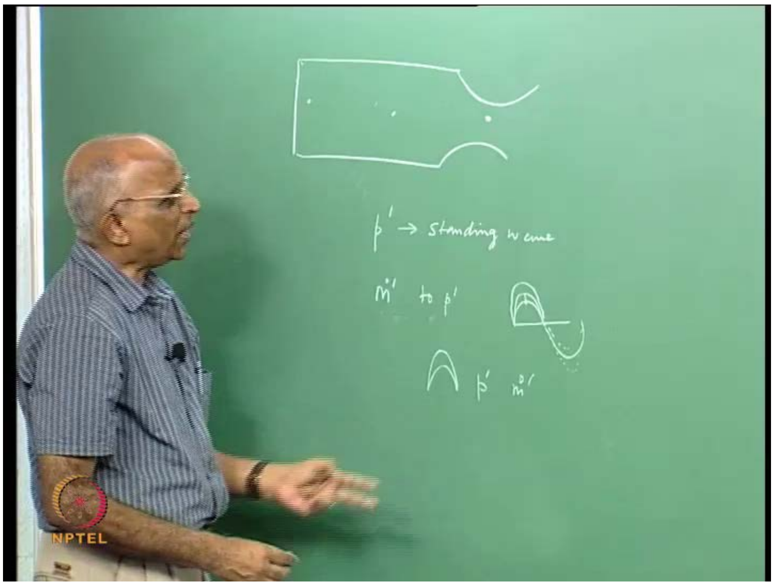
Rocket propulsion

Prof. K. Ramamurthi
Department of Mechanical Engineering
Indian Institute of Technology, Madras

Lecture No. #38

Mechanisms Causing Instabilities and strategies for avoiding Combustion Instability

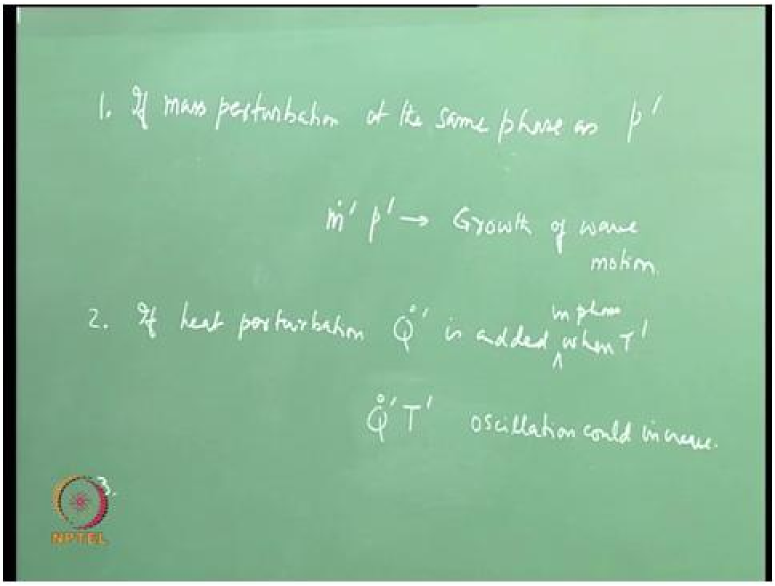
(Refer Slide Time: 00:17)



Good morning, we continue with our discussions on combustion in stability, and what we did in the last class was, we said in the, whenever we have wave modes in the chamber, you have regions where you have pressure anti nodes, you have pressure nodes you have pressure anti nodes, and this could depend on the harmonic what we have, in the fundamental I will have. Let us say this is the close end, I have pressure anti node, if this is the close end over here, I have a pressure anti node over here, and in between I have pressure node. If I have higher harmonics, I have a set of another a pressure anti node coming here, a pressure node here, pressure node here. So also wherever we have pressure anti node, you could have velocity nodes and vice versa. What is the inference the all this, let say at a particular point I have a pressure, perturbation p out of the, let say standing wave. I want p prime to increase, what can cause an increase in p prime. If I were to add mass let us say, m dot prime to p prime.

In other words I have the volume, the volume has a pressure p prime, I add some fluctuating mass to it, some mass to it, then automatically, that means I have oscillation p prime over here. I add mass at the moment of maximum p prime. Therefore, my oscillation goes up. I again add mass over here, pressure goes up. If I have were condensation or a rare fraction over here, at this point I remove I add I i I sort of add mass in the negative direction, that means I remove mass, my amplitude goes up, therefore the object of adding mass, when the pressure part maximum, can give rise to higher value pressure. All what I am looking at is, I am having a pressure perturbation p prime. If I add mass in the same space as pressure, then apparently, may be the addition of the mass perturbation to the pressure perturbation could result in amplitude of the pressure perturbation going up.

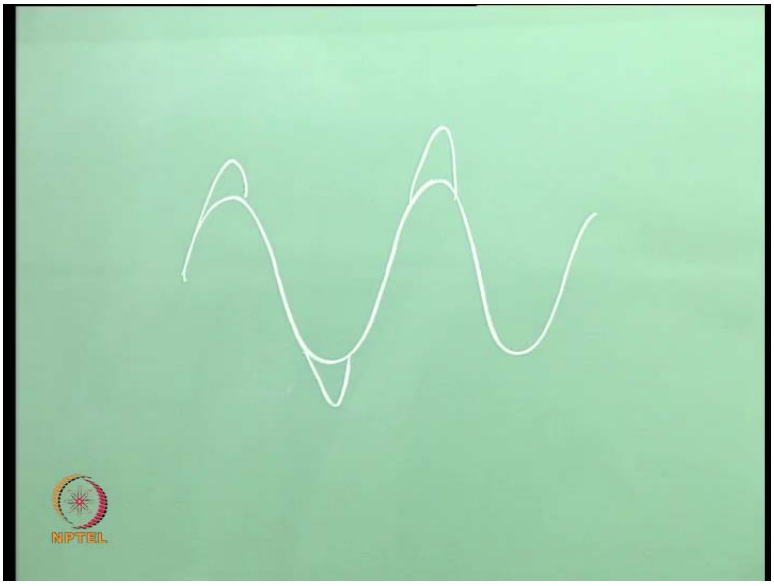
(Refer Slide Time: 02:28)



Therefore, I tell myself, first point I say is, if mass perturbation or I add mass, in at the same phase, as a perturbation in pressure, then the pressure perturbation is could increase. In other words, I am looking at the product of something like, mass perturbation; let us say m dot prime, and the value of p prime, which can lead to growth of wave motion. See instead of adding mass, let us say, the second point I consider is, supposing I have see we consider velocity changes, we consider pressure changes, whenever I have pressure changes, I could also temperature changes. Therefore, if I could add if he could be added heat perturbation. Let us say Q prime Q dot prime, is added when T prime is maximum or rather I have temperature fluctuation like this. I add heat when it is maximum, well my temperature fluctuation will increase.

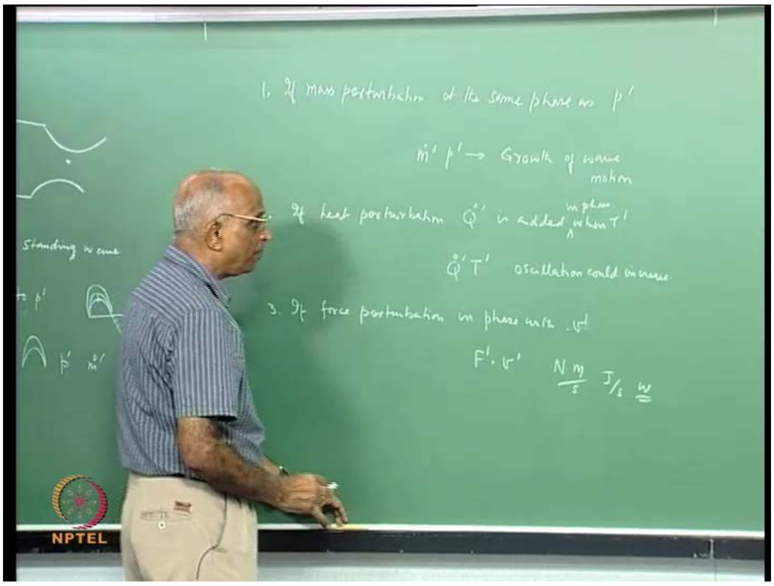
I add still further heat, my temperature fluctuation will increase. Therefore, heat perturbation, in phase is added, in phase, let say that it is important, when in phase with T prime is what will give me a higher value of this. Therefore, I can say my zoon of interest could also be, if I add heat perturbation, because in a chamber yes I am generating heat. I have has perturbation, rate of heat release perturbation along with, let us say temperature perturbation and this should also, if this is in phase with this, then the oscillation could increase. See we consider pressure, I consider temperature. Now when I say, third one, if I have velocity perturbation. Supposing we said well, my velocity could also be in this particular form.

(Refer Slide Time: 04:57)



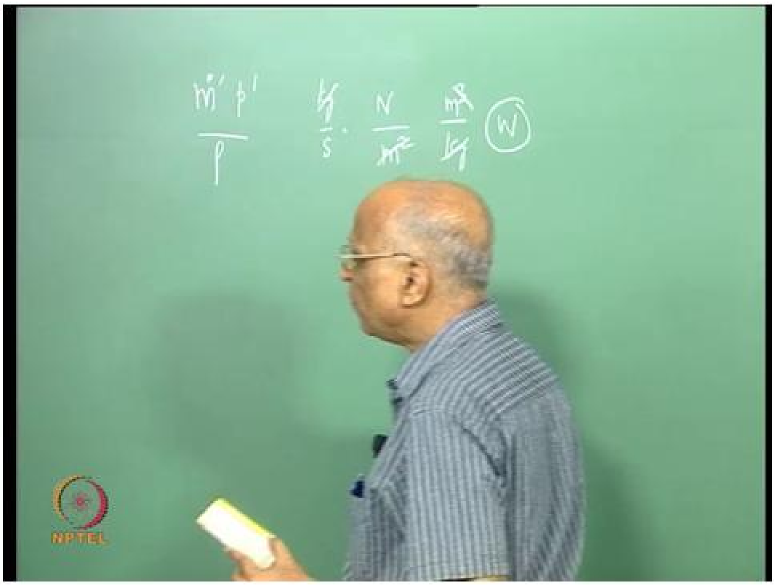
I could have velocity like this, what should I do if I have to increase the magnitude of velocity perturbation. Velocity perturbation is v prime, therefore if momentum, if rate of change of momentum; that means at this point I put more momentum into it, well could increase, here I remove, here I add; that means if the rate of change of momentum, could be put in phase with velocity perturbations, then my velocity perturbation could also increased.

(Refer Slide Time: 05:30)



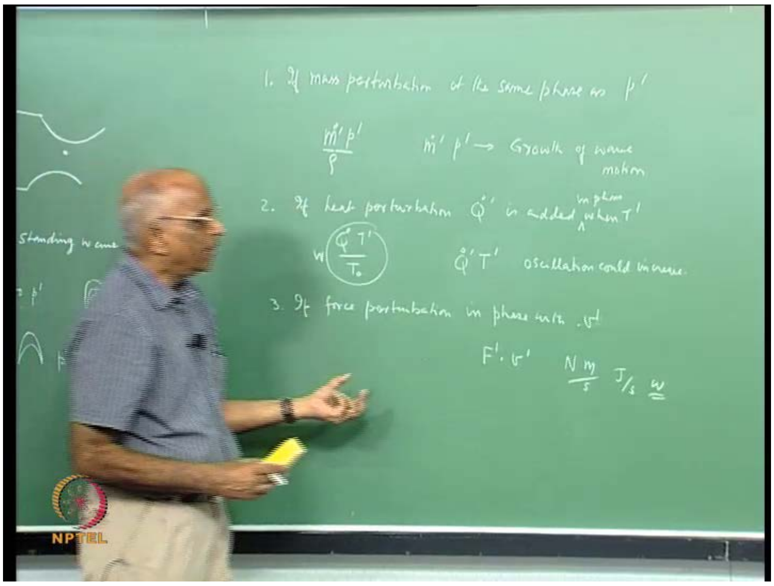
In other words, the third one I can put is, if rate of change of momentum. The rate of change momentum is force, if force perturbations could be added in phase, with velocity perturbation; that means I just say v prime, then the magnitude of v prime will increase, and therefore, the quantity there could be force perturbation, multiplied by velocity perturbation. Therefore, why I tell myself. Well pressure perturbations can increase, if I could add mass perturbation in phase with pressure perturbations. Temperature perturbation could increase if I could add heat in phase with this. Velocity perturbation could add, if I rate of change of momentum in phase with this. What is the units I am talking of, force, Newton, Newton meter per second, Newton meter per second or rather joules per second, this gives me the unit of watts. If I were to put a unit over here, what is the unit I get over here?

