Electromagnetic Forces on Stator Teeth

SyMSpace Days

September 18-19, 2024

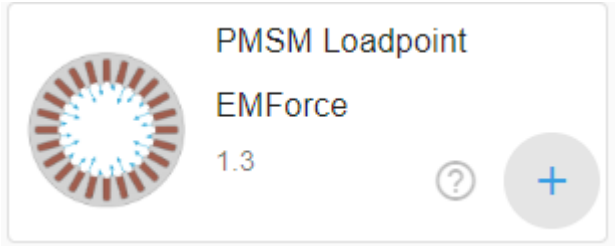
NVH Simulation Workflow

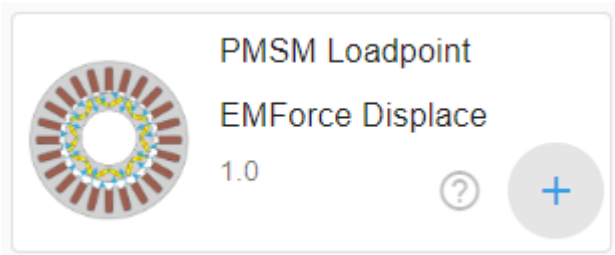
Setup of Workflow

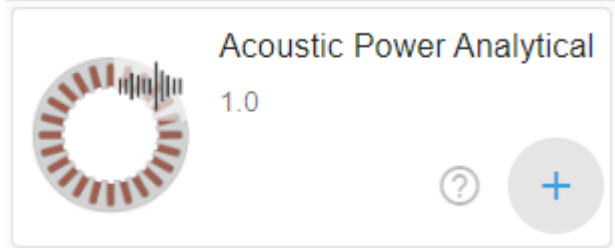
- Force excitation of stator teeth can be calculated using the component *PMSM Loadpoint EMForce.*

- Static and dynamic eccentricity of the stator and rotor can be evaluated using the component *PMSM Loadpoint EMForce Displace.*

- A simplified model for calculating acoustic power (ERP) based on cylindrical shells is available with *Acoustic Power Analytical.*



