PARTNERSHIP FOR ADVANCED COMPUTING IN EUROPE

Vibroacoustic Simulation of Claw Pole Generator

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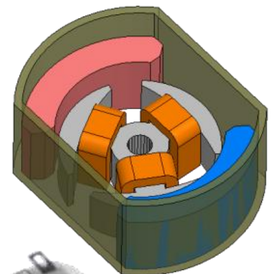
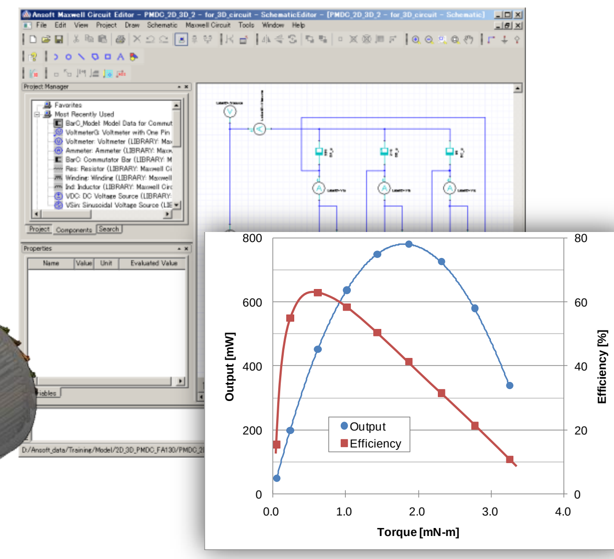
CAPACITIES

e-infrastructure

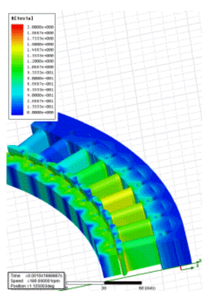
ANSYS Maxwell: Motor Simulation Overview

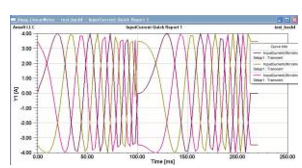
- Motor performance analysis by Maxwell, RMxprt
- Coupled with Simplorer for Motor Control

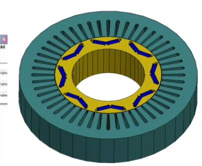


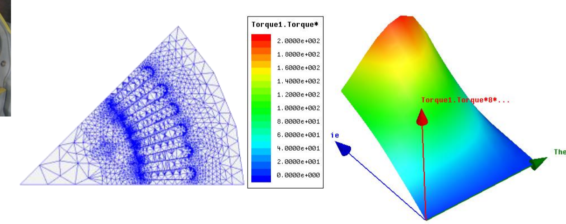


- **DC Motor**
- **Induction Motor**
- **PM Motor**
- **SR Motor**
- **Claw Pole Alternator**
- **Linear Motor**



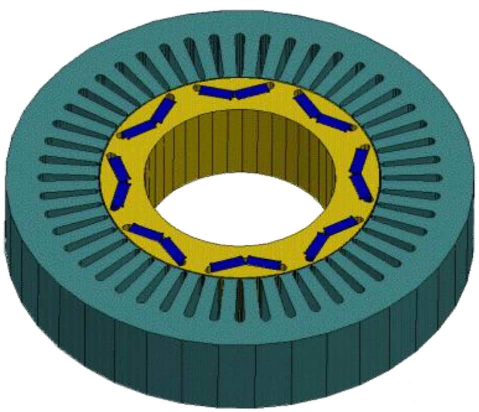


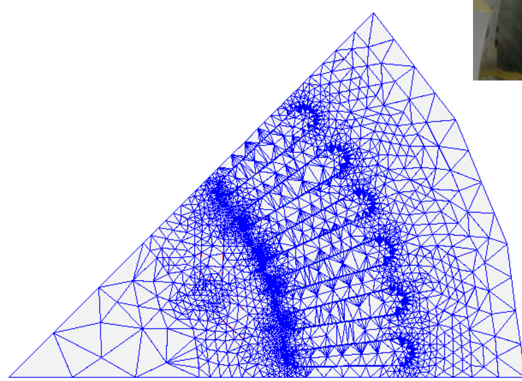


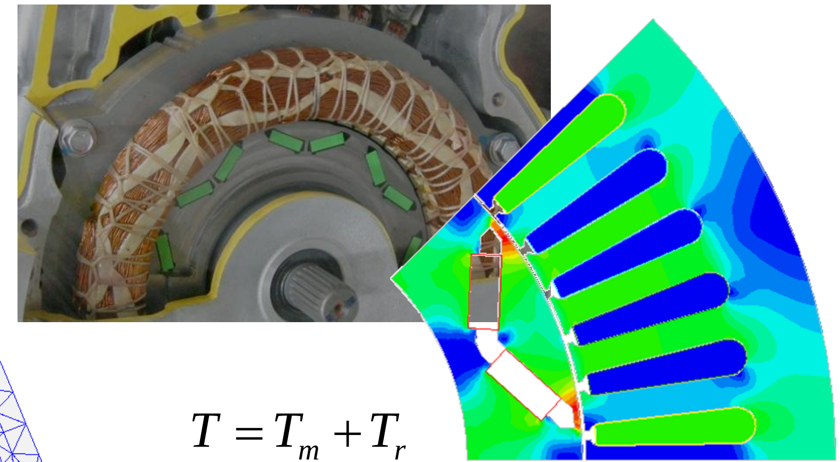


ANSYS Maxwell: PM Motor

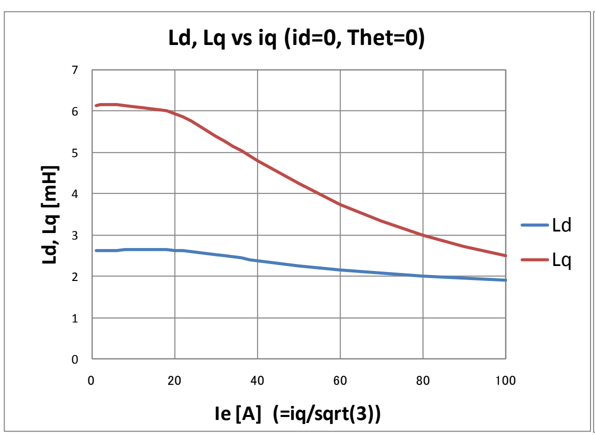
- dq axis Inductance vs Torque

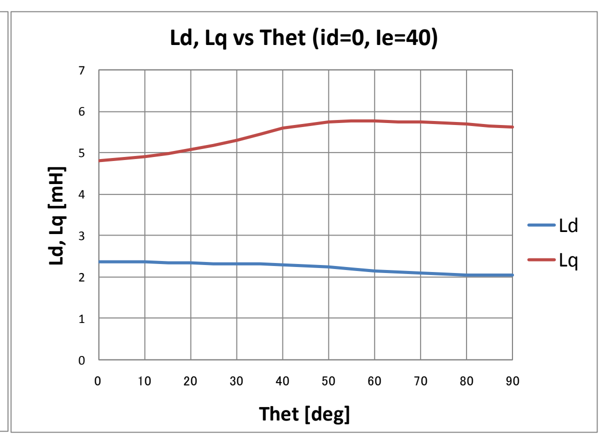


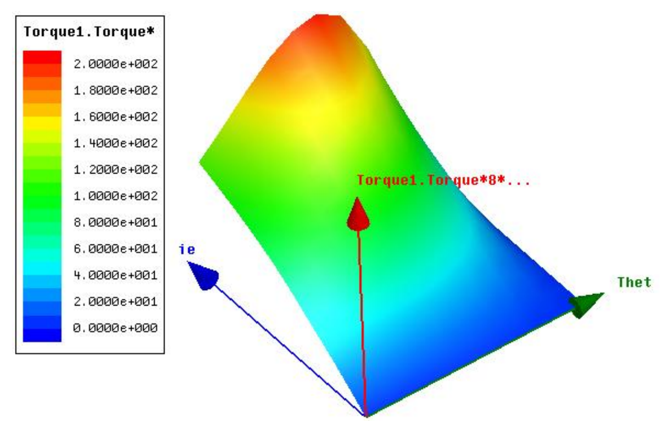




$$T = T_m + T_r = P_n \psi_a I_a \cos\beta + \frac{P_n}{2}(L_q - L_d) I_a{}^2 \sin 2\beta$$

