Acoustic Instabilities in Aerospace Propulsion
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Lecture - 1
Introduction to Acoustics

Welcome to the lectures on acoustic instabilities in aerospace propulsion. My name is Sujith and I will be delivering this class. So, before I start off with the lecture I like to give a course outline.

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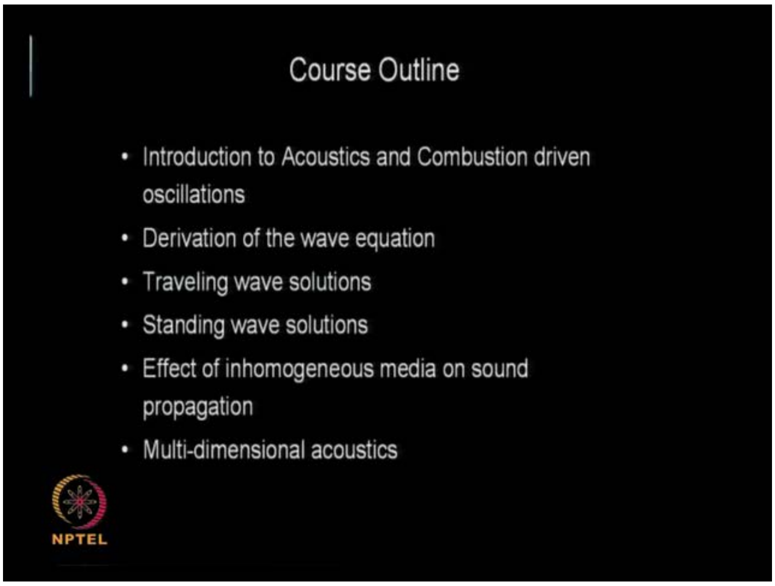

So, the course is dealing with how there are instabilities that happen in propulsion system or combustion system in the industry. And this is something which we usually do not deal with in a propulsion course. So, usually in a propulsion course we talk about designing a propulsion system or a combustion system, and those are basically based on study state principles rather than any instability analysis, but here. So you end up designing a engine or a system and then some times it goes unstable, that is the engine develops very large levels of vibration and sound inside and create problems and may lead to destruction of engine or mission failure and so on. And such scenario happen in real life and this course is to look at such phenomena.

So, the course starts with an introduction to acoustics and how combustion driven oscillations occurred. And we will then do the derivation of the wave equation, we will then speak about solution derivation equation. First we will be talking about what travelling wave solution and then standing wave solutions, then we look at effect of inhomogeneous media on sound propagation. That is in real engines temperature in the engine is not uniform its different from usual sound propagations that atmosphere or something where here the temperature be non-uniform. So we will look at the effect of non-uniformity or homogeneity media on sound propagation, then we look at multi-dimensional acoustics. So, how does sound propagate in a can type combustor or how are the radial mode, how are the tangential mode happening and so on.

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And so this much is the basic acoustic part, then we move on to looking at combustion stability. First I will look at the fundamentals of combustion instability, how it occurs and then we look at the basic principles, we derive the equations that represent the describe combustion and stability. We will speak about Rayleigh criteria which is the classical criteria that explains weather instabilities occur or not, then look at instability in solid and liquid rockets, ramjets and gas turbines engines.

We speak a little bit about pulse combustors and their use, speak then about the passive and active control of combustion instability. We will then see how we can do theoretical analysis of combustion instability and then we do model analyses, which is the conventional technique for studying analyzing combustion instability. And lastly we will look at the recent developments on non-model stability and analysis. So basically you can see the courses split into two parts in the, first part we are basically speaking about classical acoustics.

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So, we describe how waves are travelling in a medium how they get reflected, how they get transmitted and so on. So, that is what is basically classical acoustics and the second part, we will specially discuss…

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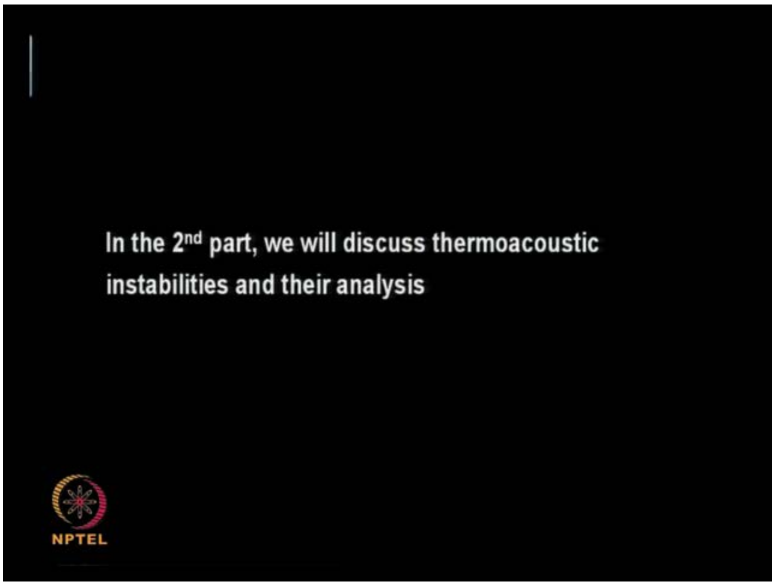

Thermo acoustic instabilities and their analysis. So, this is what the course is and in today the first lecture, we will speak about what causes the instabilities and how we will, I will just give you a very preliminary introduction about what causes instability. And how who there is established in combustors and how they can be suppressed.

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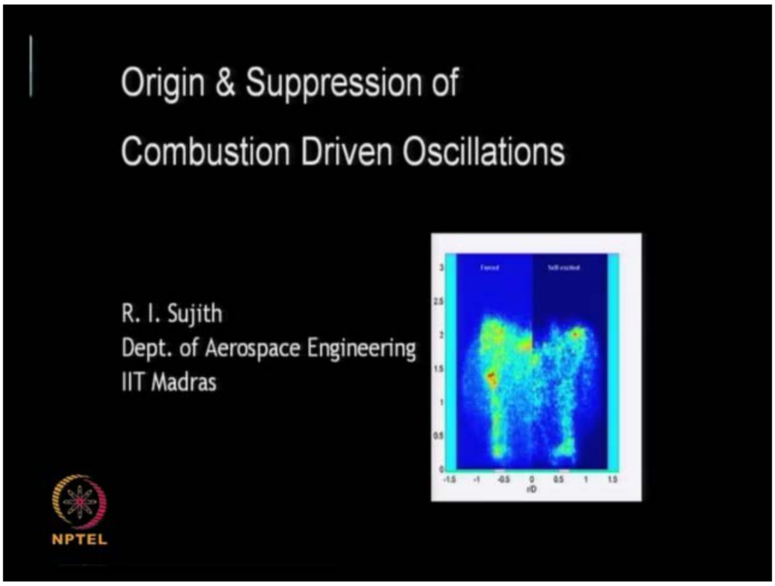

So this is the first lecture that is a origin and suppression about of a combustion driven oscillations. So, as I mentioned propulsion is usually taught as a study state phenomena, but in reality all the property system are designed based on study step principles, they are not actually that study because when the stability comes there will be loud level of vibrations, and noise. And the fluid mechanics will be unsteady and you would end up having serious problems.

So, first question is what is thermoacoustic instability? This word thermoacoustic instabilities also refer to an by some other people as what is called combustion instability or thermoacoustics or combustion dynamics. We will look at how common it is in fact it is quite common although people do not speak much about, it it is there in most of the engines and some of the literature says that fifty percentage of the solid motor that are develop have combustion instability problems. Let us speak about who we can eliminate it.

So I will giving an introduction to this subject in this lecture, so whenever you decide rocket runs in a industrial burner, whatever you decide it and then you go into tested and then bang you are struck with this instability problems. And then this is the completely new ball game, and we do not know how to deal with it, this is there it was there you must, if you look at the history of the moon program Americas moon raise to the moon they used F 1 engine, in the certain rocket which had serious instability problem and America had to work hard to get over it. Like that so many rocket have this problem so many rockets have this problem. So, many industrial burners have this problem and usually this problem is identified only at the later stages of a program and then it's very hard to fix it. So, in this lecture we look at the origin of combustion driven oscillation and their suppression.

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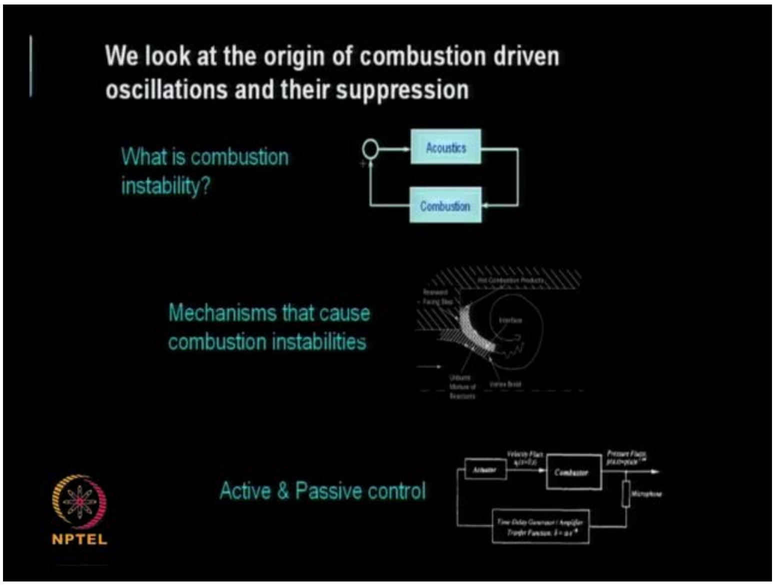

In the first part we look at what is combustion instability, then we look at mechanisms that cause combustion instabilities, how exactly these instabilities occur in various forms of various propulsive systems. And then we look very briefly on active and passive control of instabilities. So this is like a over view lecture and then we will deal with each of the topics in very serious manner, in very liberate manner.

