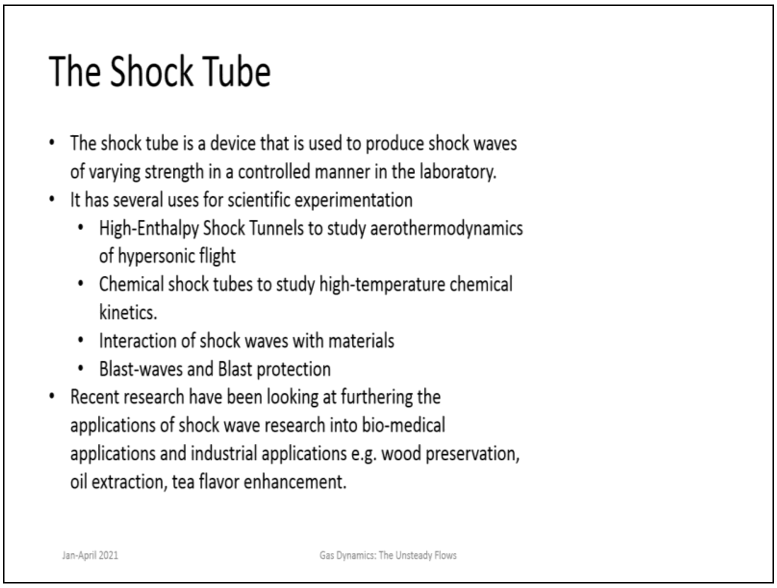
Gasdynamics: Fundamentals and Applications
Prof. Srisha Rao M V
Aerospace Engineering
Indian Institute of Science – Bangalore

Lecture 21
The Shock Tube

So until now we have been looking at one dimensional steady flows. We looked at important concepts of stagnation properties, star properties. Further on moved on to normal shocks understood what are shock waves. So now in the related context still being in the one dimensional case but we will move to unsteady flows. So where flow properties change with time. So that is the focus of this module. So, we will do that elaborately with respect to one particular device the shock tube. So, the shock tube is a perfect example of an unsteady gas dynamic unsteady one-dimensional problem. A small part of it we had begun towards the later half of the module on normal shocks which was on moving normal shock. So, the moving normal shock actually is an unsteady phenomenon.

But we saw that by a proper transformation by jumping on to the normal shock. One could convert the normal shock to a stationary frame. But now we will deal with the shock tube problem which is a 1D unsteady flow problem.

(Refer Slide Time: 01:55)



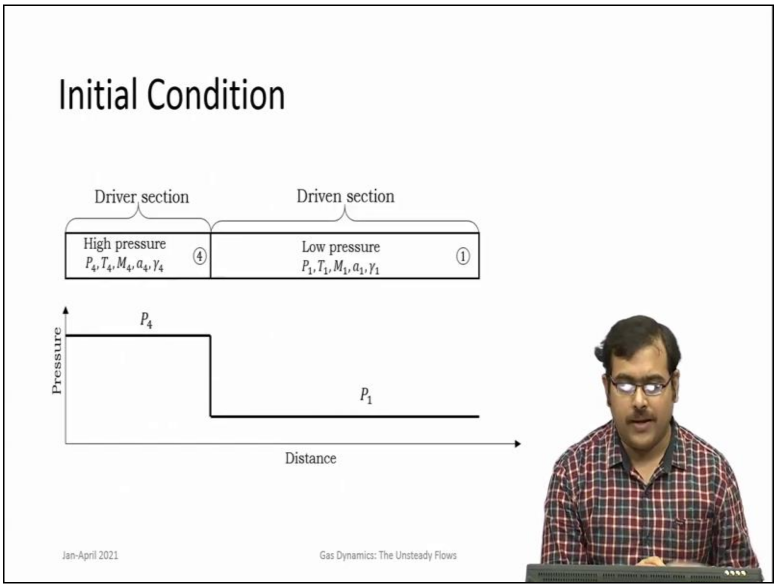
Now it is a device that is used to produce shock waves in a controlled manner and of varying strength but mostly in the laboratory and it has several uses for scientific experimentation. And mainly it is used in high enthalpy shock tunnels to study aerothermodynamic phenomenon of very high Mach number flows. We know when Mach number increases tremendously then the stagnation temperatures and pressures also increase significantly. And shock tubes are one way to produce such high pressures and temperatures.