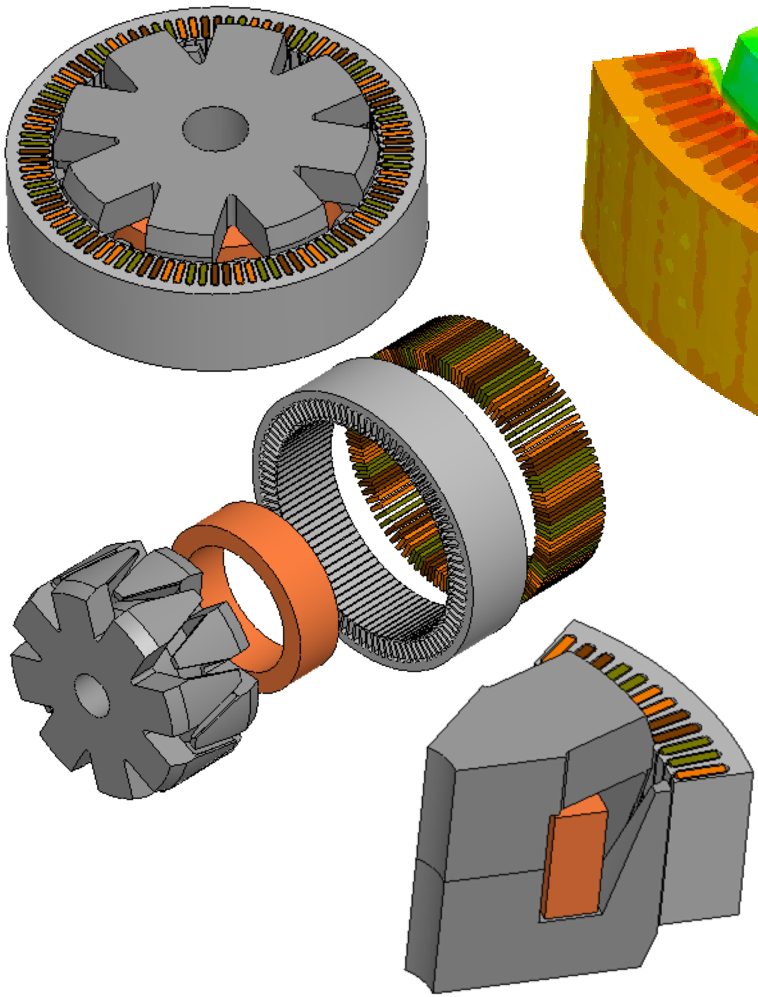


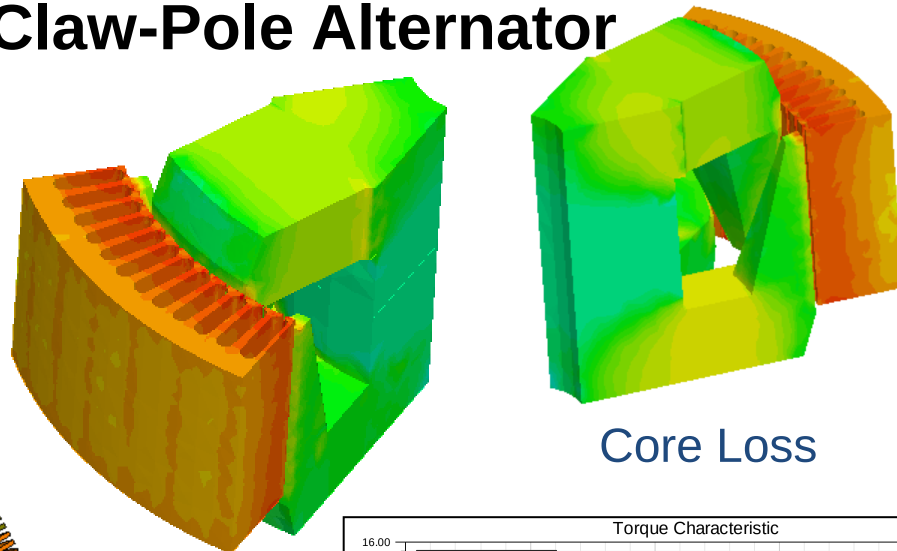


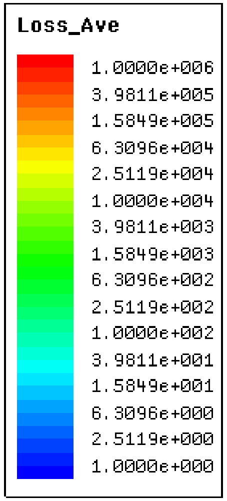


CADFEM

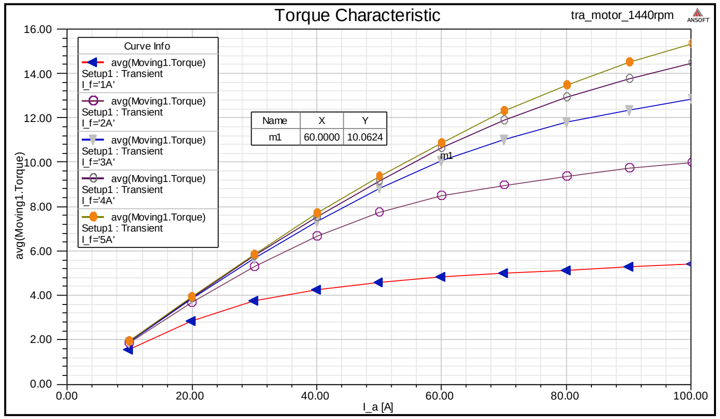
ANSYS Maxwell: Claw-Pole Alternator







Core Loss

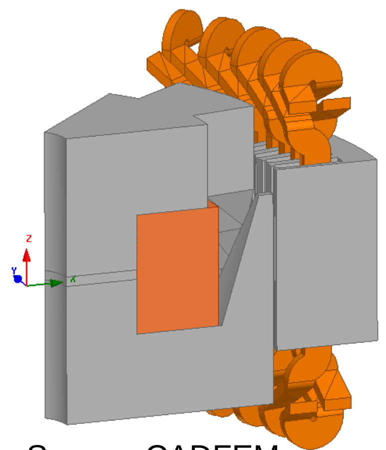


Torque

Shota Takayama, Takashi Abe, Tsuyoshi Higuchi (Nagasaki University), '22 Institute of Electrical Engineers Industry Applications large Heisei, Vol.1 No.Y-101

Object of Interest

- Claw pole alternator
  - Used widely in automotive sector
  - Low cost
  - Starter generator/ power for electronics
- Some machine parameters
  - 5 phase
  - 16 poles
  - 80 slots
  - Integer-slot winding (single layered)
- 5-phase rectifier (full wave)
  - Connects generator to supply system
  - 13.5V voltage level



