Advanced Gas Dynamics
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Lecture – 35
Supersonic Flow past a 3D Cone at an angle of attack

So, what we will do today is really to like we said we will start looking at the 3D pictures right, the 3D flow how that is different from a axisymmetric flow and so on and so forth. So, what we will start out doing is try and understand the shape of the cone right and then how the flow becomes different if this cone is not axisymmetric and has you know the axis of that cone has a certain inclination with the free strip which is basically the angle of attack. So, what we will start out doing is a look at the cone. So, what I try to do here is draw this cone and draw this cone using a sci lab, so that we can you know move it around and in space and see how it looks from various angles, so that we will try to you know have a clear picture try to visualize the flow.

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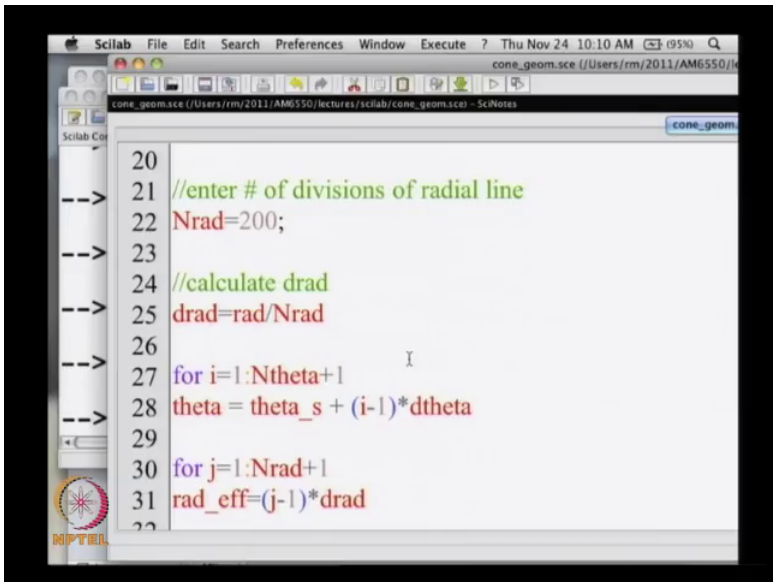

So, I mean that is we can do I guess you know in a class like this to in order to visualize a 3D flow.

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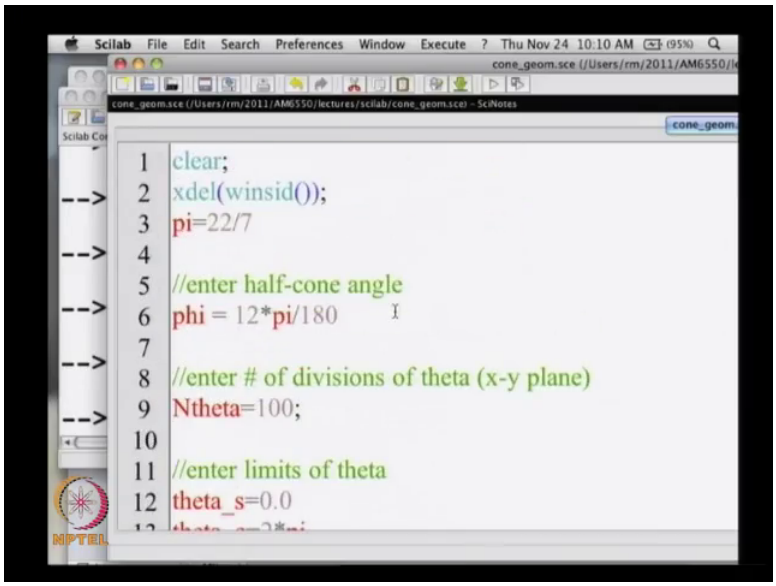

So, if I am looking at this here, so I will you know let me go ahead and you know do this plot and we will see what I am talking about. So, say I plot this.

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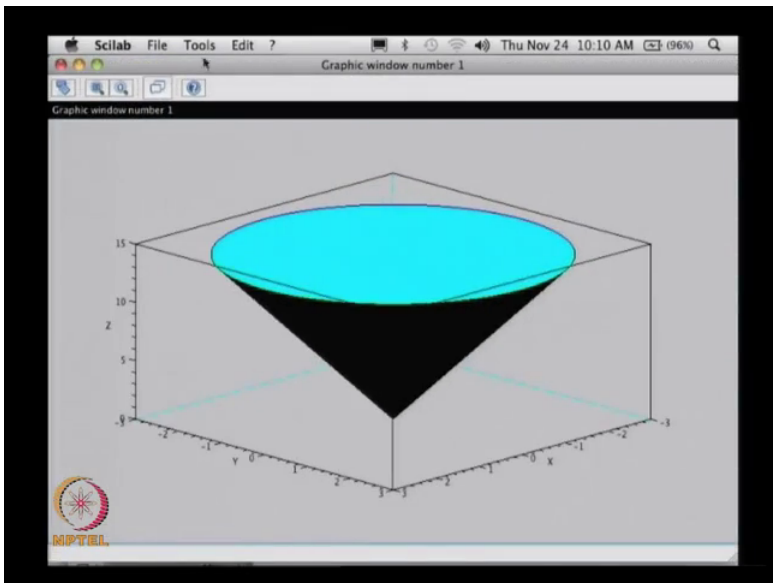

So, I get these two pictures here. So, let us say that this is essentially the cone. This is a cone, which I have plotted here. Now, what I am going to do is. So, you know it depends on the way you look at it.

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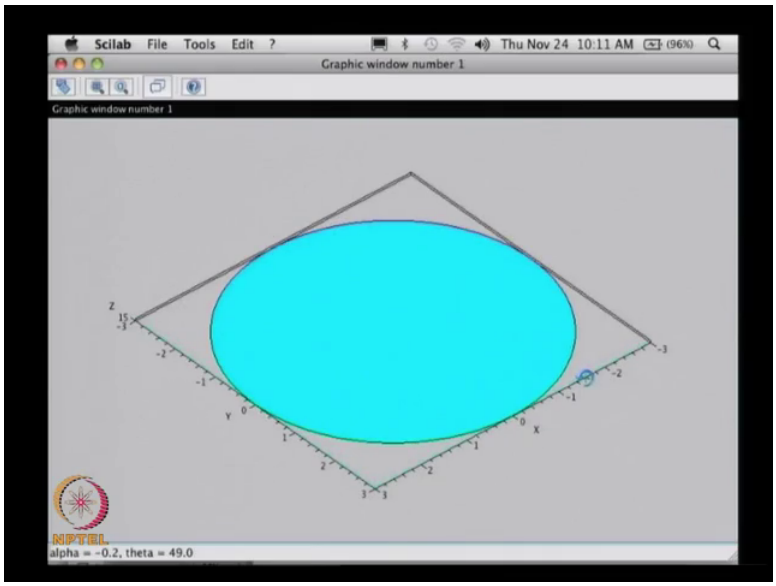

So, now say I am going to rotate this piece and see what we see. If you just look at the base, it is you know just you know a circle. If you look at the base, it is just a circle.

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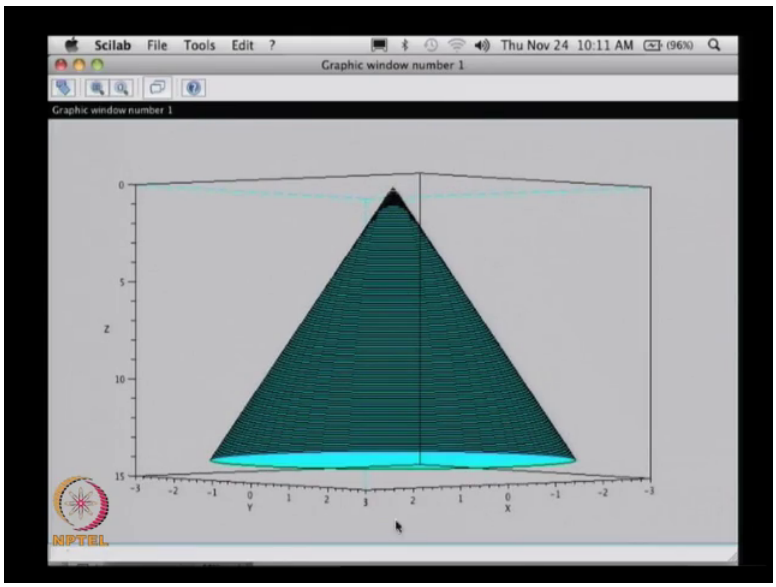

Again if you say turn this down this is actually a cone this is a 3D cone.