They are also used to study high temperature chemical kinetics. How reactions happen at high temperatures? Also, they have various applications to study interaction of shock waves with materials or structures this is relevant to blast waves because these shock waves and are also produced during a explosion event. And how that affects structures? If you want to study in a controlled manner in the laboratory, then shock tubes are one of the devices that can help to study them.

And so there are several recent researchers which have been they have been looking at applying these shock waves and shock tube into several other fields like biomedical research and industrial applications. Like including say preservation of wood, extraction of oil from say sandalwood or even as sort of increasing the flavour of tea. So people are looking into many, many different applications of the shock tube.

So that device the shock tube a problem is also significant in the context of validating numerical schemes for compressible flow.

(Refer Slide Time: 04:21)



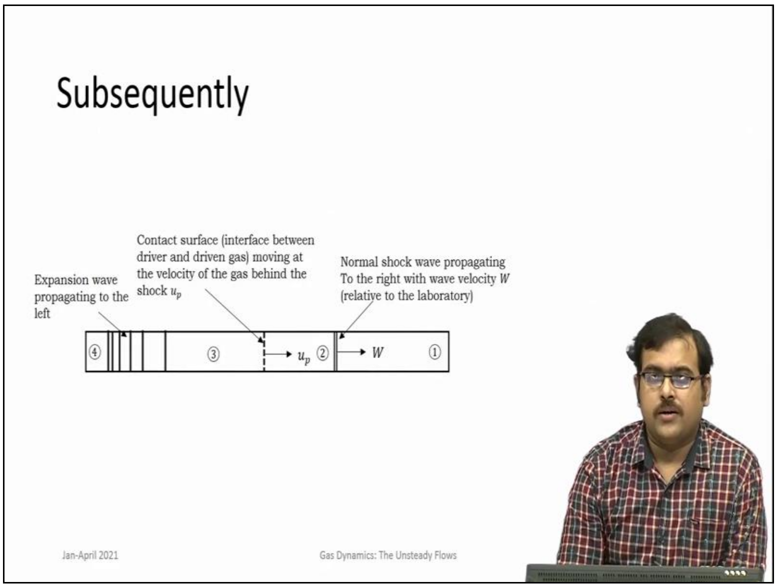
Because in the perfect gas domain the shock tube problem is an unsteady problem which can be solved analytically and exactly for the ideal shock tube (no viscous effects, no viscous). So it is an inviscid flow. But one can obtain complete unsteady flow field in one dimension exactly. So let us look at what is this shock tube and what is the problem? So it is an unsteady flow.

So there is always an initial condition for the shock tube and the initial condition is that the shock tube consists of it is basically a long tube which has two parts the driver section and the driven section. So the driver section and driven section are separated by a diaphragm. So this is a diaphragm from this is a diaphragm and when sufficiently high pressure is provided in the high pressure driver then this diaphragm suddenly bursts. This is how it is practically done. Practically these experiments are carried out. One may also introduce certain plungers to rupture the diaphragm at a specified pressure. So, the pressure differential across the diaphragm is something that is set is known. Also the gases in general at the high pressure driver side and the driven side can be different depending on the applications that the shock tube is going to be used for.

And important parameters of course are the pressures, temperatures and the speed of sound in both the high pressure and the low-pressure section. So, if you look at the initial state if you look at the pressure profile of a shock tube it will present a picture that is shown here schematically. That is, you have high pressure in the driver section and you have low pressure in the driven section and there is a sharp jump across the diaphragm.

The moment the diaphragm bursts then several things happen in the shock tube and the flow then evolves from there. So let us look at closely look at how the flow evolves the moment the shock tube, the diaphragm ruptures within the shock tube.