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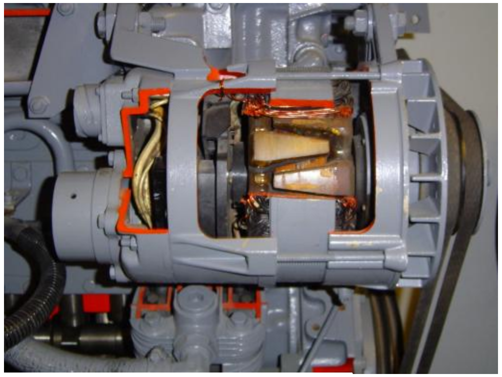
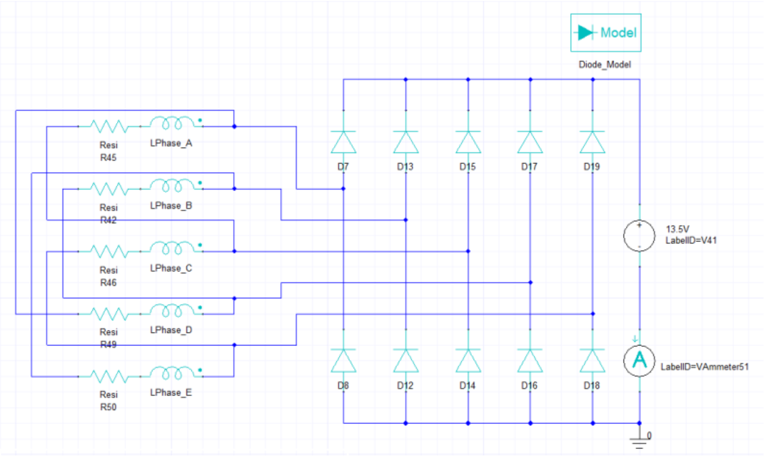


Source: Wikipedia



Source: CADFEM

HANDS-ON

Starter-Generator-Simulation with ANSYS® Maxwell 3D

HANDS-ON-Starter-Generator-Simulation-with-Maxwell3D.docx

CADFEM

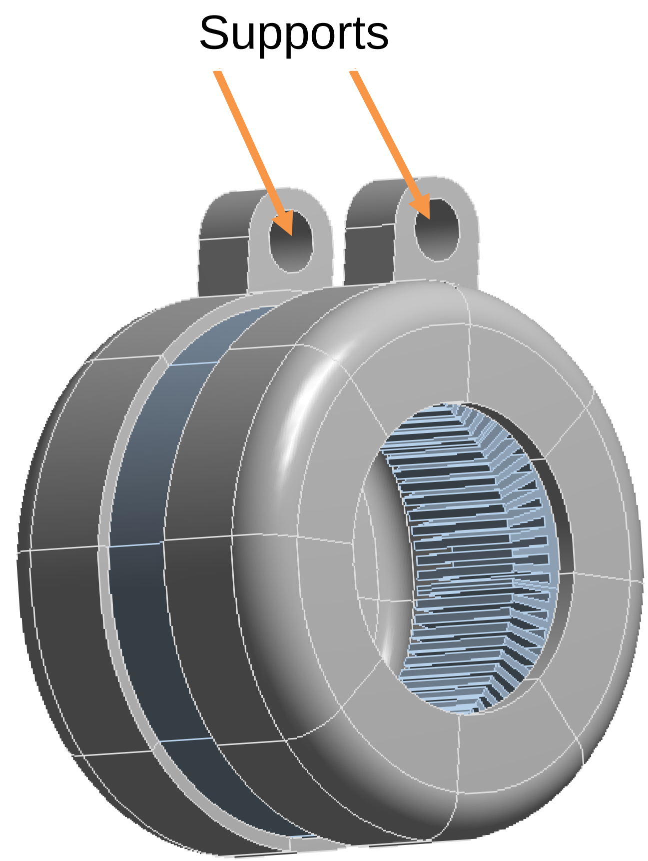
Goal of Analysis

- Predict vibration at the outer housing during operation

- Vibration behavior depends heavily on assembled condition
  - Housing is modeled
  - 2 fixed supports

Input Force ($Amplitude, Frequency, Phase$) → Frequency Response ($mass, damping, stiffness$) → Vibration ($Amplitude, Frequency, Phase$)

$$F(\omega) \quad x \quad H(\omega) \quad = \quad X(\omega)$$

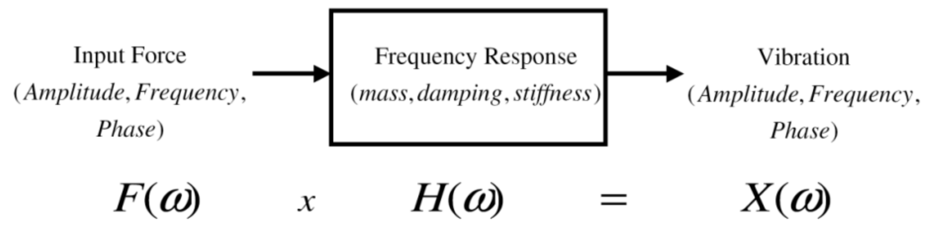


Source: CADFEM

CADFEM

Insight in Theory of Linear Dynamics

- Output depends on two quantities
  - Excitation (input)
  - System characteristics (transfer function)
- Calculation in frequency domain (obtained from Fourier transform)



Source: CADFEM

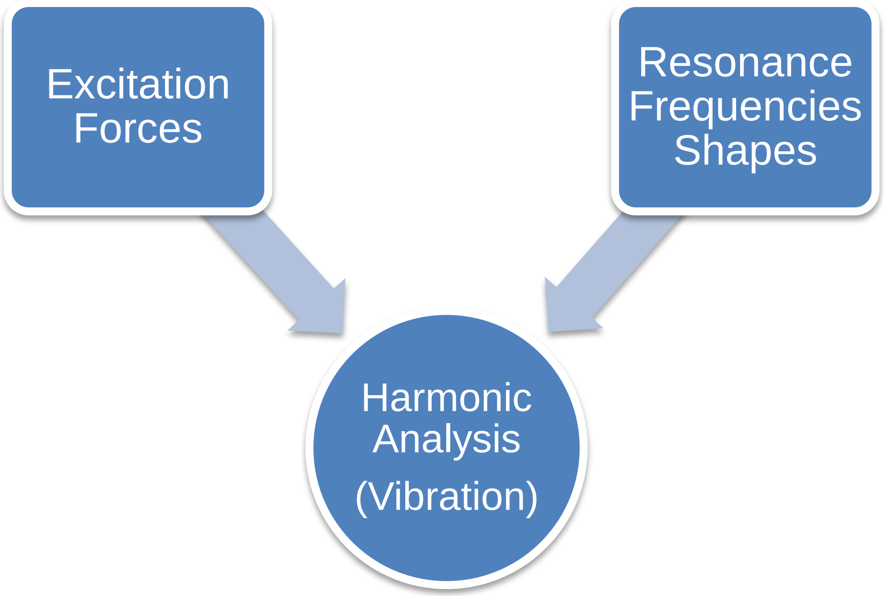
- Output obtained from multiplication of excitation spectrum and transfer function spectrum
- High output values results of:
  - High value of input spectrum
  - High value of transfer function
  - Highest values when both (e.g. resonance)

Tacoma Narrows Bridge (07.11.1940)

CADFEM

Simulation Approach (3 Step-Workflow)