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So, India is now expanding its power capability we are I think we are doubling our generation capabilities in every 5 or 6 years. So, we are now starting to use gas turban engines to produce power these, this was commonly used in the western countries, but now India is adopting this also we are having a aggressive aerospace program, we have space programs, and we have jet engine programs, we have missile programs. All these all these is powered by a common denomination is the combustion.

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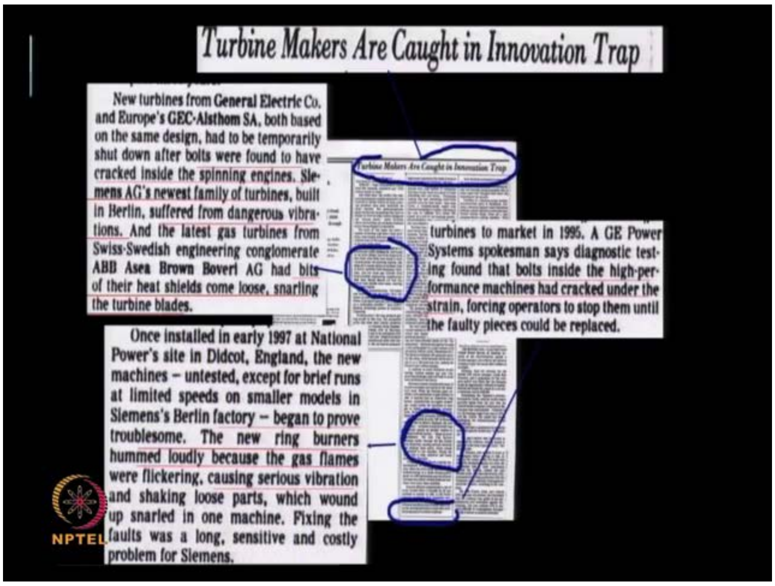

And these combustors often have what is called combustion instability. What is shown in the slide is a clipping from the wall street journal, some years back may be about 12 years back. So we in our in the eighties nitric acid rain was considered to be a serious problem and everybody was trying solutions for that and then the engineers and scientists came up with the solution, that we have to use combustors which give no anoxia that is nitric oxide NO, NO 2 and NO.

And the solution was to lean premix premier vapor burner LPP burners and these combustors were made and they were brought to the field, and then what happened they had instability. You can see that the when the combustion equability occurred loud amplitude of sound came inside the combustor and very large level of vibrations, were set in we can see this is a article says turbine makers are caught in innovation trap.

So, when the instability of curve you see the bolts were found to have cracked inside the spinning engines and dangerous vibrations, heat chills came loose, ring burner sounds loudly because gas flames causing serious vibrations, parts were coming loose nuts and bolts were coming loose flying off. And engine have to be shut down and it to shutdown it tales quite long time because they are very nice bearings it takes half an hour to shut down and half an hour to restart. So, this is really a tremendous problem in the industry and so a so on those engines that create ah that accuse to generate a power is shutdown it cause lot of money and this causes lot of revenue loss to the power companies.

In fact power companies asks the turbine companies the gas turbine companies make this engines to pay for this power loss that is happening due to a shutdown because of instability. The gas turbine companies suffer very severe severely because this of course, then this cost is built into their pricing. So in general billions of dollars are lost because this problem and it is a very serious problem in the gas turbine industry. Particularly in the recent times gas turbines are used for power production in ground base gas turbine engines.

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Also in aero space program, it is a really a very serious plaguing problem in rockets we have really high performance, but we can imagine in a rocket typical rocket motor, the mean pressure in the rocket would be about 60 bar. And even if you have like a one percentage oscillation or two percentage oscillation, we still have about a bar oscillation and which is really loud.

And these rockets are not designed typically with any of those consideration, but there design for performance and incredibly performing machine can have severe instability problem, and can have loud levels of noise inside the rocket, weather it is solid rocket or liquid rocket or it can happen barium jet or jet engine. This can lead to severe vibrations that can have very severe structural problems, and we can have increased heat transfer to the walls, which can actually create problem to a walls you can have altering of burn rates, we can have thrust oscillations, very large thrust oscillations which can actually take a toll on the vehicle.

Also even the oscillations are very low amplitude the oscillations can actually perhaps create damage to the satellite because due to the loud the electronic which cannot take this kind of loud vibrations or some of the systems in the rocket may actually lock on to frequency. For example, navigation system may have vibrated the frequency and may get completely damaged.

So, any of these possibilities can lead to a serious compromise machine and we can have a machine failure, in fact those who have studied history of the U S space program would know that a fire engine had very severe instability problem. And America pumped in lot of dollars to fix this problem. The mass lander originally was designed with no alumina that we do not want to pollute the mass environment, but the lander the fire had very serious instability problem and in the end they used lot of aluminum in the rocket 18 percent actually to shutdown, the stability because instability problem was really compromising the program itself.

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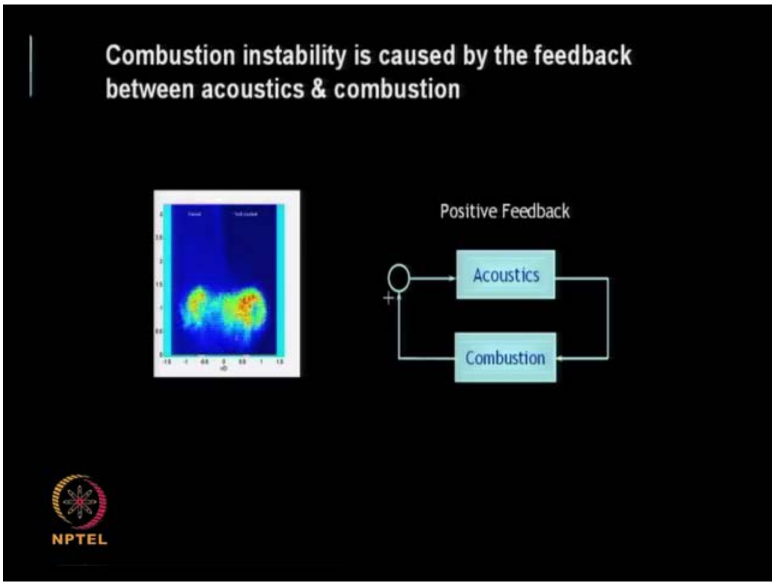

So, what causes combustion instability? Combustion can be unsteady phenomena combustion also make sound, in fact even if you see drive leaves burn you will see that they crackle and make sound. So, this sound that is produced by combustion if you if you look at burner you go to a tea shop and look at the burner, the burner actually makes a harms and makes sound, this in general in power plants or an engines this flames combustion is usually happening in a enclosed environment. So, what happens is the sound that is generated by the combustion, they travel to the walls get reflected and come back. And this sound when it comes back they affect the flame and flames become unsteady now the unsteady flame produces further sound, which goes and comes back and intern affects the flame further.

So, this kind of sets up a feedback where in the sound actually makes the flame unsteady and the unsteady flame makes sound. So, there is some kind of feedback between these two which positive feedback can be set in between the acoustic oscillation, acoustic feel and the combustion both in forcing each other. And this can actually lead to this problem called combustion instability or the more acoustics instability and this is a very, very serious problem. What happens is that when the instability occurs oscillations grow in the very large amplitude? Of course, they will the amplitude the oscillation to saturated the limit cycle either a low amplitude limit cycle, or it will be two loud that the hardware gets broken and so on.

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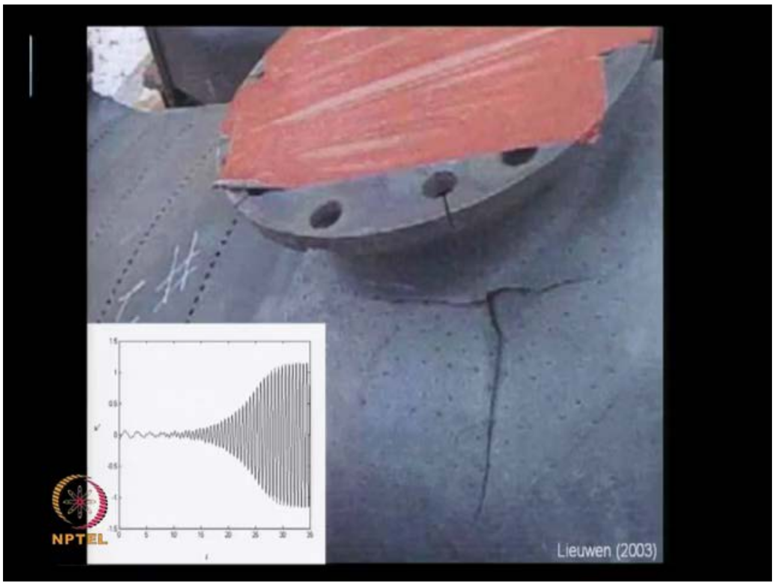

So, the oscillations actually you can see the grow and could reach limit cycle, but even if you have you can have large amplitude oscillation which can for example, destroy something like rocket engine or so on, but sometimes even we have low amplitude oscillation, these oscillation they are sustained and they are over a very large period. Now, this gas turbines which are producing power they operate for years and the low amplitude vibration itself can actually cause lots of fatigue to the ah the plans or the turbine blades or the pipes so on, and can cause crack. Here for this example a clack inlet to a gas turbine engine. So you can have such failures in gas turbine engines and in aero space program you can actually have a really machine failures and so on. So, this have been this phenomena has been non force some time.