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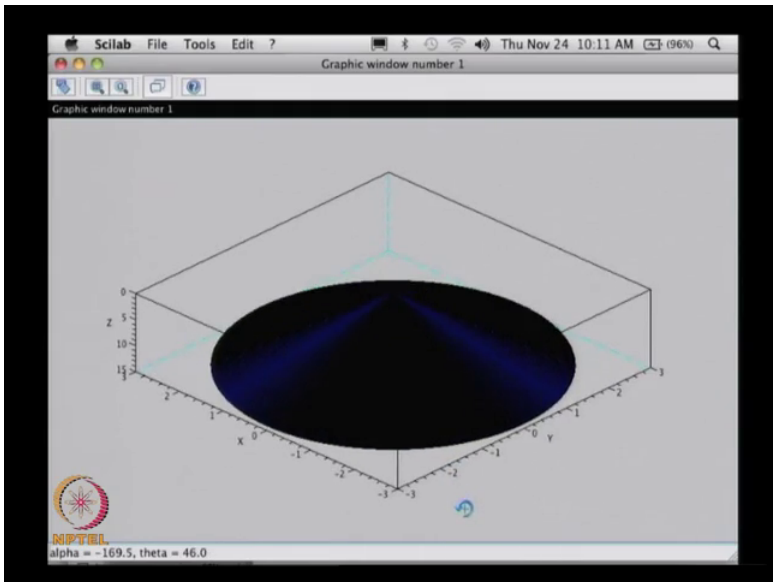

So, let us look at this from say the top. So, if I want to look at this say from the top, what you think we will see, well should instead of (Refer Time: 03:01), what do you see here. So, it is again you know just a circle; however. From now if you if you look at this you know this is the apex of it or the vertex of it or the topmost portion of it. And what you see is essentially a circle. If you look at it from the top or if you were to look at it from the bottom, so this is basically the surface, this is what we are looking at. So, now, you can. So, this is more of a 3D picture now you can see right.

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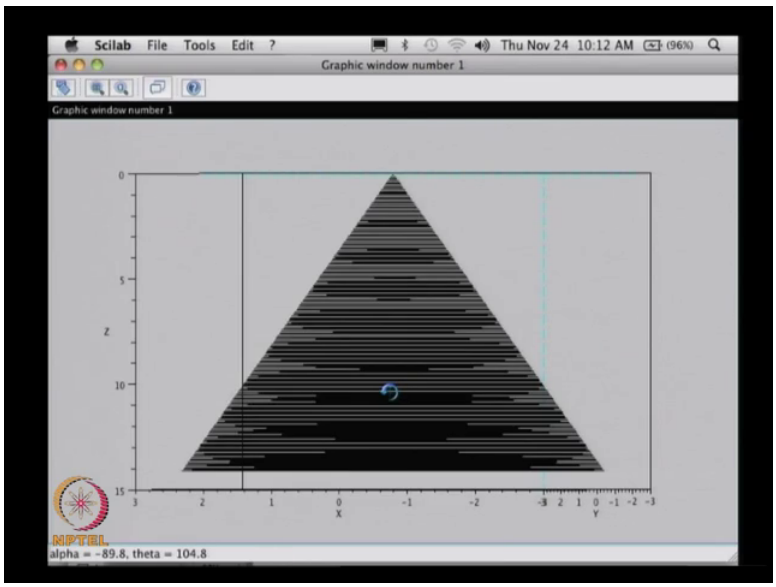

Now, let us sort of you know turn this around a little more and see what sort of this looks like. Now, this is something this is like a wedge. So, you take basically a slice. So, in one of these you know as I am moving around the cone in one of these views I see something like this, this is in fact like a 2D wedge that you know we have seen so far. So, it is something like this. So, in the sense what you should slowly try to visualize that in certain cases, when we have a flow all right it is seeing something like this, something like a wedge exactly like this which is planar which is 2D.

And in other cases it is actually seeing a total surface body you know call it however, you want. So, we have a surface of rotation and this is a surface, and this is what it looks like. These are you can see that it is totally two different you know physical body this is a two totally different physical bodies, and these lines here kind of also indicate that basically. So, it is a surface of rotation. So, one of the ways you can look at the cone right one of the ways you can look at a cone.

For example, say right so I am just going to use this very crude way. So, I say this is the axis, this is the vertical axis which is the axis which is say you know right down the from the vertex if you drop a perpendicular. So, say that this is that vertex right. So, then you take a radial line like that and you take a radial line from the vertex and you move that around you move that around, you move that around all that around and that forms your cone. So, this is your surface of the cone. So, you have a conical structure like this which as you can see although in one of the views that we saw that this did look like you know just a triangle, just a triangle for example like this, this looks just like a triangle, but it is only one of the fuse. So, this is more like.

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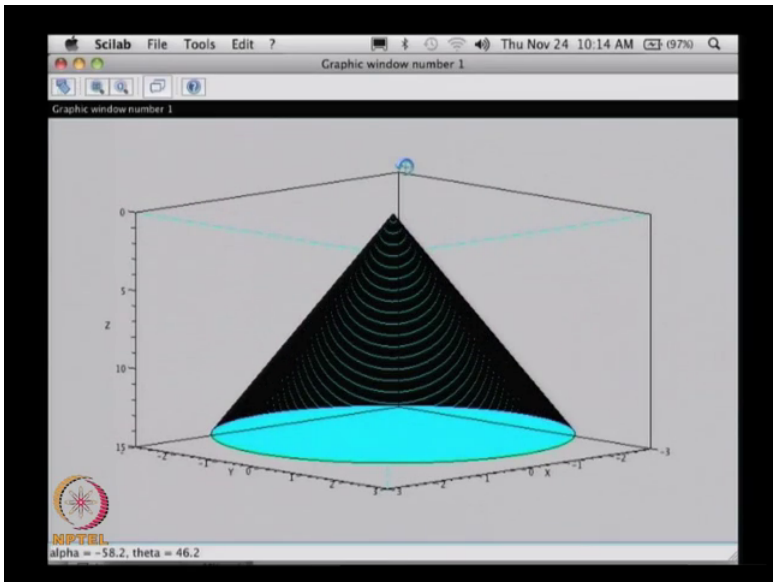

Now, so the point is that if I have such a cone and in here I have a free stream which is coming you know which is encountering this cone right and the free stream direction you know let us start with say the axisymmetric case which we have done so far. So, we have a free stream which comes here and that is in line with this with the axis of this you know right circular cone. So, then what will happen.

So, in this particular case, when you have a surface like this and you have a free stream coming in then obviously, there is going to be a shock wave. So, the shock wave is also going to be centered around this vertex, but the shock wave is also not going to be the two straight lines which we will sort of drawing so far you know which were like the two edges of the we should like the two sort of edges of the wedge so to speak. But here we actually have a surface. So, what will happen? So, is for the shock wave also we actually have a surface which is a conical surface center around this vertex.

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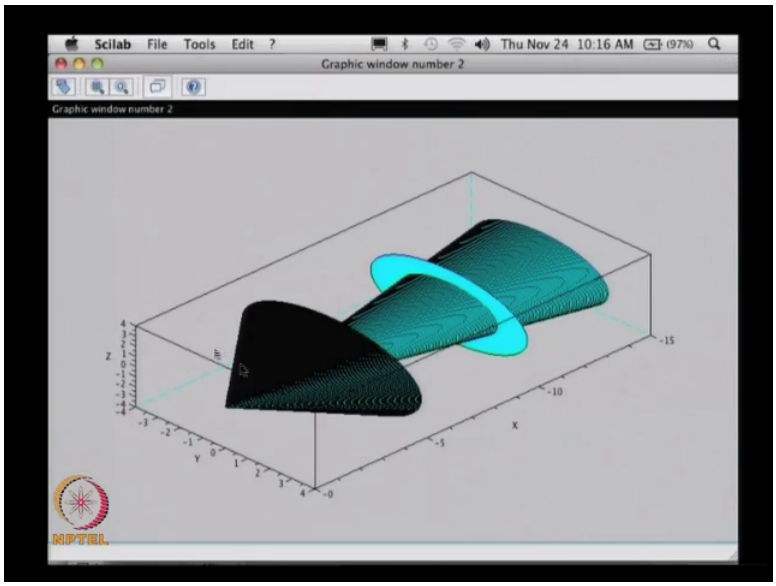

So, let us see how that would say look like say this is this is more like it. So, what you see over here is that this structure here, this is the physical cone this is the physical cone this here. And we have a free stream coming in from here you know in line with the you know in line with the axis of the cone here. And the one on the top that one on this side this one that you see here this is the shock structure, this is a shock which is encountered. So, now let me move this round too, let me move this around too.

