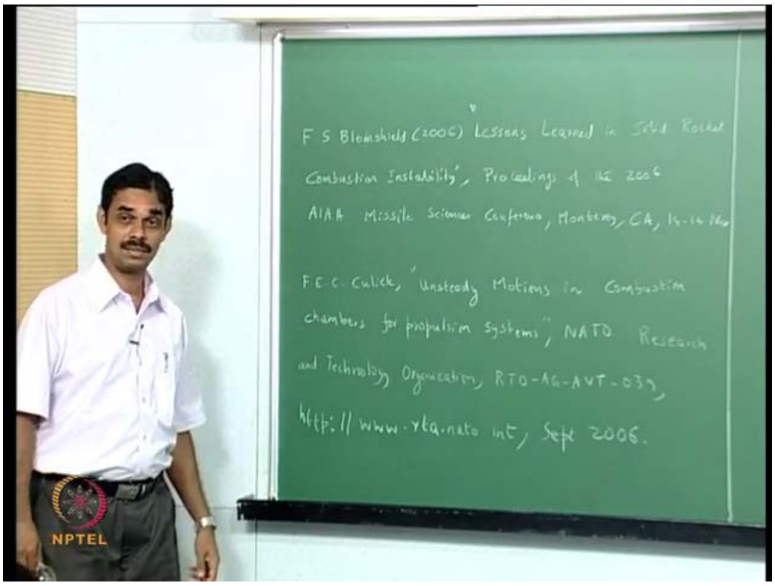
Acoustic Instabilities in Aerospace Propulsion
Prof. R I Sujith
Department of Aerospace Engineering
Indian Institute of Technology, Madras

Lecture - 38
Solid Propellant Combustion Instability-2

Good morning everyone. Let us continue with our discussion on solid rocket motors and the instability associated with that.

(Refer Slide Time: 00:18)



So, I have written down. I have written down two references. One is FS Blomshield is a person with a lot of experience and solid rocket combustion instability article stated lesson learnt and solid rocket combustion instability. It is in the proceedings of 2006 A1AA missile Sciences conference, Monterey, California. This article is there in the internet.

So, if you just search for Blomshield and type one of the words, you should be able to get it. It is a very nice article, easy to read and most of the things that I am saying, yes, from that. It does not give any great mathematical way to calculate these things. It just gives an over view and rules of thumb and so on, but it is an excellent reference, lot of to it. You are also given about seventy five plus references which will have all the details.

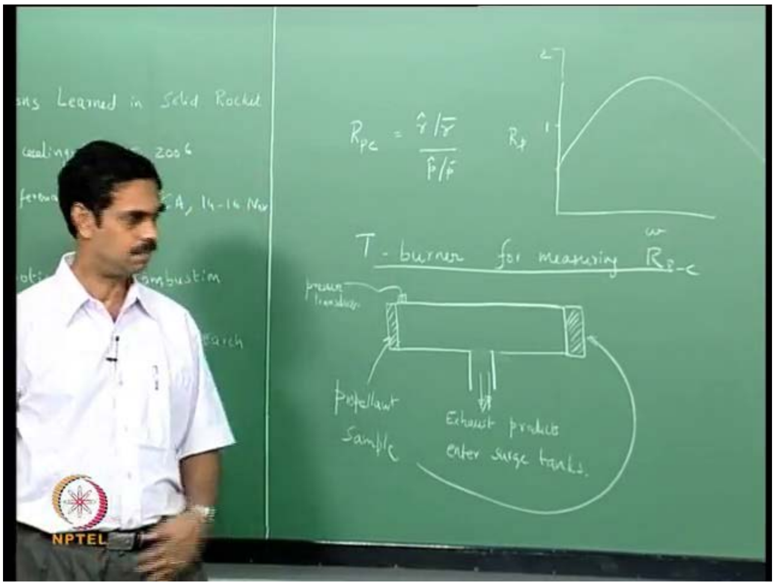
The second reference which will indeed give all the Maths is from professor Culick, Fred Culick, title unsteady motions and combustion chambers for proportion system, NATO research and technology organization, RTO, AG, AVT, 039. So, this 39 is the report number. If you type Culick and any of these keywords or if you go to this website, you can get this, get this book free. It is a full book written properly, not just a cut and pastes.

