Optical Engineering
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Lecture – 14
Tracing rays through optical pupils – Part1

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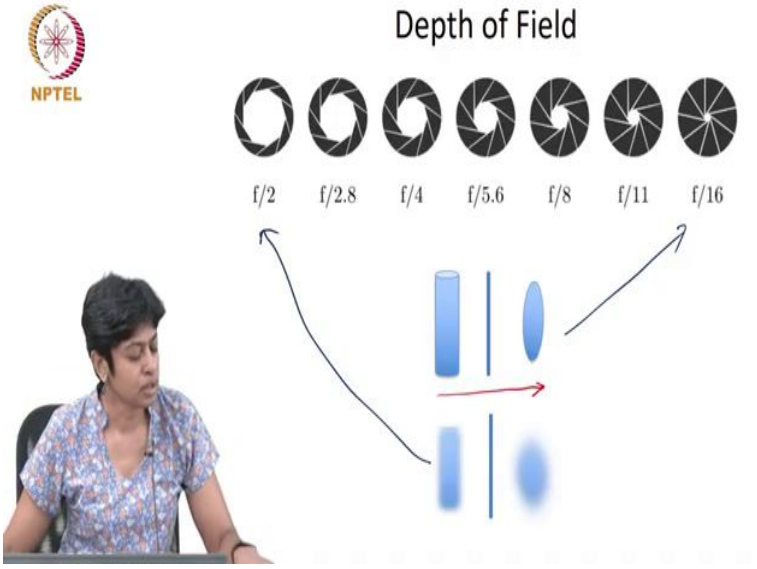

So yesterday we looked at the aperture stop of a system and I hope you began to see how important this element is. We also looked at how you calculate which element is the aperture stop. So, if you have an optical system and your many elements in it, one of them is going to act as the aperture stop and we saw how we could calculate which one it was.

We then moved on to looking at what are all the different functions that get affected by the aperture stop in this system and we saw some important features. For example, we saw the depth of field of the system. The depth of focus of the system is affected by the aperture stop. This image here is how we end the class so we said if you had a set of objects and this was along the optical axis, then you could tell which was a setting of the camera in order to have obtained such images and the one with the larger depth of field.

That means, it is capturing objects spread along the optical axis better must have a smaller diameter in other words a larger f number. So, if we were to ask whether this was a f/2

system or f/16 system, the upper image clearly must have been taken with the f/16 the larger f number image. And that also we understood implies that the exposure time would have to be longer, because f/16 is a slower lens than an f/2

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2 lens ok.

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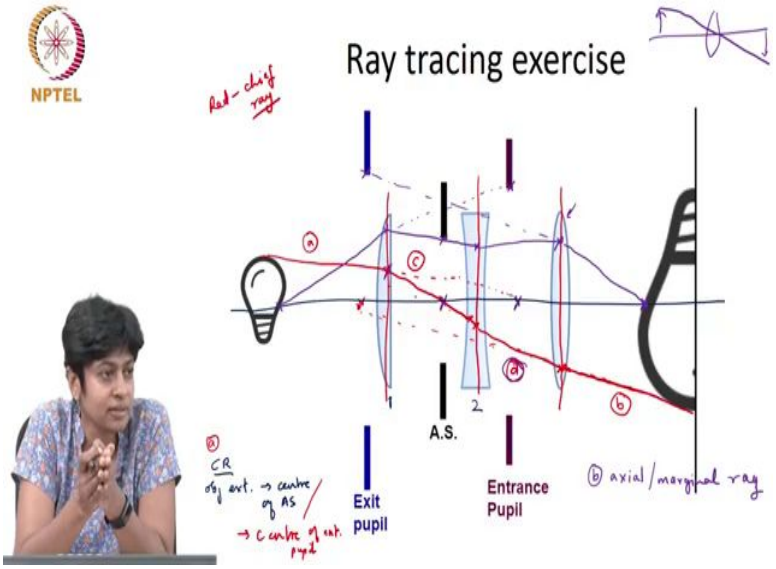

So, I want to give you an exercise to do today. So, you've been given a sheet with this picture and we need to trace 2 rays through the system. So, I want you to trace two rays through the system: the chief ray and the marginal ray ok. So, take a look and see how you would trace these rays through the system. Now to trace the ray clearly you must understand it is an it it is a necessarily going to be that you can trace one ray starting from the object and then trace it all the way to the end.