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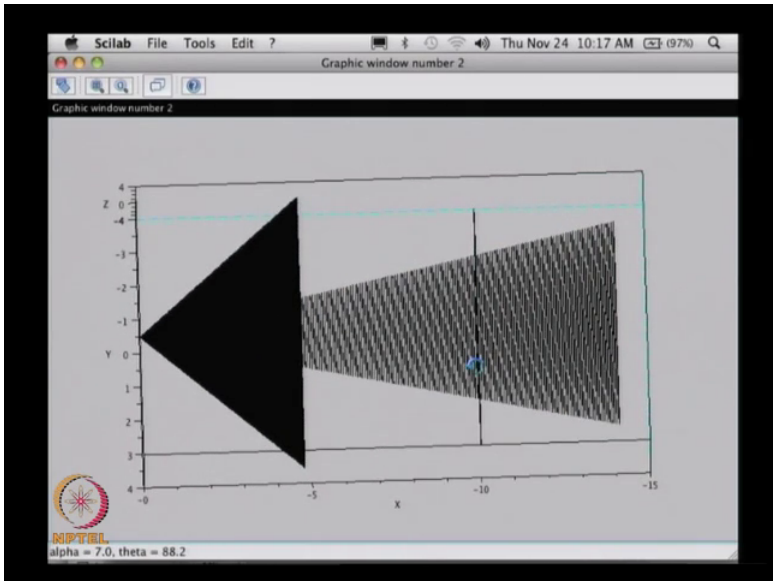

Now before I do this, let me plot this one more time. You was not wondering what this is let that.

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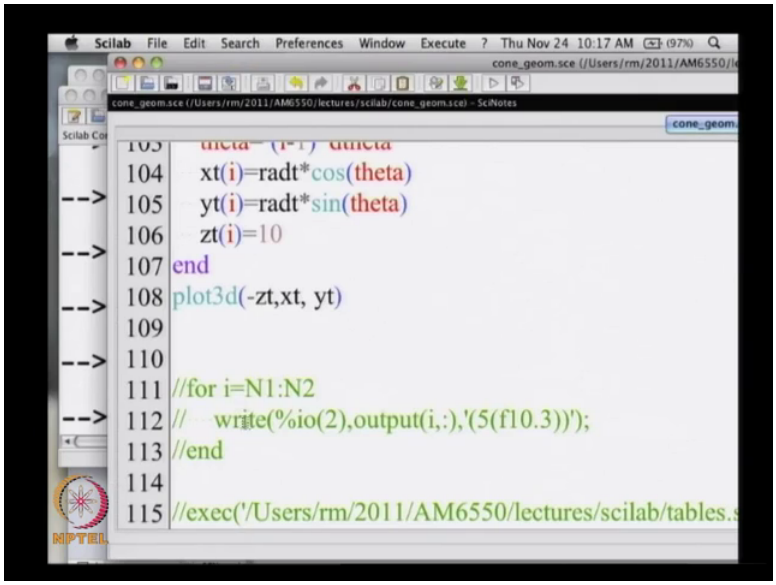

Let us just take a while and not sort of I have done this in sci labs, I can you know plot it and do it as I want. So, let us just look at this now. So, we will come back and see what the other one meant. So, here basically we have the shock structure right, this is the actual physical cone. So, what you have here is this physical cone. Now, again I am going to move this around and you can see it for yourself. Now, this is what we have been used to so far, is not it. So, we would have say you know a conical you know wedge like that then we would draw one line here and one line here and that would be a shock.

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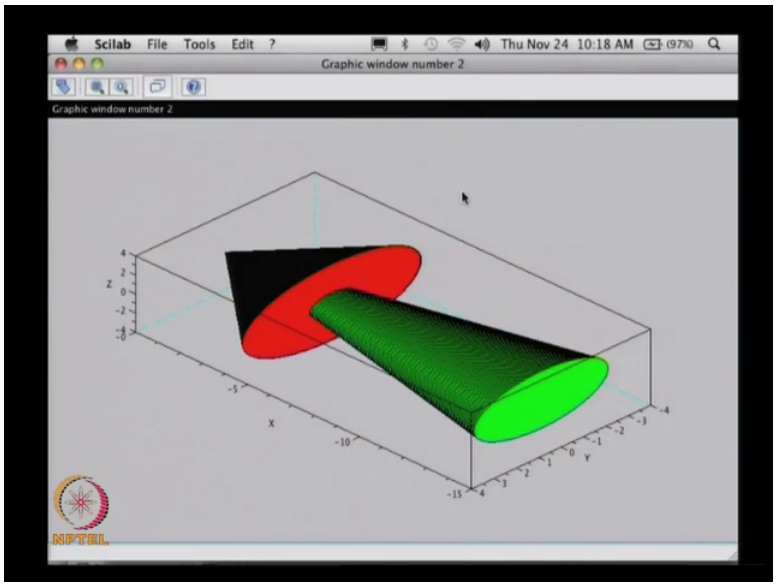

In this case; however, if you look at this ok our body itself, now it appears, now you can see this, now you can see this; there you go. So, what do you see now is that this green thing that you see out here this is the cone this is the physical cone right this is the physical cone and the red one out here is the shock structure. So, clearly you this is you know this is the radial line emanating from this vertex. So, this could be you can you can say this is the limiting radial line. So, this will give us the shockwave angle is not it, the maximum shock wave angle with respect to the axis of the cone which will go which is a straight line from the vertex up to this base here. So, this is the shock structure here.

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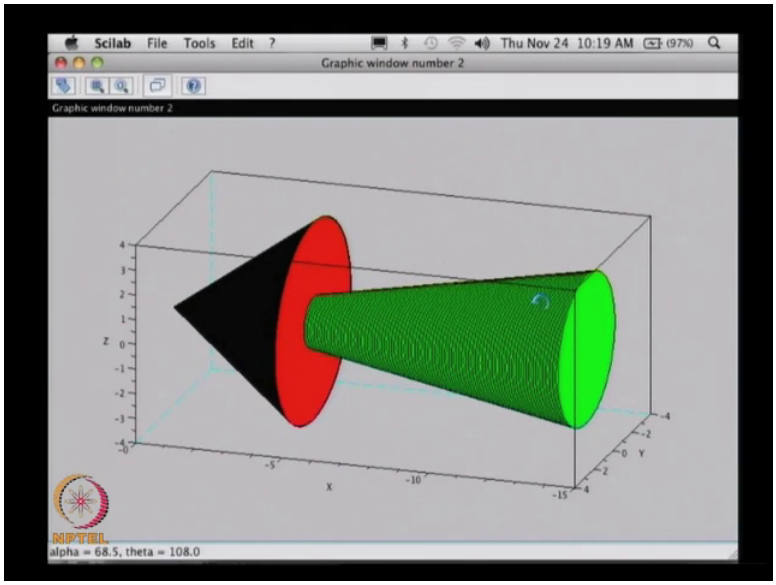

So, what you can see what you can see basically if now the major thing is that we you know move this around and understand how this you know shock structure looks from various angles that is why you know trying to do this here. Because when we do the equations and stuff we will be encountering theta and phi and z, in with you know we need to be very sure and I understand very clearly what all of those mean that is what I am doing all this exercise.

So, what you see in this case is that now you have a free stream here free stream which is coming you know encountering this vertex and you have a streamlined here. So, now, what you will see here that when it enters when it enters this region again when it enters this region, so it is entering a surface of shock, it is in entering a surface of shock. Unlike what we have seen before where we would have just you know one line you know and it would this streamlined would deflect across it.

But here in if you want to draw several radial lines you know emanating from the vertex. So, between the surface one line would basically go on the surface of this cone the other on the outer surface of this shock. So, between these two radial lines you know you actually have a shock surface. These are not just two lines you actually have a full you know actually have a full surface you know like that. So, now the point is when we are you know looking at this when we are looking at this from various angles. So, now, we will try to understand the sort of geometry over here.

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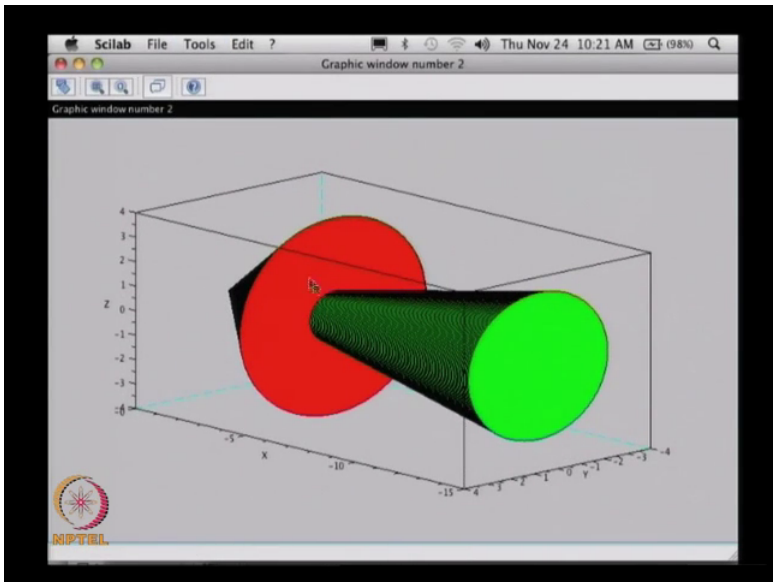

So, now, if you sort of look at this, so these are essentially concentric circles if you look at this, the base of the cone of the concentric circle as a circle and the shockwave are sort of you know cut it to half, so that we can understand so that we can we can see. So, I mean it will probably ex extended little bit longer than I have drawn it here. So, this is also a shock way. So, what the way we will look at. So, the way we will study or look at the shock properties or changes in the flow properties is basically we will take a you know sections along this along ah this length of the you know the shock this cone.

