Acoustic Instabilities in Aerospace Propulsion

Prof. R I Sujith
Department of Aerospace Engineering
Indian Institute of Technology, Madras

Module - 01
Lecture - 16
Interaction between Sound and Combustion

Good morning, we were so far dealing with acoustics, traditional acoustics, which deals with propagation of sound. So, today we are going to start talking about interaction between acoustics and combustion. And as oppose to the first half of the class where we dealt with prorogation acoustic, this is a, that was a fairly well established subject, now this we are going to speak about the subject where a lot of gray area is there. So, things may not be as crisp and clean as what it was in the first half of the class.

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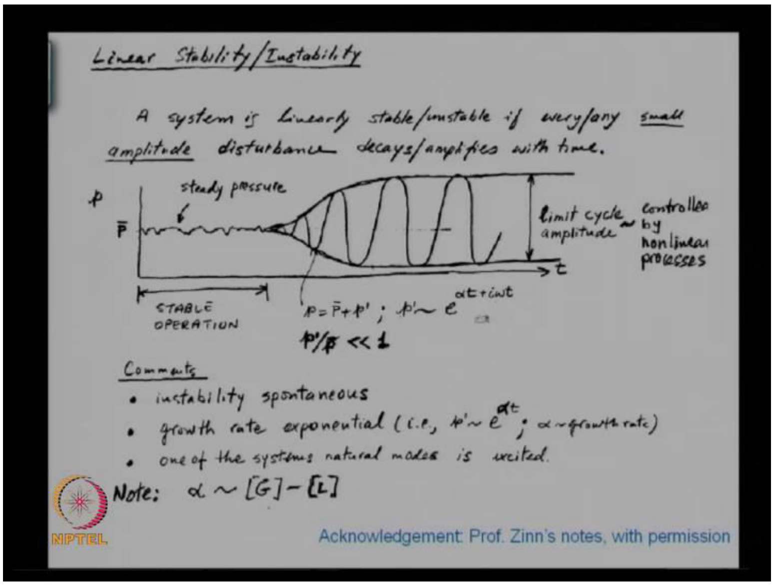

So, in general, when sound interacts with combustion, the effects will be somewhat unfavorable, mean unfavorable to the combusted. So, for example, you can have violent oscillations, which may cause problems to the structure itself. The structure will start vibrating and could be subjected to fatigue loading or if the oscillations are very violent, like in the case of a rocket motor, there can be catastrophic structural failure, there can be other problems such as increase in heat transfer.

So, you have increase in heat transfer, you have, which will put strain on the cooling system. You can have increase in mass transfer, for example if you are having instability in solid rocket motor where your burnings are made of propellant and your, you have a certain burn rate under cohesion conditions. But when there are oscillations, the burn rate can increase and once the burn rate increases, the mean pressures, thrust changes.

So, this will change the, this will change mission profile itself and you can end up with rocket having to, rocket going somewhere else than what we intended. You can have, in gas turbine engines you can have the turbine blades come off, bolts coming off, nuts cracking and so on. So, there are a whole bunch of related structural failures as well as the thermal failures.

There is yet another failure, which is, if you are talking about an aerospace kind of stuff like a rocket, the electronics, which is involved in the satellite is quite sensitive. If there is loud amplitude oscillations, the electronics will fail, so, and then the control goes off. So, your satellite can be spoiled or alternately, even small level of vibrations can affect the guidance and navigation systems and so on. So, all of this can cause different failures of different level and different kind. But some of the failures can be quite catastrophic, even in terrestrial burners like gas turbine, like I said, you can have the burn, burners crack with fatigue and so on, as well as injectors breaking apart and so on. So, it can happen even in furnaces and so on. So, in general the effects are undesirable although there is class of, so let me write this down.

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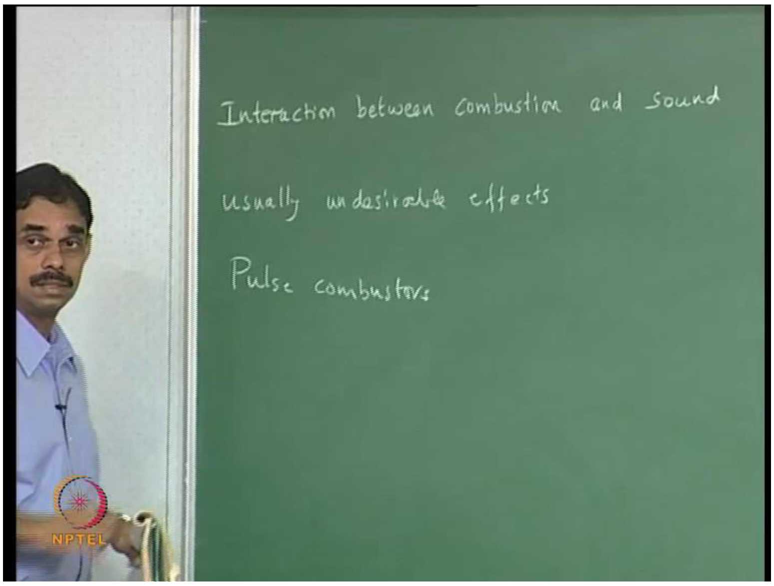

So, usually undesirable effects, but there is a class of combustors called pulse combustors. So, there we deliberately make the combustor pulse make sound and then use the sound for achieving certain phenomena. One example, very famous example is V 1 bomber, which was a pulse combustor, which was used like a jet engine and the other examples include the pulse combustor are used for home heating and drying slurries and so on; for example, in cement industry or drying milk to get milk powder and so on. So, you have loud oscillations and you try to use the oscillations to increase the heat and mass transfer and heat and mass momentum transport in this processes, which are energy intensive.

So, you can increase the productivity or consume less energy and so on. So, it is true, that while in general it is true, that we do not want the oscillation, that they are undesirable, there are some cases as in the case of pulse combustor where you actually try to set them up and try to use them for beneficial purpose of, for example, your incinerators and there you have pulse combustor, so that incineration can be faster and so on.

