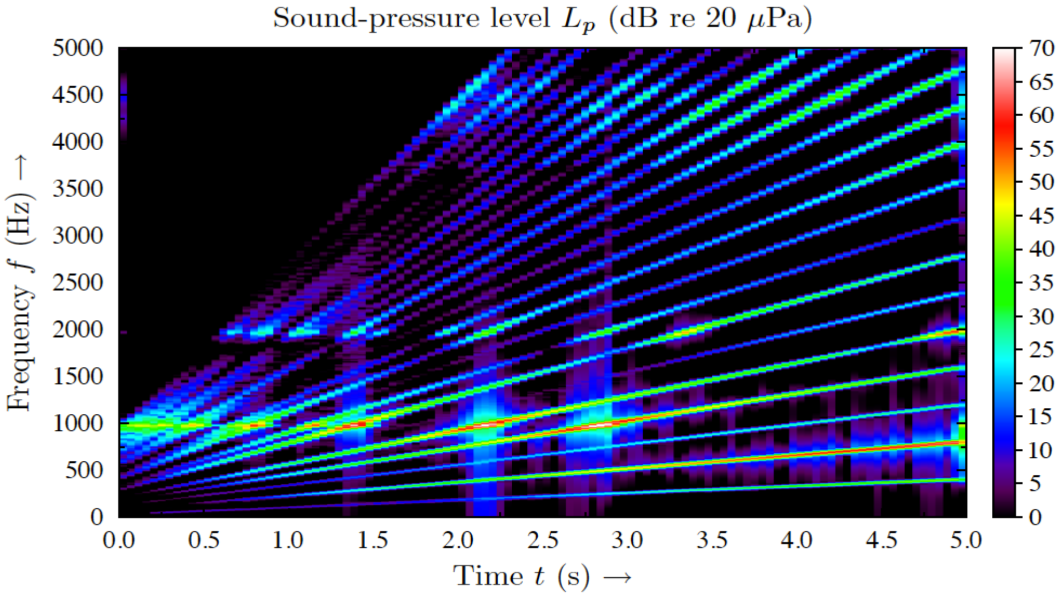

Electromagnetically excited audible noise of electric machines

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IEM Institut für Elektrische Maschinen | RWTH AACHEN UNIVERSITY

Before we start

Brief introduction

Outline

1 **Motivation**

2 **Sources of audible noise**

3 **Analytical approximation**

4 **Design aspects**

4.1 **Evaluation of noise excitation**

4.2 **Numerical modeling and simulation**

4.3 **Auralization & virtual reality**

5 **Summary & conclusions**

Motivation

There is some noise (NVA… Noise Vibration Harshness)

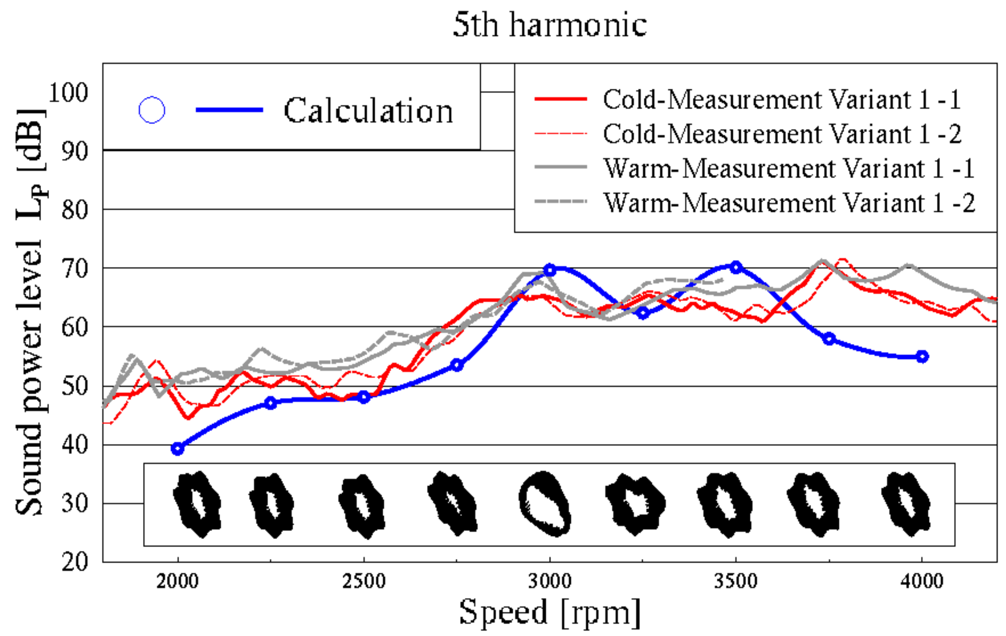
- Electric motors can change the sound impression of particular applications
- Electric motors excite strong tonal single tones
- Single tones are usually displeasing
- Can be located with their frequency in the sensitive range of the human ear
- Engineering tools are required which predict the acoustic behavior of electrical machines
- Adaptation of the sound characteristic is possible by the magnet design of the machine → low noise motor
- Evaluation of noise sources in the environment → synthetic sound for auralization

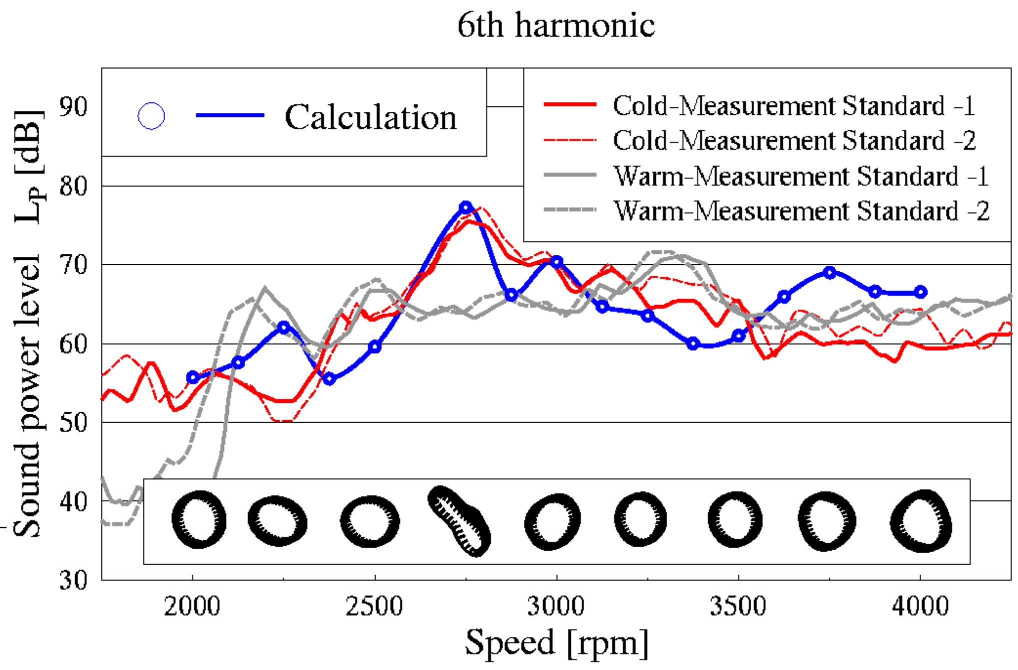
TESLA roadster 2009

How does an electrical machine sound? (example: automotive generator)

