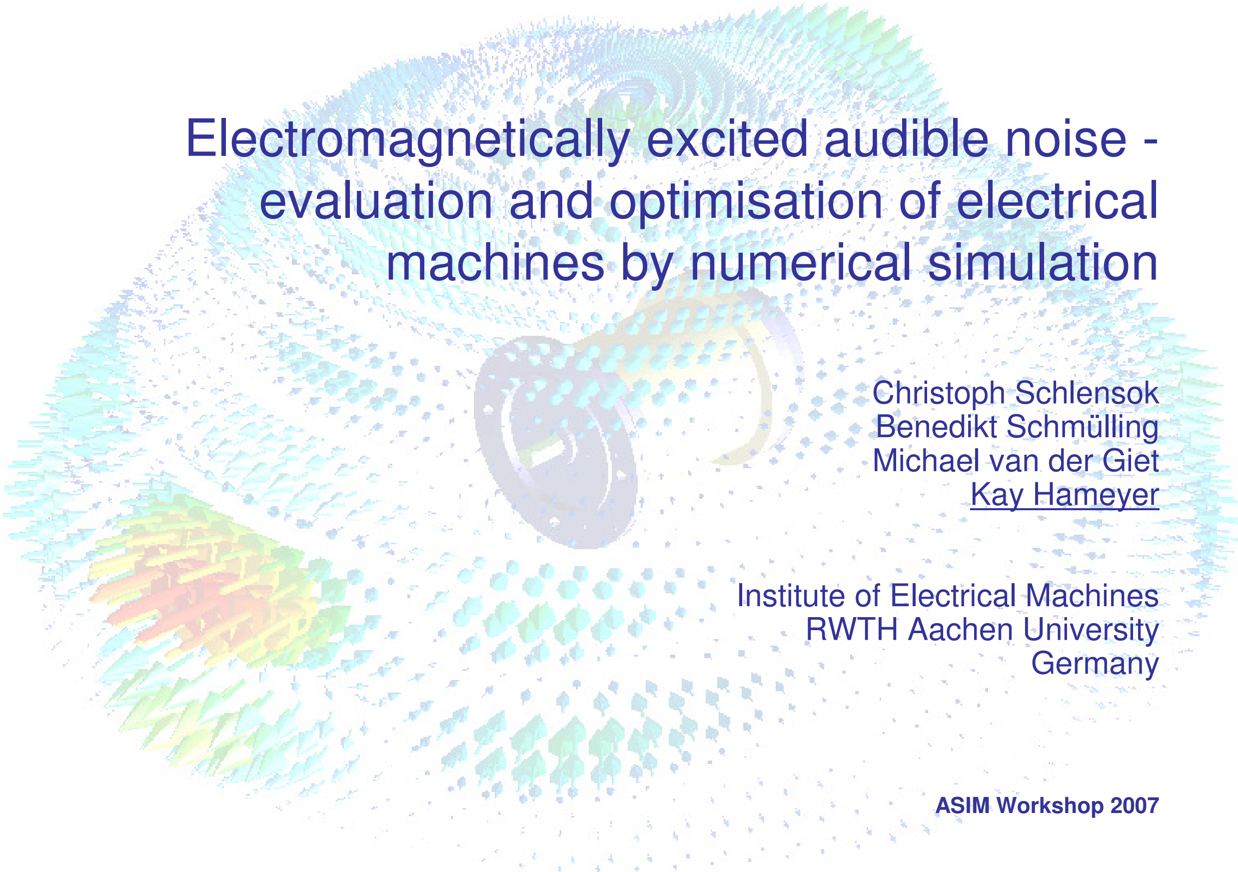

Electromagnetically excited audible noise - evaluation and optimisation of electrical machines by numerical simulation

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Institute of Electrical Machines
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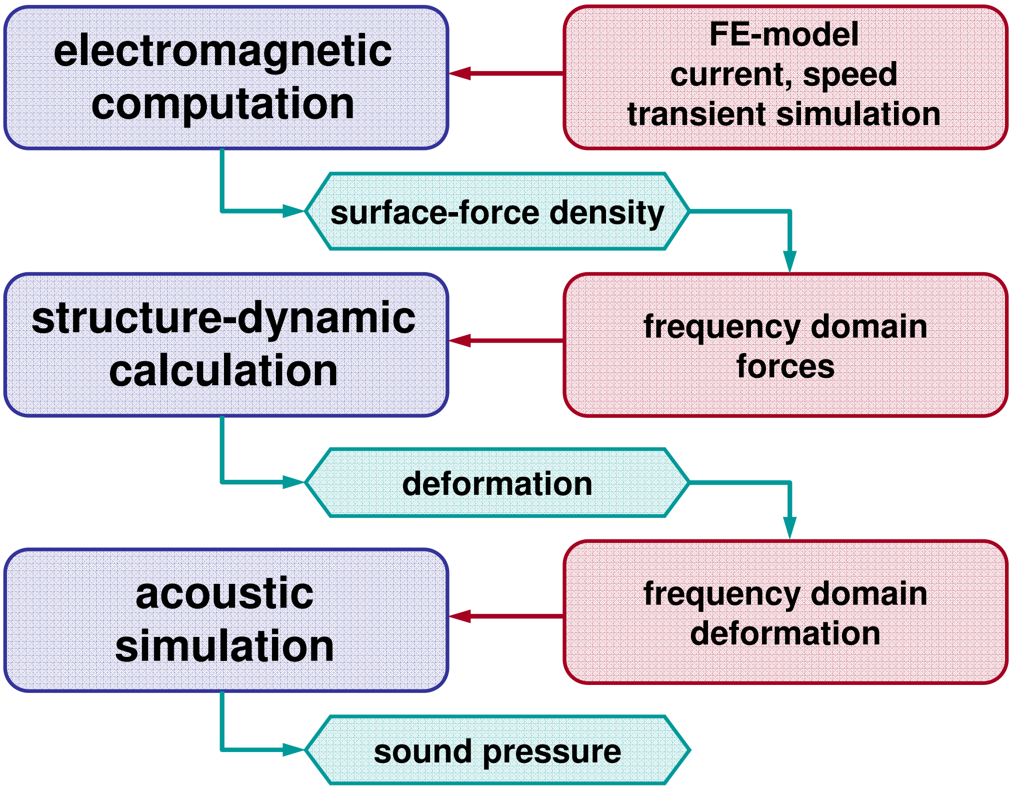
Germany

ASIM Workshop 2007

Outline

- Introduction
  - Problem description: Multi-physics
  - What are the tools
- Electro-magnetic computation
  - Modelling
  - Results
- Structure-dynamic calculation
  - Modelling
  - Results
- Acoustic simulation
  - Modelling
  - Results
- Conclusions



Introduction

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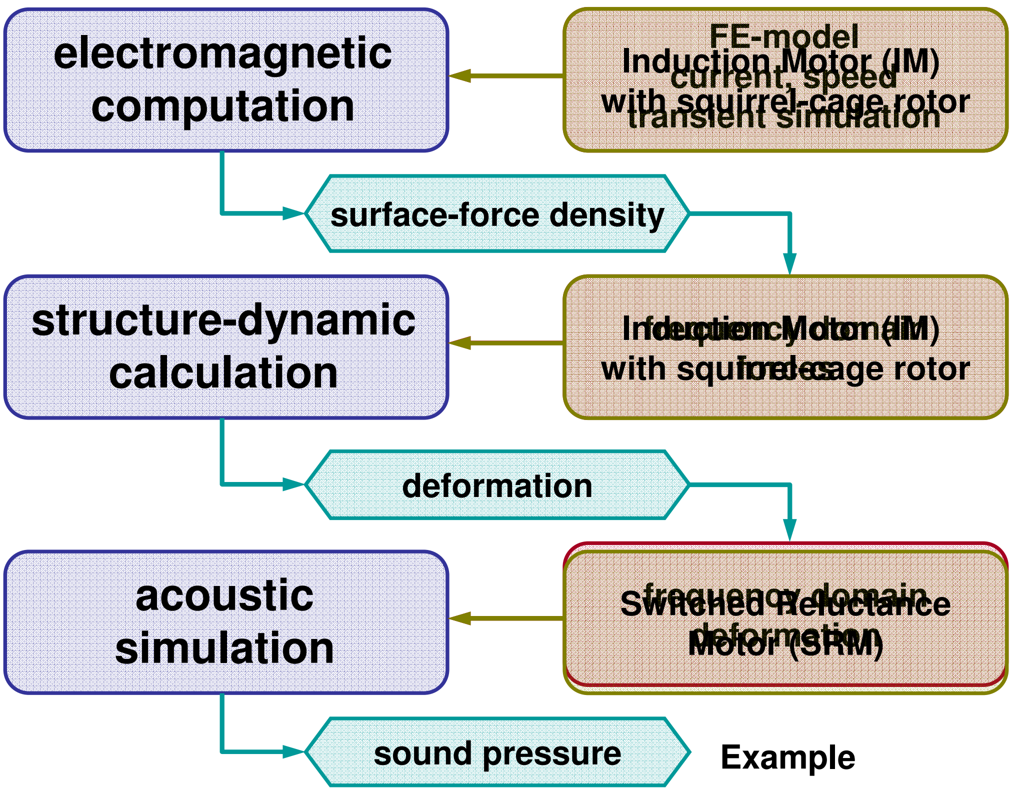

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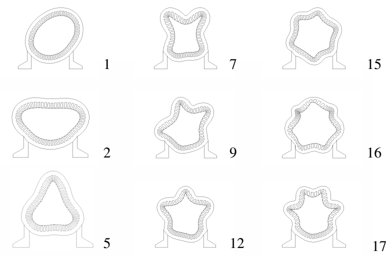
What are the tools: Analytical model

- Tables to determine the mechanical order and associated frequency regarding the source of the excitation
- Example:



Magnetische Anregungen für Geräusche bei Asynchronmaschinen (Käfigläufer):

Strangzahl m	3			Lochzahl q_1	2
Polzahl 2p	6	--> p	3		
Frequenz f_1	50				
Nutzahl N_1	36				
N_2	28				
Schlupf s	0				
Exzentrizität K	0	K=0 für stst. Ex. K=1 für dyn. Ex.			

