Electrical Equipment and Machines: Finite Element Analysis
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Lecture No 39
Computation of Forces using Maxwell Stress Tensor

Welcome to lecture 39. In this lecture, we will see how do we use the finite element method to calculate forces in electrical machines and equipment.

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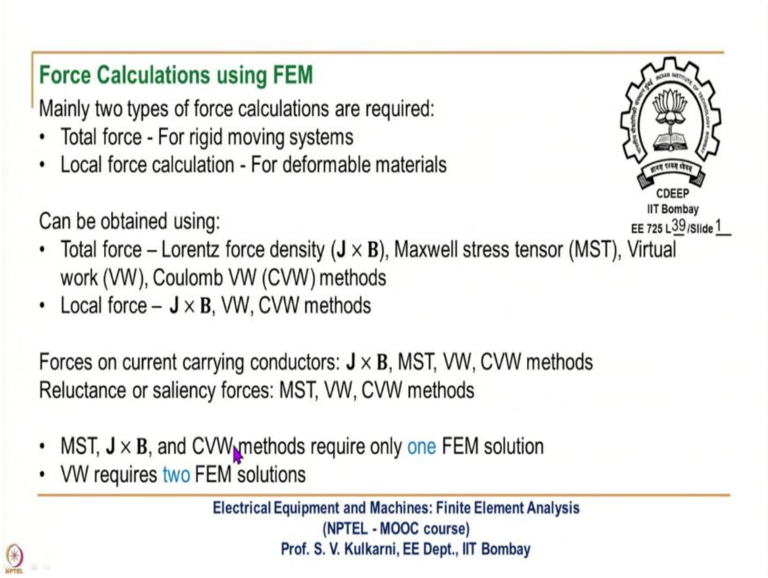

So, we will see two types of force calculations. We will see the first approach in L39 and the other approach in L40. In this lecture, we will see Maxwell stress tensor based force calculation method. Let us see some basics. Generally, two types of force calculations are required. One is the total force on a rigid moving system or body, that means the body does not get deformed locally and the whole body moves.

The second type is local force calculation wherein we have local deformations. Now, we will see how to do that. Now, these two types of forces can be obtained using the following methods.

Total force – Lorentz force density ($\mathbf{J} \times \mathbf{B}$), Maxwell stress tensor (MST), Virtual work (VW), Coulomb VW (CVW) methods
Local force – $\mathbf{J} \times \mathbf{B}$, VW, CVW methods

The total force on a rigid body can be obtained by using either Lorentz force density ($\mathbf{J} \times \mathbf{B}$), Maxwell stress tensor (MST), virtual work (VW) or Coulomb virtual work (CVW) methods. Whereas local force can be obtained by using $\mathbf{J} \times \mathbf{B}$, virtual work and CVW methods. MST cannot be used to calculate local force because in the MST method we integrate the force along a closed contour. So, we cannot calculate force at a point. Secondly, forces on current-carrying conductors can be calculated either by using $\mathbf{J} \times \mathbf{B}$ method or MST or VW or CVW method. Saliency or reluctance forces are calculated by MST, VW, and CVW methods. But $\mathbf{J} \times \mathbf{B}$ method cannot be used because J is unknown in the structure which is experiencing the force.

MST, $\mathbf{J} \times \mathbf{B}$, and CVW methods require only one FEM solution but the virtual work method requires two FEM solutions. Even though the name of CVW suggests that it is an extension of virtual work, it requires one FEM solution.

The virtual work method requires two FEM solutions because the force is calculated by evaluating the ratio of change in energy to the displacement when the body under consideration moves from one position to another. Hence we require energy values at both positions and therefore two FEM solutions are required. Whereas in case of CVW, $\frac{dW}{dx}$ (x is the displacement) is taken care in the FEM formulation itself. That is why we require only one FEM solution. In this course, we are not going to study this Coulomb virtual work method. But those who are interested to know about that method can see literature.

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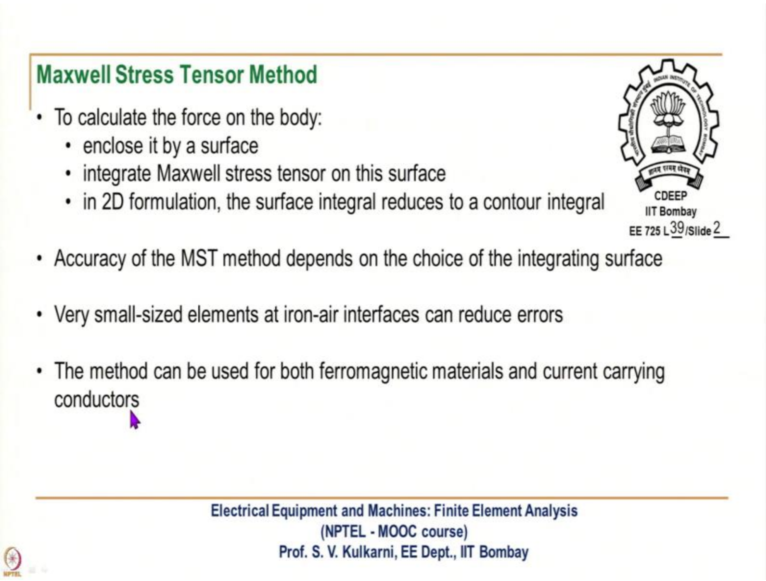

Let us see how to calculate force using the Maxwell stress tensor method. In this approach, we have to enclose the object under consideration by a hypothetical surface and integrate MST on that surface. We will see the derivation for MST in the coming slides. In the 2D formulation, the surface integral reduces to a contour integral.

Accuracy of the MST method depends on the choice of the integrating surface. If there are iron-air interfaces, then we have to use very small elements to reduce errors. Also, this method can be used for both ferromagnetic materials and current-carrying conductors, as explained on the first slide.