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And the first engineer stuff is the V 1 bomber which called buzz bomber which was used in world war 2 by the Germans just used a pulse jet engine. Although we do not use this kind of a engines any more this is a demonstration of pulsating combustion or combustion instability, but here they are used in a sustain manner to make propulsive system. Although pulse combustions are still there now they find a applications in creating low carbon monoxide a low notes burners, and there is also lots of interest now in thermo acoustics engines and refrigerators. So what causes combustion instability?

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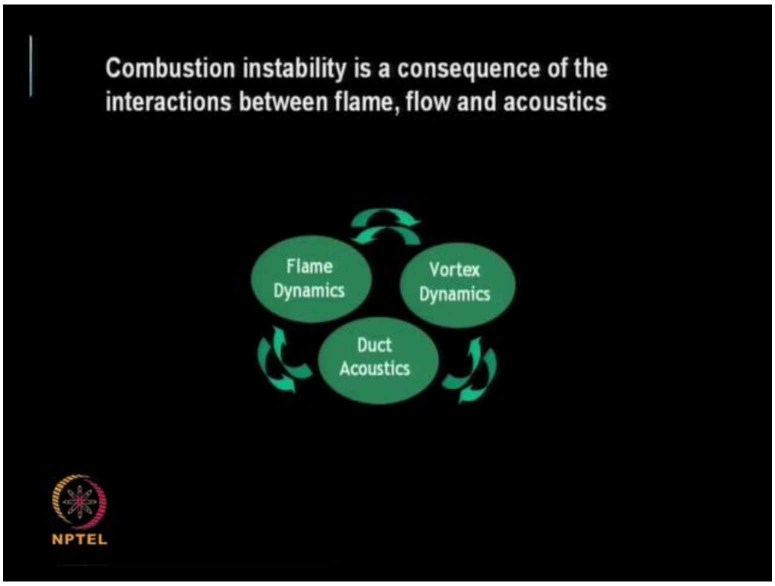

Combustion instability is a consequence of the interactions between flame flow and acoustics. So, there is three pillars or to it three icons to it there is flame dynamics that is how the flame responds to the flow and oscillations, there is what dynamics or fluid mechanics, which is affected by the combustion which is also affected by the acoustic oscillation. For example, in the case of burner which has voltage shedding in it in block body stabilize bond or something, the acoustic feel will surely affect the mechanics fluid mechanics will intern affect the combustion. And the combustion in tern affects the acoustic feel similarly, the vortex dynamic acoustic the affect the acoustic feel. So there is like a strong wake up link can happen between the flame, flow and acoustics which is what drive the thermo acoustic engines.

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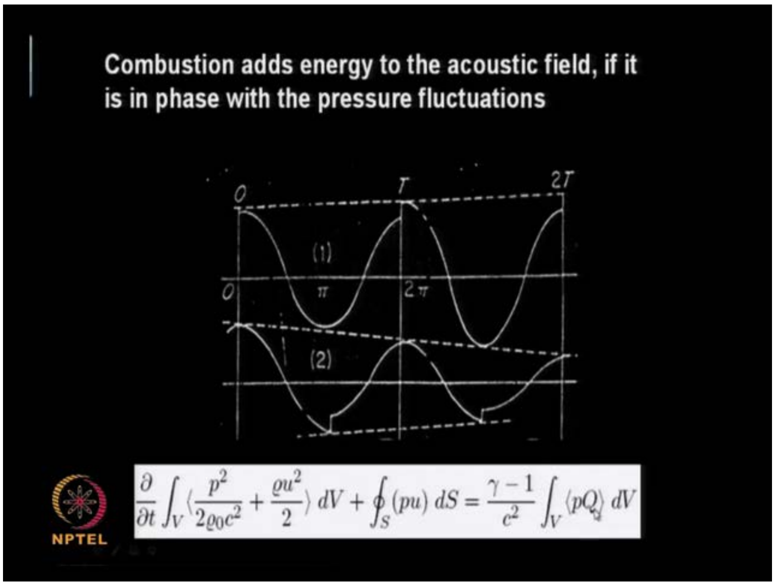

So, what causes instability, how does the energy come in to the acoustic feel from the combustion? Combustion adds the energy to the acoustic feel if it is in face with the pressure oscillation, so this was given by Lord Rayleigh in about more than hundred years back in the so called famous Rayleigh criteria so if you have a pressure wave which is there and if it can go on and on. But you know if you add heat when a pressure is at a maxima then the amplitude of the wave will grow and then again you add. So, in this hand waving crude example where we are talking about a instant heat release and if the heat release happens at the pressure maxima, then amplitude oscillations can go and you can keep on growing.

Whereas, if you actually add heat when then pressure is at minima, you can see that the amplitude with the oscillation will actually come down. Opposite is also true when you have oscillations and you add if you remove heat at the minima, then you can actually end up driving the oscillations which is opposite.

So, in general combustion adds energy to the acoustic feel if it is an face with the perception fluctuation the combustion oscillations are out of face with acoustic feel, then you actually have damping the combustion will take away the acoustic energy. So, this is called a relay criteria we can express mathematically as follows, rate of change of acoustic energy is dependent on the amount of heat that is added at this is proportional to the co relation between the acoustic pressure and the heat release, minus the losses. So, this we will derive in the subsequent lectures in a detailed manner. So if heat is added in face with the acoustic feel the oscillation will grow if it is added out if face the oscillation, the oscillations will decay that is the that is the basic criteria.

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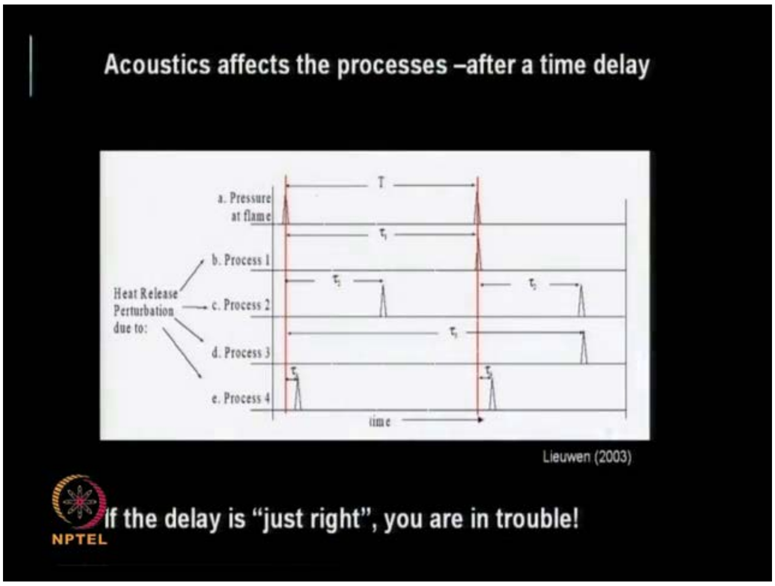

Now, acoustics affects various process in a combustion, any time there is oscillation for example, if you have the pressure going up and down that is the way acoustic oscillations happen, pressure goes up and down acoustics goes up and down. When the pressure goes up and down the pressure difference for example, that drives the fuel fluoride will be going up and down. So, if the pressure in the chamber goes up and down the flow rate can also go up and down because the pressure or the delta p, which drown the flow rate is going up and down.

So there is really a the thus really a direct affect from the acoustic on the various acoustic feel, on the various process. But the thing is it is not instantaneous it happens at a time delay lets say in this example of pressure oscillations, affecting the flow rate the pressure oscillation combustion take some time to travel to the injector. And then the injector oscillator flow at the injector has to oscillate, then the fuel and the air has to come to the combustor where the burning happens. So, there is a time delay the wave travelling here and the flow travelling back to the to the combustion zone so that is the time delay.

So, the various process similarly, there could be proper evaporation in a combustor or a vortex shedding in a combustor. So, all these are various process, so you can see if the pressure is oscillation shown by this pulse, various process and the combustor can be shown in they may be happening in the delay. So, if the delay is such that it happens like a one cycle delay then, then it will be face with the next pressure pulse and your oscillation can dry can be driven, but if it is such that your not a if you are not in phase with the pressure oscillation.

Let us say the delays are something else like in this process 2, 3 and 4 then you do not contribute to growth of oscillations, but here for example, the process one is in phase with pressure because the delay of the process one is same as the time period. And then you can drive the oscillations you can of course, also have complicated effect where you are delay may be the order of the harmonics of the combustor. And then you could perhaps end up driving the higher notes of the combustors. So, if the delay is just right you are in trouble your oscillation can be built up and just to give up a idea of the time scales involved.

