**Theory & Practice of Rotor Dynamics**
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**Module - 6**
**Transverse vibrations**
**Lecture - 25**
**Transfer Matrix Method**

Today, we will study a transverse vibration using transfer matrix method, this particular method earlier we studied for torsional vibration case. We have seen the advantage of this method that this can be applied to multi rotor system, and we have seen that this particular method once we develop the point matrix and field matrix for the disk and the shaft, we can able to use this for larger system also. In torsional vibration case, the size of the matrices was small that was two by two matrix, but we will see that for transverse vibration, these matrices point matrix and field matrices will be of a larger size.

Especially when we will be considering both plain motion of the rotor in transverse direction, especially when we are considering either the gyroscopic couple or in the system then, because these two plain motions are coupled, so we will be having the size of the matrices 16 by 16 of that order. But with single plain motion we will be having the size of the point matrix of and field matrix of the order of 4 by 4.

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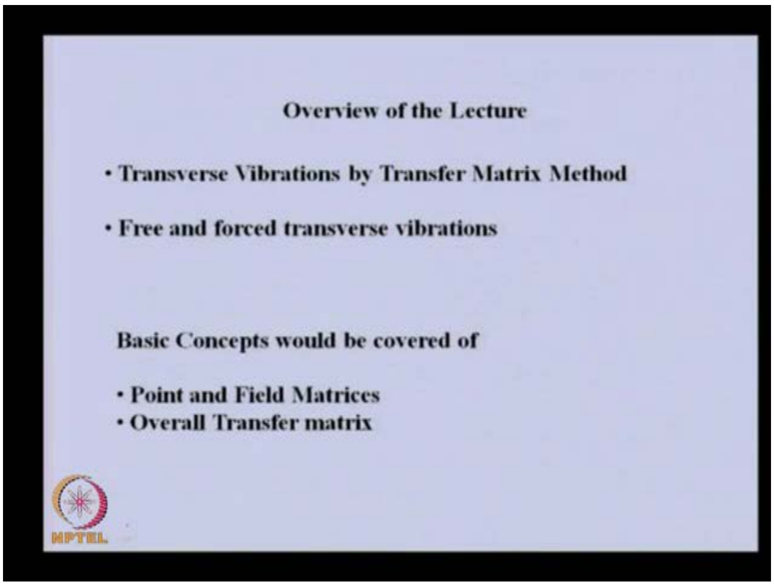

So, let us see what are the things we will be covering in this particular lecture, so transverse vibration by transfer matrix method, free and forced vibration both we can able to analyze and this similar to the torsional vibration case will be having point and field matrices development for transverse vibration. Similar to the torsional vibration case we will be having overall transfer matrix concept and then we can able to apply the boundary condition of the problem to either solve free vibration or forced vibration.

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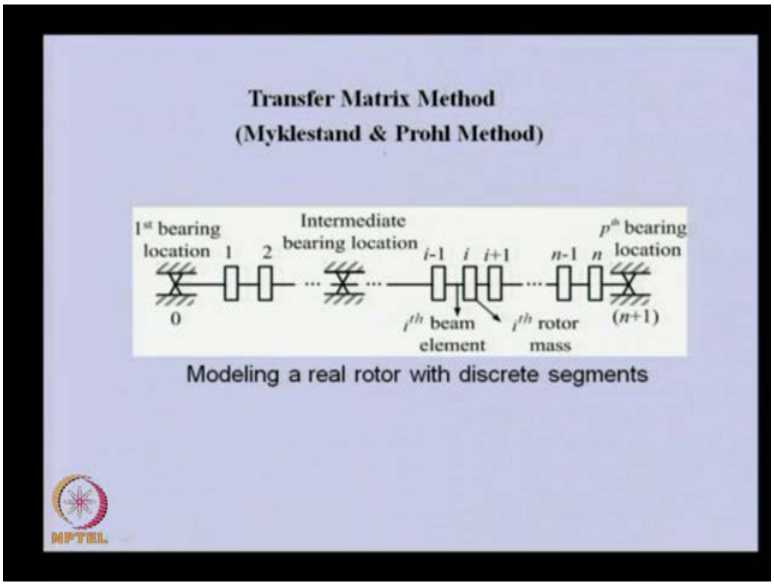


So, let us take a multi mass rotor system in which we can have multiple supports also and in this we have leveled various stations from 0, 1 up to n plus 1 and all the important disks bearing locations, we need to assign some station number. Now, for developing the point matrix or field matrix we need to take out some representative, this beam segment or rotor segment and then from the free body diagram of that we will try to derive the field matrix and point matrix for these segments.

For support we will have separate treatment because here support will give some unknown reactions, so to tackle that we will see through some example in subsequent lecture, how the support can be taken care if there is some intermediate supports are there. This transfer matrix method is also called Myklestand and Prohl method, because these two developed independently this method. That is why this method is also called Myklestand and Prohl method.

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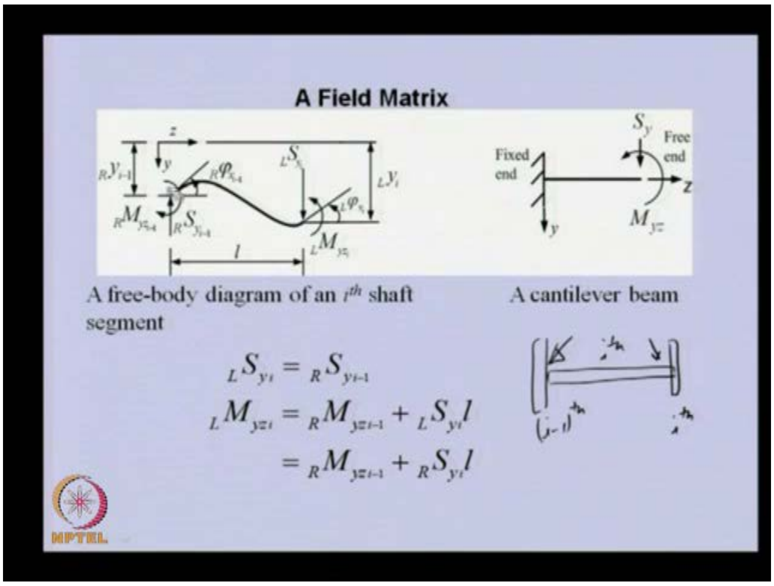


Now, if we want to develop the field matrix, so for this case this is the basically a particular shaft segment i th shaft segment. In this we have axis, z axis along the shaft axis and y is in the transverse direction, we have take the free body diagram in one of the plain and similar relations will be there for the other plain, because this shaft is symmetric. So, for y z plain one end of the shaft is having linear displacement y, this is i th shaft, so we will be having i minus 1 disk in the left hand side of this shaft and toward the right side we will be having i th disk. To represent the various field variable state variable, we will be representing the right or left with respect to particular disk.