It is a full book, proper text book, but it is available in the internet. So, you can download that in it. Culick is the person who kind of let the foundation of research on the framework for analyzing solid rocket instability. He worked; I do not know 1960s to even now he is doing the same thing. So, that is lot of wisdom distilled in the book and you should read it. He gives the normal mode analysis. He gives, he derives and get detail how to get the alphas from the response functions and, and, and so on. Of course, he says the modes are normal that is where I have disagreement, but otherwise, it is a wonderful book. He has written very good results about everything.

So, both are freely available, readily available. So, please take a look at them at least. Now, I wish to speak about, little bit more about the driving mechanism; in particular, the pressure couple response. So, the way it is defined is, it is defined as the peat burning rate over the mean burn, mean burn rate that is the way it is because how much the perturbation in burn rate over the mean burn rate, how is that dependent on the perturbation pressure over the mean pressure rate.

So, it is the ratio between these two. So, the pressure coupled response is the amplification of the coupling between the combustion process and the combustion process at the propellant surface and the acoustic pressure. So, this is the most important parameter in combustion instability in solid rocket.

(Refer Slide Time: 03:23)



So, Rpc is equal to r hat over r bar divided by p hat over p bar. So, r hat is the amplitude of the burn rate oscillation, r is the mean burn rate, p hat is the fluctuating pressure or the acoustic oscillation pressure oscillations and p bar is the mean pressure. So, this is a function of, of course burn rate mean pressure frequency and other propellant properties.

So, it is not like a constant thing. It is a function of mean pressure, mean burn rate frequency. What are the additives and propellant, what are the catalysts involved and so on? You can show that if you have a propellant burn rate of the form of r equal to a p power n, which I think you are know, then you would, you can show that that zero frequency or the quasi study response, this would be same as the n. It is a strong function of frequency.

So, Rp versus p word actually go like this. So, typically your n is less than 1, so 1, 2, but then this is at some frequency is go up and come down again. You have to determine this for various parameters with experiments. There are people trying to calculate it, but it does not that simple. It is not like a proof and calculation. I think we are still not there to calculate this properly, but we have to do experiments.

Like I said, this is the most important parameter and once again, if you think in terms of r equal to a p power n, the n gives the response only for omega is 0, but after that, it just, it depends very much on how the flame response, the acoustic oscillations. That need not be in a quasi steady manner at all. The flame may act like a filter. It may respond differently at different frequencies and so on. So, we cannot purely think quasi state. We should not think quasi steady at all. Now, there are many reasons for opening the pressure couple response of a propellant because primarily it can be used to compare propellants distains for the same application.

So, at a given frequency, if you have propellants where different Rpc response functions, the one which will be having lower response will be less likely to drive instability than the one with higher response. Now, that is one thing. So, straight away, it gives like a idea how much is the acoustic driving in general or propellants drive. It is very unlikely that propellants and we can use this. We should use this in this calculation of alpha, alpha from the pressure couple response can be obtained from this. That is what the driving mechanism, primary driving mechanism is. The issue is whether that can be balanced by all over losses. Now, this, to get a detailed idea of the stability calculation, I suggest you read this book.

It is given very clearly, elaborately, starting from three d, then it derives one d version. In some sense, it is a very more complicated version of what we did for a rike tube or something like that. There our heat release function was like a delta function sitting at one place, but as here, the combustion is distributed. So, it is there everywhere. You are having comparison everywhere.

So, you are having driving everywhere, but apart from that, it is very similar analysis. I am sure you can follow it, but, it is just involved, but it is very interesting and very nice. You will just take some time to do it. I am not doing it in class because it will take a long time to do, but the basic principle is what we did in the analysis of rile tube or n tau model that mathematics and so on so forth.

So, I think you have enough competence and background to follow this analysis in given by Culick. Of course, this analysis originally appeared in the 1970s in various general articles. He has summarized everything into this book. So, the original papers, you can read and that will give you of course, some historical insight in the how things were done and the way they are going on.

Now, we should measure the propellant response as I mentioned because that is what the input to the stability program is, in to words calculating alpha. There is no way you can simply guess what the propellant response is and it is a function of various parameters.

So, it is really non trivial task. So, there is some way. There are many ways to measure the propellant response. I will tell you the most popular way, which is called using at T burner. So, you can use t burner for measuring the pressure couple response. The device is called T burner because it looks like a T. That is all this know pressure thing about it.

So, you have a tube and you keep properly that both ans. Now, this has a problem because as you start burning, the pressure will keep on going out. So, what you do is to have some exhaust. The exhaust products go to a search tag so that the pressure does not change. The mean pressure does not change dramatically doing the experiments because we want the mean pressure to stay fairly constant during the experiment so that we can measure the proper response at such some particular mean pressure.