(Refer Slide Time: 06:47)



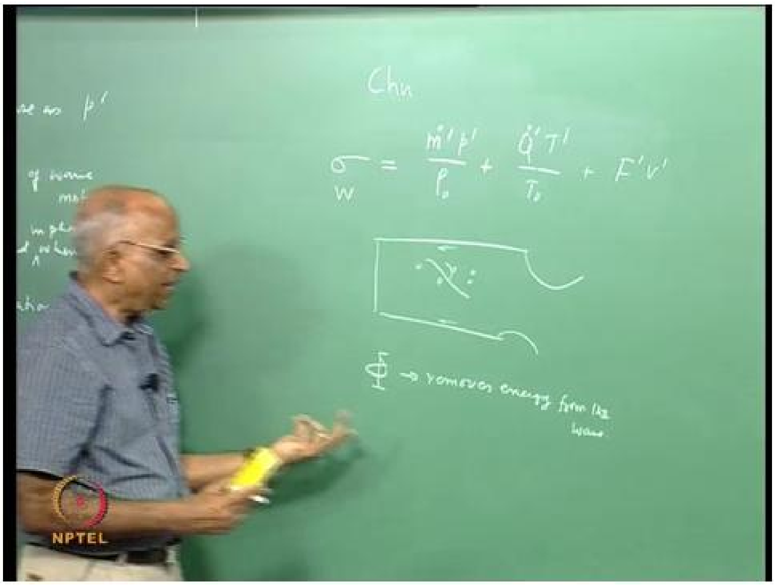
Let us put the unit over here for m dot p. m dot p is so much kilo gram per second. Now I have pressure here, Newton per meter square. And if I have to have unit of work, because basically I am doing work to increase the perturbation, then maybe I must divided by the mean density, and if I divided mean density, I have kilo gram per meter cube, and therefore, meter, meter come here and kilo gram gets cancel, this is also becomes joules per second or watts. Therefore, I can represent m dot p in terms of a function, which does work on the system.

(Refer Slide Time: 07:29)



In terms of rate of work on the system, as may be m dot prime p prime divided by mean density. How do I represent this? Q dot has energy per unit time, T prime here, its addition, maybe if I were to write in terms of, so much watts or so much joules per second, T prime divided by the normal temperature. Well this also has units of w, therefore I can say if I were to add power as a product of force in phase with velocity. Add power in terms of heat transfer, as in phase with temperature perturbation. Add mass in phase with pressure perturbation. Well, I could amplified, and all these three things, has been put together beautifully by one person by name Chu.

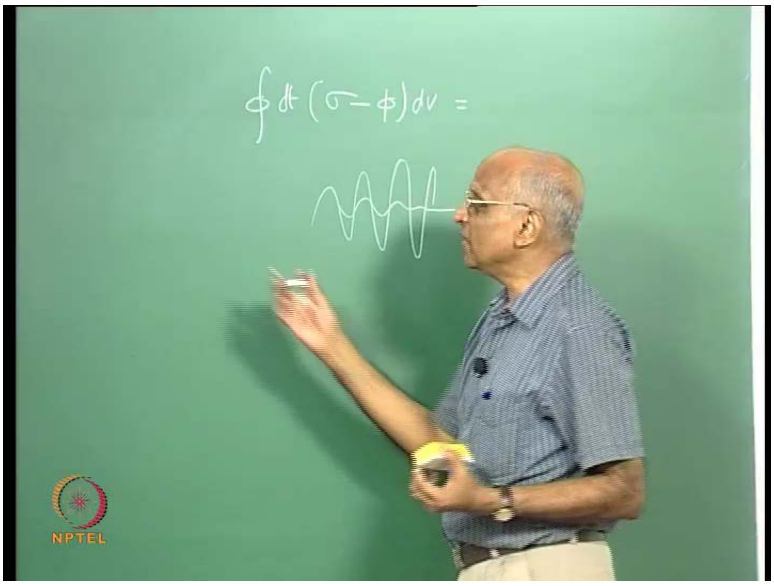
(Refer Slide Time: 08:24)



He worked for some time in the area of combustion in stability, and he put all these things together, and he called it as parameter sigma, and he said the power, which adds to the magnitude of oscillations, could be represented, by let us say m dot prime, p prime by row is a mass release, exciting the pressure oscillations. Maybe Q prime Q dot prime into T prime divided by, let us say the mean temperature, could be the mean density over here, plus you have force prime, into the velocity prime is the parameter, which causes or which proves power or energy, into the wave motion and causes wave to grow. And how do you put power, it could be from mass, it could be from heat transfer, it could be from rate of change of momentum, and we have all the three things in rocket motor. We are generating heat; therefore heat could excite the oscillation to grow. We could have mass concentration is being added. We are adding force.

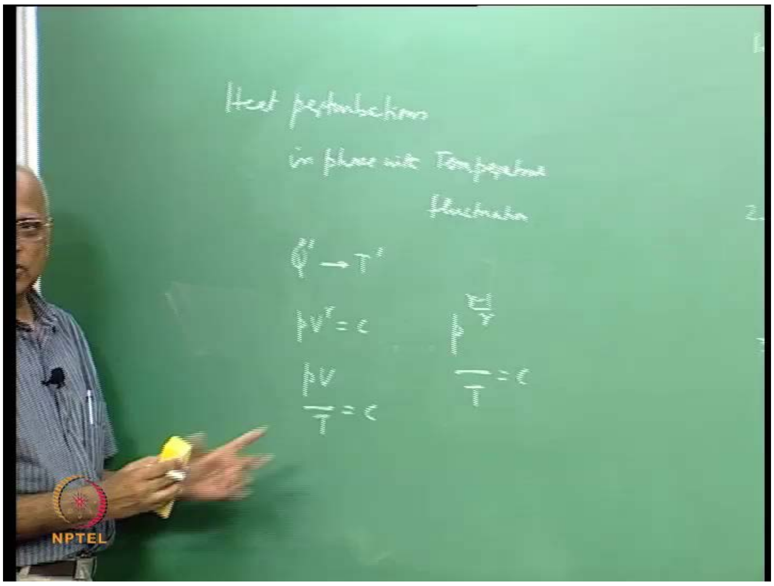
We are having rate of change of momentum, it could add. Therefore, all these three parameter are important, but in a rocket chamber again, we also have boundary layer, this point was made earlier, it could caught viscous drag. Wave in it is travelling gets retorted by the boundary layer. Maybe if I have solid propellants, I have particulates, particulates will cause drag, it will break up the wave. It could have, may be the flow turns in the, when a flow turns it loses energy. And therefore, there are also, some factors, just like I have sigma watts, adding energy. I could also think in terms of some capital fy, which removes energy from the wave; that means I have sigma watts, coming from mass release, from heat release, from force. And similarly, I have some quantity which removes it.

(Refer Slide Time: 10:37)



And the net value, it depends on sigma minus pi, taken over the whole volume, and in one cycle of oscillation, is what tells may whether the is wave will grow or not. If this is positive, well I am adding more and more mass, and they will grow, if this is there, maybe it will keep coming with respect to time like this. And this is something which was beautifully illustrated, and let us follows this up and come to some conclusion. We are just now telling, heat addition, in phase with temperature oscillations.

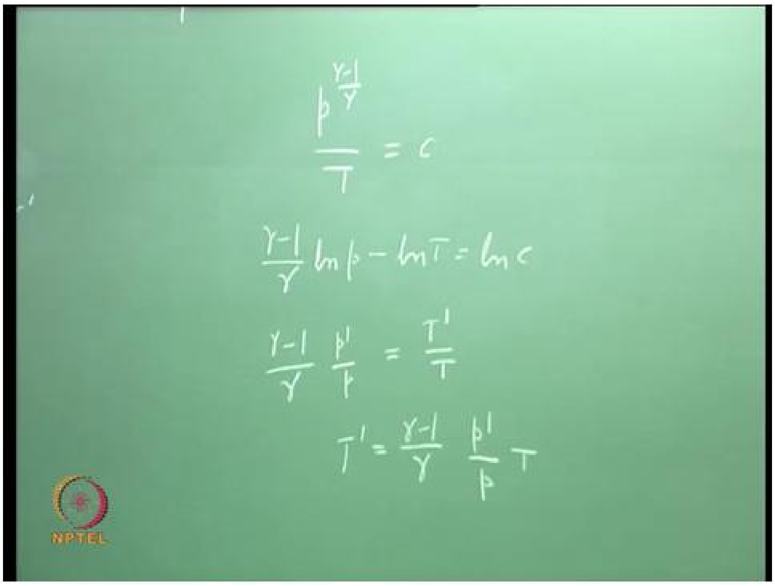
(Refer Slide Time: 11:13)



That is rate of heat perturbation or disturbances, in phase with temperature fluctuation; rather what we are saying is p prime, in phase with T prime. I am sorry Heat perturbation miss Q, Q dot rate of heat, in phase with T prime, but we are not measuring temperature fluctuations. Can I therefore put it terms for pressure fluctuation, is what we can readily measure, and that is what we have been talking all along.

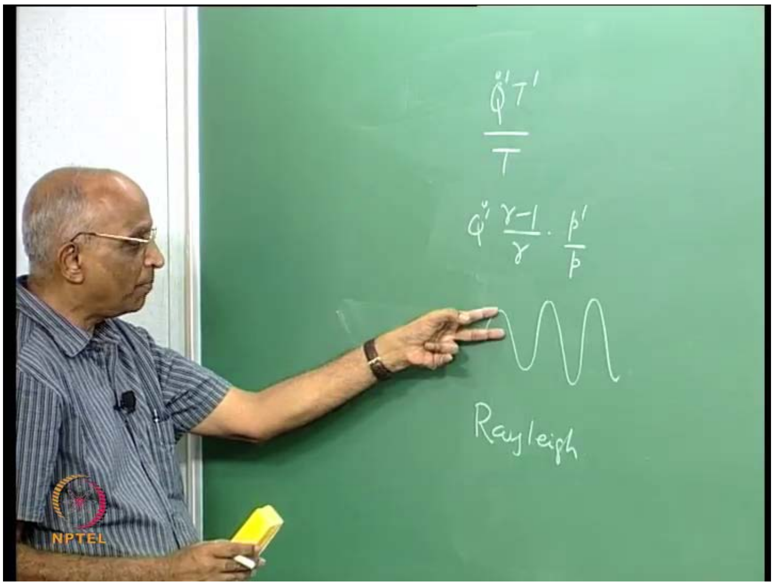
Therefore, how do I convert temperature fluctuation into pressure fluctuations? Well, we assume that the system is adiabatic, any acoustic wave is adiabatic, because the pressure perturbation is small. Therefore, I can write, well p divided by v to the power gamma is constant. I also know from the gas equation p v by T is a constant. I combine these two together, and this gives me p to the power gamma minus 1 by gamma by T is a constant. We have done this earlier, how did we do, we say p to the power gamma, v to the power gamma, T to the power gamma is there, and therefore, I divide 1 by the other, I get this expression. And if I were to take this expression, and differentiated. Let me do it on the other side.

(Refer Slide Time: 12:48)



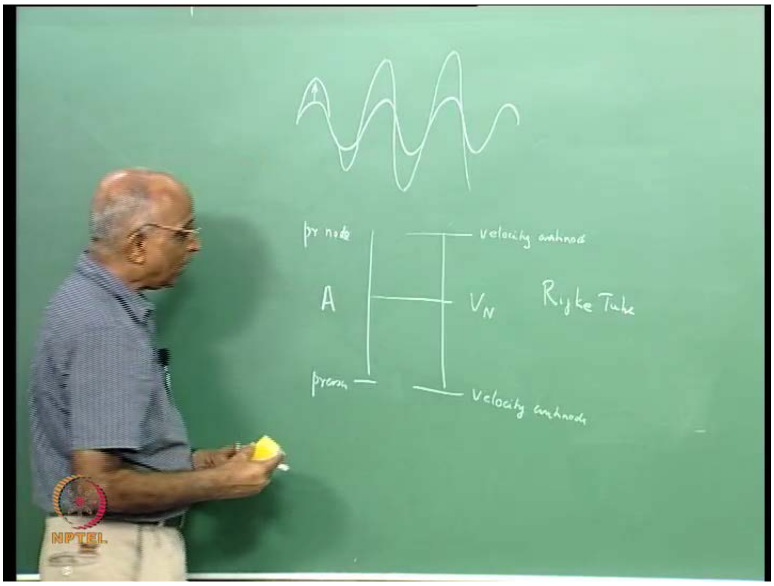
I get p to the power; gamma minus 1 by gamma, divided by T is constant. I take the logarithm, and I say gamma minus 1 by gamma, into lawn of p minus lawn of T is lawn of constant. I differentiated, I get gamma minus 1 by gamma, into lawn p that is p prime divided by p, is equal to T prime divided by T. Lawn c is a constant, this is d T by T prime perturbation, this is usual value. And therefore, now I get T prime, is equal to gamma minus 1, divided by gamma, into p prime divided by p, T prime is equal to gamma minus 1 by gamma, into p prime divided by p into T. Let us substituted in the value what we had, for the case of temperature what did we tell, that the value of sigma, or the energizing parameter, is equal to something like we talk in terms of Q prime into T prime, divided by T.