So, here we have i plus i minus 1 disk, so the field variable which is here is y i minus 1, but right of that particular disk, so the back subscript r is representing that this field variable is right side of the i minus 1 disk. Apart from this, if we see there will be slope of the shaft during bending, so that slope we are representing by phi i minus 1 back subscript r. So, these are the two field variable linear displacement and angular displacement for representing the displacement of the shaft at i minus one th disk. Apart from this we will be having the shear force or we are taking the positive convention of strength of material for representing the shear force.

So, shear force that is S y in the y direction at i minus one th disk right of that. So, this is the representing of the shear force and this the bending moment, which is again in the y z plain of an is acting at i minus one th disk and right of that, so it is the representation of the bending moment at this location. So, you can able to see there are four state components one is linear displacement, angular displacement, shear force and bending movement. Similarly, in the right side of the disk that means; toward the left side of the i minus one th disk because disk is acting here we have removed that, so this is the left part of the that particular i th disk.

So, all the variables like displacement, linear displacement will be having y i left of i, so l is representing that this particular displacement is representing left of the i th disk. This particular is the angular displacement this loop so basically if we want to see the i th shaft is the i th shaft, here we have i th disk and here we have i minus one th disk. So, we can able to see that this particular end of the shaft, which is here is representing right of i minus one th disk and other side this side of the shaft, which is here is representing left of i th disk. So, always we are representing left or right with respect to a particular disk, not with respect to shaft, but particular disk. Now, here apart from this we have shear force that is S y i left of i th disk and similarly, the bending moment.

So, here also we have four state variable and now we need to relate this state variable which are there in the right of i th i minus one th disk and left of i th disk, so if we see the free body diagram of this force balance. So, only two forces are acting on this particular shaft one is shear force here and here so they can be equated, so shear force left of i th disk is equal to shear force right of i minus 1 disk . Bending moment, for bending moment maybe we can take this moment about let us say here, left of the this shaft, so we will be having this moment equal to this moment plus this shear force and momenta.

Momenta means, nothing but the length of the shaft so and because this shear force is acting here itself where we are taking the moment, so this will not contribute to this moment. So, this is the moment balance and using this first relationship we can able to see because both the shear force are same, so even we can able to replace the left with the right, so there will not be any change. So, you can able to see that now we have represented the field variable here, all are in the left side and here all are in the right side of the i th disk. Now, we want to relate the displacements, now we want to relate the displacement, the linear displacement of this end of the disk, this end of the shaft will be… I am taking about the absolute displacement of this will be relative displacement of this end with respect to left end and the displacement of this end itself.

So, you can able to see there are two component of the displacement, one is displacement of the disk with respect to left end and displacement of this itself. So, to take care of this we can able to we take two cases, first we will consider. Let us say this end of the shaft is fixed like this, so one end is fixed now because of whatever the shear force and bending moment which is acting, what is the displacement of this end we need to calculate? Once we have calculated this, then we need to add to that displacement, the displacement of this end itself here, so let us see in the subsequent slide.

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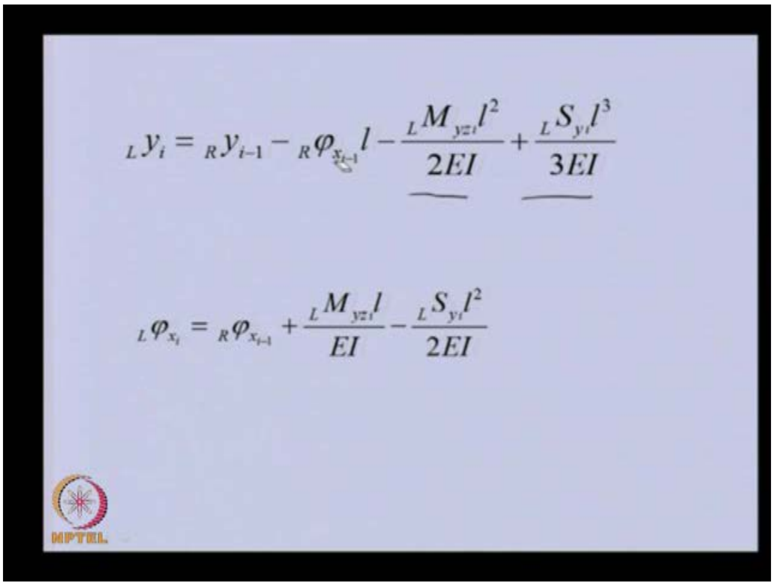


So, displacement of the left of the i th disk is given by, these two terms are coming from the cantilever, when we are considering the shaft as fixed. So, from a strength or material book we can able to get these relations that when we have shear force acting, so what is the linear displacement? When we are we are having this bending moment, what will be the displacement of the free end of the shaft? Because we are dealing with the linear system, so they can be combined. So, this is while considering the shaft as flexible and support left end support as rigid that means cantilever case.

Now, in the second case we will consider the shaft as rigid and then we will give these two displacements, this y and phi displacement to this end of the shaft, which is now in the second case we are considering as a rigid. So, you can able to see that whatever the displacement of the i minus one th right of i disk is there linear displacement same will be there, so we will put this value here.

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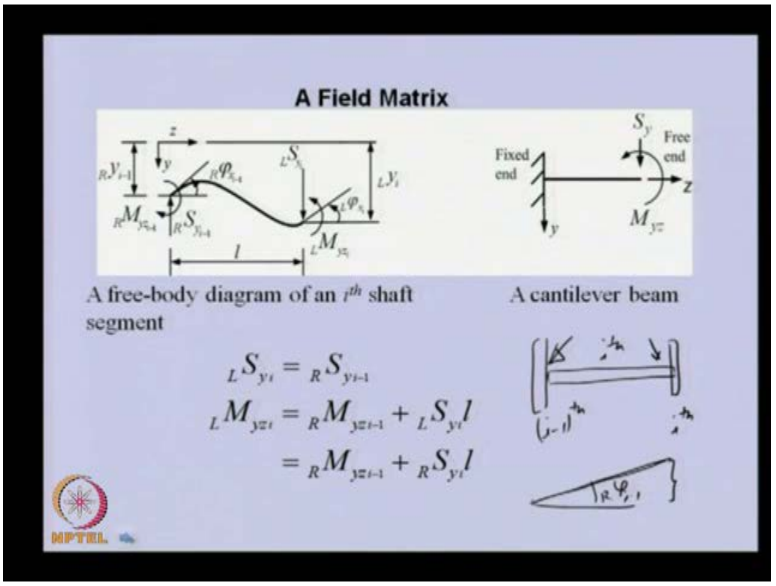


For the slope, for slope again we need to refer to the figure, for slope so whatever the slope of this end we are giving, so in this particular case we can able to see that, if this is the shaft which is rigid in the second case, if this is the slope of the shaft which is right of i minus 1. So, because of this angular displacement which we are giving to this end, what is the linear displacement of this? This will be slope into length of the shaft, so this is the same thing we have done here and because it is going toward the negative y direction, so this negative sign is there.