Geräuschanregungen der Oberfelder des Ständers in dem Zusammenwirken mit den:

Läuferrestfelder des Grundstrombelages

Nutharmonische g1/q1			-0,5	0,5	-1	1	-1,5	1,5	-2	2	-2,5	2,5	-3	3	-3,5	3,5	-4	4	-4,5	4,5	-5	5	Frequenz
g1			0	-1	1	-2	2	-3	3	-4	4	-5	5	-6	6	-7	7	-8	8	-9	9	-10	10	[Hz]
Wicklungsfelder			1	-5	7	-11	13	-17	19	-23	25	-29	31	-35	37	-41	43	-47	49	-53	55	-59	61	
g2	nue1		3	-15	21	-33	39	-51	57	-69	75	-87	93	-105	111	-123	129	-141	147	-159	165	-177	183	
	nue2																							
0		+	6	-12	24	-30	42	-48	60	-66	78	-84	96	-102	114	-120	132	-138	150	-156	168	-174	186	100
	3	-	0	18	-18	36	-36	54	-54	72	-72	90	-90	108	-108	126	-126	144	-144	162	-162	180	-180	0
-1		+	-22	-40	-4	-58	14	-76	32	-94	50	-112	68	-130	86	-148	104	-166	122	-184	140	-202	158	-366,67
	-25	-	-28	-10	-46	8	-64	26	-82	44	-100	62	-118	80	-136	98	-154	116	-172	134	-190	152	-208	-466,67
1		+	34	16	52	-2	70	-20	88	-38	106	-56	124	-74	142	-92	160	-110	178	-128	196	-146	214	566,667
	31	-	28	46	10	64	-8	82	-26	100	-44	118	-62	136	-80	154	-98	172	-116	190	-134	208	-152	466,667
-2		+	-50	-68	-32	-86	-14	-104	4	-122	22	-140	40	-158	58	-176	76	-194	94	-212	112	-230	130	-833,33
	-53	-	-56	-38	-74	-20	-92	-2	-110	16	-128	34	-146	52	-164	70	-182	88	-200	106	-218	124	-236	-933,33
2		+	62	44	80	26	98	8	116	-10	134	-28	152	-46	170	-64	188	-82	206	-100	224	-118	242	1033,33
	59	-	56	74	38	92	20	110	2	128	-16	146	-34	164	-52	182	-70	200	-88	218	-106	236	-124	933,333
-3		+	-78	-96	-60	-114	-42	-132	-24	-150	-6	-168	12	-186	30	-204	48	-222	66	-240	84	-258	102	-1300
	-81	-	-84	-66	-102	-48	-120	-30	-138	-12	-156	6	-174	24	-192	42	-210	60	-228	78	-246	96	-264	-1400
3		+	90	72	108	54	126	36	144	18	162	0	180	-18	198	-36	216	-54	234	-72	252	-90	270	1500
	87	-	84	102	66	120	48	138	30	156	12	174	-6	192	-24	210	-42	228	-60	246	-78	264	-96	1400
-4		+	-106	-124	-88	-142	-70	-160	-52	-178	-34	-196	-16	-214	2	-232	20	-250	38	-268	56	-286	74	-1766,7
	-109	-	-112	-94	-130	-76	-148	-58	-166	-40	-184	-22	-202	-4	-220	14	-238	32	-256	50	-274	68	-292	-1866,7

What are the tools: Numerical model

- Own software applied for entire simulation chain

iMOOSE & iMOOSE.trinity
Finite/Boundary Element
Solvers and Tools

iMOOSE

&

What is iMOOSE

➢ iMOOSE – innovative and modern Object-Oriented Solver Environment

Visualization & Postprocessing
- iMOOSE.trinity
- iMOOSE.vr.trinity

iMOOSE FEM Library

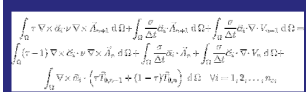
Tools & Utilities
- iMOOSE.transbinary
- iMOOSE.meshconvert
- iMOOSE.minmaxdeform

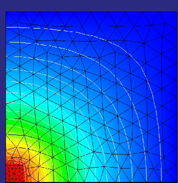
Solver
- iMOOSE.stat2d
- iMOOSE.stat3d
- iMOOSE.tsa2d
- iMOOSE.harm3d
- iMOOSE.tsa3d
- iMOOSE.modal
- iMOOSE.disp

Why do own software development

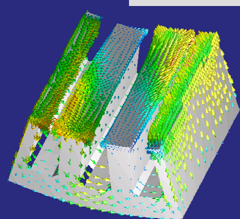
➢ Simulation & Design of Electrical Machines

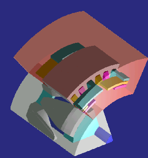
Theory



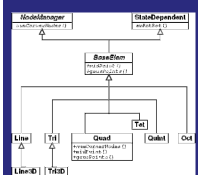


Design

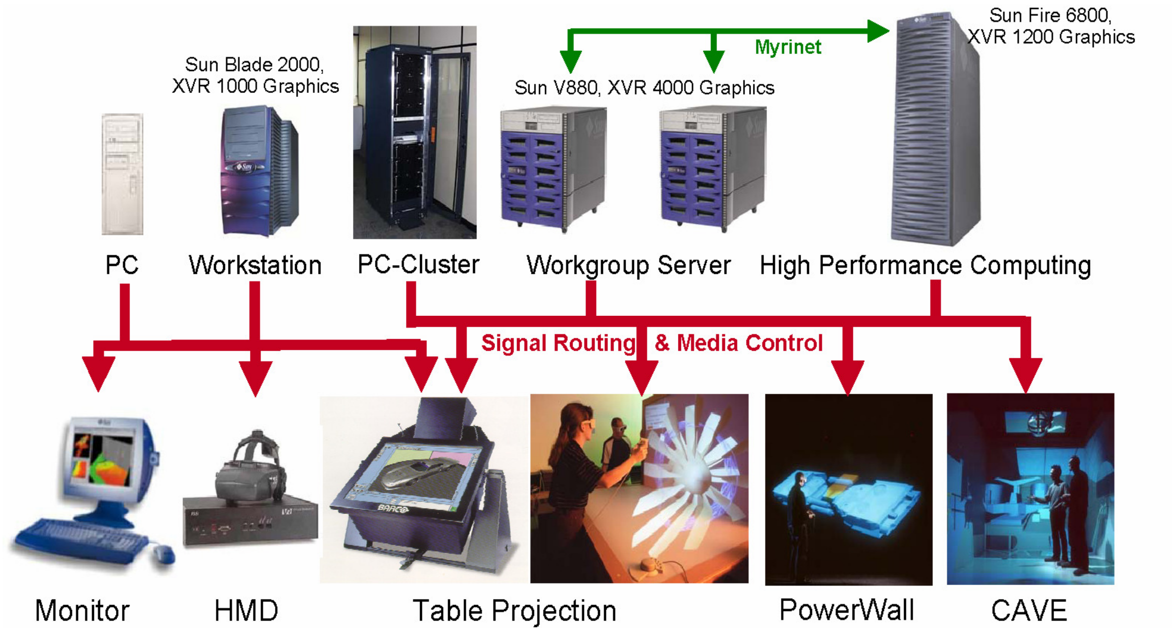




Implementation



Validation



Virtual Reality
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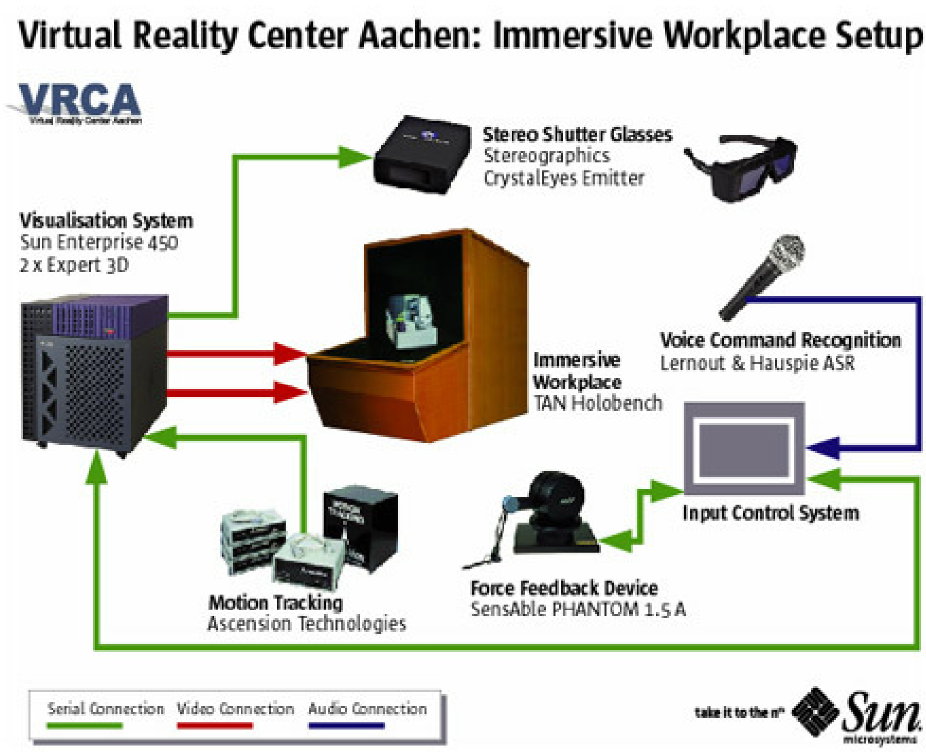

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electromagnetic computation ← **FE-model current, speed transient simulation**

- Modelling
  - 2D/3D possible in general
    ⇒ 2D whenever possible, 3D requires huge computational cost
  - static, time harmonic, transient
  - with or without movement
- This example: Induction Machine (IM) with squirrel-cage rotor
  - 2D, multi-slice model
  - transient simulation
  - rotor movement

  ⇒ transient phenomenon must die out before analysis of the simulation results can start