(Refer Slide Time: 14:00)



And therefore, now I say, Q prime and I take the value of T prime, as I get yet T prime by T, is equal to gamma minus 1 by gamma, into p prime p. And therefore now I fine heat release, when that is a perturbation in heat release, when it is in phase with the changes or perturbation in pressure, would also cause and oscillation, just the same way as heat release in conjunction with temperature, will cause this is physically, we know when I add heat the temperature increases, but this is not so apparent to us. And this tells as that heat release in conjunction, with a pressure perturbation will lead to energy, being given to the wave motion or oscillation will grow, and this is the famous hypothesis of Rayleigh. It is known as Rayleigh principle, and all Rayleigh principle says that, if I add heat at the moment of the greatest compression, or I remove heat at the moment of the greatest condensation, by condensation in the old days segment rare fraction, then and oscillation will be encouraged. I will repeat Rayleigh principle is extremely important, for the following; that it helps as to understand, the role of heat release in causing oscillation, and what does the Rayleigh theory tell you.

(Refer Slide Time: 15:36)

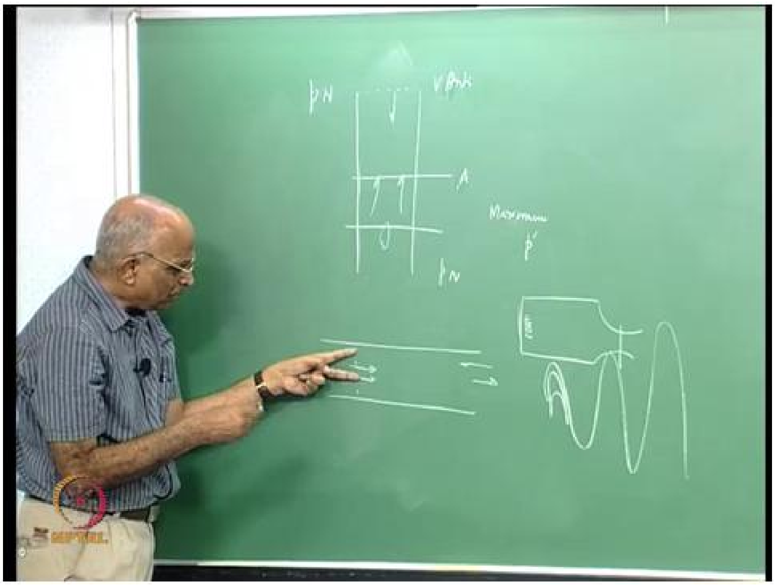


It tells you, if I have pressure oscillations. If I add heat at the moment of greatest pressure compression, or I remove heat at the moment of greatest, then oscillation are encouraged; that means oscillations will grow. This looks very apparent, but this is very basic to our thinking. Let us illustrate this through small example, what I do is, I take a tube. Now a tube is open at both ends, therefore I will get something like a velocity node, velocity anti node here, or since the pressure is same here and here. The velocity anti node corresponds to the pressure node here. Similarly, over here I get a velocity anti node, or let us say, a pressure node over here, and at this center I get a pressure anti node, I get velocity node. And let as add heat to this, and see whether the principle really works, and the principle is demonstrated in a particular vertical tube, which people call as Rijke Tube. I thought we must look at it, such that maybe when I add heat at some location, I will find automatically the tube start singing, or tube start to make a noise, and that’s what we will do now.

Let us just add heat, and for this purpose may be we will take a sparkler, we will add heat throw a sparkler, because we need some substantial amount of heat, let us do that. As I keep telling you to make a fire is not that easy, like we add a pyrogenic igniter, we need to build a small fire, to make a slightly bigger fire, and still make a bigger fire. So also we had to light a candle to, get a sparkler to go with match stick with a little difficult, especially in an A.C. room. Well this is the sparkler going; now I want to ignite a slightly bigger sparkler. I use this, because was more energetic. Now all what I do is, now I take this vertical tube. This is the tube I have, and now I hold it vertically, I introduce the. You hear the noise, noise comes down, at the location where I make a mark here, which is one four the length, it makes maximum noise, and then as I keep coming down, the noise keep coming. The question is you, just had a tube, in which there is hardly anything, and all of us sudden its start making a noise.

And what is noise, noise is sound; that means causing pressure perturbation, we would like to understand a little bit more. Therefore, all what we are saying is, let me invert it, if I hold it horizontally and if I add here, nothing happens. Very little, but because I am having some air motion, but I do not get the type of sound what I normally get, when it is vertical when it is much louder. And therefore the question is, what causes this particular sound to come, and this is what may be we will try to understand, and if we can understand this. Well I think we have understood a major part of the combustion stability, think what we have to do. Let us almost over, therefore what is the experiment, which we just did. Let us try to analyze it.

(Refer Slide Time: 20:28)



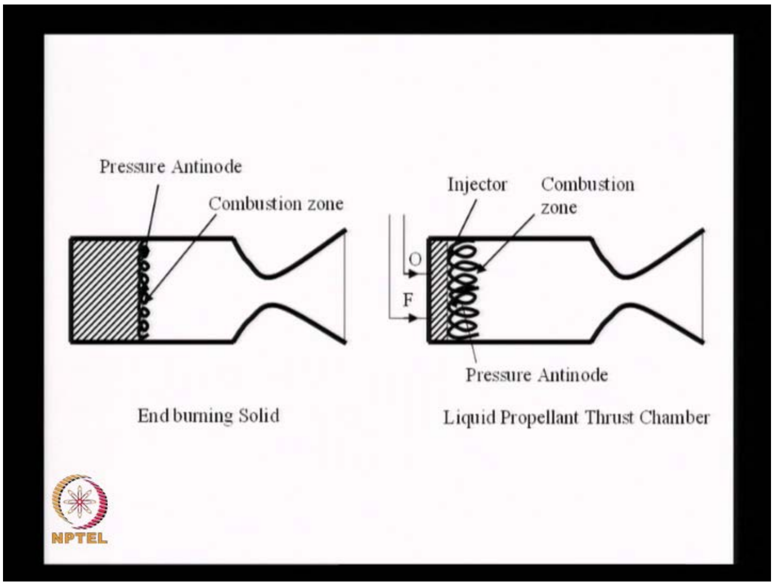
We found, that the tube in the vertical condition, may lot of noise. Where as in the tube which was in the horizontal direction also make some noise, but was not as I in the vertical tube what did we do. We put some heat source at some location, when I put some heat source, hot gases are converted of, hot gases are converted of, they meet this boundary, when I have the velocity node, it gets reflected. I get something like a pressure anti node over here, I get a pressure node here, I get velocity anti node here, pressure node over here. And what is happening, at this central place between these two. I have something like I still have pressure oscillation and velocity oscillation in the standing wave mode, because my tube diameter is small, I do not give room for the tangential and radial modes, and therefore the location where I have significant velocity, I have lot of energy being added from these sparkler, into the flow medium. It is also where the pressure is significant, and therefore this location when I put my sparkler, I have maximum noise, and what is maximum noise, and I have maximum value of pressure perturbation.

Therefore, putting a heat source as caused, the pressure magnitude to jump up, and that's what happens in a rocket chamber, what happens in a rocket chamber. You have the gas flow, I have pressure anti node, pressure node here. Supposing I put a heat source at the location of maximum pressure. Well my pressure amplitude keeps increasing, and my amplitude goes up. And this is precise the principle, in this case is convective, I had an open tube to do as simple experiment, if I put horizontal tube. Well my mass generation is large, therefore some gases goes up. I have the oscillations coming like this, and I when I put it here, I get still get some sound here, but normally the sound in this case was much higher, the reason being I am able to get the convective motion, to give me a stronger wave interaction. Whereas in this case, the velocity is are much lower, because here I have the boinsy effect, which help me in which case it does not help me here.

I will get mix more had really looked at the sound; I would have got some something like radial modes and other modes coming here, where as here it is purely actual. If this part is clear, let us quickly go through, what little we have understood so far. Well we tell also it is not only that, you know long back in UK. which was the hub of all experimentation in engineering. You had this philosophical society, and in this society every weak end people is go and display whatever they have learnt. This particular person tyndall, he was in 1897. He demonstrated, when it played the piano, when it struck the piano notes, the flame would just jump up. And the moment he stopped it, it is to come back again, but in the, when the piano is not there, you would get the study flame.

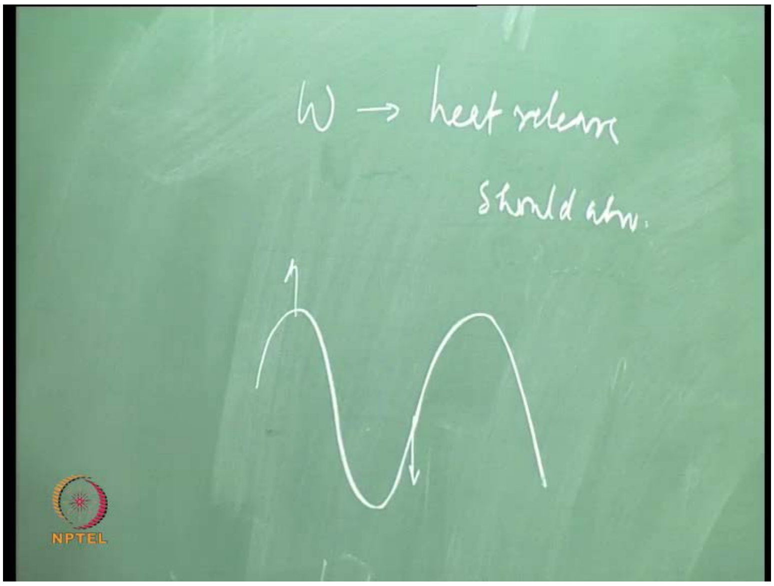
In other words acoustics, like what we are showing, that is the heat addition, or the acoustics is affected by this and that happens, because of the pressure perturbation in resonance or in phase with the pressure or velocity fluctuation; that is heat release fluctuations, in here you are striking on node is generating the waves, which is going up and down. And you have an astonishing variety of process, not only that. Infact tyndall at that time thought, may be by looking at a flame and when sing something, maybe by looking at flame even a person who cannot hear music, will able to appreciate the signals which have coming from a flame, and will be able to appreciate the music, that was he thinking, even a person who cannot hear, maybe visually can see a singing flame, and thus appreciate whatever he was doing.

(Refer Slide Time: 24:39)



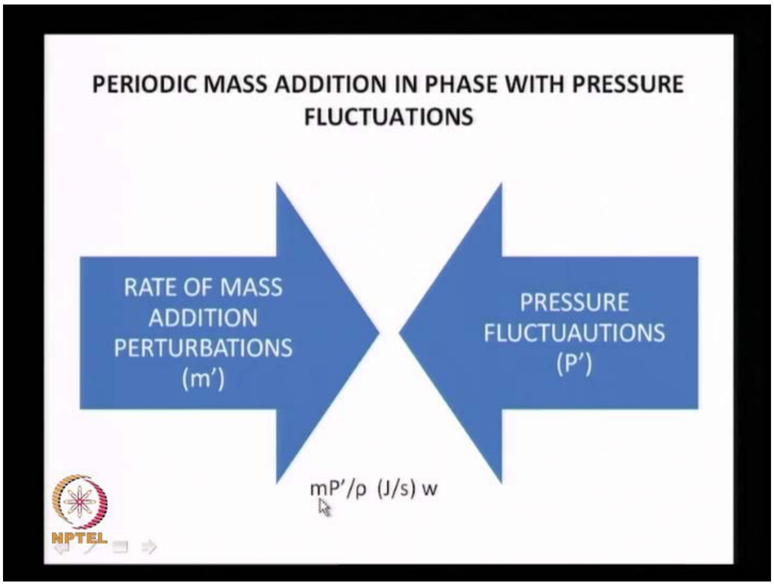
Well what is it we have been telling. Now let us put things together, I have a solid propellant rocket end burning grain. This is the region of closed and I have and pressure anti node. The energy release or the heat release is a phase with the pressure anti node, I could have the thing go up. In the case of a liquid propellant rocket, I inject. I have ciz near the header, maybe if I have maximum pressure oscillation here, I could still thing have oscillations to grow. But one thing which is important, which we have not set so far is, we have told ourselves, well I have something like a frequency, I have standing waves of a given frequency.