Small sound analysis

- Frequency
- Oscillation mode





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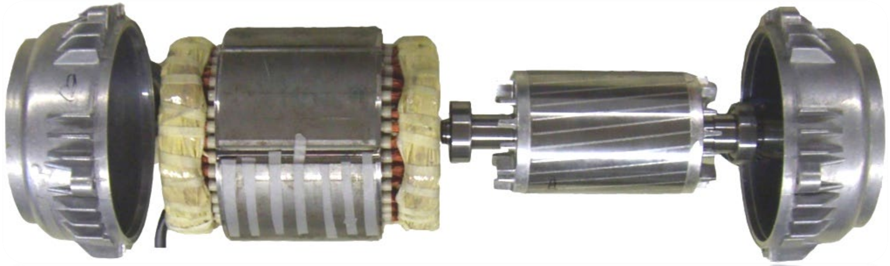
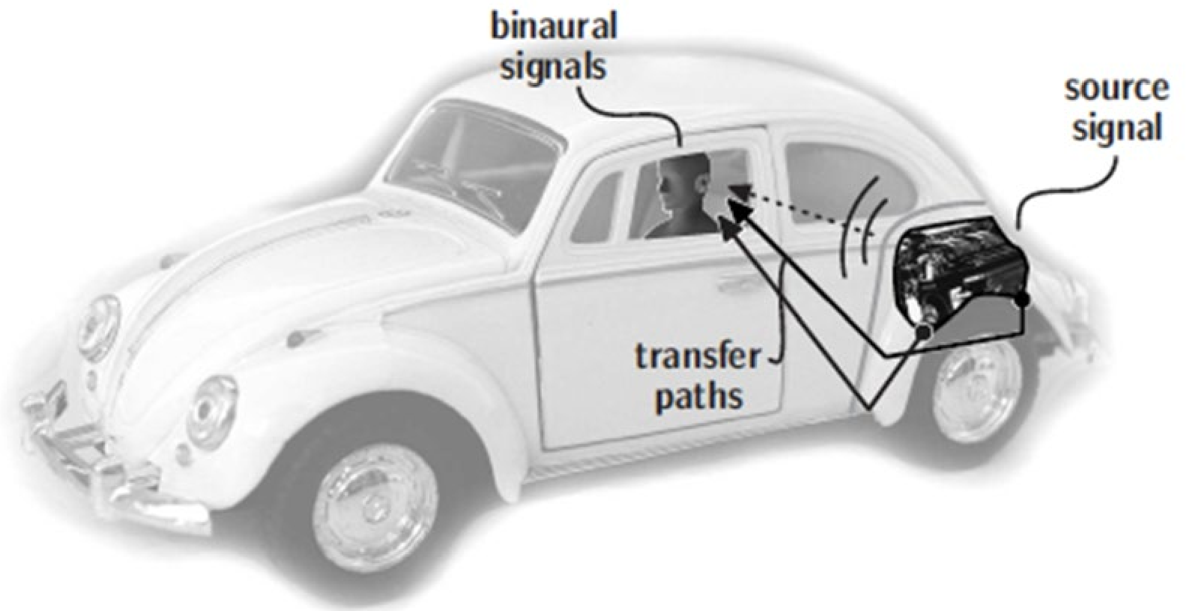
Motivation

The aim is …

- To understand the entire chain of the sound signal
  - from the source to the ear
    - Motor as the source



    - Transfer paths
      - Car body
      - Other components
- Design of low noise motors
- Evaluation of noise source by room acoustics

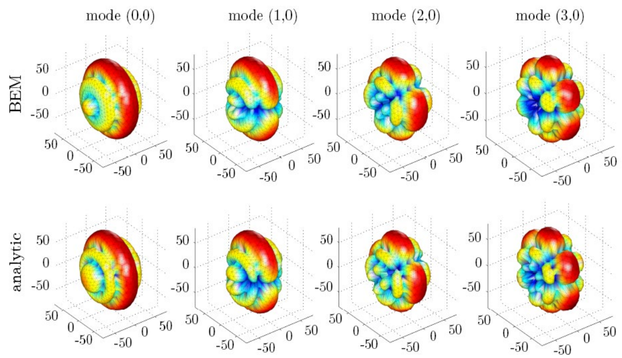


Source: Vorländer, M.: Auralization – Fundamentals of Acoustics, Modelling, Simulation, Algorithms and Acoustic Virtual Reality, Springer, 2007

Electric motor – room acoustic

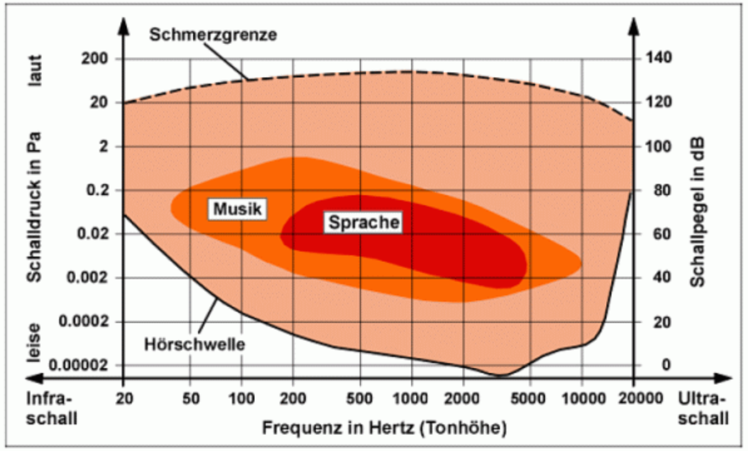
Overall acoustic models

- Actual room acoustic
  - Determined by measurement
- Simple acoustic motor model
  - Radiator models
    - Point
    - Cylinder
    - …