So, we can able to see that the total displacement of the left of i th disk; that means this disk is summation of four components. One is linear displacement of the right side of the i minus disk, anglular displacement of the i minus right of i minus one disk, bending moment and shear force, so four components are there. Similarly, the angular displacement at the left of i th disk; that means again we need to refer here, so in this also we will be first considering this as cantilever beam and whatever the angular displacement, because of the shear force and bending moment is there that will come. So, this is also we can get it from strength or material book by the deflection of beam relations, these are available, so these are the angular displacement due to shear force and bending moment.

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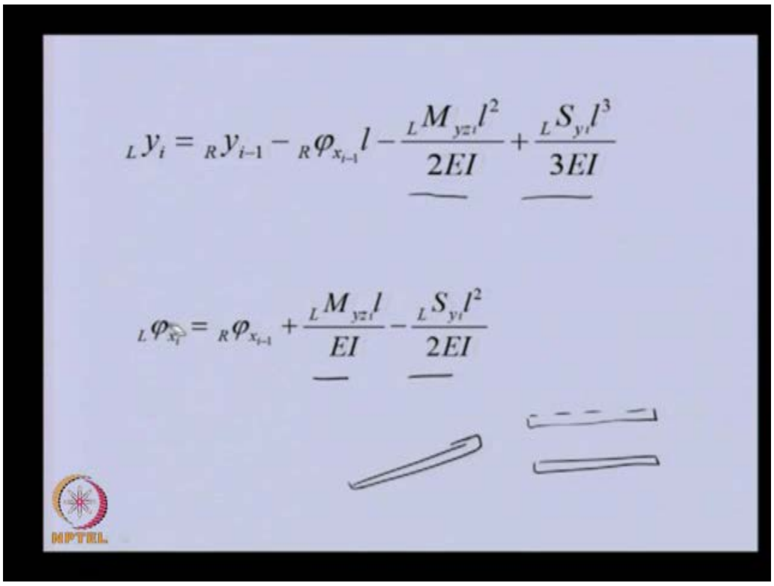


When we are giving a linear displacement of this there is no change in the slope because in this particular case shaft if you are giving a linear displacement like this, there will not be any change in the slope, this is in the second case when we are considering shaft as rigid. But when we are giving a change in the slope like this up to the rigid shaft, we will be having same amount of the slope at this end also. So, whatever the slope we are changing at this left end, right end will be having same angular displacement, so this is that particular component.

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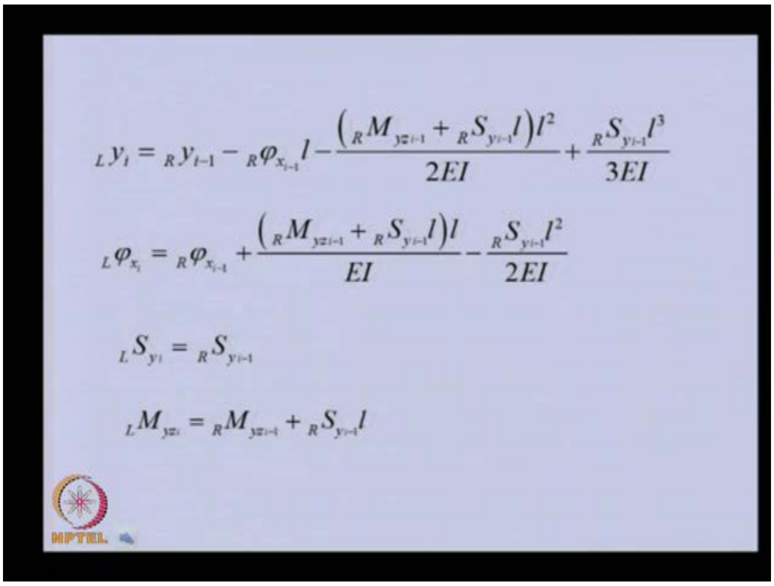


So, now you can able to see that we have related not only the shear force, bending moment, this translational displacement, rotational displacement these relations we can able to summarize like this, here this is the first equation, linear equation. Here if we go back here can see this particular moment, now I am replacing with this moment because we have already these relations. So, I am just substituting this expression here so that all the terms in this side is toward the right of i th minus disk terms. Similarly, in the angular displacement case replace this term and these are the two relations which we obtain for the shear force and bending moment, there is no change in this.

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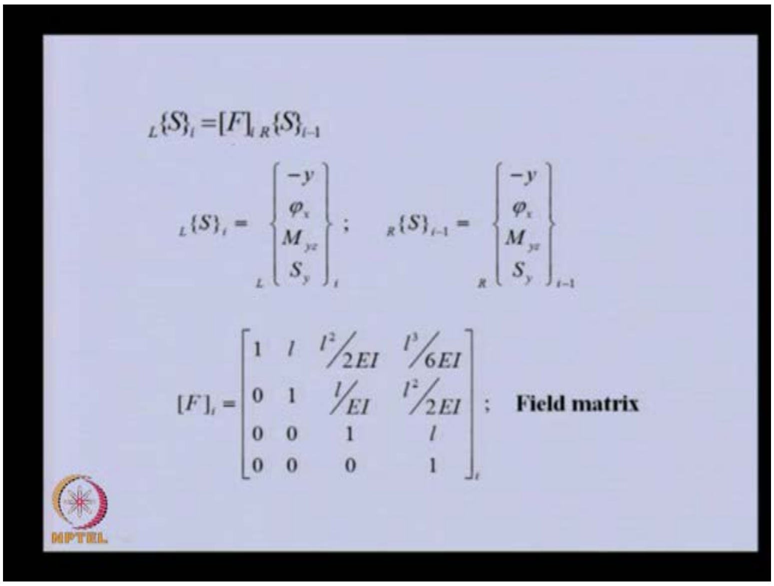


Now, we can able to rearrange this equation and we can able to put them in matrix form, so basically we are stacking the state vector like this, first linear displacement minus, this minus we are taking so that in matrix all the terms are positive, then angular displacement, bending moment, shear force. So, this particular state vector, which we are attempt is for left of i th disk this for right of i minus 1 disk and this is the field matrix which is for i th shaft. Now, if you go back to this four equations, basically you can able to see these are the vector which we have arranged I think if we put this here, then this will be of the similar form.