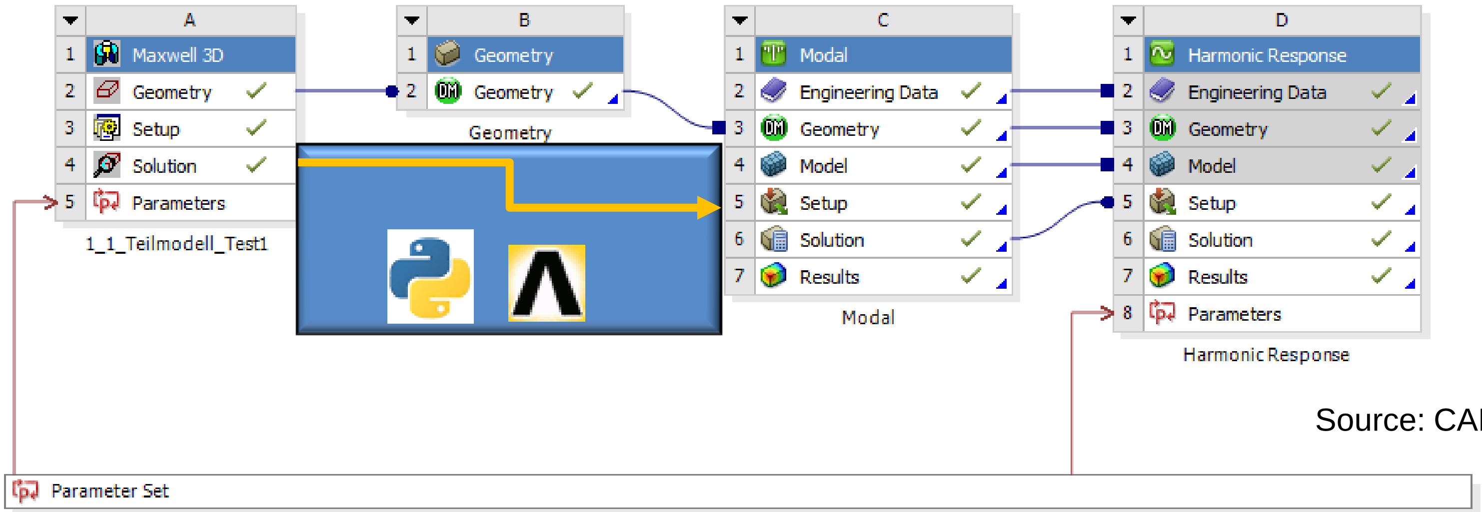
- Transient electromechanical simulation
  - Extraction of excitation forces on stator‘s teeth
- Modal analysis of stator and housing
  - Corresponds to transfer function extraction
- Harmonic analysis
  - Mode superposition
  - Using Extracted excitation forces



Workflow Implementation in Workbench

- Workflow steps are implemented in Workbench environment
  - Visualization
  - Easy geometry share
  - Consistent parameterization

- ANSYS Design Modeler (B) is used to add housing to geometry from Maxwell

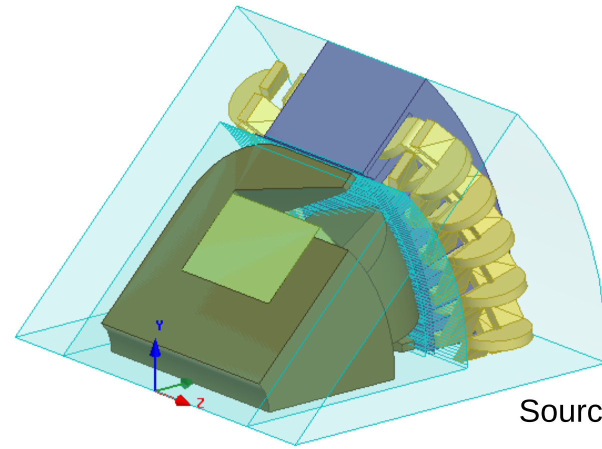


Source: CADFEM

CADFEM

Transient Electromagnetic Simulation inside Maxwell

- 3D geometry of machine
- axis of rotation: global Z-axis
- Simulation setup should include 1 stationary period for force evaluation
  - Period not necessarily always electric period (e.g. fractional slot winding)
- Objective: Extract periodic excitation of stator's teeth during stationary period
  - Available data from simulation: electromagnetic field distribution



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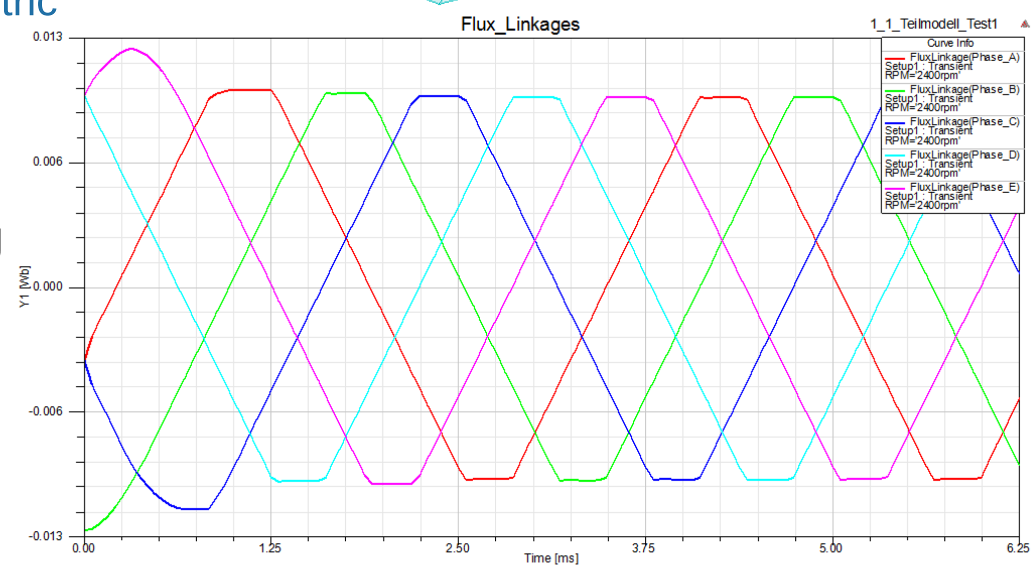


CADFEM

Maxwell Stress Tensor

- Calculation of forces from EM fields
  - Simple situations: Lorentz force law
  - In continua, (2D/3D) becomes more complex
  - Maxwell stress tensor is a powerful tool
    - 2nd order tensor
    - Makes use of tensor calculus
- Tensor product of σ and surface normal is force density
- Straight forward procedure:
  - Compute B/H fields
  - Program expressions for σ
  - Multiplication of σ with normal vector at each point of surface
  - Result: surface force density

Matrix Notation

$$\underline{\underline{\sigma}} = \begin{pmatrix} (H_x \cdot B_x - |B||H|/2) & H_x \cdot B_y & H_x \cdot B_z \\ H_y \cdot B_x & (H_y \cdot B_y - |B||H|/2) & H_y \cdot B_z \\ H_z \cdot B_x & H_z \cdot B_y & (H_z \cdot B_z - |B||H|/2) \end{pmatrix}$$

Index Notation

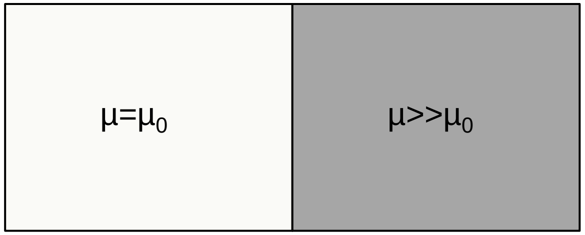
$$\sigma_{ij} = H_i \cdot B_j - \delta_{ij} \cdot B_k H_k / 2$$

$$d\underline{F} = \underline{\underline{\sigma}} \cdot d\underline{A} \quad \text{(3 equations)}$$