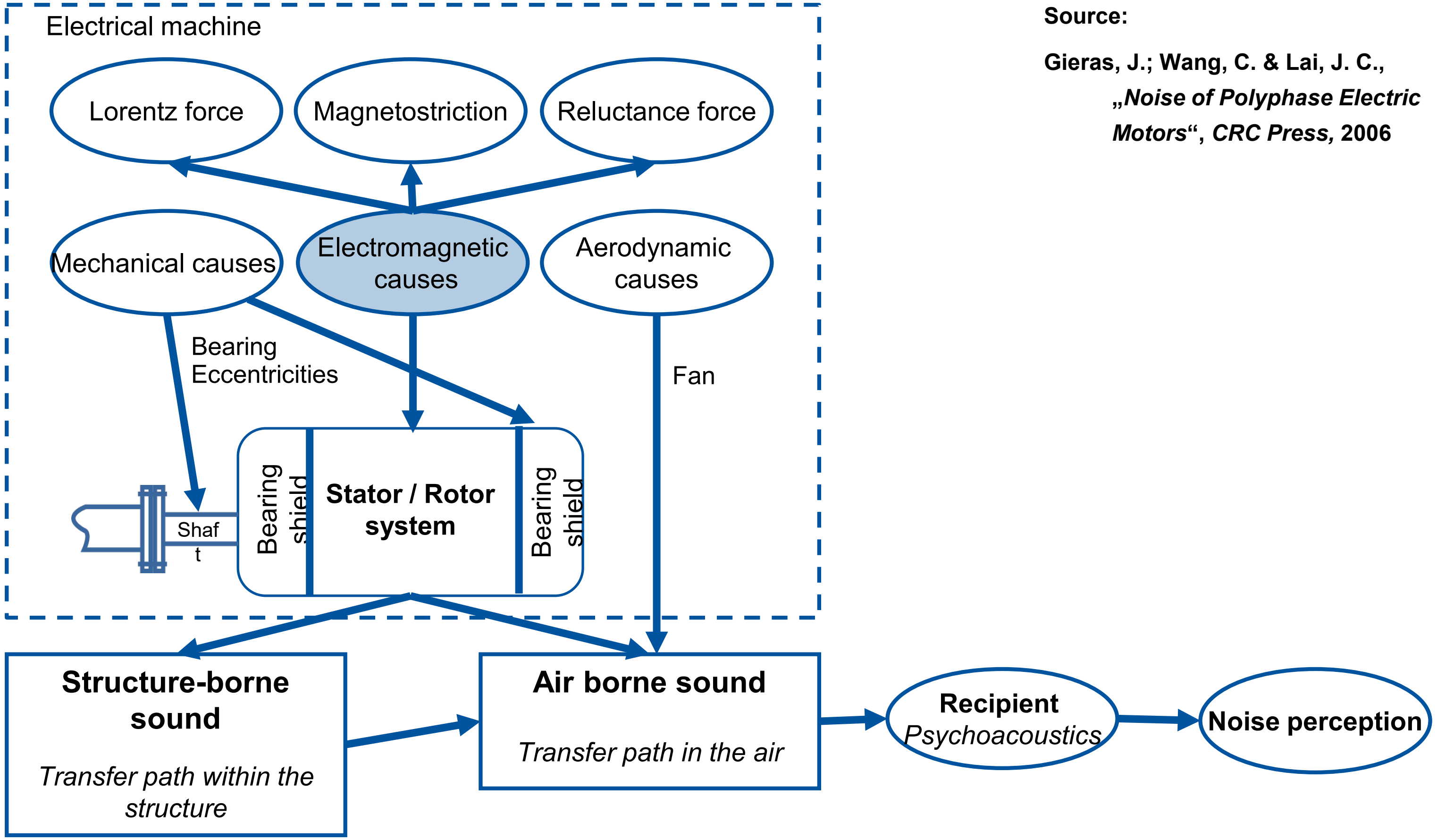


Cause of electromagnetically excited noise in electrical machines

- Bearings
  - Single tone (>3 kHz)
- Ventilation
  - Wide band noise (500 Hz… 1 kHz)
- Electromagnetically excited noise
  - Single tone (entire spectrum… 4 kHz)



Audible range of human ear



Electrical machine

Lorentz force

Magnetostriction

Reluctance force

Mechanical causes

Electromagnetic causes

Aerodynamic causes

Bearing Eccentricities

Fan

Shaft

Bearing shield

Stator / Rotor system

Bearing shield

Structure-borne sound

Transfer path within the structure

Air borne sound

Transfer path in the air

Recipient

Psychoacoustics

Noise perception

Source:

Gieras, J.; Wang, C. & Lai, J. C., *„Noise of Polyphase Electric Motors“, CRC Press,* 2006

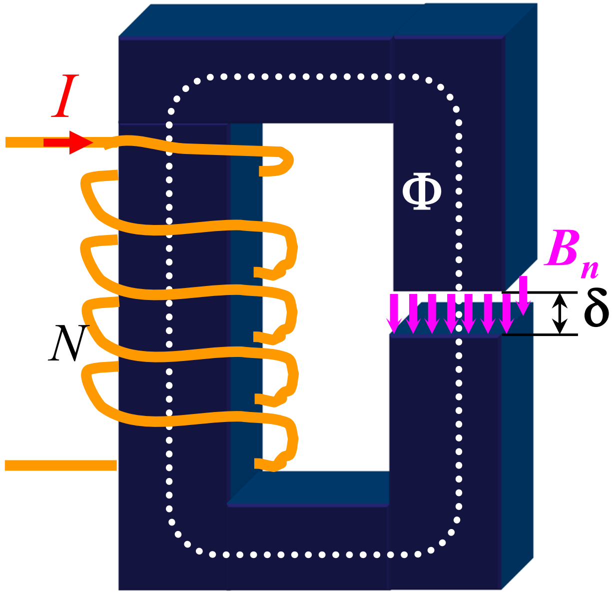
Air gap field

Relation between excitation current and resulting magnetic field

- Ampere's law

$$\text{rot}\,\vec{H} = \vec{\nabla} \times \vec{H} = \vec{J}$$

$$\oint_{\partial A} \vec{H}\; d\vec{s} = I$$



- *Current excitation*

$$\Theta = NI = R_m \cdot \Phi$$

- *Air gap magnetic field*

$$\begin{aligned} B_n &= \Lambda \cdot \Theta \\ &= \frac{\mu_0}{\delta} \cdot NI \end{aligned}$$

Electromagnetic forces

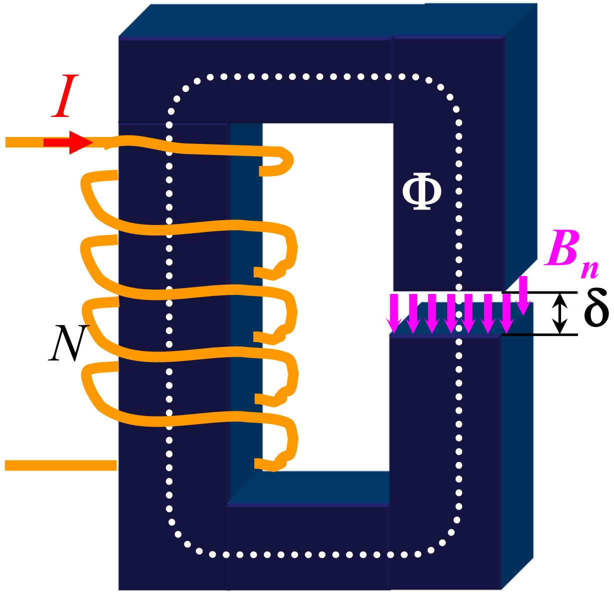
In rotating machines rotating air gap force waves

