound will go to some boundary, let us say choke nozzle, whatever, and come back. So, there is a very good possibility, that sound is reflected, well reflected and come back. So, we are in a standing wave and what would be the acoustic intensity for a standing wave that is the question that I wish to address next.

So, what is in the linear region? We can think of a standing wave as super imposition of two travelling waves, one going to the left and one going to right that is. But if you, we know, that if you have a standing wave going to the right, what is the velocity expression? For velocity let us look at one-dimensional quantity, not c , what is the particular velocity or the acoustic velocity? No, particle velocity u , what is u ? How do you get velocity? We did problems in the last class. p' by ρc , absolutely right. Yeah, c is the speed of the wave, that is not the particle velocity or that is not the acoustic velocity. It is the phase speed of the wave, we are talking about particle velocity.

So, in this acoustic intensity, which is defined as p' times u' , that is actually the u' corresponds to the acoustic velocity or the particle velocity. It is not the speed of the wave at all, it is not c , let us be very clear about it.

Now, if you have a left running wave, what would be the quantity? Minus, so you have a right running wave. We have to divide by ρc and left running wave, it is minus ρc . So, it is, so the total velocity is not equal to pressure over ρc because pressure goes like, $f + g$ over ρc and velocity will go like, $f - g$ over ρc . So, that is not a, not a simple ratio. So, either you have to know how much of the wave corresponding into left running wave or right running wave or you have to be more careful and do the analysis.

So, this thing I wish to warn you. So, often without even thinking we think, that velocity goes like pressure over ρc and that is, you must remember that that is only for a travelling wave, which is to left or right. To the right it is p' over ρc ; to the left it is p' over minus ρc . But if it is a combination of left and right, one has to be very careful as to which way you go. So, let us consider a general case where you have a standing wave. So, we will write a general expression for pressure and velocity and as...

So, once again let me check with you about the understanding of pressure. So, if I am, if I am giving you a complex acoustic amplitude what would be the actual amplitude that you measure? What will be the instantaneous pressure value that I measure? How do you get that from the complex amplitude? Can you speak loudly? I am not able to hear.

Student: ((Refer time: 21:26))

No, actually you have to multiply your pressure amplitude by $e^{i\omega t}$ and then take the real part; that is what gives the instantaneous pressure. So, it is, I hope you review the notes from last time. You have to take the, multiply this complex number with another complex number here and you will have a combinations coming from real part and imaginary part, which is what results in a certain phase. So, we cannot simply take the modulus of this complex amplitude. This is a common mistake that we make. So, let us be very careful about this.

So, if you do this calculation and take the real part. So, real and then you can write p' as $\cos \omega t + \phi$ and I will put a subscript p because I want to keep distinguish this phase with another phase. So, if you, similarly if you write u now for a travelling wave, this ϕ_p and ϕ_u will be same, but we are, if you are having only one travelling wave. But we are not really talking about one travelling wave, we are looking

at a general standing wave. So, if you now take the average, this would be what the acoustic intensity would be.

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$$= \frac{|\hat{p}| |\hat{u}|}{2} \int_0^T \cos(\omega t + \phi_p + \phi_u) + \cos(\phi_p - \phi_u) dt$$

$$= \frac{|\hat{p}| |\hat{u}|}{T} \cos(\phi_p - \phi_u) T = |\hat{p}| |\hat{u}| \cos(\phi_p - \phi_u)$$

Admittance $Y = \frac{\hat{u}}{\hat{p}} = \frac{|\hat{u}|}{|\hat{p}|} e^{i(\phi_u - \phi_p)}$

$$Y_{real} = \frac{|\hat{u}|}{|\hat{p}|} \cos(\phi_u - \phi_p)$$

And now, we can use some trigonometric identities and to make the integration possible, so this $\cos \omega t$. This product term can be written as $\cos 2 \omega t$ plus $\phi_p \phi_u$ over 2 plus $\cos \phi_p$ minus ϕ_u over 2 dt. And when you integrate this over a time period, I think it is, you can guess what happens to this term. This will drop out because you are integrating a periodic function. Over a period you will get net value 0 and this will be multiplied by t over 2. So, you will get, so this is the acoustic intensity, time average acoustic intensity for a general wave, which is p prime p hat u hat. You take the modulus, multiply them and the face between the pressure and velocity. Hope this is clear.