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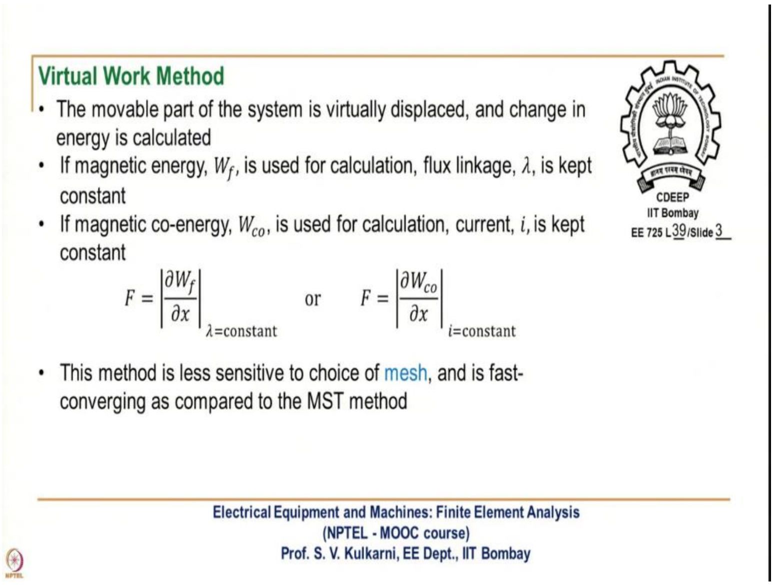

In this slide, let us see some theory about virtual work method. We are going to see the application of this method in the next lecture (L40). In this virtual work method, the movable part of the system is virtually displaced in simulation and the change in energy is calculated. If the magnetic field energy (W_f) is used for calculation then flux linkages λ is kept as constant and this is the first approach of the virtual work method. Whereas, in the second approach if magnetic co-energy (W_{co}) is used for calculation then current i is kept constant.

We will discuss about both approaches in next lecture. We can see the difference between the two approaches by the following expressions

$$F = \left|\frac{\partial W_f}{\partial x}\right|_{\lambda=\text{constant}} \quad \text{or} \quad F = \left|\frac{\partial W_{co}}{\partial x}\right|_{i=\text{constant}}$$

VW method is less sensitive to the choice of mesh and is fast converging as compared to the MST method. That is why it is preferred for force calculation in many commercial software.

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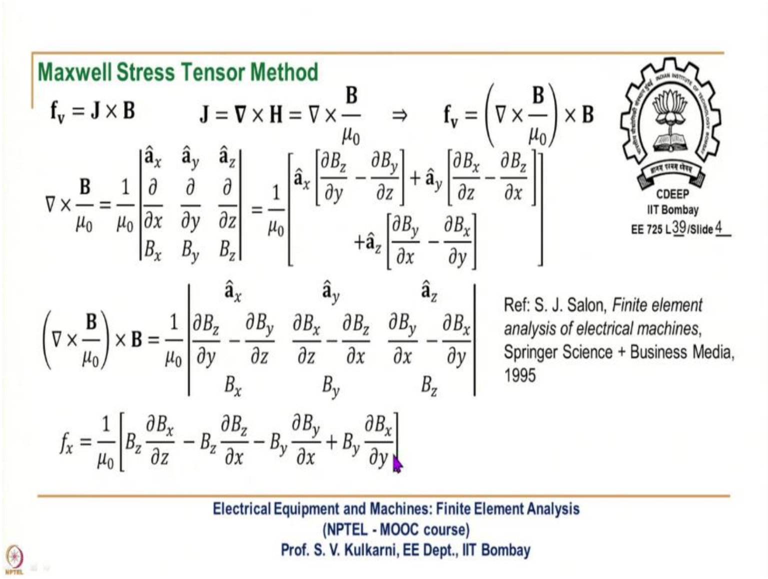

Let us understand more about the Maxwell stress tensor. We know that $\mathbf{J} \times \mathbf{B}$ represents the force density (force per unit volume) and $\mathbf{J} = \nabla \times \mathbf{H}$, as we are neglecting the displacement current density. H is replaced by $\frac{B}{\mu_0}$ as given below

$$\mathbf{f_v} = \mathbf{J} \times \mathbf{B} \qquad \mathbf{J} = \nabla \times \mathbf{H} = \nabla \times \frac{\mathbf{B}}{\mu_0} \quad \Rightarrow \quad \mathbf{f_v} = \left(\nabla \times \frac{\mathbf{B}}{\mu_0}\right) \times \mathbf{B}$$

First, let us calculate $\nabla \times \frac{B}{\mu_0}$ which is given by the following determinant.

$$\nabla \times \frac{\mathbf{B}}{\mu_0} = \frac{1}{\mu_0} \begin{vmatrix} \hat{\mathbf{a}}_x & \hat{\mathbf{a}}_y & \hat{\mathbf{a}}_z \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ B_x & B_y & B_z \end{vmatrix} = \frac{1}{\mu_0} \left[\hat{\mathbf{a}}_x \left[\frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z}\right] + \hat{\mathbf{a}}_y \left[\frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x}\right] + \hat{\mathbf{a}}_z \left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right] \right]$$

Here, $\frac{1}{\mu_0}$ is taken out and if $\nabla \times \mathbf{B}$ is expanded then we will get the above expression. Now, use the components of $\nabla \times \mathbf{B}$ in the force density expression as given below.

$$\left(\nabla \times \frac{\mathbf{B}}{\mu_0}\right) \times \mathbf{B} = \frac{1}{\mu_0} \begin{vmatrix} \hat{\mathbf{a}}_x & \hat{\mathbf{a}}_y & \hat{\mathbf{a}}_z \\ \frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} & \frac{\partial B_x}{\partial z} - \frac{\partial B_z}{\partial x} & \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \\ B_x & B_y & B_z \end{vmatrix}$$

We have to expand the above determinant.