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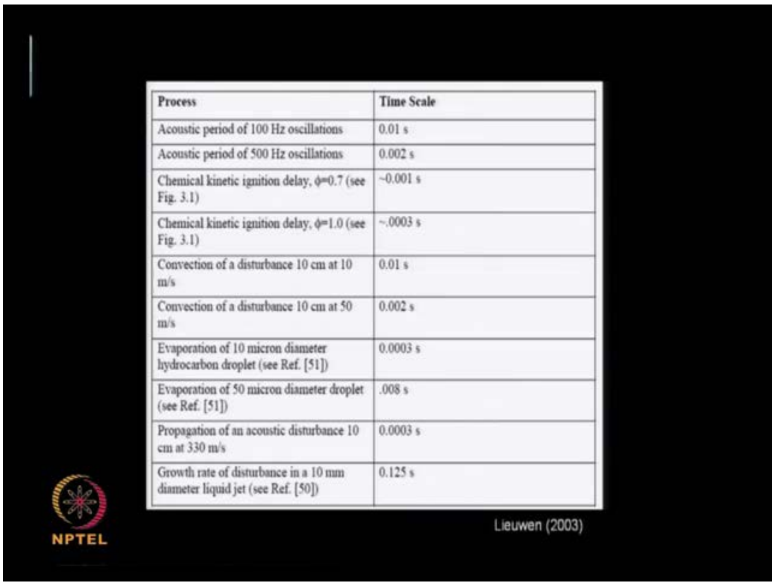

Process	Time Scale
Acoustic period of 100 Hz oscillations	0.01 s
Acoustic period of 500 Hz oscillations	0.002 s
Chemical kinetic ignition delay, ϕ=0.7 (see Fig. 3.1)	~0.001 s
Chemical kinetic ignition delay, ϕ=1.0 (see Fig. 3.1)	~.0003 s
Convection of a disturbance 10 cm at 10 m/s	0.01 s
Convection of a disturbance 10 cm at 50 m/s	0.002 s
Evaporation of 10 micron diameter hydrocarbon droplet (see Ref. [51])	0.0003 s
Evaporation of 50 micron diameter droplet (see Ref. [51])	.008 s
Propagation of an acoustic disturbance 10 cm at 330 m/s	0.0003 s
Growth rate of disturbance in a 10 mm diameter liquid jet (see Ref. [50])	0.125 s

You can see the acoustics period of 100 hertz oscillation is of the order of 0.1 second acoustic period of five hundred oscillation this is the order of 0.002 seconds chemical equation delay is the order of 0.001 second. If you have equal ratio 0.7 if you consider ratio of 1, you can say it is the order of 0.0003 seconds. If you look at a convention convention is a low phenomena it happens much lower speed the speed of the flow, but never the less the distance over which the convention happens is also very small.

So, the acoustic feel is spread over the entire combustor which is the order of meter or meters were the conventional. For example, from the fuel injected flames will happen over 10 centimeter, 20 centimeter. So, although the speed is lower the distance over which the convicted disturbance have to travel is also much, much lower. Therefore, there you end up having parity of times scale although the speed are very despaired. So, the change in the length scale so you convection of a disturbance of 10 meter per second over a distance of 10 centimeter is of the order of 0.1 second which happens to be the same as that of a 100 hertz oscillation.

100 hertz oscillation is there and the disturbance of 10 meter per second, travelling over 10 centimeter you are having a parity of time scale and you can end up having stability. The convection of a disturbance over 10 centimeter 50 meter per second happens to 0.002 second, which is in line with this five hundred hertz oscillation. The evaporation of

10 micron hydro carbon droplet is of the order of 0.003 seconds which is slightly shorter time skills.

So, it could work with a higher frequency a 50 micron droplet takes 0.008 seconds so it depends on the size of the droplet, what is the time scale involved in evaporation. And therefore, it could interact with a appropriate frequency if the length scale of the combustor is giving that kind of frequency. Propagation of acoustic disturbance of 10 centimeter 10 centimeter 330 meter per second this 0.0003 seconds is very short, but you know that in acoustics the length scalars matters the line of the combustors which is of the order of 1 meters, 2 meters. So, then time scale that is involved is 0.01 second kind of thing liquid jet brake up another thing.

There are so many phenomena happen and each have time scales and when the acoustic time scale come close to the time scale of this process. And then the delay of the process is of the order of the period of the acoustics then we are prone to tending instability.

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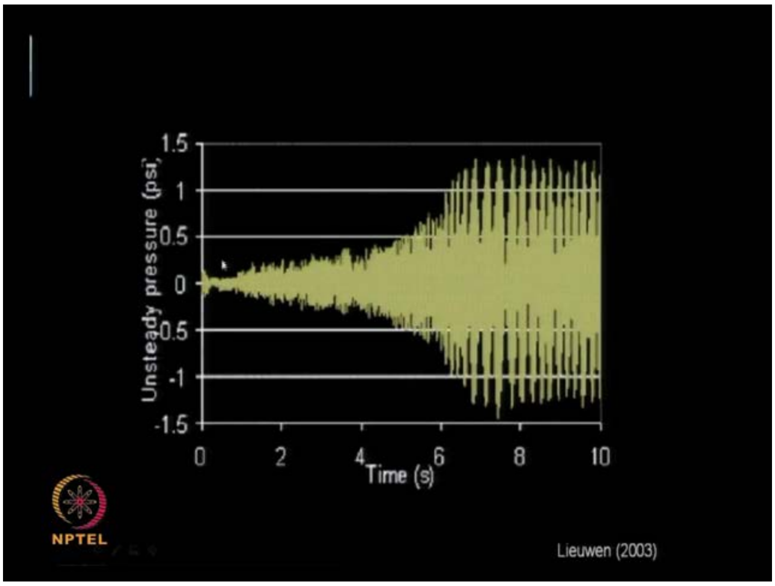

So typical instability evaluation looks like this you have amplitude small amplitude oscillations which grow, which keeps on growing and then they reach some kind of limit cycle. So, the oscillations first grow they go very rapidly they grow exponentially, but then they tale of amplitudes do not grow further because the as the oscillation grow you entering non-linear regime, and non-linear oscillation they tend to attend limit cycle.

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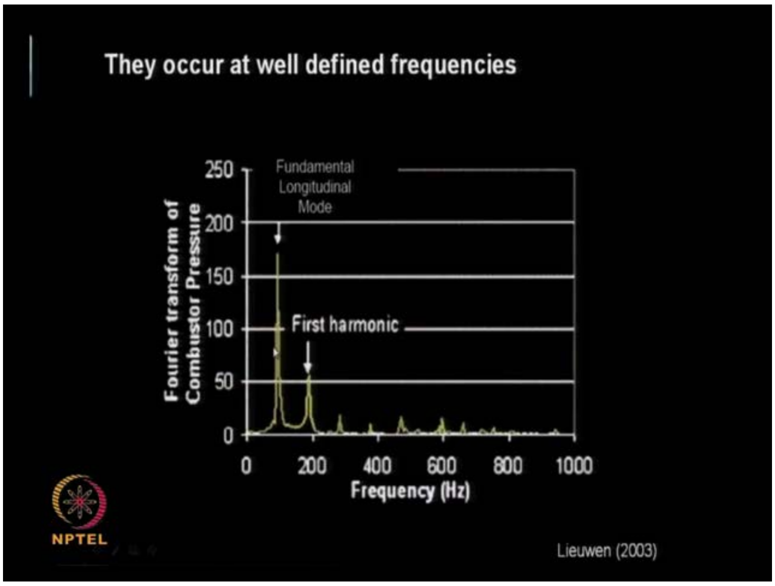

They are also quite tonal that is you have a crisp frequencies, occurring you have very crisp for your transforms if you look at it and the well defined frequencies are suppose to broadband sound. Broadband sound does have combustion when the instrument dosent happen that is generally referred to as roar or a combustion noise and so on.

But when the instabilities occur you have very precise frequencies hundred hertz or two hundred hertz some time many harmonics also occur, but they are clear tones. You know that tone would be like when you play flute you have crisp sound or when you play whistle you have crisp sound that kind of toner sound is what is usually there in instability.

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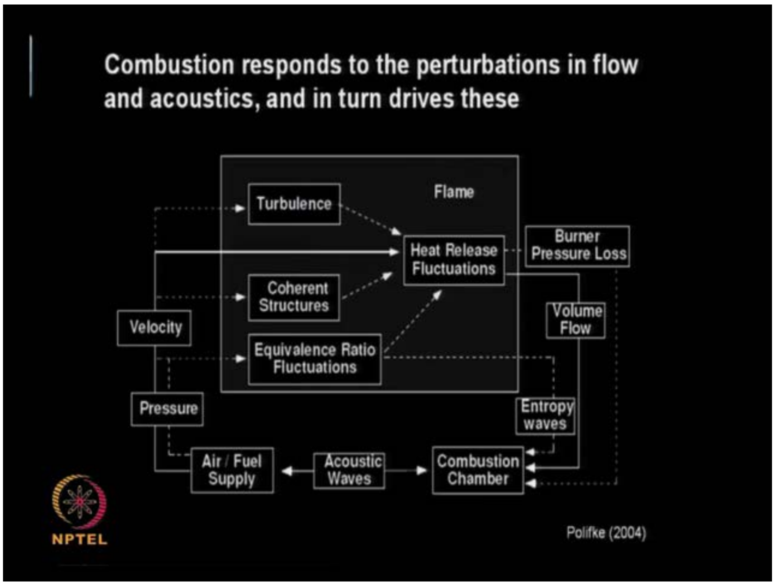

So, combustion responds to the perturbations in flow and acoustics and in turn drives these. So here is a picture of various phenomena that can combustor which I have borrowed from professor ((Refer Time: 24:03)) so you have heat links fluctuation and heat release fluctuation acts as a volume and source sound. So, they act as resource sound create acoustic sound waves and there are so many things happen the acoustic wave could affect the air or the fuel supply. And you can up if you have were pressure oscillation can actually change the flow rate of the fuel because delta p changes. If you have a air flows relations your flow rate of ah air itself can change because the velocity is oscillating and this can cause.