(Refer Slide Time: 07:18)



So as soon as the diaphragm ruptures there is a large pressure difference between the two sections, and it is a compressible gas in inside the tubes and so you have compressible flow phenomena and ultimately, they lead to the formation of shocks. So as a consequence, you have a shock wave that travels within the driven section of the tube. So this is what is represented as W is a shock wave that moves within the driven section of the tube.

So one should be careful about the nomenclature that is being used it is more or less a standard when describing shock tubes. The driven section is given the number 1. So, all flow variables like pressure temperature will be referred to with the subscripts 1. So, P1, T1 and rho1, so a1 and in the case of high-pressure side it is P4. So four is the nomenclature for the driver section.

So both at the initial state both M4 and M1 they are questioned so these are zeros there is no velocity at all at the beginning. So this nomenclature one should always keep in mind when describing shock tubes often people refer to P4 by P1 or P2 by P1. So what is this 1, 2, 3, 4 they are regions within the shock tube as the shock wave progresses into the driven section. So the shock wave progresses into driven section so driven section is one.

Just behind the shock wave the region of gas is region 2 and we know that moving shock so shock wave when it moves it carries gas with it. So that phenomena is quite unlike sound waves so shocks carry gas so they produce bulk motion of gas and therefore you have the region 2 where gas is moving. Also this shock compresses the gas from M1 so you have pressure is greater than P1, P2 and temperature is greater than T1, density is greater than rho1.

So you have this bulk motion of a compressed gas and please remember all the time that shocks are always supersonic. So this W by a1. So that is referred to as the shock Mach number Ms, W by a1 is always greater than 1. So it is always supersonic. So, now the region 2 comprises of the driven gas which is processed by the shock wave and has been compressed.

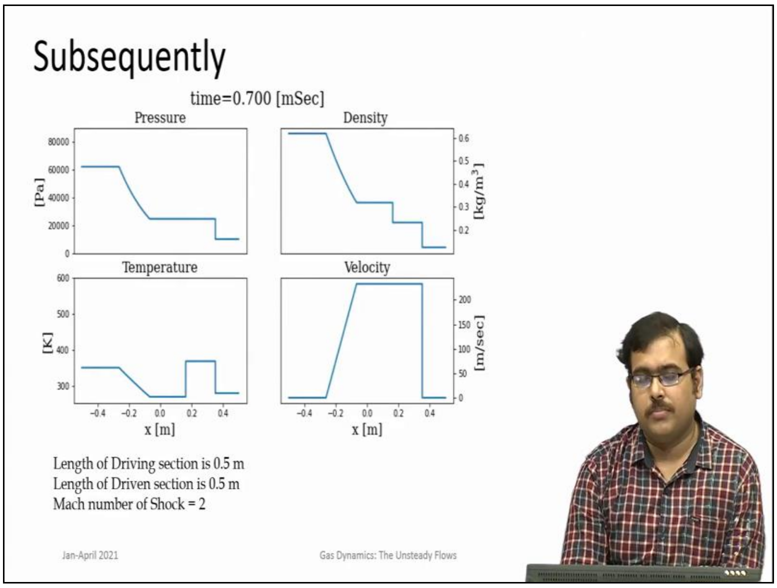
Now initially when the shock tube started out the shock wave started off there was a differentiation between driver section and driven section. So now in the driven section a shock wave progresses it compresses the gas and on the other hand in the driven section in the driver section you have the expansion waves. So these expansion waves, gradually, they decrease the pressure in the driver side.

So these are expansion waves that are shown as a series of waves and that is true for expansion means because they are not a sharp discontinuity like a shock and this is something that we have discussed earlier on that there is no expansion shock. It violates second law of thermodynamics. So expansion processes are more gradual and they are isentropic. So it is true here also. These are expansion waves and they travel left side into the driven sorry driver section.

So there they reduce the pressure. So there is a section in between these 2 this is section 3 these is the section of driver gas that has been processed by the expansion waves. So in if you consider the region between the expansion waves and the shock wave there are two kinds of gas that is one is the driver gas this is coming from driver and there is a driven gas which is processed by a shock wave.