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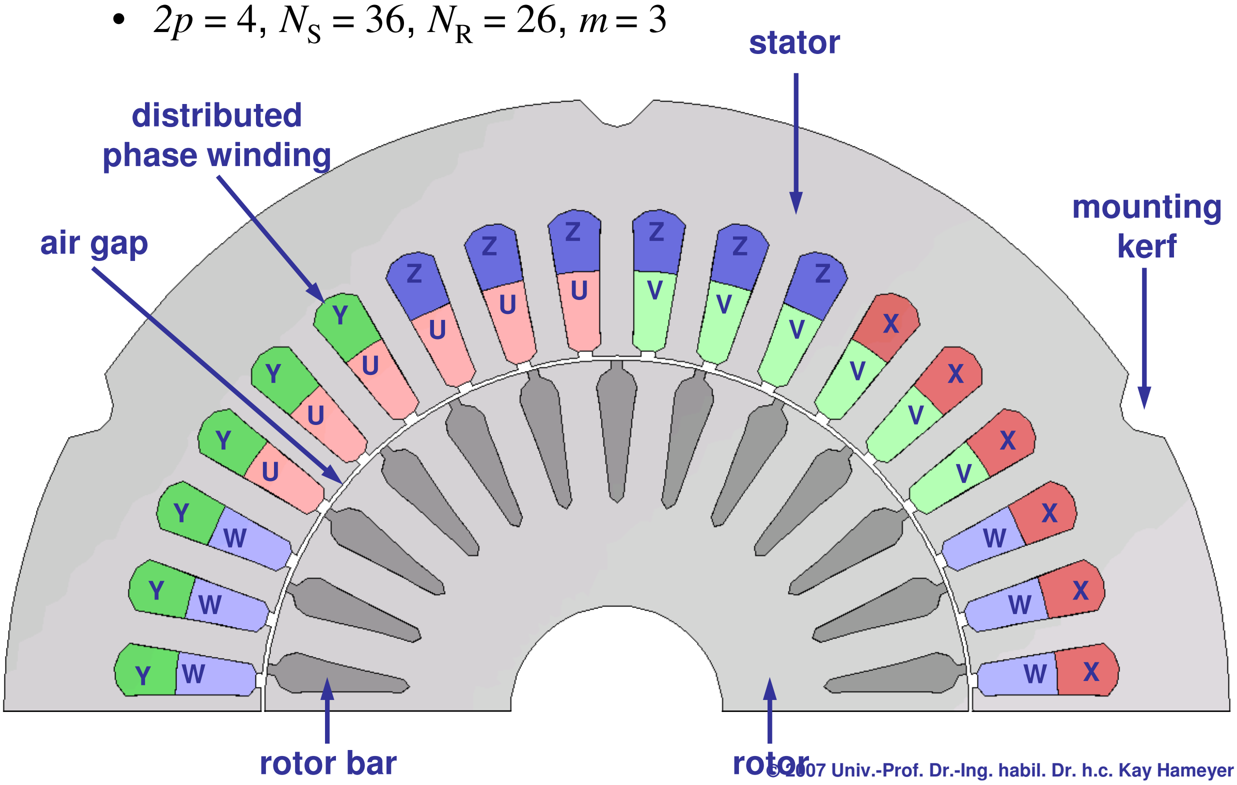
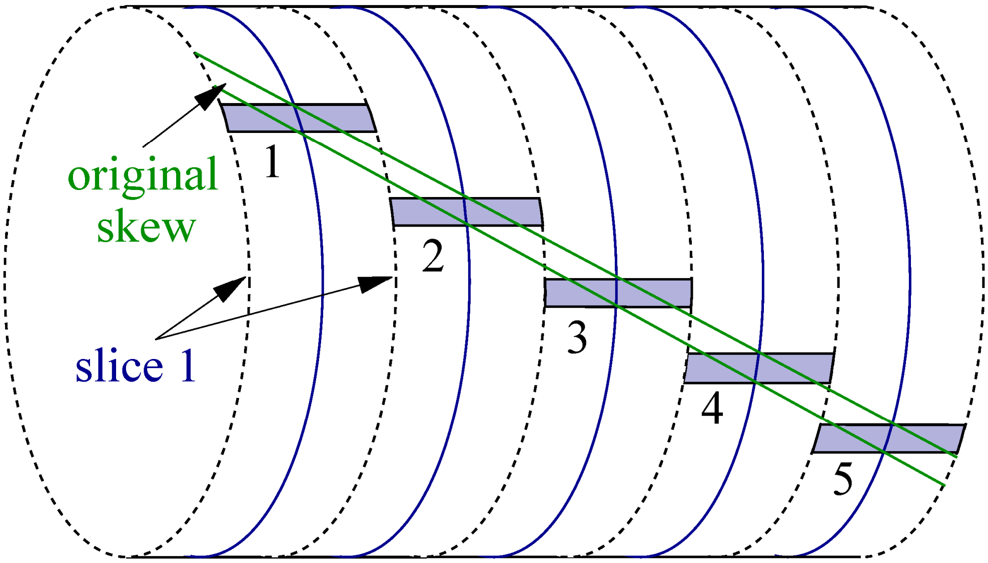
- Electromagnetic model of IM
  - $2p = 4,\ N_S = 36,\ N_R = 26,\ m = 3$



- Skew of the IM is modelled with multi-slice technique



- 5 models are coupled
  - each ≈ 15.000 triangular elements

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- Simulation parameters

f_1	48.96 Hz	stator frequency
n	1200 rpm	rotor speed
I_1	85 A	stator-phase current
Δt	243.153 ms	simulation-time step
$\Delta\alpha$	0.875 °	rotational step angle
N	4200	number of simulation-time steps

- Results from each simulation time step
  - magnetic vector potential
    $\Rightarrow$ flux-density distribution: $\vec{B} = \mathrm{curl}\,\vec{A}$
  - derived from the flux density (Maxwell-Stress Tensor)
    - net-force F
    - torque T
    - surface-force density σ

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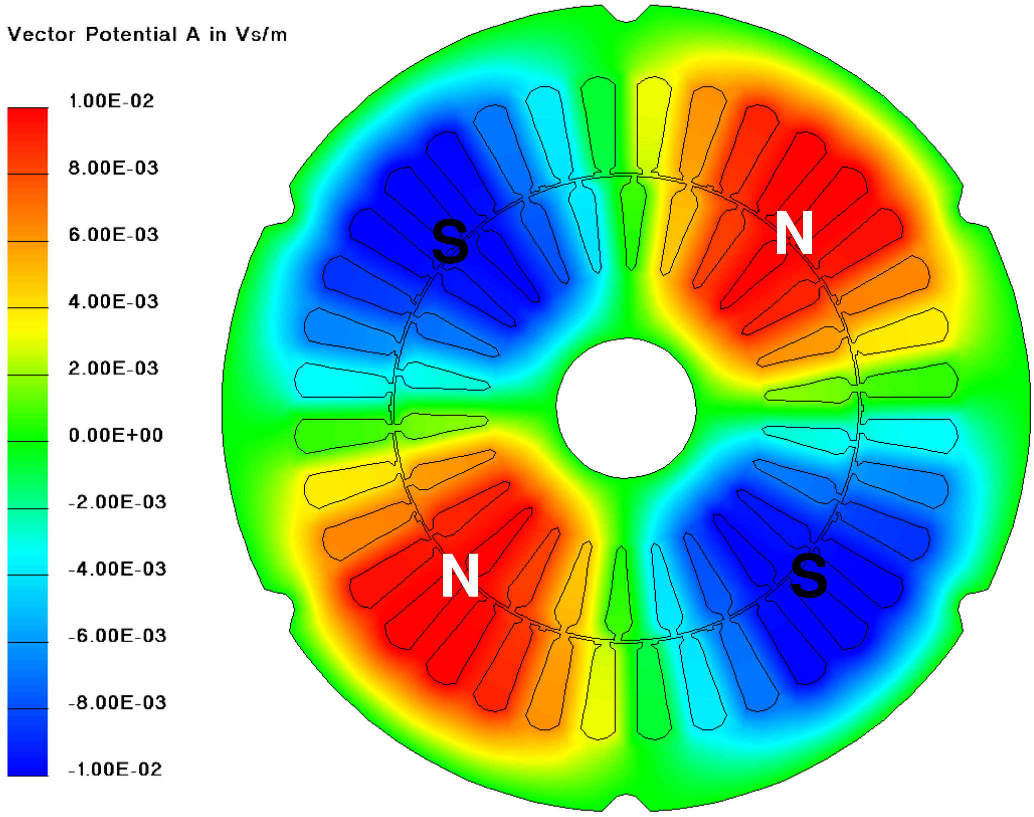

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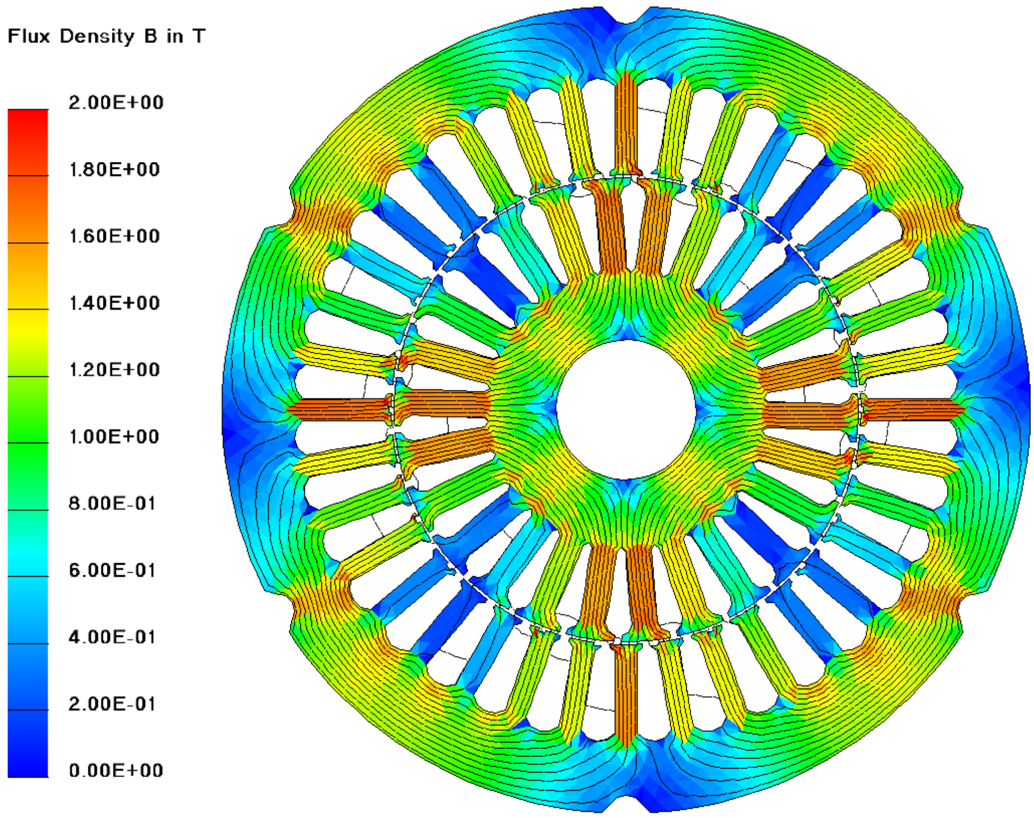