So, by expanding $\left(\nabla \times \frac{\mathbf{B}}{\mu_0}\right) \times \mathbf{B}$, we will get the 3 components of forces. We are skipping some of the intermediate steps, but those who are interested in knowing all steps can refer to the following book wherein a detailed derivation is given. When we expand the determinant, we will get the following expression for the *x* component.

$$f_x = \frac{1}{\mu_0}\left[B_z\frac{\partial B_x}{\partial z} - B_z\frac{\partial B_z}{\partial x} - B_y\frac{\partial B_y}{\partial x} + B_y\frac{\partial B_x}{\partial y}\right]$$

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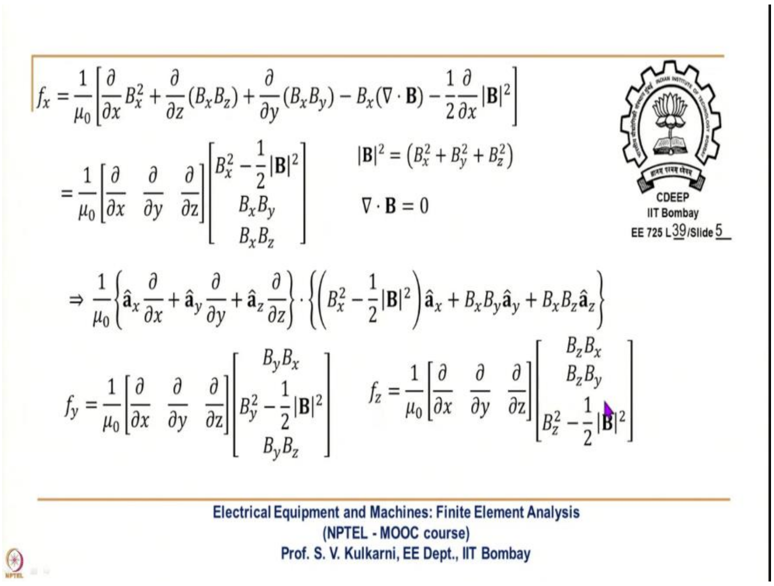

So, when we further manipulate the above expression we can get the following expression.

$$f_x = \frac{1}{\mu_0}\left[\frac{\partial}{\partial x}B_x^2 + \frac{\partial}{\partial z}(B_xB_z) + \frac{\partial}{\partial y}(B_xB_y) - B_x(\nabla\cdot\mathbf{B}) - \frac{1}{2}\frac{\partial}{\partial x}|\mathbf{B}|^2\right]$$

Note that $\nabla \cdot \mathbf{B} = 0$ and $|\mathbf{B}|^2 = B_x^2 + B_y^2 + B_z^2$. We can rewrite the above expression in matrix multiplication form as

$$f_x = \frac{1}{\mu_0}\begin{bmatrix}\frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z}\end{bmatrix}\begin{bmatrix}B_x^2 - \frac{1}{2}|\mathbf{B}|^2 \\ B_xB_y \\ B_xB_z\end{bmatrix}$$

In the above expression, a row vector is multiplied with a column vector.

The row matrix in the above equation is ∇ operator. In this matrix, unit vectors $\hat{\mathbf{a}}_x$, $\hat{\mathbf{a}}_y$, and $\hat{\mathbf{a}}_z$ are implicit. So, when we write it in matrix multiplication form, we do not write the unit vectors. Similarly, f_y and f_z can be written as

$$f_y = \frac{1}{\mu_0}\begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix}\begin{bmatrix} B_yB_x \\ B_y^2 - \frac{1}{2}|\mathbf{B}|^2 \\ B_yB_z \end{bmatrix} \qquad f_z = \frac{1}{\mu_0}\begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix}\begin{bmatrix} B_zB_x \\ B_zB_y \\ B_z^2 - \frac{1}{2}|\mathbf{B}|^2 \end{bmatrix}$$

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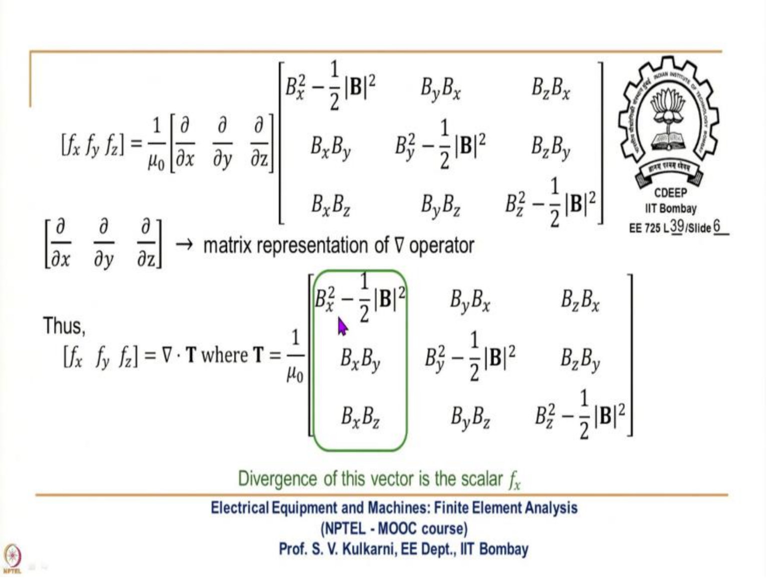

We can write the complete force expression as

$$[f_x\ f_y\ f_z] = \frac{1}{\mu_0}\begin{bmatrix} \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \end{bmatrix}\begin{bmatrix} B_x^2 - \frac{1}{2}|\mathbf{B}|^2 & B_yB_x & B_zB_x \\ B_xB_y & B_y^2 - \frac{1}{2}|\mathbf{B}|^2 & B_zB_y \\ B_xB_z & B_yB_z & B_z^2 - \frac{1}{2}|\mathbf{B}|^2 \end{bmatrix}$$

So, the above 3×3 matrix can be written by combining all three expressions that we obtained in the previous slide. As already explained the row matrix in the above equation represents ∇ operator.