For example, equal ratio fluctuations because you are having a the fuel flow rate oscillate and air flow rate oscillate equal ratio itself is fluctuating, which will lead to heat fluctuation lead to further volume source of sound, which will keep building the feedback. You can have equivalent structure, which can modulate the heat release and heat release can occur certain periodic manner. And this modulation will make the heat release fluctuate all this is complicated, but the coupling with ah turbulent flow and the flame week link of occurs and so on.

And we can also have entropy ways which is also driving the sound, when the pressure wave come and go into a conversion diversion nozzle or something, where the flow is accelerating the sorry the if you have hot spots from the combustor, which is the entropy wave they come into the nozzle. And go through this accelerating flow they actually get reflected as a acoustics pressure waves. So, you can have combustion instability happening by this entropy, entropy waves which interact with the accelerating flow.

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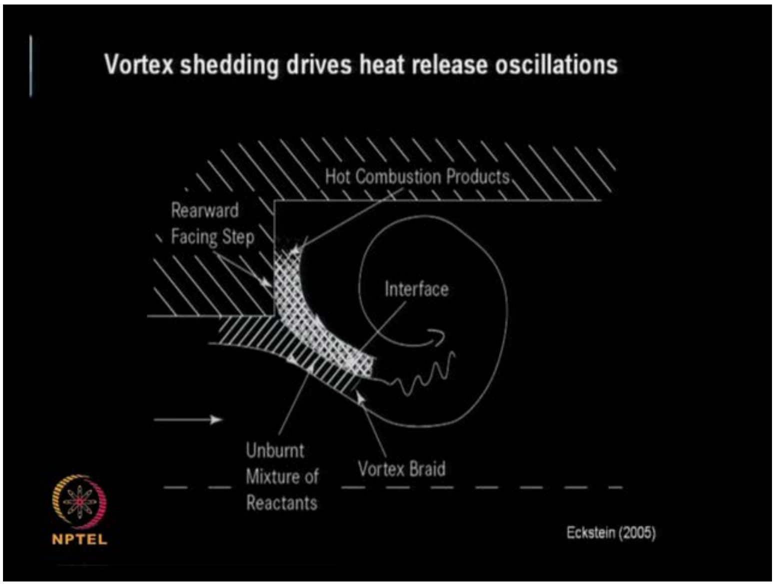

We can have vortex shedding driving heat release, why does vortex shedding combustor? In a typical combustor let's see gas turbine combustor you want to have flow happening at Mack number 0.1 or a 0.2 and the flame speed lamner flame speed of hydro carbons are typically of the order of meter per second or smaller, even if you are a turbulent flow you can get it up to a meters. But never the less we cannot hold the flame at hundred meter per second and so on.

So, then we have to have some kind of flame holding mechanism so a typical flame holding mechanism could be to use a backward spacing staff, and one would be to use a smaller and you have a vortex break down. And reason there can be a central toridal de-circulation and so on, where you can hold the flame or you can have like in after burner we can have v gutters where the flame is cell. So, all this is a mechanism for flame go flame holding basically some kind of flow separation happens and in this separated flow in the re-circulating flow, there will be hot ridicules which are their velocities. And this ridicules help to hold the flame so in a practice combustor you have some kind of flame holding mechanism, either under form of a solar which creates vortex breakdown or a backward spacing step or V gutter or or or block body something like that.

Now, any time you have this thing for example, if you would have backward spacing step you actually have vortices being shed at this step and the vortex shedding is a periodic phenomena. Now, you have a flue mixture coming typically fuel will be injected very close to the step. So you have a fuel mixture coming it comes with the vortex periodically comes and sheds and burning gets modulated by this vortex shedding, same thing can happen a block body combustor with a vortex, vortex shedding can periodically modulate the modulate the burning. In addition if you have using a sole flow what can happen is the ah the sole flow can have instabilities such as the precising vortex core and so on.

So the precising vortex core happens at it precise at certain frequency and therefore, instability can happen that frequency. So, in general the combustion the fuel packet comes with this vertex and burns and therefore, vertex shedding can drive heat release oscillation and this is one possible mechanism with which heat release oscillation fluctuation can give can happen heat release fluctuation in acoustic can give raise to heat release oscillation. Now, what happens is when there is sound and vortex shedding vortex shedding can get synchronies get locked to the acoustic feel and will look at this mechanism in more detail later course. So, this kind of coupling vortex shedding and the acoustics and the heat release that gives us instability.

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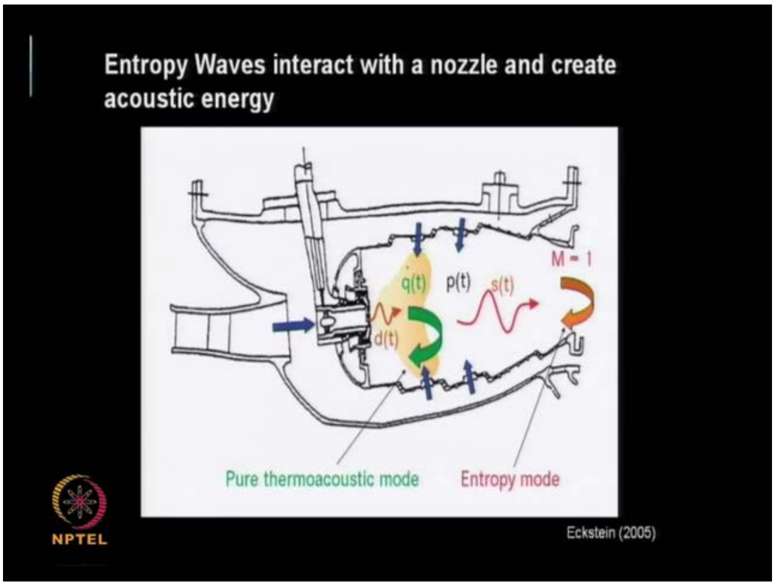

Another mechanism is the entropy mode so the entropy waves the combustion has hot packets of high or temperature sports coming, and they come in to the nozzle through which accelerating. So, when this entropy waves come they get reflected back as pressure and so you do have pressure oscillations coming back, and they can come here and again you can get a feedback loop. So, you can in addition to the pure thermo stick mode you should search for, but you can also have entropy modes which can also drive oscillations in a thermostatic engine, but this necessarily this happens in engine where the flow is choked.

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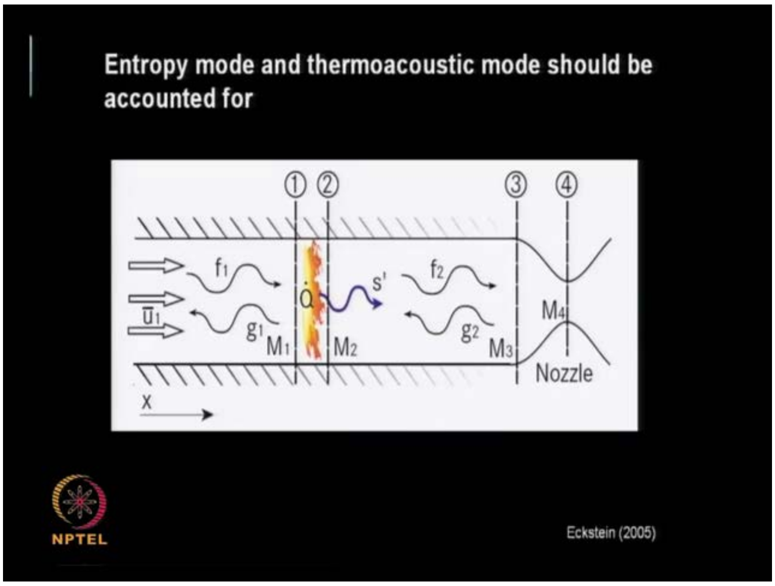

So therefore, entropy mode both the entropy mode and thermo acoustic mode should be accounted for an one should check for this things.

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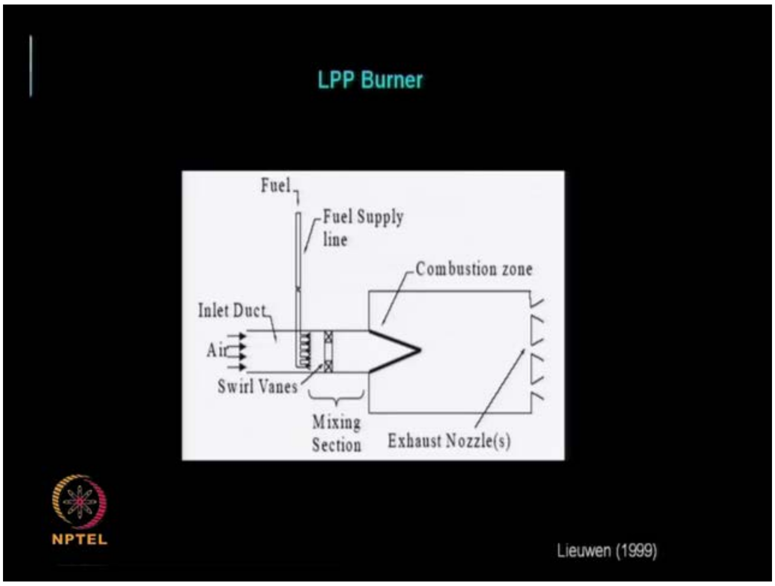

Now, I will give you example of another example I was mentioning earlier that when this ah lean preamp burners where were build as a solution for the acid rain that you want to make low nox burner. So, we wanted to you know you want to pre vaporize the fuel and mix it and you basically a premix combustor and so on, this developed lot of in instabilities when this was brought on operation. What happens is in a simple physical terms, you have some kind of fluctuations here they come here and the pressure oscillation cause a fluctuating pressure difference or a delta p.