CADFEM

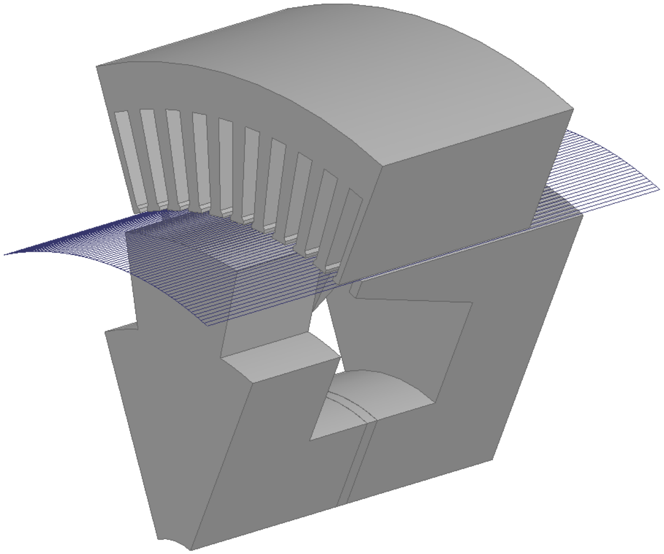
Force Calculation

- Calculation of surface force densities not in real iron to air interface
  - μ is not defined
  - B and H have to be known for σ



Source: CADFEM

- Force densities on virtual surfaces in the air gap
  - Air gap is usually small
  - Good engineering precision
  - Surfaces should be segmented to obtain more accurate results



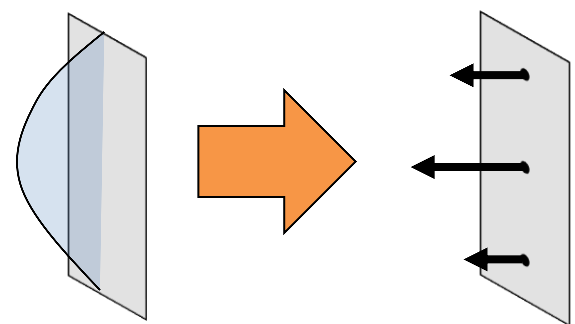
CADFEM

Force Calculation

- Using force densities
  - compute moments of rising order with respect to rotational axis
  - e.g. for k=0 M_k correspond to forces in x, y and z directions
- Goal is to represent force densities through discrete forces (later in Mechanical)
  - Resulting in the same moments until kth order
- In Maxwell we just calculate the Moments until kth order for x,y and z for teeth

$$\underline{M}_k = \int z^k \cdot d\underline{F} \quad (3 \cdot \text{k equations})$$

z- coordinate of d$\underline{F}$



Source: CADFEM

Force Calculation

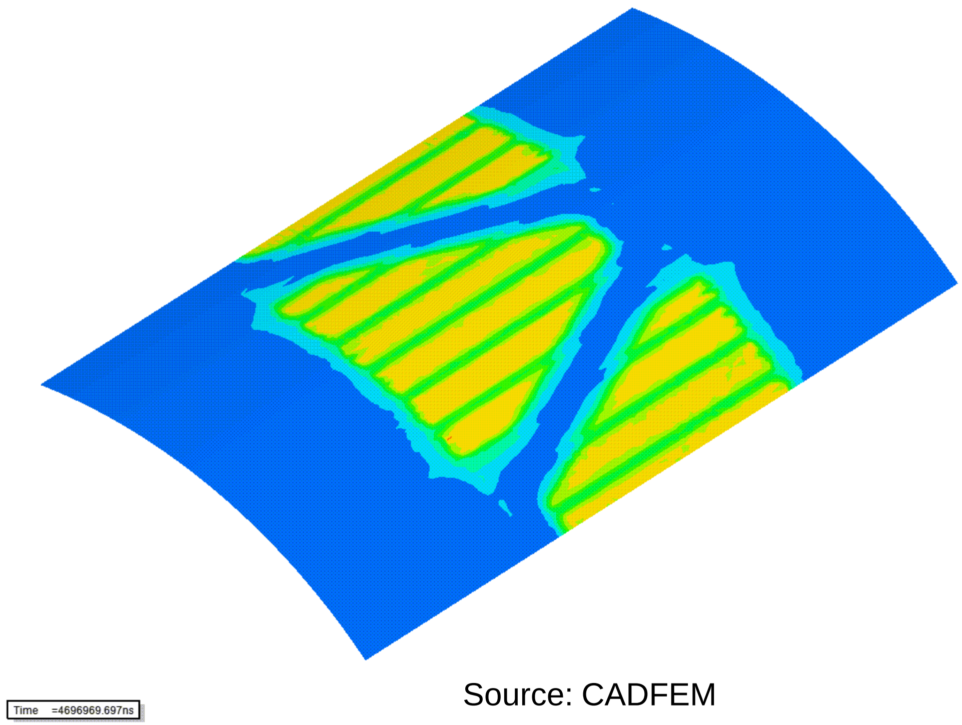
- kth order moments are needed for each stator tooth
  - Simulation during rotation over all relevant teeth
  - Number of files:

$$N_{files} = n_{teeth} \cdot k \cdot 3$$

(x, y, z)

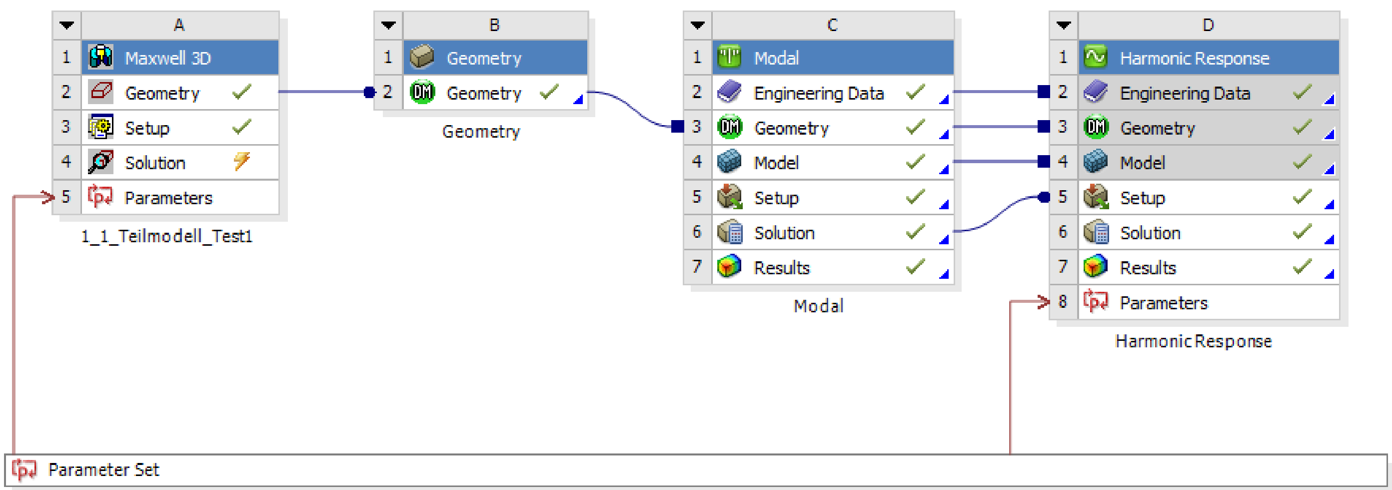
Max. moment order

- Smart approach:
  - Each tooth experiences same fields (in this example)
  - Leads to same force densities
  - Time i.e. phase shifted
  - See animation to the right
- Moment calculation for 1 single tooth