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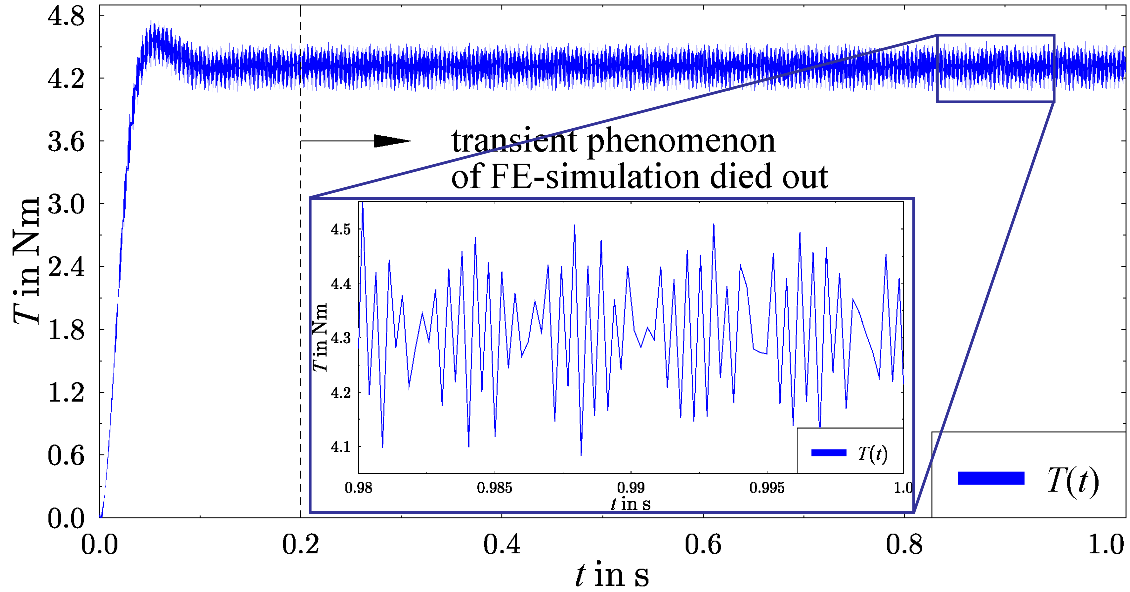
- Torque behaviour
  - transient phenomenon from transient solving
  - average torque: $T = 4.31$ Nm
  - peak-to-peak torque ripple: $\Delta T = 0.45$ Nm



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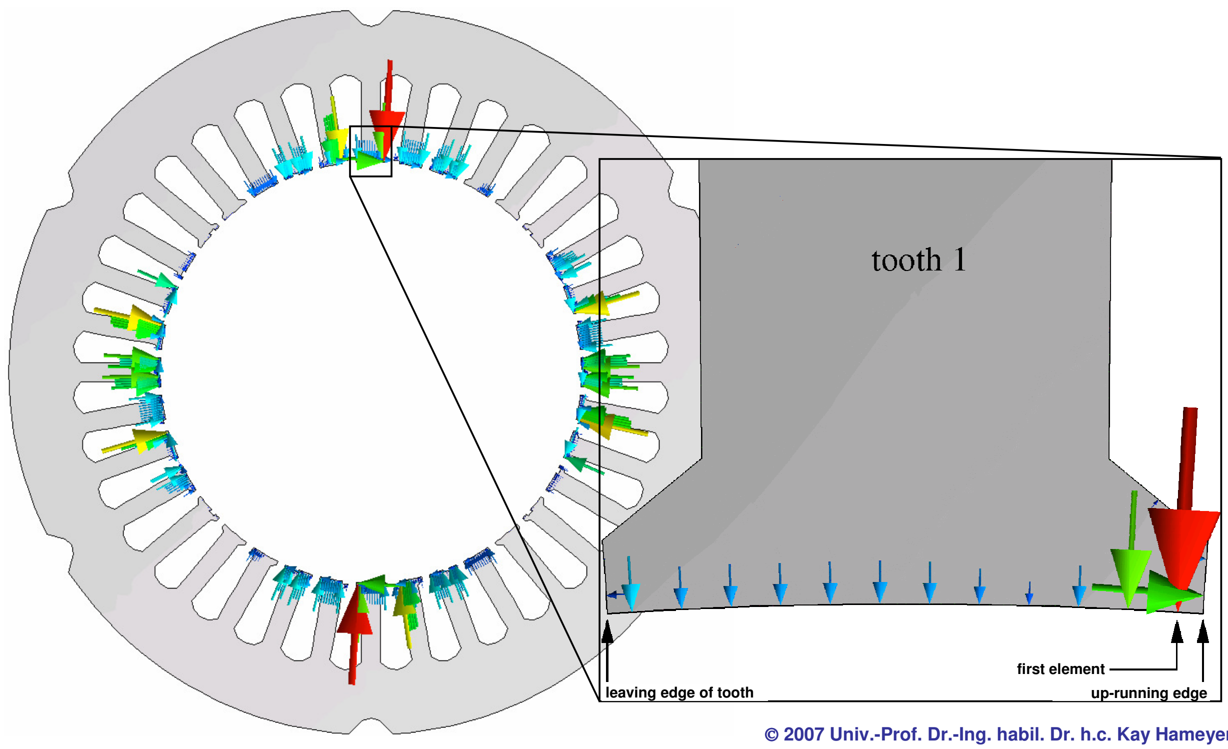
- Surface-force density derived for each time step



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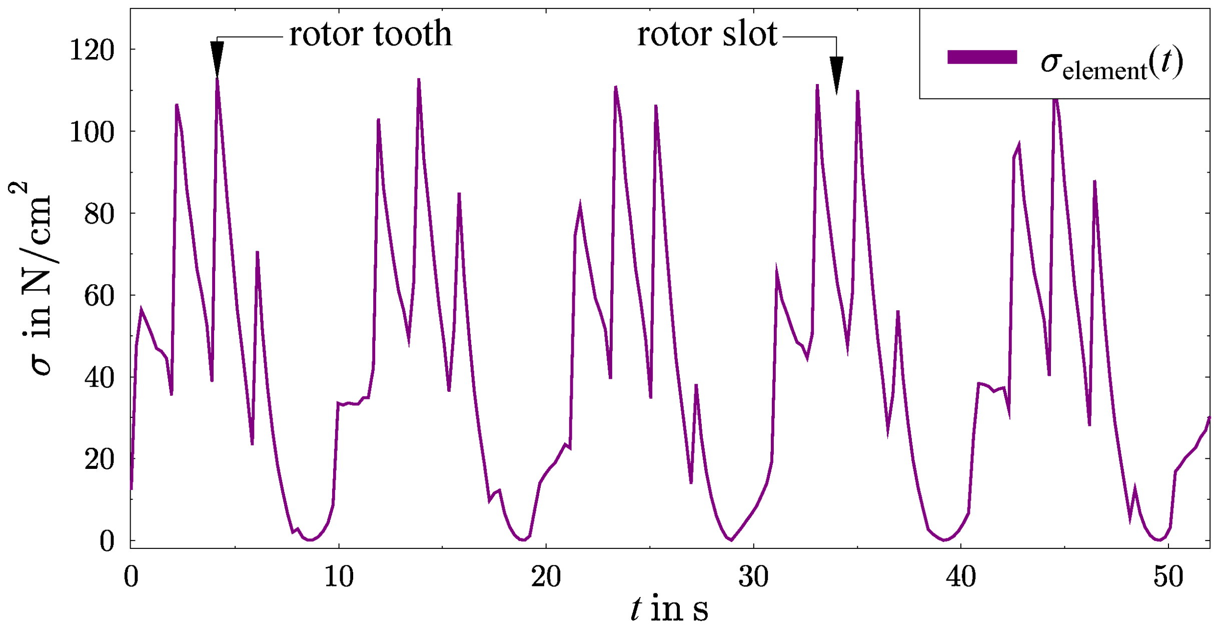
- Behaviour of surface-force density
  - force pulsates, depending on n, N_R, N_S, f_1, p