Now, we can actually define a quantity called admittance, which is the reciprocal of impedance. We talked about impedance earlier and what was the definition of impedance. What does it mean? Prime, yeah, so in the, in the frequency domain it is p hat by u hat. So, you similarly define admittance, u hat over p hat, it is similar to conductance in electric engineering.

So, if you look at the real part of this, these are complex quantity because it is ratio of two complex numbers. So, y real equal to... So, we see, that y real is u hat over p hat times the phase between the velocity and pressure. You can write ϕ_u minus ϕ_p or

phi p minus phi u, it does not matter, it will get the same result. And so, we can then write the intensity, which we got here in terms of this admittance.

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The chalkboard contains the following equations and definitions:

$$\langle I \rangle = \frac{y_{\text{real}} |\hat{p}|^2}{2} = y_{\text{real}} p_{\text{rms}}^2$$

$$\langle I \rangle_{\text{traveling wave}} = \frac{p_{\text{rms}}^2}{\rho c}$$

Y = non-dimensional admittance = $\frac{y_{\text{real}}}{(\rho c)}$

$$Y = \frac{\langle I \rangle}{\langle I \rangle_{\text{traveling wave}}}$$

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So, I is really y real into... over 2. So, the intensity is real part of admittance multiplied by r m s value of the pressure. So now we can actually have a non-dimensional admittance Y. This is non-dimensional admittance, which is equal to Y real over 1 over rho bar c. So, then, the units are matching, so this will actually be equal to Y. You can show this is equal to... So, if you have intensity of a general standing wave and if you were having at the same pressure, amplitude, a corresponding travelling wave, this ratio between them, that would give actually the non-dimensional admittance. I hope this is clear physically or what is meaning of that.

Student: Sir, will we have a source?

Yeah

Student: And to this we are giving signals, which are non-trigonometric functions because we give elliptical, square or triangular functions.

Yeah, so we...

Student: Then, the sound propagating, will it adjust itself to be a...

Well, you can give any amount of signal you want and you can still do four year transient and split it into harmonic and then use this analysis. So, that is, if you, if you want to do it in the frequency domain you are also welcome to work in the time domain, only thing is things will be simpler in the frequency domain. But if you have transient signals, then time domain is what one should work on. But if you are not really having transient phenomena, then harmonic domain is convenient and it is much simpler.

So, in summary, for a travelling wave, I will be $p r m s$ squared over ρc , right, we saw that. And for a general wave it will be $p r m s$ squared times Y_{real} , that we saw. So, this is Y_{real} times $p r m s$ squared and we know, that I travelling wave equal to $p r m s$ squared by ρc . So, if you take the ratio of this I over I travelling wave you will actually get Y divided by 1 over ρc , which is like a non-dimensional admittance. So, this is like a reference value 1 over ρc is the, is reference value. When a travelling wave, that is the maximum intensity that you can get through because the pressure and velocity are in phase, you can have situations in standing wave where they are out of phase and then no intensity flows in or out.

Are there any questions? Yeah...

Student: P_i equal to $k x$ ((Refer time: 31:44))

Sorry...

Student: Here the P_i equal to $k x$...

Yeah, yes and we will work out that for a general case. Now, we will solve the problem with the $k x$ term. So, we did some examples earlier where we looked at nice standing waves in ducts, which are open at both the ends or closed at both end, both the ends, one side open and one side closed and in all the cases we got the, in the solution we got either A equal to B or we had $A e^{i k x}$ and $B e^{-i k x}$, those were the left and right running waves. And then, we had either A equal to B or A equal to minus B .

Now, what if A is not equal to B ? And I think, what are the general features of the standing wave and so, in the way the acoustic problem is posed, you actually have a wave equation, which is the differential equation, which is governing our phenomena and then what do we need. And in the harmonic domain we had taken the time dependence out

and then what do we need to solve this equation boundary conditions. So, how do we know the boundary conditions? And in the earlier case the problems we worked out what did we do?

We consider some problems where the tube is closed or open and so on, but in reality it may not be anything of that sort. It may be neither close nor open and I said it is of the order of, it is like a mixed boundary condition, $A \text{ times } p \text{ plus } B \text{ times } u \text{ equal to } 0$, that kind of, that is the admittance or an impedance boundary condition. Now, in, if you are given tube and there is a boundary do we know the boundary conditions? Now, we know, that in classroom problems when we studied differential equations and so on, the professor gives you a differential equation and gives you the boundary condition, then solve the differential equation this is, but in reality it does not work this way.