This is left of i, left of here all are left of i and in this side we have right of i minus 1 components, similar four components are there; that means these components which are right of i minus 1. Whatever the coefficients of these are there in the right side we are keeping in the field matrix. So, this is the field matrix, so if you can able to see shear force relation if you want to see, shear force is at the end and here because these field variables are getting multiplied by 0, so we will be having shear force in the left of i is equal to shear force toward the right of i minus 1.

Similarly, for bending moment, this is for angular displacement, this is for the linear displacement. So, basically if we substitute this here and multiply, we will get all the four equation which we have derived this. So, we can able to see this is the field variable and field matrix, earlier in the torsional vibration case the size of that was 2 by 2, but now it is 4 by 4 matrix.

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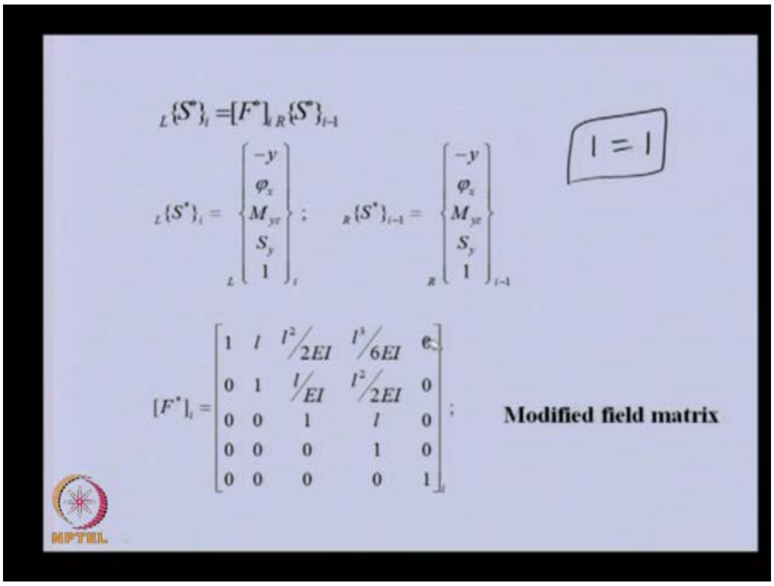


If we have external force, then as we did in the torsional vibration case we need to modify this field matrix by adding one identity at the lower position. So, basically we are adding 1 equal to 1, so we can able to see this field matrix is added all the 0 except the diagonal term and here also 0. So, again if we substitute this here and this state vector here if we expand the last equation, we will get this and because this is identity, so as such it will not affect the equations. But this will help us in putting the unbalanced force, which will be there at the disk location when we will be deriving the point matrix, that particular force will come in the last column, so that we will see once we will derive the field matrix point matrix.

Now, as I told so we derived the field matrix for one plain motion of the shaft, but generally rotor have both the plain motion, that is in the vertical plain and horizontal plain. So, we expect that if you want to analyze the both plain motion simultaneously, then we need to modify this particular matrices to incorporate both plain motion. Also as I pointed out when we have gyroscopic couple in the system or damping in the system, then we will be having phase difference of the displacement vector and the velocity component vector by 90 degree.

Because of that we will see that we will be getting the complex quantity within the field matrix and point matrix. And as we have seen in the torsional vibration case with damping, the point matrix and field matrix become complex. But if you want to work we work with the real matrices only, we need to separate this matrices real part and imaginary part separately and then we can able to recombine this equations, so that the matrices are in the always in the real from.

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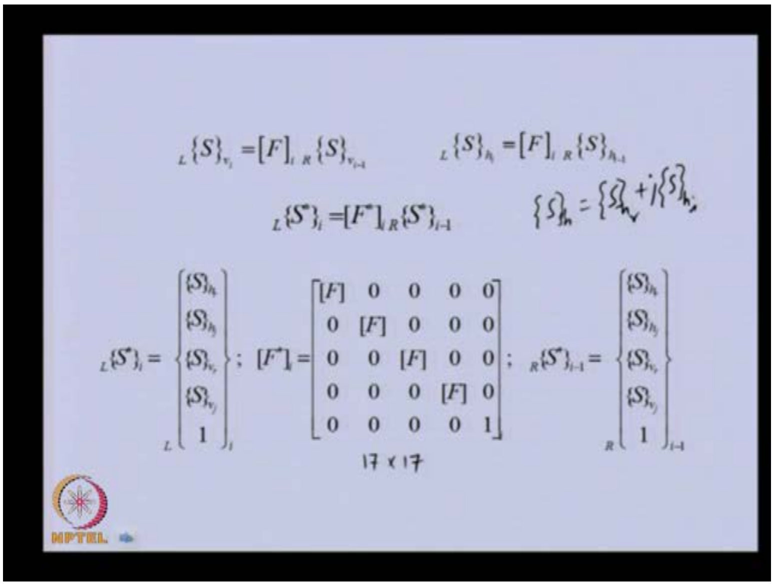


So, for that case when we are considering both the plain motion and when we want to consider the damping or gyroscopic aspect also then we need to, so here you can able to see this is the state vector, which is in the horizontal plain, these two are in horizontal plain, these are two are in the vertical plain. In horizontal plain itself we have taken the real component and the imaginary component; that means a street vector which is there in the horizontal plain will be having two component, because of the phase, real component and imaginary component.

Now, what we have done it, when we are substituting this in such field matrices, we are separating the real part and imaginary part separately and recombining them, so we can able to see that if we expand this matrices after substituting here this will be equal to f into this part. So, horizontal real part multiply by this field matrix and horizontal real part and left of this particular disk i th disk and right of i minus 1 disk. So, basically here we can able to see these field matrices which we obtain earlier are having 4 by 4 size each of them. We added the identity also at the end. So, basically this modified matrix is having 17 into 17 size. If we want to consider damping or the gyroscopic effect or any other aspect, then this is most general form of the field matrix.

Only thing is some extra terms will be added up in this if we are considering damping, but as such this is ready for the addition of any other complexity are there in the form of damping or gyroscopic couple or any other complexity which we want to analyze. So, this is the most expanded from of the field matrix, which we will be having and when we will be considering the gyroscopic effect, then we will see that, especially the point matrix will get affected and some of the terms which are zero will have some matrices.