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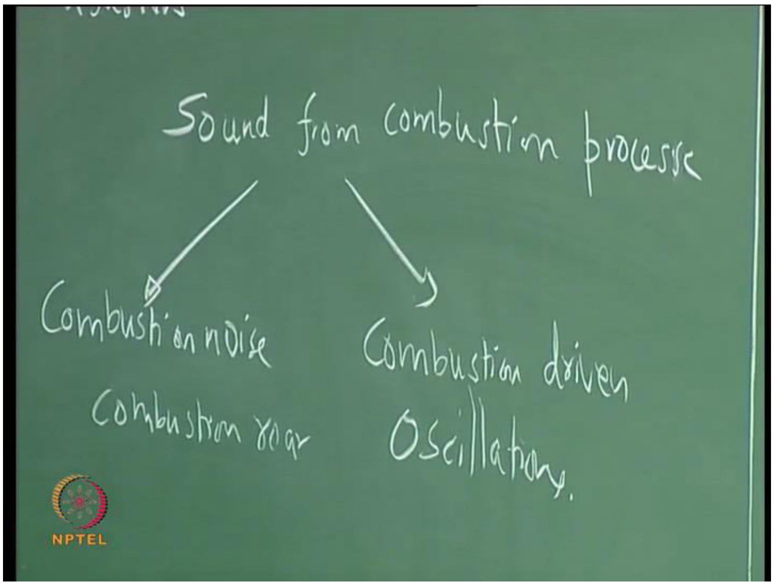

So, there are two types of sound that comes from combustion process. So, one would be combustion noise and the other one would be called combustion driven oscillations. This combustion noise is also called, sometimes called combustion roar because it makes kind of, roaring kind of sound, so this would be a broadband spectrum. That means, we do not have a sharp tone, whereas instability would be sharp tone; the combustion noise basically come from the turbulent fluctuations. And so, this really not giving rise to feedback between combustion acoustic, but just that the combustion flame generates noise.

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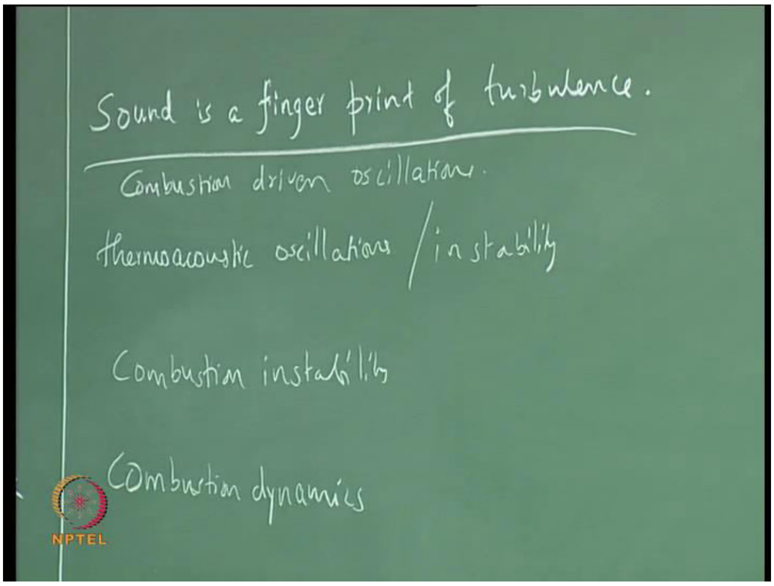

And one reason why people are very interested is that the sound is a finger print of the turbulence in the flame. So, you can actually measure the noise and try to quantify the turbine oscillations in a combustor. But when we talk about thermoacoustic oscillations, we are talking about a, about a feedback and feedback leads to very large amplitude oscillations.

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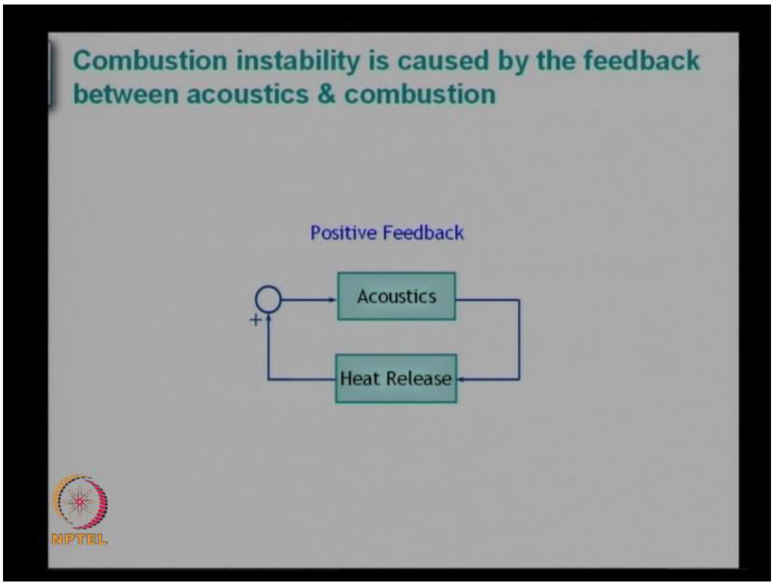

So, you have an acoustic field, which is and a, and a flame or a heat release rate, which is actually feeding back into each other. So, sound is produced by the combustion flame or the combustion and the sound actually travels to the end of the burners and often gets reflected very well, comes back and affect the flame. The flame produces, flame is unsteady and the sound makes the flame further unsteady.

Now, the flame produces more sound, goes, comes back again, influence the flame. So, this kind of feedback results in amplitudes growing and to large values. So, this is what is combustion stability as opposed to combustion noise, where there will be no feedback. The heat released generates acoustics, but this feedback is cut off, that would be combustion noise.

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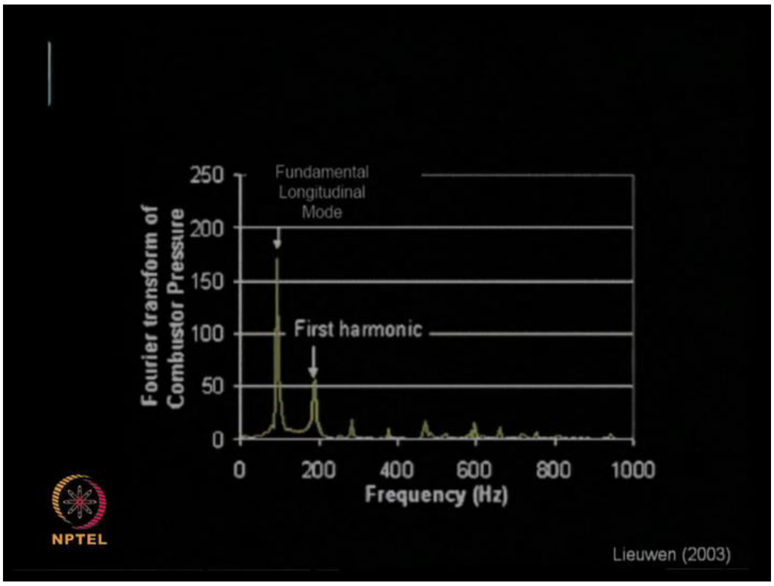

So, when I speak about spectra, so this is how the spectra would look like when you have combustion driven oscillations and there will be well-defined frequencies. It will be like sound of a flute or something, weather like nice tone or whistling as opposed to the combustion noise, which is like a roar. It has all frequencies. It does not really have any specific tone or anything like that. So, this is the first thing, main difference between these two.