And there is an interface that separates these two gases, and that interface is known as the contact surface or contact discontinuity. There is it is also a discontinuous surface but its within the fluid there is no solid surface. It demarcates the boundary between driver and driven gases. So when one looks at this problem now at a certain intermediate stage you have shock wave moving to into the driving driven section and expansion waves moving into the driver section and a contact in between.

(Refer Slide Time: 13:49)



So let us look at how the pressures and temperatures vary between at different sections due to these different waves. So if you look at the pressure, so pressure so you can see that here you have the shock wave moving suddenly the pressure increases across the shock. And then you have the pressure remaining constant all through until the expansion waves. So if you see if you go back to the picture that is over here the contact surface is not a solid surface.

So across the contact surface pressure remains constant so P3 is actually equal to P2 and same way the velocity of the gas also is a constant u3 is equal to u2 which in this case is written as up this is also coming from the piston analogy we were discussing in the beginning of the normal shocks. So you can consider this as a piston that is driving the shock that is moving ahead.

So that problem also has relations to the shock tube problem. So sometimes it is also referred to as up. So, u3 equal to u2 is the boundary condition. So boundary condition across the contact surface is P3 equal to P2, u3 equal to u2. Because of the contacts there is no difference in the pressure across the contact surface, it remains all through both region 2 and 3 and then you see that there is a decrease of gradual decrease of pressure from P4.

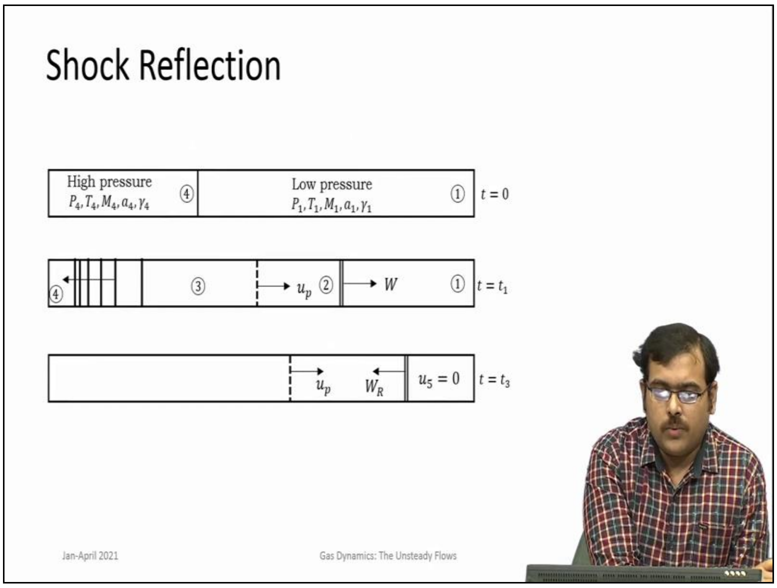
So this is P4 and this is P1. Now what happens to temperature immediately at the location of the shock.? The temperature increases to T2. Now the boundary condition at the contact surface is only for pressure and velocity and they do not necessarily hold good for temperature and density. So temperature and density can vary and they vary discontinuously that is why contact surface is also called as contact discontinuity. The regions of driver and driven to start with need not have same temperatures or densities.

They can be even of different gases. So now there is a discontinuity here so that is T3. So this discontinuity in temperature also manifests in discontinuity of density. This is consistent with the ideal gas law. So this is density rho1 and rho4 this is the contact discontinuity. So always when you want to look at contact discontinuity it is always good to look at the density profile.

There the contact discontinuity is shown very clearly or the temperature profile, but pressure or velocity will not give you any information on the contact discontinuity. So this is V3 equal to V2, P3 equal to P2. So at any instant after the rupture of the diaphragm assuming that the shock wave is instantaneously formed the general picture of the flow within the shock tube is plotted in various graphs here.

This is how the pressure density temperature and velocity profiles look. And the through the course of this module we will come up and understand how to solve the various equations so that we can come to this profiles.