The ray bends as it travels through the system. So, they are different; it has a different slope in every section of the system. It may be that you have to trace the end of the ray before the start of the ray. This is just an exercise to see if you have understood the concept of the aperture stopping the pupils as well as the chief ray and the marginal ray.

Now, what is it that you do know about the chief ray, what can you say about the chief ray. It should arrive at the extreme point of the image appearing to come from which point the Exit pupil right. It is going to appear to come from the centre of the exit pupil right. So, I can draw then this so here is the centre of the exit pupil right.

Obviously the ray is not really coming from there, but if it were and this is really putting my skills as at. What we wrote over here the centre of the chief ray goes through the centre of the aperture stop this is not wrong. But I need to be careful whether the Entrance pupil and the aperture stop are one and the same thing right, because I know that the chief ray goes through the centre of the entrance pupil isn't it.

So, this is not incorrect, but it also goes through the centre of the entrance pupil. The system has 3 lenses and an aperture stop. So, the aperture stop lies between this lens and this lens, because there are lenses both before and after the aperture stop. That means, that there is an image of the aperture stop because of this lens 1 this lens precedes the aperture stop. So, it is image creates the pupil, but there are lenses after as well right. You have not been asked to calculate the exit pupil here, so someone has done that calculation and found out where the location of the exit pupil is and entrance pupils are.

So, here they have found out for this system given the focal lengths of these lenses, that the entrance pupil lies over here right. So, my first ray actually has to be drawn going through the centre of the entrance pupil right. So, I actually need to draw a ray that is doing this, it is supposed to be a straight line right. So, the first ray I draw is the ray that goes through the entrance pupil, that is why it is called the entrance pupil that is the first ray.

I draw it as if it is going up to the entrance pupil, but of course at the very first element with power I have to stop because the ray is going to bend them. At this point I do not know how it bends I only know that it bends ok. What I did next was to say how does the ray exit the system, well it must it is the chief ray where plotting the chief ray so this red colour is chief ray ok. I know that it must reach the extremity of the object image plane and it appears to come from the centre of the exit pupil. So, that is what we have drawn here again. We only drew the ray from the last lens to this point, because before this lens it of course would have bent and arrived here.

What can I draw next, well when I go back to this first part. So, this is the first part that I traced, it is going to bend at the lens. What is the next element it happens to go through it happens to be seeing the aperture stop next. Now we know the chief ray has to go through the centre of the aperture stop. So, this is the centre of the aperture stop. So, I am gonna draw this right and now I have this point over here this surface and let us all let us just consider all of these lenses to be straight lines ok, because we were seeing thin lenses.

So, I will draw it up to this point I will draw it up to this point. Now I can finish off the last part because I have this point over here I have this point over here. So, clearly these two are going to connect. So, I plotted this ray from the extremity of the object to the first lens, using the fact that the ray must extend to the centre of the entrance pupil. I plotted this ray next this part of the ray next from the edge of the image appearing to come from the centre of the exit pupil.

If the aperture stop had been here, I would have plotted that next saying this ray this one here it should have gone through the centre of the aperture stop. But the aperture stop was not there. So, I took this part of the ray through the centre of the aperture stop. So now, let us look at this ray. This is the chief ray is it doing everything we know the chief ray ought to be doing. The chief ray needs to go through the centre of the aperture stop needs to be coming from the extreme point of the object hitting an extreme point of the image.

The ray that is hitting the extreme point of the image must appear to come from the centre of the exit pupil, the ray leaving the extreme point of the object must appear to come from the centre of the entrance pupil right. And if we look at that this ray that we have drawn meets all those requirements. Now my drawing is not very accurate, of course each of these segments of the ray are straight lines because, we know that light travels in straight lines in a homogeneous medium right ok.