And the second thing is that when you have combustion roar, although it is irritating and polluting the environment, combustion noise and all, that the noise level, the amplitude levels of the sound is not that high compared to what you get when you have combustion driven oscillations. When you have combustion driven oscillations the pressure amplitudes will be very high. So, this would be very high pressure amplitude, this would be relatively low amplitudes.

So, we are going to focus in this semester on studying this combustion driven oscillations, which are called the thermoacoustic oscillations or we can view this as a stability problem, so we can call it thermoacoustic instability or also called combustion instability. Some people also called combustion dynamics because instability sounds can be bad. So, this is more like a fancy name. Now, we are always trying to have ((Refer time: 10:18)). For a bad thing you do not call somebody dumb, you say that their intelligence is challenged or something. So, it is the same way, you do not call somebody short, you say that they are vertically challenged. So, similarly we say combustion dynamic instead of calling combustion stability, just so that it sounds very good; shareholders will like it.

Combustion is really a volume source of sound I we will go into the mathematical aspects of this later on this will give rise to fluctuating densities and then that will interact to produce fluctuating pressure and fluctuating velocities and so on. And so, it is the heat release fluctuations, which actually drive the oscillations in the duct and drives the acoustic field and the heat release oscillations themselves depend acoustic field; that is the whole idea about the feedback.

So, we can think of the flame as being located in a resonator and the flame is adding energy to the resonator. Of course, there will be some loss of energy from the resonator through the walls or vibration and so on. So, once you have enough energy being created and if the energy created the acoustic energy, which are added to resonate is more than the acoustic energy that is lost, then the oscillations will grow. And when if they are eventually balanced, then you can say, that the oscillation will stay at some steady level, which would possibly lead to formation of limit cycles.

Now, we can study these things in the context of dynamical systems theory and I will attempt to do that after some days, but initially we will take a classical view of things, which is more like an acoustic view of things before going into the modern dynamical systems view of things. I know, that many of you are doing physics minor and so on, so I think you, it will appeal to you dynamical systems way of doing things. So, first I want to give some introduction about certain terms.

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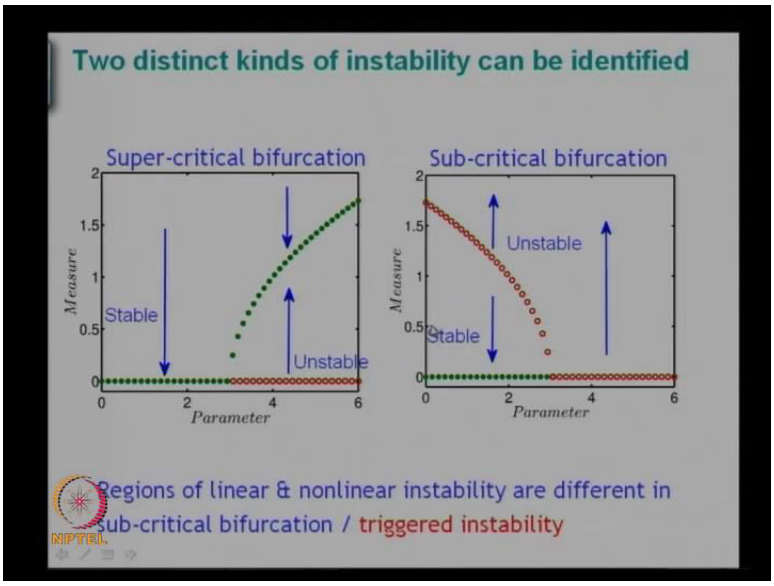

So, we can in general think of two kinds of instability. So, let us say we look at some parameter. This parameter on the x-axis can be equivalence ratio or mass rate or heat release rate, mean heat release rate or any such parameter thermal loading and the y-axis can be some measure; measure would means something, which quantify. So, pressure amplitude or velocity amplitude. Pressure amplitude will be an easy thing to measure and that can be used as a measure.

So, if you change this parameter, let us say, mean heat release rate or thermal loading or ((Refer time: 13:08)) ratio, if you increase it slowly in this region where my mass is, the combustor is staying as, I mean, at the, at the moment there are no oscillations, you had 0 amplitude and you come at some point where the oscillations get onset and the oscillations keep growing in amplitude and it is actually coming on very smoothly.

Now, as, so this would be one type of oscillations and another type of oscillations would be, you have, you keep increasing your parameter, you come till some place and when the oscillations became unsteady and then it went up and before this region, you have some kind of threshold. So, below this if you excite, let us say, you have some kind of initial conditions, you have some kind of noise or some initial disturbance if each of the disturbances is below some threshold, it comes back to this quite state. But if you disturb it as above, this you actually go to a higher state and there can be a, like a limit cycle or some other state on the top. So, you have a stable and unstable here. So, this would be a supercritical bifurcation as per non-linear dynamics.

I will give an introduction to non-linear dynamics and explain what is bifurcation and what is the kind of thing that you see here. This is actually, those of you know the subject, this would be half-bifurcation. So, this one where you, if you are below this threshold, you are stable, above it is unstable and beyond some parameters it is unstable. So, that will be called subcritical bifurcation, which is also in thermoacoustics or combustion stability language, it is called triggering instability.

So, in, when you are subcritical or supercritical there is a clear difference. So, when you have supercritical oscillations, the sound comes on slowly and steadily and keeps on increasing and here this, this is the region where you have linear instability as well as non-linear instability. So, if you have a small disturbance, it will become unstable. Even if you are a large disturbance, you will get to the same instability, whereas here with a large disturbance you can get instability right here itself.

But to the right of this even a small disturbance can make you unstable. So, there are different regions of linear stability and non-linear stability. So, this kind of difference is there. We will, we will speak about this in the language of the dynamical systems theory later on in more detail But I just wanted to say that there are this two types of instabilities. If you have any questions feel free to ask, have this like a conversation.

So, this is actually notes from my thesis advisor ((Refer Time: 15:44). He was kind enough to let me use it. So, traditionally we call it, there is a linear instability and there is a non-linear instability. So, a system is considered linearly stable when any small amplitude disturbance will amplify the time and the system will be, sorry I said wrong, a system is linearly stable if any small amplitude disturbance will decay with time and system is nearly unstable if any disturbance will amplify with time. You have very small disturbance, it can be infinitesimally small. Infinitesimally small means, you can make it small and smaller, but it is above 0. But you can, so you can mathematically write saying, that you can define epsilon and epsilon can be going like 1 over n and you can pick n large enough and infinitesimally small.

Second, pick n even larger than what you have and then you can pull lots of theorems about what is infinitesimally small and so on. But I hope you have an intuitive understanding what is infinitesimally small. It means there is some disturbance, which is non-zero, but it can be as small as you want to be. If you want to put 10 power minus 25, 10 power minus 100, that is fine; 10 power minus hundred thousand or ten power minus billion or whatever, there is no problem. So, that is arbitrarily small or infinitesimally small.