We can know the differential equation; that is fine, somebody has derived it. We can also know the solution because you can have microphones mounted on a transducer or you can traverse a microphone in a duct or microphones mounted on the tube and you can actually measure the pressure. So, there is nothing big deal about, there is no big deal about knowing the solution because we can measure it even if we are idiot and we cannot solve the differential equation, we can actually measure it, but can we know the boundary condition?

No, actually that is the answer. You can have the equation, we can have solution, but there is no way to know if I give you, a given material like this clothes or reflecting liner or some kind of, this kind of material, which is used in a studio, I mean, by looking at it you cannot know the impedance or admittance of those quantities. So, it is hard to know the boundary. In reality, we do not know the boundary condition, but it is interesting, we actually know the solution. This was very striking to me when I made this relation first, that I know this solution, but I do not know the boundary condition.

So, in reality what is the problem? It is really inverse problem. It is the, we know the differential equation because it is derived and it is peaceful. We know the solution, can we determine the boundary condition that is the actual problem. I mean, text problem may be different, why do we need to do this thing? That is, you measure the solution from there, from there we determine the boundary condition, what is the advantage of it?

Student: So that we can predict some other situation.

Yeah, so that if you have, so once you know the boundary condition, then for any other situation you can predict the acoustic field in duct, if you, for given this boundary. So, with this for example, if you are looking at an absorbing material like this, this screens here, which actually absorb sound or we can have carpet or there absorbing liners and so on or so, incident wave comes there, it may not get reflected and comes back. So, you have to minimize the equation.

You can also have in after burners for example, they use liners in the ducts, in the, in the tube, so that there is lot of sound, but liner absorbs lot of sound. If you have flame for example, wave may hit the flame and the flame may absorb some amount of the incident wave and a part of it may get reflected or if things are not going very well, the incident wave may come here, flame may amplify the wave and bigger devil comes out of it, a bigger, a wave of bigger amplitude comes out of it.

So, give, so it is important to, so in the linear theory this admittance can be characterized what a boundary does to your acoustic field and if you know the equation and the boundary condition, then we can predict the thing in a general sense. But of hand we do not know the boundary condition. Boundary condition has to be characterized and the best way is to measure the solution and solve the inverse problem and find out what boundary condition would give the solutions.

So, it is like you have to guess what would be the boundary condition, which should give a certain solution, it comes to that. So, that is the, as an experimentalist this is my real problem and as a student of differential equation my problem was different. I knew the equation and I solve for it with the known boundary condition, but that, no, yeah, you...

Student: ((Refer time: 37:23)) we want to find the boundary conditions, so what kind of parameters would be ((Refer time: 37:30)) special kind of parameters ((Refer time: 37:33)).

So, I think you can, given the, given a tube and given whatever medium is there and you put an acoustic field, then you can find out how the boundary behave. That means, there is, like you can measure the admittance or the impedance. Now, that thing if you want to express as properties of certain thing, for example, you have, you have certain type of material and you want to characterize the admittance in terms of the pore size there or

void fraction there and so on, then you have to characterize that boundary condition reflectivity or the admittance in terms of the further properties of the material.

But from an acoustic point of view or from a duct acoustic point of view, I have duct, there is a boundary and I want to characterize the boundary. So, for that the simplest way is to send a wave, get it reflected and see how the reflection is. If the wave does not get reflected at all, what does it mean? It is a travelling wave, so there was nothing in the boundary, it was just characteristic impedance. And there is an infinitely long duct and the wave continue to go, if it got reflected back to the equal amplitude it must be either a close-end or open-end. From the fact we can determine whether it is a close-end or open-end depending on whether the velocities are cancelling out there or whether the pressures are cancelling out.

If it is anything else we have to examine carefully, but the crux of the matter is we send a wave, get it reflected, find the ratio between the reflected wave and the incident wave and that is the crux of the matter. Now, of course, before solving the inverse problem it is, it is important, that we solve the forward problem and then understand the features of the forward problem and then it is easy to do the inverse problem, because if you do not know how to do the forward problem, it may be very hard to solve the inverse problem.