In a similar fashion can you now plot the marginal ray right. So, that is the ray that starts off from the object point which is on the axis. So, we want the rays starting off from here, that is why I have drawn it in segments now his question is how do I know how it bends a to c. I did not draw it directly to c right. If I had said I let me trace the chief ray and I start at a point and then I just do this you can ask how it would bend.

The reason we draw it in segments is from the information given here you are just given a figure, I have not given you any of the data how do I know how much it bends. That is the reason we are drawing it in segments ok. So, you understood how I draw the first segment, I draw segments a by starting from an extreme point on the object and drawing as if that ray were hitting the centre of the entrance pupil.

At the first lens it is going to bend so I stop at that first lens right. What I next did was to draw a segment by saying that it is arriving at the extreme point of the image and it should appear to arrive from the centre of the exit pupil, so I drew that segment. Then I came to segment c and I said well after this lens l 1 the first lens.

Student: But there are c is (Refer Time: 11:34) centre of the exit pupil.

See each segment is a straight line.

Student: Ok.

That is what I said right, my drawing is not good but.

Student: (Refer Time: 11:41).

Within a region of homogeneous refractive index they are straight lines. So, a is a straight line, c is a straight line, d is a straight line, b is a straight line, like it should not bend in between right. It has to follow Snell's law if there is no change in refractive index it should not bend. How did we draw segment c, well from this point we know the ray must go through the centre of the aperture stop. Since the next element is the aperture stop. So, I know I have to draw a straight line from this point to this point and so I continue that straight line on till I reach the next element with power. Does that answer your question?

Student: Yeah.

Is this clear to everyone or there any more doubts?

Student: (Refer Time: 12:26) straight to the entrance pupil (Refer Time: 12:29).

How can it go straight to the entrance pupils, does it not have to bend is question it does it go straight.

Student: (Refer Time: 12:38) there is no objective and there is no (Refer Time: 12:41).

In order to draw segments of the ray, I have to assume this is the definition of these rays: they appear to come from some direction or they come from some direction. But I cannot ignore the fact there are elements with power. If I want to draw it straight, in fact I would not be able to draw it straight. How would I be able to draw it straight, because if so let me just change the colour here.

If I were to do what you are saying, that means I need to draw a straight line from this point through the centre of the aperture stop and this is the chief ray. So, it also has to go through the centre of the entrance pupil. I cannot draw a straight line to the through these three points in any case can I that they do not lie on a straight line.

Student: (Refer Time: 13:37).

So, I think the confusion you are having is you are thinking, when we gave a definition of the chief ray we said this is a ray that will either travel through the centre of the aperture stop or appear to travel from through the centre of the entrance pupil and the exit pupil. They may act if the ray may actually travel through the centre of the entrance pupil, in the case where the aperture stops and the entrance pupil are the same element right. Let us say I had a system which did not have 3 lenses, it had just 1 lens.

Right I have an object and I have an image, the chief ray here will go through the centre of this I would do this. Now the lens is both the entrance pupil and not both, it is the entrance pupil it is the aperture stop it is the exit pupil also. So, in this case the chief ray is actually going through the centre, it is physically going through the centre of aperture stop entrance pupil exit pupil. But in a case like the one we are looking at now there are 3 lenses, the entrance exit pupil is not the same as the aperture stop.

The chief ray will appear to go through the centre of those two elements. But obviously, it cannot because you have to take into account the fact it bends whenever there is an element with power ok. That is the reason why I draw this ray in segments, because I know the first

segment what it ought to be doing and I draw a straight line from the extreme point of the object to the centre of the entrance pupil. But I have to stop the moment it hits an element with power. I say this is the direction this ray would take, but there is an element of power here, so at this point it is going to change direction.

Now, I want you to carry out exactly the same exercise, but for the marginal ray. Can we trace this part section d using some part of our definition and we cannot tell if this ray happens to lie in a zone where there is no way to use the definition to help us trace it. So, this is not the way you would actually check to trace a chief ray through an optical system. Because you could then argue what happens if I have 20 elements or 30 elements going to become very complicated.