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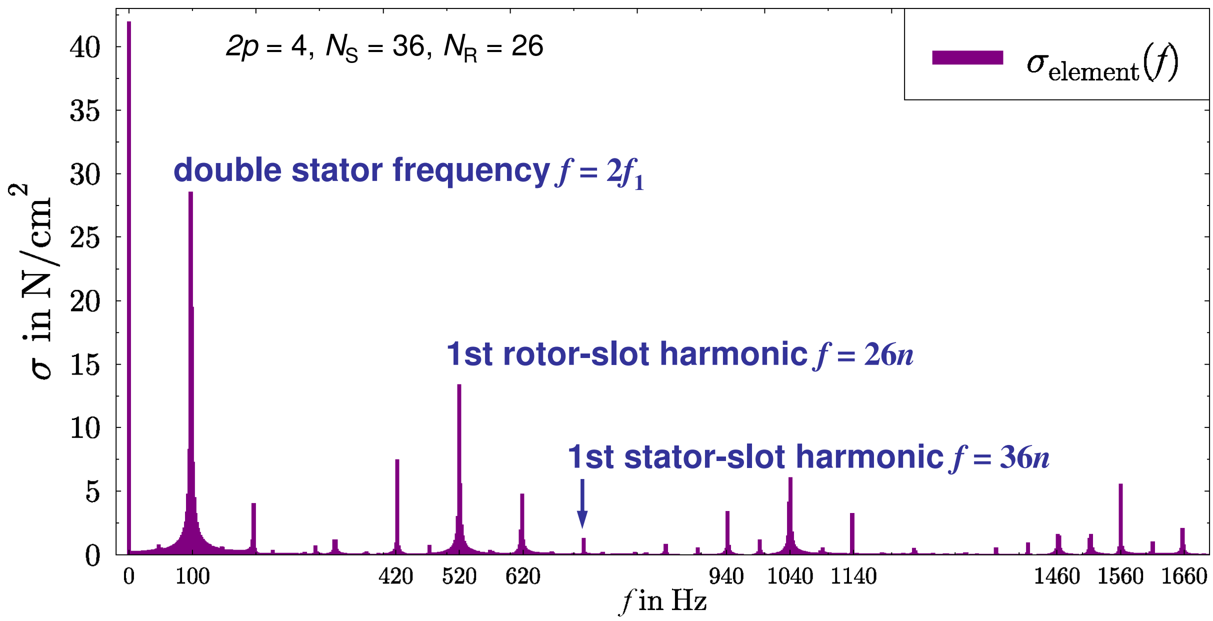
- Spectrum of surface-force density
  - significant frequencies are selected



structure-dynamic calculation ← **frequency domain forces**

- Example: Induction machine
- Deformation → displacement of individual nodes

$$\varepsilon = S \cdot \vec{u}$$

with
$$S = \begin{bmatrix} \frac{\partial}{\partial x} & 0 & 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial z} \\ 0 & \frac{\partial}{\partial y} & 0 & \frac{\partial}{\partial x} & \frac{\partial}{\partial z} & 0 \\ 0 & 0 & \frac{\partial}{\partial z} & 0 & \frac{\partial}{\partial y} & \frac{\partial}{\partial x} \end{bmatrix}^T$$

- Tension σ is coupled by Hooke's law with strain ε

$$\sigma = H \cdot \varepsilon ,$$

$$H = \frac{E(1-\mu)}{(1-\mu)(1-2\mu)} \begin{bmatrix} 1 & \frac{\mu}{1-\mu} & \frac{\mu}{1-\mu} & 0 & 0 & 0 \\ \frac{\mu}{1-\mu} & 1 & \frac{\mu}{1-\mu} & 0 & 0 & 0 \\ \frac{\mu}{1-\mu} & \frac{\mu}{1-\mu} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\mu}{2(1-\mu)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\mu}{2(1-\mu)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\mu}{2(1-\mu)} \end{bmatrix}$$

E: Young's modulus, μ: Poisson's ratio

- System equation by Threshold-Accepting Method:
  - potential energy

$$\Pi_p = \int_\Omega \varepsilon^T H \varepsilon \,\mathrm{d}\Omega - \int_{\partial\Omega} \vec{u} \cdot \vec{\sigma}_s \varepsilon \,\mathrm{d}\,\partial\Omega,$$

  - kinetic energy

$$T = \int_\Omega \frac{\rho}{2} \cdot \dot{\vec{u}} \,\mathrm{d}\Omega,$$

  - Lagrange function

$$L = T - \Pi_p$$

  - Minimisation of Lagrange function

$$0 = \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\vec{u}}}\right) - \left(\frac{\partial L}{\partial \vec{u}}\right) + \left(\frac{\partial F}{\partial \dot{\vec{u}}}\right),$$

  - F is the damping

- Discretisation results in the differential equation of motion:

$$K \cdot D + C \cdot \dot{D} + M \cdot \ddot{D} = F.$$

K: global stiffness matrix
D: vector of nodal deformation
C: damping matrix
M: mass matrix
F: exciting force matrix

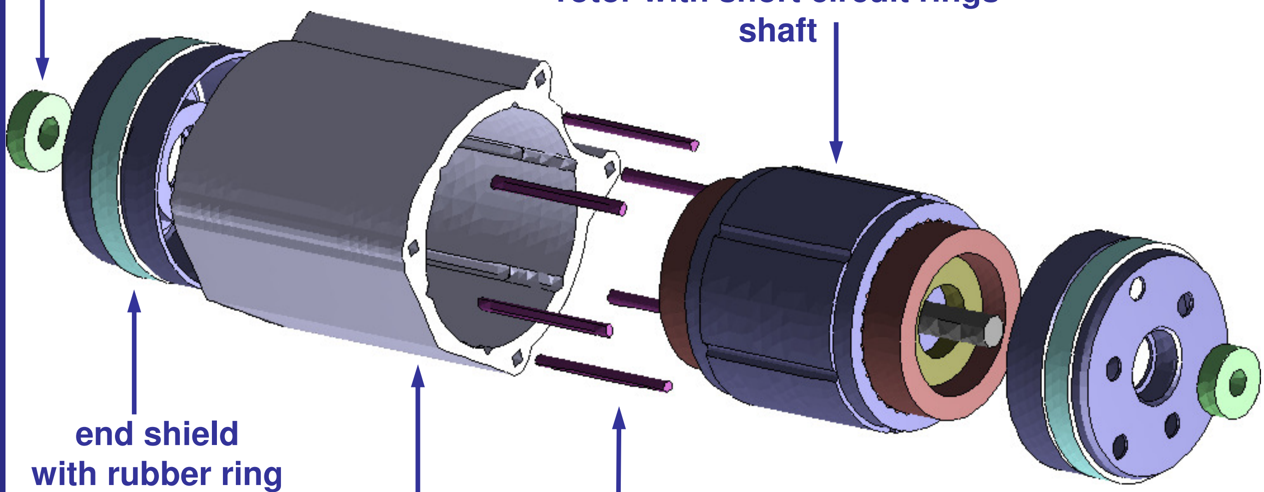
- Time derivative

$$\dot{D} = \frac{dD}{dt} = j\omega D$$

$\Rightarrow$

$$(K + j\omega C - \omega^2 M) \cdot D = F.$$

- Mechanical model



Structure-dynamic calculation
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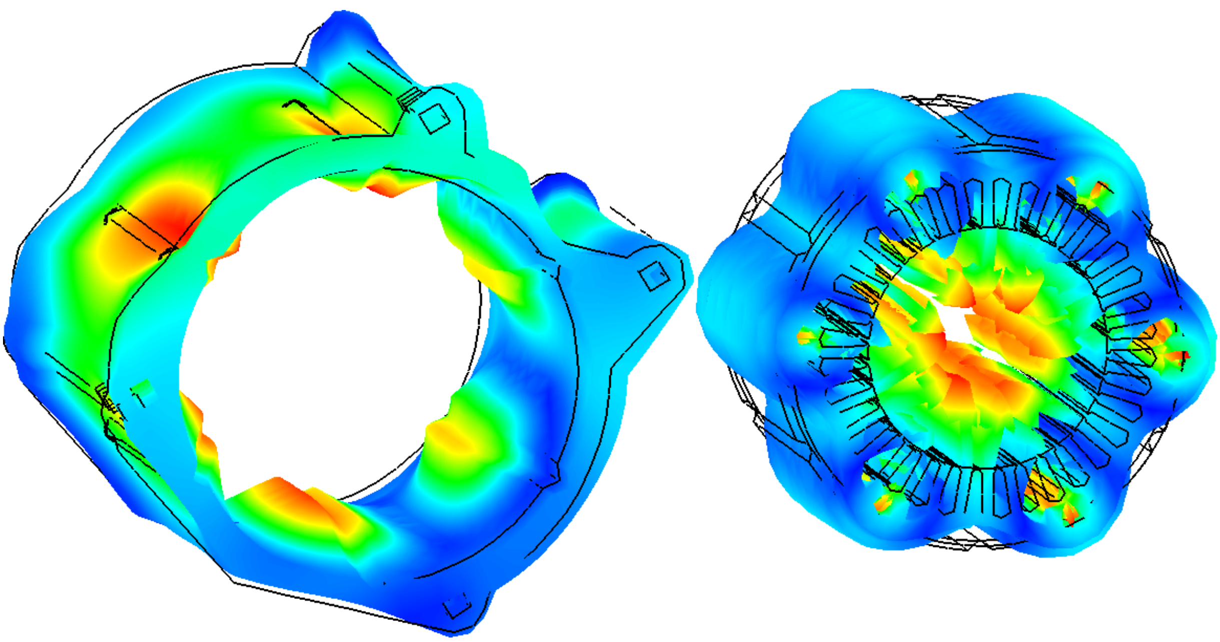
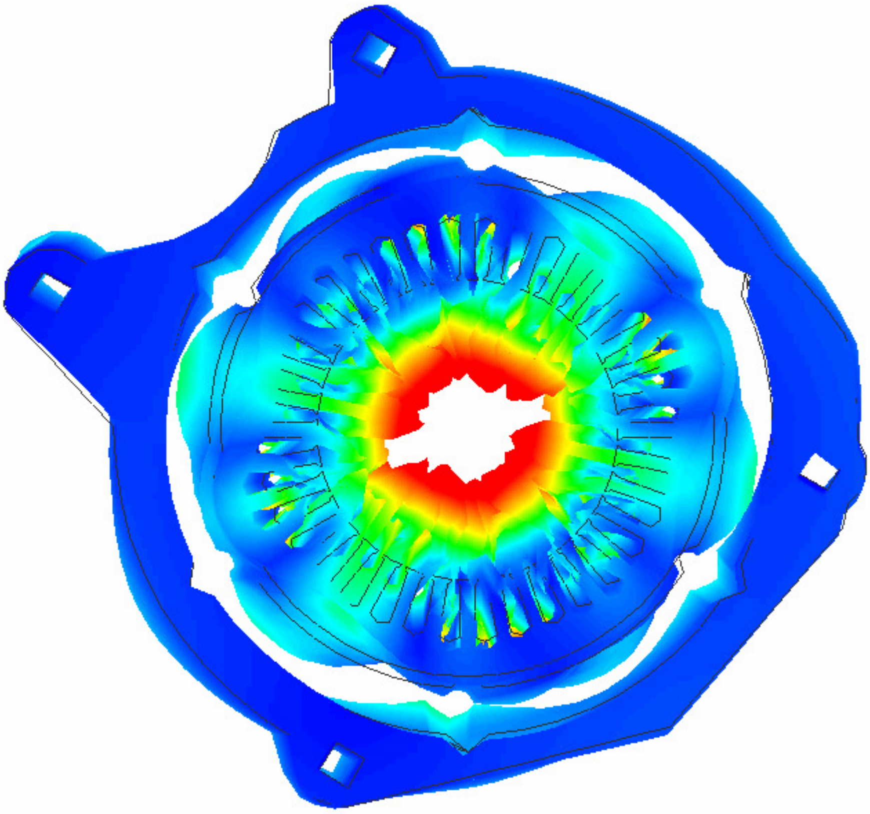
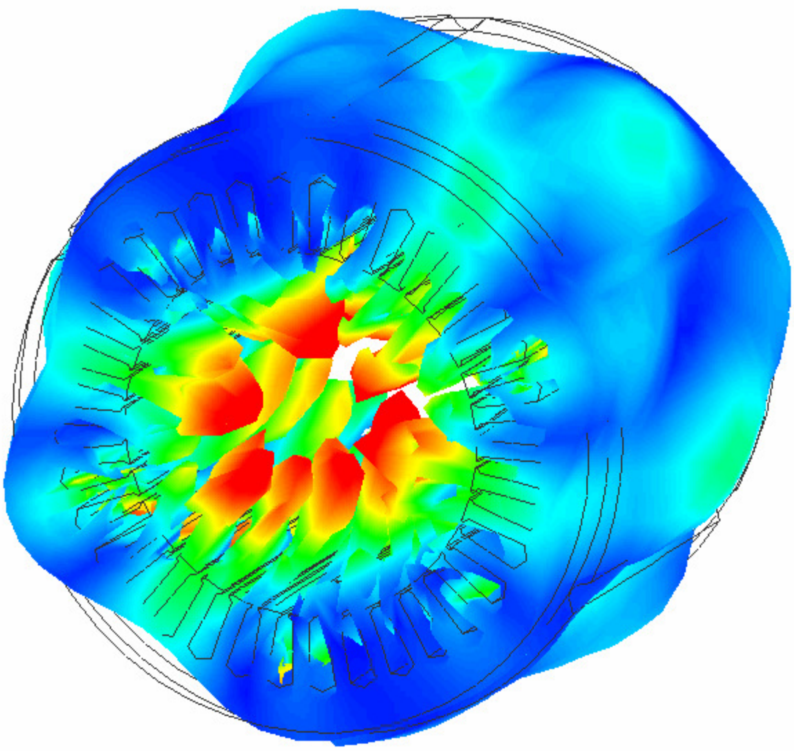
- Simulation result
  $\Rightarrow$ deformation of entire machine in frequency domain
  $\Rightarrow$ example deformation at $t = 0$ for $f = 618$ Hz