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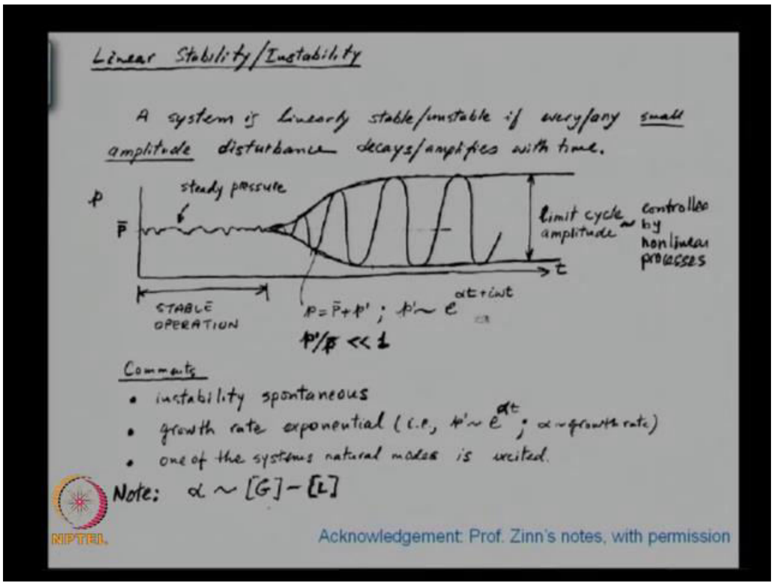

We can start from an arbitrarily small disturbance, but the oscillations will come on spontaneously and eventually. Of course, it is unlikely, that the oscillations will keep on growing forever because eventually a non-linear processes, as the amplitude keeps growing the non-linear processes will become important and then this unbounded growth may not happen. It is like economy, it can grow forever, I do not know, and after some time you will stop getting, I mean non-linear, this will come into.

So, if you are have having E grade and if you study hard you can get a D; if you study hard you can get a C; even harder, you can get a B. But you get a S, maybe one at this, it may not be very linear and there is no grade beyond S. So, that is, that is it. So, it is not like if you study 10 times what you study to get A, you get some S double plus because such thing exist, does not exist. So, eventually the oscillations can saturate off in because of the definition of non-linear definition of grades. So, it is the same way here the oscillations can taper off to a limit cycle oscillations.

So, we think of what pressure you can have, mean pressure. Just like we defined in the case of acoustics and you can have a mean plus the fluctuation and we can plot the fluctuation and see how the fluctuations go and the fluctuations will go like e power alpha t, that is hypothesis and we will see whether it likely grow like that or decay like that. And in general, we will exact mode, which are close to the natural modes with that and this growth rate will depend on the gain minus losses. So, the flame puts in some energy into resonator, there is always losses and whatever is the difference that is what is driving the sound.

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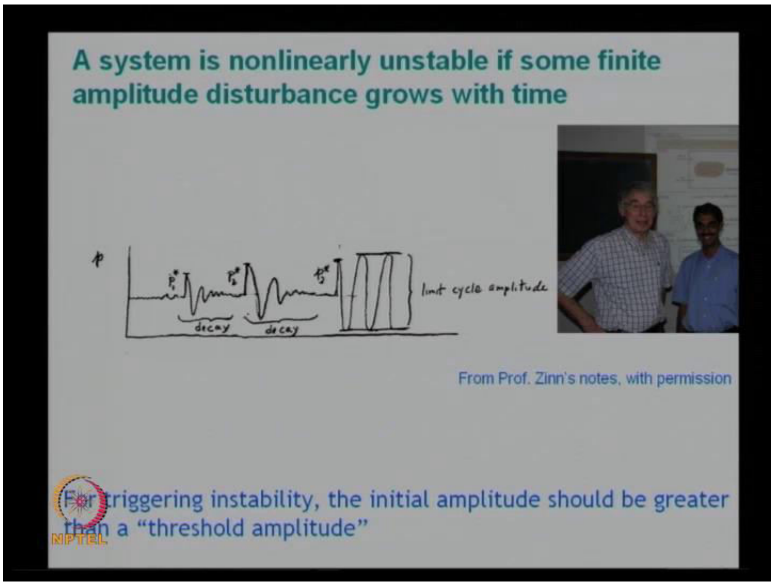

Now, I must say that the triggering instability was seen in rockets in 50s and 60s and so on when there was a cold war brewing between America and Russia and lot of work was done. And of course, you probably know, that the dynamic systems theory kind of where subject became hot in 1970s and probably in 80s theory was kind of well-established and so on. But this combustion instability was there before that and people were studying it. So, in those days they did not have terms like subcritical half bifurcation and so on. So, the term was that triggering instability that is what they called.

So, a system is nonlinearly unstable if some finite amplitude grows with time. So, the keyword some finite amplitude, it does not have to be every amplitude, certain particular amplitude disturbances grow with time and it is enough that some of them grow, not all need to grow. And the other keyword is the finite amplitudes. So, we are not talking about infinitesimally small amplitude, but finite amplitude.

That means, you cannot keep on saying, I want 10 power minus 20, 10 power minus 100, it can be small or big, but it is not arbitrarily small. It is finite amplitude and for triggering instability the initial amplitude should be greater than that of a threshold amplitude. So, this is the way people viewed this subcritical half bifurcation in those days in this language. Is there any questions? You, no? So, there are different ways in which you can have heat release oscillations and I will give some examples.

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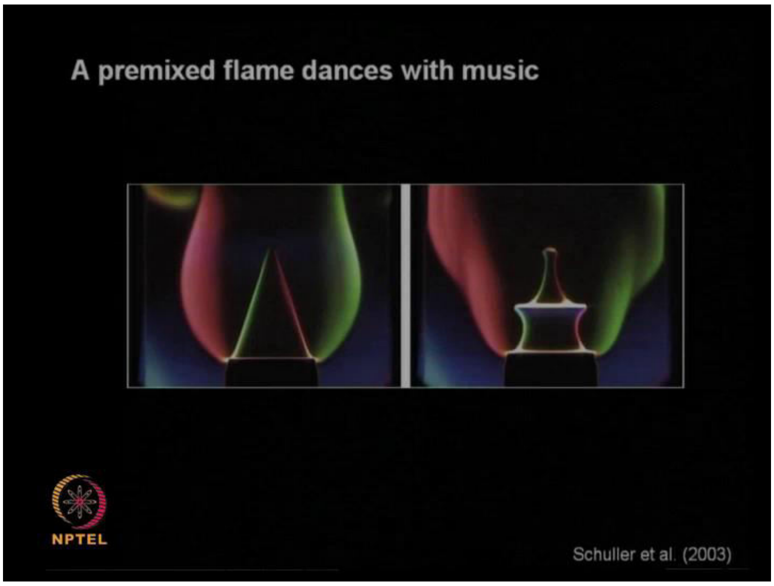

A very simple example is premixed flame. So, you can take a Bunsen burner and you can actually keep a Bunsen burner near a woofer, and you will actually see the flame moving back and forth. You can try this experiment, it is not dangerous or anything. You can also take a candle and put in front of a woofer and you will see it off dancing. It is a very simple experiment, not dangerous at all, you can do it at home. And the, so this is a steady flame and this is actually a, you are exciting with some kind of oscillations. This is a snapshot, it is shown in picture. So, it is premixed flame, will actually dance with this. Sorry?

