Optical Engineering
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Lecture – 17
Monochromatic Aberrations - part 1

Good morning. We have been looking at aberrations and we are going to start in this class looking at the specific Monochromatic Aberrations. We defined an aberration as basically the case or the time when the array or how much array misses its paraxial image point, that amount is what we call the aberration of a system. And, in yesterday's class we looked at many different ways we can quantify that, there are several different ways that we can quantify that. And, now we are going to look at specific aberrations, we also ended the class by saying how can we correct the aberrations.

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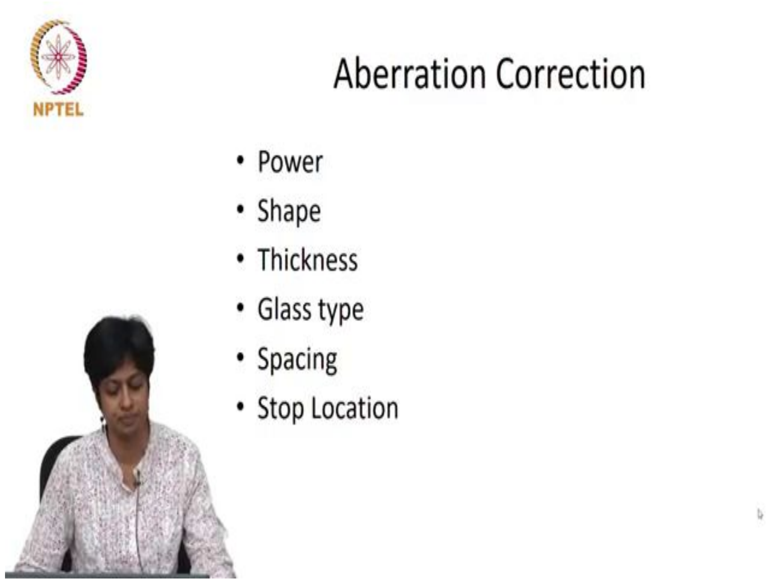

And, we found that there are several ways that we can correct them and of course, the purpose is to be able to quantify them. And, then figure out how to minimize or even eliminate them in your optical system.

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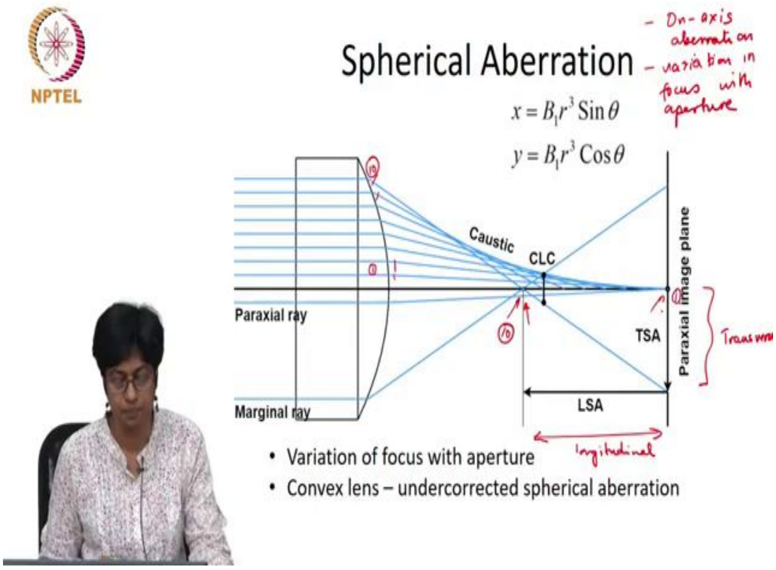

So, we start with spherical aberration, spherical aberration is called sometimes as an on axis aberration. And, you can consider it to be a variation in the focus, a variation in focus with aperture ok. What does that mean? Rays that come to a different location of the lens will focus at a different location on the axis. So, normally we consider a lens, we take a lens and we say this lens has a certain focal length.

You developed the equation for the lens, we said the lens focal length is 1 $\frac{1}{f} = (n-1) * (\frac{1}{r_1} - \frac{1}{r_2})$ So, that gave us the impression that if I am using a single wavelength; so, n is a fixed value and I have taken one lens and I do not change that in any way. So, the radii of curvature of that lens are the same $\frac{1}{r_1}$ and $\frac{1}{r_2}$ do not change, this lens has one focal length associated with it right.

But, what is going to happen in reality is that different rays and when I say different rays I mean the rays that hit the lens at different points. So, you can consider each of them as coming at a different height and therefore, that is why we say variation with aperture, because they are at a different height. Each of those rays comes to focus actually at a different location and; that means, you have a spread of the focus along the optical axis.

Now, in this figure you have a convex lens and you can see the paraxial rays, the rays closest to the optical axis that is why we assume the ideal focus. They are the rays that will form the ideal focus and you can see these rays. So, of course, the ray that is traveling along the optical axis, but just to make it clearer let us take the ray just above the optical axis and you can see that ray is focusing over here. So, this point over here is the paraxial focus and that is why this is being indicated as the paraxial image plane.

As you go further and further away; so, you go to this ray and this ray and so on and you go to this ray, this is the topmost ray and you can see this ray is coming to focus over here. So, it has been exaggerated in this figure, the spread may not be this large, but this has been exaggerated to clearly show you that the rays coming from up here. So, this ray let us say this we call ray number 1 and let us say we call this ray number 10, number 1 is focusing over here and number 10 is focusing over here.

So, this spread is all focused, but then the overall result is that it's not focused right. So, as we talked about yesterday, this is basically spherical aberration, a variation of the focus with aperture. It is an on axis aberration because this is true for rays that are coming from on access points. And, we will always consider a bundle of rays coming from infinity as coming from a single point. Because, if they are a parallel set of rays they are coming from someone point, one direction very far away from the lens.

