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

Lecture - 36
Active Control of Thermoacoutic Instability Revisited

We in the last few classes, we are speaking about combustion instability involving damp combustors and so on. So, what we saw was the predominant features in the damp combustor, the kind of fluid mechanics that happens the kind of heat release rate that happens and how the fluid mechanics affects the heat released rate and so on. Nevertheless we did not learn any quick calculation procedure because there is no real simple quick calculation procedure, what we would need is to experimentally study, we will have to use the experimental devices like you have to use measurement devices like pressure, transducers for the acoustic pressure. Like piezoelectric transducers or microphones and to see the flow we can do optical flow diagnostics, to see the velocity field we can either use particular image which will give a whole field view, or to get the spectrum and so on.

And we can do to see the combustion we can use planar fluorescence or even chemi luminouscence and so on and so forth. To be able to calculate we have to make a model and it is the phenomena is so complicated that you cannot make a simple, very simple model. We have to actually solve the partial differential equation of the flow and combustion. So, we should necessarily mean we have to use CFD computational fluid dynamics and in the end we have to get the heat released rate, which you can directly then there are two possibilities. So, we can actually couple it with the time domain solution and we can mark step by step both in the acoustics as well as in the combustions step by step, in a very closely coupled manner. So, that would provide you a time domain solution right.

And what is the other alternative either you can solve in time domain or in frequency domain and for that we would in the linear analysis what we would do is we would distil this combustion response into transfer function, and feed it into the analysis in the form of end term model or something. And if you are in a time domain you do not have to do it you just have to march directly and you can do a linear or a non-linear simulations, and so which we have studied actually, we have learned quite a bit that is how to analyse a system in time domain, as well as in frequency domain. The important catch here is how to get the heat release response, once you do that we know how to solve the problem.

And I told you that that how to catch the heat release response is not a really very trivial problem it has to be solved keeping all the physics in that. So, if you are looking at a Bunsen burner kind of flame, we wrote the equations and we learnt how to do it, we do it for did we do it for any other one for a combustor, we made a model which was driven by fluctuations. But then so in the same manner if you have a model then we can do the analysis and then once you have the analysis, we can find the Eigen values we can find the growth rates, we can or the decay rates we can find the frequency of oscillations. We can find we can perform the normal stability analysis and look at growth factor and so on. We can draw the bifurcation diagrams using continuation methods or direct time marching.

So, we have actually learnt a quite a bit in the course the only thing that we have not learned a general prescription is to get a simple relation for heat release just like that for any combustor, that is elusive and that is elusive because it is quite a combustion is inherently difficult and in intricate complex phenomena, and so we have to calculate it properly, understanding all the physics. And therefore, you have to do the experiments because you may have a model and we have to ensure that the model captures all the physical phenomena that you see in the experiment. So, this is by definition every complex process therefore, the calculation will also be complex and you have to be very careful and we cannot be this away.

So, I hope you have got this message we also briefly looked at some aspects of passive control very briefly and so the several other combustors were stabilise combustors, liquid rockets, solid rockets itself will have composite propellant or a double base propellant. So, each of them would have a different analysis because in each case the flame is behaving differently, in some cases the flame will respond to the pressure oscillations in if there is a pressure couple response in solar rocket motor as the pressure goes up and down the flame would behave differently.

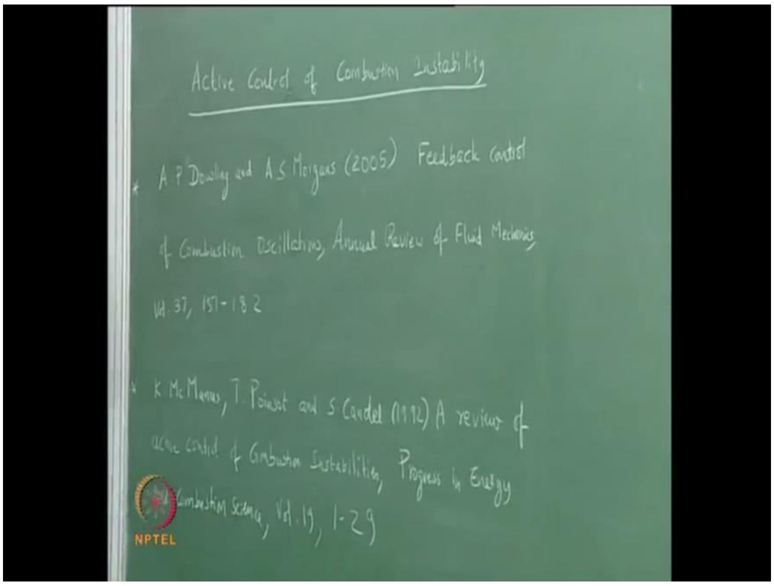
Whereas, in some other combustor the flame may not respond to the physical, the flame may not respond to the velocity fluctuations at all flame may be responding to only pressure fluctuations or some other set of combustors flame may respond only to the velocity fluctuations, and not to the pressure fluctuations or in some complicated situations like rockets sometimes the flame responds both to the velocity fluctuations and the pressure fluctuations. And also we have this time delay and so on.