So, we will have to put, mount some pressure transducer and this would be the propellant sample. You mount them symmetrically on both sides. This is also propellant sample. Sometimes, you have provision to drive oscillations externally. They would also have photo transistors to check is the combustion over, but those are just details. So, you put to this out propellant. Typically, this pipe is about one and a half inch diameter. That is what is used in practice; probably that is a good size on experience.

I am sure they must have tried one engine, two engines; three engines found that this is the best part. Typically, if you see literature, in the open literature, it seems like one and the half inches, the most common size and you have them mounted on both sides. You ignite them simultaneously. You mount pressure transducers near the n. The reason for mounting pressure transducer near the n is because pressure is maximum there whichever more details. So, you pressurize it to begin with so that we can get the right mean pressure. So, what you say…

Student: The n…

Yeah…

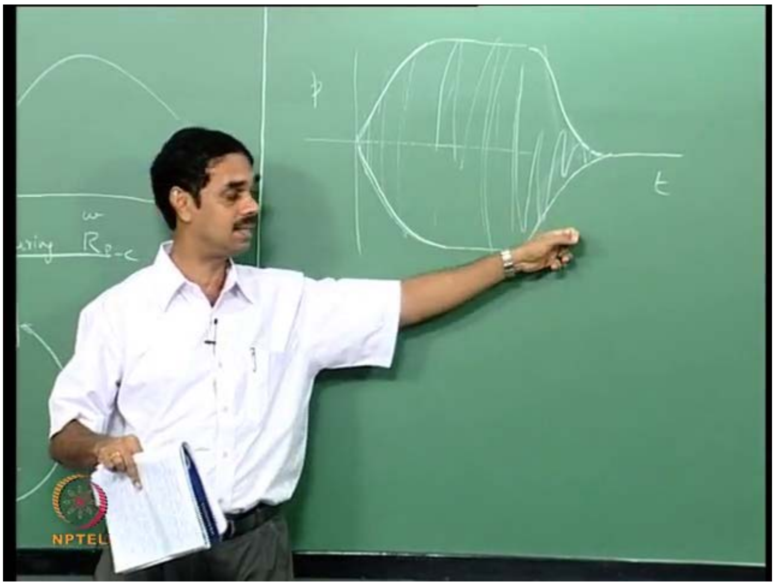
Student: So, we have burning the surface…

Yeah…

Student: It will be received and if the pressure maximum after sometime…

Fine… It will be only receding slightly. So, I mean propellant is like, so what is the samples, so it will receive slightly compared to length which is like one meter or sixty centimeter one and half meter. The length is determined by the frequency that you want to excite the natural mode and so compared to that, if you among burning will not change frequency low.

(Refer Slide Time: 12:00)



So, what you do is if you look at the time trace in such a condition, so the oscillations will grow initially and reach some kind of limit cycle kind of thing and then eventually follow. So, this will be pressure versus time. Let us say that we can record it. These experiments were done in the nineteen fifties. I think the first one was reported in 1958 or somewhere around that.

So, in those days, they were no SD cards and all that, but still they doing it with an oscilloscope. You would have this, the storage oscilloscope. Then, you take a photograph with the oscilloscope. That was the fancy technology. Then, there came the tape recorders. I do not know if you have seen these types of tape recorders. So, you could use that and then later on analyze that is to do something. But, in any case, you find. So, this is the growth with the propellant money, but, in reality, you can imagine that you are having the propellant driving as well as the gasses damping. I mean the volume is damping. So, there is damping in the system, is always present.

So, what you are seeing is driving minus damping, but we want the driving. So, how do you do that? We have to measure the damping. What is the best way to measure damping? Eventually, this half inch of propellant is going to finish burning. So, when that finishes burning, these oscillations will die down. So, the rate at which it will die down, the decay rate will give the damping. So, you have just to subtract. So, this is the damping rate. This is driving minus damping. You just add this rate to that rate. You will get the total driving from the propellant. From that, you can. So, this is the crux with the matter.

There are no more complexities. From that, you can actually determine the pressure coupled response in this form. So, that is the crux to the matter. That is you have growth, but when it grows, there is not only propellant driving. So, let say, there is a certain alpha one quantity of driving minus alpha two which is a loss, but you have to measure the alpha two. Then, what you have measuring, the alpha one minus alpha two. Suppose in alpha two that can be added to alpha one minus alpha two plus alpha two which will give alpha one. The way you find the alpha two, the decay is by looking at, once the combustion complete; you look at this slope of this curve.