The three components (f_x, f_y, f_z) of the force can be written as the divergence of tensor T as given in the following equation

$$[f_x\ \ f_y\ \ f_z] = \nabla \cdot \mathbf{T} \text{ where } \mathbf{T} = \frac{1}{\mu_0}\begin{bmatrix} B_x^2 - \frac{1}{2}|\mathbf{B}|^2 & B_yB_x & B_zB_x \\ B_xB_y & B_y^2 - \frac{1}{2}|\mathbf{B}|^2 & B_zB_y \\ B_xB_z & B_yB_z & B_z^2 - \frac{1}{2}|\mathbf{B}|^2 \end{bmatrix}$$

Divergence of this vector is the scalar f_x

The divergence of the column indicated in green colour results in a scalar f_x, the divergence of the second column is f_y, and the divergence of the third column is f_z.

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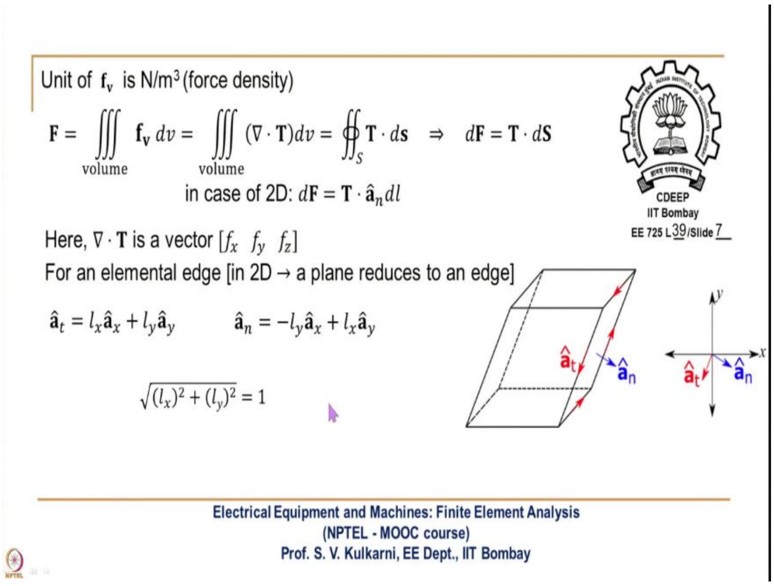


Now, the total force vector can be written as

$$\mathbf{F} = \iiint_{volume} \mathbf{f_v}\, dv$$

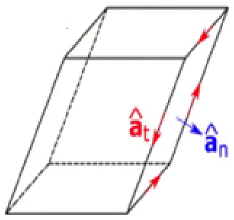
Here, $\mathbf{f_v}$ is the force density and it is represented as $\nabla \cdot \mathbf{T}$. Then we invoke the divergence theorem and write the force expression as given below

$$\mathbf{F} = \iiint_{volume} \mathbf{f_v}\, dv = \iiint_{volume} (\nabla \cdot \mathbf{T}) dv = \oiint_S \mathbf{T} \cdot d\mathbf{s} \Rightarrow d\mathbf{F} = \mathbf{T} \cdot d\mathbf{S}$$

In case of 2D approximation, we can write $d\mathbf{F} = \mathbf{T} \cdot \hat{\mathbf{a}}_n dl$. Here, $d\mathbf{S}$ is $\hat{\mathbf{a}}_n dl$.

Since we are formulating 2D approximation, *dS* will be equal to *dl*. So, here $\nabla \cdot \mathbf{T}$ is a vector with three components (f_x, f_y, and f_z). Let us understand a little bit more about the tangential and normal unit vectors which will be required in further calculations.

Now, let us take an elemental edge of the following problem domain.

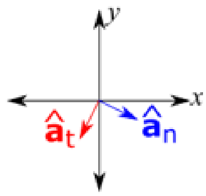


In 2D formulation, a plane reduces to an edge. Let us take a surface and the contour marked with red as shown in the above figure. We will consider $\hat{\mathbf{a}}_n$ and $\hat{\mathbf{a}}_t$ as tangential and normal unit normal vectors. Let $\hat{\mathbf{a}}_t = l_x\hat{\mathbf{a}}_x + l_y\hat{\mathbf{a}}_y$ be the tangential unit vector for the considered edge. Since this is a unit vector, $\sqrt{l_x^2 + l_y^2} = 1$. Remember that l_x and l_y individually can be positive or negative.

The sign and values of l_x and l_y depend on how the vector is oriented. For this tangential vector, outward normal will be $\hat{\mathbf{a}}_n = -l_y\hat{\mathbf{a}}_x + l_x\hat{\mathbf{a}}_y$. If we take the dot product of $\hat{\mathbf{a}}_t$ and $\hat{\mathbf{a}}_n$ then it will result into 0 because they are orthogonal vectors. So, now we will see how to find the values of l_x and l_y in each of these vectors?

We will now see how do we express $\hat{\mathbf{a}}_t$ and $\hat{\mathbf{a}}_n$ in terms of the chosen coordinate system. Let us see the example. The direction of $\hat{\mathbf{a}}_n$ will be same for the entire surface. So, now consider $\hat{\mathbf{a}}_n$ at the point where $\hat{\mathbf{a}}_t$ is indicated.