- *Ampere*'s law

$$\text{rot}\,\vec{H} = \vec{\nabla} \times \vec{H} = \vec{J}$$

$$\oint_{\partial A} \vec{H}\; d\vec{s} = I$$

- *Maxwell*-stress



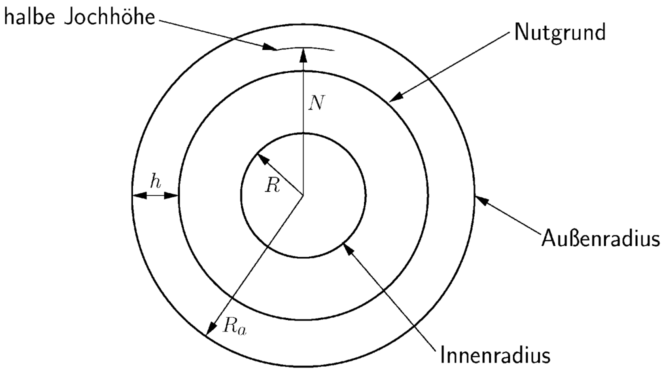
- *Attracting forces at the interface air - iron*

$$\sigma = \frac{B_n^2}{2\mu_0}$$

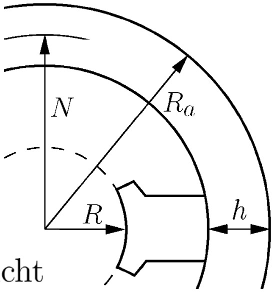
Generation of radial force waves in the air gap of an electric machine

Structure dynamic model

- The simple mode Δ is a kind of damping factor
- Mass is represented by the cross sectional area



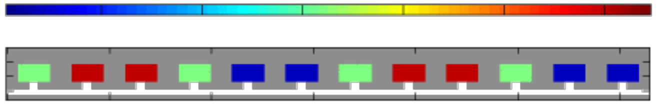
$$f_0 = \frac{C_s}{2\pi \cdot N \cdot \sqrt{\Delta}}$$



$$\Delta = \frac{\text{Jochgewicht} + \text{Zahngewicht}}{\text{Jochgewicht}}$$

Electro magnetic model

machine



Symmetric 3-phase current system

Basic analytical approach

- Fourier decomposition of air gap field

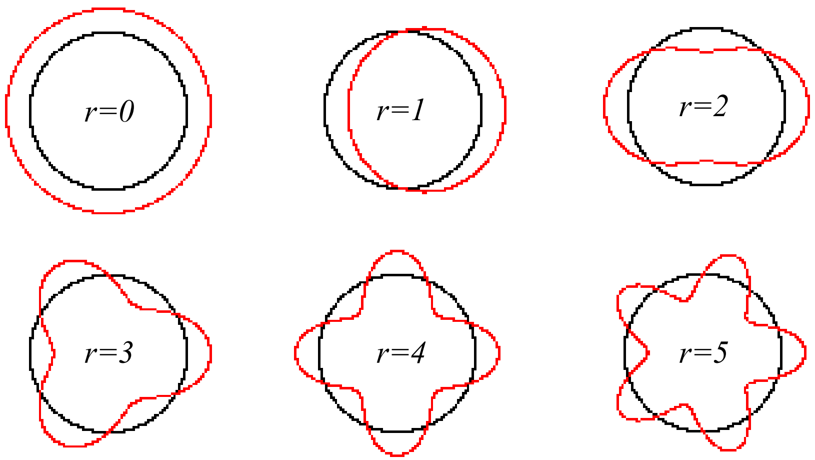
$$b_n(x,t) = \sum_i \hat{B}_i \cdot \cos(\nu_i x - \omega_i t - \psi_i)$$

- Radial rotating force waves
  - oscillation mode r (pole pair number)
  - Frequency f (angular velocity)

$$\sigma_r(x,t) = \frac{1}{2\mu_0}\left[\sum_i \hat{B}_i \cdot \cos(\nu_i x - \omega_i t - \psi_i)\right]^2$$

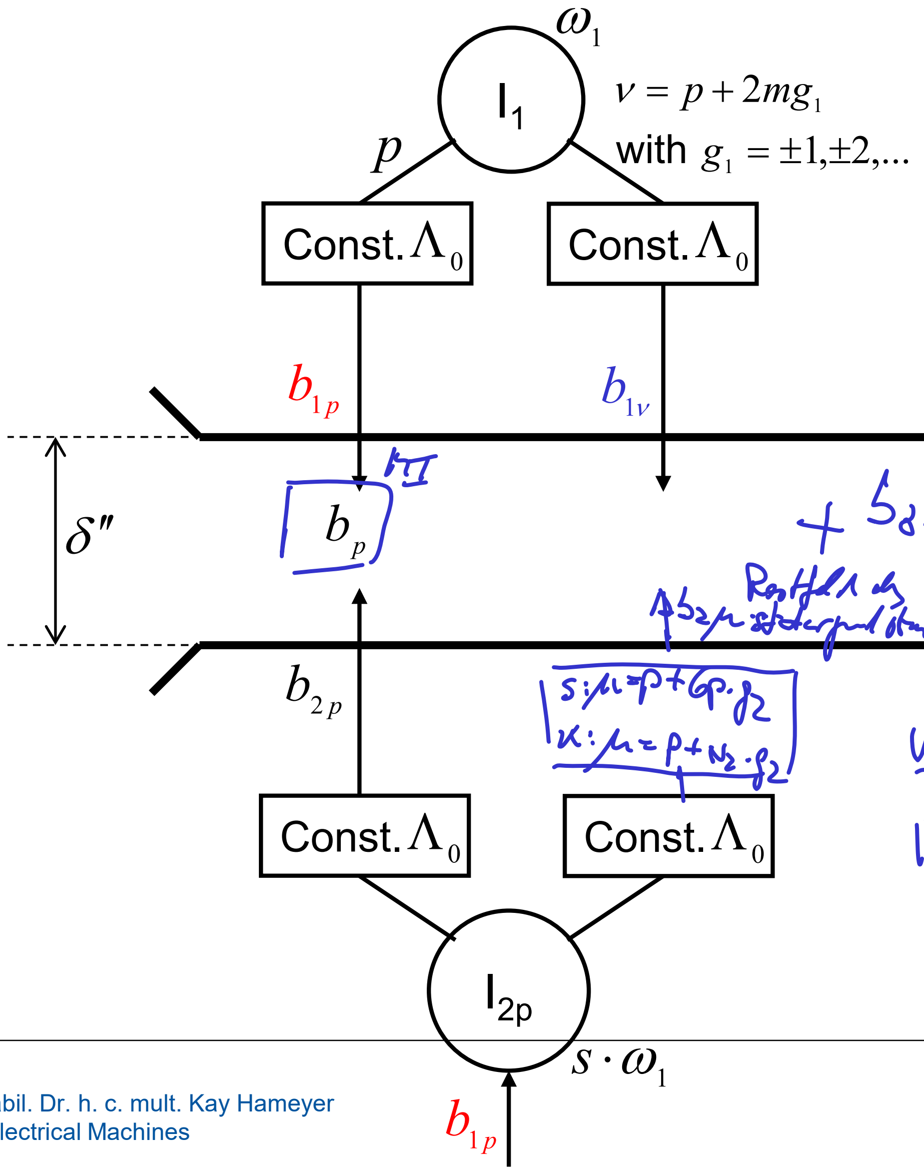
$$\sigma_r(x,t) = \frac{1}{2\mu_0}\sum_j \sum_k \frac{\hat{B}_j \hat{B}_k}{2} \cos((\underbrace{\nu_j \pm \nu_k}_{=r})x - (\underbrace{\omega_j \pm \omega_k}_{=\omega_r})t - \psi_j \pm \psi_k)$$