From that, you can get the decay rate. So, I hope this is clear. There is externally different version of this called pulse T burner in which there is a possibility to get the oscillation kick because sometimes the propellant driving may not be enough so that it may not start one. But, this is the basic principle. I do not want to go any further in to it. If anybody is interested, I have a PHD thesis on this. This paper by Blomshield gives nice references about T burner, which we can actually get from the web. You may have to correct it. They may not be the same. You are talking about a very important point because once the burning gets completed, the temperature might change.

So, your natural frequency will change, but you will have to do this at various lengths and then determine this alpha one minus alpha two at various lengths and alpha two at alpha one minus alpha two for various frequencies and then alpha two for various frequencies. The alpha two corresponding to this experiment, we have to determine from some other experiments because the temperature changes. So, that will have, that has to be some correction to it. So, I mean strictly speaking, but it may not vary so much also with temperature, but yes, this is important point. Any other question?

Student: is not is it constant all in the time…

Well, see, in some sense, it is constant only when you are having a linear growth. Then, it grows exponentially and so on. But, then after that, it is, let us strictly speaking, if you zoom in here, you would see some kind of exponential growth. But, then, you can see it is coming down. So, you will have to catch in this region. So, it is a constant growth is a perfectly valid region? It is not, but you have to find reason where it is constant. I mean the growth is exponential. That means the growth rate is constant. Then, do the measurement in that.

Student: Other part is…

One more thing is these are very deep questions that you are raising because your amplitude as to be small for the linear theory to be valid and so on. So, that is when the non-linearity is small that is when the growth rate is constant. But, when the amplitude is very small, you may not be able to get the growth rate very well. So, there is always a compromise and the same thing here.

Student: in the constant part …

Yeah, it has reached a limit cycle, but I mean I am not looking at the linear theory. So, growth rate does not mean there is no instability. It can mean that we have reached a limit cycle. Any other questions?

Student: Increasing the mean pressure will be there not so ah…

So, we have to collect these. We have to connect this search tank, search by sep exhaust product enter search tank and which has a very big volume compared to this volume so that it would not, pressure would not change much.

So, if you are moment Diller very rich, the expenses you make would not bother your financial status much. But, if you do not have money, if you spend something today, your financial status will change dramatically, but if you are connected to the pockets, your parents, then pressure would not change. The money would not; the money level you have with you would not change. So, this is the same thing. So, you want to make search tank quite big and the some gate blanks to that.

So, you see, make sure that the pressure does not change. The mean pressure would not change more than a few percentages. I think very brilliant points, but all this has been taught about and incorporated. Getting a T burner work is the device is very simple and principle. But, it is actually quite an art and very difficult thing to do. That is what I would say. Some stories can be told off the camera later. Any other point? I am really impressed with the questions.

So, I was not planning on speaking about motor instrumentation, but since, Vishnu raised this point few times, I will speak last class as well as earlier is very interesting measurement. So, I thought somebody interested will do, speak little bit. I have some idea, having seen instrumentation in real rockets, but I cannot say where due to this. I do not want to go to this.

So, we have to instrument the rocket correctly because the test is very costly, doing the static test. Do you have any idea how much a test costs? Can you try to guess? Yeah, it is kind of, what it is, when PSLV that motor was tested, I remember the price. It was forty crore. This was in in late eighties. I think know that p s one. I do not know how much it cost for s two 100, but would probably around 100 crore. So, it is so expensive and this is tested in India. I mean in abroad, it may be one more expensive. Yeah.

Student: For the complete burning timing…

Yeah, 100 and twenty seconds, whatever it takes. So, you take the motor. We have to make sure that the rocket does not fly off. So, the thing has to be sufficiently strong to hold it, otherwise you know, you can expect. I mean the power associated thrust is so much that they have a device that has to hold that as it is there. Have you seen? Have you been there? In Trivandrum, they have little want to test the sound in rockets. I have seen that live fire, it is really impressive, but as in shall, they have that massive thing. I think you have to stand seven kilometers away from it when the test is done in case this wall breaks. So, they directly measure to the thrust.

But, small rocket, they can actually do it vertical and all that so that you can hold, but here that is too difficult. So, it is done horizontally, but of course, a 100 crore will be a big amount or small amount may not be, it will be proportional to small amount, but it is quite expensive in either case. So, it is strongly recommended that all development motors will be instrument that with all the transducers is electronic piece of resistive transducers to observe combustive ability.