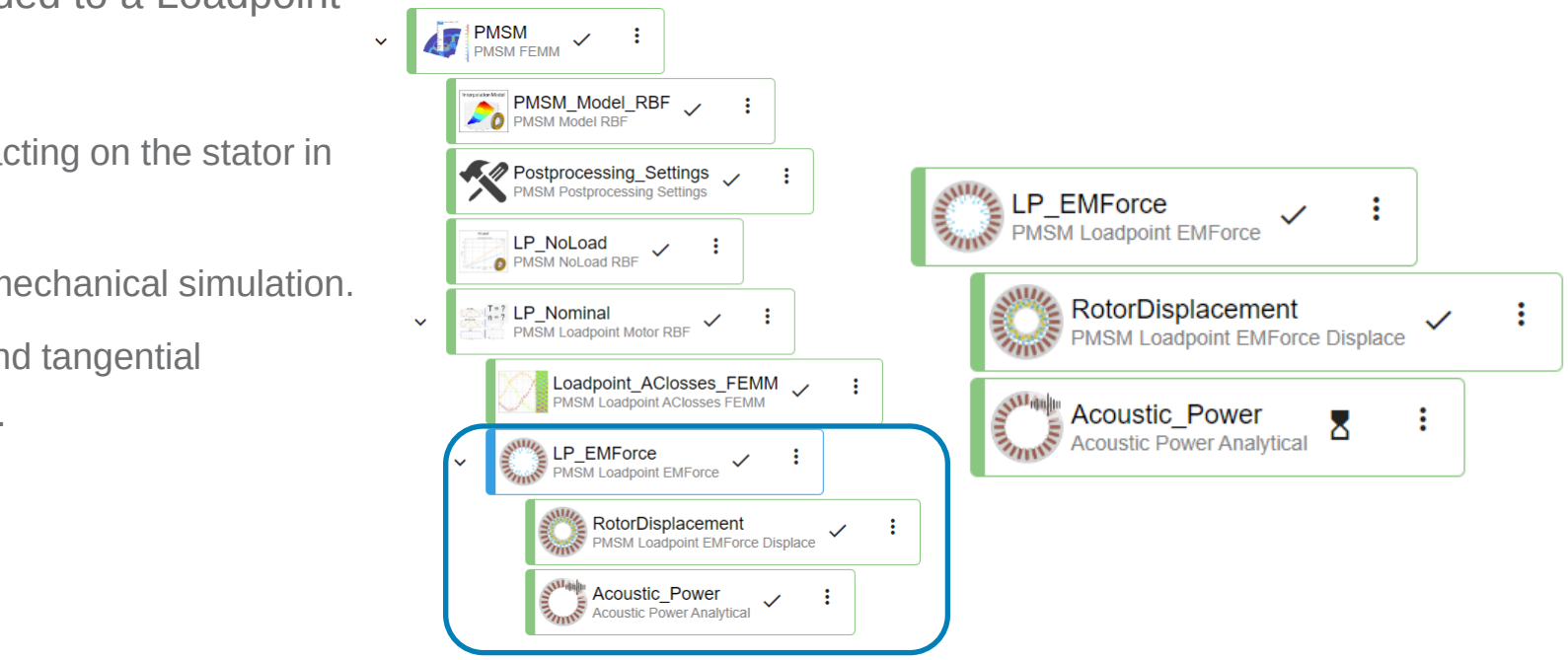




NVH Simulation Workflow

Example: TeslaModel3

- The EMForce component is added to a Loadpoint
- Calculation results:
  - 2D FFT of forces and moments acting on the stator in radial and tangential directions.
  - CSV table for data exchange in mechanical simulation.
  - Visualization of forces in radial and tangential directions for each skewing layer.



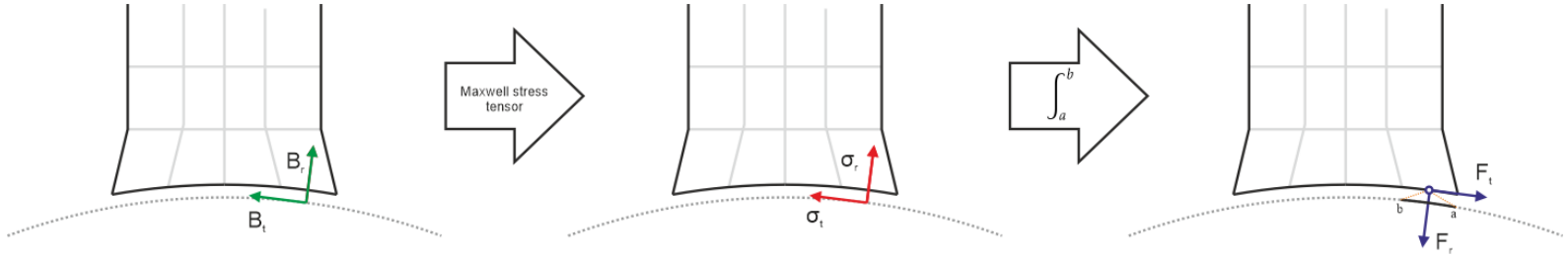
Force Calculation

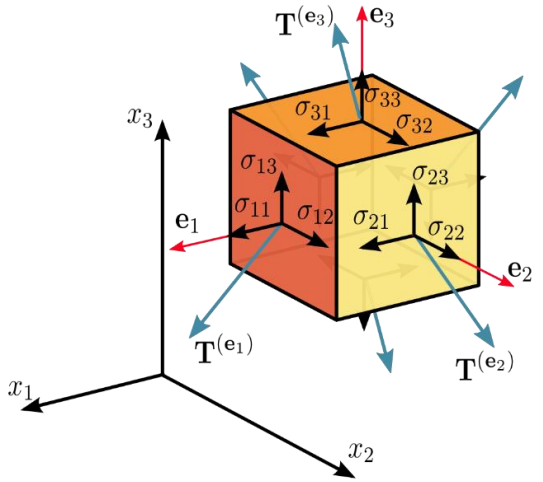
Calculation of the force on an element of the stator tooth

PMSM Loadpoint
EMForce
1.3

- The flux density in the air gap is used to calculate the stress on the stator surface using the Maxwell stress tensor.
- By integrating the stress over an element, the radial and tangential components of the force are determined.

$$\bar{S} = \frac{1}{\mu_0}\begin{bmatrix} B_x^2 - B^2/2 & B_xB_y & B_xB_z \\ B_xB_y & B_y^2 - B^2/2 & B_yB_z \\ B_xB_z & B_yB_z & B_x^2 - B^2/2 \end{bmatrix} \qquad B^2 = B_x^2 + B_y^2 + B_z^2$$