(Refer Slide Time: 25:22)



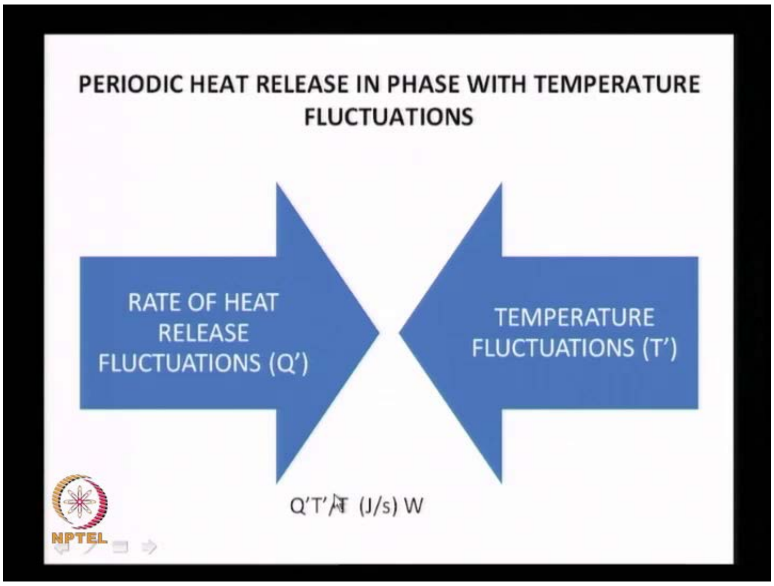
We also tell, well the heat release or mass release or the velocity changes, should be in phase; that means the frequency of the heat release, must also be at the same frequency. If the frequency of the heat release is different from the frequency of the standing wave, maybe ones I add heat, second time I add heat, it is not possible to get it. Therefore, it is essential that the frequency of heat release, should also be the same, and therefore we talk in terms of, it's not only what I am showing here, that it is just not the dump heat release, but the frequency if I add slightly shorter (( )) tube, it would have made very much higher frequency; such high frequency we may not be able to hear even, and that is why I choose particular length of 1.2 meter source.

(Refer Slide Time: 26:14)



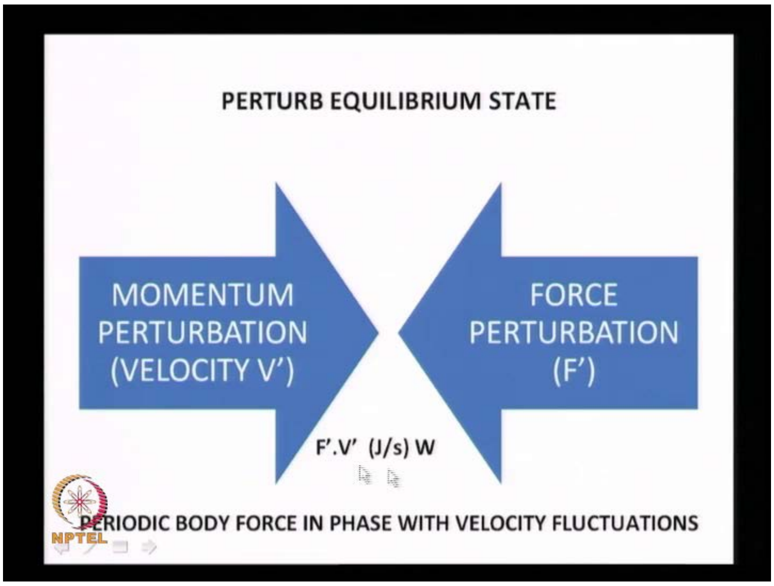
This is all what I showed earlier, maybe rate of mass addition perturbations in phase with pressure will lead enhancement.

(Refer Slide Time: 26:22)



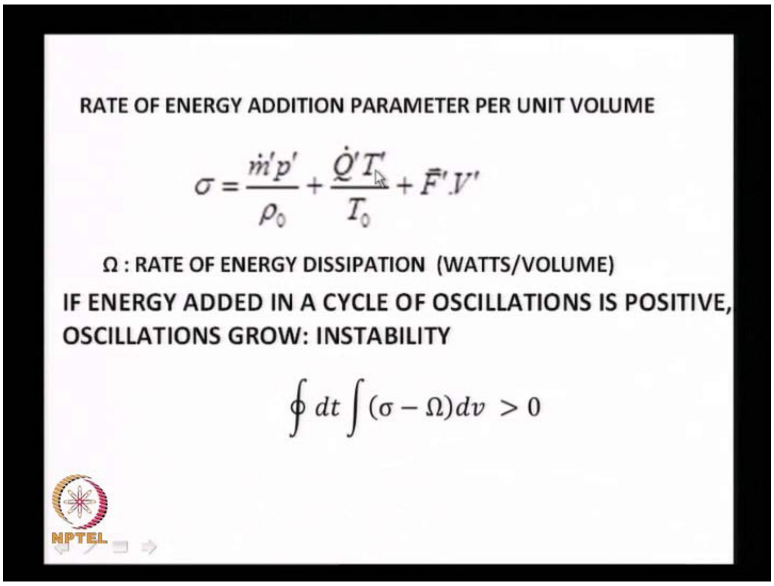
Similarly, rate of heat release fluctuation in phase with temperature fluctuations, and from this we derive the Rayleigh criterion for heat release.

(Refer Slide Time: 26:32)



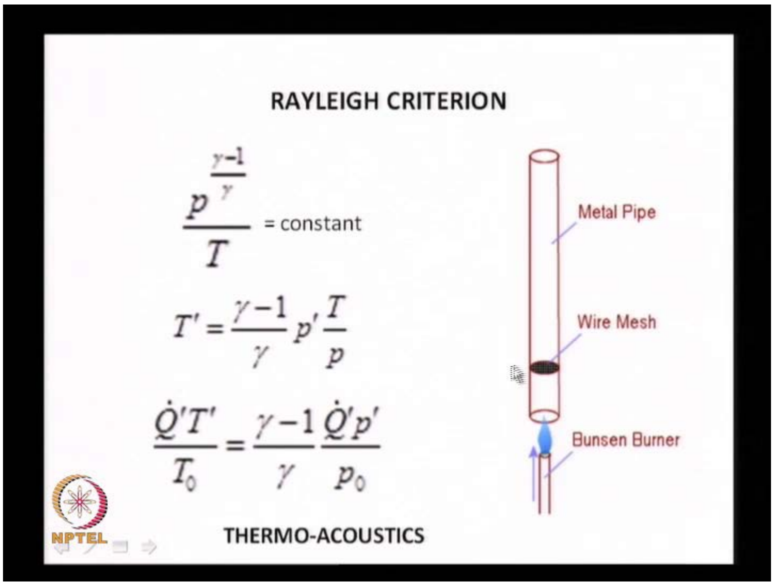
Similarly, you have force perturbations in phase with velocity perturbations, or body force or periodic body force in phase with velocity fluctuations, giving power to increase the phases.

(Refer Slide Time: 26:46)



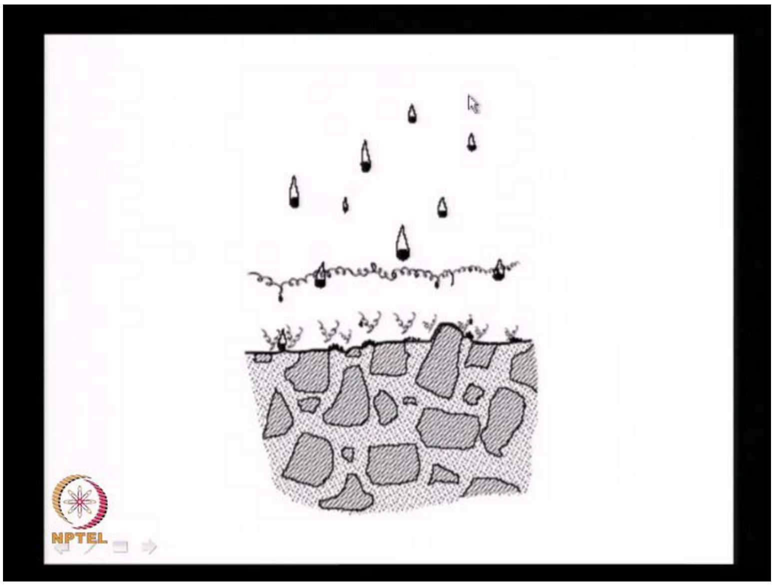
And we put the all these things together, we had a dissipation term and energy supplying term, over cycle of oscillations, if it is greater than zero, well and oscillation could occur. Only thing which is important for us to remember is, Q prime and p prime should have the same frequency, otherwise it is just not possible to have this.

(Refer Slide Time: 27:09)



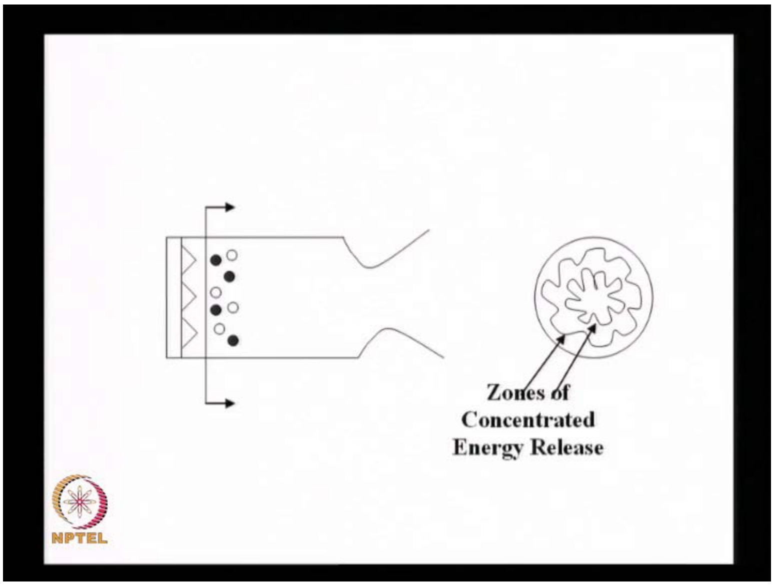
I think that is basic to it, this is what we just know thermo acoustics, maybe we put a heat source here, and we could hear the sound; that means pressure perturbation growing.

(Refer Slide Time: 27:17)



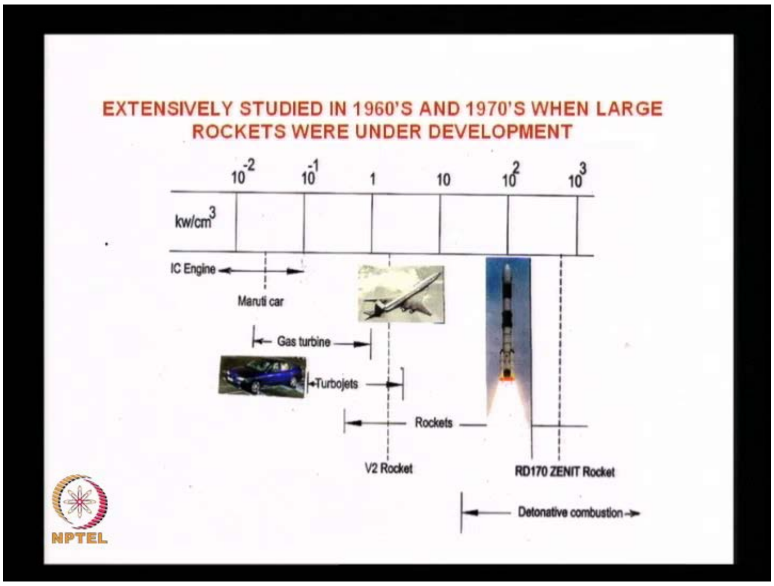
And if I have a solid propellant, these are all a p particles in the region over here. I have a flame stand of here. Aluminum particles are burning here, it dampens the wave, just like boundary dampens the wave, and therefore we have we 5 minus sigma, which reach to this.

(Refer Slide Time: 27:34)



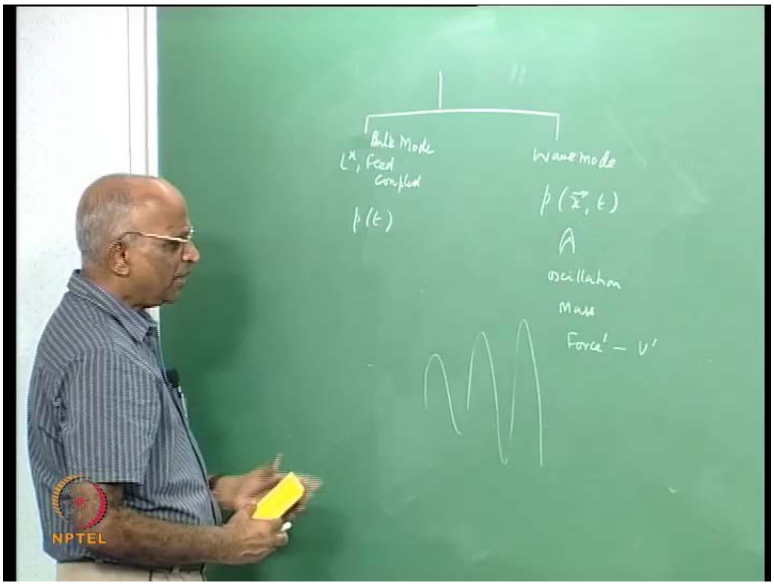
If I have a liquid propellant rocket, well I have injector; I have zoon of heat release like this. Therefore, I could have tangential and radial modes also causing this, and you could end up having pressure perturbations.