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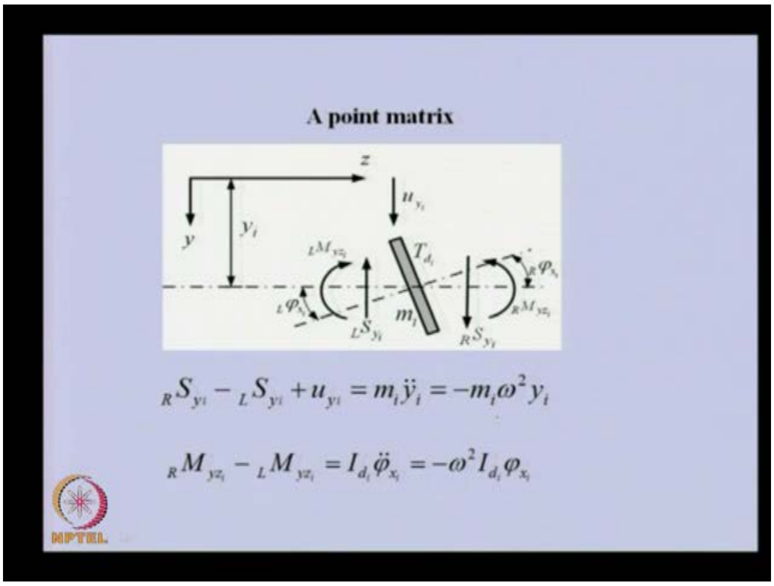


So, once we have done with the field matrix, now let us come to the point matrix, for that I have taken the free body diagram of the i th disk case. Now, we will be having linear displacement, there translational displacement, which we will be i th of disk. So, because this is a thin disk, so we will be having displacement in the left and right of the disk as same. Similarly, the slope we can able to see this is the left of i th disk slope and that is the right of that. Because this is a thin disk the slope will also be same at both the end. Apart from that we have shear force at both ends and bending moment and apart from that if there is some eccentricity in the rotor, let us say u i, u i i is the unbalanced force which is acting toward the y direction positive y direction. So, now we can able to obtain the relations as we obtain for field matrix.

So, first the force balance, so you can able to see the shear force, this one which is acting toward the positive y direction, this is acting in the negative direction, unbalanced force is acting in positive direction should be equal to inertia, m i into y i double dot is time derivative. For harmonic motion which will be there for free vibration or forced vibration, we can able to write this like this, where omega is spin speed of the shaft. If we are dealing with the free vibration unbalance will not be there and this frequency will be natural frequency of the system.

Similarly, moment equation we can able to see this is the right this moment, which is in the positive direction, this is negative direction or positive previous one is equal to the rotor inertia, i d dimaterial mass moment of inertia into angular acceleration about x axis. So, for simple harmonic motion we can able to write this like this, so these are the shear force and bending moment moment and force balance.

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$$-{}_R y_i = -{}_L y_i$$

$${}_R\varphi_{x_i} = {}_L\varphi_{x_i}$$

$${}_R M_{yz_i} = -\omega^2 I_{d_i}\, {}_L\varphi_{x_i} + {}_L M_{yz_i}$$

$${}_R S_{y_i} = -m_i\omega^2\, {}_L y_i + {}_L S_{y_i} - u_{y_i}$$

As I pointed out the displacement, translational displacement at both ends are same, slope is also same, these are the previous moment equation and shear force. The force equation, I have written such that all the terms related with the right of i th disk is this side and all the terms which are having left of i terms are this side, so here all the terms are having l back subscript. Now, these we can able to combine similar to the field matrix.

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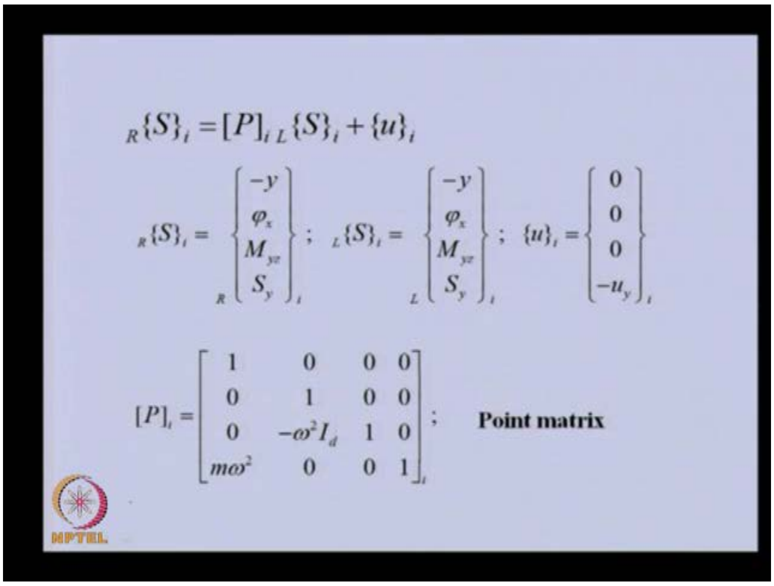


So, you can able to see that this is a point matrix, this one which is coming from various coefficients of the these state vector, state vector components and we have additional vector, which is unbalance vector which is coming from the unbalanced force, because we have the force, the shear force at the last so it will come at the end. So, basically this is this equation is if we expand this equation the fourth equation we will get this equation and this is the last term, which is corresponding to the external force. Now, to accommodate this external force inside the point matrix we need to modify this point matrix by adding identity as we did earlier.

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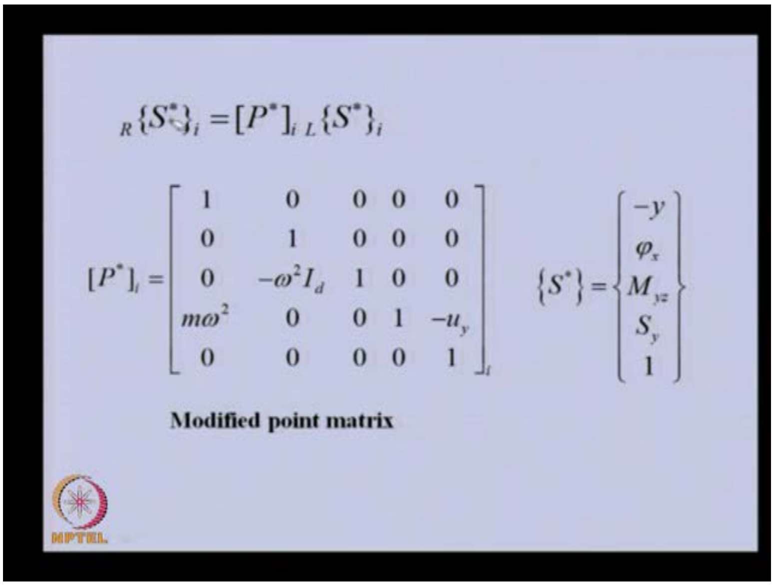


So, if we add identity and now we can able to see that we can able to include this external unbalanced force inside the point matrix which we will be calling as modified point matrix. So, basically this fourth equation, if we substitute this point matrix here, state vectors here, if we expand the fourth equation we will get the same equation as the previous one, this one, but now this unbalance is there inside the matrix. Now, on the same lines as we did for the field matrix, if we want to analyze both plain motion also we want to analyze damping or gyroscopic effect, we need to have both plain state vector and there real part and imaginary part components.