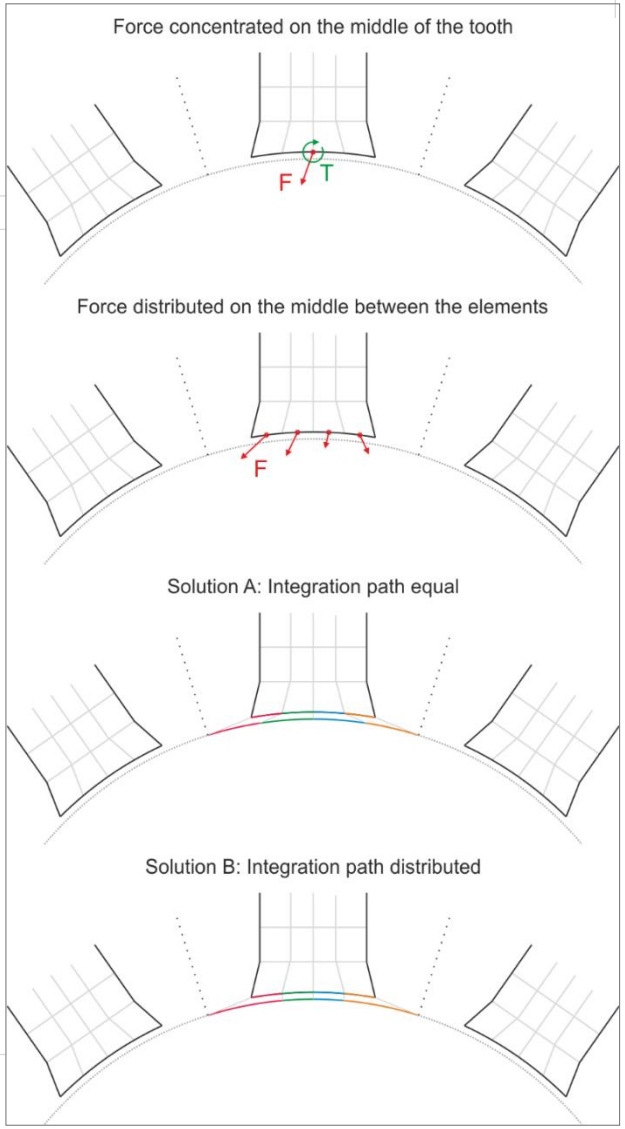




Force Calculation

Integration Methods

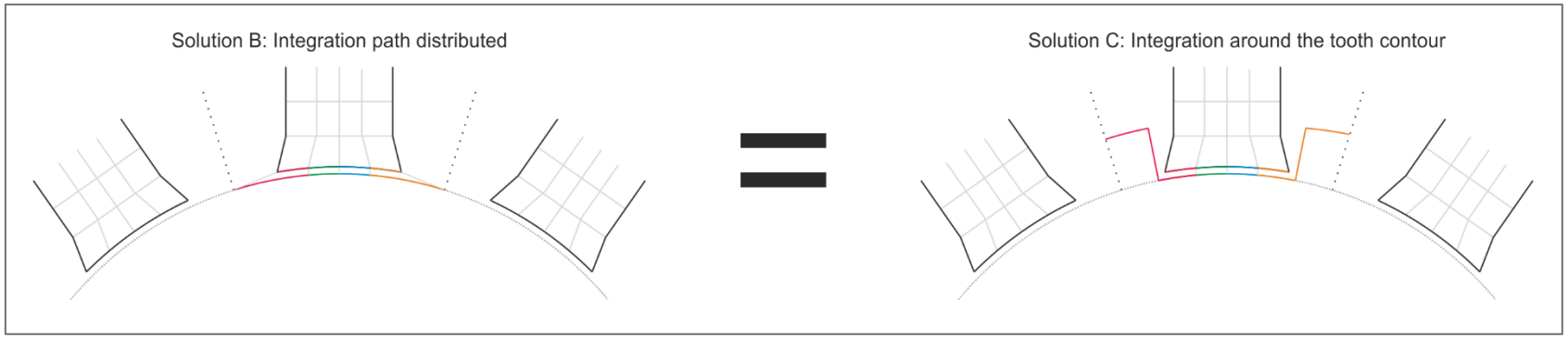
- The mapping of the electromagnetic forces to the mechanical simulation software can be done in different ways
  - Mapping of a single force and torque per tooth
  - Mapping of forces onto tooth surface elements
- The number of force vectors per tooth depend on the tangential mesh density
  - Example on the right has 4 elements per tooth
  - The forces are computed by integrating the radial and tangential stress acting on the tooth
  - Solution B will be used as the stress integrated over the slot opening is acting upon tooth edge
    - This method was verified by stress integration around the tooth.