Now, you may say that let instability come. Then, I will measure it, but there is a count argument at least the way in done in India I think in America. They do several lots of tests, may be fifty or 100 tests, but here, they do not want to do. But, we rely more on analysis simply because we do not have kind of money to be honest. So, you have to be more careful. So, I mean p s one was tested that first one, one twenty five tone rocket was tested two times. They then upgraded to 100 and thirty nine tone. They tested it once. So, I mean which is really impressive, but that means that everything has to be accounted for so that we do not see.

Now, you may say that, then again you may say that there is instability may not happen. I am expert in designing. I would, I know to make instability not to come, but if you look at the history, then lots of cases were there. There was no instability in a rocket for several years. Then, all of sudden, out of the blue, it came. So, at least, you know what was there to begin with. So, I think buying a transducer for, I do not know two lac rupees and put putting two or three or may be less one lac. That is much better than this times spend on 100 crore.

Then, you forgot to put this transducer or you do not have it. Then, as I said, you can, if everything goes well no body is going to blame, but if things go wrong, then like dhoni was saying that if India did not win, all these questions as to why did I come number four, why did shreeshant bowl and that was there. He was so keen that we win. So, it is the same thing. If something works in, you know, you can. The chairman will give hi fi to the prime minister and this entire president and all that. But, these things will go long. It is people like ask you get the x. So, we make sure that engineers make sure that everything is put in stories in my room.

So, we can always have, I mean we preferred to have pressure data always strain gauge data because strain gauge for is generally for measuring mean pressure. That is what the use is as a experience with strain gauge, but sometimes it fix up oscillations also. But, do frequency it may pick up, but would not really pick up high frequency. Sometimes, I mean you have accelerometer data. Now, many times, you end up looking at accelerometer data and strain gauge data because they did not put the piezoelectric or piezo resistant transducer and then instability came on. Then, this is the only thing you have. So, you might as well look at it.

So, then you end up by looking at this. It will be really nice to have pop up pressure, proper piezoelectric transducers or piezo resistant transducers put into thing piezo resistive because a DC shift can happen and mean pressure can elevate quite a bit. If you are talking about this small rocket like the air to air missiles or something like that or this small hand held, then the frequency can be very high because the smaller the motor, the frequency will be high. If you have, so there you have to have high response high frequency response transducers. You have to have good piece of electric transducers, but if you are talking about a 20 meter long motor longer than that, then the frequencies will be very low that will be typically like this space shuttle oscillation 15 hertz or something and the area.

I think it was like twenty something twenty five hertz or something. So, natural modes will be having very low frequency. So, there you do not need very high frequency transducers. Now, where to place the transducers? We would like to measure them at pressure maxima. So, if you have it had the end, and then you will always have pressure maxima. Therefore, you will defiantly measure the pressure, whatever mode it is. If it is a longitudinal mode, but if it is a tangential mode, then you have to put them at different locations. Then, you have, we can see, you have to see the phase whether all transducers going up all the pressure is going up together or one is going up and one is coming up later.

Then, you have a mode like this. So, typically you can put in laboratory. You can put ten transducers into circumference, but not in a real rocket. So, they put at 100 and twenty degree interval to see. That is the best they can do. It will be preferable to put it. If the oscillations is in the middle to put it there, but that may not be possible. So, they often mount at the end and see what is happening.

Student: The solid rocket and radial molds can dam to itself be there.

See, any mode can be dammed or driven by all this mechanisms, but ultimately what comes depends on whether you can excite, if there is a mode at a certain frequency whether the propellant can drive instability that frequency and whether the driving is having is putting in more energy than the acoustic energy take a note by the damping.

So, there is no general thing like propellant will damp radial modes. So, axial modes are very easy to get because these rockets are typically long. So, it is quite easy. There is a lower frequency that is easy to come. The next dimension is the circumference. Radius of the dimension is very small.

So, naturally the frequency associated with radial model is very large and propellant may not respond to, but there is no blanket statement because every kind of thing has been seen somewhere, or the other. So, whenever possible also, use redundant transducers because many times. So, when things go well, everything goes well. You cannot put 100 transducers, but you can put not just one. This is because you may put one transducer and it may fail in the test. That is quite possible because you are talking about I mean high temperature and high pressure and all that. So, full scale firings are too expensive, not to take the extra instruments in other words of Blomshield.