And now, why should you characterize impedance from a, I mean, you said why should you or what kind of parameter should be used, but there is something more fundamental that about why one should characterize the boundary condition, because... You had a question.

Student: ((Refer time: 39:44)) already we are doing an experiment and we are finding a solution by means of measurement, so cannot we just ((Refer time: 39:51)) the boundary condition ((Refer time: 39:53)).

Yeah, so if you know how to do it, so only way I know is to send an incident wave and get it reflected. So, as long as you can, yeah...

Student: Since we are actually measuring the pressure...

So, you have to, once you measure the pressure, you can get the boundary condition that is all. But now, if it is a function of parameters you can express the parametric

dependence. But even more fundamentally, why should you know the impedance from some acoustic point of view. So, let us say, remember acoustic energy or corollary, that if more energy is coming in, then what is going out? What happens? The energy in the field grows and if more is going out and less is coming in, then you are having a kind of decay. So, if we know the intensity that can be related to the growth or decay of the system, if you, is not it.

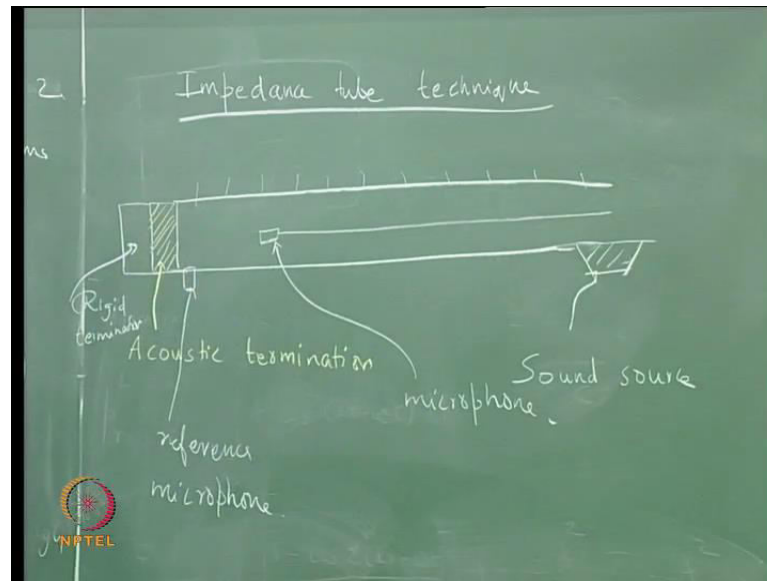
And the, so if you have something at the boundary, which is driving the flow field I mean driving the acoustic field in side and then what happens? In the linear system you will have exponential growth if it is driving and if it is damping, there will be exponential decay. So, in fact, the growth or decay can actually be related to the intensity at the boundary, which can then be characterized based on the boundary condition. So, that is the crux of the matter. Yeah...

Student: We did a problem before on ((Refer time: 41:16)), then we considered close boundary condition. Is it because at the nozzle the flow gets choked, that is why the...

Well, I made a very simplistic approximation. So, it is quite close to it, close, closed quantity condition, then chock nozzle reflects most of it. In reality some amount of acoustic waves are going out and there are lot of people who have characterized the amount of face, that amount of power that is lost in terms of admittance values of the nozzle and so on. In fact, there is some formulas, simple formulas available for short nozzles and so on.

So, what I did was a very simple approximation to get the problem done, but I mean, you can have a more complex answer, which will account for the nozzle actually takes out the acoustic energy. So, in ((Refer time: 42:04)) there are several factors involved. For example, the propylene grain can give an energy or take out energy, often it gives energy and the nozzle is sink, it takes out the energy. So, it is a balance between these things. So, I mean, you study ((Refer time: 42:16)), you actually characterize the nozzle admittance accurately. The other questions?

(Refer Slide Time: 42:39)



So, we study some experimental device called impedance tube and this technique is called impedance tube technique and it is quite simple. And I can also tell you ways to complicate it and make it very difficult. So, impedance tube is nothing, but a simple tube, nothing fancy about it. So, if somebody says I am making impedance tube, he is just taking a piece of pipe and calling it impedance tube, there is nothing more than that. And, so we need a sound source, let us say this is an external source and you have the material, which you want to characterize ((Refer time: 43:28)). I will get a color chalk here.