Source: CADFEM

Demonstration



Emvib.wbpz

CADFEM

Implementation in ANSYS Maxwell

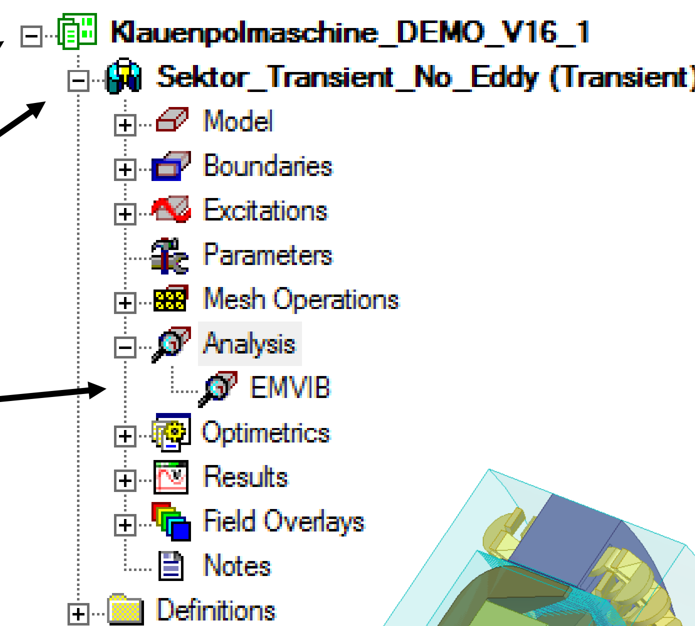
- Steps Recap
  - Define simulation model
  - Define integration surface in air gap
  - Compute B and H fields
  - Use expressions to calculate σ
  - Compute surface force densities
  - Evaluate moments until kth order

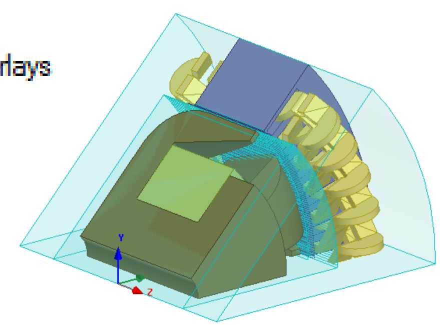
- This results will be exported to be used as excitation
  - Fourier Transform still needed
  - done in Mechanical to apply phase shift manually
  - Use forces of one tooth phase shifted for all (for cyclic cases)

Implementation in ANSYS Maxwell

- Simulation Process is controlled by one Python script
  - Emag_Vibration_FIX.wbjn

- Some adaption can be performed at the header (e.g. file paths)
  - Name of project ("Klauenpolmaschine_DEMO_V16_1")
  - Name design ("Sektor_Transient_No_Eddy")
  - Name of analysis setup ("EMVIB")
  - Path of 2 calculator files
    - Expressions for (σ, $d\underline{E}$, M_k)





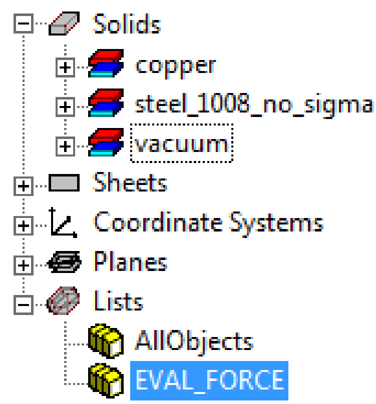
Source: CADFEM

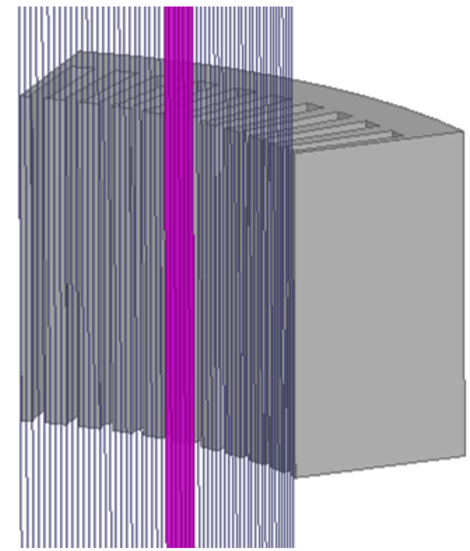
- Required: rotation around global z

CADFEM

Implementation in ANSYS Maxwell

- Define segmented integration surface(s) at air gap
  - Sheet
  - Here: only for one tooth
- Add sheets corresponding to integration surface to object list
  - Required name: EVAL_FORCE
- Specify middle angle of integration surface in script's header
  - Here: 22.5°





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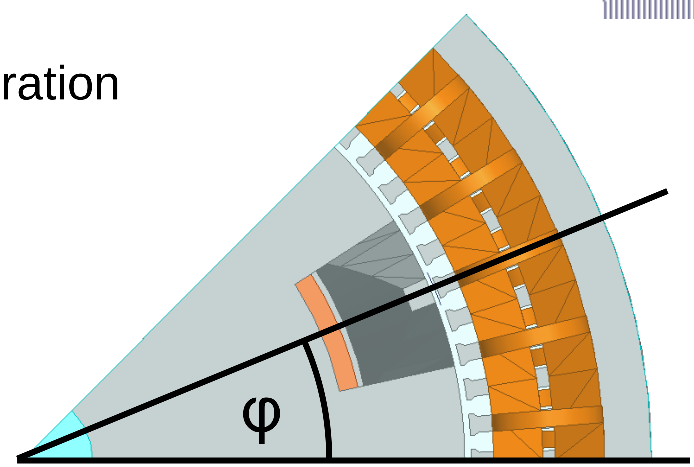
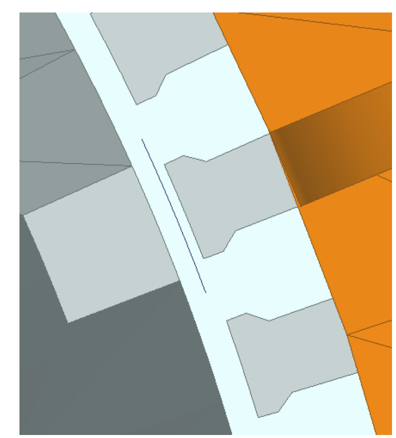




CADFEM

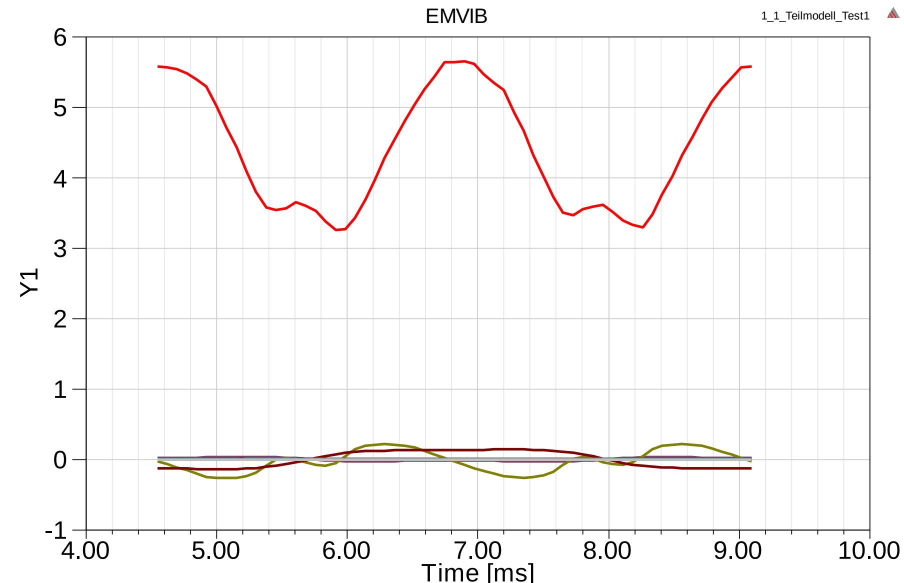
Handling and Export of Moments

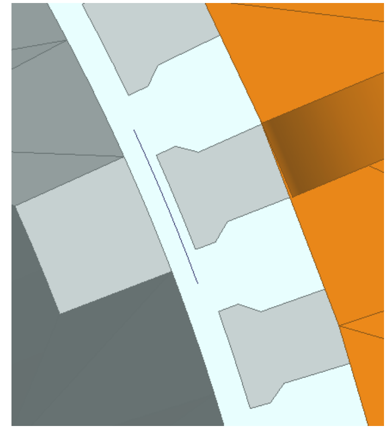
- Moments (up to kth order) are plotted in report
  - Units differ (N, Nm, Nm²…)