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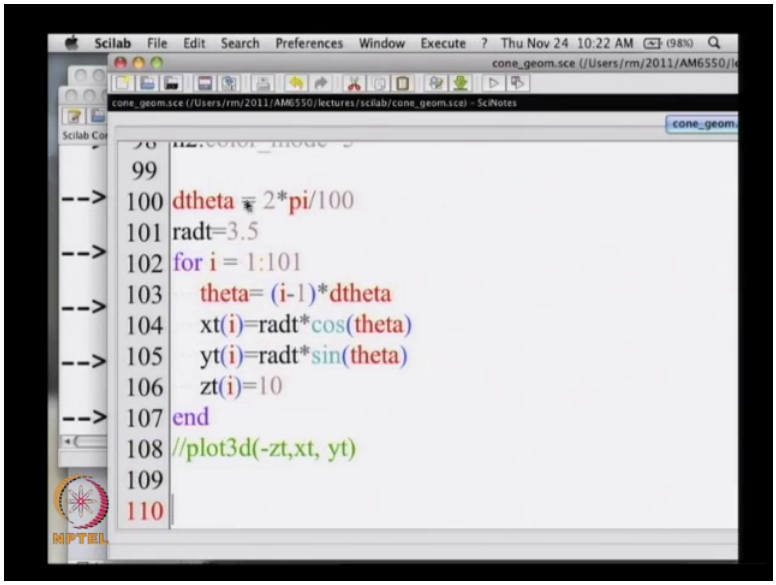

So, let me go here and do this. So, if I were to do this let me call this as say this. So, let me just say fine. So, essentially what you know I am doing here is for example, interesting. So, probably oh sorry let us do this here.

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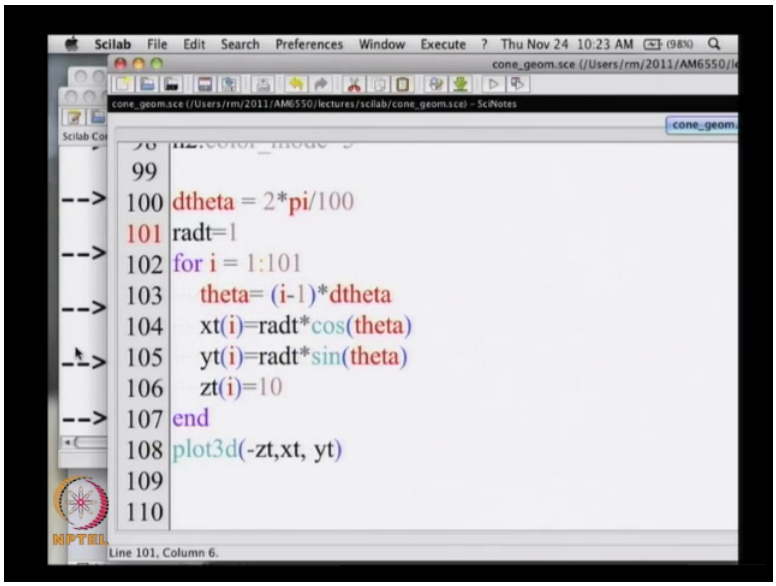

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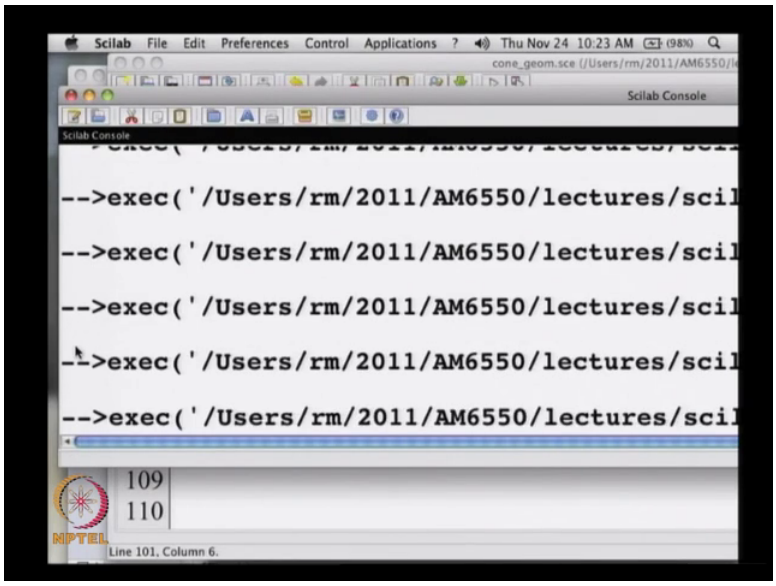

Let us see. So, am I getting something here (Refer Time: 15:25), so let me look at this. So, what I am basically looking at is just. So, now let us go and sort of look at this. So, what I am going to do here basically we will run that you know the other surface that strings I change then do this on this.

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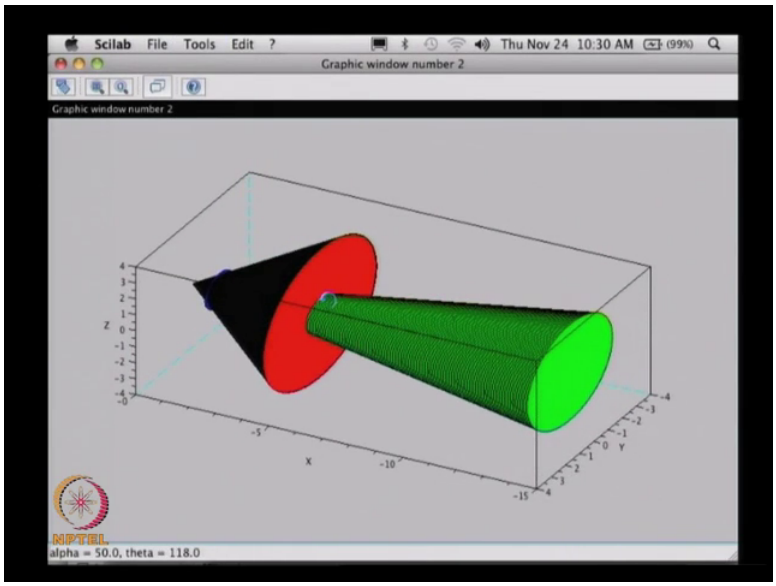

So, what you see over here is this little ring that ring is here. So, what we will see here is that you know you can see the small ring, ring there. So, when we when we are going to study as you know structure like this you know we are going to sort of look at these rings. Look at the geometry of the ring and you know in this case and you can see that if this ring is actually going to have you know sort of the middle portion scooped out. And the middle portion is going to be scooped out when you know depends on where you are located along this structure over here.

So, in this case, when you when you see this. So, there is it this ring this way. So, you can just think of you know a structure like this the green portion is a solid cone it is a solid surface cone, and this is a shock structure, this is a shock structure which and both of these have the same vertex. So, now what we do is we will just take this ring and pass it through this so which means that let me go and pass the ring, let me go and say pass that ring.

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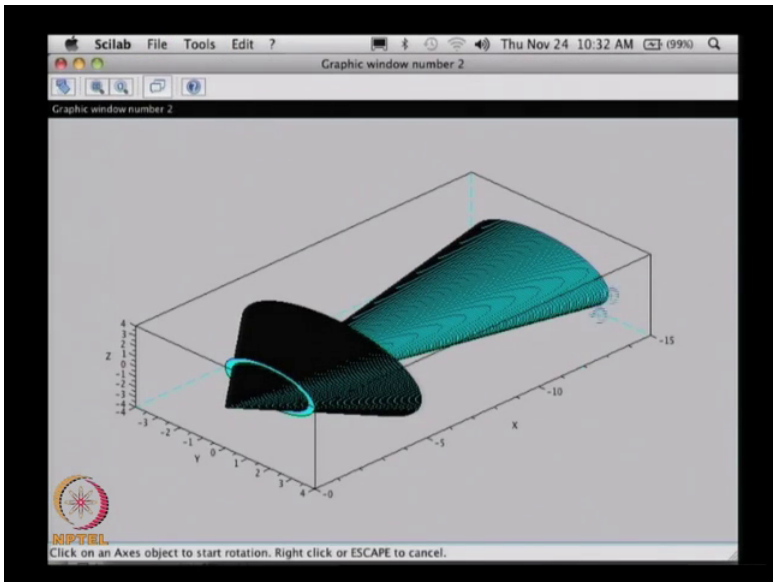

So, I sort of extend that. So, I move that ring further down because I am going to study this part. So, I move that ring further down. So, if you look at this, so I got that ring out here.