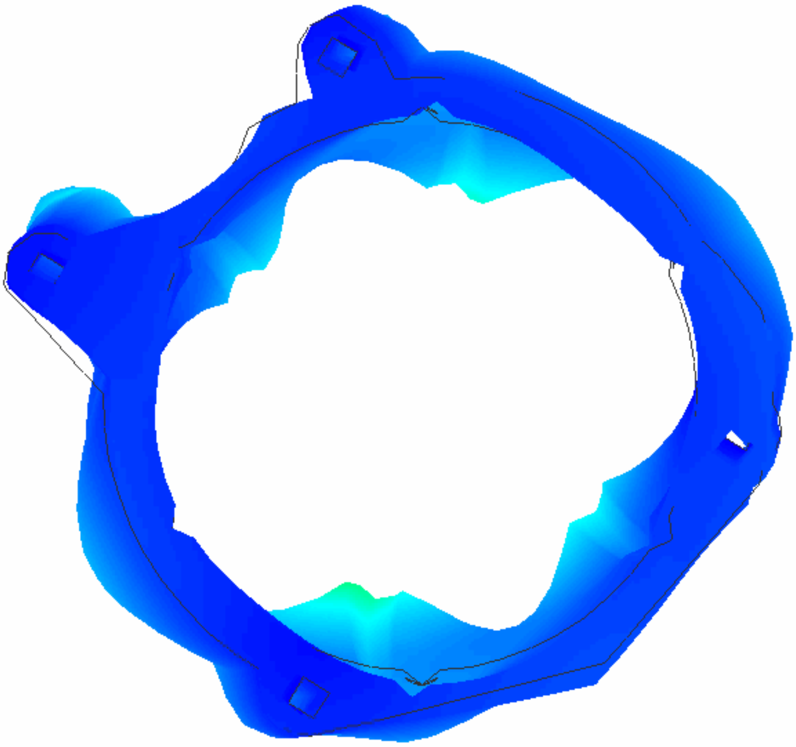
Structure-dynamic calculation



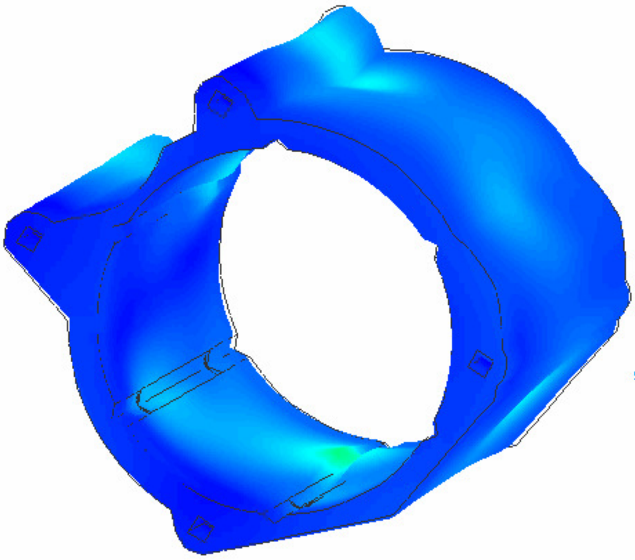
Structure-dynamic calculation

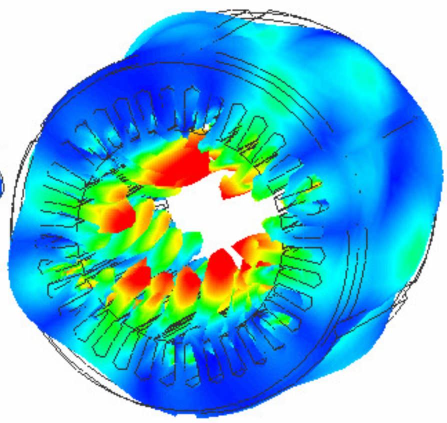


Structure-dynamic calculation



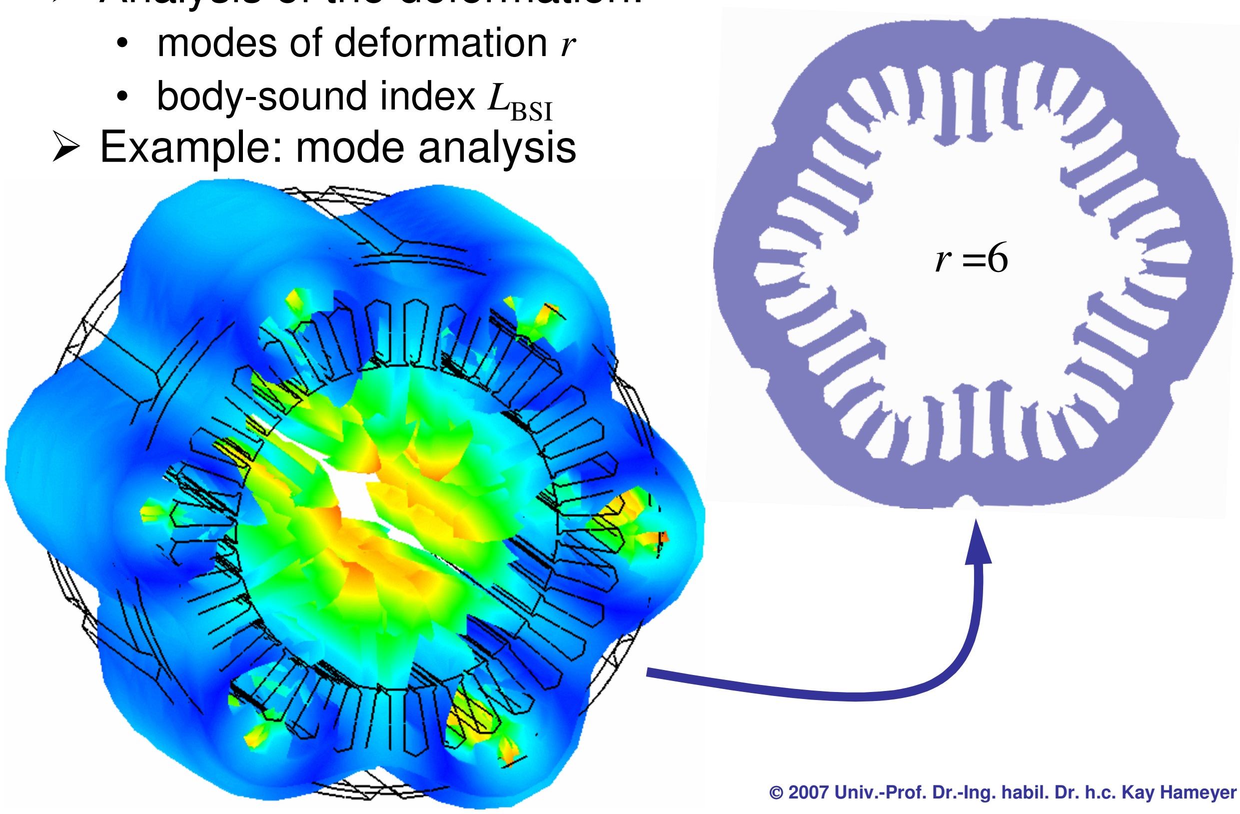
Structure-dynamic calculation





Structure-dynamic calculation

- Analysis of the deformation:
  - modes of deformation r
  - body-sound index L_{BSI}
- Example: mode analysis