(Refer Slide Time: 18:41)



So now the shock wave can go all the way. Suppose this shock tube is closed at both the ends then the shock wave proceeds all the way towards the end of the shock tube. So at the end there is a solid wall and boundary condition there is that the flow cannot penetrate inside the solid wall. So the bulk motion of gas that was happening behind the shock with a velocity u2 on meeting the wall should abruptly stop or come to a velocity as soon as it meets the wall its velocity should become zero.

So the way the flow accomplishes this task is by creating a reflected shock another shock which now progresses into the u2 section or region 2 and then further on but we are focusing on the region 2, section where the reflected shock goes in. And as soon as the reflected shock goes into through the gas in region 2 behind it the shock converts the velocity to 0 and this is stagnant gas.

Of course now a shock has passed through the section 2 twice that is of section 2 was initially a result of the processed shock first primary shock processed gas. And now another shock wave passes through the region 2. So, now you can expect significant increase of pressure and temperature after the reflected shock has gone through the region 2. So now this region after the reflected shock has passed is named as region 5.

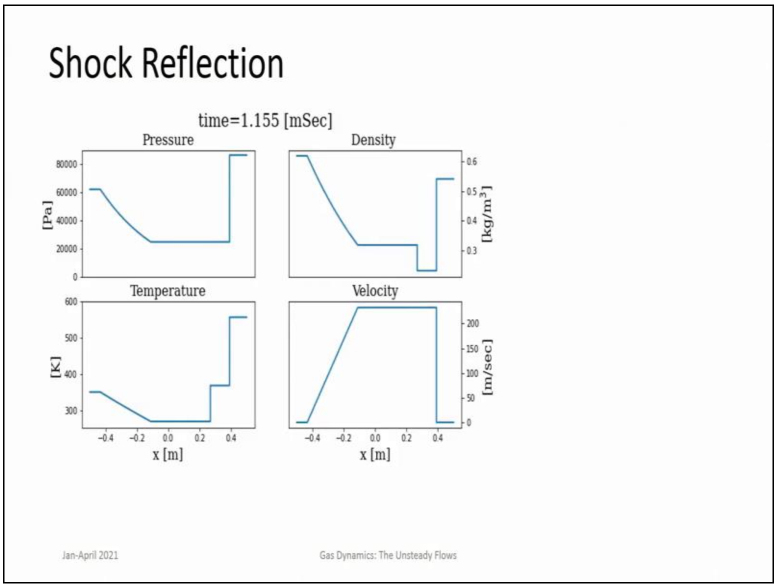
So that is the region 5. So, often people describe P5 by P1 and T5 by T1. So when one looks at applications of shock tube you can have several applications one where you use only the primary shock you do not look at any reflected shock. In that sense usually some kind of an apparatus will be attached directly to this section without having any end wall.

And the shock just progresses on into the device example of such devices are shock tunnels which are wind tunnels attached to a shock tube to look at very high Mach number flows or high enthalpy flows. And this flow just goes on into the test section and behind you can have a motion of gas. So this is the slug of gas which is useful for testing and since these processes happen very fast, W is always supersonic.

These shock tubes produce typical testing times which are very, very short of the orders of milliseconds. So that is the key point here but they can produce very high pressures and temperatures. When you need much higher temperatures and pressures than what is produced in this scenario we can use certain devices so that a reflection of the shock is produced and this stagnant gas after reflection is of much higher pressure and temperature that can be used for other certain experiments.

So both kinds of uses are there this kind of operation is known as reflected mode, mode of operation.