Now, we define or quantify as we talked about yesterday, either with the longitudinal error or with this transverse error or you could even talk about an angular error ok. With a convex lens, now when I say longitudinal error we can go to the next. With the convex lens we have what is called under corrected spherical aberration and that is the case where the rays from further away are being focused closer to the lens, that is under corrected spherical aberration.

So, these rays are getting focused closer to the lens and these rays are getting focused further away from the lens, that is under corrected spherical aberration.

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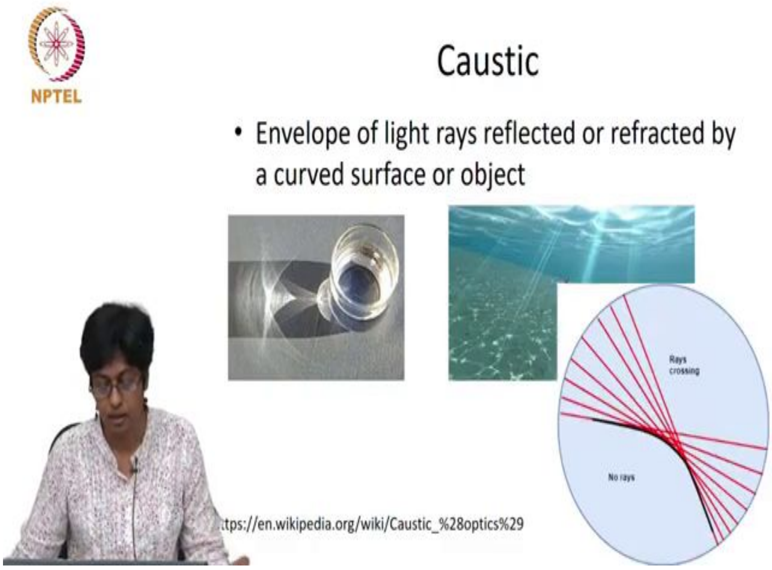

Now, just a small aside you even notice in this figure that you have this bundle of rays that come and are incident on the lens. And, then there is a region here where you have all these rays that have been refracted by the lens. So, this is kind of an envelope, this last ray here is kind of an envelope and beyond that in this region at least there are no rays. We call this the caustic and you would have actually seen these caustics quite often right.

Any time you have a curved surface and light is incident you see these caustics forms. So, they are really the envelope and one side of that envelope or what does it envelope, it envelopes a region where the reflected and refracted rays exist. It very clearly demarcates the region where those rays exist as opposed to where they do not exist. And, it brings out very nice patterns and I just wanted to mention it, because I am sure this is a phenomena that you would have really noticed, anytime you have a curved surface, reflective dielectric surface.

Very common in water bodies and there you see a number of these regions because the surface of the water is not absolutely flat. There are variations. So, each is acting like an individual lens, if you will and its set of rays are being focused to some end, causing a region where there are refracted rays and a clear region where there are no refracted rays. There are a lot of people who study the mathematics of these, because you get these nice cusp regions.

And, people who are looking to see how you can use this as some kind of diagnostic tool as well.

So, it is not just that it gives you pretty patterns; they are also people studying to see how it can be used for different applications ok. So, I just wanted to bring that to you as a point of interest.

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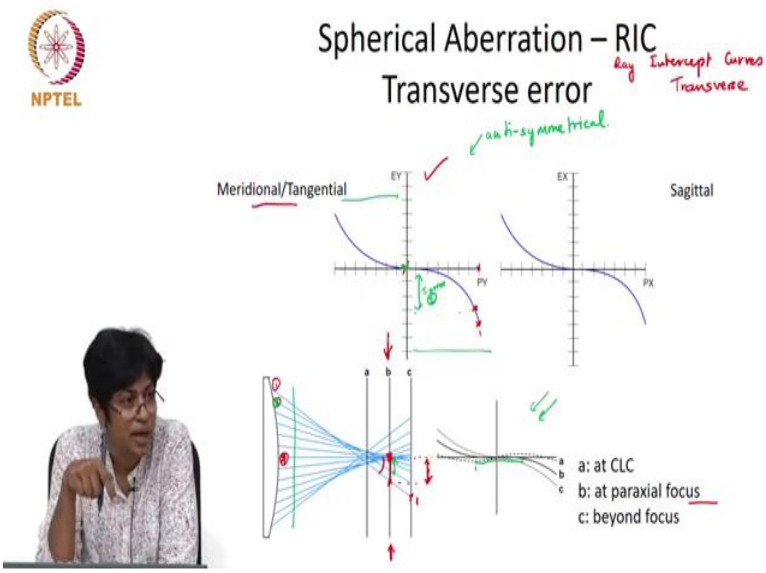

Now, if I am going to talk about spherical aberration or any aberration, we said we need to quantify it and one of the ways to do that is to use what we call the Ray Intercept Curves. So, that is the RIC curves. So, we can plot the RIC curves for different sets of rays. So, what is plotted here, this figure is a curve for the meridional rays. Now, let us look at the figure below here, we have a convex lens. The rays from further away from the optical axis have been focused closer to the lens, those closer to the axis have been focused further away from the next right.

What is an error that we are plotting in these RIC curves? We talked about this yesterday, what was the axis? I said we never label the axis. What are we plotting? Tangential error was the y axis and the x axis was tan of the angle right. And how did we plot? We said we always start by taking this way first and its error gets plotted and so, that is the first data point; then the error of this ray will be the second data point and so on.

Which one is the on axis? I am not let us say 3 4 5 6 7, let us say this is my own axis and that is this data point right. So, what is the error that is being plotted in the RIC curves? You are plotting the transverse error, not the longitudinal error. You are plotting the transverse error. So, if I look at ray number 1, its transverse error, the ideal focal plane so, b is the ideal focal plane. So, this is where the paraxial rays are getting focused. So, ray number 1 has a transverse error, ray number 1 is this ray, but the paraxial focal plane is this.