Student: ((Refer Time: 21:27))

Ok.

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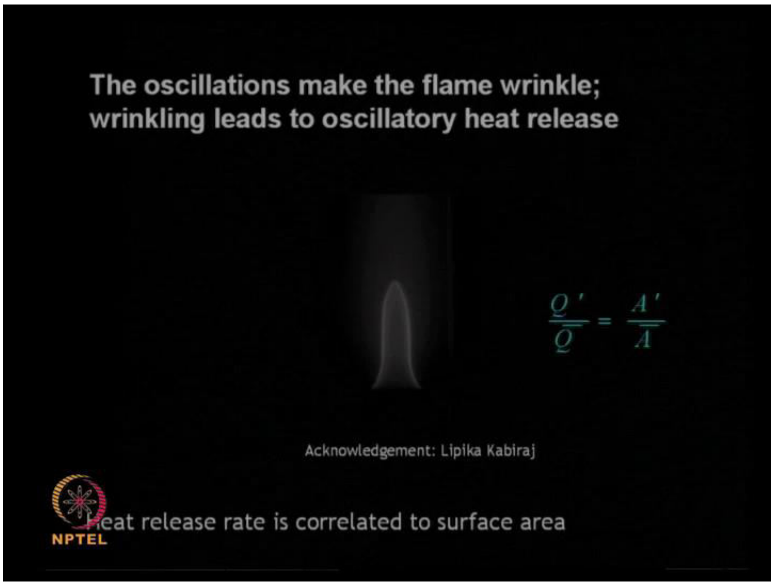

So, if you actually put a tuber on the premixed flame you can see this is, these are high speed images, which are because the lights you cannot see, I guess you can see. So, you can see the flame oscillating back and forth and so, what, there is no loudspeaker here. I am actually putting, there is a Bunsen kind of flame and I put a tube around it and then self excited oscillations are coming and the heat release fluctuation is coming from the area fluctuation.

So, in a premixed flame the amount of fuel that is burnt depends critically on the flame area, whatever crosses the flame area will burn. So, if you have, if the flame has more area, more fuel is going to cross. Just to give an example, if you have flame this way, you are having fuel or mixture coming out and whatever is coming out will burn. You know, if the same flame, if it was stretched to this, you have more area through which fuel or mixture can come out. So, more heat release will be there because more fuel, more of the mixture is burning. So, similarly if you actually have flame this way and, colored chalk, and if I am wrinkling it, so that is more stuff can come out.

So, in general the flame area, surface area is, I mean, the heat release proportional to flame surface area. So, you have more surface area, we will have, we will be burning more premixed fuel or mixture. For less surface area you will be burning less mixture. So, therefore, as the surface area oscillates the heat release rate will oscillate and this will give rise to a driving in the, driving to the acoustic field. So, that is what I have written in this formula here. So, in general, you can, I mean there could be other effects, but you can say, that under certain assumptions heat release rate fluctuation will be proportional to the, area fluctuate, area fluctuation.

So, heat release rate is definitely correlated surface area and the oscillations will make the flame wrinkle and the wrinkling leads to the oscillatory heat release. The oscillatory heat release drives the sound and the sound in turn comes back and wrinkles the flame. So, this is like a feedback process. So, this is one way in which you can have oscillations in premixed flames. Is it clear? Everybody sleeping here, no emotions today. So, let us think about, I will talk about a few different mechanisms. Before you start writing equations you can have lean premixed, pre web page burners.

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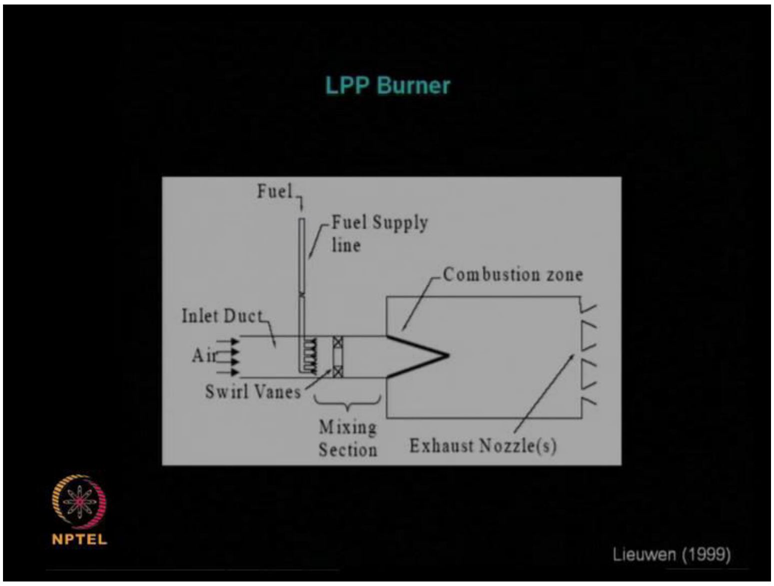

So, these where the burners, which were going to solve all the problems related to nitric acid rain, which was a big hot topic in the 1980s. All the liberals said, that the world is going to be destroyed with nitric acid rain and you have to, you have to stop the nitric acid rain and the combustion engineers came up with this strategy to reduce NOX, that is, lean premixed, pre-vaporize burners where they said, that we will burn very close to the lean limit, that way you have temperature is, very low temperatures and when temperatures are low, NOX production will be low, that is the idea.

So, we are trying to push it and trying to burn it clean. And now, what happens when this burners came and they are brought to site, I think they started developing very severe oscillations to the point, that like I said, blades, crane, turbine blades broke loose and bolts and nuts came out and air inlet pipes crack and so on. So, there was quite serious problems related to this, but this is not quite difficult to understand except that we do not expect it.

For example, I will give a very simple example. I think, maybe I already gave this. Let us say my grades are going down and I get scolded by my dad or mom and I decided to study. I tried to study very aggressively and grades are now going up, but now my girlfriend is upset with me. And now, because she is trying to leave, because she says you are studying all the time and I have nothing to do with you and then you try to pacify the girlfriend and then your grades come down again. And depending on you will reach some kind of, some level of oscillations and your grades also will reach some level of oscillations and so on. So, this is kind of a linear instability.