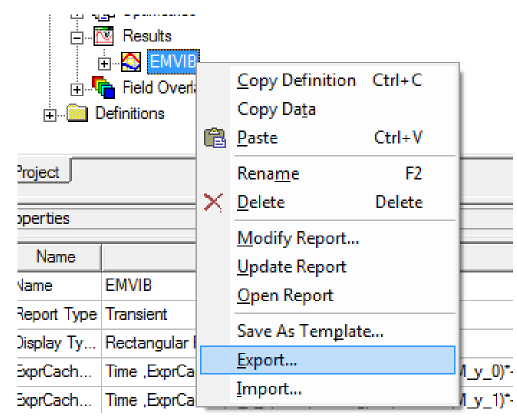
- In this case
  - Moments in z direction unchanged
  - Moments in x and y direction converted
  - Using sin / cos of 22.5°

- Results in Moments in radial, tangential and axial direction for tooth used for force evaluation

- Report content exported as csv file





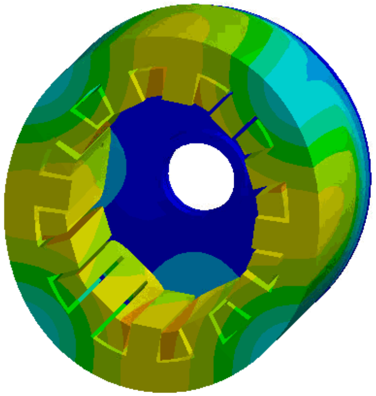


Source: CADFEM

Vibration Simulation

- Description of nodal displacements
  - Two possibilities
  - For each node (magnitude, phase)
  - For each modal shape (magnitude, phase)

$$s_n = \sum_{m=1}^{\text{max mode}} u_{m,n} \cdot s_m$$

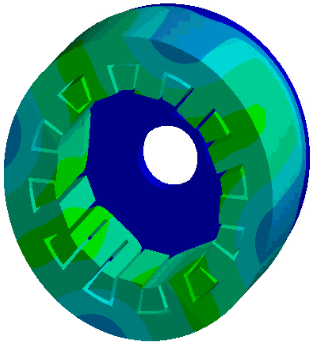


Source: CADFEM

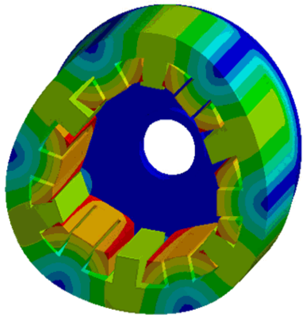
s_n: nodal displacement
s_m: modal displacement
$u_{m,n}$: participation (projection) factor

- Vibration analysis with mode superposition
  - Modal analysis to extract eigenmodes
  - Arbitrary periodic displacements summation of weighted eigenshapes

1st normal mode



4th normal mode



Source: CADFEM

- First step: Modal analysis
  - Calculation of frequencies/shapes

Vibration Simulation

- Velocities squared (mean value) better than displacements
  - Sound power (density)

$$s_n = \sum_{m=1}^{\text{max mode}} u_{m,n} \cdot s_m$$

$$p = c \cdot \rho \cdot v^2_{n,normal,RMS}$$

$$v_{n,normal,RMS} = \omega \cdot \sum_{m=1}^{\text{max mode}} u_{m,n} \cdot s_m$$

$$P = c \cdot \rho \cdot \iint \frac{v^2_{n,normal}}{2} \cdot dA$$

$$v^2{}_{n,normal,RMS} = \omega^2 \cdot \sum_m \sum_{m'} u_{m,n} \cdot u_{m',n} \cdot s_{m'} \cdot s_m$$

- All equations already programmed in scripts
  - $U_{m,m'}$ matrix will be computed in modal analysis for radiating surfaces

$$P = \frac{c \cdot \rho \cdot \omega^2}{2} \sum_m \sum_{m'} s_{m'} \cdot s_m \cdot \iint u_{m,n} \cdot u_{m',n} \cdot dA$$

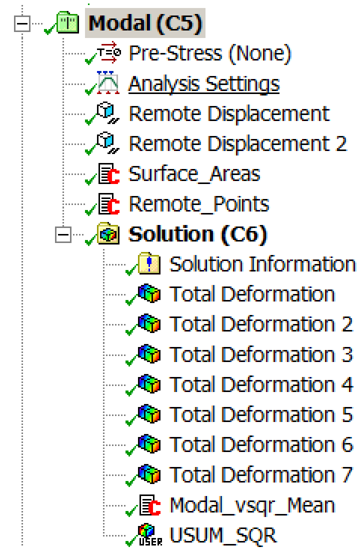
$$P = \frac{c \cdot \rho \cdot \omega^2}{2} \sum_m \sum_{m'} s_{m'} \cdot s_m \cdot U_{mm'}$$

CADFEM

Modal Analysis

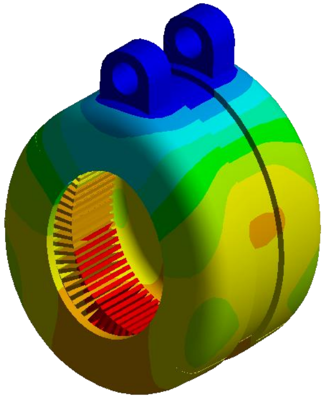
- Additionally to eigenmode extraction
  - Creation of remote points
    - Used later for excitation of teeth
  - Calculation of projection factors
    - Only for surface interface with air
    - Here: outer cylindrical surfaces

- 3 APDL snippets
  - Order of scripts is important
  - Surface Areas
  - Remote Points
  - Modal_vsqr_Mean

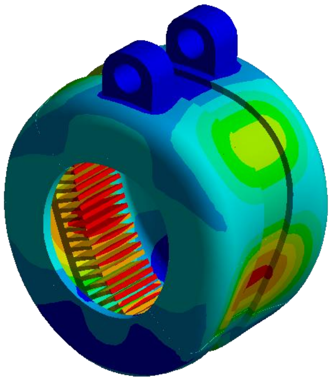


Source: CADFEM

3rd normal mode

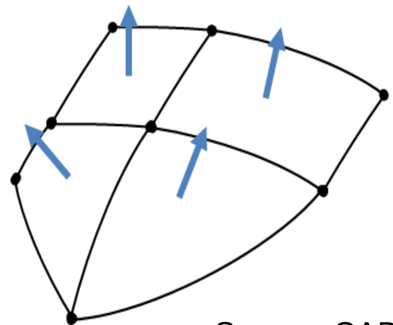


6th normal mode



Modal Analysis (Snippets Functionality)

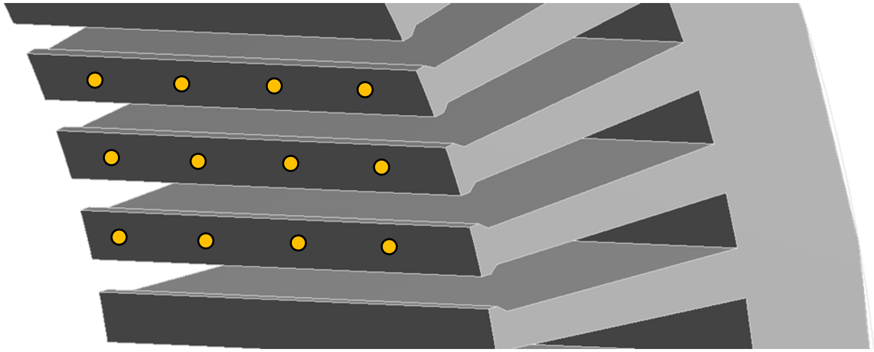
- Surface Areas
  - Needs surface named selection of radiating surfaces
  - Calculates normal vectors for surfaces
    - Magnitude is area
  - Saves data in matrix