Force Calculation

Force integration path

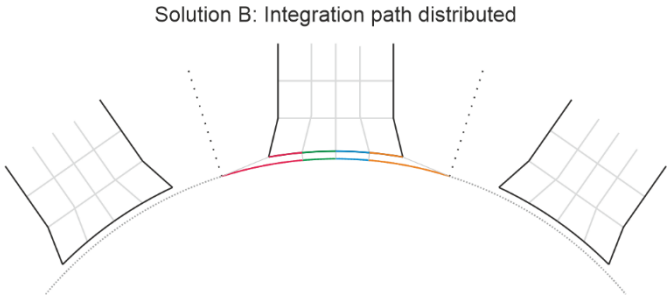
- The force integration should be performed along the tooth surface.
- The integration path on an arc in the air gap yields equivalent results.
  - Evaluation is simplified since results only need to be determined on an arc in the air gap.
  - Meshing of the air gap can be adjusted to improve the accuracy of the calculation results.

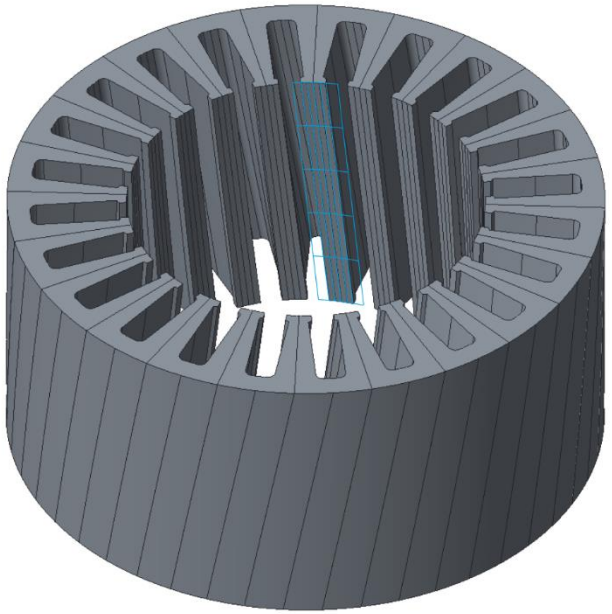


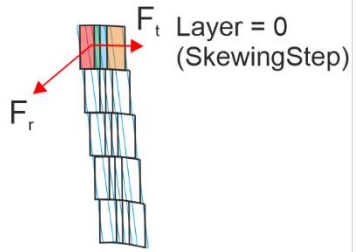
Force Calculation

Forces on different skewing layers

- The stator tooth is divided into *n_nodes* (circumferential direction) and *n_layers* (skewing_steps).
- Forces are integrated over the surface according to the figure.
- The points of force application are the midpoints of the surfaces on the tooth.