So, its transverse error then is this, this is the transverse error of ray number 1 and its angle is this. So, I will take tan u, that is this location on the x axis. This x axis we call it the x axis, but it is not a traditional x axis, in that it does not necessarily start from minus n and go through 0 to plus n. It just goes from that value of tan u for that ray and keeps on going for the values of tan u of the subsequent rays. So, need not depending on the rays you are plotting, its need not going through a 0 origin. The origin here is the tan u of course, it is for the paraxial ray ok.

If I look at this is the transverse error for ray number 1, clearly this smaller distance let us do another color. So, this distance is going to be the transverse error for ray number 2 right. So, the transverse errors reduce which is why this now corresponds to the transverse error for ray 2. And, as you take subsequent rays, subsequent rays are getting closer to the optical axis, the transverse error goes on decreasing. The ray that is on the axis has no transverse error.

And, then the rays from below, this is a spherical aberration you can consider your object point as on the axis or symmetrically seeing the lens. So, you expect this curve that you developed in this region to be identical here except its flip now, because the values are positive. So, this is a curve that we have drawn for spherical aberration, for the tangential or the meridional rays. Now, in this diagram I am drawing a convex lens and I have a set of rays incident and I am showing you what happens when the spherical aberration.

But, in an actual optical system, I am never going to have the case where I say oh look here is spherical aberration, oh look here is coma, here is a stigmatism. When a ray travels through an optical system, it experiences all the aberration simultaneously. The ray bends or traverses through the system because of everything that is happening to it at the same time. Its not seeing these aberrations one by one, its not seeing them individually.

So, these figures we are now studying individually, so that you get a sense of the shape if the RIC curve has this shape; that means, spherical collaboration dominates the system. I am never or I am very rarely going to have a case where the optical system has only one aberration right. But, from the shape you will be able to tell which one of the ray which one of the aberrations is dominant in the system. So, in this case we are just acting or we have pretending we have designed a system which has no other aberration in it except for spherical aberration.

So, this is a pure spherical aberration curve right and so, one point to note for a curve or for a system with spherical aberration is this anti-symmetric nature to the curve right. The whatever is on the left half is going to be identical in magnitude to whatever is on the right half, right and left half; however, they will be flipped ok. So, that anti-symmetrical nature is something that you will see with spherical aberration ok. Now, I can do the same thing, but I plot it for these sagittal rays ok.

And, now I am plotting the transverse error here is the error or how much the ray has missed the paraxial point. But, now its displaced along the x axis and not along the y axis right and you get a very similar curve. It is quite a symmetrical aberration. Now, what this set of curves is showing you? I can plot the RIC curves at any plane and even in OSLO, you tell OSLO which is the image plane. OSLO does not automatically decide some plane is the image plane; you tell OSLO to put the image plane at this distance from my surface and look at the aberrations there.

So, you could look at the aberrations anywhere, you could look at the aberrations here. Of course, the aberrations will be enormous there, you are nowhere near the focal position. But, if you so desire to look at it there you could. So, one thing is by looking at the ROC curves at different planes, you can even tell which of those planes is the best focus right. So, in this case this graph over here is showing you the RIC curves, let us say the tangential RIC curves, at planes a b and c.

You can see they all have very similar forms, they are all anti-symmetrical in nature, they all have very similar forms. However, the curve at plane b has all a region in between. So, you could almost consider this region where the tangential error is 0, the transverse error is 0.

And, that is because if these are paraxial you are at the paraxial focus and so, you have the minimum error there.

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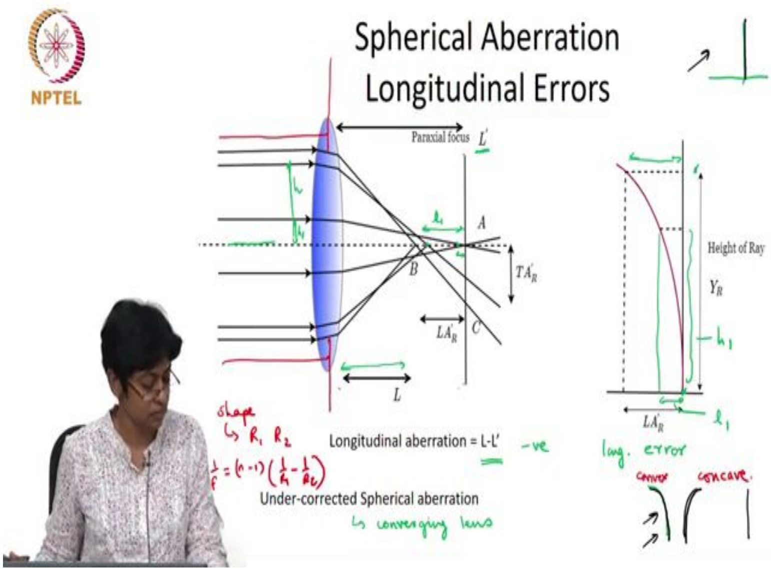

How do we define the longitudinal area, that was the transverse area, but how do we quantify the longitudinal error? So, if you see in this figure you have these rays incident and we have a convex lens, yes.

Student: (Refer Time: 17:14).

Yes. So, his question is since we define an aberration as the deviation from the paraxial image point, why would we even look at it at other planes? You look at it on other planes because you can sometimes get valuable information. And, you will see that the paraxial image plane is not necessarily the best image plane and you will see that enough as we go down in this class today. So, then you often need to move away from the paraxial image plane. If you are not at the paraxial image plane, then you are measuring the aberration as the displacement or the difference between any ray and the paraxial ray at that plane, that is how you would define it.

So, the longitudinal error, the RIC curves if you are looking at an RIC curve it's always a transverse error right that you are looking at. So, the longitudinal aberration is measured as the difference between this distance capital L and this distance is where the further off rays come to focus, minus the paraxial focus this distance here. So, you can see in this particular case this is going to be negative; because, capital L is always smaller than L dash and this is on the corrected spherical aberration. So, its negative in nature and it is typically what you see when you have converging or convex lenses.