Face	nx	ny	nz
1	…	…	…
2	…	…	…
…	…	…	…

Source: CADFEM

- Remote Points
  - Creates excitation points on teeth
  - Here: 4 point/tooth in axial direction
  - Requires number of stator’s teeth as argument 1

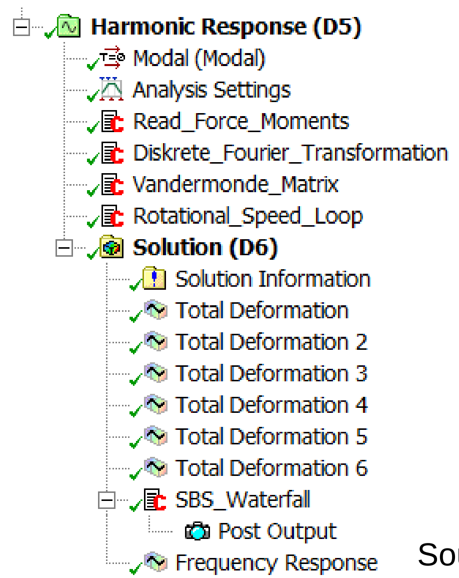


- Modal_vsqr_Mean
  - Calculates participation factors (for velocities squared)
  - No global expansion pass needed

$$P = \frac{c \cdot \rho \cdot \omega^2}{2} \sum_{m} \sum_{m'} s_{m'} \cdot s_m \cdot \boxed{U_{mm'}}$$

Harmonic Response Analysis

- Mode superposition
  - Supports are inherited from modal
- 5 APDL snippets
  - Order of scripts is important
  - 4 for setup
    - Read_Force_Moments
    - Diskrete_Fourier_Transformation
    - Vandermonde_Matrix
    - Rotational_Speed_Loop
  - 1 for post processing
    - SBS_Waterfall



Source: CADFEM

CADFEM

Calculating Excitation for all Teeth

- Kth order Moments are periodic functions (period = T)
  - Fourier series (complex notation)

$$f(t) = \sum_{r=0}^{\infty} a_r \cdot \cos(r\omega t) + b_r \cdot \sin(r\omega t) = \sum_{r=-\infty}^{\infty} c_r \cdot e^{i \cdot r \cdot (2\pi / p) \cdot t}$$

- Different teeth exposed to shifted function

$$f(t-s) = \sum_{r=-\infty}^{\infty} c'_r \cdot e^{i \cdot r \cdot (2\pi/T) \cdot t} = \sum_{r=-\infty}^{\infty} c_r \cdot e^{i \cdot r \cdot (2\pi/T) \cdot (t-s)} = \sum_{r=-\infty}^{\infty} c_r \cdot e^{-i \cdot r \cdot (2\pi/T) s} \cdot e^{i \cdot r \cdot (2\pi/T) \cdot t}$$

$$c'_r = c_r \cdot e^{-i \cdot r \cdot (2\pi / p) s}$$

$$\begin{pmatrix} a'_r \\ b'_r \end{pmatrix} = \begin{pmatrix} \cos(j \cdot (2\pi \cdot s / T)) & -\sin(j \cdot (2\pi \cdot s / T)) \\ \sin(j \cdot (2\pi \cdot s / T)) & \cos(j \cdot (2\pi \cdot s / T)) \end{pmatrix} \cdot \begin{pmatrix} a_r \\ b_r \end{pmatrix}$$

Harmonic Response Analysis (Snippets Functionality)

- Read_Force_Moments
  - Reads kth order Moments files from Maxwell
- Diskrete_Fourier_Transformation
  - Performs Fourier Transform
- Vandermonde_Matrix
  - Solves equation system to the right
  - Create forces on remote points
    - Discrete forces lead to same moments as distributed surface force densities from Maxwell (until order k)
- Rotational_Speed_Loop
  - Varies rotational speed
  - Scaling of time while Fourier transforming

- Arguments
  - arg1: relative Ω step size for scaling
  - arg4: rotational speed steps for scaling
  - arg5: nominal rotational speed (Ω) in rpm
  - arg2: # of header lines of csv (here: 2)
  - arg3: # pole pair of machine

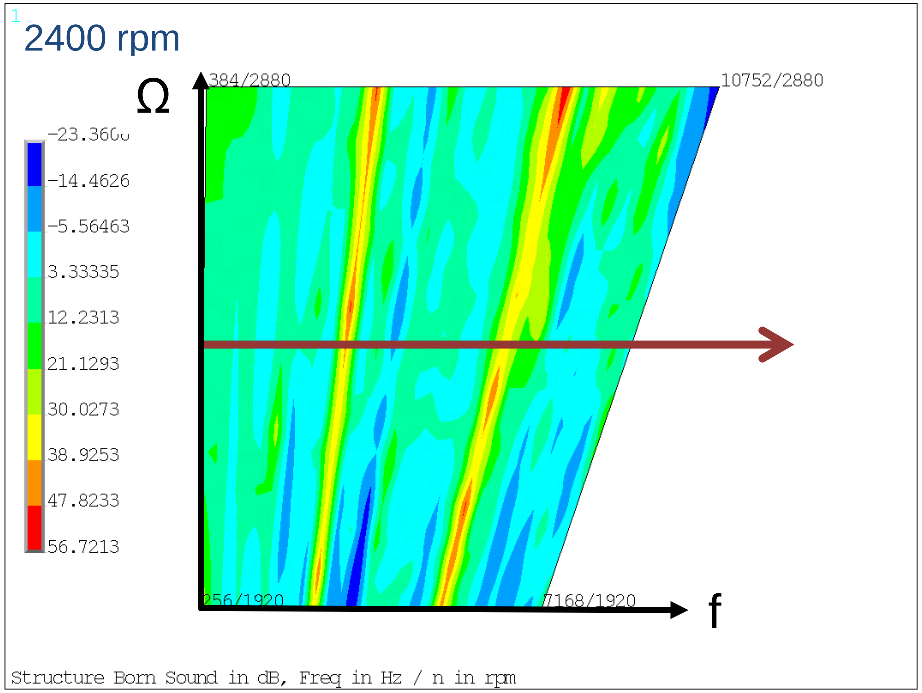
$$\iint_S z^k d\underline{F} = \iint_S z^k \underline{\underline{\sigma}} d\underline{A} = \begin{pmatrix} M_x^k \\ M_y^k \\ M_z^k \end{pmatrix}$$

$$\begin{pmatrix} 1 & z_1^1 & z_1^2 & .. & z_1^{n-1} \\ 1 & z_2^1 & z_2^3 & .. & z_2^{n-1} \\ 1 & z_3^1 & z_3^2 & .. & z_3^{n-1} \\ .. & .. & .. & .. & .. \\ 1 & z_n^1 & z_n^2 & .. & z_n^{n-1} \end{pmatrix}^T \bullet \begin{pmatrix} F_{1,x} \\ F_{2,x} \\ F_{3,x} \\ .. \\ F_{n,x} \end{pmatrix} = \begin{pmatrix} M_x^0 \\ M_x^1 \\ M_x^2 \\ .. \\ M_x^{n-1} \end{pmatrix}$$

CADFEM

Resulting Carpet Plot

- Simulated Result:
  - Harmonic response for single angular speed Ω defined in Maxwell
- Ω sweep:
  - Through time axis scaling in Fourier transform
  - Using arguments of Read_Force_Moments script
- Carpet plot:
  - Locate critical modes at specific rotational speeds



Source: CADFEM