So, this is the case and then this is what this is what we have learnt, now the only thing that just to reemphasize is which we are we have left loose is a general strategy to calculate heat release rate, but if you are confident to do combustion CFD unsteady combustion CFD, which I trust you can learn it from some other classes or on your learn. And then we have the framework to study the linear and non-linear analysis thermocoustic instabilities. In this context you have any general questions too early in the morning for questions.

So, we did speak about we did speak about passive control and stability, we will take a brief very brief look at active control instabilities, this is not going in any depth or I am not going to into depth like, we did the end tau analysis with Eigen values and frequency domain and time domain. And after my lecture you would not learn how to analyse how to design a controller or anything, but I will just give a very brief introduction that is all we can hope for, anything more would need very large number of lectures and end up in knowledge of control, which I am now myself is not working in active control.

So, to summarise combustion often arises due to a coupling between the unsteady heat released and the acoustic combustion oscillations occur because of the coupling between unsteady heat release and the acoustic waves. So, I mean the key is to remove the coupling or if sounds come get out that is the idea of control.

(Refer Slide Time: 06:59)



And in this context I have two references for active control of combustion of stability that is what we will do today. So, Dowly and A S Mergeus feedback control of combustion oscillations in this journal, annual review of fluid mechanics volume 37 page 151 to 182 annual review of fluid mechanics is a impressive journal in which every year the editor about selects, looks at what are the developments that are there. And if some subject has come to some level of understanding or closure and then they are starting off in some other directions. They will invite the best person in the subject to come and write a article and you cannot just go and send them a article. And so that is annual review of fluid mechanics so it is a very prestigious thing to get an invitation to write there.

So, these are relatively new article in 2005 and then this one we have looked earlier when we started off the frequency domain analysis by Mc Manus, T Poinset and Sebastian Candel a review of active control of combustions and stabilities, progress and analogy and combustion science volume 19 1 to 29. And so this one the first one has a more recent stuff this is older stuff much older stuff and lot of things happened in between and so it is worth reading both because then you get the idea of how this subject evolved.

So, a unsteady combustion is a efficient source of acoustic oscillation actually and combustions seem to be highly resonant system, combustion does not resonate if these. If you are never having a confinement then if you are always burning everything outside there we wouldn't have combustion stability because the waves are going they are not coming back to create any problems. Therefore, when unsteady heat release rate generates a acoustic waves they reflect of the combustor and produce a flow unsteadiness in the flame and that is the key thing, flow unsteadiness and heat release unsteadiness.

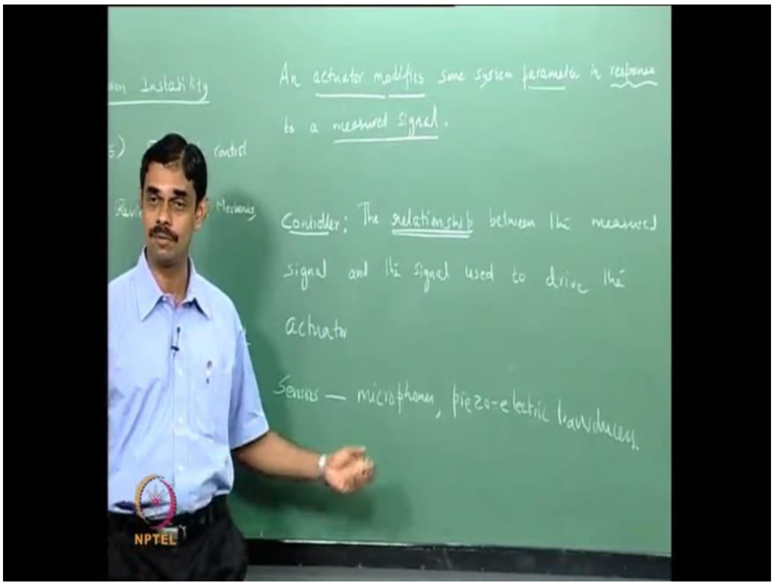
So, this may cause more unsteady heat release for example, through we saw many mechanical local changes in fuel error ratio through hydrodynamics stability, through flame area modulations or through change in mixing patterns. So, many ways we can have unsteady heat release coming up and we saw a bunch of mechanisms. To eliminate combustion of oscillations the coupling between the acoustic waves and the unsteady heat release must be disrupted, then you do not get the oscillations and this is the key stuff.

So, people did passive control methods we saw that included a modifying fuel injection system or the combustion geometry or removing energy from the sound waves, using acoustic dampers, perforated plates, baffles liners ((Refer Time: 09:50)) tubes. So, in this we are not really not having see in the active control, we have the instability and then we do something simultaneously to keep it balanced, but in passive control we try to do something passively. That means we do one thing and leave it there and then let us see what happens. So, we are not dynamically pulsing the fuel injection or keeping a loud speaker on passive means we do something and then we see what happens, that is the idea.