Now, the longitudinal aberration is plotted slightly differently, its plotted with a its not called or RIC curve, because the rays are not intercepting the focal plane here, that is why it is not an intercept curve. Here you are measuring some distances along the optical axis. So, on the x axis you are plotting the y axis is the height of the ray. So, you are you for example, the paraxial ray would have height 0 and that is what you would plot here and its error. So, this is actually the error, the longitudinal error.

So, the paraxial ray has 0 height and 0 errors, so it's plotted here. The next ray has this much of height, let us say h_1 and it is focused. Let us say somewhere over here, so this is its error right. So, maybe I should take a ray which is a little further off, let us say I let me take this ray. So, this has height h and it's focused here; so, this is its error let us call that l 1. So, this maybe corresponds to the ray with height h 1 and this distance corresponds to the error l 1 ok. So, you are plotting along the y slightly different from how, because normally we take the independent variable on the x axis.

And, but I tell you these optics people always try to do things differently with their graphs. So, the y axis is your independent variable, it's the height of the ray and the dependent variable is on the x axis. And, in this case because we have a convex lens and the longitudinal aberration because, its defined like this its always negative, the curve is bending this way. As you go further and further away you can see this is the highest ray and it has the largest aberration, negative aberration ok. You should be just by looking at these curves, now getting a sense of how you could do a correction.

Because, I am saying in this case I have the longitudinal error like this. Just intuitively how would I know what I should add to this to make it.

Student: (Refer Time: 21:49).

What is the longitude best case when I have no error, what should this graph look like?

Student: (Refer Time: 21:57).

So, if this is my longitudinal axis to plot the longitudinal error and there was no longitudinal error, what would I, what should I have there? And, I have a straight line, all rays no matter what their height have error 0. So, if this is what I have, how could I convert this to this?

Student: (Refer Time: 22:26).

Pardon.

Student: (Refer Time: 22:29).

I would no, forget there are other ways, I am not talking about that; I am saying intuitively looking at this curved graph here; how could I make this curved graph a straight graph like that? Not optically, what would I do, mathematically what would I do?

Student: (Refer Time: 22:45).

You are still thinking, if you say move the screen you are thinking optically, I am saying mathematically what I it of course, has an optical implication and would not I just add a curve like this. If I could somehow add something into my system or do something so, when you say move something, change aperture, do something maybe those things are adding this curve might be. But, if I could somehow if my system has this shape, the error has this shape. If I do something to my system, the error now has this shape; would not the resultant error be this? And, that is one of the ways you correct for you add some other elements and you will see what effects spherical aberration.

So, somebody said to change aperture and you can see that aperture clearly is one of the ways of correcting. Why? Because, we have said that the rays that come from further away these rays have of course, the largest aberration. So, if I were to put an aperture stop and block these, clearly I have reduced the aberration already; both longitudinal and transverse, simply because I blocked rays right. So, yes one way to reduce spherical aberration is to change the aperture.

But another way to reduce spherical aberration which may not be so obvious is to change the shape of the lens. And, what do we mean by the shape of the lens? The shape of a lens is governed by its R_1 and its R_2. Now, since focal length is defined $\frac{1}{f} - \frac{1}{R_1} - \frac{1}{R_2}$; I can change $\frac{1}{R_1}$ and $\frac{1}{R_2}$ such that f does not change because finally, I want my optical system to stay the same. But, I can change $\frac{1}{R_1}$ and $\frac{1}{R_2}$ such that f is constant and yet with the lens of a different shape you will find the cell collaboration is slightly different and that is a powerful tool that we have.

And, maybe I have to add some other lenses to my system and we will see, again I gave you a clue when I said under corrected spherical aberration is what a convex lens sees.

Student: (Refer Time: 25:15).

So, you add a concave lens and this is a typical graph of a convex lens, this is a typical graph of a concave lens. Now, clearly I am not saying add two lenses of the same power, then I remove the focusing ability of my system. But, you will add a concave lens, adjust distances so that overall you get power in your system, but the concave nature of the lens you have added offsets and reduces a spherical aberration.

So, that is why I am looking at these aberrations with these curves is very useful, because the curve gives you an idea of what you need to do ok.

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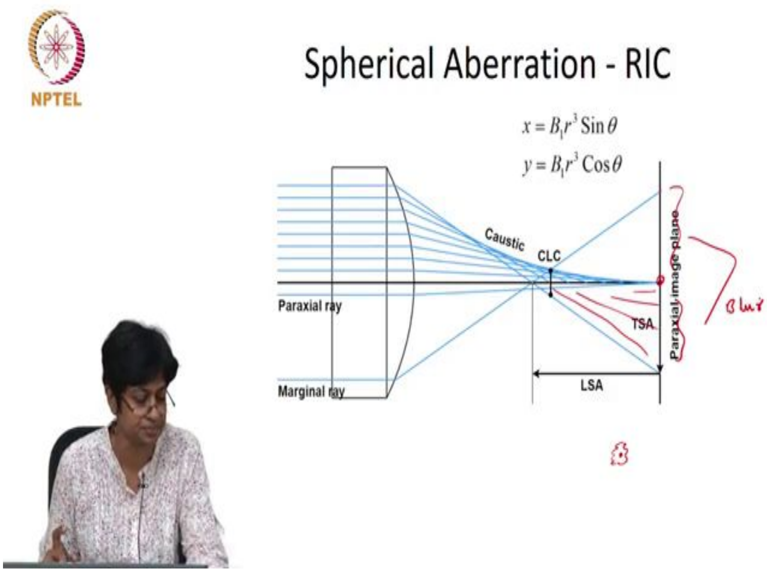

If you look at an image which was taken with the system that had spherical aberration, what you would see is or if make it simple and say if you are looking at the image of a point that with an image that had sorry with the system that had spherical aberration, the image should ideally also be just a point. So, your object is a point, the image should be a point, but if the system has spherical aberration you are going to see a sharply focused point with a kind of blurry circular ok, those are these rays.