$$\Rightarrow \boxed{f_r = f_j \pm f_k, \quad r = \nu_j \pm \nu_k}$$



[illegible] Sprung

Induction motor air gap field



Wicklg 1

$\bar{\nu} = p + N_1 \cdot g_1^*$

Ex : $\bar{\nu} = p \pm 1$

Sättigg : $\bar{\nu} = 3p$

+ $b_{\delta\nu}$ ... Ständerwicklungsoberfelder

Restfeld des $b_{2\mu}$-Ständergrundfeldes

$S: \mu = p + 6p \cdot g_2$

$K: \mu = p + N_2 \cdot g_2$

$b_{2\nu}$

$b_{2\mu}$ ... Restfelder der Wicklungsoberfelder

ν

$S: \mu = \nu + 6 \cdot p \cdot g_2$

$K: \mu = \nu + N_2 \cdot g_2$

$I_{2\nu}$

$b_{1\nu}$

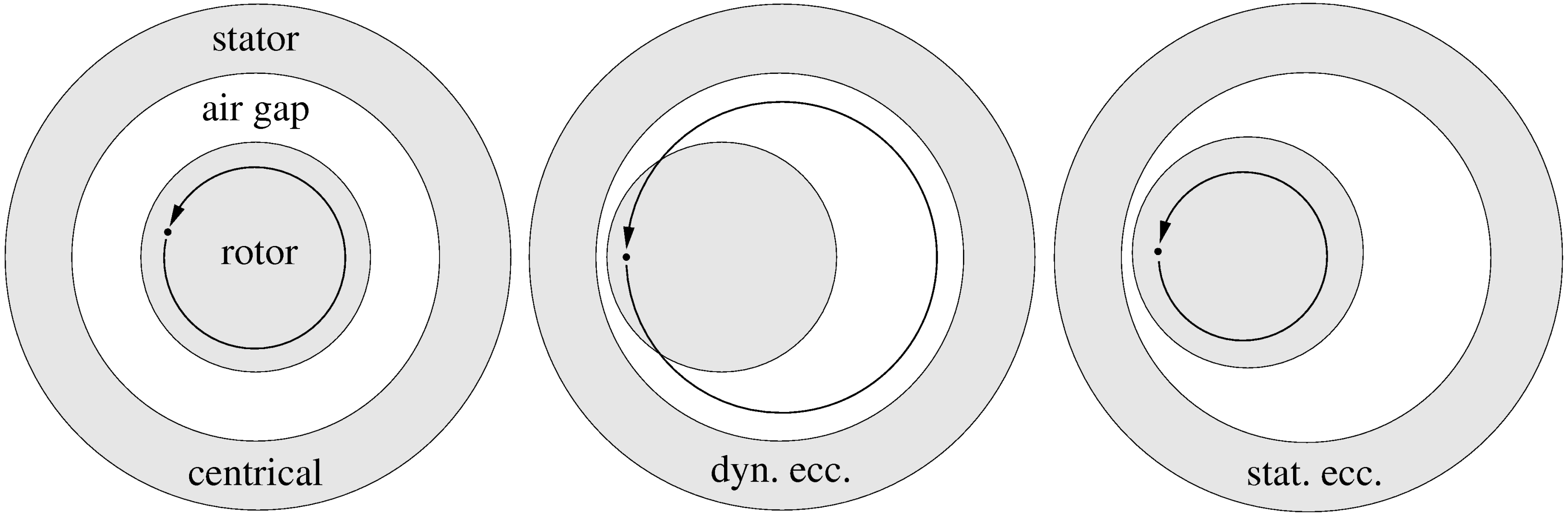
$\bar{\nu} = p + N_2 \cdot g_2^*$

Wicklg 2

Most important parameter and analytical spread sheet approach (example: induction machine)

Spread sheet tables for noise excitation estimation (induction machine, squirrel cage rotor)

- Rotor fields combined with stator field excited by current with fundamental frequency
- Rotor fields combined with tooth saturation fields
- Rotor fields combined with eccentricity fields (static and dynamic)



Analytical approach (example induction machine)

Stator winding harmonic
$\mu_w = 2mg + 1$

Rotor winding harmonic
$\lambda_w = \frac{gS_2}{p} + 1$

Stator slot harmonic
$\mu_1 = \frac{gS_1}{p} + 1$

Rotor slot harmonic
$\lambda_2 = \frac{gS_1}{p} + 1$

Saturation harmonic
$\lambda_{Sätt} = \frac{gS_2}{p} + 3$

Excentricity harmonic
$\lambda_{exz} = g6 + 1$

$$r = \mu_w \pm \lambda_w$$

$$f_r = f_1\left[\frac{gS_2}{p}(1-s) + \left\langle\begin{matrix}2\\0\end{matrix}\right]\right]$$

$$r = \mu_w \pm \lambda_{sat}$$

$$f_r = f_1\left[\frac{gS_2}{p}(1-s) + \left\langle\begin{matrix}4\\2\end{matrix}\right]\right]$$