So, the problems with passive approach is that they tend to be affective only over a limited range of can operation, operating conditions they one what is that one size would not fit all and they are very ineffective at low frequencies for some reasons because low frequencies, it is quite difficult to damp the oscillations. And the changes in design are usually costly and time consuming when you go to this meetings where they are trying to solve the combustion stability, they will say that somehow stop it, but do not change anything. And this is kind of I do not know you have to be a spiritual guru or something to magically pump spiritual energy and stop it something like that, but that is what they say I am telling from my experience. So, the other possibilities active feedback control or active control of combustion stability.

So, here we as supposed to be actively passively meddle with things and actively try to disrupt the coupling. So, we have an activator which modifies some system parameters and respond to a measured signal so this is the cuts of the active control.

(Refer Slide Time: 11:40)



Again you can have many actuators, but I just write it symbolically. So, the key thing is measured signal, so we are kind of live we are measuring what is happening. And then we have a actuator and actuator has to modify some system parameters, and it is in response to the measured signal. So, that is the that is what we mean by the active control. The aim is to design the controller and such that the unsteady heat release and the acoustic waves interact differently, there are some ways of interactions and then you wanted to interact some other way.

So, the controller means the relationship between the measured signal and the signal used to drive the actuator. So, that is the actually the meaning of the controller. So, controller means it is a relationship that is what this between the measured signal and the signal which is used to drive the actuator, so that is what meaning of the controller. So, the aim is to design a controller such that the unsteady heat release and acoustic waves interact differently, differently as a we want to make the acoustic oscillations die down.

We can also have the controller such that you set up oscillations for example, if you want to setup the first model or second model and you can program a controller that, it will setup the natural frequency you do not need a frequency generator to set it up if you have active controller. But generally we want the oscillations to die down or to decay down so that we do not have combustions stabilities so that is the idea is this clear this basic concept.

So, we will so what I am going to discuss is to I think to learn about controller you can take classes learn about feedback control you can take classes in chemical engineering, where there are many classes in control systems, as well as in electrical engineering we also they have classes in control theory. Here I will deal with some specific thermocoustic issues which will perhaps create kindle your interest.

So implementing feedback control on practical controller system require one careful choice of sensor and actuator, assuming that we know how to deal with a controller attending a course in electrical engineering your chemical engineering, and you get everything into your head and let us say we can design the controller, and we have the equations. Or we have we either have a model based controller or we have a controller which is based on system identifications where we do not worry about model, let the system identify about it going around and then we have anyone of this thing. So, then how would you deal with it that is the system.

So, we have to have a careful choice of sensors and actuators which will work for our thermocoustic instabilities, I mean actuate box for something else may not really work here. So, sensor must provide a measurement of a dynamic quantity relating to combustion oscillations because our quantities fluctuating on by definition as supposed to some other processes, where you may have a input and an input and you want to control the rate of output depending on what is the input and you want to change it. So, that those are like not dynamic process, but they are kind of I do not know non dynamic processes, but here we have oscillatory phenomena by definition. So, we have to be able to capture the oscillatory phenomena.

If you have any questions you can ask me. Sensors must provide measurement of a dynamic quantity related to thermo acoustic oscillations. So, although this is a kind of straightforward task for the unstable system, it is more difficult for low amplitude control or low amplitude oscillations because if the system has become unstable and then bang bang oscillations happen at very large amplitude, then your everything will work. But the idea is we want to use linear controller, which will work at small amplitudes because if you let the amplitude go very large then the oscillations are non-linear regime and they are very loud maybe system is already destroyed and so on.

So, we want to have them work at low amplitudes and at low amplitudes if you have your controller to work your sensor has to work at low amplitude. But anytime you want to measure something the smaller the signal strength, the more difficult the measurements will be because in thermocoustic instabilities there will be in addition to this instabilities signal, there will always be this background turbulent flow and this makes things quite difficult. So, the possible candidates are microphones and piezoelectric transducers usually microphones would condensed microphones or we have piezoelectric transducers, which can measure the dynamic pressure we can also have piezo resistive transducers, which measure the fluctuating plus the steady part, but they are more expensive to buy.

So, the advantage of using acoustic transducers or sensors like microphones and piezoelectric transducers is sound always propagates. So, if something is happening here you do not have to go here, you can stand there and listen. And I am standing here and thanks to acoustics you can sit there and you do not have to come near me, if the mode of propagation of this information was not acoustic dynamic, but hydrodynamic or something then you would have to come very close to me thankfully not. So, we can measure acoustics standing from quite far distances and combustors are typically a few meters long at the most. So, definitely sound will propagate that much there is no problem with that.