But then, let us say you can also have this more catastrophic problem. For example, this thing goes on and your girlfriend got upset the day before end-semester and she threatened to walk out or she already walked out or on the verge of walking out. And then, you got so upset, that you failed in the end-semester examination and then you got so depressed, that your end-semester in acoustics went bad and then all the other slots are also went bad, that is one possibility.

Another possibility is you stayed up all night crying about your grades or girlfriend, one of these things and whatever it is, depending on local conditions, and then you or boyfriend whatever, and this can happen to girls and boys, and then you stayed up all night and then could not get up in the morning and then the attendance went down. And so, this is like a new effect now coming into picture, and the attendance went down and then, now you are stopped from writing the exams and then you will get the new set of problems.

So, instabilities can happen in life also and it is generally because of coupling between things, we, if grades was separate, girlfriend was separate, there was no problem or boyfriend was separate. But generally, life, in life everything is coupled with each other and then you like this heat release in acoustics. If they were in separate places, there is no instability problems. You can have heat release in one place, acoustic field another place. No, the heat release is happening in the burner, the acoustic field also is there in the burner. In same way, in your life you have grades, dean, girlfriend, everything together and we have mom and dad, and they are all interfering with you and then you have this instability set in.

Now, sometimes instability may not set in. So, as the, as I mentioned during, when I talked about the bifurcation diagram, that when the thermal loading goes up, instabilities keep increasing. So, in life also, when things are cooled during vacation, if girlfriend threatens to walk out or you are not studying, there was not really a problem. But as you come closer to the stability margin, which is the day before end-semester or mid-semester, whatever and then the onset of instabilities can happen very easily.

Whereas, in some other play times there is no problem, but the same episode will die down, any disturbance may die down. And then, the, some, if it is quiz for example, it may be like a triggering instabilities. If they have disturbance above some threshold, then you can mess up the quiz, but below you can deal with it. But in the same, for the end-semester it may be, that any disturbance can mess you up or something.

So, I mean it is a very loose hand waving example, but I understood instability thinking about my life and how it can get messed up with the coupling with lot of things and this is the same way with combustors. So, and generally this you do not design your life for instability you design your life for performance or you say, I want to have the best grades, I want to get the best job, I want to study PhD with the best professor, I want the best girl or best boy as my girlfriend and boyfriend. So, you design for performance, you do not design for stability, but then when your instabilities just hits you. I give you one more example, which is really can be modeled this way. Any of you were athletes? Yeah, what do you do?

Student: Weight lifting

Weight lifting; what you do?

Student: Running

So, running and…?

Student: Playing games.

Playing games… So, let us say you want to do very well and you were really working hard, and you are really running in the morning, evening, doing weights and all kinds of cross-training, everything, and very likely, before the day of the event you can get injured. If you are really training too hard because the training actually pushes your muscles and you have to push them very hard, so that they crack and rebuild and so on. But they may crack beyond the level of rebuilding and you get and it is very common.

You speak to athletes and they will say, that many times I got injured just before the event. So, they always say, that you should not peak before too early and we have to build up such that just before the event you, because the difference between peak performance and injury is a very fine line. I guess you accept that. Right, I mean, if you go and lift something beyond you can, you can probably do it one time and that is probably is the day of the event and after that you probably cannot even, that is quite risky.

Now, let us give an example of instability in modern management. The modern management says, if you, if you want to get something done ask a busy person to do. So, the earlier management was, that if somebody had less work you ask him to do and the some other guy. Let us say Anveesh is working very hard, I would not ask her to do anything. This fellow is not having, he is having less work, so I will make him do. But now all of this has been thrown away and the modern management gurus with the tie and MB and all that, they are coming and saying, that this is all old wisdom. If you want some new to be done, ask the busy guy to do.

The busy guy Anveesh is working hard, I give her more work, she does even more and given even more work, she does even more and then what happens? She is peak performer, given award and all that and so on, and one fine day stroke. I do not mean, that you get this, but that is one, just one of the option I had. I have, some of my classmates are very extremely successful in their life. They have, I mean, all kinds of medals, decorations, like they are, they are having their own companies, they are having book written, all kinds of anything, you name it and so on.

So, one had a stroke and recently, actually he came to see me one day here in July and he came to my room and on the way he said, I got, I am coming in IIT bus, I am, something is happening to me come and help me and he had a stroke actually. Anyway, you, my classmates, neighboring room fellow and he does not drink or smoke or anything of that sort, but he is working very hard. So, that is what it is. So, if you push very hard and very hard and very hard, you can either get a stroke or you can get, you can go crazy, alright. You can get depressed and you can or you can, lot of things can happen you can get heart attack that. So, thus the many of asymptotic state which you can reach. So, that the thing. So, we always we are more greedy and we want more performance and our engines are designed for incredible performance. So, I think you have to phrase that correctly.

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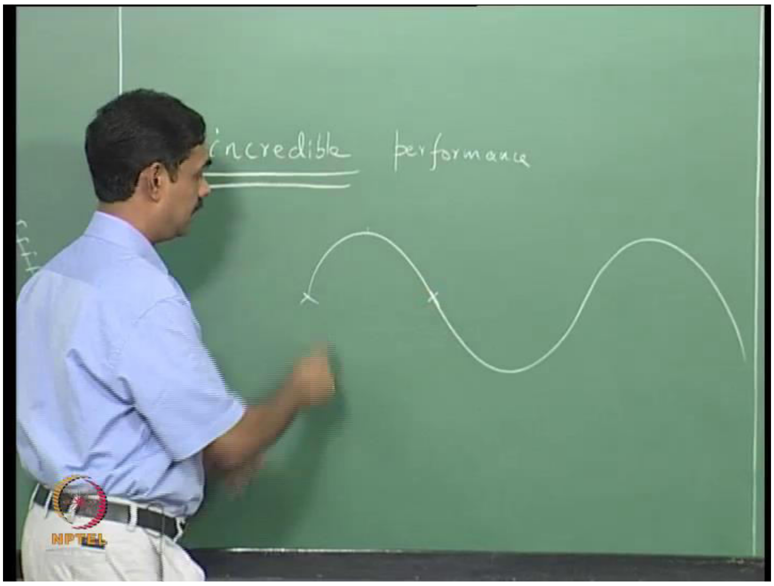

Our rockets are designed for, and I must underline this word, double underline the word incredible performance. So, we have machines, which can perform incredibly well, just like I said, the human beings who can perform incredibly well with their word. But there is a fine line and as you push the things, instability will come even in the engines. If you are, if you speak to people who are developing gas turbine or anything, in the initial testing these things do not turn up because they are not really pushing the engine to its limits, but as you push and push and push, you get, you get the instability.

So, instability is a fine line. It is just like injuries, fine line between performance and I mean, the, sorry, there is the fine line between performance, peak performance and injury, just like instability happens when you are pushing the power of the machine. So, what happens in this case? This, all the left wing liberals wanted the nitric acid rain to stop. You come up with this burners, which are supposed to drop their burning ((Refer time 34:14)) and once you burn ((Refer time: 34:15)) you have low NOX. There is no problem with any of that, but something unintended happen.