So, the flow rate oscillates so when the pressure in the combustors low a rarefaction wave comes here. And therefore, the pressure delta p increases so the fluoride increases. When the compression wave comes the delta p decreases and the flow rate comes down. So, you have a oscillating flow rate so oscillation flow rate can actually lead to oscillating flow rate of fuel can lead to oscillating heat release. Similarly, when the oscillation come here the air flow through the air duct ah will oscillate to you have both simultaneously fuel flow oscillations, as well as air flow oscillations which intern leads to some kind of equivalence ratio fluctuations.

So, you have a pockets of fuel air mixtures they come here and they are coming of course, there is a time delay in time which acoustics waves are coming here and this mixture is convicted here. So, the there is some kind of modulation of equation ratio which results in the modulation of heat release rate, and this can intern get in phase with the acoustic oscillation and lead to large amplitude oscillation, this was big problem in the 90's when people developed this burners, which were to operate in the lean limit the lean limit the combustion, the combustion is very unstable. So, we have to go away from the linear limit to make it stabilize. So, equivalence ratio fluctuation are a big factor in driving instabilities in lean premixed premier priced burner in summary.

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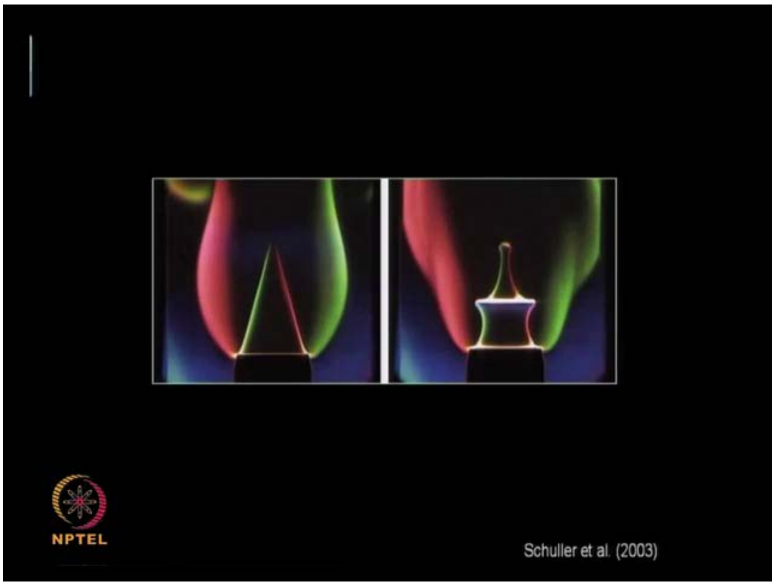

If you take a candle and you put in front of a woofer you can try it at home just take a simple candle and put it in front of a woofer. And let's play some music in the woofer you can see actually the candle flickers you know it respond to high frequency also, but low frequency you can observe with your eyes. Similarly, if you take a boons and burner flame and put a woofer next to it you will actually see flame in front wrinkle.

So, in a the oscillations and they cause the frames to wrinkle these are pictures borrowed from ((Refer Time: 32:25)) and sorry, these wrinkle happen in the wrinkle propagate up. And when in premix flame the heat list depends on their amount of flow that is going through because there is flame and premixed reactants, reactants in the air oscillations are coming through the flame. So, the amount of heat this depends on the surface area so when the wrinkle surface area oscillating. So, in the surface area oscillating due to wrinkles your heat release fluctuation heat release itself is oscillating causing heat release fluctuation.

So, you put a tube around the this boon burner you will hear very nice toner sound so it is a very simple device, but you can actually get very nice oscillating acoustic feel very very nice acoustic and this is at another mechanism for making thermo acoustic oscillation.

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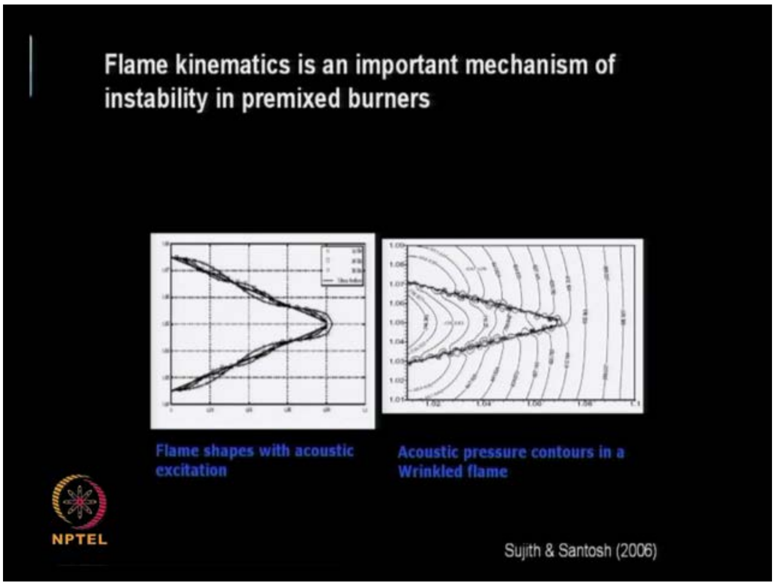

So, in some flame kinematics is an important mechanism of instability in premixed burners that is the flame wrinkles with the oscillation and the wrinkles cross the flame area to fluctuate and the flame areas fluctuating, the heat release oscillations fluctuates. So, how do we analyze thermo acoustic stabilities? So, we have to write some kind of equations and we have to solve them, so how do you study fluid mechanics we write conservations of mass momentum and energy. So, acoustics is some kind of fluid mechanics acoustic is a branch of a fluid mechanics those also derived from in the same way we studied fluid mechanics except that we have to write the unsteady equation, we write the unsteady equation conservation equations.

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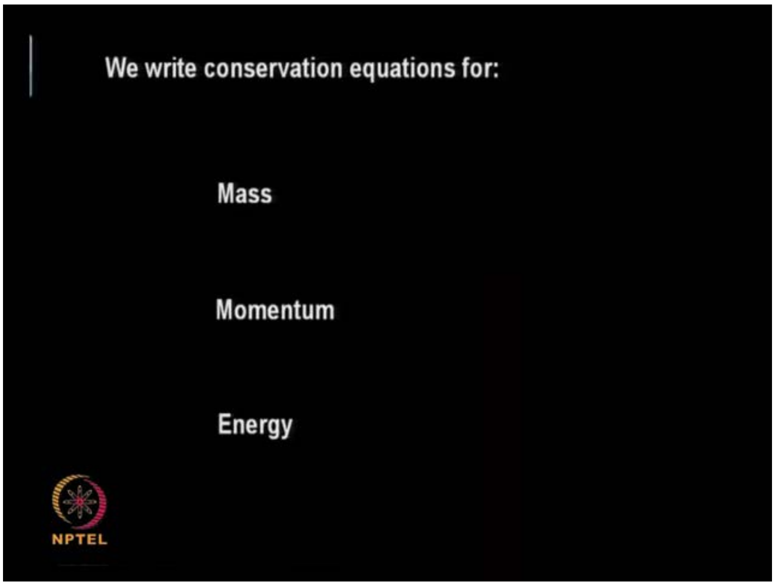

First for mass then for momentum and then for energy and then we work with these equations and derive a wave equation.

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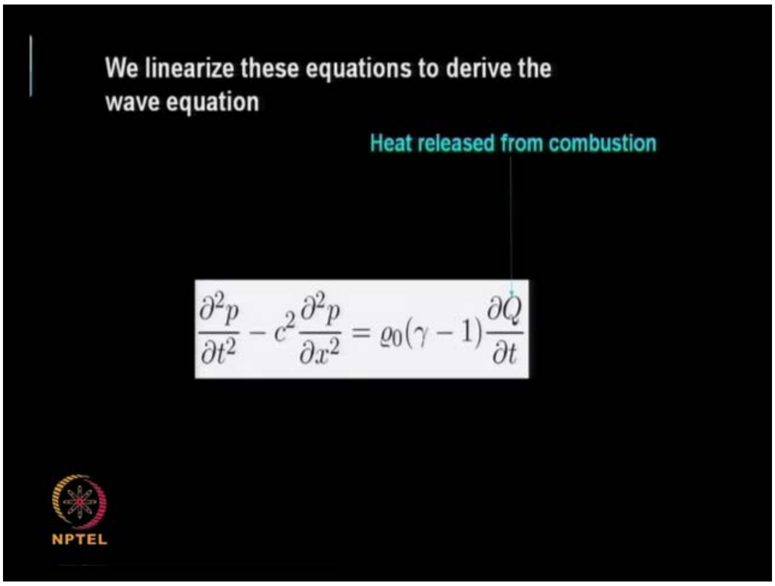

So, classically we linearize the equation and then we do some algebraic manipulations and derive the wave equation. So, in a typical classical wave equation the right hand side term is 0 that is d square p by d t square minus c square times d x square equal to 0 that is a classical wave equation that is been studied over and over for last few hundred years. Now, you have some kind of term and the right hand side there is a simplistic form, but here this term on the right hand side mod else the heat release from combustion. So, now the issue is how to model this heat release, we have to have some kind of model link or the flame and the effect of acoustic on the flame that causes the un study acoustic heat and that has to be input in this wave equation. And then you have to solve for it, and how do you solve for it?