Acoustic simulation

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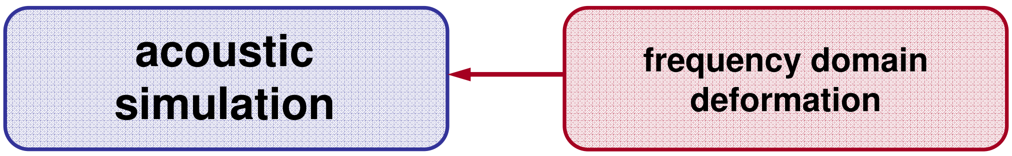

- Three sources for acoustic noise:
  - broad band fan and ventilation noise (500 - 1000 Hz)
  - single tones from the bearings > 3000 Hz
  - vibration and oscillations excited by electromagnetic forces
    → single tones in the entire audible spectrum
- Acoustic simulation considers electromagnetically excited vibration as noise source

Acoustic simulation

- Acoustic noise:
  - vibration is decoupled from the surface of the machine
    $\Rightarrow$ Boundary Element Method (BEM)
- Sound pressure derived from Helmholtz equation:

$$\Delta \underline{p} + k^2 \cdot \underline{p} = 0$$

- Discretisation results in the system equation for solving:

$$H \cdot \underline{p} = G \cdot \underline{\vec{v}}\ .$$

H and G are system matrices and v the vector of the local surface velocity

Acoustic simulation

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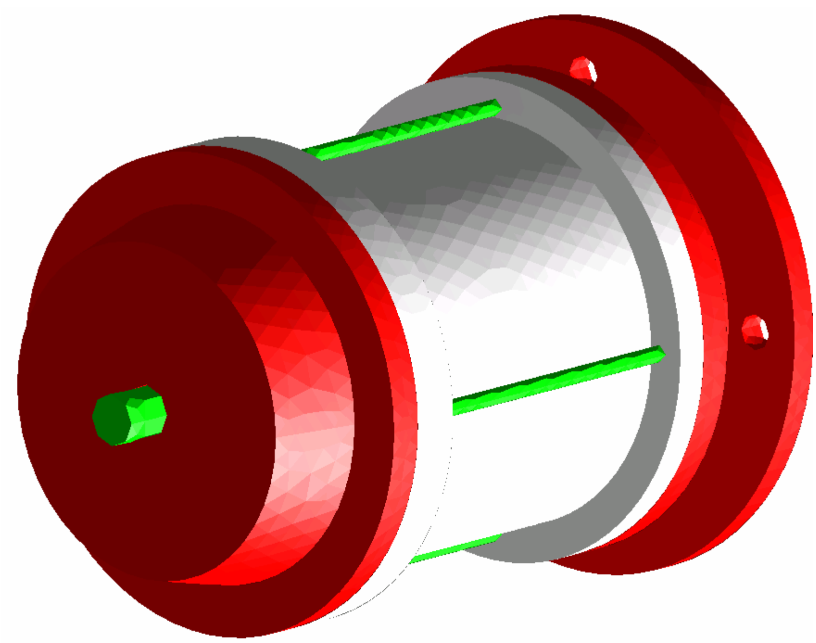
- Example for acoustic simulation:
  Switched Reluctance Motor (SRM)
- Model consists only of exterior surface of the SRM



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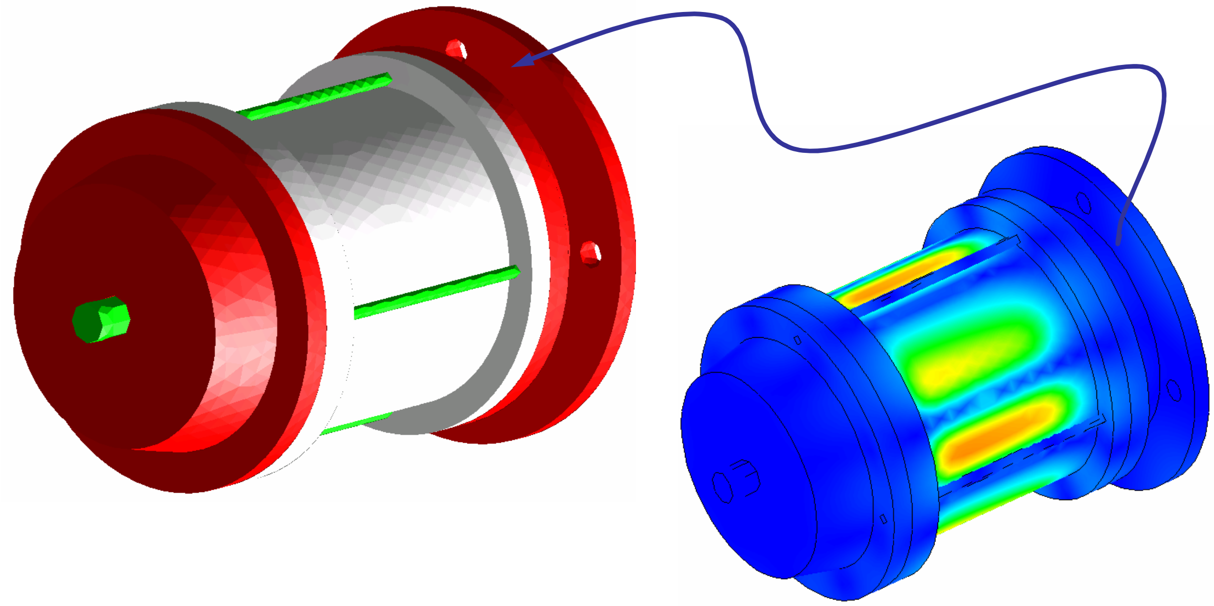
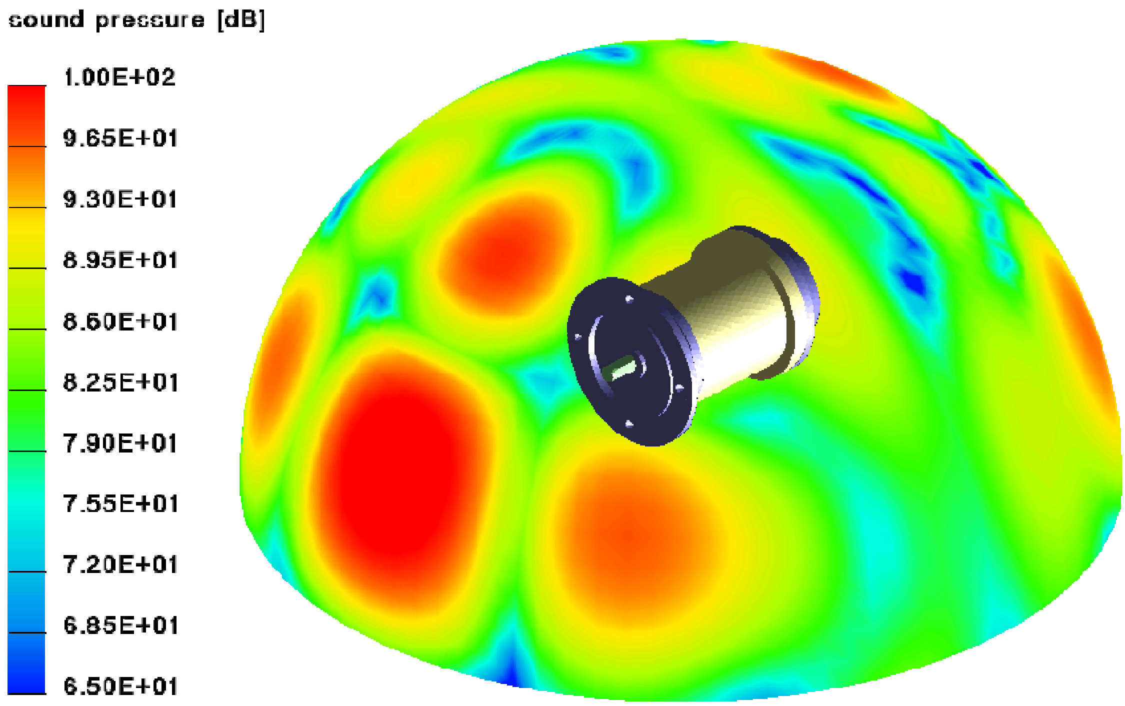
- Deformation is transformed from the mechanical model onto the surface of the acoustic model

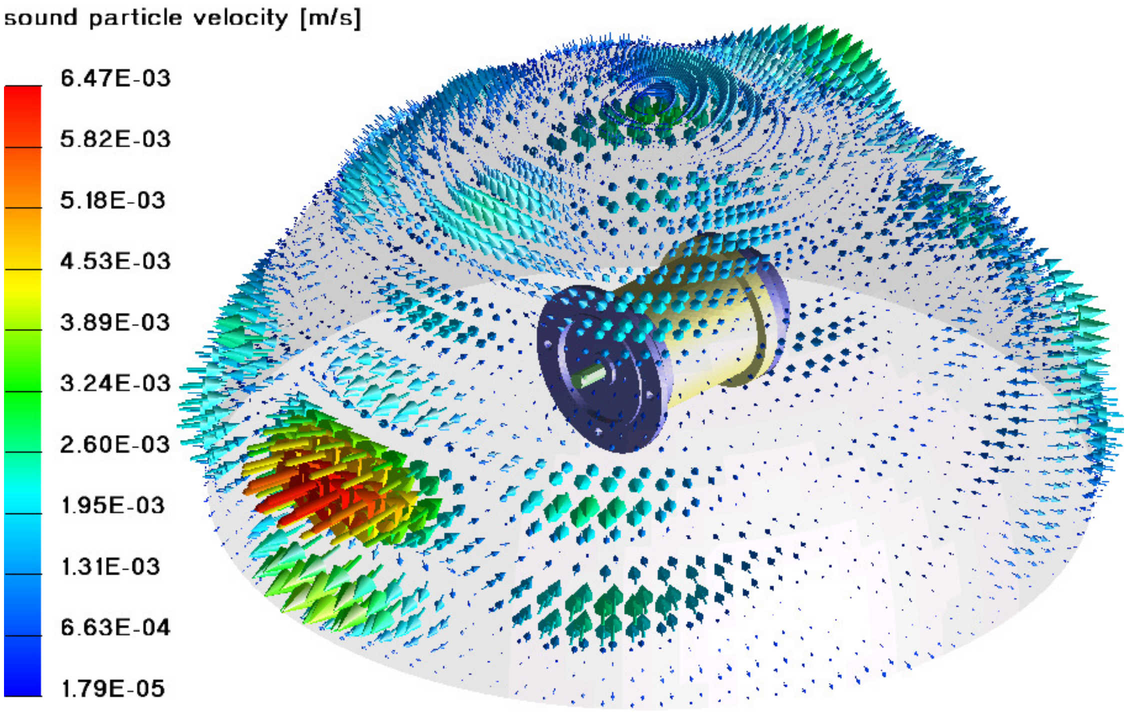


- Acoustic sound pressure is calculated on an analysis surface, e.g. a sphere (1 m distance from surface of SRM)