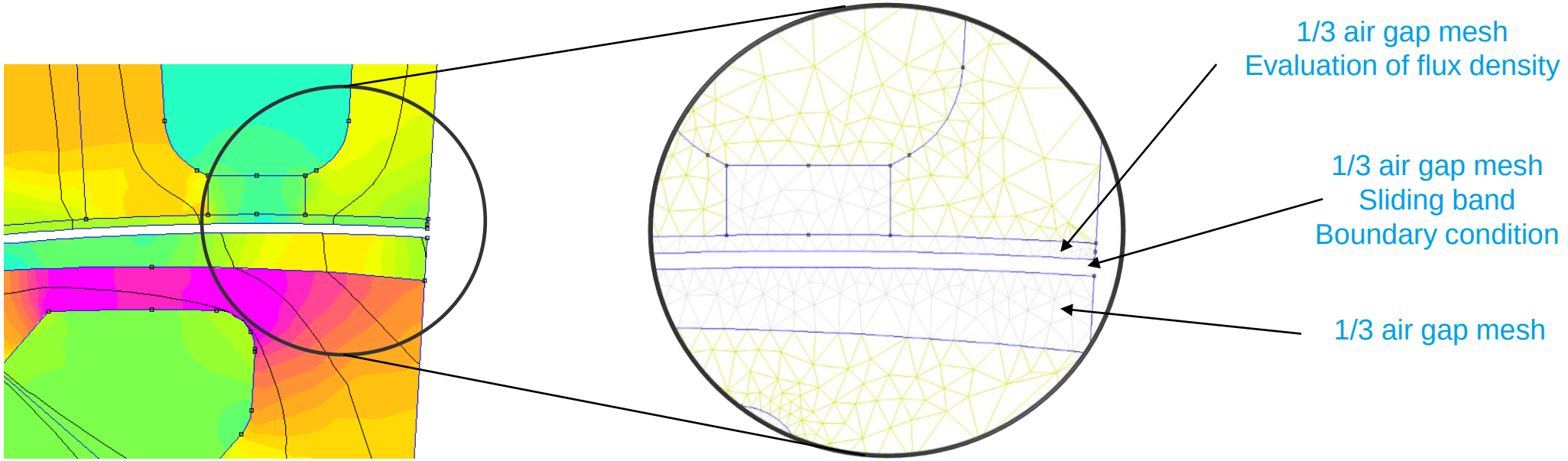




Air Gap Meshing

Three mesh layers

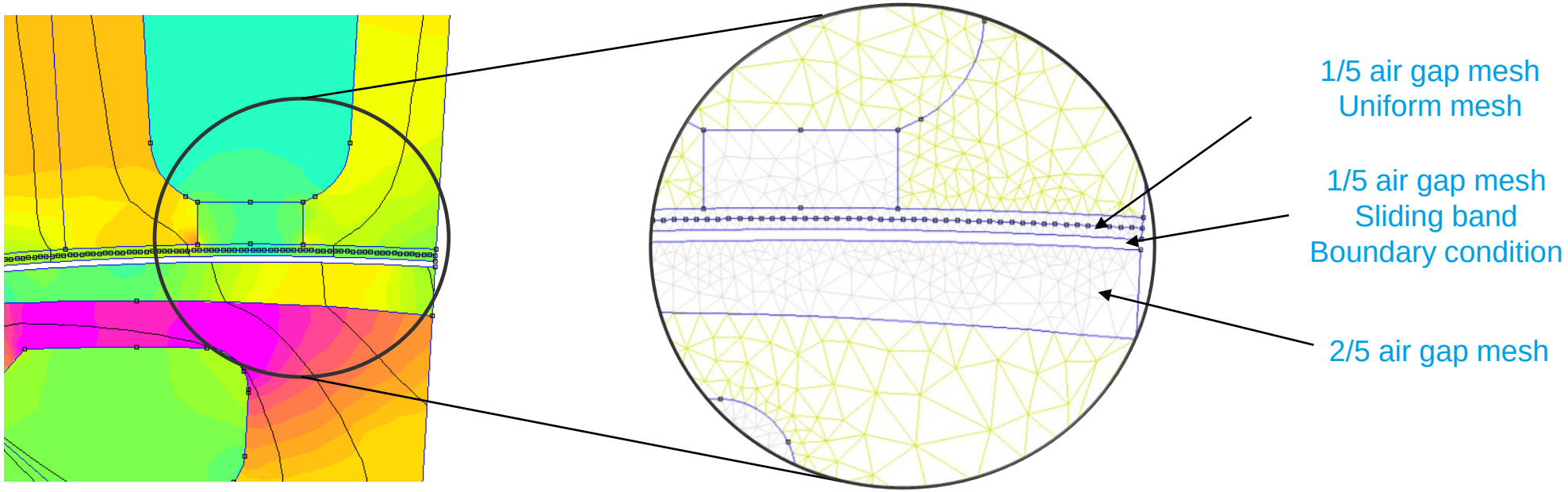
- Air gap is divided into three mesh layers
- Parameter *Stress_Settings.EquidistantAirgapMesh* set to *False*



Air Gap Meshing

Five mesh layers

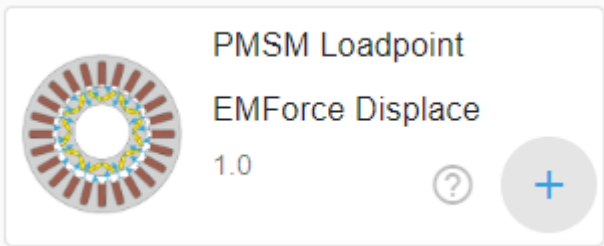
- Air gap is divided into five mesh layers
- Parameter *Stress_Settings.EquidistantAirgapMesh* set to *True*