So, this could be the acoustic termination and we put this against a rigid backing, rigid termination. I mean, this is to make sure that everything goes into this and not anywhere else. So, this is the boundary and there is a source from which sound comes and you have a microphone, let us say. So, it can be a condenser microphone or you can use a piece of electric transducer and so on.

And now, I have to tell you some stories about how to make the measurements. So, if you do have a hardware anemometer here or fancy laser technique and people do it, sometime you can measure the velocity and the pressure and then u hat by p hat and you can get the admittance that is peaceful and if you have all those things you can do that, but otherwise we will use only pressure measurements. So, if you have a microphone how would you convert that into, how would you read out the value of pressure? How

would you get it? So, microphone converts the acoustic pressure into electrical signal. So, eventually get overtake signal, whether it is a condenser microphone or a pressure transducer or I mean, a piece of electric transducer, so the, so you have a voltage signal. And how would you read it?

Student: ((Refer time: 45:23))

So, we can use the simple voltmeter and measure the signal if that is all we have, but then we get only the amplitudes, we do not get the, get the face if you are measuring at different locations simultaneously. So, one possibility is you, to know the face of the standing wave you have to have a reference microphone. Alternately, if you are having lot of microphones you do not have to traverse the microphone, you can mount all the microphone, several of them, in the walls. Of course, that means, to have more money to buy more microphones now and sometimes it is absolutely mandatory.

For example, if you are measuring the admittance of a solid rocket motor, in a solid rocket motor kind of situation where you looking at the response of the propeller and something and the whole propeller and will be finished in something like 1 second or half a second or point, 0.2 second or something. So, there is no way you do not have time to traverse the microphone throughout the duct, but if you are looking at measuring the acoustic admittance of a carpet, you can mount the carpet, turn on, put a loudspeaker that turn on the speaker and there is no, I mean, it is cheaper to move the microphone back and forth rather than do the experiment with 20 microphones and so on. So, it just depends on the circumstances that you are working under.

Now, earlier, so it is, so one thing is to use the voltmeter than you can get amplitude. I think it is, that is the simplest thing. If you want anything more than that, you could connect two of them, the reference transducer and this transducer to an oscilloscope and you can read out the face out of the oscilloscope or you can use a fancy data acoustic system. So, data acoustic systems are now really easily available and they get the very nice programs to use with them, for example, like lab view and so on, so forth.

But when I was doing experiments in several 30 years back, 20 years back or something like that, more than 25 years back, I mean, the data acoustic systems were very crude. So, you would have, the programs will be on a paper tape and you have to wind the paper tape and that itself was a big job. And then, the computers in those days had, you

know, hard disk size of 20 MB or 40 MB, now that, which was considered big in those days. And now, you know, you have, computer hard disks are the order of several GB. So, in those days that, but even in 80s and so on, people did work with the ((Refer time: 48:05)) card, I mean, with this kind of digital data systems and before that, into 70s and 60s, they used actually tape recorder. You would, just like you would record music on a tape recorder, you would record this sound from this microphone on a tape recorder and then try to extract all these values out of it. So, and then people did spectacular work in the 60s and 70s and 80s.

In fact, some of the people I spoke to, who are doing experiments on solid rocket motor as now with all these fancy modern instrumentation and them not got in any, anything better than what people got in the 70s and 60s and 80s and so on. Because I guess, in those days when things were very difficult, people used their brain, so that you would understand things and so on. Now, we just do things without thinking. So, you can, I just told thing, so that nowadays we do not appreciate the level of improvement and that is happened to data acoustic system and we take lot of things for granted. But I mean, really lot of technologies involved over long period to get lot of improvements.

So, what we do now is to measure the acoustic field includes amplitude and phase at different locations. You, seeing this microphone and then we will try to see how that can be used to determine this reflection or the end condition here in terms of what happens to incident wave and how it gets reflected and so on. So, basically we have a, we cannot measure travelling waves because you have left running wave, right running wave, together that is our way of seeing things, but we will measure the pressure at several locations and then we will see if we can try to decompose it into a left running wave and a right running wave and then we can see how the left running wave will get reflected as right running wave. I will do that tomorrow and we stop here.

So, in summary we looked that the definition of acoustic admittance and what is the physical meaning of it. And now next class we will try to find the way to measure it

Thank you.