Remember $\hat{\mathbf{a}}_n$ is 0, at every point on this surface and the direction of $\hat{\mathbf{a}}_n$ is same all along the surface. So, the $\hat{\mathbf{a}}_n$ vector shown at the center of the surface is brought to the point where $\hat{\mathbf{a}}_t$ is indicated in the figure. Consider a plane passing through $\hat{\mathbf{a}}_n$ and $\hat{\mathbf{a}}_t$ vectors as shown in the following figure and we call that as *xy* plane.



From the above figure you can observe that for $\hat{\mathbf{a}}_t$ vector both l_x and l_y will be negative. For $\hat{\mathbf{a}}_n$ vector, l_x is positive and l_y is negative. This orientation ensures that both these vectors are orthogonal and their dot product will be 0.

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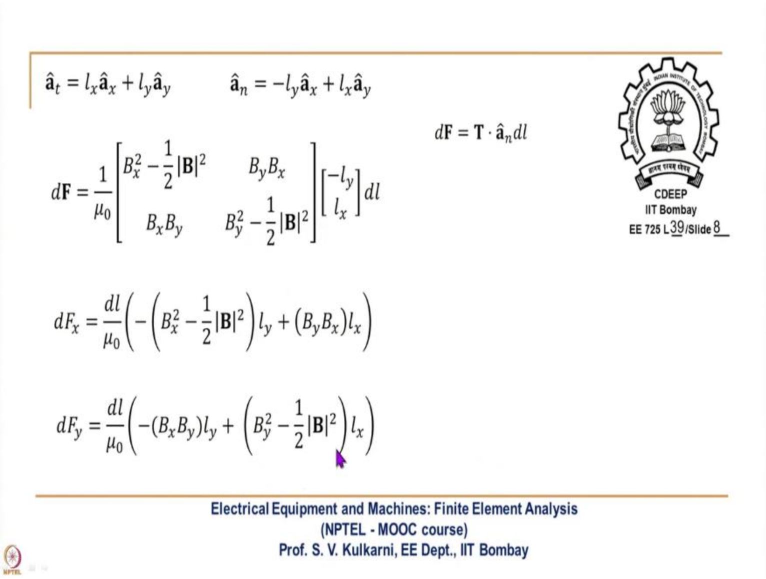

The expressions for the two unit vectors are given below.

$$\hat{\mathbf{a}}_t = l_x\hat{\mathbf{a}}_x + l_y\hat{\mathbf{a}}_y \qquad \hat{\mathbf{a}}_n = -l_y\hat{\mathbf{a}}_x + l_x\hat{\mathbf{a}}_y$$

Since we are considering 2D approximation and the tensor matrix that we saw in the previous slide reduces to the following 2×2 matrix.

$$d\mathbf{F} = \frac{1}{\mu_0}\begin{bmatrix} B_x^2 - \frac{1}{2}|\mathbf{B}|^2 & B_yB_x \\ B_xB_y & B_y^2 - \frac{1}{2}|\mathbf{B}|^2 \end{bmatrix}\begin{bmatrix} -l_y \\ l_x \end{bmatrix} dl$$

Then *dS* will become *dl*. $\hat{\mathbf{a}}_n$ is written in column matrix form so we are not writing the unit vectors $\hat{\mathbf{a}}_x$ and $\hat{\mathbf{a}}_y$. Now, if we expand the above matrix multiplication, we will get the following two expressions.

$$dF_x = \frac{dl}{\mu_0}\left(-\left(B_x^2 - \frac{1}{2}|\mathbf{B}|^2\right)l_y + (B_yB_x)l_x\right)$$

$$dF_y = \frac{dl}{\mu_0}\left(-(B_xB_y)l_y + \left(B_y^2 - \frac{1}{2}|\mathbf{B}|^2\right)l_x\right)$$

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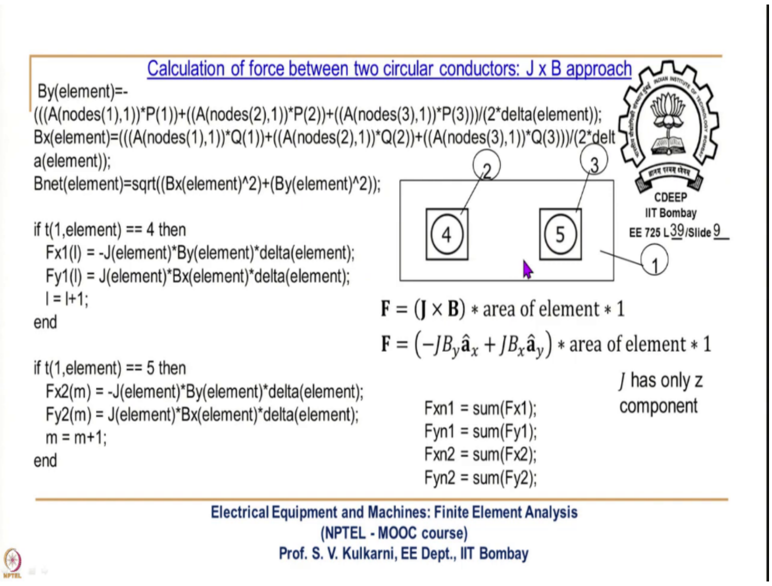


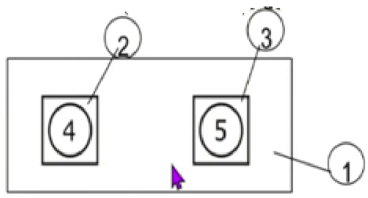
Going further, now let us see how do we calculate the force acting on two parallel circular current carrying conductors. First, we will calculate the force by using **J** × **B** approach and then we will also see how to calculate force using the MST approach. Now, the following part of the code is used to calculate B_y, B_{net}, and B_x components.

```
By(element)=-
(((A(nodes(1),1))*P(1))+((A(nodes(2),1))*P(2))+((A(nodes(3),1))*P(3)))/(2*delta(element));
Bx(element)=(((A(nodes(1),1))*Q(1))+((A(nodes(2),1))*Q(2))+((A(nodes(3),1))*Q(3)))/(2*delt
a(element));
Bnet(element)=sqrt((Bx(element)^2)+(By(element)^2));
```