(Refer Slide Time: 27:49)



This is all about combustion instability, and now I should be able to put things together in the next 20, 25 minutes together. Let us now take review of what we have done so far. Let us say, yes we have understood what combustion instability means.

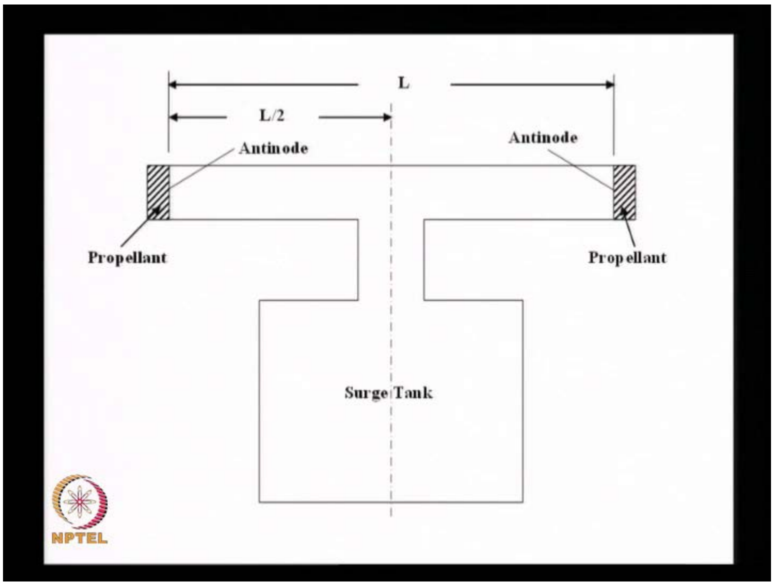
(Refer Slide Time: 28:07)



We started with the thing, with respect to, maybe feet coupled oscillations, in which we said p is a function of time alone. Then we talked in terms of wave mode, I should have written here, maybe the bulk mode. And in the wave mode I have p as a function of distance, and a time, which is vary. Here you form standing waves, if heat release is at the same frequency, and because its unsteady heat release, and it is in conjunction at the point of maximum perturbation you add heat, well I get a oscillation. It may not be heat alone, it could be from mass addition also, in phase with a pressure perturbation or it could also happen with force; that is the body force perturbation in conjunction with a velocity perturbation. And now we know, well why does combustion in stability have to occur. Well we have energy being supplied by the combustion process. It drives the pressure. It drives the oscillatory pressure. In some cases it pressure perturbation keep on increasing.

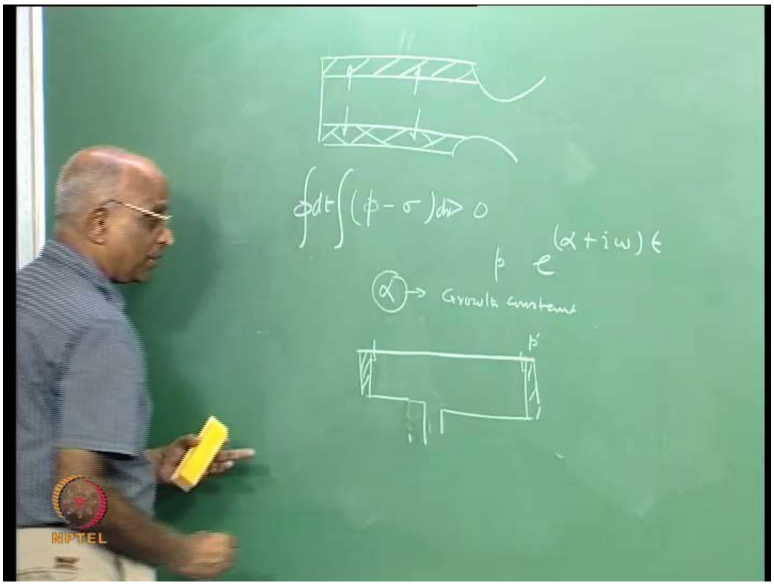
Therefore, now let us put the subject in proper focus, we tell are sells first. Well rocket is a small chamber, it generates lot of heat, compare to let us an airplane gas turbine chamber or a car whose rate of heat releases, something like 0.1 kilo watt per centimeter cube, much lower than that compare to plane which is the order of 5 kilo watt per centimeter cube. A rocket gives something like 100 kilo watts to something like worlds. I showed you that R D 170 engine, we said it burns liquid kerosene and liquid oxygen, at a pressure of are almost, we said around 245 bar, and we said this is the very power full stage combustion engine. The type of energy what we are getting is something like 1000 kilo watt or centimeter cube. And whenever we talk of something like an explosion, this is the type of energy release what we get. Therefore, even as min its small amount of this energy, if it gets into the wave mode, well I could starts getting some oscillations.

(Refer Slide Time: 30:33)



Inner to be able to figure out, how much of heat release, gets into the oscillations, we have specific devices. Now this is something which we must know, supposing I want to measure the growth constant of propellant, supposing I have let us say solid propellant in a chamber.

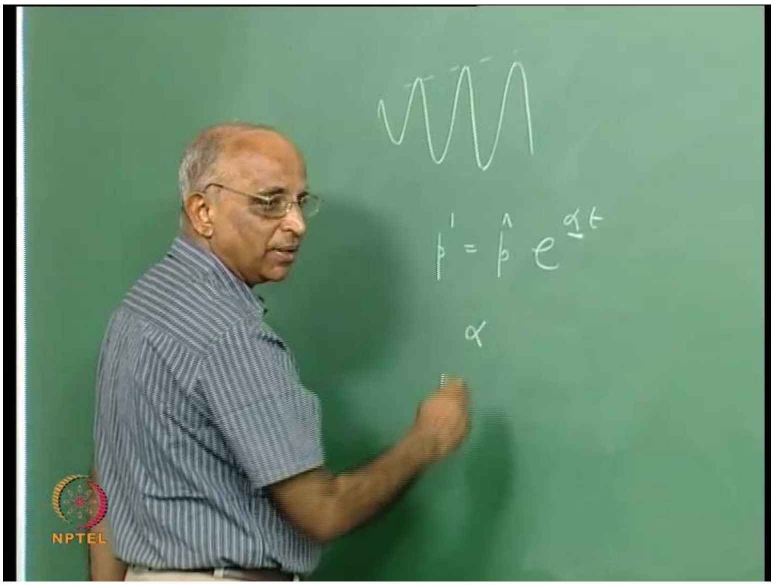
(Refer Slide Time: 30:53)



I have the propellant which is burning radially over here. I find that the propellant which burns here is at a pressure anti node, at this center it is a pressure node corresponding to fundamental. Here it is near to pressure anti node; therefore, different points are at different location, but what I am interested is in, maybe I am interested in the value of 5 minus sigma, if it is greater than 0, well it is unstable, and what did we say integral over the volume, over cycle of time; that means over cycle of oscillations, must be greater than 0 or rather I can reduce this forms, as the growth constant; that is if I were look at the propellant and evaluate, whether I can evaluate we said oscillations can be put in terms of growth plus the frequency to the power t.

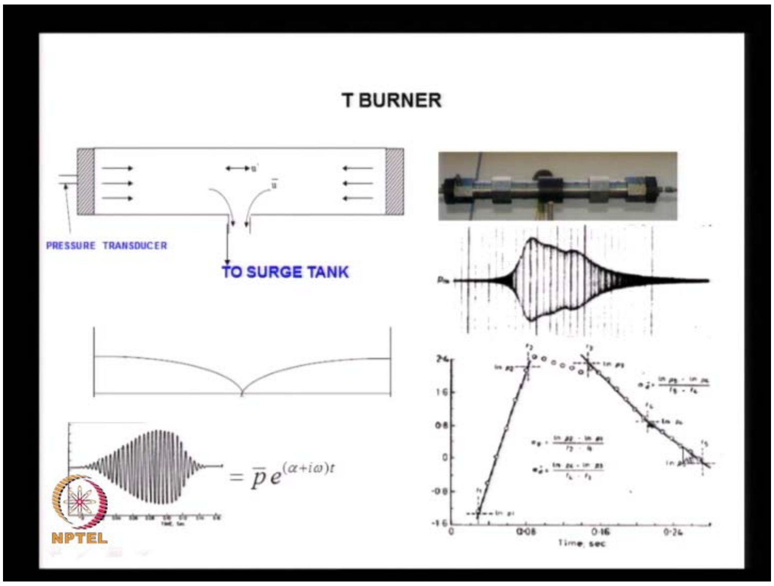
This tells me the rate at which oscillations of growing. Can I measure this growth constant of propellant. To be able to measure this, I make a tube; I make the length of the tube, such that I am getting the same frequency as my chamber over here, standing wave mode of the chamber. I make the length, and how do I say in the fundamental this length is may this frequency. I put a slab of propellant the end; that means the pressure anti node. I can get the precise value of the pressure anti node. I ignited, I burn it, what is that I observed; that means I have something at the anti nodes. I put the solid propellant; the length is well for the given frequency. I also put a tank over here, such that I can maintain the pressure, at the level of the pressure in the chamber.

(Refer Slide Time: 32:52)



We would like to know the rate at which the oscillations grow, rather we are interested in finding out, the value of p prime has a function of p hat. And since we are interested in growth of these oscillations, we are interested in finding out the growth constant alpha, and this, when the oscillations grow is positive, and that is what we measure in a T burner. Let me come back to this.

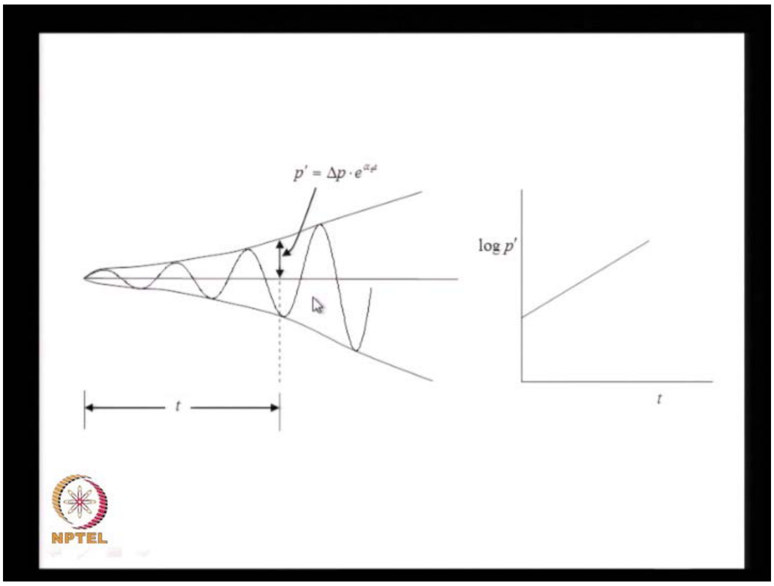
(Refer Slide Time: 33:22)



In a T burner, as you see here, you have a tube like this, you have the propellance at the ends of the tube. At this center you have a hole, and we told ourselves earlier, that at the ends you have pressure anti nodes, at the center you have a pressure node; therefore at the pressure node position, you connected to a huge surge tank by which, by keeping a pressure of gas here. You can maintain the pressure in the tube to be at any value what we want. We also would try to keep the length of the tube, corresponding to the frequency of interest. We have already seen this earlier, namely the length of the tube will control the frequency of the oscillations which take place. Therefore, when the propellant is ignited at the ends, and has some disturbances taking place. The waves tent to grow as shown over here, till the time the propellant burns, when the propellant gets burnt out.

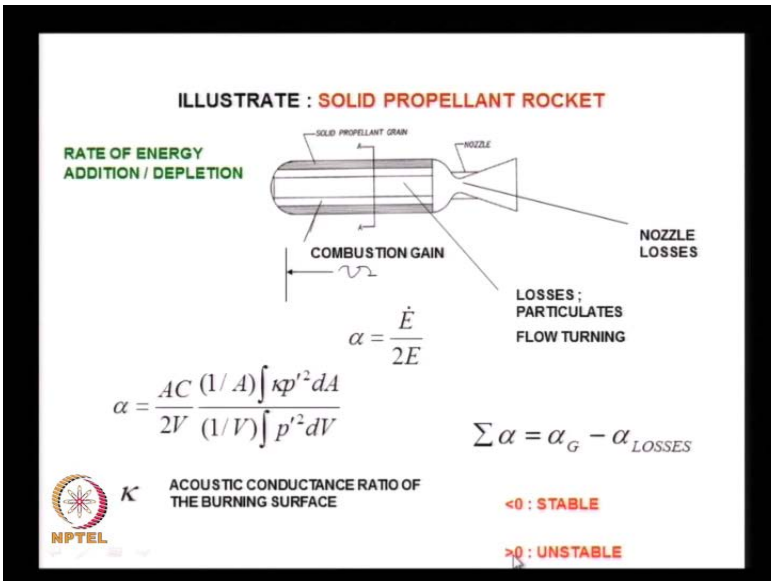
The damp damping effects in the chamber cause the wave amplitude to decrease and it comes down. In other words the wave is grow in amplitude, and there after the waves decrease in amplitude, and I show in this particular figure, this is an experimental plot, where and this is your T burner. The propellence are kept at the ends. I have the search tank mounted at this center, and this is the way the waves grow, which maximum value, and once the propellant has burnt out, the pressure amplitude d k is down. Now, if I plot this the change of pressure amplitudes as function of time, and maybe on a log plot are otherwise, I find yes this is the rate at which the, these are the pressures at different times or pressure is increasing, and the pressure is (( )) like this. In other words I can sort of measure or determine, the rate at which the growth of oscillations take place; namely the alpha in p prime is equal to p hat alpha t, and also the rate at which it is d k using this. I go to the next one namely.