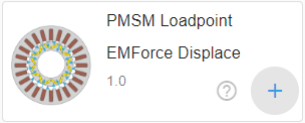
Force Calculation

Advanced settings

- The NVH behavior of the motor is significantly influenced by certain operating parameters:
  - Currents in d- and q-direction.
    Parameters *ild* and *ilq* are linked to load point results (or can be set manually).
  - DC component in the phase currents.
    This parameter can be set by *Idc_percent* (DC current in percent of RMS terminal current)
- Mechanical tolerances e.g. displacement of stator or rotor cause additional harmonics in the force spectrum.
  - A mechanical displacement of the rotor or stator is calculated by inserting the *EMForce Displace* component.
  - Select *Mode = Stator* for stator displacement (static eccentricity)
    Mode = Rotor for rotor displacement (dynamic eccentricity)



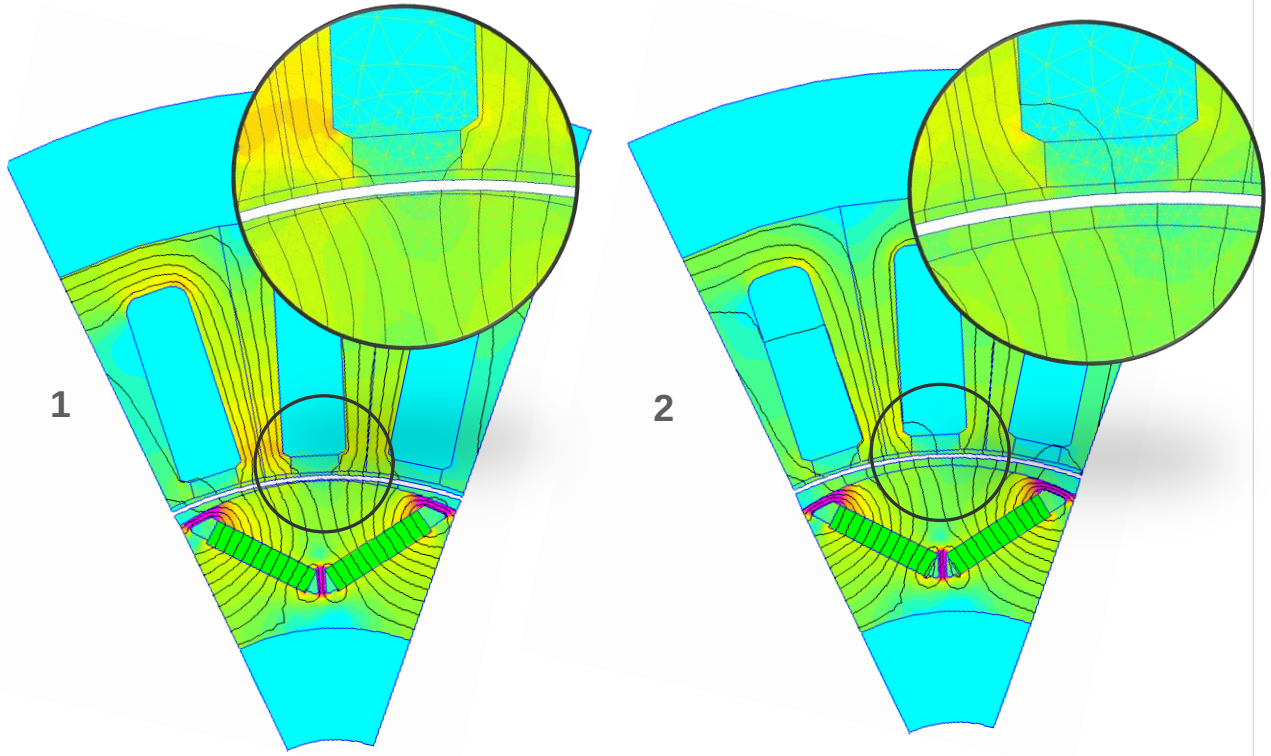
Force Calculation for Rotor / Stator Displacement



Simplified simulation method

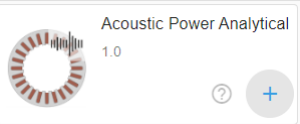
- Two additional FEMM simulations are performed for the sector:
  1. The rotor is shifted upward by the eccentricity to reduce the air gap.
  2. The rotor is moved downward by the eccentricity to increase the air gap.

- For a stator or rotor displacement, the flux density as a function of rotor position is interpolated between the increased air gap, the nominal air gap, and the decreased air gap.