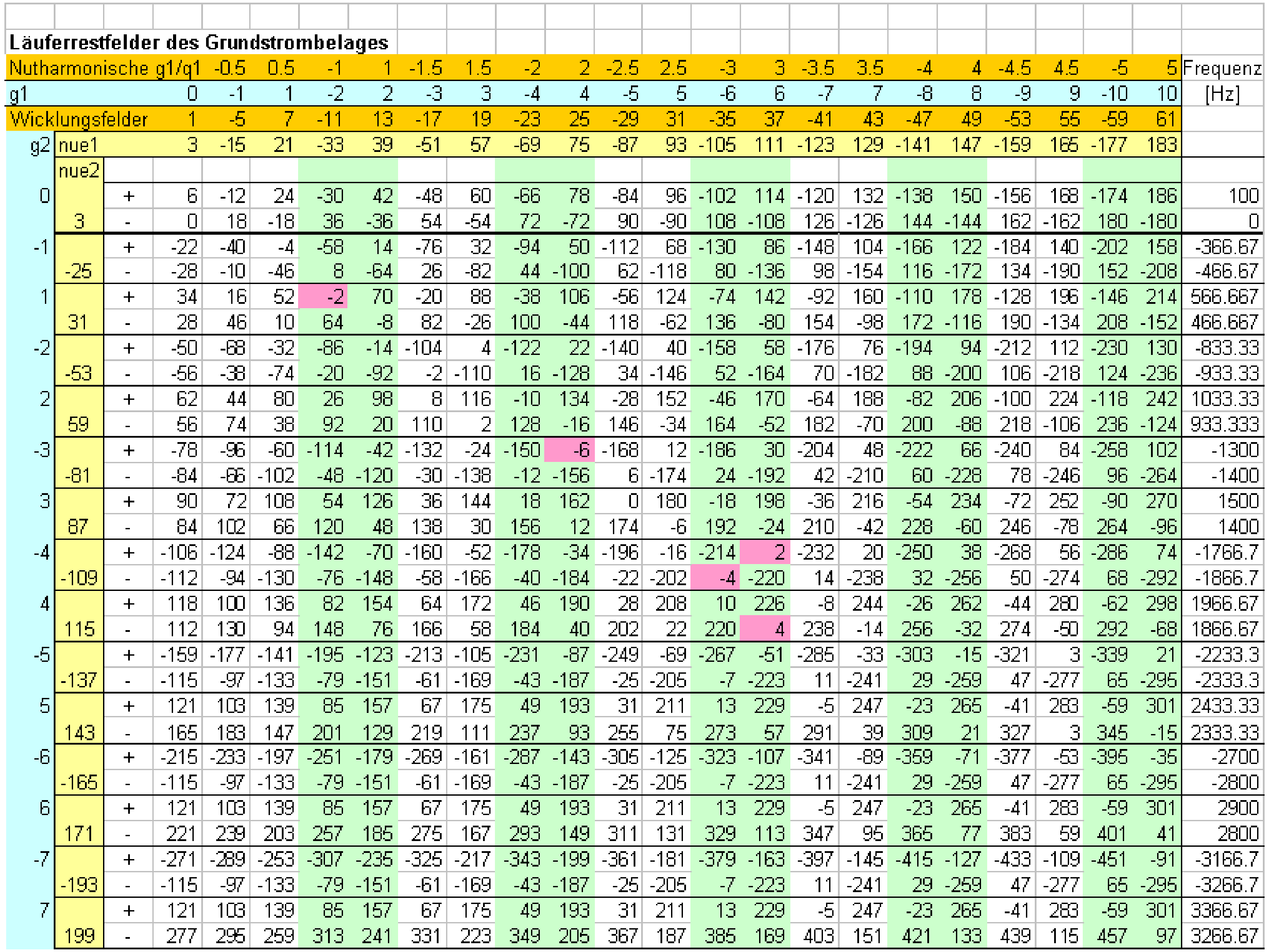
⋮

- Resulting force waves have mode number and direction of rotation
  - $g = 0, \pm 1, \pm 2, \pm 3, \ldots$
  - S_1, S_2: Slotnumber stator resp. rotor
  - p: pole pair number
  - s: slip
  - f_1: stator frequency

g	$\mu_w = 2mg + 1$	$\lambda_w = \frac{gS_2}{p} + 1$	$\mu_1 = \frac{gS_1}{p} + 1$	$\lambda_{Sätt} = \frac{gS_2}{p} + 3$
0	1	1	1	1
-1	-5	-12	-17	-12
1	7	14	19	14
-2	-11	-25	-35	-25
2	13	27	37	27
-3	-17	-38	-53	-38
3	19	40	55	40

Excitation with current of fundamental frequency

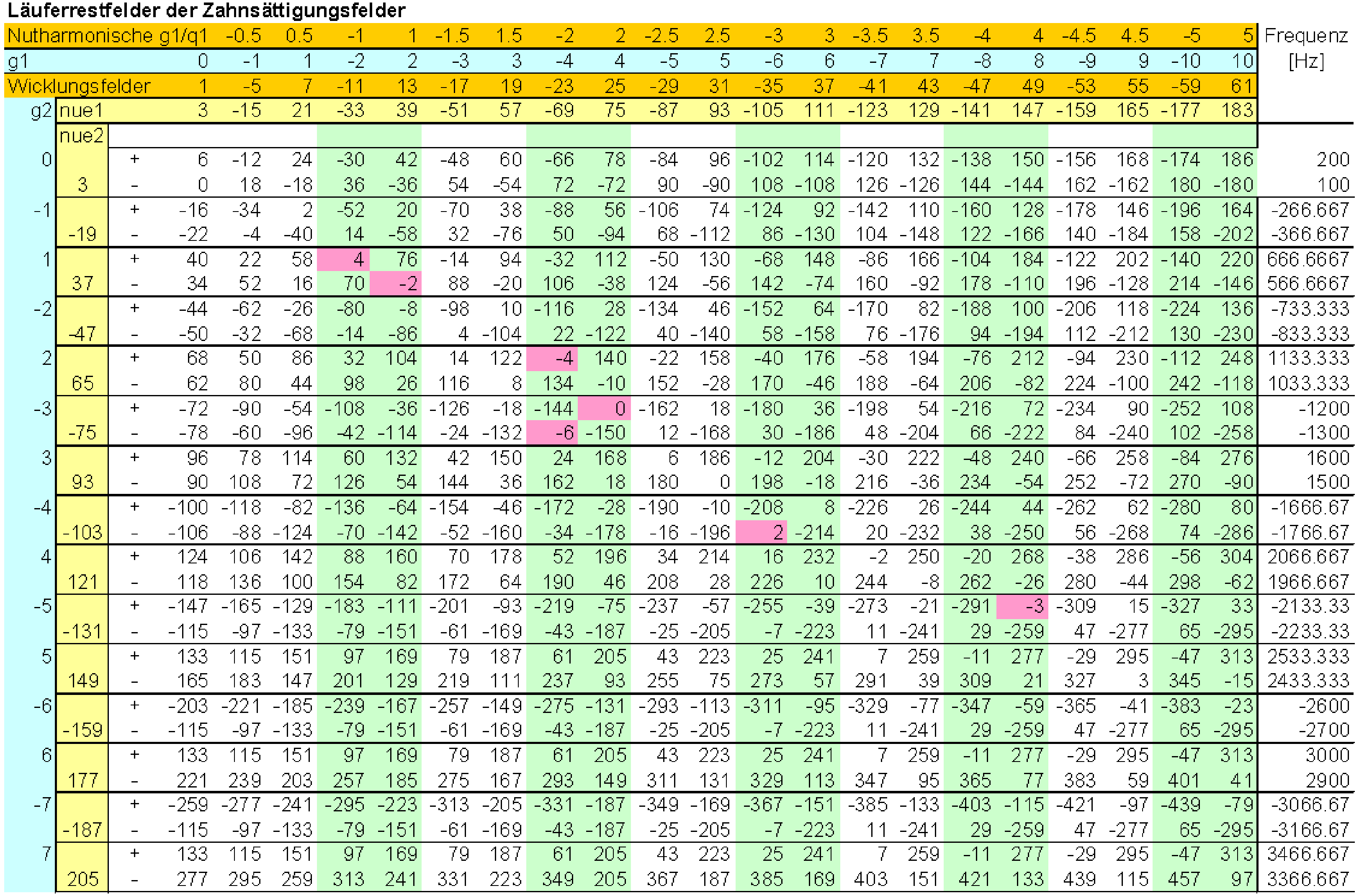
No-load operation (s=0)