(Refer Slide Time: 35:31)



I show here, the growth of oscillations, the magnitude of the lock pressure versus time increases, and therefore I can determine my growth rate. I would like to use the growth rate as I measure. In the previous case in this particle T burner, it is in the form of the center the top of t and the position, the hub that is the t comes over here, connecting to the surge tank.

(Refer Slide Time: 36:07)

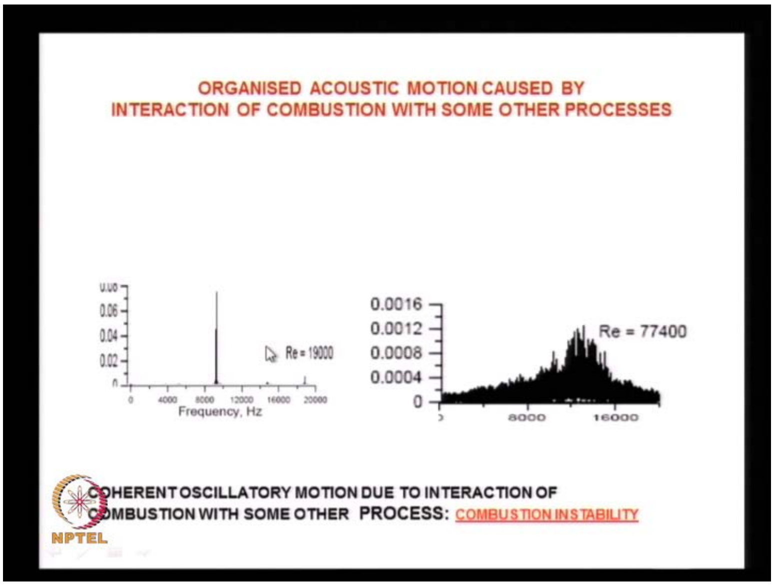


I would like to make use the growth constant as measured in the T burner to be able to predict the stability of combustion in a solid propellant rocket. To be able to do that I have one more problem to reconcile with, and that has to be sorted out. Namely in a T burner, the propellance burn at the antinodes, but in this particular case propellance are burning at both the anti node, as well as in the node region and in the different regions. Therefore, I have to measure, I have to correlate, the growth constant of oscillations in the motor; namely alpha with respect to what I measure in T burner. For this case I go ahead I define something, like and acoustic conductance ratio of the burning surface and I derive in expression for the growth constant, in terms of the energy release per unit time divided by twice, the average energy, and then evaluate in a T burner.

The value of K substitute in it in the expression for the wave form in this, and get the value of the growth constant in the particular rocket motor. In other words, I am able to get the growth constant in the rocket motor using this expression. I also measure the losses, like the losses which I measured in the T burner; namely the losses could be from the nozzle where in some element of acoustic energy gets radiated out. I could have particles of aluminum in the rocket motor, which again leads to dissipation of energy and reduction in the d k constant. And therefore, I sum up of the value of the growth of oscillations due to the propellant, and I take all the d k effects; namely the loss effects, and if the net value of alpha is less than zero, I say well alpha is less than zero, its negative, and therefore the motor is stable.

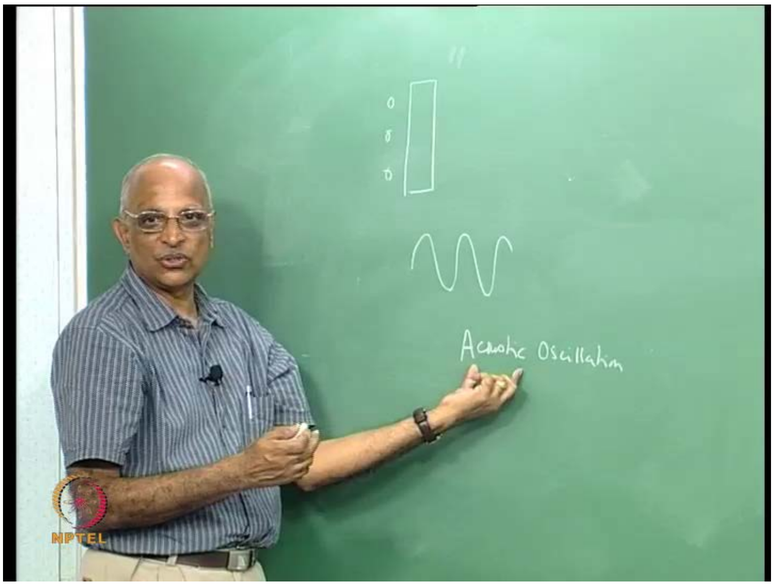
If alpha is greater than zero, well the oscillation keep growing and the motor becomes stable. And this is the way we make use of the T burner to evaluate the growth constant, with the propellant kept at the anti node position. Convert the growth constant for a motor, for which case I take the hole wave, get the net value of the growth constant for a motor, and then subtract the loses due to the different dissipate effect and find out the net value of alpha, and if the net value of alpha is less than zero, we say that the motor is stable, because the energy in the wave is less or the pressure amplitude keep decreasing, while if it is greater in zero the motor becomes unstable.

(Refer Slide Time: 38:48)



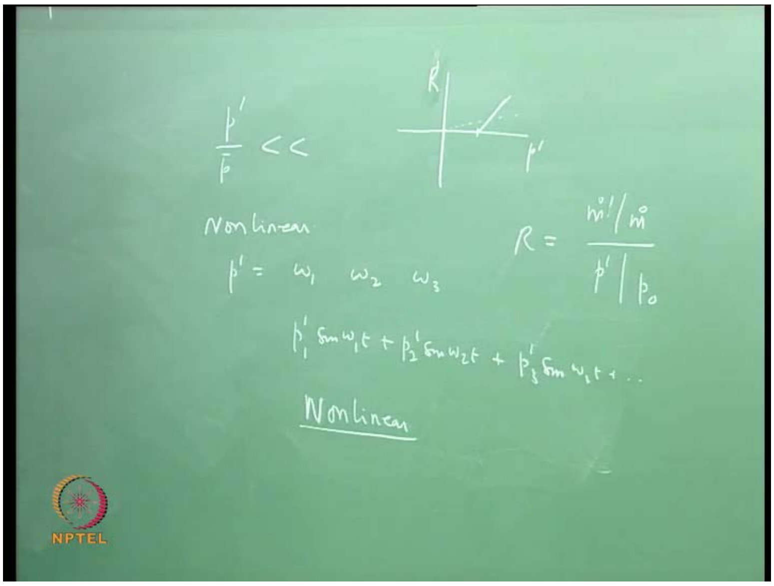
We must keep one thing in mind, whenever we talk of oscillations, whether it is in T burner, whether it is in a rocket. They are at a particular frequency, I get a spike over here this tells me the pressure amplitude, has the function of frequency. I get pressure amplitudes at a given frequency, and they are not distributed over range of frequencies. In other words these are unique to particular frequencies, and I evaluate the growth constant in a T burner, at the frequency of the rocket motor, use that value to be able to get the growth constant in the motor, subtract the loses and thereafter determine the stability of the motor.

(Refer Slide Time: 39:41)



You know what I was trained to tell you was you know. And certain conditions, depending on the chamber conditions or the rate at which drop less are introduced. You have zone at which energy is getting released. If I have pressure anti node or velocity anti node, where in the heat transfer is higher or pressure anti node is in the same phase as the heat release. Well the oscillations will grow, and such type of oscillations are also referred to acoustic oscillations, why acoustic oscillation, because of the acoustics, that is the sound wave, getting reflected, forming a standing wave, and is of calling it as wave mode oscillation is also known as acoustic oscillations.

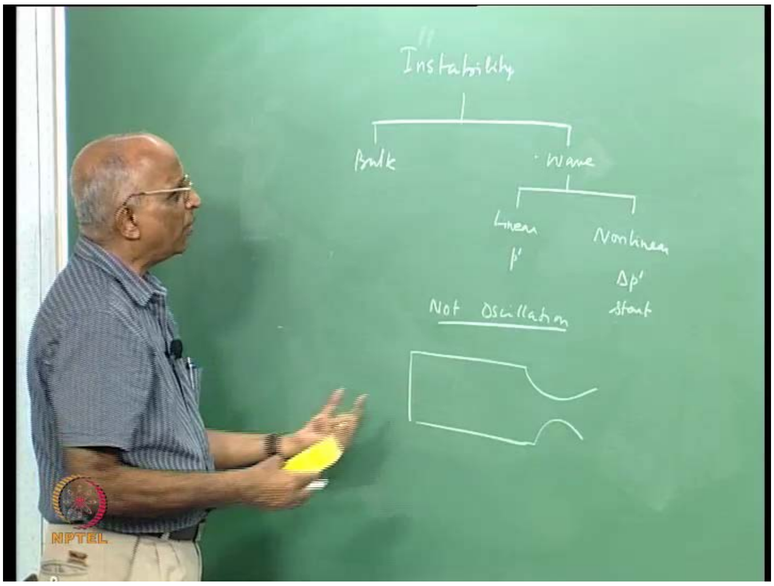
(Refer Slide Time: 40:22)



Well what is the characteristic of acoustic oscillation. The pressure perturbations are small compare to the mean value of pressure, like when I talk hardly it is all isentropic. The pressure changes are very small; that means we are talking of very small value, but under certain conditions, the oscillation becomes non-linear. What do you mean by non-linear. In a linear process, I can de couple this, I can say p prime happens at a frequency omega 1, the first fundamental. The higher harmonics omega 2 omega 3. I can write the equation as maybe p 1 into p prime 1 sin omega 1 t, plus p 2 prime sin omega 2 t, plus I can write p 3 sin omega 3 t and so on. And this are all clearly, they can be removed, because it’s a linear system. But when it becomes non-linear, the frequency here could interact with the frequency here, and I could get new set of process; that means the wave interaction could still happen in a non-linear mode, and if it happens in a non-linear mode, what happens?

Supposing I were to say, well this is my pressure, there is let us say perturbation over here, and this is my response, and how do I define response. I can say response is equal to, the rate of mass fluctuation divided by the rate of mass fluctuation divided by the mean value, divided by pressure perturbation, divided by the mean value, let us say p 0. What happens if I plot the response over this, normally I should have got the response which is somewhere over here, but what happens is I do not get any response over here. When I have a sufficiently large value, all of us sudden response comes up; that means I have a finite pressure oscillation to start an instability, and these are known non-linear instabilities. Therefore, we can characteristic the instability further into. Let us now put whole things together.

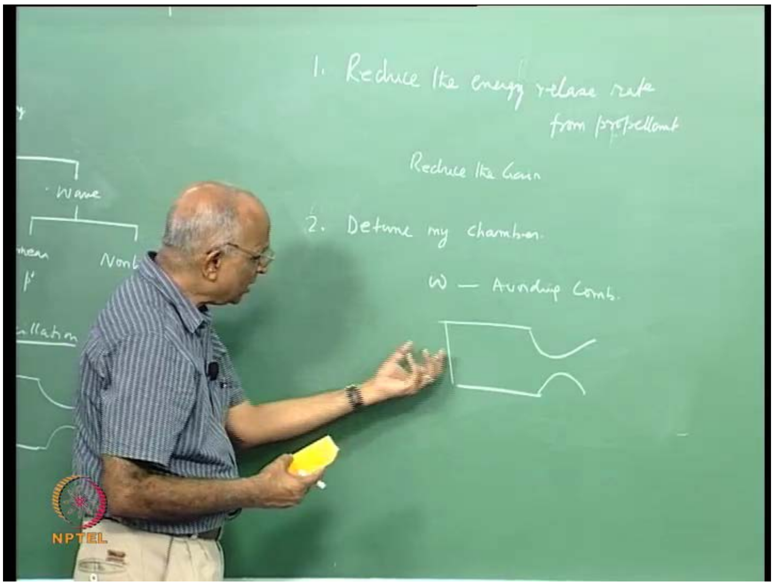
(Refer Slide Time: 42:25)



Combustion instability as happening from bulk mode oscillation. We have covered enough, we have done about it. We say it could be the wave mode; it could again happen that it could be linear mode. Wherein I am talking of small threshold values of pressure which excited, non-linear wherein a definite value of delta p prime is required to start an oscillation. Why is a delta p required, because some loses to be overcome. It becomes non-linear, but then I cannot use all these things together to get field for the problem.