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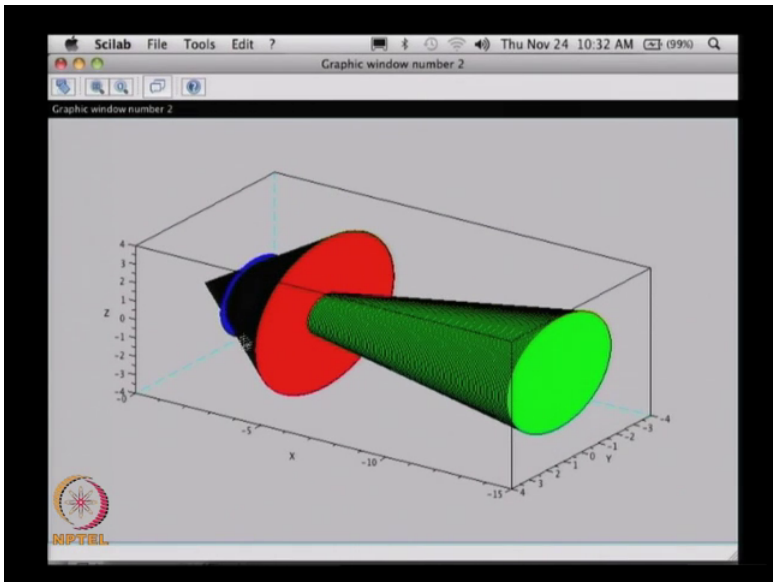

So, if I were to look at this then I would look at I am in location like this. So, similarly, so if I were to sort of look at trying to figure out, how this geometry would look like.

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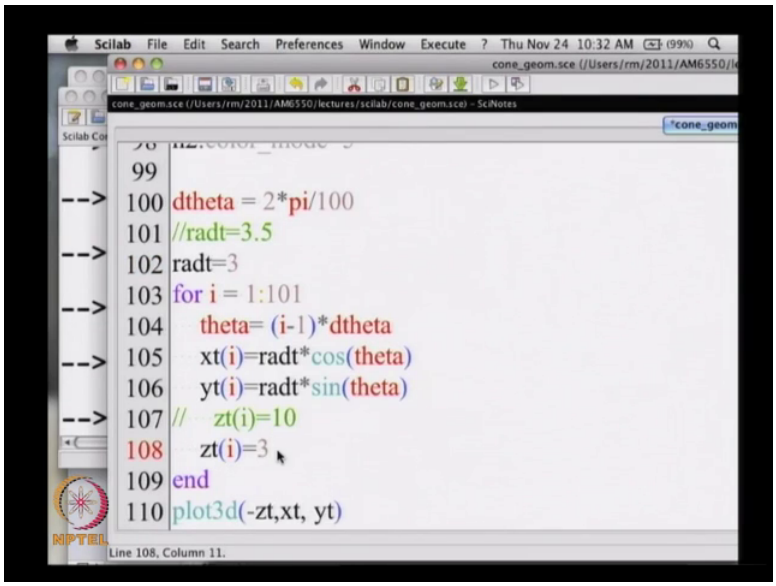

For example, I move it further down if I move it further down, so there you see.

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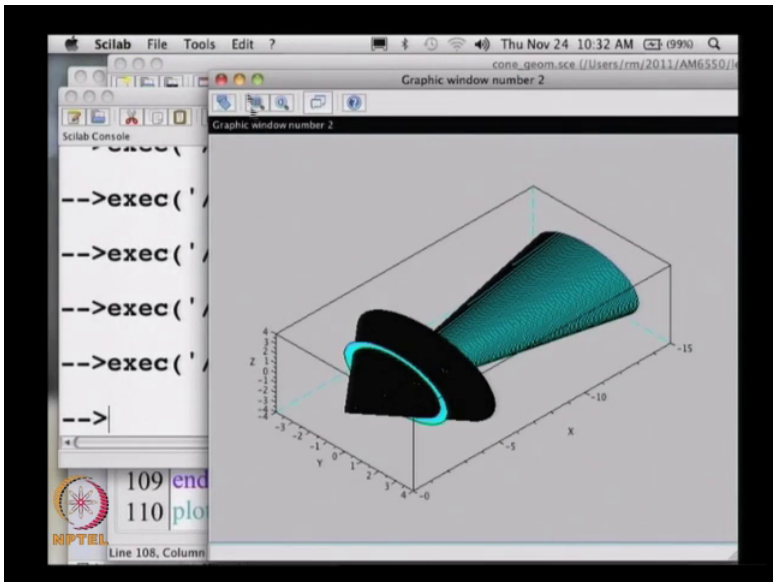

So, I am basically passing the ring I am passing the ring through this conical you know structure. So, we have one solid cone, and we have a conical shock out here. So, if that is the case, so let us look at say so now if I look at this, so I have I am basically looking at a shock looking at a you know at a location which is somewhere over here.

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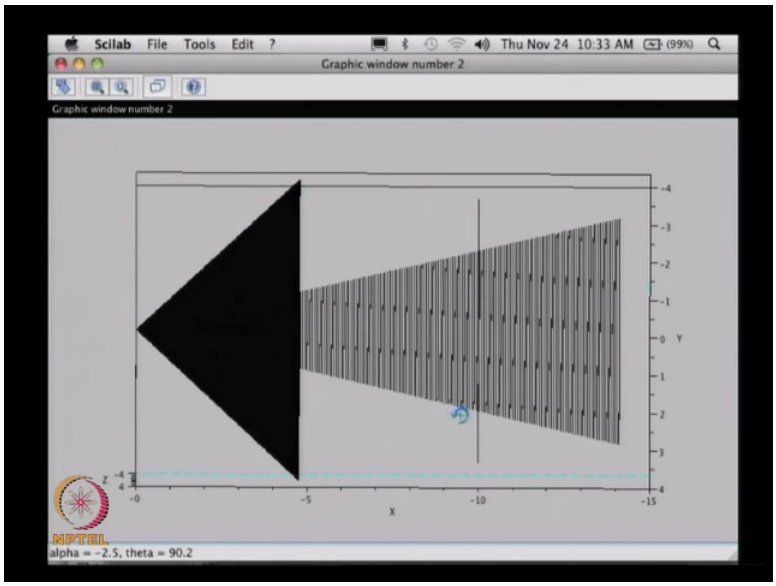

So, if I were to look at you know in say a position like this, if you look at this all we are seeing is basically one straight line here, another straight line here a straight line here and these two edges. Now, this is not any difference from whatever we have done so far in terms of oblique shocks and so on and so forth. We have been drawing these pictures over and over again on the board and you know in the plane of your notebooks and so on and so forth.

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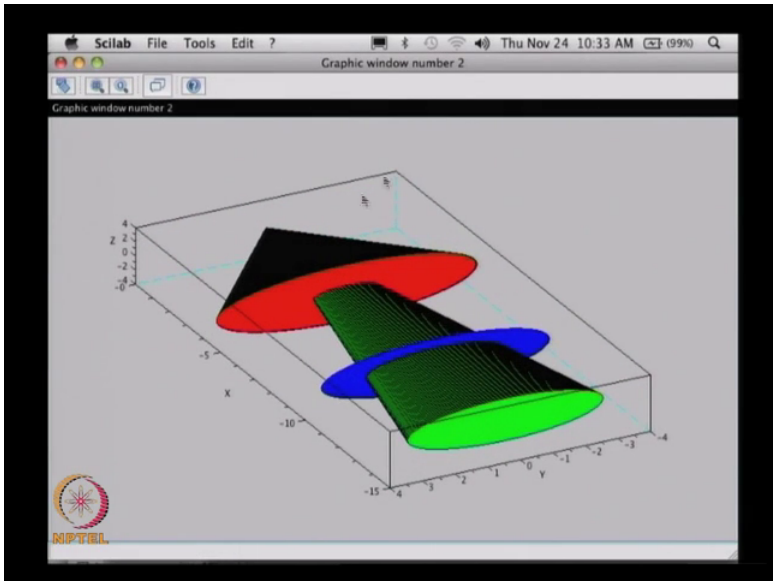

Now, this is something that you know this is something that it is actually above. So, if you look at this, if you look at this let us sort of turn this around move this around and look at this from various angles. So, what I am looking at here is basically this you know if you look at these three out here, so if there is a red circle, there is a blue circle there is a green circle. So, we essentially have you know three parallel circles, we have three parallel circles. So, I can also sort of think of you know think of this.