So, you can see the image point is here, but you do have over here right and you have raised we have not shown all of these. So, you have raised all over here right. So, you will have a sharp focus point in the center and you will have a blur over here. So, that is what you expect with spherical aberration, that is how your image deteriorates ok.

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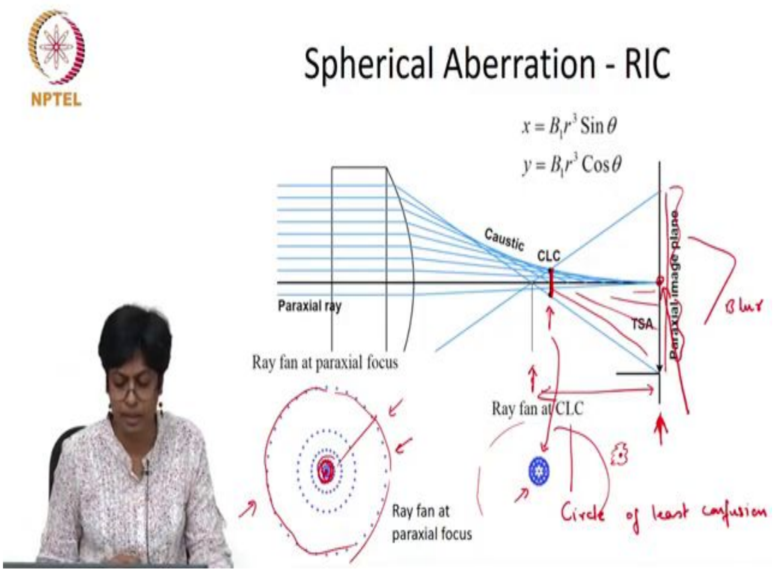

So, one of the ways of looking at it is then to just look at the ray and this is you will do this when you look at the lab today, you will see the ray trace the. So, you have this fan of rays and how they intersect the plane and these images are just showing you how the rays intersect the plate. So, it is a concentration of rays in the center; these are the focused paraxial rays, but you do have raised in a larger circle outside. And, they are there as part of your image though you do not want them to be there.

So, this comes to the question someone had asked some time back, why would I move away from the paraxial focus plane? Well, if I look at the paraxial focal plane this plane, this is how the spots are spread. But, if I move now this is the furthermost rays are being, the furthermost rays are being imaged here, the paraxial rays are being imaged here. So, I have spread this whole region can be considered a kind of focal region. So, if I move within this region, it turns out that there is one place where the spread of the rays is minimum.

Here the spread is only this much, here the spread is this much even though a lot of the energy may be concentrated in this region, I am still having this effect whereas, if f is my this place this the rays intercepting here is just this. So, the central spot here, this spot may be much smaller than this spot here, but I do not have anything else outside. And so, this when, what is CLC? It is CLC because it is called the Circle of Least Confusion that is (Refer Time: 29:12).

So, you often will use your best image plane, not as the plane where the paraxial focus is, but you will move to the center of least confusion; sorry circle of least confusion. Now, you can see if in OSLO or in some optical software you were asking to do an axial ray height solve, you always set the conditions for that axial ray heights all as; move the next surface or choose the next surface to be where the axial ray height goes to 0 and that is going to be this plane. So, you might do that and when you start studying aberrations you may see that is not the plane where the aberrations are least.

So, the solution might help you get to approximately where you need to be, you might have to actually do something else to get to the best imaging plane right. You might have to look for where the aberrations are less and choose that claim rather than the plane may accelerate height is 0 ok. So, I think that is all I wanted to say about spherical aberration.

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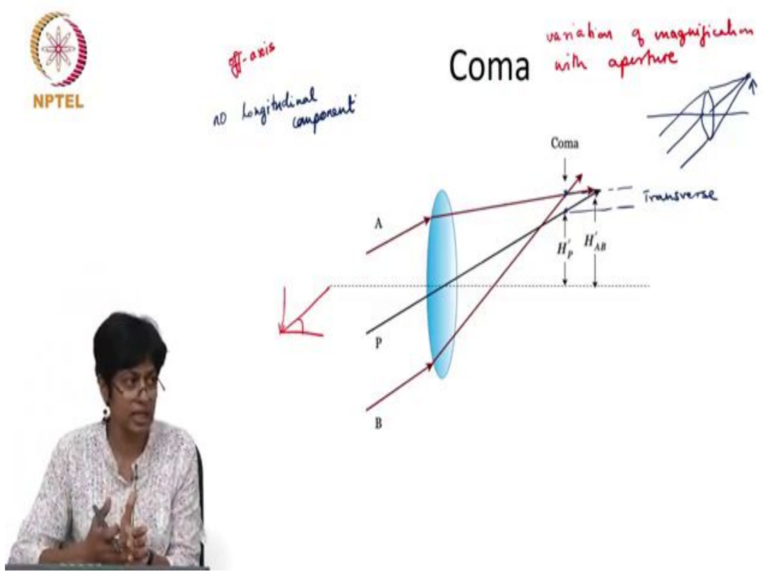

Coma, now coma is an off axis aberration. What does that mean? It arises when you have rays coming from a point not on the axis ok. Again for demonstration purposes here we have a parallel set of rays coming from the axis, but it could be that you had some object and you are looking at all the rays coming from this off axis. So, they are not parallel, but they are coming from an off axis point ok.

Coma spherical aberration we said could be considered to be a variation of the focusing ability of the lens with aperture. Coma on the other hand is a variation of magnification with aperture. Now, all these parallel rays in an ideal system, if I had an ideal lens and I had a set of parallel rays coming; they would all focus at one point over here right. This would be may ideal focal point. But, as you can see in the image drawn here, the two rays equidistant from the center are focused at the same point that is this, but the paraxial is actually focused here.