Now, so the it is not that we can you may not want to come close to me, but it is there is no particular difficulty in locating the transducers anywhere. For example, if the sound is produced at the combustion we can place the transducers there it is not having difficult to access, maybe you can water cool and so we can make sure that the structural integrate is not spoiled. But the transducer makes it spoil if they are very close to flame or something. So, there is a option to keep them away and you can still measure, and a typically a microphones have large bandwidth and they have the reasonably robust.

Particularly microphones may break at large amplitude, but piezoelectric transducers are microphone, if you drop it will surely get spoiled piezoelectric transducers they are much more robust. So, just to tell you a story I used to have microphones that is what I used as a PHD student, but I was very careful handle them like babies because they are very expensive each cost like two lakh rupees and so on. And I bought many of them and I had many B tech students working with me and they were dropping it and destroying it and many were dropped. So, after that I decided to switch to piezoelectric transducers, so I dropped microphones as well as the B tech students because they were very expensive so even if and you and are not careful.

So, this is more robust, but I think you can use there are microphones will take 180 d b 165 d b without breaking. So, if you are careful you can use a microphone but, it is very expensive, we do not need microphones because microphones have very high bandwidth this condenser microphones they can measure sometimes 20 kilowatts or even 80 kilowatts and so on.

The air acoustic people use that because many times they want to scale this spectrum and therefore, they have to have maybe they measure a small jet which has a very high frequency and then scale up to larger so that the spectrum there frequency may not be so much, but when you scale down you may have large frequencies. We do not have any such problems because we get frequencies of the order of I mean fifty hundred several hundred hundreds or thousand hertz so microphones or piezoelectric transducers both work very well. The piezo transducers are like roughly half the price of the microphone one third the price of the microphone.

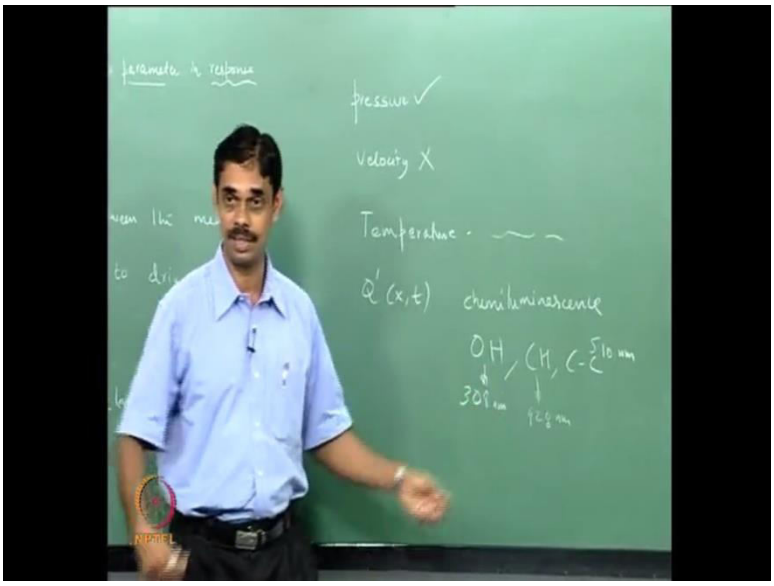
So, although I said that the microphone can be located anywhere sound will travel the location itself is quite important because we may have pressure nodes, pressure minima and we have to ensure that we do not locate the microphone at pressure minima. Or even if you have it may be possible that a good location for one thing maybe a bad location for some other thing. Generally it is like that if you want best of something for sure he will have that thing will have worst of some other thing, I mean life is like that and if you do not want and if you want, if you do not want to lose out on so much. Then you would not lose out on other thing also then you can be in the middle little bit of this little bit of that or you want to have best of something worst of that or you want to have best of the other thing and worst of that.

So, the same thing if you want the best microphone you have to be at a pressure maxima, but generally that location will be minimum of another mode. So, then you have to cover your bases by putting atleast more than one, so that if this minima comes the other maxima is captured or atleast some reasonable measurement. So, some kind of common sense trade of would be necessary so that you do not miss out on the signal by having them located on the pressure nodes or the pressure minima. And if you are having the azimuthal modes then you need many microphones, so that you can get the phase right and at there you have to have many more microphones only then you will know which mode it is. The most common alternative to measure and the heat for measurement of dynamic quantities other than microphone what else is oscillating sorry other than the pressure signal velocity is oscillating so how do you measure velocity

That's very expensive measurement compared to microphone because hardware system will cost like about thirty lakhs, so it is twenty five lakhs even a cheap one as opposed to two lakh for a microphone or piezoelectric transducer is one lakh. So, what else are the velocity measurements, laser topline.

So that is one crore here we are talking about so again that is going worse again same with particular must be of the order of one crore plus we have to elaborate processing. So, I think measuring velocity is in general a bad idea, if you just want to measure velocity at see if you put a hardware in a hot zone, you wouldn't measure anything you want to have a and a combustion is by definite hot. So, some people use in the laboratories hardware in the cold zone just to measure the fluctuating velocity in the base of the flame, where it is cold or something like that. So, that is the best you can do so in general we will not try to measure velocity.