Of course, many times, these transducers are mounted on extension tube like because they cannot be mount at straight on. In that case, we have to be very careful to calibrate those mountings because otherwise, you may end up having, first of all, this tube extension duck may actually change the frequencies responsive transducer. You may actually measure modes which are belonging to that rather than the rocket. So, you may end up having things which really do not have anything to do with the actual thing. So, one has to be quite careful. So, this is some general observation about incrementing a rocket for having some idea about combustibility. Then, any questions?

So, I will give some general observation about solid rocket motor instability before I move into explaining triggering and non-linear instabilities. These are observations done over long period of testing from the fifties. The first test started, this rocket instability was first reported during this as World War two. So, I do not know if it was there before that rockets whether longtime. I do not know whether instability was reported.

The first study started in the fifties with a massive thrust and massive thrust in this rocket programs because the cold warms and the military race as well as the space race and so on. So, then it tries to push hard and then you cannot delete push hard because they make the motor and it goes unstable. Then, you have to solve it. So, a lot of money was invested, but then, once the motor works or they somehow manage to get the vehicle flying, then the funding for the instability will be cut because of problem is fixed. Why should these guys be fixed, be given money? So, let us forget about it.

Then, sometime later, any other model instability at that time, they will go hunting for somebody who knows anything about it. Then, some guy will be caught and brought here and given royal treatment. You will fix the problem and again will be thrown out without anything. So, there has not been a tradition of continuously supporting this instability program. I would not; prime reason is this may be one reason. The other thing may be that I mean, in my experience, the people who run the programs, often I have no idea what instability is. So, if you do not appreciate this thing, what is going on? It may be just treated as which craft or black art or something.

So, then chance of you, supporting it is very less compared to some regular fluid mechanics to study something which looks like more like a professional science. So, that is another thing, but any way, so quite a bit of it is this kind of general knowledge and quite a bit of it is from the experience. So, you cannot quite read papers, and then say I am expert because you have to have worked on it. Only then, you will be able to make the connection between the readings. These many times, you have to make a call on which is, we will what to do there in there is one person in our department, Chakravarty. I think you know him. He is very good at this which craft.

I mean he has lot of experience with fixing, fixing in solid rockets in each. As I mentioned earlier, in each device, the specific driving mechanism is different, but the general principles are same. The out coming features of the oscillations are same. So, I mean I am very good at fixing things with geyser system, but I do not have any experience with a solid prevalence. So, if I do not have the idea, saying put 1 percentage of this, of 0.1 percentage of this and the thing magically vanishes and that kind of thing, I do not have whereas in a gas tribune kind of combustor, I have some black magic.

So, if the driving mechanism is very specific to the device and you have to have experience with that thing to be able to get specific idea about the driving. Your all acoustics features will be very same for rocket or gas tribune anything. So, I think, this is, these are something you have to keep track of. I think there is no substitute for experience. So, very fine and ultra fine means typically less than one micron a p oxidize particles usually give high pressure coupled response. So, you use very small a p. The reason for using small a p which to you have small a p particles. You can increase the burn rate. You must study and some proportion classes.

So, then proportion with fine a p is known to combustibility generally. So, if you have particles which are less than five macron size a p particle quite a bit. Of course, a p size is always a distribution. So, you have a lot of very small a p. That is the way you are going to increase the burn rate. I think you have to be careful about instability occurring. In general, if a p particle size is constant, higher burn, burning rate will give the low pressure coupled response. That is it may sound continuity, but if you keep a p particle size constant, you can get higher burn rate by additives of catalyst.

So, if that happens, then typically you see less accessibility to instabilities and vary course a p. Again, a p's ammonium perchlorate gives instability and the response function. This pressure coupled response function is a very strong dependence on p bar. So, you must do elaborate testing and propellants with a low pressure exponent will in general have lower response function. So, it is not that n is same as the response function, but generally, it is seen that propellants with lower n. These exponents burn rate in that will have a lower response function. In general, if you increase the mean pressure, then that is what everybody wants to do.

You want to increase mean pressure because you can have more thrust. That is it. So, if you increase the mean pressure and if you keep other factors same of course, the question is how to increase mean pressure in rocket keeping other factors, keeping the same propellant. Now, you keep your same motor, same propellant, you cannot, you are not, you cannot burn more remains. It is a rocket. I have given you a rocket. How will you increase the pressure? You change the nozzle. What do you do in the nozzle change through? Yes, but then, when you have reigning the mean pressure, it reduces the stability margin things, go on stable easily.