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
4		+	118	100	136	82	154	64	172	46	190	28	208	10	226	-8	244	-26	262	-44	280	-62	298	1966.67
	115	-	112	130	94	148	76	166	58	184	40	202	22	220	4	238	-14	256	-32	274	-50	292	-68	1866.67
-5		+	-159	-177	-141	-195	-123	-213	-105	-231	-87	-249	-69	-267	-51	-285	-33	-303	-15	-321	3	-339	21	-2233.3
	-137	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-2333.3
5		+	121	103	139	85	157	67	175	49	193	31	211	13	229	-5	247	-23	265	-41	283	-59	301	2433.33
	143	-	165	183	147	201	129	219	111	237	93	255	75	273	57	291	39	309	21	327	3	345	-15	2333.33
-6		+	-215	-233	-197	-251	-179	-269	-161	-287	-143	-305	-125	-323	-107	-341	-89	-359	-71	-377	-53	-395	-35	-2700
	-165	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-2800
6		+	121	103	139	85	157	67	175	49	193	31	211	13	229	-5	247	-23	265	-41	283	-59	301	2900
	171	-	221	239	203	257	185	275	167	293	149	311	131	329	113	347	95	365	77	383	59	401	41	2800
-7		+	-271	-289	-253	-307	-235	-325	-217	-343	-199	-361	-181	-379	-163	-397	-145	-415	-127	-433	-109	-451	-91	-3166.7
	-193	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-3266.7
7		+	121	103	139	85	157	67	175	49	193	31	211	13	229	-5	247	-23	265	-41	283	-59	301	3366.67
	199	-	277	295	259	313	241	331	223	349	205	367	187	385	169	403	151	421	133	439	115	457	97	3266.67