We are finding these components for one element. We always run FOR loop and then for each element we calculate the components and other performance parameters. Same thing is being done here. Now, using the following code, we find out whether the element under consideration is lying in the first conductor whose subdomain number is 4.

```
if t(1,element) == 4 then
  Fx1(l) = -J(element)*By(element)*delta(element);
  Fy1(l) = J(element)*Bx(element)*delta(element);
  l = l+1;
end
```

In this problem we are considering two circular conductors shown in the following figure.



In this domain, the conductors are enclosed in rectangular boundaries which will be required for the MST based force calculation. So, now if the element is in subdomain 4, then x and y components of the force can be calculated by using the above code. How do we get them? We know that $\mathbf{F}_v$ is nothing but $\mathbf{J} \times \mathbf{B}$ (force per unit volume). The force density is multiplied by volume which is equal to area of the element*1 because it is two-dimensional approximation with 1 m depth in z direction. Remembering that J is in z direction then $\mathbf{J} \times \mathbf{B}$ is given by the following expression

$$\mathbf{F} = \left(-JB_y\hat{\mathbf{a}}_x + JB_x\hat{\mathbf{a}}_y\right) * \text{area of element} * 1$$

So, if we consider B_x and B_y components individually and J with only J_z component then we can easily verify the above expression.

The x component of force $F_x = -JB_y$*area of element*1. Similarly, $F_x = JB_x$*area of element*1. So, using the above code, we can calculate the x and y components of forces acting on each triangular element of conductor 1 and we call them as Fx1 and Fy1. We keep doing this for all the elements and store all the force component values in this column vector. The similar thing is done for the second circular conductor. Remember, this is a circle in 2D but it is a cylindrical conductor in 3D. In 2D formulation, z direction is not shown. So, we calculate the force components for each element and calculate values of forces on all the finite elements in individual matrices. Then using the following code we can sum all the force components of all elements to determine the resultant x and y components of forces on the two conductors.

```
Fxn1 = sum(Fx1);
Fyn1 = sum(Fy1);
Fxn2 = sum(Fx2);
Fyn2 = sum(Fy2);
```

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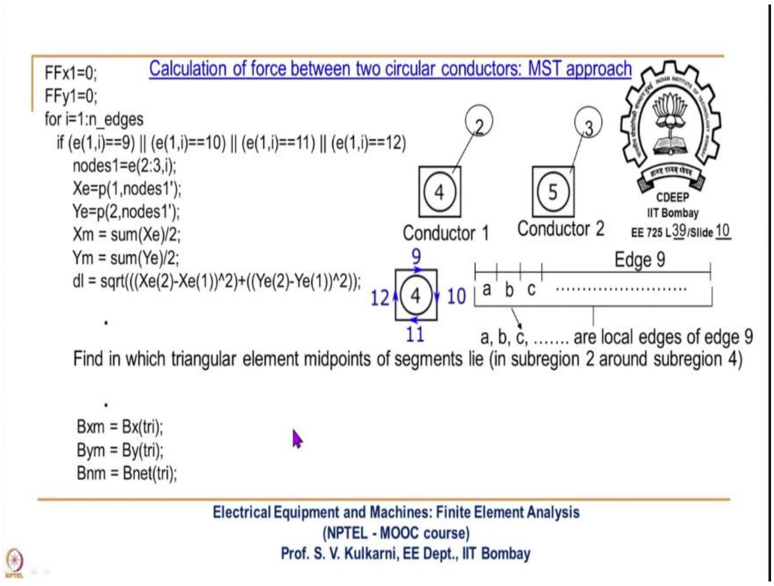
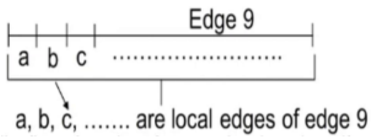


Now, let us see how do we calculate the force acting on the same two circular conductors by using the MST approach. First, we are just initialising the components of forces using the following commands.

```
FFx1=0;
FFy1=0;
```

Then as mentioned previously, the two conductors are enclosed in two fictitious contours over which we will evaluate the integration of Maxwell stress tensor.

The integral is evaluated as follows. We will run a FOR loop from i=1 to number of edges. Here, n_edges is the number of edges. The edge numbers of 4 main edges enclosing the first conductor are 9, 10, 11, and 12. Now, consider a global edge whose edge number is 9 and it will have a number of sub edges as shown in the following figure.



These sub edges correspond to the elements attached to edge 9.

The sub edges will form sides of triangular elements. So, when we run a for loop from i=1 to n_edges, we are basically going over all the sub edges. If the sub edge under consideration is lying either on 9, 10, 11 or 12th main edge then we are integrating MST for conductor 1. In nodes1 column vector we take node number of the corresponding sub edge using the following code because the second and third rows of e matrix will have starting and ending node numbers.

```
nodes1=e(2:3,i);
```

Then using the following two commands we get the *x* and *y* coordinates of the end points of the sub edge under consideration.

```
Xe=p(1,nodes1');
Ye=p(2,nodes1');
```

The mid point of each edge is calculated by taking the average of *x* and *y* coordinates of the end points as given below.

```
Xm = sum(Xe)/2;
Ym = sum(Ye)/2;
```

By using the following command we can find the length of the corresponding sub edge.

```
dl = sqrt(((Xe(2)-Xe(1))^2)+((Ye(2)-Ye(1))^2));
```

Then we have to find in which triangular element the midpoint of the sub edge under consideration lie. After determining the triangular element number in which that midpoint lies we can get the corresponding B_x,B_y, and B_{net} values of that triangle.