That is primarily because you are actually decreasing the nozzle damping because when you increase the mean pressure, the nozzle reflects more acoustic wave back. You are decreasing the nozzle damping. You are also reducing the flow turning losses that has been found. So, a stable motor may tend to become unstable. If that does not happen, a stable motor may become susceptible to non-linear instabilities. That is positive stability that everything is fine. But, suddenly it goes unstable because some disturbance happens and disturbances can happen because a small piece of propellant can break off. It will be carried out through nozzle and momentarily, it will block the nozzle.

So, that will lead to a special spike and that spike can actually initiate the oscillations and that is being triggering instability. So, you can have triggering instability when the motor did not have its own. If you increase the mean pressure, may be it will come in. So, if there is instability, then one possibility is to reduce the pressure. This is one thing that you can try, but then, nobody will like that because if you lower the pressure, you are kind of compromising the performance and some sense.

So, to summarize and explain the statements, if you increase the burn rate with catalysis, propellant comb stance response will tend to go down. But, if one increases the burn rate with fine a p, the propellant response will actually tend to go up and very fine or coarse ap also is not good from a or very coarse both are not good from combustibility point of view and for very fine a p crystals burning in these crystals are surrounded to that fuel binder. So, the chemical reaction processes are kinetically controlled. That means the reaction is the slowest thing that is there and they have a relatively high reaction order. So, the reaction order is the pressure exponent in the chemical equilibrium equation and so very large a p.

Therefore, if you have a large pressure index, naturally the burning is now susceptible to pressure. So, the burn rate will depend on the pressure fluctuation and that will give the pressure couple response. Now, if you have very large a p crystals, combustion rate is kind of controlled by a p mono propellant flame, then a p itself will act as a mono propellant that means ammonium fluoride has both the fuel oxidize. There will be big crystals where this flame is there and this is also a high order reaction. So, as the pressure fluctuates, the reaction get fluctuated there by giving high pressure couple response. So, in between these extremes of particles size, combusting process are believed to be controlled more by delusional affects which are not as sensitive to the pressure oscillations.

So, that is why, we do not want to go to very fine a p. You do not want to, you have to be careful if you are going below five micron or if you having very large a p size, coarse a p, then also you have to worry about it. We will briefly look at the flow effects. I mean we treat acoustic as if there is no flow, but there is a flow. One thing is when you design a motor, if there are sharp corners; you will have rotate shifting ammonium fluoride ammonium fluoride rotate shifting. Rotate shifting can actually interact with the acoustic modes. You can drive large oscillations. Even on its own, it makes sound. But, when you have inside a cavity, you can have resonances.

So, avoid protruding inhibitions which is what the suggestion rocket instability is. They will give, but then, you need inhibitors because otherwise, you cannot have segments of motors. So, always things are conflicting, but that is the way it is. Avoid the radial slots. We put radial slots to put or give stress relief because this is under stress because you are casting it and so on. But, again that is when the propellant is, you are putting two things and in between that, there is a little gap. There it will start burning and the thing will expand.

Student: burn rate as…

That is not inhibiting. Then, it is not inhibiting. It is also burning. So, these are two things are pressing and this is burning. So, the slot will open up. So, we do not want it to burn this way, but if you do not want to burn this way, it would not burn that that way also. Anything you do, you achieve something, else life as well as in combusting instability. So, oscillations created by vortex shedding. It was not bang bang oscillations or they are not varying loud as the oscillations created by thermo acoustic instability. Typically, the amplitude may be one percentage and so on, but even that may be quite, may lead to quite a bit of thrust oscillations in a big motor.

In fact, I mention that the thrust oscillation percentage may be about ten times that of burn rate that are the pressure oscillations. Try to see. Think about it. It may be asked to you in the exam how this happens. See, if you can think about it, maybe it was there. All the questions that I give you are also in the question papers.

So, if you have large size, you have low frequencies. Those low frequencies, even small oscillations may create lot of damage actually. Perhaps, this is because everything can respond to low frequency oscillations so that even though the amplitudes are very small, so the other thing is if you have large area, then what happens? It can increase driving due to velocity coupling because you know if you have large burning, if you have a star grain or something to words the nozzle, then you have large area in this large burning.

Then, the amount of propellant is burning is a quite large and there is high velocity over it. You can actually have velocity coupling affect.

So, typically star grains put right at the beginning. If you have a lot of burning area at the end, you can also end up decreasing the nozzle damping because most of the aft cases are exposed as the motor burns. So, we try to put stars at the head and not near the nozzle. If possible, some motors which are multiple nozzles are in general, they can give damping, but then anything which will help you under circumstances can boom around under some other circumstances. If you mount them, then it says that there is some flat area in between. Then, that would reflect the waves very well and then probably create more problems than the increase in damping. You got mounting nozzles. One has to be very careful.