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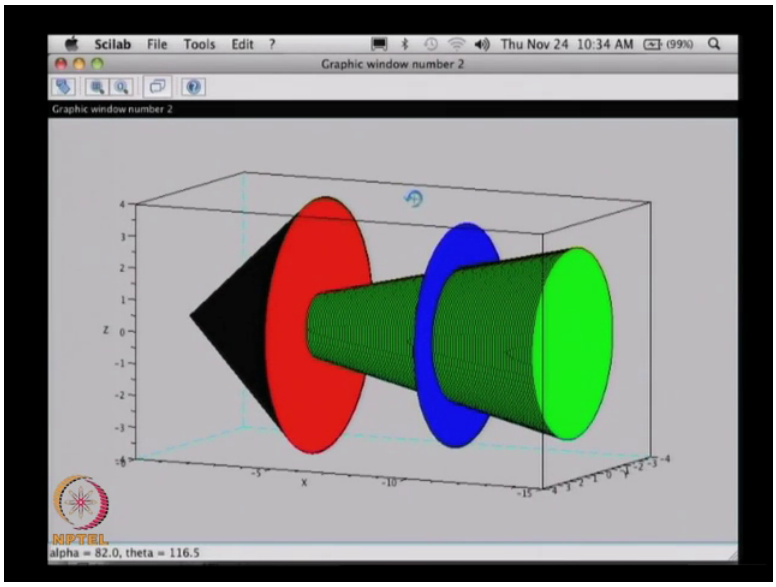

If you look at this way, let us look at it here. So, if you look at this we basically have three parallel circles we have green this blue and this red. You can also think of this blue as a section, you know as if I sort of slice, it is almost like I am slicing this whole thing. So, the shock structure with obviously will be you know will extend I have cut the short here in order to make this a little more visible. So, if I were to take this blue, you know and you know here and slice it and move it in here, and that is what I would do and then look at the properties.

So, you can see therefore that even within the shock structure, even within this red you know cone out here, which is a shock. So, basically this is also this also this cone also consists of several parallel you know planes like this. So, I have various parallel planes out here, which is making up the shock cone; shock this conical shock structure here.

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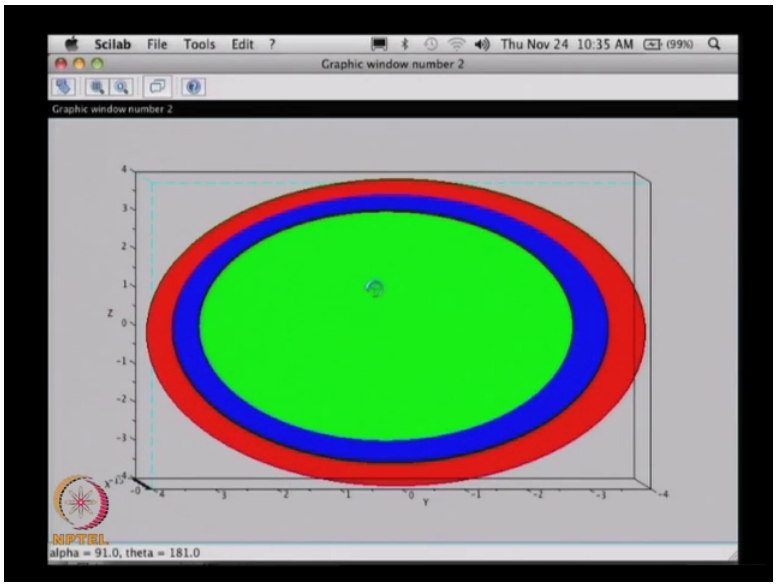

Now, if I would look at all of this from the base how would this look like, make sense right, this is how it would look like. So, it is nothing but three concentric circle. So, if I have to just look at this here it is nothing, but three concentric circles. So, what you are actually seeing here is this green. So, this is how this is when you look at this shock structure through the base, you are looking at it from the base. So, if you look at this, so we have this green part, which is the solid cone, this is a solid cone. And this red part is the shock structure, the red part is the shock structure; and this blue is a slice which I have taken anywhere in between the shock structure in anywhere between this whole thing. It does not necessarily have to be you know in a non shock zone the way it is now you know. So, this is what it looks like if you want to look at it this way.

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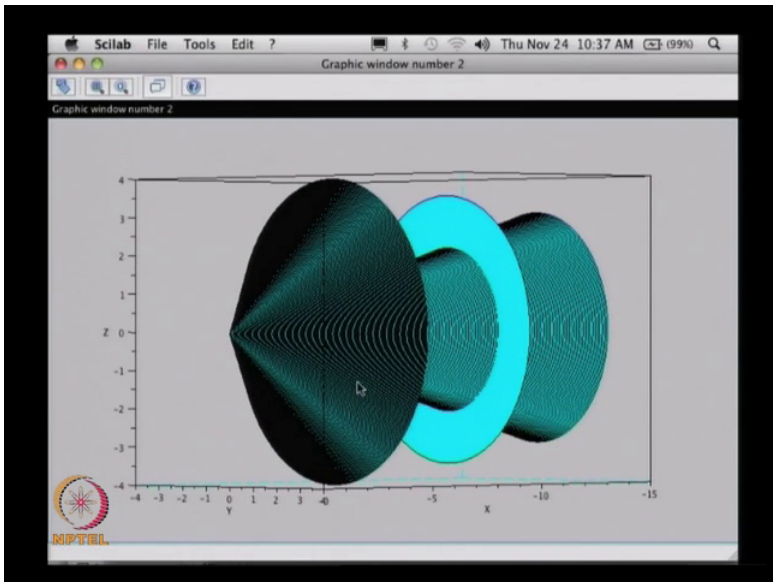

So, let us just sort of turn this around and see how it would you know look like from the other side. So, it helps kind of moving this around and looking at it and trying to understand. So, this is if you look at this, if you look at this angle over here, so if you see this, so this is a distinct of now that now just think about this. Now, this is a solid cone here, this is a solid cone and this is the shock structure.

So, if you have a free stream, which comes in here. So, you can see when the free stream will come in it you know a free stream free stream will come here and encounter the shock you know it is on a surface you can look at this it encounters a shock like that. So, encounter the shock layer, there are no single straight lines like we have been doing so far. So, it will encounter a shock in this way in a sort of it will move around in a circle and encounter this. And therefore and then there will be deflections you know in those streamlines.

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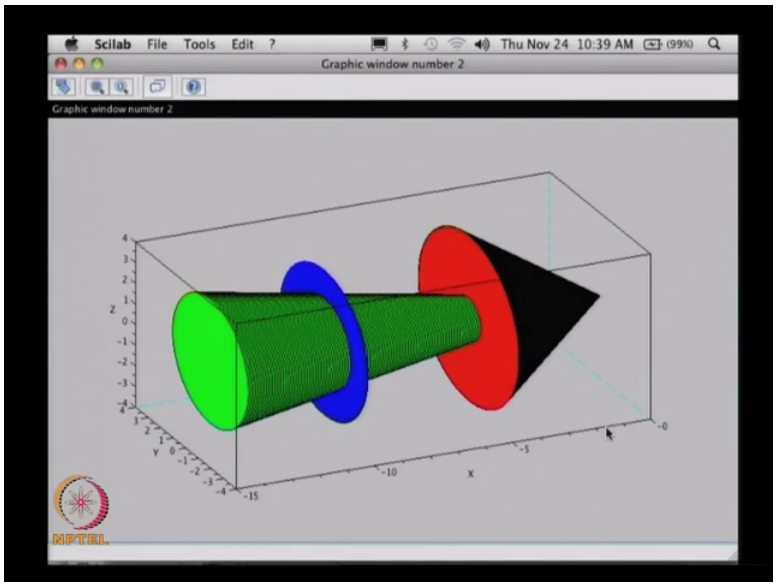

So, in that case if I take a slice like that and pass it through this, then I should be hoping to see some property changes in that slice. And then if I put several slices together and I then I and I put all those information together I might have something to I am at might have enough information about this whole structure. So, if you look at this here, so if you look at this here, now it just looks like that obviously, if you are looking at from the vertex side if looking it from the vertex side. So, again just try to take a look at this is almost like a hat is not it this almost like the cone is wearing a hat if you look at this.

So, just I am going to turn this around and you know give you a little bit of view. So, if you look at this. So, right and one view could be see this straight line and then you move this around and then you see this. So, you can think of this as a hat actually the shock as a hat. So, when we have a free stream you know it is going to sort of encounter this entire shock structure and how this is going to be here so that is basically our job today.