(Refer Slide Time: 23:51)



So, pressure yes velocity no of course, there are people who have lots of money and lots of equipment and just because this they have and you have you use may uses, but in general I wouldn't recommend this. And what other thing can we measure very peacefully very easily. Sorry I see your lips moving, but I do not hear anything.

Student: ((Refer Time: 24:15))

Temperature and how easy is this.

Student: ((Refer Time: 24:23))

See lips moving, but I do not hear anything so no acoustics is coming around

Student: ((Refer Time: 24:30))

Thermocouple yes that is a good point will it calculate will it capture this fluctuations. There are for low frequency oscillations, there are fast acting like fine micron size thermocouples, but the problem is its the frequency of thermocouples is varying with I mean with frequency. So, the response of the thermocouple see you have to elaborate calibrating mechanisms, and there are transducers which can measure temperature fluctuations, but they do not want that easily and that well and you have to have large enough fluctuations in temperature. So, and there maybe cases where temperature may not be fluctuating, but mass flow maybe fluctuating and therefore, this may not work out.

So, temperature fluctuations yes we can, but in general ever not that easy with thermocouple and with optical said that we can do it with optics, imaging see how expense it is. See imaging can be done with will your cell phone camera and wonderful so is it possible to do that.

Student: ((Refer Time: 25:48))

So, at temperature the typical the more successful technique is two line fluorescence which will cost probably two crore something like that. So, I think I will rule that out so what else is left over.

Student: ((Refer Time: 26:06))

Heat releaser perfect q prime and how can we measure this. So we can do that but, that is expensive but, that is possible what else.

Student: We can measure the ((Refer Time: 26:20))

How can we measure heat released. We actually spoke about it in last class briefly, Ganesh how are you doing it in your experiment.

Student: ((Refer Time: 26:46))

Ok how are your friends doing.

Student: ((Refer Time: 26:55))

Camera, but no lasers right so what are they measuring

Student: They are measuring radicals.

So, chemi luminescence perfect thank you so people measure O H or C H C C these are the radicals that are sometimes you put O H star C H star to show that radical these are the radicals that are there in the flame zone. So, if you just take a video camera and look at a flame you will see a flame, but that is not just the heat release zone, but you will see some other things also, what else will you see?

(Refer Slide Time: 27:54)

If you look at a Bunsen burner flame you will see a flame like this, but maybe you have a very fine place where the all combustion happens, but the entire thing will glow like that.

Student: ((Refer Time: 28:03))

So, radiation from the gases or black body radiation or whatever so we do not want that that is why we need this chemi luminescence because we want to look at the place where the reactions predominantly happen. So, in the places where reactions predominantly happen, there will be activated species which are occurring only in those places like O H C H and C C. So, we will look for that, how do we look for that and how do you not see a filter, like I am reminded of some Vivekananda quote if you wear blue glasses you will see the world as blue. So, if you wear blue glasses you will see C H so well does C H and if you wear U V so this is like I think 308 nanometer for U V, C H is 428 or 427 I think C C is 500 or something I do not remember how much?

Student: 510.

510 nanometer so you can use band pass filters which will let only this light glow so that we see only that and lot of things are coming, we just focus on what we want. And this for a perfectly flame O H is a V H or directly marked heat release rate sometimes this maybe influenced by law other things. For example, if there is equal ratio of fluctuations this will depend on that also and so on. So, it will be not be a direct indicator like it

maybe a like it have to be a correct for that and so on, but if the heat release fluctuations this will also fluctuate only dependence may not be linear and so on, but there will be fluctuations.

Now the problem is you cannot stand away and measure these things because this you have to see the flame zone, let us take about the other things in the signal we can filter them out by putting a band filter. And of course, the biggest problem is requiring optical access, so in optical access may not be a problem in a Bunsen burner flame with a glass tube surrounding it, but in a real combustor I mean it is made of metal and putting a optical axis, the it may be under pressure also 5 bar or 10 bar 20 bar.

So, the engineers would not like you to drill a hole and mount something, but then you argue saying that you have nuts there. So, you can put a small hole on a boat and I will mount a fiber optic coupler there and then I would not mount any transistor there give me a smallest one eighth inch and then I will use fibre optic cable to take the signal somewhere else and then see, and then you can maybe get one measurement out of it. So, we need optical fibers there is limited field of view and the readings will be quite noisy.

And another problem is the flame may shift its location so you may generally keep the thing focussed somewhere and flame maybe one day during one mode, it may be go somewhere else during another mode and so you can have a lot of problems so it is difficult but, you can do it. And there are people working to reduce the cost of this laser based techniques for temperature and so on like diode based lasers are coming up and so on. But it is not like they are all readily available that just like that you can buy a microphone you can buy a temperature meter with laser and put them state maybe 5 years or 10 years late it may be the state.