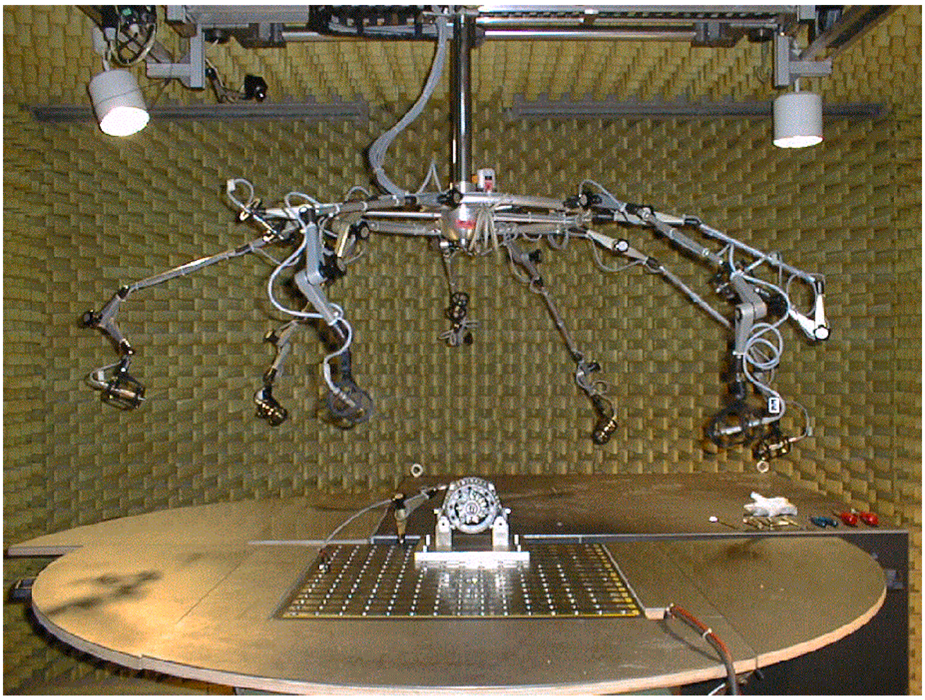


Acoustic simulation

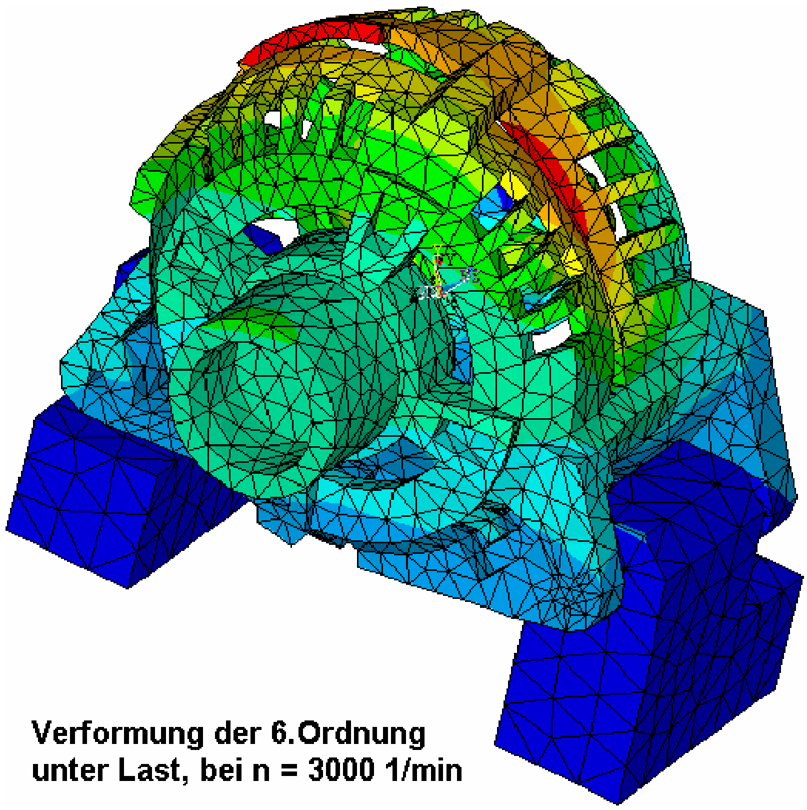
- From p the sound particle velocity is derived



Measurement set-up



Automotive generator's deformation



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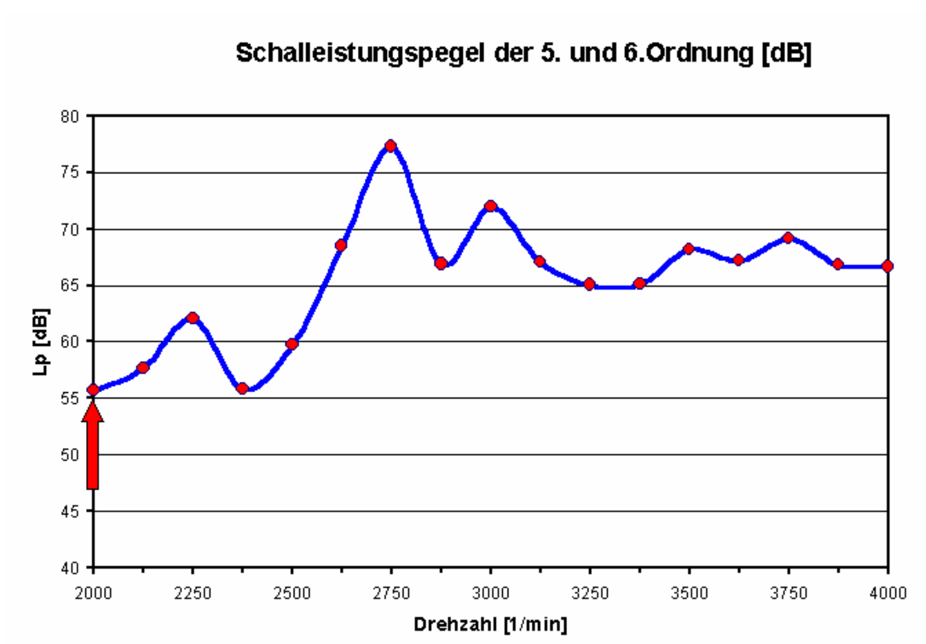
RHEINISCH-WESTFÄLISCHE TECHNISCHE HOCHSCHULE AACHEN

Computed acoustic noise power

ASIM Workshop March 1, 2007, Aachen



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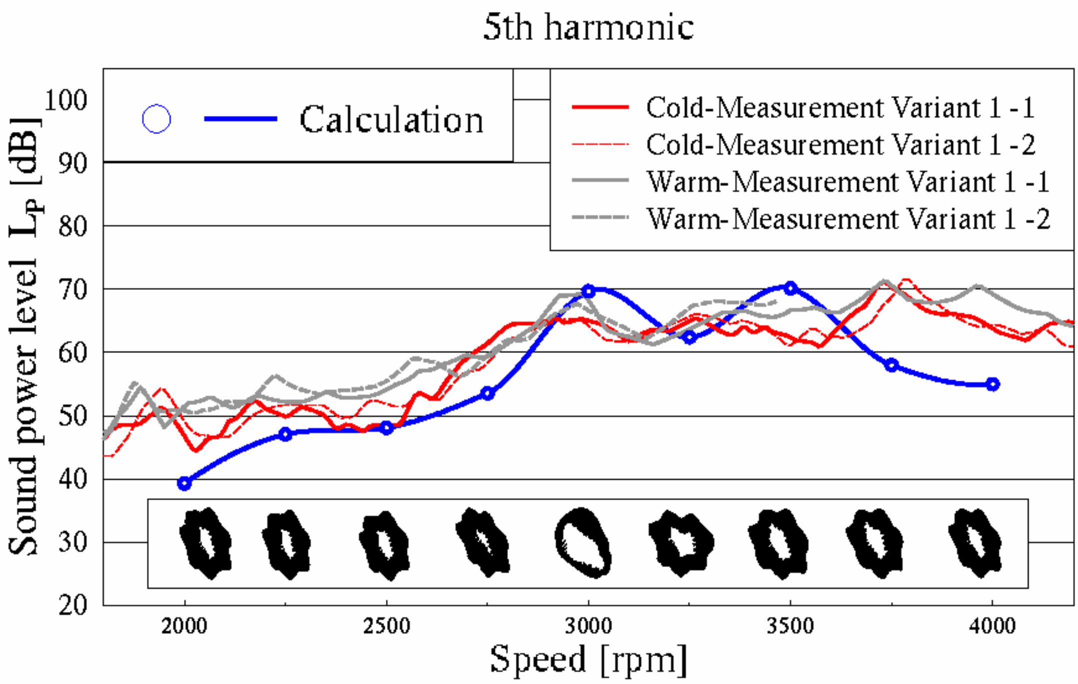
Comparison of simulation - measurement



Conclusions

- Numerical simulation
  - **consideration** of structure-dynamic and acoustic behaviour of electrical machines **a-priori** during design
  - examples of IM and SRM show potential
- Presented method
  - **designed** to be used for **any electrical machine**
  - **verification** by measurement is possible
- Structured analysis
  - **consideration** of manufacturing **faults**
  - **optimisation** of materials and electrical values