Noise Calculation

Simplified analytical model

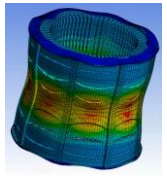


- Noise calculation base on cylindrical shell elements.

  “Noise of Polyphase Electric Motors” by Jacek F. Gieras, Chong Wang, Joseph Cho Lai; ISBN: 0-8247-2381-3

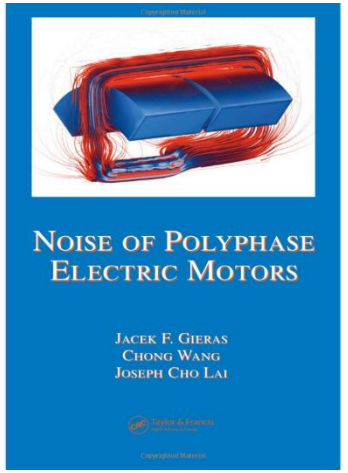
- Calculation of ERP (Equivalent Radiated Power) based on simplified calculation of natural frequencies of shell elements.
  - Natural frequencies are evaluated for different modes

Mode 0: Breathing mode 



Mode 2: 

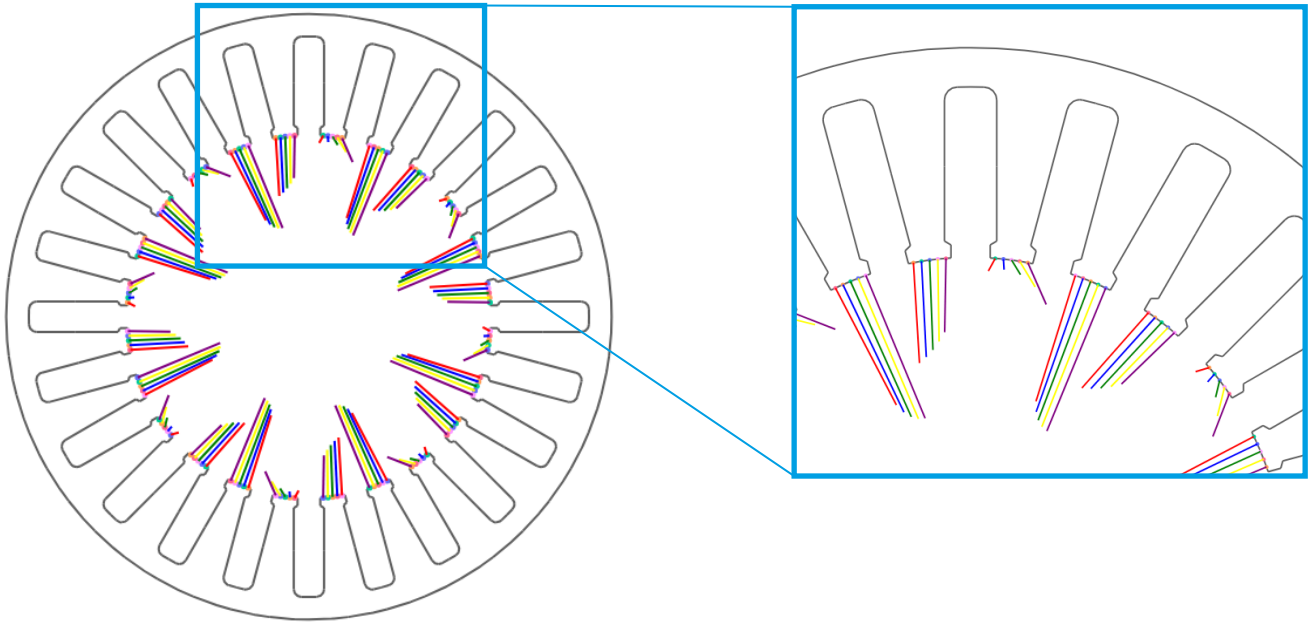
Mode 3: 