So, in summary we have we can use this, this is the best possible thing and we can use a chemi luminescence with photo multiplier and combination of fiber optic cables and so on is this clear so far. So, we have the spice in place, but now we need the forces so that is the actuated to interfere. So, first we have to know what is happening and then we have to interfere so if I want to know whether and when I see you somebody else is this fellow was studying or disappeared, or is he into something else. And then once I find what he is in to then I try to catch you and do something to you so that is the idea here.

Now, if you speak to engineer who designs combustors not a thermocoustic expert nor a control expert, but just a guy who is only worried about combustors and he want combustor to work. Let us say someone who designs a engines or burners or something he would say he does not want any active control, even if you are the most lovely active controlled works beautifully you still do not want it, you will say that first of all we have to actuate. That means, somebody has to work several times a second and combustors typically run several thousand hours and then years continuously without stopping. And they do not want they do not think anything else will work, so long with basic we can move any movable part can work that long without maintenance.

Then we will say that anything you put into it what is the guarantee that will work as you desire, say I may try to find out how you are doing and try to make you study well and all that. But in the process I may make you get upset with everything and you may just completely quit also that is possible. You put a actuator and then I am you may had a very bad second mode instability now that is conquered, but you have a very large amplitude first mode of stability and that happens in thermocoustics very peacefully.

So, to avoid all these things and then you have to spend a lot of money and extract for this design a controller, design a control pay the controller the guy who designs gets quite a bit of money, and then the actuator sense and then you have to modify this and put it in. So, all that will cost require a lot of money, so the engineer will say we will reduce the or we will reduce the heat release rate, if it comes then he will deal with it I do not want to deal with this active control. And people have setup this things in real combustors we speak about it, but unfortunately there isn’t that much confidence that these things will work peacefully, robustly like there are other places where dynamic systems can be controlled.

For example, in aircraft I mean it is highly risky system you are flying and you can fall down and but you have controls are all electronic, there is controller which is often doing it and then the whole thing can work by itself without having a pilot and that that kind of so that is and probably much more riskier. But people actually fly unstable aircrafts controlling purely with the controller because they have so much confidence in the theory and its implementation. So, in thermocoustics to be honest there is no confidence on the theory at all and still everything is very much debated and everything maybe wrong.

And even if it is right I mean see if you read the thermocoustics book they will this you have frequency domain analysis time domain analysis, and all that. You can say that it is like politician India is a great country democracy is thriving everything is wonderful we are shining and what not. But if all this things were happening you wouldn't have to say that I mean people would be happy on their own it is like a aeroplane, they do not say that if you speak to control aircraft control people they do not say that we have theory and theory is wonderful and we have wonderful activities, and all that they do not say anything they just make this things work that is all. Whereas, if everything works say whereas, here we say that we have recently understood everything and we are making marvellous progress blah blah blah that means there is lot of problem.

So, if you speak to engineer I mean this is the truth I am saying very bluntly, they would not be very keen on putting your active control, people are some companies have one or two episodes done this. But if it was wonderful it would have caught on, but that does not mean it would not come tomorrow, suddenly something may change and suddenly everybody may use it and these things cannot be predicted. So, at the moment I will speak about what is the status and for everything for long time nothing happen and suddenly overnight something happens, and then suddenly everything changed.

So, maybe we are in for active control revolution thermocoustics and you maybe the one who is doing this, I do not know so that is the hope with which people work only work as scientist. We do not have fun and we do not care about anything as a combustor guy is about the combustor to burn, so he will see this guy is having fun and he is making something if it is going to work for me I will buy it otherwise leave it so the economics will take care of itself.

So we speak about activities which are in this active control because like I said engineers do not believe that this things can work for so long. So, satisfactory activation of combustion systems poses a real challenge because you have to operate this actuators under high temperature. For the first if you look at the history of combustor and instability control it is first the active this anti sound concept came that is the active control of sound by sending sound out of phase with the incoming acoustic field. So, that is like you might have I do not know some of you may have this speakers from Bosch which will cancel the aircraft noise or train noise and so on. So, then people try to extend the same idea to thermocoustic instabilities, so you can control laboratory combustors like Bunsen burner with duct around it or something loudspeakers and the first actuator is were loudspeakers.