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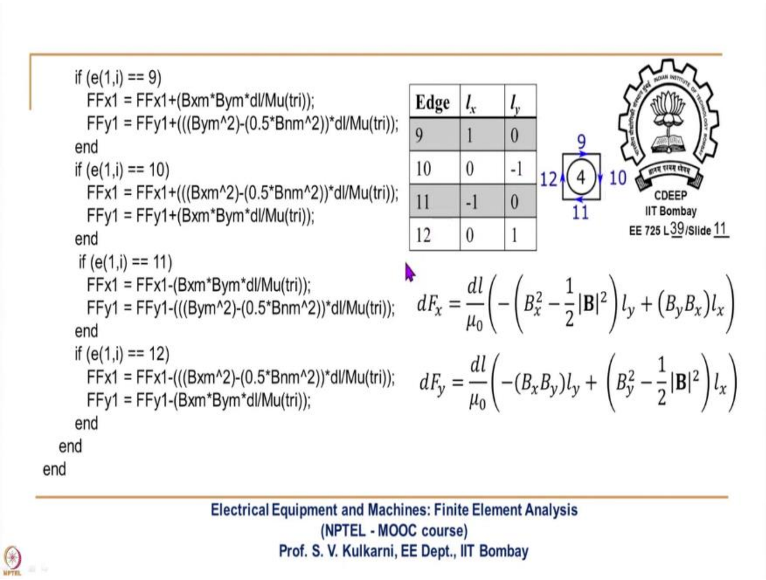
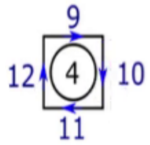


So, now let us see how we can calculate forces. Depending on the orientation of sub edge or on which global edge it is lying we will execute the sets of commands given in the above slide. For example, if the sub edge is lying on edge 9 then $l_x = 1$ and $l_y = 0$ because $\hat{\mathbf{a}}_t$ is directed as indicated in the following figure.



So, any sub edge on edge 9 is along *x* direction, so $l_x = 1$ and $l_y = 0$.

If $l_x = 1$ and $l_y = 0$, then the expression of force will be modified as given below

$$dF_x = \frac{dl}{\mu_0}(B_y B_x) l_x$$
$$dF_y = \frac{dl}{\mu_0}\left(B_y^2 - \frac{1}{2}|\mathbf{B}|^2\right) l_x$$

The above equations are valid for any sub edge along the edge 9. These equations are coded as given below.

```
if (e(1,i) == 9)
  FFx1 = FFx1+(Bxm*Bym*dl/Mu(tri));
  FFy1 = FFy1+(((Bym^2)-(0.5*Bnm^2))*dl/Mu(tri));
end
```

So, this is how we can calculate *x* and *y* components for any sub edge which is part of edge 9. Similarly, using the following code we can calculate the components for all other sub edges if they are lying on edge 10, 11 or 12.

```
if (e(1,i) == 10)
  FFx1 = FFx1+(((Bxm^2)-(0.5*Bnm^2))*dl/Mu(tri));
  FFy1 = FFy1+(Bxm*Bym*dl/Mu(tri));
end
 if (e(1,i) == 11)
  FFx1 = FFx1-(Bxm*Bym*dl/Mu(tri));
  FFy1 = FFy1-(((Bym^2)-(0.5*Bnm^2))*dl/Mu(tri));
end
if (e(1,i) == 12)
  FFx1 = FFx1-(((Bxm^2)-(0.5*Bnm^2))*dl/Mu(tri));
  FFy1 = FFy1-(Bxm*Bym*dl/Mu(tri));
end
```

Remember, for edge 10 which is vertically down, $l_x = 0$ and $l_y = -1$ because it is in $-y$ direction. Similarly, for edges 11 and 12.

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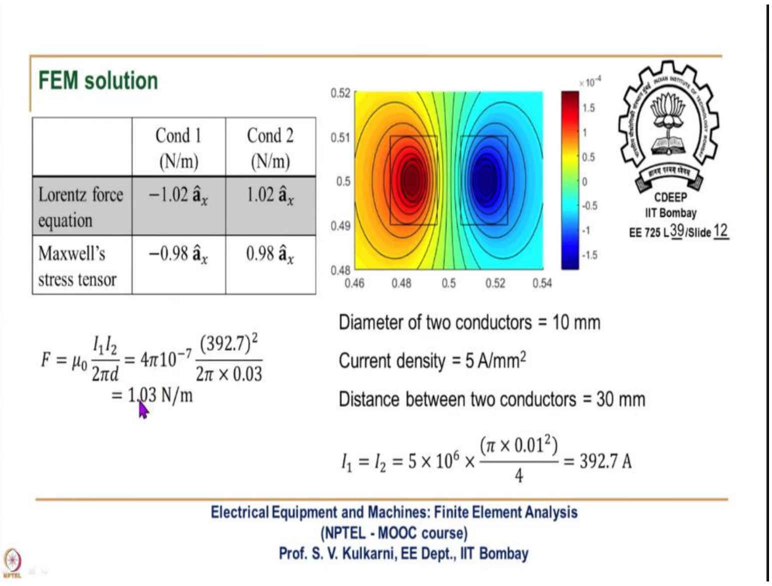
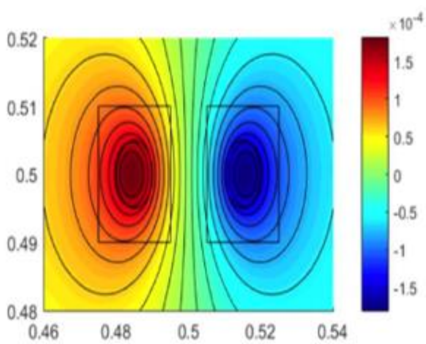


Now, we will compare the solutions for both methods: Lorentz force equation and Maxwell stress tensor. Also, we will compare the forces calculated using an analytical formula. The force values calculated using Lorentz force equation and MST methods are given in the following table.