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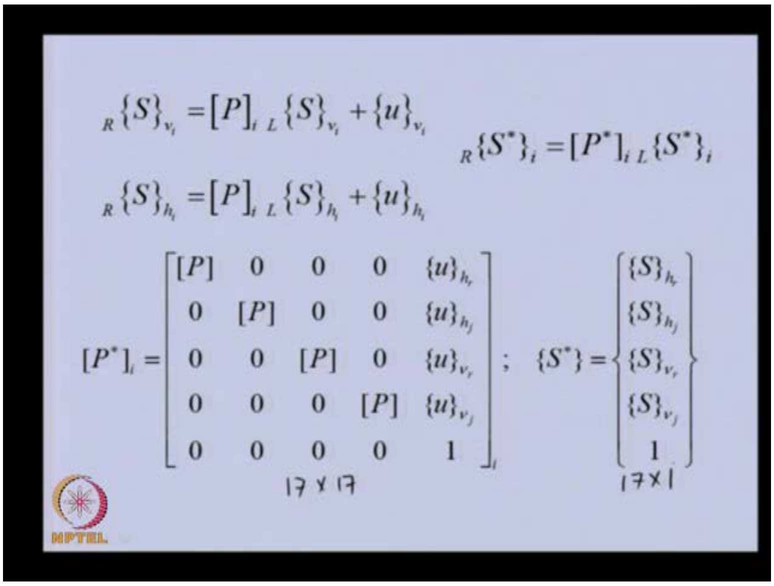


So, again I am expanding that thing here so you can able to see, point matrices are here, so here again the size of the modified point matrix is 17 into 17, here we have the component of the unbalanced force in vertical direction, horizontal direction, real part imaginary part, real part imaginary part of the vertical direction. So, here additional force external force, external force vectors are coming and these are the unbalanced force. So, you can able to see that the state vector for such case is, this is in horizontal plain these two, this is in vertical plain, the real part and imaginary part. So, size of this state vector is again 17 into 1, this will be same for the field matrix state vector also. We have derived the field matrix and point matrix, basically for most of the case we will be analyzing single plain motion.

So, point matrix and field matrix which we will be considering will be 4 by 4 size or if there is unbalance then it will be 5 by five 5, but that 17 into 17size of the field matrix and point matrix, just I will illustrate it. In case we are considering the damping or gyroscopic couple, then we need to consider both plain motion and because there is a phase components, because of the velocity term we need to take care of the real part and imaginary part of the this state vector.

So, we need to expand this into 17 into 17, but most of the cases will be illustrating here through example, we will see that the point matrix and field matrix will be of 4 by 4 size unless otherwise unbalanced force is there. In that case we will be considering 5 by 5 matrix. Now, the procedure for obtaining the overall transfer matrix and the application of the boundary condition is similar to the torsional vibration case, but here we will because the size of the matrices are bigger. So, we will see some more complexity in the frequency equation which we are getting earlier.

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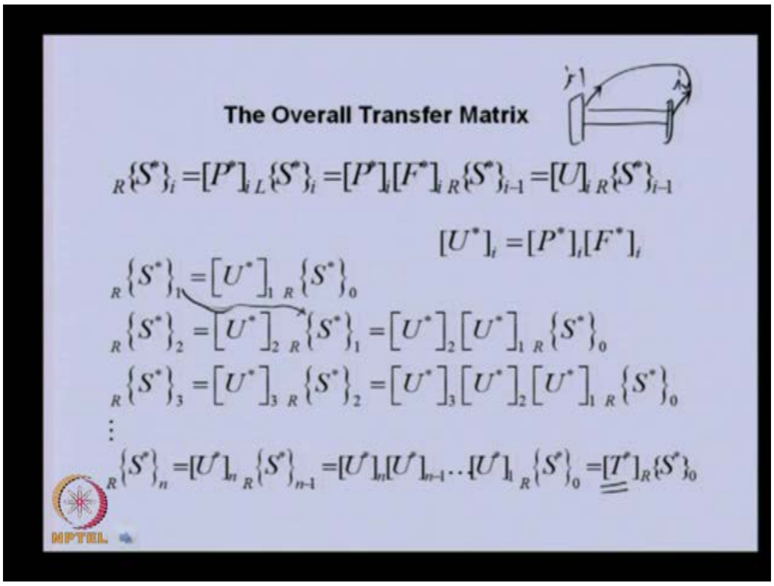


So, let us see how we can able to get the overall transfer matrix? So, earlier we derived the point matrix, so that was a relating the state vector right of i th disk to the state vector to left of i th disk. Also we related the state vector left of i th disk to the right of i minus 1 disk using field matrix, so that if you substitute we can able to see that, we can now able to relate the state vector which is right of i minus 1 disk to state vector right of i th disk. This p into f we call it as transfer matrix and this is basically transferring the state vector from, if we see from figure if this is i minus 1 disk this is i th disk.

So, your state vector here which is right of i a minus 1 disk and the state vector which is right of i th disk we are directly getting. So, information from here directly we are getting to the right of i th disk. Now, these i disk can we can able to take 1, so if we are taking i as 1 so you can able to see that state vector right of 1, we can able to relate with the u n and this is the state vector at zero th station. Now, if we want i is equal to 2 to right of 2 is equal to u 2 and right of 1 state vector. Now, we can able to substitute this here and if we substitute this here this will be u 2 into u 1 state vector at 0 station.

Similarly, we can able to write for 3, then it will be multiplication of u 3, u 2, u 1 and state vector at 0 station. We can able to expand this up to n th station, so in that particular case we will be having multiplication of all these transfer matrices up to 1 and multiplication of these, all these are we are representing as T which is the overall transfer matrix. Now, once we have got the overall transfer matrix we can able to apply a boundary condition, because we have n th station in the extreme right side of the rotor system and 0 station at the extreme left side of the rotor system, so like this.