So, there is now a transverse error here and that transverse error is nothing but this. There is no longitudinal measurement of coma, the coma is always measured only in the transverse. So, there is no longitudinal component ok. Coma is a terrible aberration because, if you think about it spherical aberration you could kind of locate very easily the center of gravity of your image. You had a central spot and then there is a spread around it, but the comma gets spread in this direction and not symmetrically as you will see.

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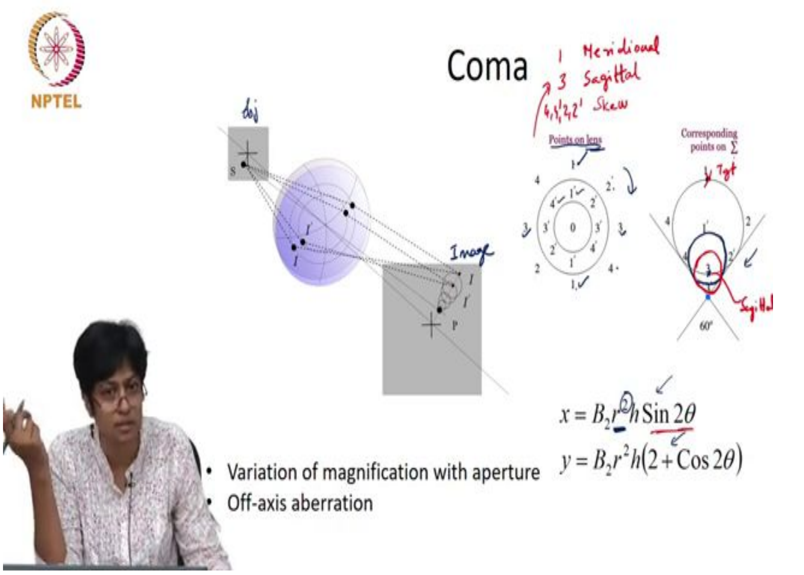

So, you have so, this is your object plane, this is your image plane and then you have the lens in between. And, what has been traced here is a set of rays all coming from the same object of the axis object point, but these rays are all traveling through different regions of the lens. And, instead of all coming to the same image point are each forming a different set of images in the image plane. Now, what happens with a coma? And just to make it clearer you can look at this figure, assume this is your lens ok.

So, this is the surface of your lens and at these points marked 1 to 4 and 1 dash to 4 dash. These are rays that are coming and hitting those points of the lens. What happens in coma is look at this, you have 1 2 3 4 and that repeats; in the image plane rays 1, this ray 1 and this ray 1 they both focus at this point here. So, the ray that hit the top of the lens and the ray that hit the same distance, but below the optical axis they both imaged the same point, so that is good.

But the rays 3 and 3 ideally these rays I am showing you the location of the rays on the lens, but all these rays came from the same object point. So, they are all coming from one point on the object, ideally all these rays must go to a single point in the image. But, rays 3 and the rays marked 3 on the lens are forming an image here. So, what lies on an annulus on the lens is forming a circle not a point in image space. So, rays 1 2 3 4 formed 1 2 3 4 in the image space.

And, you can see that while I traverse these rays sort of you I have rays 1 and 1 again and 2 and 2 again. In this point in the image plane they both the rays 1 come to the same place, both the rays 2 go to the same place. Both rays 3 go to the same place, both of the rays 4 go to the same place, but none of these are the same place instead they lie on a circle. So, instead of getting a point you are getting a circle.

So, for every point you should have got as an image, you are getting a circle and that is why it is a terrible aberration. Now, these rays 1 to 4 all lay on the same annulus of the lens. If I take another annulus, I get another circle, but that circle isn't centered about the same origin of the previous circle. It's slightly shifted and centered which is why I cannot have a nice center of gravity of my image, whatever it was not spherical aberration the image was centered.

Here, I the next set annulus here which is 1 dash to 4 dash they form another circle which is laterally shifted now. And, because I am just pulled out the terms from the aberration polynomial here, you see an r^2 here. So, you see what goes around twice on the lens is going around only once over here, that is happening because of this r^2; you know just for you to see why having that general form of the aberration polynomial tells you something about the images.

So, every annulus on the lens is going to give you a slightly displaced circle here, you have another circle over here and so on right. So, you have this it is called coma; because it has this comet like do you know the tail of the comet that is the kind of image you get for every image that should have looked like a point; you have a like a comet shaped image ok. Now, you can see that the tangential or the meridional rays are forming in this image; whereas, the, these are the tangential ray image whereas, 3 these are the sagittal rays.

Which are the skew rings of the system? So, in this figure in this figure 1 corresponds to meridional rays, 3 corresponds to sagittal rays. Which are the skew rays of the system? Skew rays are the rays that do not traverse the optical axis. So, which are the skew rays here? They are all skew rays except for the rays that will are the meridional rays right. So, rays 4, 4 dash 2 2 dash these are all skew rays alright.