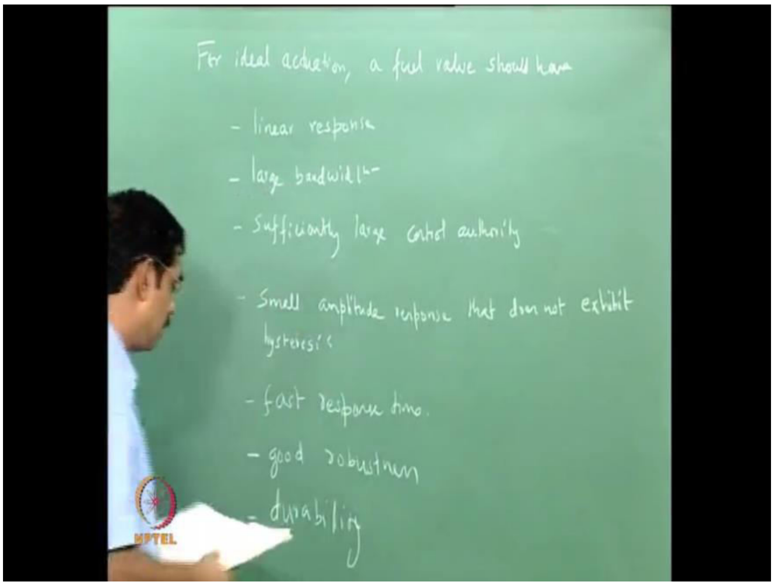
Loudspeakers do have high frequency response a high fidelity system and so naturally, but they are not sufficiently robust for using in industrial systems. You mount a speaker on a combustor tomorrow it may not work something would have burned or shorted or something, and it needs cooling to work under hot conditions. And the power requirements become prohibitively expensive at larger scale, I mean the amount of power that is required is I mean you have 160 or 170 d b oscillations or combustors or something comparable to that magnitude has to be put in and that is nothing compared to this speaker powers that are there in the big auditorium.

So, I mean that kind of power actuator needs in a combustor system cannot be given by loud speakers. So, those are the three main problems, let me repeat. The power requirements are very prohibitive and the speakers are not that robust to work in this combustion environment, which is dirty and high temperature. And it needs cooling which is again makes things very complicated, the cooling maybe very peaceful in a laboratory combustor, but cooling of loud speaker industrial burner may not be that easy.

So, then we have to come up with some other means of actuating and so easiest way is to modulate the fuel supply. So, you just fluctuate if the fuel supply somehow with a valve which in the fuel supply line, which is fluctuating. And then you can fluctuate the fuel supply line and so you are actually fluctuating the fuel supply lines. Means you are actually fluctuating the fuel release rate, so you can fluctuate the primary supply line or you can inject fuel in a secondary way somewhere else and have a heat release rate. And use that to have damping because if heat release rate is out of phase with a pressure it can can damp, so it likes use the devil to fight the devil or something like that. And then absorb the sound which is generated by heat release at some other place by this heat release trace to take it out. So, this is possible and it has been practiced.

But for ideal actuations a fuel valve should have a linear response to allow linear control theory to what. See if you had some other control theory which does not need the a fuel line to be responding in a linear way, then we could be having we could use any, but your problem is your theory will work only for, what I mean we are using only linear control theory, which is simpler than anything else non-linear control theory is very complicated.

(Refer Slide Time: 40:20)



So, large bandwidth was not a problem for loudspeakers, but for valves it maybe a problem because you are basically fluctuating the area. And therefore, it may not be that easy and not only that you have to have if you have to have a sinusoidal get the sinusoidal response, the area has to fluctuate sinusoidally and at low frequencies we will get a sinusoidal response. But that happens at higher frequencies even if you get the area to fluctuate sinusoidally which itself is very complicated, you know you have valve you open the opening and closing has to be sinusoidal, which is not that trivial all the people have made such. The other thing is even if you have sinusoidal variation it may still generate harmonics so it is not that easy to get this.

Then we need sufficiently large control authority, that means we have to pulse enough flow rate. So, that you can get enough acoustic power being absorbed by this secondary heat release rate. So, you have to have so these are the big problem with loudspeakers, but here I think it is possible to get sufficient control authority. And we need small amplitude response that does not exhibit hysteresis, and fast response time because of the small amplitude response should not exhibit hysteresis. And usually it does that is the problem and then you have we need fast response time because if the response time is very slow, I mean we are talking about inherently fast oscillatory phenomena. So, it would not work and the robustness and durability.

So, you have to have this word first several years without any only a problem, to the people who make this actuators they say that for example, in cars you are having this fuel injection cars and they are working for many years without any problem, but for some reason engineer engineers do not have that much confidence in the system. So, we do not have something which has all this qualities I mean they do not exist. So, we kind of a little bit of that a little bit of that or quite a bit of this quite a bit of that so that we can get it to work so that is the idea, but these are the desirable quantities.