So, whatever you do, I think it is a very good idea to measure the nozzle at mittens. We know how to measure at mittens. You can mount the nozzles and measure the standing wave. Then, from that, you can get that way. So, for star or vegan wheel or other similar slotted geometries, they are used in propellant. You know why star is used. You want. Initially, I have to have very rapid pressure. Then, you may want to have star circuit. So, the traditional wisdom is that you have to have odd numbers of stars or odd number of eigenvalues so that you know the tangential modes. It would not support because your harmonics would not be there.

This is because we have odd number that is not that. If you have four, it may support second mode. If you have five, it would, but that is traditional wisdom. But, lately some studies are saying that this may not be true. The number of slots seems to make no difference. So, I do not know, but if you see the traditional wisdom and the rule of thumb, you say go for odd number of ranges, but some people are saying that it does not matter. We also spoke about s star instability.

You remember what it was, non-acoustic instability, acoustic instability would mean what? Pressure is, these are modes here the whole pressure goes up and down. So, if you have low volume, and then you are creating certain, you are generating certain amount of gases by proper burning, some amount of going out through a nozzle and you may, at some instant, I have more gas and then mode may go and more pressure. Then, as more gases are pumped out, the pressure may come down and so this can oscillate. This particularly happens when your volume is less. So, l star would mean, do you remember what l star is? It is volume divided by through area.

So, when you have low l star that means low volume, you have this instability is like the same thing. Also think about that if you spend money, if you do not have too much money, there will be lot of fluctuation, but if you have the pockets, then you spend or do not spend, it is not going affect your balance a lot. So, it is something like that. Now, the last thing I want to speak before I close off this course is particle affect. So, you have particles that are added and primarily for damping, the oscillations. Particle damping is, of course, the most common particle is aluminum. So, aluminum burns to form alumina. Also, things like silicon carbide, which are added as stability additives, they not only form this particle, but they also influence the reactions in the surface and so on.

So, particle damping at a particular frequency is very dependent on the particle size. So, if you have high frequencies, you need small particle size to damp them. For lower frequencies, you typically use bigger size particle and some of the additives like silicon carbide, you add. They actually modify the response function. They actually change the pressure index in these chemical reactions. So, they actually alter response function in addition to having these two phase flow losses. Of course, the wave particle responds to oscillations is particle, they can be molten drop. It is not, when it is a particle, we think solid, but it can be droplets also.

Now, it is not quite linear responds. For a particle to give a liner response to velocity for drag, you have to have even under quasi steady conditions. You have to have very lower and 0.01 to gives Stokes's drag, but here, the Reynolds's number will be quite high. So, I mean quite high as ten, twenty or thirty. So, it will not be Stokes's drag. So, it is a non-linear function, but this aluminum is burning to give alumina. That is a good thing. That is what the main tool is. The designer has to bring the instability down.

Not only does it bring the instability down, but it also increases the specific impulse. The only thing is you have to use the correct size so that and the size has depends on the frequency that I excited. So, that you have to keep track of. Of course, if you use very small propellant, very small aluminum size, then it may also affect the propellant responds the pressure couple response. One has to be careful about that, but in general, aluminum is used so that it burns to give alumina. Then, that is, that can damp the oscillations and the amount of aluminum that is put is very high. It is like 18percentage in the western rockets. The Russians say that they can use as highest 23 percent, but that kind of thing is not done by us or the western countries.

I am not sure why we are unable to. It seems a question of technology. Then, there are some places where you cannot put aluminum. We have to have smoke less propellant for military applications and there you are not allowed to put any of these additives. So, these adding additives to the propellant and affecting like silicon carbide and affecting the burn rate that is a delicate art, which you have to have. That is what another thing that is tried because sometimes you already have 18 percent aluminum and still you are having these oscillations. That is probably what is left. You have one composition. If you ask an expert, which way to go, you will say both sides; whichever works, stay here.

I mean that is the way it is. I mean unfortunately it is. So, you can affect the reaction, but it is not very easy to know because there is no experimental evidence to really understand the controlling mechanisms that cause some propellants to respond differently to pressure oscillations and some other propellants. But, I think over the fifty years, a lot of improvement has happened in understanding combustion, but not really stopping it. But, may be in next fifty years, it may be even better as to we can stop it. So, we will stop the discussion on combustibility today here.

Thank you.