You can always trace out the first part, because if you know where the entrance pupil lies you would say here is the starting point on the object, here is the entrance pupil and I know the direction it should go. But this would be a very cumbersome way of actually tracing a chief ray through the system. So, this is not how people trace rays through the system. The way we trace rays through the system are using the methods I talked about in yesterday's class, which are the YNU method of the YUI method or the matrix method which will start either in today's class or in the next class. Those are the ways you actually calculate and trace a ray through the system.

This exercise is just for you to get clear on these definitions right. It is for you to get clear on the definitions of chief ray axial ray as well as entrance exit pupil and aperture stop, that is the point purpose of this exercise. So, I want you to carry out the same exercise now, but for the axial ray. It is called marginal ray. It starts from the or axis point right, where the object in the axis point intersects right, but it is called a marginal ray. Why?

Student: It has edges.

It goes through the edges of the pupils and goes through the margin of the pupils right ok. Will you try to sketch that? Same procedure do it in segments do the segments you know for sure first and then try to fill in the gaps. So, what would be the first segment you would draw,

you need to start from this point the object point on the axis and that ray has to appear to travel towards the edge of the.

Student: Entrance.

Entrance pupil, so our entrance pupil edge is here. So, I would need to draw a straight line starting from this point and heading all the way to this edge. So, I am going to start off like this, but the moment it hits an element with power I know the rays are going to bend. So, I would just continue the rest as a dotted line ok. So, at this element the first lens of the system the ray bends. So, let us leave it there.

This next segment I am going to draw is the one that contributes to the image here right. Now this ray has to come from the edge of the exit pupil. So, I should draw a straight line all the way from this point to this point. But of course, I know there is a lens over here with this lens here, so the ray would bend after this lens and then come in that direction.

So, I draw the dash line and I ignore everything and then from this point onwards I draw a straight line, that is supposed to be a straight line. So, I am confident that I have got the slope of this part of the ray accurately, I have got the slope of the first part of the ray accurately, I still have two parts two segments left to draw.

Now, let us go back to what happens to the first segment. The first segment was traveling happily onto the edge of the entrance pupil and then it had to abruptly stop at lens l 1 because it had to bend. It has to obey Snell's law here and it has to go through these reflective surfaces, how does it bend well it. So, in this particular case the next element is the aperture stop and I know that the marginal ray has to go through the edge of the aperture stop. So, all I need to draw a straight line at 2 points I have got my 2 points.

It starts from this point it has to go through this point and I draw it as a straight line and I continue that straight line past the aperture stop till I reach the next lens of our element with power. And now it is easy for me to draw the remaining part, because I have a point here and I have a point here. There is nothing in between that affects the bending yes the entrance pupil happens to lie there.

But the entrance pupil is a virtual concept, it is not affecting the direction of the ray. So, at this point it is going to bend like this and luckily, because my drawing skills are not good. You can see you had a concave lens there and it is nice to kind of see that the ray did not converge as you normally draw when we draw our standard convex lens.

Actually it diverges and you are not surprised by that behaviour, because you do see a concave lens over that ok. So, with this exercise I hope this whole idea of these rays and the entrance exit pupils and the aperture stop become a bit clearer. What physically exists in your system are all the elements with power plus you may have mirrors. If the mirrors are planar in nature they do not have power they only change the direction of the optical axis right.

So, in all the examples I have been drawing, I draw a straight line through my system that is always how I start. I draw that straight line and say this optical axis of the system. If I were to put a planar mirror into my system, I am changing the direction of the optical axis ok. I could have a mirror with curvature in which case that is also an element with power. So, the moment as an element with power the rays then going to change direction it is slope is going to change.

What the aperture stop does is tell us what is the maximum cone of light that goes through the system and this immediately tells us how much power is reaching a point on the image plane. But as we saw in yesterday's class it is not just power that gets controlled by aperture stop, you see that it also controls some very important features like the depth of field and the depth of focus and I said also it controls things like aberrations.