So, you have this fuel being coming into this line and you have air coming in. So, let us say there are some small fluctuations, small amplitude fluctuation, which you think inconsequential. They come and travel to the burner, travel to the fuel line and what happens? So, when, let us say the pressure is coming down, when a ((Refer time: 34:39)) will come, pressure can come down, pressure can go up, both can happen. When in the oscillations pressure is coming down what happens to delta p? You are, you are, line is certain delta p and now we are decreasing the exit pressure little further, so that delta p increases. When the delta p increases what happens? Mass flow rate increases.

Now, let us say we are on climbing up the oscillations. We are at a high amplitude oscillation, we are at the peak of the oscillations. So, now the survived pressure has a certain value and the exit pressure has come up, so the delta p has decreased. So, your delta p is oscillating, so the mass flux or the volume flux is oscillating, so your fuel flow rate is oscillating. So, similarly there are oscillations, which are travelling to the airline. So, when the velocity fluctuations are towards the, towards the right, then the air flow rate is increasing. When the velocity fluctuations are to the left, air flow rate is decreasing. So, both the fuel flow rate is modulating and the air flow air flow rate is modulating, so the equivalence ratio itself is modulating.

So, as a consequence, heat release rate will oscillate and when the heat release rate oscillates, you again drive the acoustic field. The acoustic field now gets stronger. The acoustic field now sends back stronger waves here, delta p increases even further. So, you have more fluctuations and more fluctuation lead to even more heat release. Even more heat release leads to even more strong acoustic field till these things level off at some limit cycle or something like that. So, I hope this was, for this mechanism, it is actually a request, the other mechanism is clear. Any questions?

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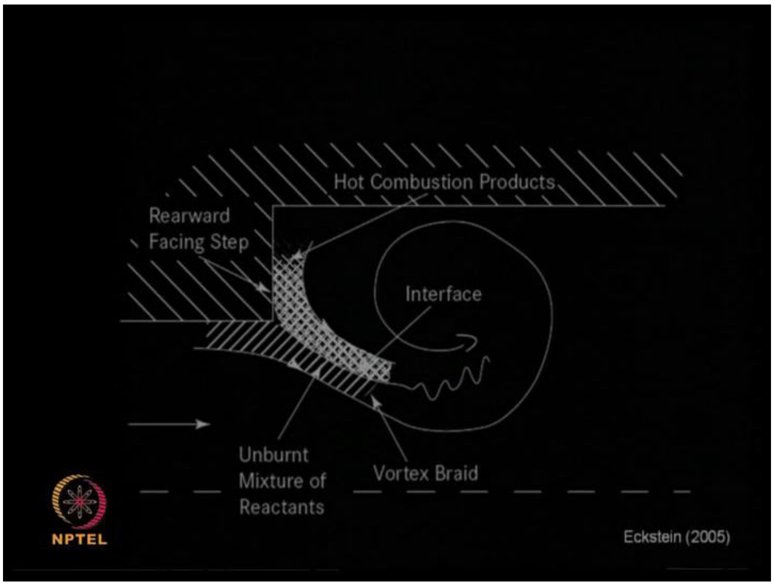

So, the other mechanism with which we can oscillate also, you have a hydrodynamic instability, which is a vortex shading, which is what is there in kind of backward facing step combustors or what is called dumb combustors and so the fuel. So, what is this shade? Now, you may ask why you have a backward facing step or why have a bluff body in a combustor to begin with. So, we want to hold the flame at higher speeds, which are much higher than the flame velocity. So, the flame velocity is in the order of…?

Student: ((Refer Time: 36:54))

Meter, lambda velocity is the order of sub-meter per second and so turbulent burning velocity will be meter per second, but we want 100 meter per second flow in the combustor or 50 meter per second flow in the combustor. So, we are greedy, so then the flame will be blown out. So, stop the flame from burning out. We have to have some kind of region where you hold the hot radicals or you need hot radicals, so that the heat can ignite heat and hot radicals. They can act as an ignition source and then keep the fresh fuel air mixture that is coming, burn.

But the problem is this bluff bodies, which hold the flame, they are actually shared vortices, and so there is a hydrodynamic fluctuations scale and there of course, the acoustic fluctuation scale and these two can come in close contact. This scales can match and we can have instability. So, the fuel air mixture comes in this bracket, which is brought by the vortices, comes and burns and again the next packet comes and burns, another packet comes and burns. So, you have some kind of periodic burning. Again, periodic burning leads to fluctuate in heat release, which in turn can drive the oscillations.

Now, you can also have swirl stabilized flames like, and a gas turbine. So, the swirl is another way of folding flame. So, swirl as a recirculation, sound in the middle, because the vortex break down, but the recirculation, so one actually process it. It has an instability and it will process and because of this there is some kind of natural oscillations that can come up in half the burners. You hold the flame with some kind of v-gutter and so that behaves in a similar way. It also share vortices and so on, you can have instabilities. Now, there is yet another mechanism with which instabilities can happen. You can have droplets that are, when you have liquid rocket engines or liquid fuel combustors you have atomization of the liquid fuel to droplets. Why do you atomize liquid fuel?

Student: ((Refer Time: 39:03))

Sorry, to increase surface area. Why do you want to increase surface area?

Student: ((Refer time: 39:13))

They are, the fuel has to, first fuel has to first vaporize and then react, so you want to have maximum surface area. So, when we have, so we have droplets and the droplets, first of all the atomization process itself can start oscillating when the perturbations in the chamber. So, you can, you have droplets diameter that diameter distribution that comes out of the automizer, can oscillate.

So, individually each of the droplet can actually move with the sound. It can start fluctuating, you can actually dance with the sound and the evaporation rate of each droplet can actually fluctuate with the oscillations plus this spray itself can fluctuate in addition. This can actually interact with the vortices and the droplets can go along with the vortices as the vertices role up and so on. And also, the droplets can cluster and decluster with the acoustic field. So, the lot of complication that can happen, but all of it can lead to unsteady heat release. So, there is a, lot of this mechanism that can lead to unsteady heat release rate. So, this actually leads to the setting up of thermoacoustic oscillations or instability.

So, in each of these cases, depending on the combustor and the mechanisms involved, you will have locally a different mechanism, but the unifying thing in all this cases is you have unsteady heat release rate driving the acoustic field and the acoustic field feedbacks into the heat release rate. So, the actual way in which the heat release rate is modulated, I give you several different examples, you can have premixed flame having wrinkles, you can have a vortex combustor where you have periodic vortices, we can have equivalence ratio fluctuations, modulation of fuel and air flow rate. And if you are having a diffusion flame, the mixing in the flame in diffusion flame, it is a mixing, which controls the reaction the heat release rate.