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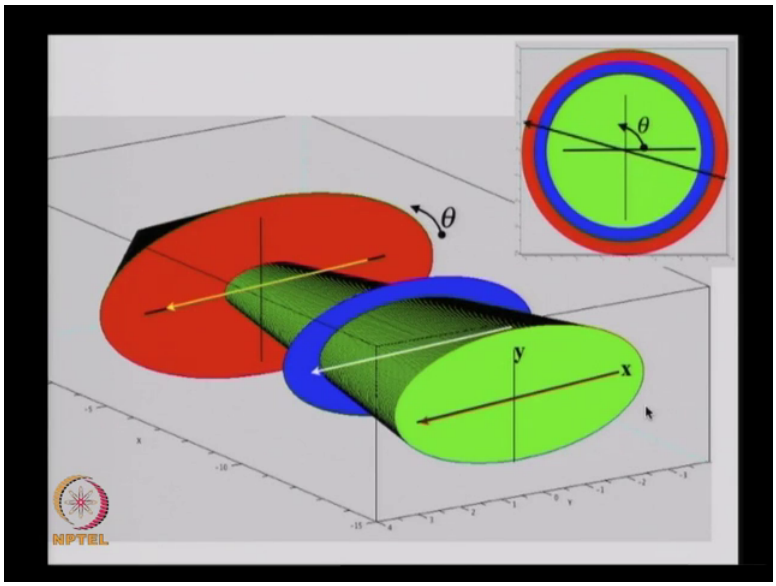

So, let us again you go and sort of and just and decipher this geometry part even a little more. So, let us look at some this with a little more detail. So, this is what we looked at just line now one of the pictures how we looked at it right now. So, let us have you know this x and y. Now, this x and y, so axis is just in the plane you can think of this is just in the plane of the this is the base plane then this is the plane of the shock and this is the slice that we were taking. So, this is another sort of ring. So, this x y is it just is not that plane and the z axis is actually a line if you drop from the vertex and to the base.

So, if this is true, now what I am going to do here is draw these three sort of you know radial lines like that. So, these are right now these are three diameters, you can think of three diameters; obviously, you can see that all these three sections that I am taking the base here is of a different diameter then the slice blue and the shock base red. So, these have three different diameters. So, I am basically taking three diameter vectors in that diameter on these three you know slices so to speak.

Now, let me rotate this, let me rotate this. So, what we are basically sort of you know doing here. So, if you think of this, if you sort of think of this as the base of the cone, if say that this is the base of the cone. So, then all we are doing is we have an access system which is x and y, this is an x and y, this is my access system. And then all I do this is my access system and all I do here is or you know just think of the edges. So, this

as say x and this is y, this is the base that you can think of this is the base of the cone. And then you take this diameter axis and move it in this plane, move it in this plane.

So, what you just saw now what you just saw now is rotation in these planes. So, what you can see basically from here is that if you give, if you are rotating it by the same angle, if you are rotating it in this plane in this conical shock structure out here you can take any plane along the z axis, and rotate it by any angle, it will be the same on any plane. You can you if you have an angle of say 30 degrees and your rotating this diameter say in at the base of the cone, it is the same as if you take another plane somewhere here changes the blue. It will also have you are basically again rotating it at you know the diameter here by 30 degrees and or here by 30 degrees is the same thing because these are basically parallel planes.

Now, if I have to look at so now, this angle is essentially theta. So, this angle is theta and it is the angle which we are making in the plane in the parallel planes which are making of the cone shock structure or you know in the base of the cone whichever way you want to look at it as long as you sort of have a feel for this it is fine. So, theta is basically the angle that we are making in the plane.

Now, let us look at this. So, what would this look like if I were to just look at this from the base side. So, if I am looking at it, so if you remember just now as I showed you. So, I have this structure here. So, what you can see is if I draw an axis system is pretty much the same is the same for all the three planes that we are looking at. Although here this is a solid cone the green one, the red is a shock structure right, and this is a slice somewhere in between right. But if I take, but these are all concentric circles and these are all centered around the same point. So, therefore, if I take a radial line here and move it and I move it, so it is going to make the same angle and all these three planes if you know what I mean.

So, theta is essentially giving you just the location in the you can think of in the x y axis. So, does not necessarily give you tell you whether this is a cone or not, so obviously, we need more information to make this more into your cone. So, what more information do we need, so that we can say this is a conical structure? When I look at it I know it is a cone sure, but when I am going to do the mathematics, how am I going to look at a point,

what are the things what are the parameters that we will need to locate a cone that is the exercise here.

So, if I would go back one more time. So, what we will looking here is that we have basically taken three parallel surfaces just for the one is the base of the solid cone, and there a base of the shock structure, and just the slice somewhere in between. And I draw an access system and I look at it you know in this 3D sense, so axis system, so these are all concentric circles these are all parallel planes. So, then I draw these three diameter vectors and instead of move them with the same you know degree in all the three planes.

So, I see something like this. And this angle what it makes in the plane is theta. And as if I if I look at this here which in the in the sort of if I look through the base of the solid cone here, I see a picture like this, this is like a 2D space. And then so this is what it will look like if I take a radian line is pretty much you know is just the same radian line moving through all the three planes. So, theta basically gives me the location in the xy plane that is all it does, so theta.

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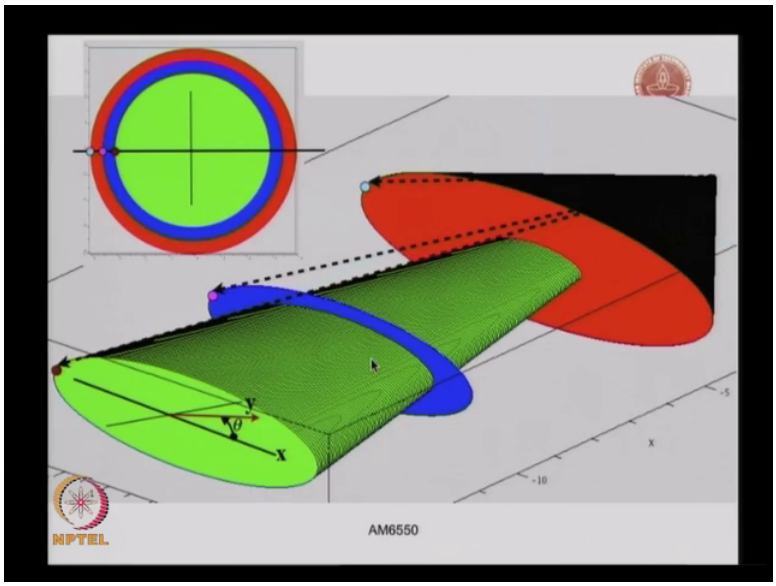

Now if I go here, now, let us look at this structure a little more carefully. So, what I will do is. So, this is my x y plane. So, x y is essentially located in the plane of these you know say green, blue and red. So, if I do that, so I take that any line. So, this is the theta. So, the theta is essentially in the plane is not it. So, theta essentially in the plane of the body here, which is the shock and cone, now so let us consider these three points you see

that. So, I have taken a point here you know. So, these are three different cones if you can think about it. So, this point out here is a point on this solid cone. This point is on the slice here and this point is on the shock structure. So, these are essentially three different points. Now what is different between them what exactly is different between them?

Now, if you look here in the planes in the planes here, theta is equal to pi is not it. It is 180 degrees it is making 180 degrees with the x axis here this point. Now, on this blue plane also this is making theta is also making pi again this is 180 degrees in the blue, blue plane. And if you look at this blue a little blue point here, so this is also making pi in the red surface, but you can clearly see that these are three different points three different points. So, what is it how are we going to define the difference because if you look at theta is the same in all the three planes.

Now, what we can do is look at the view from look into through the base of the cone if I look at this. So, this is the shot this is the cone and this is a shock. So, if I were to look at this 2D space, why do you think the points would be located if you know why do you think the points will you look at it if you look at this point here it is at the right on the leftmost point. So, basically this is how the points would be located is not it. So, for all the three planes, if you look at, so all the three planes if you look at this is that the leftmost end, so that is where we have this point if you look at this it has a leftmost point which is here and the red one again a left most point which is over here. So, these are the three points we are looking at.

Now, what we are going to do here, what I have just done is that I dropped a line; I dropped a line from the vertex and reach this point here. So, basically if you sort of you know look at this. So, this is a plane. So, this is a plane, and I am looking at say a point over here. So, if you look at this. So, I have a plane you know this is the base of the cone say I am looking at a point over here. So, this makes an angle pi with the positive x axis. Now, I actually have a cone sitting up here I have a sitting up here. So, what I am doing is, so I take from this vertex I drop a radial line which touches this point to reach this point. So, I drop a line from here, so that is what this arrow is here.

So, similarly I will drop one more for this point here for the blue that and then again this for this. So, what is the difference exactly between these three? So, essentially what I am looking at you know this is essentially a cone structure is not it. So, at the base I have

this point and the cone then sort of you know fact it comes up like that, then you have a blue structure there in here. And the way the shock structure here is that either the shock has a larger, the shock base has a larger diameter and that sort of decreases, the cones has a smaller diameter compared to the shock.