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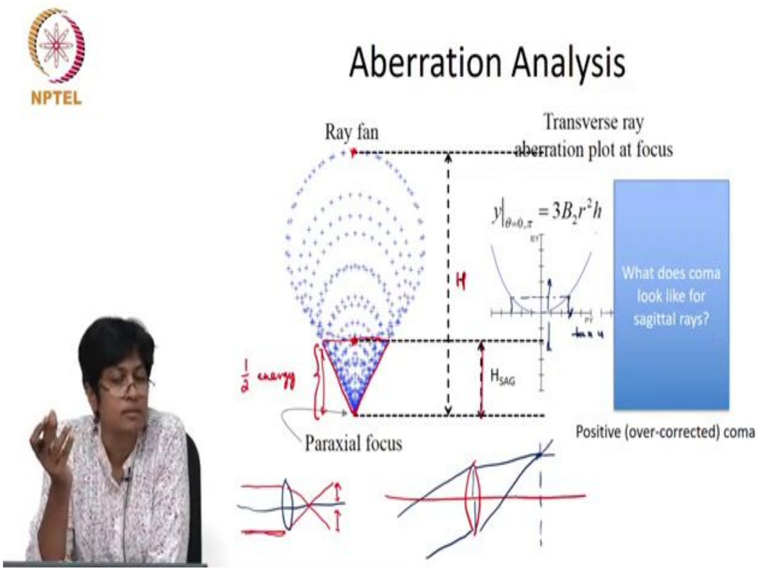

So, the ray fan if you look at the paraxial image plane, the ray fan is going to look like this figure on the left. The paraxial focus is down here and the sagittal focus let me show you that. So, the sagittal focus is here, the tangential focus is here right. And, it turns out if you look at the, these are the rays coming from one point on the object; one of the access points on the object, but they are spreading out and forming this comet-like shape. Half of the energy is actually located in this region.

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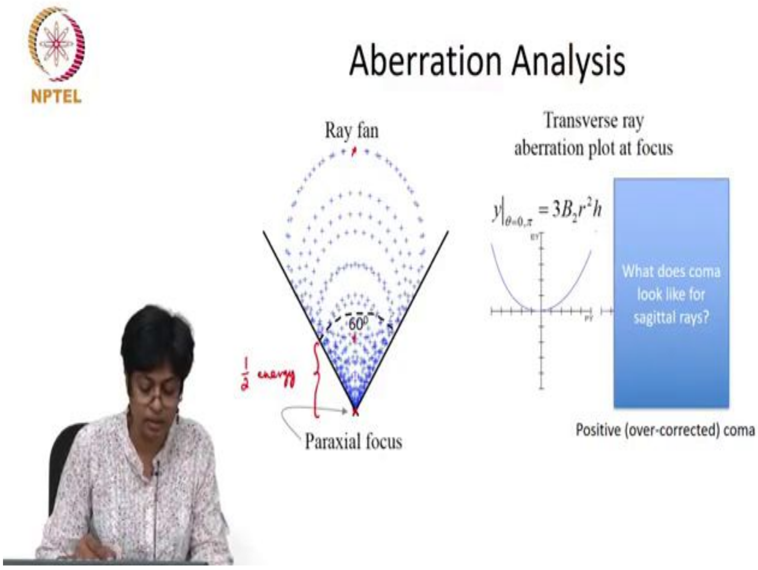

So, yeah this as the point of interest this angle is always going to be 60 degrees and we define the sagittal focus as. So, in the previous figure this is where the rays 3 would have come to focus, this is where the rays 1 came to focus. So, we call this the sagittal coma, it is a measure of the sagittal coma, capital H is a measure of the tangential coma. But, since half of the energy lies in this region, the sagittal coma is considered to be a better measure of coma than tangential coma ok.

Because, more of the energy lies in this sort of triangular region over here ok. Now, I have plotted the RIC curve here for the meridional rays right. Why does it have this shape? If I look at the lens and with rays coming in over here, let us say this was the paraxial focus plane. These two rays did come to focus at the same place right. So, assume these were both equidistant from the optical axis. So, these are in the meridional plane and they both come to focus at the same height.

So, then they have this error here, the error is always in this direction correct, this is tan u yeah; the rays have slightly different angles. So, for this way it has some value, for this ray its value will be where they have the same height. So, this will correspond to one ray and this will correspond to another ray right, but they both lie on the top; so, they are both positive.

So, here you see now a big difference between the RIC curve of spherical aberration and of coma.

In spherical aberration your curve had an anti-symmetrical nature; because, in spherical aberration the ray coming from the bottom from the top of the lens this was its error. So, it was negative, but the ray coming from the same distance sorry the ray coming from the same distance below it came up like this. So, it had the same magnitude transverse error, but a sign was opposite.

So, the two rays in spherical aberration have the same magnitude and opposite sign, but in coma they have the same magnitude, same sign right. So, the curve here is symmetrical in nature, it is not exactly the same because the tan u's are not the same. The rays have different angles coming here, but it is not anti-symmetrical in nature. And, here you should start getting the idea; if you are given the RIC curves of a system and you do not know anything about the system.

Just by looking at those RIC curves you will be able to tell this system is dominated by the aberration coma. This system is dominated by the aberration spherical right, because in one case clearly they will be anti-symmetry and the other not. Now, I have drawn the RIC curve for the meridional rays, what would it look like? And its positive; so, we call this over-corrected coma right. And, this is sort of what is expected for a convex lens. What do you think the rays will, the curve will look like for the sagittal rays?

Student: (Refer Time: 43:25).

So, that is correct.

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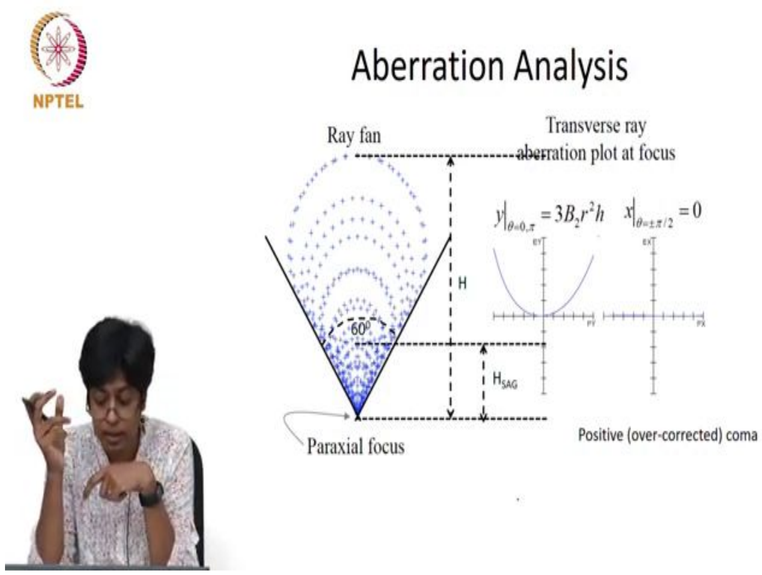

In fact, there will be no errors and if you also go back to the polynomial expression; let us see a lot of right. You have $sin\theta$ in this right and your theta for sagittal rays is $\pi/2$ So, this x term is going to go to 0 anyway right. So, this is what you expect ok.