So, when the oscillations is the mixing between fuel and air streams can be affected seriously and therefore, this can lead to the flame being oscillatory and the heat release being oscillatory. So, you can have several different mechanisms in which you can have the heat releasing rate being affected. But the unifying thread is that there is oscillatory heat release rate, which dries the acoustic field and the acoustic field dry, in turn dries the oscillatory heat release rate. So, I hope this is clear.

(Refer Slide Time: 41:44)

Last thing I want to talk about today is combustion adds energy to the acoustic field if it is in phase with the pressure fluctuations, and this was given by Lord Rayleigh. It is there in his famous textbook, Theory of Sound and it is also there in his papers and ((Refer time: 42:04)) and so on. It was quite old, this criteria is called, now called Rayleigh criteria. Combustion adds energy to the acoustic field if it is in phase with the pressure of, pressure fluctuation. The heat release rate should be in phase with pressure fluctuations.

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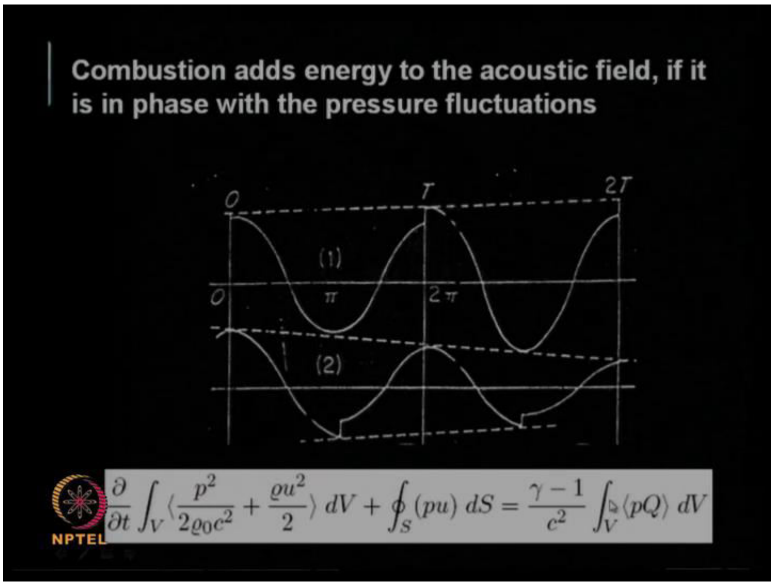

So, let us look at a very hand waving example. So, let us think about, you follow my mouse. So, there is an oscillation and let us say, added heat, which result in a temperature rise and a pressure rise and so on. When the heat release, when the, when the wave raised is maximum, so I had heat here and then the amplitude of the wave increases and then it comes here and again I had heat. So, it will increase further. So, there is kind of a growth.

Now, let us on the other hand say, that I added heat when the, when the pressure is the minima. So, what happened? The amplitude comes down because you are trying to go down, but you are trying to add heat, so the pressure will go up. So, the amplitude will actually come down and then again you come to the next minima and you add heat here. So, the amplitude will further come down. So, this way it keeps on dying down. So, the timing of the heat release rate or the phase of the heat release rate with respect to pressure is quite important. In the first case I added heat in phase with the pressure and I, the oscillations kept increasing.

In second case, I added heat release rate in out of phase with the pressure, it kept decreasing. Now, you can also have examples where I can cool here. If I can remove heat when it reaches the maxima it will damp and if I can add heat, sorry, yeah if here, if I remove heat when I reach the minima it can actually increase. So, I have to add heat when your pressure is, pressure amplitude is high. If I, if I, that will dry. If I take out heat when the pressure amplitude is low, that will also dry, but if I add heat when the pressure amplitudes is low, then I will damp the oscillation. So, it is like a swing. If you are swinging you have to push the swing. If somebody is swinging and trying to push the swing you have to push it in the appropriate time. The wrong time if you push, you can stop the swing. So, this is something like that.

Now, how does this relate to our acoustic energy corollary, which we derived and made a big deal out of it in the earlier classes? So, in that acoustic energy corollary we derived the right hand side was 0, if you remember. So, now this is the final result we will derive it in the next class. So, if the right hand side was 0, it says that the net acoustic energy will grow, decay if sounds comes in or sound goes out and if more sound is coming in from outside, then the energy will grow; more sound is going out, it will decay. But now what it says is the acoustic energy can grow if there is a correlation between pressure and heat release fluctuations.

So, if acoustic pressure is in correlation with heat release fluctuations, then this integral will be positive. If it is not in correlation, that if it is, if it is in phase, the pressure, this term will be positive; if it is out of phase, term will be negative. So, if it is positive, we have a, let us say in heat release rate fluctuations are in phase with the pressure fluctuations, this term will be positive and so this term represents the energy that is coming in or going out of the surface; in general, we have losses.

So, this term on the right, let us say, you move this term to the right, so this pQ term minus this term, that is the net gain minus loses because this is, this represents the amount of acoustic energy added; this represent the amount of acoustic energy, which is lost. So, heat gained, I mean, the energy gained minus the energy lost equal to rate of energy, change of energy, ((Refer time: 46:05)). So, this is a quantitative way of expressing Rayleigh criteria. We will derive that in the coming classes.

So, to summarize, so I, before that I have a question. I want you to think at home, what if you add heat like here a quarter period after the maxima or like quarter period before the maxima? Now, I am talking about that, will show nothing will happen, nothing will happen to amplitude, anything else can happen.

Student: ((Refer time: 46:42))

Yeah, phase will change, so?

Student: ((Refer time: 46:46))

Frequency will change; can you try to work out which way. We can discuss it in the beginning of next class. Let us, let us consider the case where you have, so let us add heat here and add heat here, see what is the effect on the frequencies? Your frequency will change. So, just think about it at home and we can discuss it first thing tomorrow.

So, in summary we said, that oscillations are in general not good for the, not good for the hardware except in the case of pulse combustor where you deliberately want the oscillations. You can actually have structural failure, you can have component melting or damage due to excessive heat transfer. You can have change in the burn rate, which leads to different thrust. You can have interference with the control system operations or with the electronics or destroy the satellites. So, there is a lot of ways you can have damaged the oscillation and you want to control the instability. So, we talked about linear instability and non-linear instability.

We spoke very briefly about supercritical bifurcation and subcritical bifurcation. I promise to speak a lot more on it later. We took a brief look at different types of mechanisms that can create fluctuating heat release and different ways, heat release state can have feedback from the acoustic field and then we spoke about the condition, the Rayleigh criteria where, which says that heat release should be in phase with the pressure for the acoustical energy to grow.

And if it is outer phase, the acoustic energy will decay. Of course, in general it is the acoustic energy will grow, depending on gain minus losses. So, in actual system there will be losses. So, there is some energy added with the p prime Q prime term, but there is some energy lost. So, the difference, if it is positive, you will add energy to the system. So, I will stop here.