So, therefore, I have a point here and the next point is somewhere over here. So, for the first one I drop a really line from here like that; and for the next one I drop a line like that; and for the third one again I drop a line from here and probably reach there, so that is what I have done in this case. So, if you want to think about it this way, so here you can think of this for this particular point. So, if I have this sort of vertical axis, so for this particular point, so I have this angle.

So, if you look at this you know this radial line makes a certain angle with this vertical axis. And the next point is somewhere over here. So, then this has to move like that is not it, this is the next point which you can think of this as the blue plane. So, this angle is what it is making with the vertical. Again the shock is somewhere over here, so I have to increase the angle. So, this is the surf this is the surface in which I am acting. So, when I am drawing these radial lines, it is in this place. And the angle which it has made with, in this particular plane is theta which is in this plane. So, if you do clockwise anticlockwise rotation here and this rotation is in this plane which is this plane is actually perpendicular to the plane in here.

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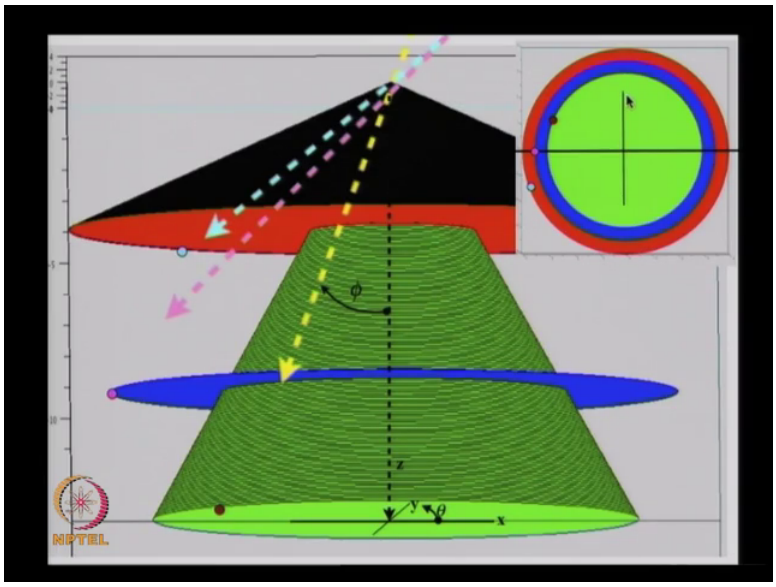

So, if I have to sort of look at this let us look at this from another angle. So, you can see here now you know, this is my cone, this is a cone base, this is the shock structure up here and you have this in a cutting plane somewhere over here. So, then these are my three points is not it. We located these three points somewhere over here. And then if I drop a perpendicular from the vertex into the base of the cone. So, in this plane actually plane of these concentric circles over here, this is the theta; and you can see the theta is equal to pi for all the three cases. So, you have this like I just now try to show you. So, this say I have this vertical I have this vertical and then I lift I so that it is it be this radial line basically gives me this particular point. This radial line is being originating from the vertex.

Similarly, let us try and look at this point here on the blue plane. So, you move that and it goes that way. So, again we take this and remove this, so then again it goes. So, essentially we have three radial lines and this angle that it makes is the angle phi this angle is the phi angle of the azimuth angle. So, if now we located for example, so these three points right at the edges. So, what we looked at, so now we looked at we took three points exactly on the you know left at pi basically theta is equal to pi.

Now, what if we do not do that, what if we take different points. So, now, let us look at each slide each you know circle here or plane here. If you look at the green place here this is not pi degrees, it is less than pi, this you know something less than pi. So, it could be 150 degrees for example. And this one is pi, on the on the blue plane it is still pi it is still pi. And if you look at the red plane and this is more than pi is not it if you look at just the red plane it is more than pi. So, it could it would probably be know 180 degrees you know plus 30 degrees or plus 45 degrees probably not 45 maybe 35 degrees. So, pi plus 35 degrees. So, we have this.

In this case how will this if I will drop the you know the radial lines from the vertex how will they look like? So, what this means is that I have this radial line, I have this radial line and then I move it here, look here. And I do that and I move a here that moves there then over here. So, if I were to sort of what exactly am I doing here? So, in the previous case we said we are looking at basic. So, the again this is the base of the cone, again this is the base of the cone. And say this is the point that you are looking at; this is a point we are looking at. So, there are three points. So, then at the first instance I have it is just a straight line. So, the first instance is this just a straight line along the body of the cone

which reaches here, so that you can just take that as the surface of the cone, so that comes up here.

So, you can also think of a radial line occur in which you drop. So, radial line is here and you basically point it to this particular point. Now, the next radial lines should look at where the next radial line should look at is the point, which is higher up here. So, we went like this. So, this was our next point, this is our next point; and the third one again it went up here. So, these are the three points that we locate it. And all the three points here where the left or theta was pi.

Now, theta is not pi for the first one what I am locating is a point somewhere over here it is making less than pi, it is actually making less than pi. So, if you look at it the point is here actually the point is here is not it. So, in that case in that case of first if I drop a perpendicular, so in the previous case I do the perpendicular the my radial line was here. Now, the radial line is going to shift by this theta. Again previously when I had this radial line, now for the next one, which is for the blue one.

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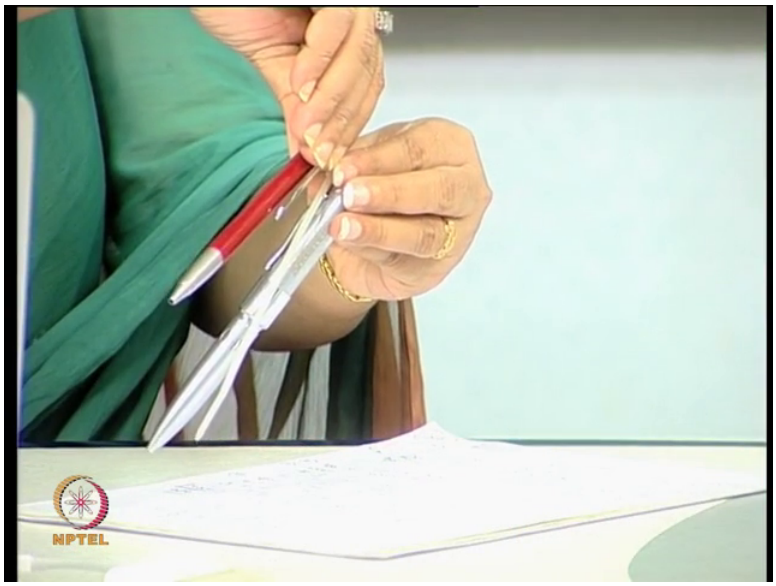

So, if I have this previously what I had was like this. Now, it is going to remain at the same point because it is still theta is pi. So, this is still going to remain at the same point and the third one again previously again it was here in the same plane. Now, that is going to move it is going to be here. So, hopefully you can see the difference you hopefully

you can see the difference look. So, that is the theta which is creating the difference. So, essentially so I have this vertical which I am dropping from this vertex.

So, I have say this is the point which I am located. So, point at this point at this particular location it is in this plane is making pi degrees what if it makes more than pi. So, then I am going to just track the particle, I am going to track the particles, I am going to go behind. So, say the particle is moving. So, I track it. So, I track it I move this move this now it is making 0 degrees. So, then I move it then I am move it then that forms my cone that forms my cone. And you can see is still the same radial line, it still makes the same angle with the vertical sort of speak it still makes the same angle with the vertical still my same angle the vertical because this point is now moving in this x y plane ok. So, the theta is changing. So, this also moves, but the pi remains same. The phi remains changed, but because of the theta changing this moves, so that is what essentially these radial lines are you know mean over here.

So, if you again if I sort of look at this, so I am looking at these three points. So, I this goes up by radial line that and this. And this again if I look you know through again if I look sort of into the cone structure through it, if I look at this then in this particular case what would you notice. So, now you can see that in this plane in this plane these are three concentric circles, but if you look at just the green circle here which is the base of the cone, it is making less than pi is not it.

It is making less than pi, this is again at pi theta and blue is more than pi. So, you can see it from here. So, essentially now and of course, another difference is that this is also at a so besides just the height besides just the angles. Now, we are able to sort of locate this not only just in the plane, but also not only just in this plane the x axis, but also in a conical plane like this. But whether we have the base of the cone or we have the slice here or we have the base of the shock structure is again going to be decided by the height z, so that information is also necessary.

So, I think we will stop here right now and then when we take it up from here again what we will start doing is now go ahead and try and understand the difference between the axisymmetric and symmetric case of the shock structure. So, we will stop here now and can take it up from here.

Thank you.