(Refer Slide Time: 23:21)



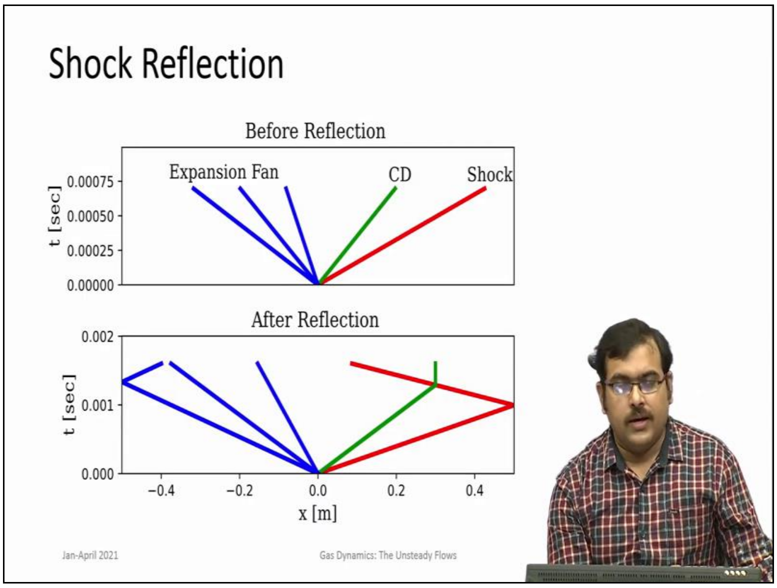
So let us look at this so now you see that what happens upon reflection the same shock tube problem which we started with. Now this is this is a pressure profile we were having P2 here

P2 remains constant but the moment reflection of shock happens you can see the sudden jump that is produced by the reflected shock. So this is P5. Now you can see in the density also you are having the reflected shock here, rho5 and similarly T5 in the temperature profile. So this was T2 the shock is moving into P,2 T2 and rho2. So it produces significant jump and on the other hand in the velocity the moment it reflects u5 is zero. So if you look at the flow features that are present in a shock tube. So you understand that basically you started off the initial condition is that you have region 4 which is the driver side high pressure.
And region 1 which is driven side low pressure in between there is a diaphragm or there is a separation. And at t equal to 0 that separation is removed and instantaneously there is a large pressure difference that appears between the driver and driven sides of the gas and consequence of that is a wave structure is set up in the shock tube consisting of a shock wave that goes into the driven section.

And expansion waves that move into the driver section and the surface or sort of virtual boundary that separates both the driver and the driven sides is the contact discontinuity or contact surface. And across the contact surface pressures and velocities are the same. Further on the shock waves going and hitting at the end wall get reflected back the condition at that reflection is that the shock should process the as that is bulk motion of gas that is coming towards it with the velocity u2 is converted to a stagnant gas or u5 is equal to zero.

The expansion waves similarly can reflect from the driver side end wall and they continue to expand. So a shock wave has reflected as a shock similarly an expansion wave they would reflect as expansion waves and further reduce pressure.

(Refer Slide Time: 26:42)



So now the aim throughout this module is to model this to understand this mathematically how to get the solutions what are the equations. And towards that we will have to look at various concepts both flow physics as well as some of them mathematical in nature. So we will go through them in detail. We will start with because it is all wave dominated flows you see expansion waves and there are so many waves here.

So we start with the simple waves, linear waves of pressure as very small perturbations of pressure and density which are nothing but sound waves. And then we look at much larger strength waves finite waves and then we will see how these equations of finite waves model the expansion waves in the shock tube. The high pressures the compression part of it which is done by the shock wave is already modelled by the moving normal shock.

We have to just change the frame of reference so that part is already covered but we look at in detail at the expansion side and then couple all of them together to give us the complete solution for the shock tube problem. A very useful way of representing these waves and flow features in shock tube is the XT diagram. So where you see all the different flow features this is shock contact discontinuity and the expansion fan represented in an XT diagram.

So shock has a certain velocity. So this slope of course here is dt by dx which is 1 by W so that is the velocity. So dx by dt is velocity. So shock runs very quickly, its supersonic. Contact discontinuity is slower. Expansion fans move into the driver section. Now the moment reflection happens so this is a reflected wave and it turns everything after it passes through it turns the various velocities. So u5 is zero as a consequence you see that the contact is goes still. So this is the picture of ideal shock tube. In the next class we will begin with waves and then proceed from there towards all the other topics.