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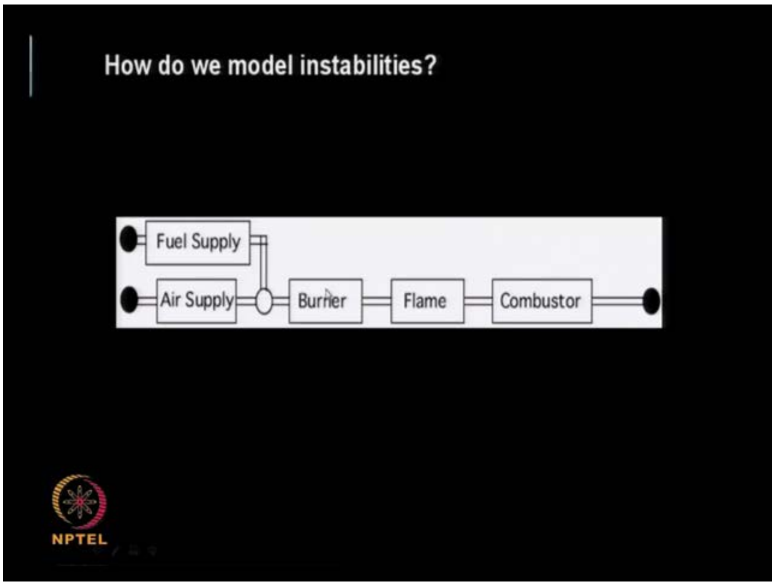

Typically in practical combustion it is solved using what is called network modules. So in network modules we have you have a typical combustor as combustors as various components like fuel supply, air supply, burner, flame and combustors. So, you write equations for each of this, so you have some kind of input output relation for the fuel supply which is described in terms of some kind of transfer function. So, you have transfer function for each of these element and you put them to gather, we will learn this in the later part of the course. And then we write a series of equations to gather and typically these equations are linear equation.

So, we then take this equation and solve for the Eigen values for the network model. And if the Eigen values are complex then we can look at the imaginary part of the Eigen values and then see if your combustor is going to be unstable or stable easier said than that, but we will go over it in the later part of the course.

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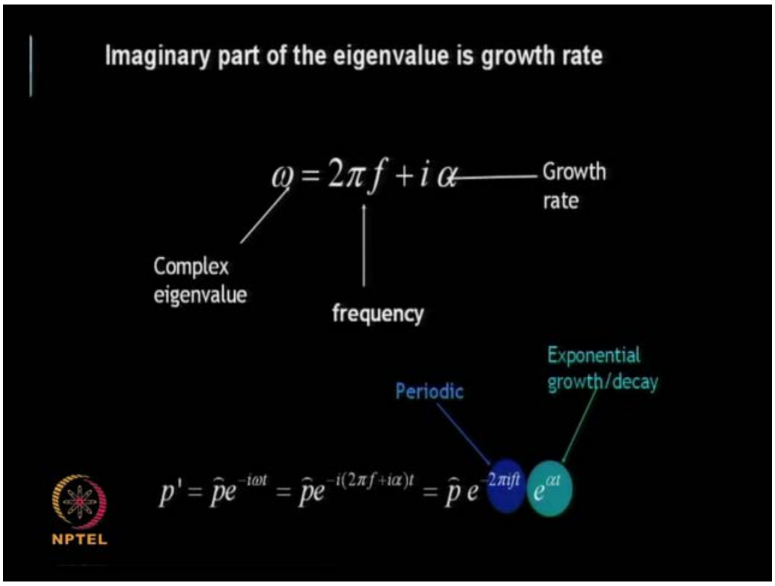

So, if the imaginary if the frequency is complex as I have described complex Eigen value happens then we have a the complex frequency real part and the imaginary part real part if you express omega a 2 pi f plus i times alpha. So, this f denotes the periodic component of the oscillations and alpha denotes the growth rate as we will see now. So, if you write p prime which is the pressure fluctuates as p hat e power i omega t so this we can substitute expression here from a omega as p hat e power minus i into 2 power f plus i alpha t which can be reconsidered as p hat times e for minus 2 pi f t.

So, you can see there is a periodic component then there is a so here is a i periodic there is no i here so this is a exponential growth or decay. So, this term in blue that is a periodic component, which is what the real part of frequency in decades and the imaginary part of frequency indicates the exponential growth or decay. So, in summary we can saw for the Eigen value look at the imaginary part of the Eigen value and look at the grown rate the growth rate is indicating, the Eigen vectors are going exponentially then you are in trouble because the there is instabilities Eigen vectors are decaying.

All the Eigen decaying exponentially there’s no problem it is going to be stable, but one of the Eigen vectors is growing exponentially then you have instability or you are prone to instability. So, this is the standard way of studying combustion instability using network model different people call it by different terms. So, we looked at how we looked at how instabilities occur.

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Now, we see whether we can suppress these instabilities so how do we suppress combustion driven oscillations.

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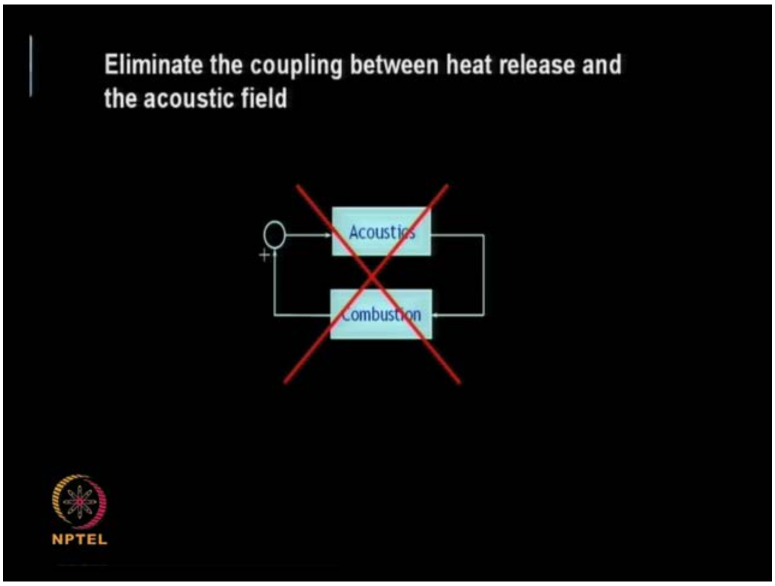

See first the two way you can suppress one is to eliminating the coupling between heat release and the acoustic field. So, I said that the instabilities happen because the acoustic feel is coming in phase with combustion there are positive feedback. So, if you can eliminate coupling between heat release and acoustic feel, that is a simple way of eliminating the thermo acoustic oscillations. Now, easier said than they done, but quite difficult and how do we do this so I mentioned about the time scales involved in the previous process.

So, let us say we have a injector which responds to acoustic oscillation and the character stick time are matching with the acoustic frequency. So, either you can change the acoustic time scale that mean changing the length of the combustor, which may be often very difficult because it is a big thing its already built you cannot change it. So, then if you want to change the diameter of the droplets or if you change the nozzle if you change the diameter of the nozzle, when you are actually altering the time scale of the droplet evaporation.

So, in this case that would be a easier solution or in the LPP burners that I described, you have a time delay dependence on the distance between the injector and the combustion time zone. So, one possibility to change the location of the injector or alter the injection velocities or change the flow speeds. So, all this will alter the time place, so you have to come up with some way to disturb the coupling between the heat release and the acoustic feel. And typically we have the idea of the time delays and you alter the time delay and the coupling will get disrupted, and typically it is easier to change the injector or something rather than change the combustor itself.

So, this is the this is the way of so when the oscillations you make sure that the oscillations do not come at all. Now, in order to practice this approach even before the combustors is design, that means you have good stability analysis to rules if you have them you can check for instabilities even before you fabricate the combustor. If you done have them if the instabilities are happening then you check for the time scales and alter the time scales.

The next possibility is to have damping so you can take the attitude let the oscillations be there and I will take them out by observing them. So, it is like in you know in studios you have perforated walls which will absorb the sound so you can have perforated liners, we use that in the engines or in solid rocket motors you have lot of aluminum in it. It solves 2 fold purpose the aluminum actually burns to form alumina, and alumina gives a very high specific impulse the performance of the rocket is improved, but alumina also serves a very important other purpose. That is these alumina which ah which is more turn and it it droplet moving they actually take out sound energy.

So, the droplet actually go back in force with oscillations and take of course, the sound feel and that is all they move when you have a oscillation and the droplet moving they are moving, they are taking the energy of the sound filed. If there are significant amount of alumina then lot of acoustic feel can be absorbed so these are classical practice used in space rockets, rockets are used to get to space to make sure instabilities do not happen in fact, typical rockets have something of the order 18 percentage aluminum loading. Although in missiles you sometimes may not be add aluminum because you do not want to have alumina, so that you can avoid the signature then those rockets will be more prone to instability. You can have other mechanism like putting baffles and so on.

We have a region of high acoustic velocity and put a baffle so that you take out the maxima you disrupt the acoustic feel somehow take away the energy out. So, the this would be so that like I said that two ways of removing the acoustic make sure that does not generate by disturbing the coupling between the acoustic and combustion. The other thing is let the sound be produced, but will upset all of it by using damping material.