Therefore, but now the question comes how do I, if I have understood the problem, all what we require as engineers is, the rocket chamber must not go through a process of oscillation. It must not build up oscillation, how do I do. One of the things is, may be if I have chamber. I add energy to the chamber and what did we tell ourselves; rocket chambers are huge energy. If I can reduce the amount of energy, like into the propellant I add some water, such that I decrease the rate of energy which I put in, into the oscillation then it is grow. Therefore I can say, I can prevent an oscillation by reducing the energy rate of release.

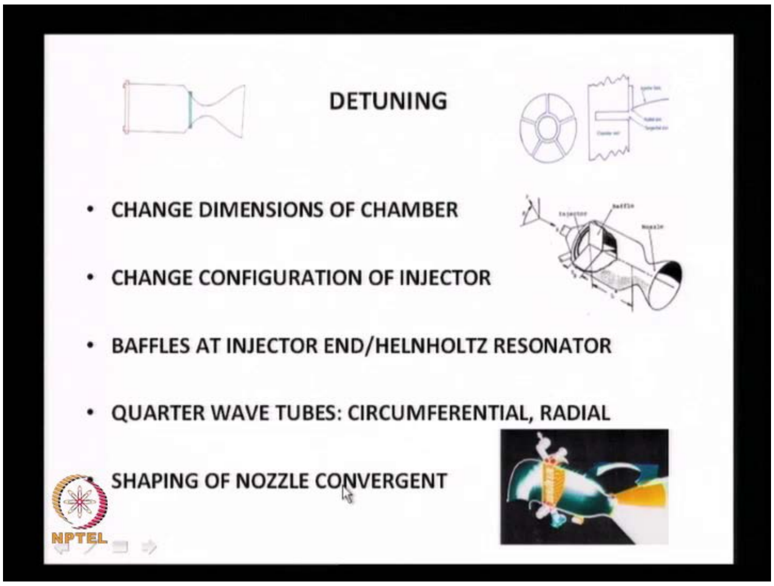
(Refer Slide Time: 43:57)



That means one - reduce the energy release rate, from propellant, this is one. You know what is it we are doing; we are essentially having some gain in the energy. The oscillation is gaining some energy from the propellant, therefore what is it we do is, you reduce the gain. Let us take a simple example, I switch on a TV, I want to increase a volume, I increase again, I have low, I hear something loudly, I reduce the gain; such that my input energy itself is reduce. Second is I sort a detune my chamber, what you mean by detuning in chamber. After combustion is occurring we said combustion happens, maybe at a response, frequency of so much. And now when my frequency of combustion and my frequency of chamber are same, I get oscillations, therefore just the same way, wherein I tuned to different for frequencies, different signals.

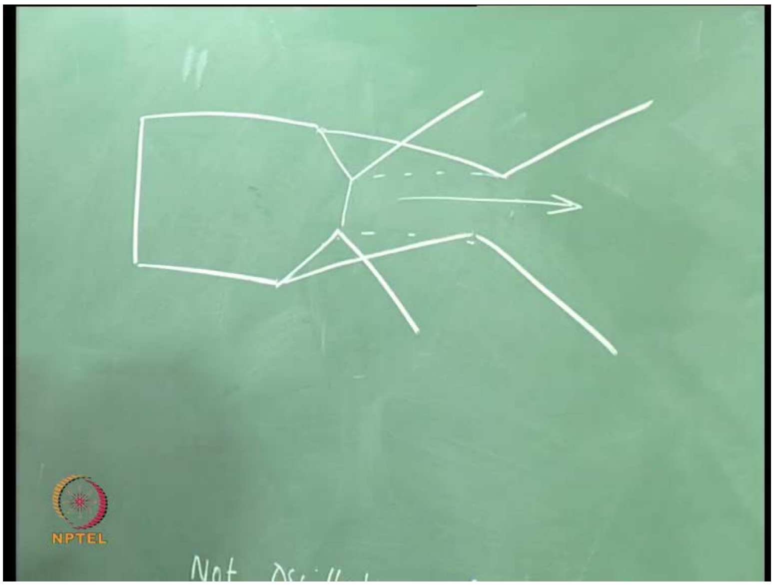
It may be, if my chamber is like this, and it is in the actual direction. Maybe I make the chamber little shorter, such that now I increase the frequency of the chamber, keeping the combustion frequency same. Therefore, I detune my chamber with respect to combustion, and that is one way of avoiding instability. Therefore, the basic processes of avoiding combustion instability are; rather you reduce the gain, coming from the propellant, or I make t.he frequency of the chamber different from this. How do I make the, see is very difficult to the reduce the length or change the diameter, what is it we do is, we put something like what I show here.

(Refer Slide Time: 45:53)



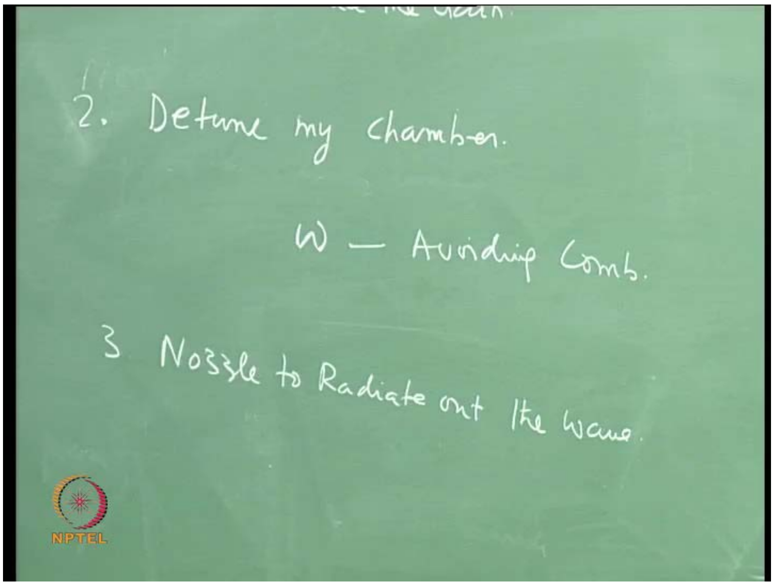
Either you change the dimensions of the chamber, maybe I change the configuration of the chamber, such that of the distribute the combustion in a different way, away from the anti node into the node. I put something like a baffles, that means in the chamber I put some proturation here, which are like a baffles, and when something is rotating tangential direction, it bricks it up, it increase the frequency of the standing wave in the tangential and radial directions. And therefore, I sort of detune my chamber. I can also have something like; I put something like Helmholtz resonator. I put some other resonator here, and such that I change the frequency of this, maybe I put a different frequency here. I get a net frequency which is different, or I put some something like a tube are opening over here, I put an opening over here; such that I increase the effective length and change my frequency, these are known as quarter wave tubes, or one of the things which the Russians seems to follow, is something which is of interest to us, and that is what I show in the figure here.

(Refer Slide Time: 47:02)



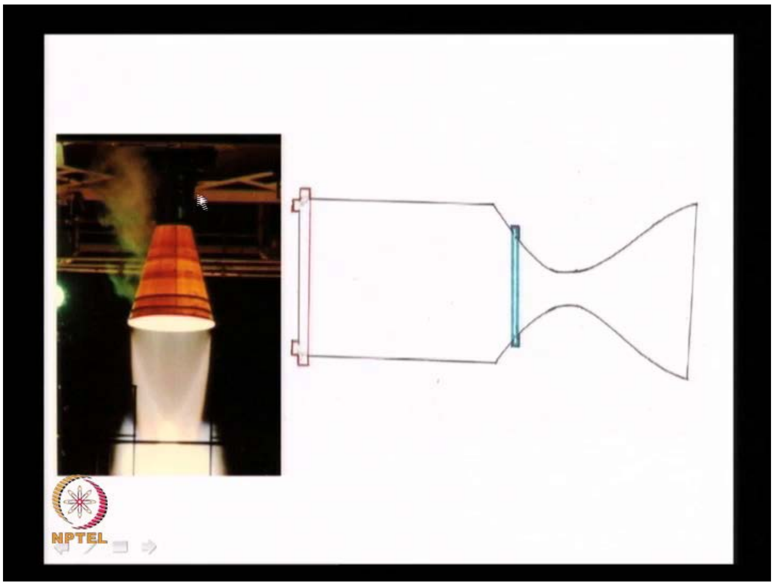
If I have a chamber like this, I have a nozzle which is like this, if I can mass I convergent much longer; that means I get the rate of density variation are quit smaller, because now my density variation for this same plot size, that is replotted. Initially this was my throat here, this is the area of my throat, and I have divergen. Now is to of this, I delayed over here. I get something like this, now I have my divergent here; that means my rate of density variations is much lower, I can allow some of the acoustic energy to radiate out, it is not getting into the stationary wave pattern, and stationary standing wave pattern, and therefore, my chance is are there.

(Refer Slide Time: 47:52)



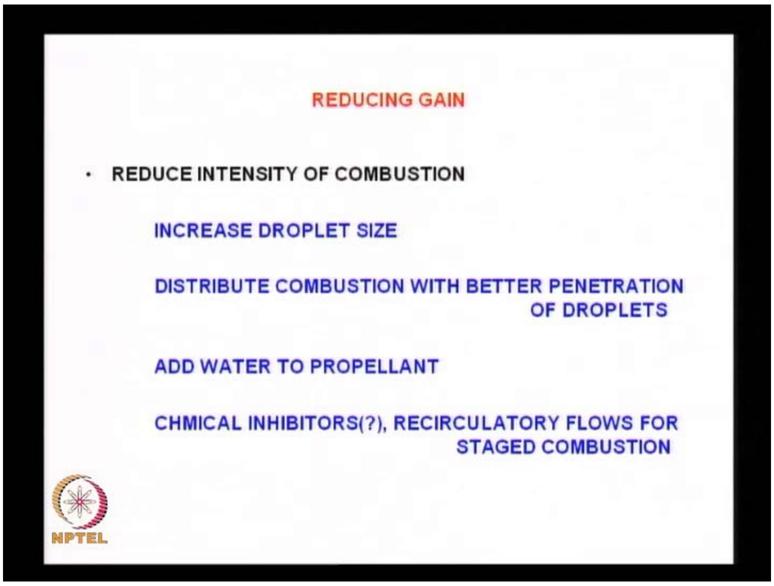
That means I say they allow the nozzle to radiate out the wave. Well these are some correction strategy.

(Refer Slide Time: 48:08)



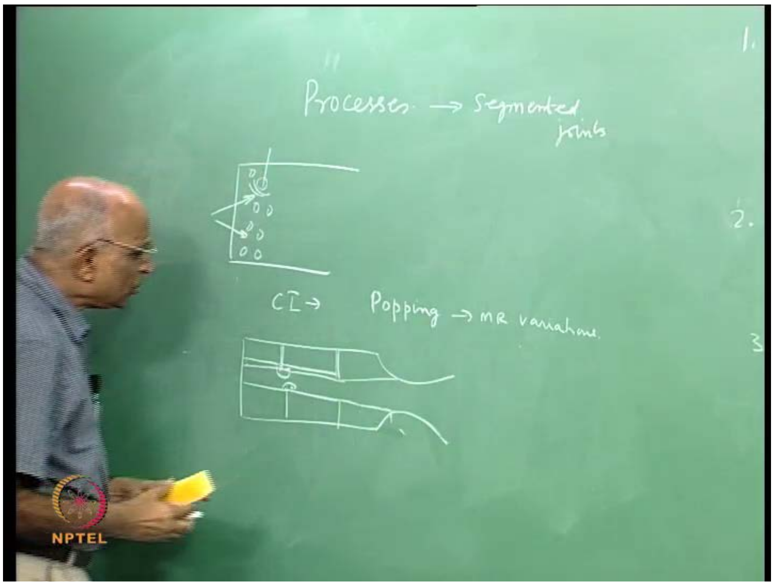
This figure shows, opening here; that means I slightly changed the tangential mode, because the dimension being inside here, and I put a slot. The dimension increases and this is been effective in reducing in the combustion instability of one of the Viking engines of 60 ton liquid propellant rocket. Let us go further, now we said there are different types of instabilities.

(Refer Slide Time: 48:42)



And let us now talk in terms of third type of instability, in which we said, instead of the wave mode or the bulk mode of instability, combustion instability could also be caused by process.