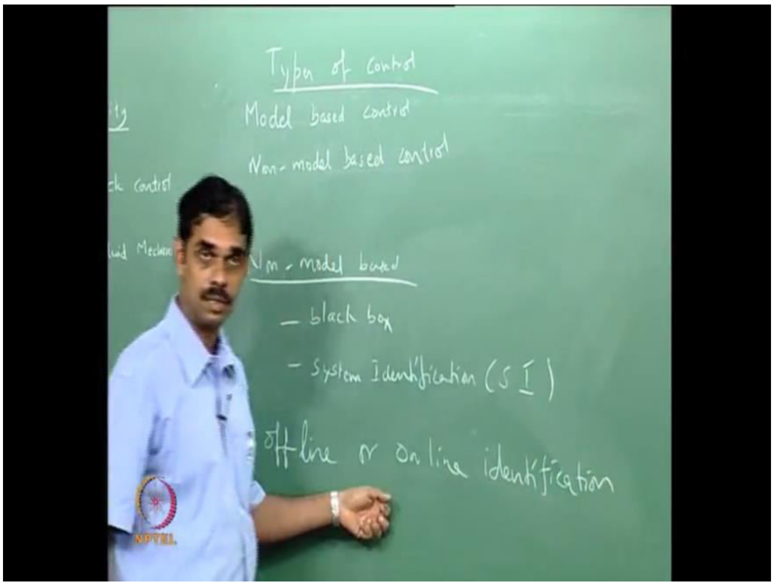
Furthermore we should take care that the acoustic pipe work or the ducks, which connect the actuator to the field injector position, they should not have large response because otherwise that is system may have either sluggish response, and then you may not respond a lot. Or if it is very good response then it may setup some other instability by itself. So, we have to be careful. So, opening a satisfactory fuel valve is one of the main challenges that faces the reliable implementation of feedback control on practical combustion systems. So, this is the main control atleast that is what the experts say.

In my opinion there are two problems one is the theory itself is not proper and understanding is not proper, but I think if you speak to experts in the subjects they are experts and they understand everything. So, they would not agree, but this is my personal opinion is that the theory is all not proper so that has lot to do with if you do not understand your system properly, properly you cannot control properly that is my opinion. But the mainstream opinion is that theory is all well understood, but nevertheless even if it is understood, you do not need very good actuators and that is which the engineers have full faith on and that is where the problem is at least that is what the community thinks.

The first fuel modulation systems were on off car field injector valves and non-linear so, but then people started using solenoid valves which have the advantage of a linear response and the problems are limited bandwidth and control authority. And you have hysteresis at low amplitudes and not sufficiently durable for practical applications. The car on off valve in automobiles they have they are durable and all that and so on, but they are not linear so that is that is control theory people do not like it because we have linear theory.

And then there is this magneto restrictive valve which combines fast response time with increased bandwidth and show promise, as long as controlled authority can be maintained at high frequencies. And there control authority comes down at high frequencies and these are also expensive valves so that is where things are. So, there are different kinds of active control designs and one is model based control and other one is non model based control.

(Refer Slide Time: 46:28)



The non model based control design considers the it treats the system as a black box and then we have to learn its behaviour. So, we will look and find out that is called system identification procedure. So, we will look at you treat it as a black box and then we have a system identification to find out about its behaviour. And we can identify the system before we keep the controller and find out about it and then start controlling, or we can let even the controller be on simultaneously find out the system as well as control. So, one is called offline, so we can have offline or online identification both kind of system identification exist.

So, the big advantage of online system identification over offline system identification is that controller keeps track of changes in combustion system dynamics, due to varying operating conditions. So, for example, the mean temperature maybe slowly rising or maybe the fuel composition may change slowly and so on. So, if there are changes in the parameters then the online identification procedure can identify adaptively and respond to these changes in the operation of the combustor.

So, non model based control is attractive because they can be universally applied. So, if you are having a model based control for each thing to control you have to have a model based, you have to have model and then you have to write model for each system and then you try to control, but then if you are non model based control then you just treat it as a black box and then get it to work. And therefore, you can use it anywhere.

But the biggest drawback is that it has no guarantee that the controller will work. Whereas, if you had a model based controller we will practically theoretically give you some guarantee atleast on theory it works. So, in practice if it do not work there must be some problem in implementation, whereas this you setup a controller, but there is no there is no mathematical guarantee that it will work. A model based control design requires a detailed knowledge that is a model of the unstable system with the actuator sensor and based on this model based on this knowledge, the model based control design can provide strong mathematical guarantees that it will not go unstable and cause harm.

So, since the combustion system is known to the controller you do not need to have any system identification required. So, of course, the model based controller can be either be designed for fixed operating point or it can designed for a varying operating points. So the dilemma while designing a active controller is so either the controller does not need to know about this system, but there is no guarantee that it will work or the controller can give guarantees. But you need a detailed knowledge of the system which would mean equations and solutions and all that which is difficult for practical large scale combustors. So, this is the challenge that has to go this way or that way and that has to be based the challenges should be tackled based on the specific system that you have in your hand.

Student: ((Refer Time: 50:57)) Why should we start with a model based system and like change the parameters based on the system size.

There is no problem with that as long as you have a model if you do not have a model then you cannot start with a model based.

Student: ((Refer Time: 51:10))

For some systems like or a swell burner I think it even the basic model may be quite involved. So, if you have a model then you can do that and then you can couple it with non model based identification and then you can have a hybrid thing, lot of things can be done, but it may not be there if it is there I can do a model based control. And then there is a guarantee that will work it is a good point actually, but it is a difficult question what you are asking anything else we will stop here.