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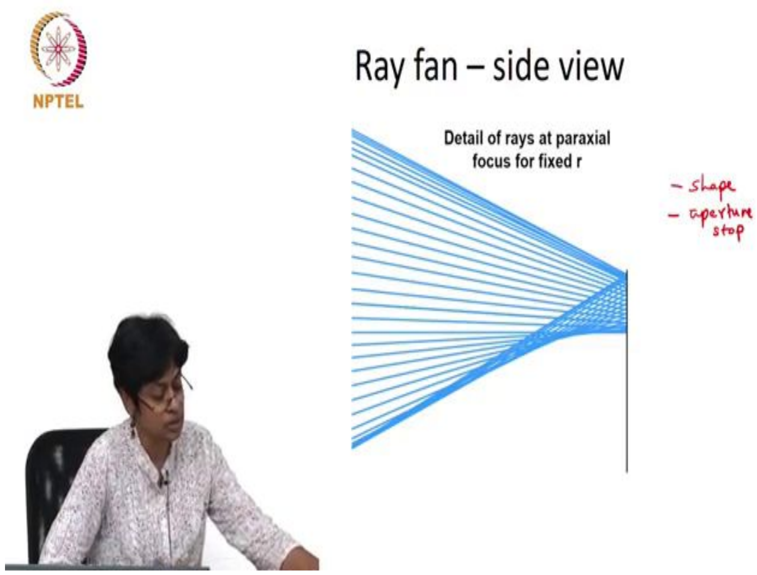

And, this just gives you a side view of the rays coming in and you can see this, these were all supposed to form one point right. So, you can see how bad it is right, again coma is an aberration that is affected by the shape of the lens. So, shape is one way to correct it, clearly aperture, stop position or aperture stop, size. So, I will just say aperture stops because its position as well as the size will affect coma ok. I do not think I will have time to go to the third aberration today, but what I will do is because.

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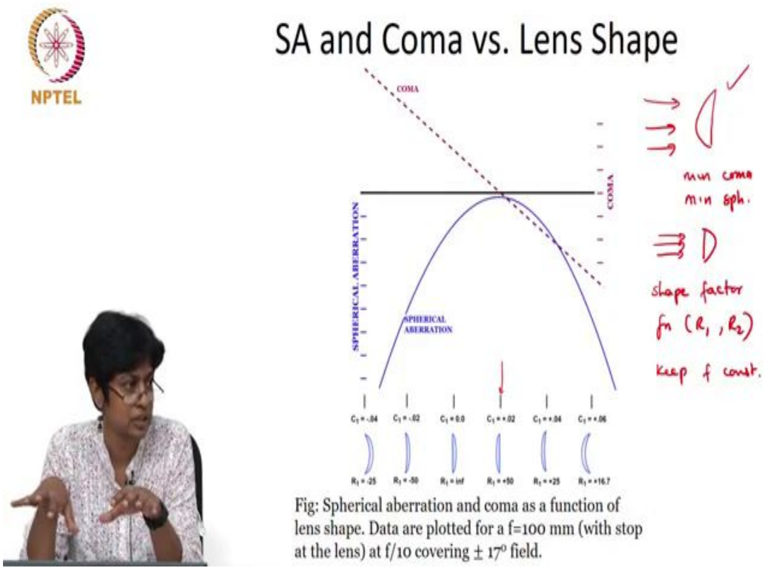

So, you can take so, today's lab exercise is for you to understand aberrations better and to see also how you can correct aberrations. So, we are only looking in this graph at two aberrations; spherical aberration and coma. And, what has been plotted here is along the x axis you are plotting something called shape factor which is a function of R_1 and R_2 of a lens. So, you are taking a single lens, you are going to keep the focal length constant, keep f constant, but change R_1 and R_2.

And, you see that as you do that, these are the figures you see over here. All these lenses, the focal length of all these lenses is 100 millimeters. But you can see the shape has changed so much right and that is by changing R_1. So, R_1 is varying through these parameters therefore, you will have to calculate what is the value of R_2 such that f stays 100 millimeters. But, in all these cases the spherical and coma has been these aberrations have been calculated and that is what is plotted. So, the x axis is plotting the shape factor and the diff the two vertical axis are plotting coma on the side and spherical aberration on the side.

And, you can see this is how spherical aberration varies for this lens and this is how coma varies. And, the interesting thing to notice is that there this place, if you have not tried to minimize the aberration at all here. You are just saying, if I change the shape keeping focal length constant how do the aberrations vary? That is all, you are just studying that. But, you see there is a natural position or rather a natural shape for which both coma and spherical aberration become minimum. And, you if you look at what that shape is, it's very close to a planner convex lens.

So, if you have a planar convex lens and light is incident from the curved side, that is also important. This is where you will have minimum coma and minimum spherical aberration. It's actually the actual value as one radius of curvature 6 times more than the other one. But, you can just use a planar convex lens and get close to this behavior right. If you turn your lens around and you use it like this, you will not get that benefit ok. So, this is the way to use a planar convex lens and have the best case that is the minimum coma and spherical aberration.

So, in today's class we have started looking at the mono chromatic aberrations more specifically and we have covered two spherical aberrations and coma. And, what you will do in the lab later is to plot this graph; so, you are going to have to generate these lenses, same focal length varying curvature and find the values of aberration and plot them and you should see this behavior.