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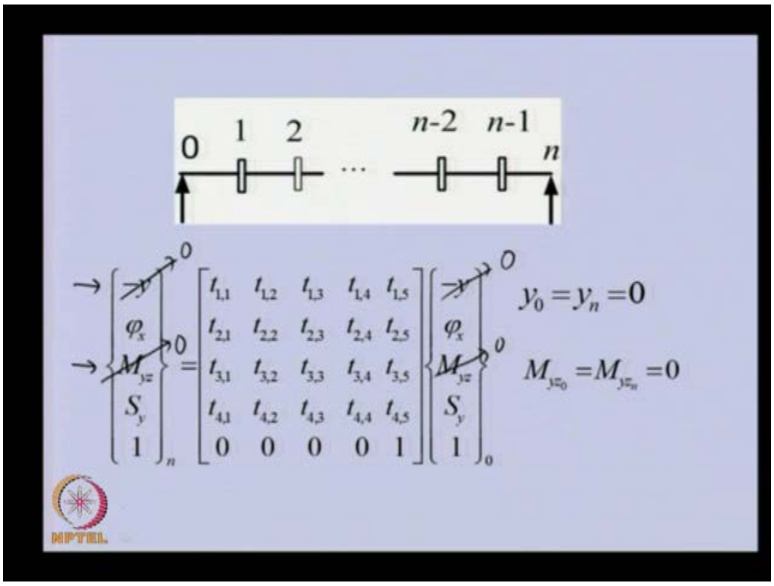


So, this is the n th station this is 0 station in the previous over all transfer matrix T relates the state vector here to the state vector here. Now, that particular last equation I have expanded here, so this is state vector at n th station, this is the state vector at the 0 station. Because if there is a unbalance in the system the form of the overall transfer matrix will be this, so last row will be 0 0 1 these are corresponding to the unbalanced force. Other terms are multiplication of various point matrix and field matrix and basically all these will be function of omega, which is spin speed of the shaft for forced vibration and for free vibration, then these terms will be 0 and omega we can able to take as natural frequency of the system.

Now, boundary condition, for boundary condition here we have linear displacement 0 at y 0 station. Similarly, at n th station we have linear displacement 0 because this is simply supported ends, the moments, the bending moment will be 0 at these two ends, so these are the boundary condition of the system. So, we can able to apply this, this is 0 here, this is 0 then bending moment is 0 at both the end. Now, we can able to see that, we can able to take out the first row and third row, because in the left hand side, which is a vector we have 0 values in the z tree. So, I am taking out the first row and third row and in second case I will be taking the reaming rows.

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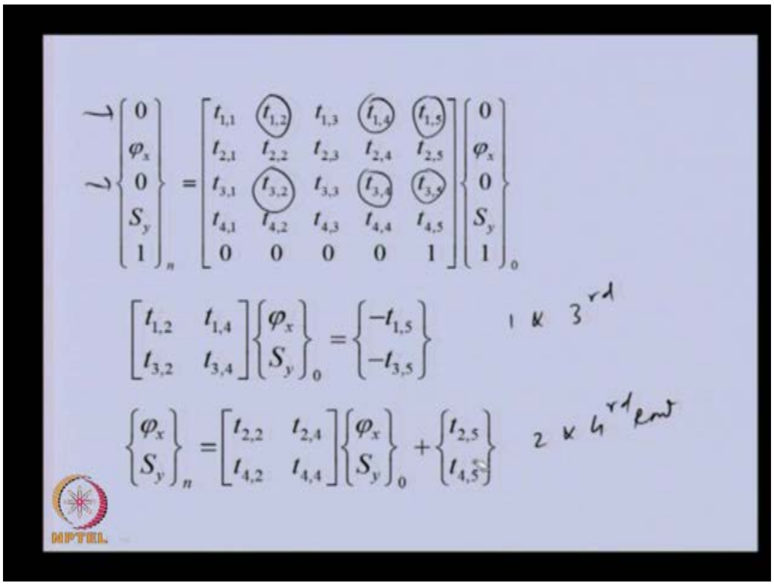


So, basically this is the application of the boundary conditions and this is the first row and third row, first and third row if we take out from above equation. So, you can able to see that first row is t 1 1 is multiplied by 0, so this will not contribute, t 1 2 you multiply it by this angle, so this is coming here similarly, this will not contribute this will come. So, we will be having this four terms in this, corresponding to the first row and third row, so they are here and they will also come, which are coming on this side. This is the external force components. So, basically I have taken out first and third row and I have combine them. Similarly, the second and fourth row if I take out I will get this equation, this is from the second and fourth row, so here also the unbalanced terms are coming.

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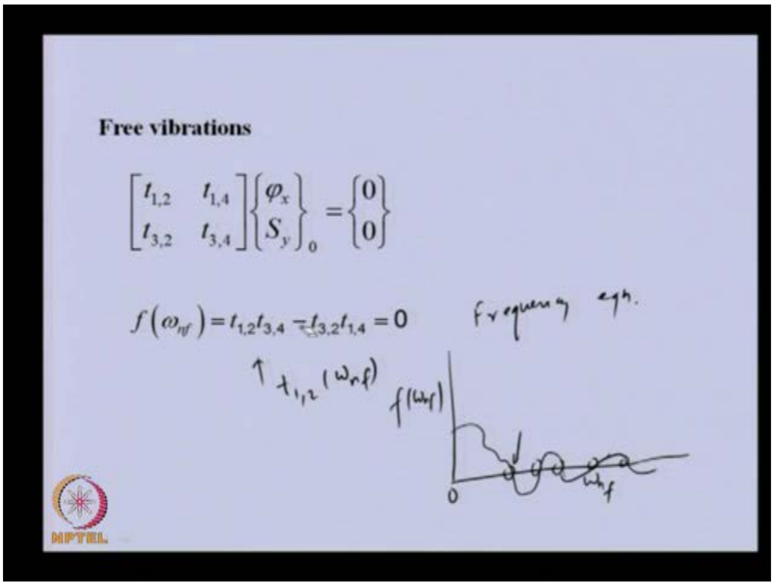


Now, if we are dealing with the free vibration, so from this equation this if we, these are as I told they are coming from the unbalanced component here. So, these terms will be 0 here also, this terms will be 0, but if you see compare these two equation, this equation is homogeneous equation if we are equating this equal to 0 for free vibration and that is the equation we got here, this is a homogenous equation. For nontrivial solution of this, for this the matrix of this determinant should be 0, so we have equated this equal to 0. So, basically the this is the frequency equation, this t 1 2, t 3 4 all these are basically, they are function of natural frequency terms or t terms are function of natural frequency term.

So, basically here we expected polynomial, for a transverse vibration case these generally polynomial will be of higher degree, because if you are dealing with a larger mass rotor system then obtaining this polynomial will be not be easy, so generally we solve this frequency equation using numerical analysis technique. We explain that in torsional vibration case also, some kind of root searching technique can be used to obtain this particular frequency equation. Basically we if we are expressing this as a function of omega n f, so if we are plotting this function with respect to omega n f for various values let us say from 0 to some value.

So, we expect this function will vary and it will intersect the line of 0 at various locations. All these intersections will give us the roots, which will be the natural frequency of the system and depending up on the degree of freedom of the system that many intersects, we except from this function.