Another strategies using distributed time delay is the various combustors like in annual combustors there will be so many burners, and we can have time delay associated with each of them to different. So, that they do not act all to gather in big bang, but they are act with the distributed time delay so you don't get a very strong acoustic feel because you have the affect being dispersed or distributed.

So, there are various ways of removing the stability, typically in practice in stability occurs then only people notice it. Although we are trying to design for combustor which without instability and some people we call them residence black magicians, who are who are called in when there is a instability problem comes and fix it. And this and then you will do some adobe measure and fix it and then in a what is wrong with it is any time you change something when the instabilities comes, and you do something remove instability takes a tool on the performance. And lot of combustors most large number of combustors have lot of instability problem, but the company is which make them they do not like to speak a word because it is very bad publicity so this is seldom talked about.

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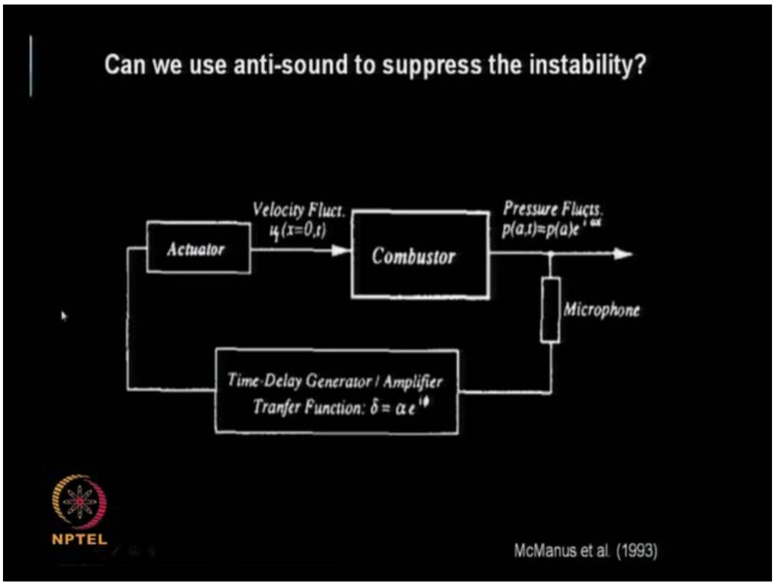

Now, the last part is about active control can we use some ideas of anti sound to suppress the instability. So, you must have seen bosh speakers and so on where you put them on and you sit in a aeroplane you do not hear anything or factories your speakers actually cancel the sound, and you reduce the amplitude of the sound. So, can we have some such concept in thermo acoustics, where you are having a active control. So, let the sound reproduce all actively suppress it, rather than having a passenger control is so far people prefer the engineers prefer passive control because they are more robust. The problem with passive control is each measure works for some kind of frequency range, not for all frequency range. Whereas the active control should be able to in principle suppress any sound, although it's far from deployed in the industrial sense.

So, it simple scheme given by mcmanus point seven candle in their various famous 1993 paper and progress in energy and combustion sciences is given below. So, the combustor you mess up the pressure in the combustor using a micro phone or a piezo electric fluctuate then you pass it through a time delay generator amplifier. So, you amplify this signal, but you also delay and you then feed this signal to activate it and actuator actually introduces let's say velocity fluctuations. You can have actuator simple simplistic actuator would be a loud speaker so which we will have diaphragm and it will introduce a velocity fluctuation in the combustor. And this will be introduced such that the original you had a stable combustor, but you put the fluctuation such that it cancels the affect of the instability.

So, have originally unstable system, but you have actually pushing the unstable eigen values to stable Eigen value so you make this activator vibrate such that the net system is stable. So, this is the concept in the very elementary sense, this is very simple to say, but it is quite hard to do it in a practice. In reality the actual combustors employ that employ and active control of combustor instability has very complicated mechanism, it is a very complex study by itself and it's very far from being perfected but, will take a look at it in the course. And so we can use active control to suppress the instability the very various forms of sophisticated control is that argues to suppress the some optic instabilities.

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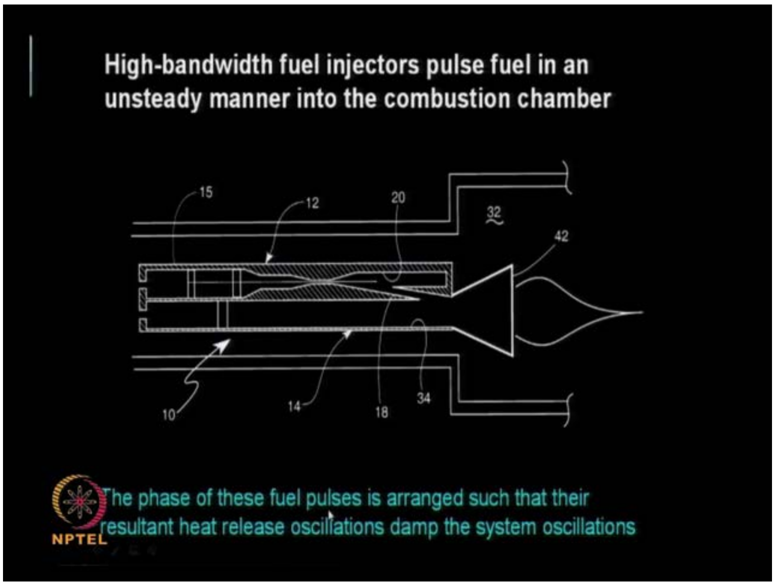

In reality we do not put loud speakers in the combustor because you know you can imagine, if put a loudspeaker in a combustor loud speaker burn off because it is a very hot style environment combustors. So, what you do typically you can have a second refill injection, which is pulse you can have. Now, you have very high bandwidth fuel injection pulse fuel in an unsteady manner to the combustion chamber. And you send the second refill it produce a second refill heat release. The phase of the fuel pulses is arranged such that you have the secondary heat release fluctuations, these fluctuations are out of phase acoustic feel and you can actually show that there is very small amount of secondary heat release fluctuations can actually produce serious amount of amount of damping in the system.

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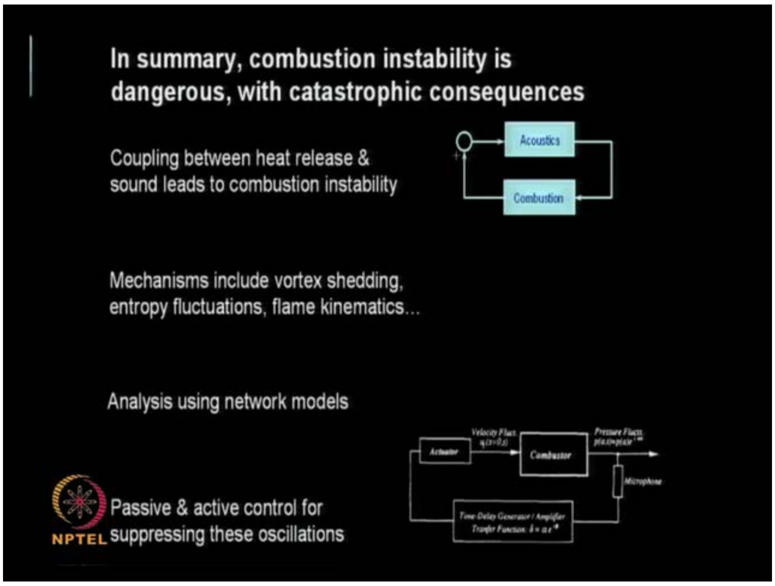

So in summary the combustion instability, in summary combustion instabilities very dangerous with catastrophic consequences, you can have a the whole engine being destroyed or you can have slow and slow failure by fatigue. We say that combustion instability happens between the because the coupling between the heat release and sound, and this positive feedback, is what is causing the combustion instability thermo acoustic instability if like this one reason why we study acoustics.

So, we have to have a good knowledge acoustic because what is involved is sound that is produced by combustion, how it interacts with the combustion. So, we have to study two thing that is why the first half of the course deals with acoustics, how does sound propagate and then we have to study, how combustion generate sound. That is how the acoustic feeds back with the combustion and produces, how do the combustion produces acoustic feed.

We discuss various mechanism in different combustions we have a different mechanism that include. For example, vortex shedding and entropy fluctuations, flame kinematics, droplet evaporation, unsteady drop evaporation and steady droplet evaporation there are various different mechanisms that cause combustion instability and we saw that when the combustion is in phase with the pressure. So the pressure oscillations affect the combustion fluctuation and there is a delay, and if the combustion oscillation are in phase with the acoustic feed in phase with the acoustic pressure specific you get the onset of instabilities.

And we saw that these instabilities can be analyzed you sing the so called network models, which are what is used in practical industrial burners. And we use we can use passive control of instability, which is what is used in the often in practice that is either do something to damp the oscillation by putting some muffler or liners so on. Or you do something to the injector or the fuel location or something and affect the coupling or we can also have a very sophisticated active control, where you use fine activators which are driven by controllers, which can actually affect the sound.

So, in summary I have given a introduction to what is combustion driven oscillation and how it occurs and propulsive systems and industrial combustors and so on. So, then about 20 lectures we will have on acoustics it is how we explain we derive the equation acoustic and study the equation and so on. And then the next lecture will be on how combustion produces produce a sound. In the next class we will speak about we start with acoustics we stick with what the very elementary acoustics and then we go on to deriving the equations of the acoustics, deriving the wave equations and the solutions for it so that is the end of lecture one.

Thank you.