Force Calculation

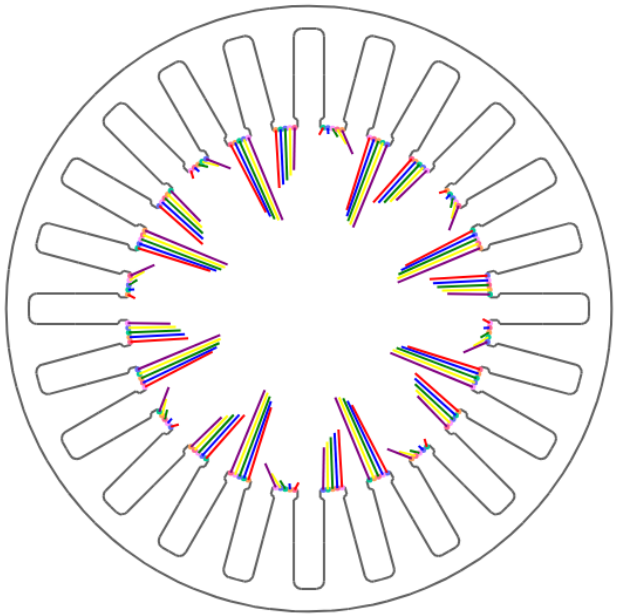
Example: Stator with 24 slots

- Number of slots: 24
- Number of pole pairs: 4
- Number of nodes per tooth: 1
- Number of skewing steps: 5
- Skewing angle: 30°
- Type of skewing: quasi-continuous

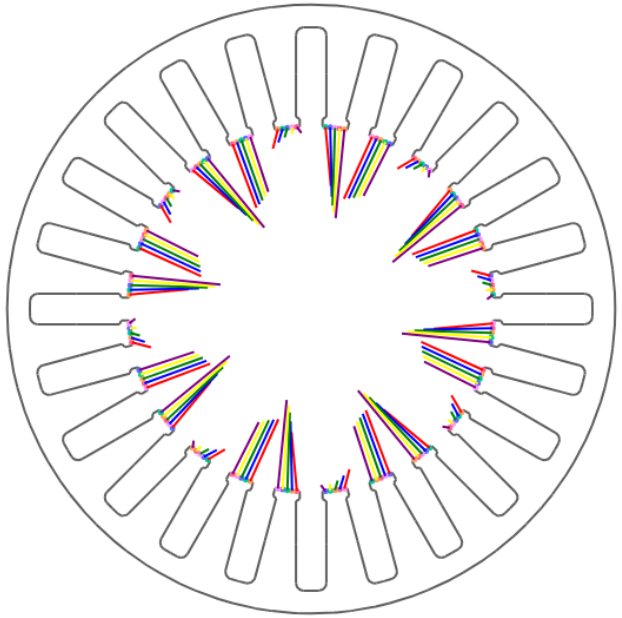


Force Calculation

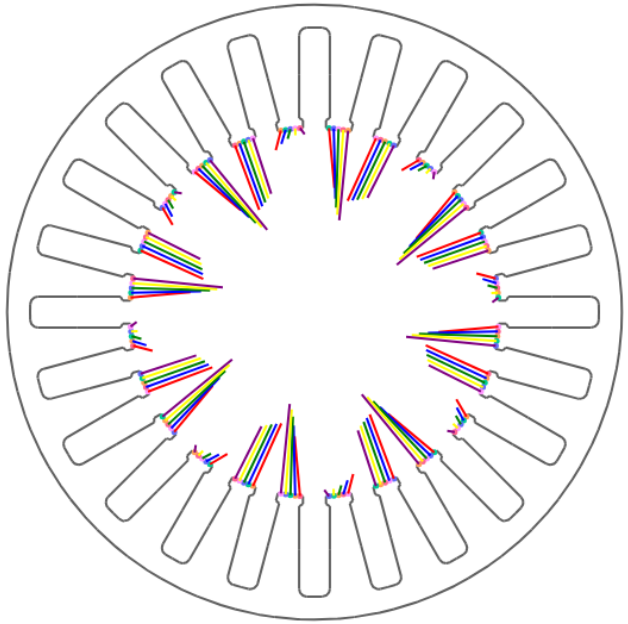
Example: Stator with 24 slots



Rotor angle: 0°



Rotor angle: 45°



Rotor angle: 90°

Force Calculation

2D FFT of the radial force component

- Values in the table correspond to the amplitudes of the respective force components.
- Rows represent the orders of the temporal component (i.e., rotor rotation).
- Columns correspond to the mechanical modes.

- Order 0 and Mode 0 correspond to the radial magnetic force on the stator surface.

	Mode 0	Mode 8
Order 0	301.84153	1.40646
Order 8	0.59538	1.31262
Order 16	0.43806	41.19042
Order 24	3.81983	0.16582
Order 32	0.05192	0.03018
Order 40	0.01571	0.30042
Order 48	0.01527	0.00069
Order 56	0.00632	0.01069

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