	Cond 1 (N/m)	Cond 2 (N/m)
Lorentz force equation	$-1.02\ \hat{\mathbf{a}}_x$	$1.02\ \hat{\mathbf{a}}_x$
Maxwell's stress tensor	$-0.98\ \hat{\mathbf{a}}_x$	$0.98\ \hat{\mathbf{a}}_x$

The values calculated using both methods are quite close to each other which confirms that the MST approach is validated. For the two conductors in the problem domain, we are assuming that currents are in opposite directions. So the field will be as shown in the following figure.



Since the currents are in opposite directions, the conductors will repel each other. That is why we are getting forces in opposite directions. From the above table, we can say that the force on conductor 1 is in $-x$ direction and on conductor 2 the force is in $+x$ direction. The analytical formula to calculate force is

$$F = \mu_0 \frac{I_1 I_2}{2\pi d}$$

The above equation gives the force between two parallel conductors. Since we are calculating per unit depth (2D approximation) the length in z direction is 1. So, if we substitute the values then we get this as 1.03 N/m.

In this example, the diameter of two conductors is taken as 10 mm, current density is assumed as 5 A/m^2, and the distance between two conductors is 30 mm. So, currents I_1 and I_2 will be calculated as given below

$$I_1 = I_2 = 5 \times 10^6 \times \frac{(\pi \times 0.01^2)}{4} = 392.7 \text{ A}$$

So, if we substitute the values of I_1, I_2, and the distance d as 0.03, we get the value of force as 1.03 N/m which again is quite close to the values calculated using Lorentz force and MST methods. This comparison verifies our calculation methods.

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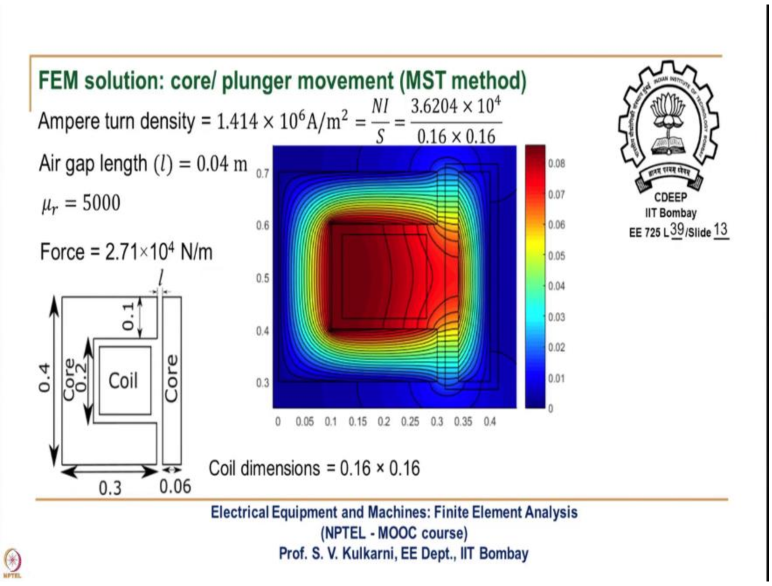
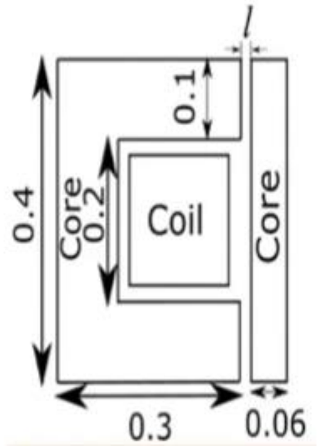
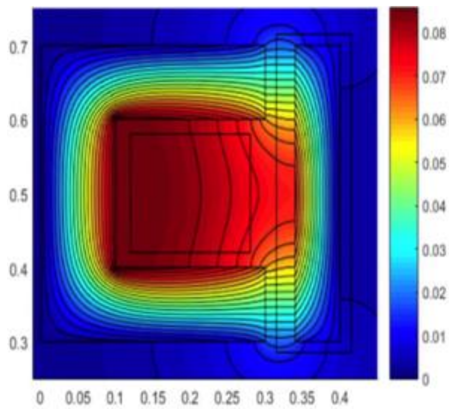


Finally, we will also calculate the force on the following core or plunger by using the MST method.



Here, there is one C shaped core, a movable core piece, which can be called as plunger, and a coil. When we pass current through the coil, flux shown in the following figure is established and the C shaped core will attract the rectangular core piece.



If north pole appears on the C core then there will be south pole on the core plunger and the two opposite poles will attract each other.

Now, we will enclose the plunger piece by a fictitious contour and integrate MST over this contour. In the above figure, the dimensions of the air gap length is specified as 40 mm. The value of μ_r for the core material is taken as 5000 and the other dimensions are given in the previous figure.

So, when we calculate forces using the MST method which was described in this lecture, we get the value of the force as 2.71×10^4 N/m. Again remember that the calculated force is in per metre depth because we are using 2D approximation. So, we will solve the same plunger problem using the virtual work method in next lecture. Thank you.

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L39: Review Questions

Q1. Why the Lorentz force equation cannot be used to calculate saliency forces?

Q2. Why local forces cannot be calculated by using the MST method?

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Electrical Equipment and Machines: Finite Element Analysis
(NPTEL - MOOC course)
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