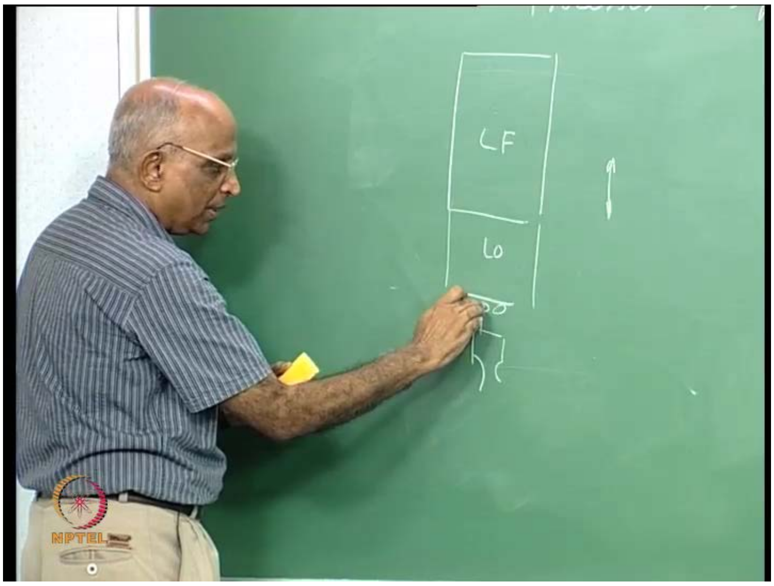
(Refer Slide Time: 48:55)



What are the processes we are talking of. In a, let us consider fluid, let us consider hydrazine are M M H to be injected as a fuel, N 2 O 4 to be injected as a oxidizer. You have variations in mixer ratio in the different parts. You remember we did the string tube model analysis, and in some places I could have very good stock metric mixer ratio. In some places, I could have something like a very lean mixer ratio, and therefore I could have variations of mixer ratio variations. In the region stockometry, the fuel burns readily. It creates wave motion, and this wave motion could lead combustion instability, and very often the stoichiometric composition when heated is, so power full or creates explosions which creates wave motion and this is known as popping.

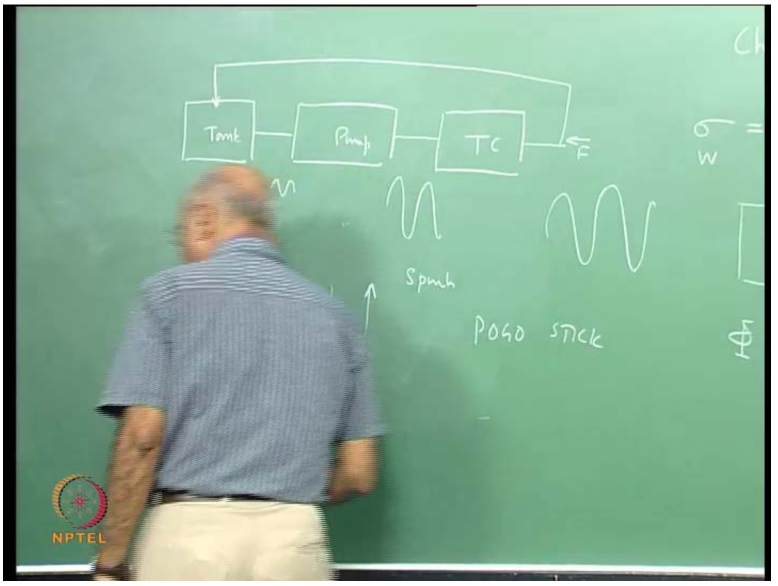
You hear popping type of sound. Well it couples with the chamber acoustics, and therefore here popping instability, which is essentially due to mixture ratio variation. You also would remember that we talk in terms of solid propellant rockets. I told you it’s all segmented rockets, segments are joined together, and whenever segments are join together, you have some inhibitors which are joining together, as propellant burns the segments get exposed. You have eighties which are being form. If the frequency of these eighties co inside with the natural frequencies. Well I could have the oscillations; this also we talked of; that means I have the second process, which is segmented joints and solid propellant rockets. I could also think of something else. Let us think in terms of new process.

(Refer Slide Time: 51:01)



And this new process is, whenever I talk in terms of liquid propellant rocket, we have large tank over here, large propellant tank. Maybe liquid oxidizer, maybe liquid fuel another tank, with a common bulk at here. Let us say this is liquid fuel, this is liquid oxidizer; this is supplying throw pumps over here, to my liquid engine; that is the thrust chamber over here. Now, let us say, under certain conditions, when the thrust is generated, I have the head of the propellant over here, and now I have these are all columns tank which is here. The tank can vibrate in the normal direction like this; it can oscillate up and down. The structure of this tank could vibrate something like this, and when it vibrates, the head of the fuel which is available at the pump inlet increases, rather let us say. Let me draw as schematic diagram.

(Refer Slide Time: 52:00)



I have a tank, the tank supplies fuel and oxidizer to pump, from the outlet of the pump its get into my thrust chamber, which is the combustion chamber, and this is what produces my first force. Now because of the structural oscillations of the tank, may be my inlet head to the pump changes; that means I get a modulation in the head over here, at the outlet pump pressure increases, the modulation increases. When the modulation increases I am supplying propellance at a modulated rate into the thrust chamber, and therefore my force changes, what happens to the force.

Force changes further or gets in phase with the structural changes, and therefore I get a feedback, because of this force into my tank, it increases the structural oscillations, and therefore my rocket now will go, it finds that some pressure is there, all of sudden thrust increase. It jumps of like this, and again comes back again goes up; it goes something like in spurts. Instead of the rocket going normally like this, in a mission what happens is under certain condition it goes like this, goes like this, goes like this, like hopping. And name of hopping is what we know as pogo; I will show this in a slide, let us go back and see this.

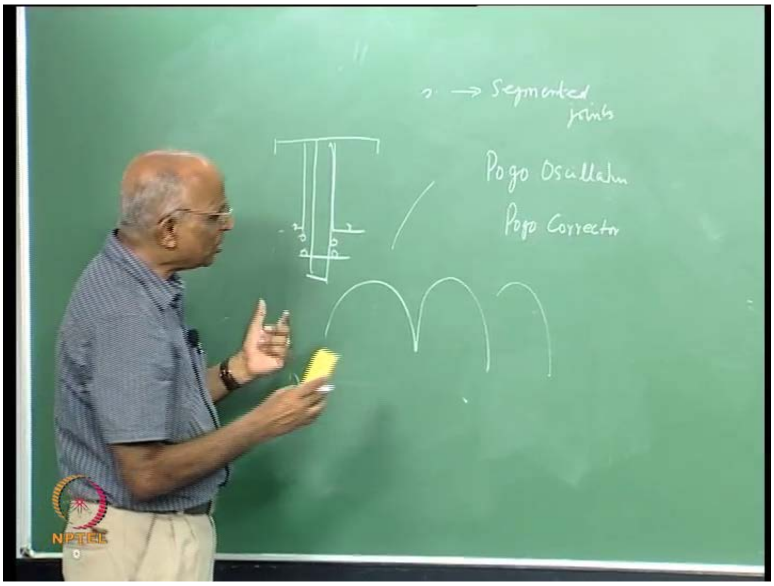
(Refer Slide Time: 53:40)

This is the large tank ages what is shown here, this is the pump, this is nozzle.

(Refer Slide Time: 53:53)

And let us see this is the boy on a stick the stick has a spring over here, he puts on a pedal over here, there is a spring over here, he sits like this and this is where I show this, this is the place where you keep you foot, this is where you keep your hand, and here you have a spring mechanism between this and this. Supposing I want to hop, he puts hand here, he puts his here, puts it together and able to hop. This is known as a pogo stick what is it we are telling.

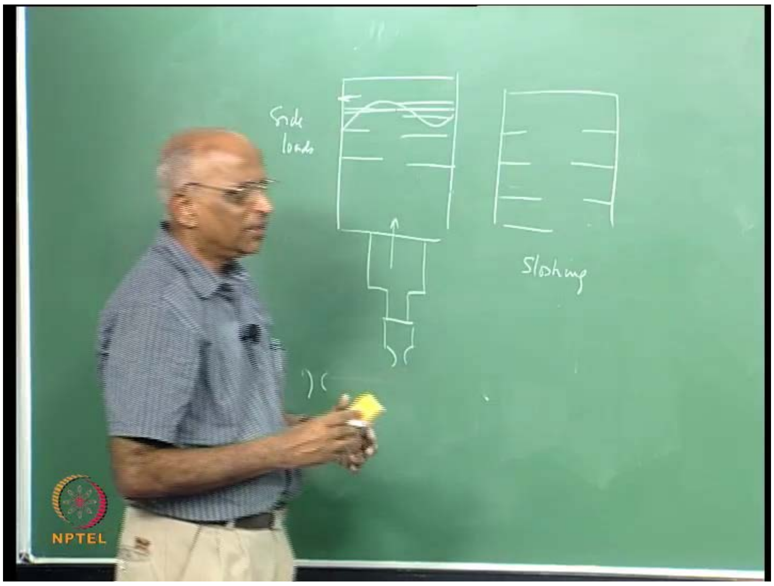
(Refer Slide Time: 54:31)



Well I have contraction a like this, I have a handle, I hold on to the handle put my foot over here. I have a series of springs over here, and this is what is connected to my bottom over here, and therefore, supposing I want to go like a kangaroo. I go from here to here, I can hop like this, and in fact in many countries you have pogo stick races which are held every year. And therefore, my rocket instead of going up smoothly, goes in hop like this, and therefore, this type of oscillation, due to this process is known as pogo oscillation. And how do you have to control it. I must reduce the coupling between my pump and thrust chamber.

Therefore, maybe if I can put over here were in I get this oscillations. I put some gas into the liquid; that means I put some small vapor bubbles into the liquid. Vapor bubbles can absorb lot of energy, and therefore I will not get this oscillation, and therefore, I have something like a pogo corrector, which I put over here and it corrects my oscillations. This is there in many nations in all rockets are all launch vehicle we have pogo correctors, and similarly one of the points which some of you made was, how about slashing.

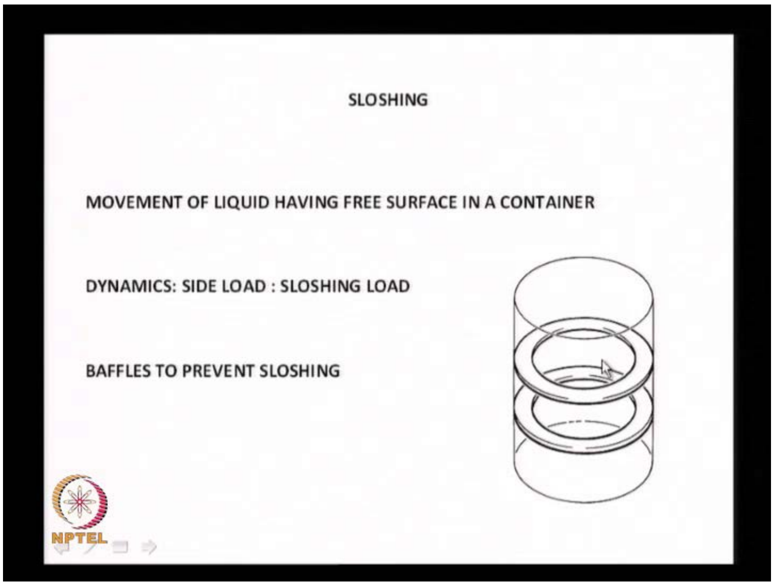
(Refer Slide Time: 55:51)



I have a liquid in a tank. See the rocket is going up, see it does not happen when you grown fire a rocket, this is a propellant tank, from the propellant tank I take the propellance, give it in to the chamber. Now if the rocket is going up, I just get straight actual load, but the rocket also turns and all that; that means I could get side loads. Not only rocket maybe from the when by maybe I get the side loads, and when I get the side loads, my surface of the liquids instead of being plane, it becomes a wave motion. And this wave motion when it is travelling up and down, includes again provides side loads to my rocket. And therefore what is it we do, we start getting side loads, because the propellence slashes; that is the free surface of the propellant changes.

And therefore, it becomes necessary for me to put some material, something like a baffle over here, which will because of the viscous dissipation, will not allowed this to happen, and therefore, I put baffles in my propellant tank to avoid sloshing. Sloshing is not a form of instability, but it is again with a mission and the reason is free surface area changes. You would not like this free surface changes, and therefore, you put baffles to avoid sloshing. Therefore let us take a look at this, baffles what are put for sloshing and then we will conclude.

(Refer Slide Time: 57:28)



Yes this is where it is, no you put some baffles over here, and so that the liquid that does not slosh; that is the moment of liquid having free surface in a container, when it goes from side to side gives your sloshing load and baffles are used to prevent sloshing. Well will conclude whatever we have to say, by saying. Well liquid propellant rocket or a solid propellant rocket is acceptable to instability, and this instability could be defined in terms of bulk mode oscillations, or in wave mode oscillations or in terms of different processes. We didn't get into details of solid propellant, where in you could have oxidizer burning up giving you particular frequency of depletion, but these are all details and what we have covered is the basics of combustion.

Therefore, to summarize in today's class, we started to with wave modes. We looked at the standing wave modes, we found out under what conditions wave amplification can take place, and then we said well combustion energy is getting liberated, and therefore instability can found. We also talked briefly about the process induces combustions to release. I think we stop with combustion instability here, in the next class will start with maybe electrical propulsion. thank you.