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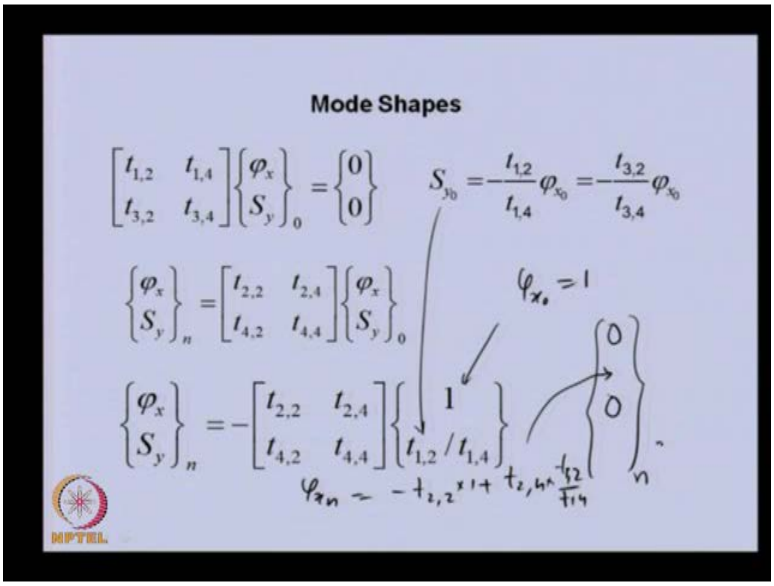


For mode shape, once we have obtained the natural frequency we can come back to this equation and now if we expand this equation let us say the first equation, first equation will give this term or similarly, the second equation will give this, so we can able to use any of them here. So, if we have yes, so here we have related the state vector zero th station that is shear force with the angular displacement. Now, this is the equation second set of equation which we obtain this one, so here we are recruiting this equal to 0, because there is no unbalanced force and using this equation here. Now, let us assume this angular displacement as unity, so we will be obtaining the mode shape with respect to this reference.

So, I have substituted that as 1 here and this shear force which is at the 0 station then will be given by either this or this because, now this is 1, so this we are subtitling here. So, now we can able to see that the state vector which is a angular displacement at n th disk and state vector there is shear force at n th disk is know. If we see the boundary condition at n th disk, we have linear displacement 0 because this is simply supported case and angular displacement we are taking, we can able to get from here, because now phi x n will be given by the first equation here. So, phi that will be given as phi x n is equal to minus t 2 comma t into 1 this one plus t 2 comma 4 into t 1 2 by t 1 4, this term.

So, we can able to see that we know this vector here, so this will be substituted in the second place, then the third place is for bending moment that is 0 for simply supported case, because n th disk we already seen is having these boundary conditions. Now, the shear force, shear force will be given by this, so t 4 2 into 1 and t 4 4 into this term will give us the shear force. So, we know the state vector at n th station completely and once we know state vector at one station completely, we can able to use transfer matrix to transfer back the state vector from one station to another, so we need to know only state vector at one location.

So, these can be used in the previous transfer matrices, which we developed here to get back the various state vector in between. Now, once we have got all the state vector, we need to pick up the linear displacement separately, angular displacement separately and at various stations whatever the displacements are there. If you want plot the linear displacement, we can pick up various linear displacement from various state vectors and we can plot them. If you want the angular displacement, we can pick them up from this state vector. So, we have seen how to obtain the natural frequency and the mode shape.

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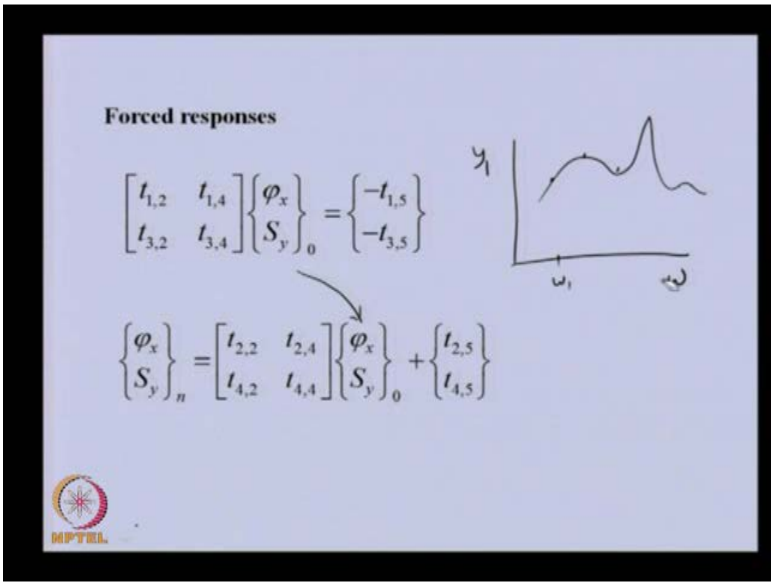

If you want to solve the forced vibration again we need to come back to this previous two equations, so which we obtain from first and third row, so here now we are not keeping this unbalanced force as 0. So, if we know this unbalanced force, we can able to obtain this vector, because they will be know now because speed omega will be speed and we can be able to invert to get the state vector here at 0 th station. This then we can able to substitute here to get the state vector at n eth station, because this unbalance will be known and all these terms will be field and point matrices including the speed will be known.

So, you can able to see that we can able to obtain these responses for various speeds, and we can able to plot the response with respect to speed, how they vary, so this is how we can able to analyze the forced vibration in the system. So, basically if we are interested in one of the station that is transverse vibration linear vibration, so with respects to speed we need to solve this several times one speed at a time, we will get one point for another speed we get another point like this. So, we can able to get other response like this, through numerical example we will illustrate how we can able to get this kind of response in subsequent class.

So, today we started with the transverse vibration using transfer matrix method, which we call as method Myklestand method also, we developed the field matrix and point matrix by free body diagram of the shaft segment and the mass. We have seen that as compared to the torsional vibration case, these the size of the this point matrix and field matrix is more and especially it will be very large of size of 17 into 17, when we want to consider both plain motion and other complexity like damping and gyroscopic couple. Through simple simply supported condition I illustrated how the frequency equation can be obtained.

Then how we can able to obtain the natural frequency from that and once we obtain the natural frequency how the mode shape can be obtained that is nothing but the relative displacements at various stations, how we can able to get it. Then even forced vibration using t m m can be done, once we know what is the unbalance in the system, then we can able to analyze the forced vibration also. In the subsequent class through numerical example we will see the illustrations of this method, also we will be dealing with the if there is a intermediate support in the shaft, how to deal with that or in the subsequent class, even we will consider the gyroscopic effect in that how the size of the matrices becomes very large.