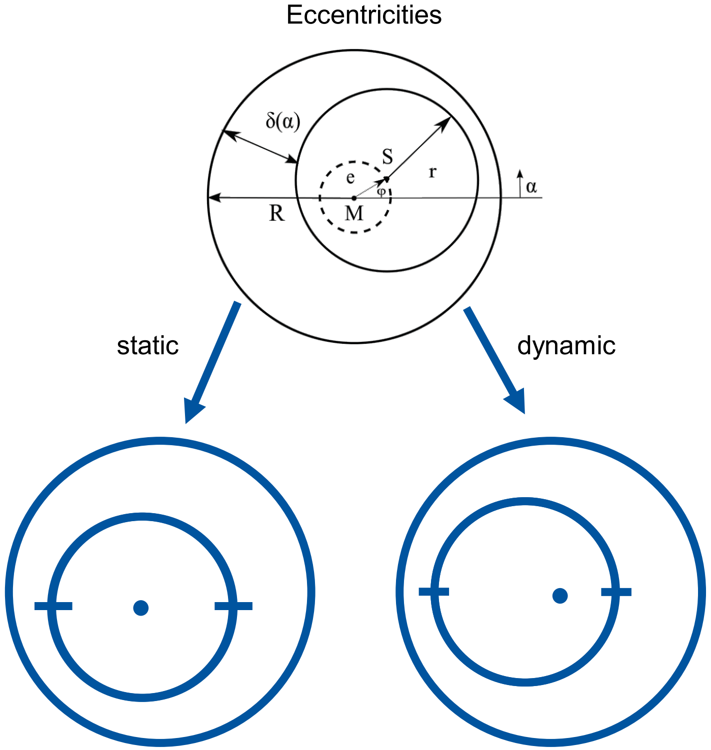
Tooth saturation

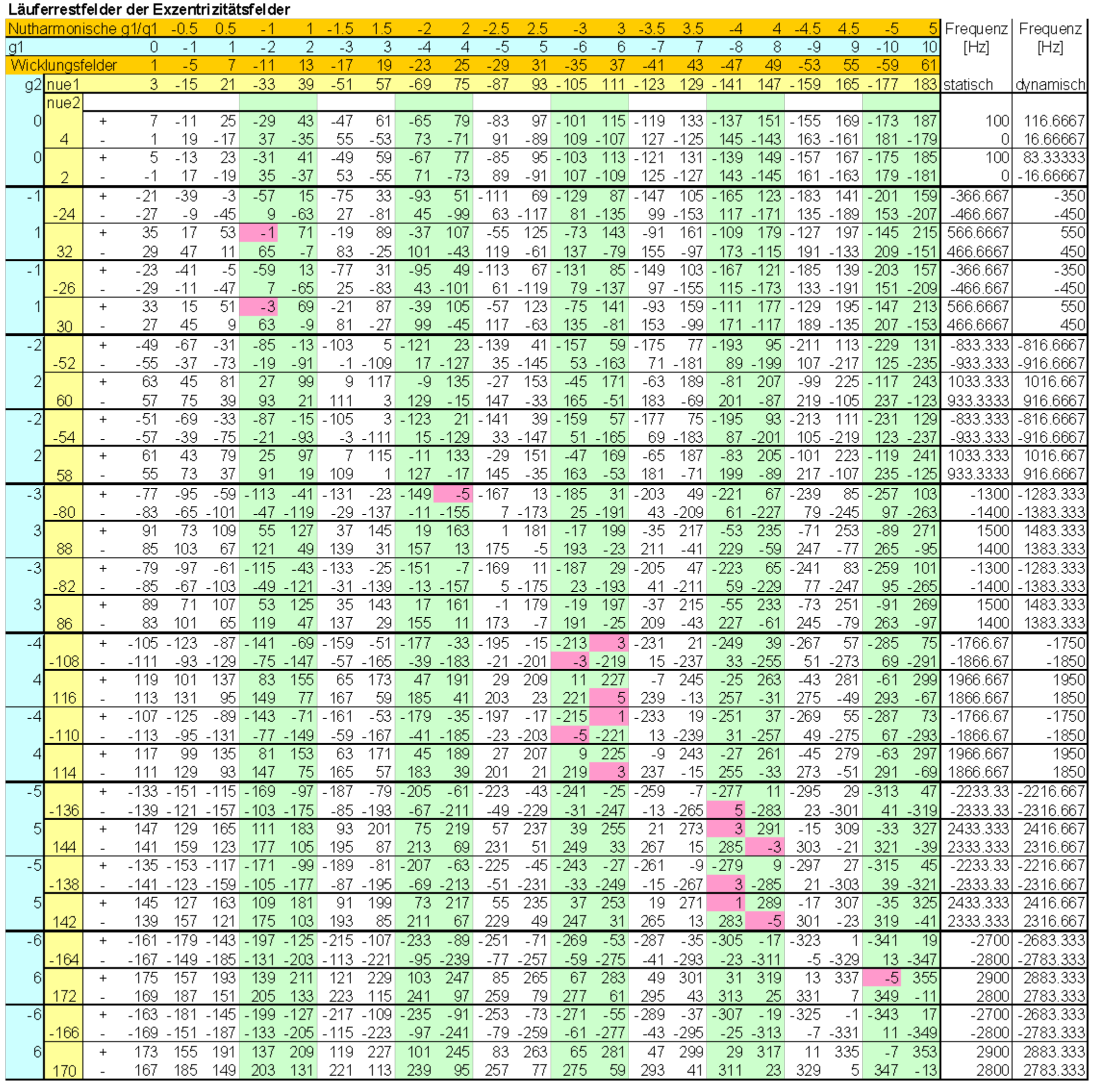


Läuferrestfelder der Zahnsättigungsfelder

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 [Hz]
g1			0	-1	1	-2	2	-3	3	-4	4	-5	5	-6	6	-7	7	-8	8	-9	9	-10	10	
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	200
	3	-	0	18	-18	36	-36	54	-54	72	-72	90	-90	108	-108	126	-126	144	-144	162	-162	180	-180	100
-1		+	-16	-34	2	-52	20	-70	38	-88	56	-106	74	-124	92	-142	110	-160	128	-178	146	-196	164	-266.667
	-19	-	-22	-4	-40	14	-58	32	-76	50	-94	68	-112	86	-130	104	-148	122	-166	140	-184	158	-202	-366.667
1		+	40	22	58	4	76	-14	94	-32	112	-50	130	-68	148	-86	166	-104	184	-122	202	-140	220	666.6667
	37	-	34	52	16	70	-2	88	-20	106	-38	124	-56	142	-74	160	-92	178	-110	196	-128	214	-146	566.6667
-2		+	-44	-62	-26	-80	-8	-98	10	-116	28	-134	46	-152	64	-170	82	-188	100	-206	118	-224	136	-733.333
	-47	-	-50	-32	-68	-14	-86	4	-104	22	-122	40	-140	58	-158	76	-176	94	-194	112	-212	130	-230	-833.333
2		+	68	50	86	32	104	14	122	-4	140	-22	158	-40	176	-58	194	-76	212	-94	230	-112	248	1133.333
	65	-	62	80	44	98	26	116	8	134	-10	152	-28	170	-46	188	-64	206	-82	224	-100	242	-118	1033.333
-3		+	-72	-90	-54	-108	-36	-126	-18	-144	0	-162	18	-180	36	-198	54	-216	72	-234	90	-252	108	-1200
	-75	-	-78	-60	-96	-42	-114	-24	-132	-6	-150	12	-168	30	-186	48	-204	66	-222	84	-240	102	-258	-1300
3		+	96	78	114	60	132	42	150	24	168	6	186	-12	204	-30	222	-48	240	-66	258	-84	276	1600
	93	-	90	108	72	126	54	144	36	162	18	180	0	198	-18	216	-36	234	-54	252	-72	270	-90	1500
-4		+	-100	-118	-82	-136	-64	-154	-46	-172	-28	-190	-10	-208	8	-226	26	-244	44	-262	62	-280	80	-1666.67
	-103	-	-106	-88	-124	-70	-142	-52	-160	-34	-178	-16	-196	2	-214	20	-232	38	-250	56	-268	74	-286	-1766.67
4		+	124	106	142	88	160	70	178	52	196	34	214	16	232	-2	250	-20	268	-38	286	-56	304	2066.667
	121	-	118	136	100	154	82	172	64	190	46	208	28	226	10	244	-8	262	-26	280	-44	298	-62	1966.667
-5		+	-147	-165	-129	-183	-111	-201	-93	-219	-75	-237	-57	-255	-39	-273	-21	-291	-3	-309	15	-327	33	-2133.33
	-131	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-2233.33
5		+	133	115	151	97	169	79	187	61	205	43	223	25	241	7	259	-11	277	-29	295	-47	313	2533.333
	149	-	165	183	147	201	129	219	111	237	93	255	75	273	57	291	39	309	21	327	3	345	-15	2433.333
-6		+	-203	-221	-185	-239	-167	-257	-149	-275	-131	-293	-113	-311	-95	-329	-77	-347	-59	-365	-41	-383	-23	-2600
	-159	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-2700
6		+	133	115	151	97	169	79	187	61	205	43	223	25	241	7	259	-11	277	-29	295	-47	313	3000
	177	-	221	239	203	257	185	275	167	293	149	311	131	329	113	347	95	365	77	383	59	401	41	2900
-7		+	-259	-277	-241	-295	-223	-313	-205	-331	-187	-349	-169	-367	-151	-385	-133	-403	-115	-421	-97	-439	-79	-3066.67
	-187	-	-115	-97	-133	-79	-151	-61	-169	-43	-187	-25	-205	-7	-223	11	-241	29	-259	47	-277	65	-295	-3166.67
7		+	133	115	151	97	169	79	187	61	205	43	223	25	241	7	259	-11	277	-29	295	-47	313	3466.667
	205	-	277	295	259	313	241	331	223	349	205	367	187	385	169	403	151	421	133	439	115	457	97	3366.667

Excentricity





Läuferrestfelder der Exzentrizitätsfelder

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 [Hz]	Frequenz [Hz]
g1			0	-1	1	-2	2	-3	3	-4	4	-5	5	-6	6	-7	7	-8	8	-9	9	-10	10		
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	statisch	dynamisch
	nue2																								
0		+	7	-11	25	-29	43	-47	61	-65	79	-83	97	-101	115	-119	133	-137	151	-155	169	-173	187	100	116.6667
	4	-	1	19	-17	37	-35	55	-53	73	-71	91	-89	109	-107	127	-125	145	-143	163	-161	181	-179	0	16.66667
0		+	5	-13	23	-31	41	-49	59	-67	77	-85	95	-103	113	-121	131	-139	149	-157	167	-175	185	100	83.33333
	2	-	-1	17	-19	35	-37	53	-55	71	-73	89	-91	107	-109	125	-127	143	-145	161	-163	179	-181	0	-16.66667
-1		+	-21	-39	-3	-57	15	-75	33	-93	51	-111	69	-129	87	-147	105	-165	123	-183	141	-201	159	-366.667	-350
	-24	-	-27	-9	-45	9	-63	27	-81	45	-99	63	-117	81	-135	99	-153	117	-171	135	-189	153	-207	-466.667	-450
1		+	35	17	53	-1	71	-19	89	-37	107	-55	125	-73	143	-91	161	-109	179	-127	197	-145	215	566.6667	550
	32	-	29	47	11	65	-7	83	-25	101	-43	119	-61	137	-79	155	-97	173	-115	191	-133	209	-151	466.6667	450
-1		+	-23	-41	-5	-59	13	-77	31	-95	49	-113	67	-131	85	-149	103	-167	121	-185	139	-203	157	-366.667	-350
	-26	-	-29	-11	-47	7	-65	25	-83	43	-101	61	-119	79	-137	97	-155	115	-173	133	-191	151	-209	-466.667	-450
1		+	33	15	51	-3	69	-21	87	-39	105	-57	123	-75	141	-93	159	-111	177	-129	195	-147	213	566.6667	550
	30	-	27	45	9	63	-9	81	-27	99	-45	117	-63	135	-81	153	-99	171	-117	189	-135	207	-153	466.6667	450
-2		+	-49	-67	-31	-85	-13	-103	5	-121	23	-139	41	-157	59	-175	77	-193	95	-211	113	-229	131	-833.333	-816.6667
	-52	-	-55	-37	-73	-19	-91	-1	-109	17	-127	35	-145	53	-163	71	-181	89	-199	107	-217	125	-235	-933.333	-916.6667
2		+	63	45	81	27	99	9	117	-9	135	-27	153	-45	171	-63	189	-81	207	-99	225	-117	243	1033.333	1016.667
	60	-	57	75	39	93	21	111	3	129	-15	147	-33	165	-51	183	-69	201	-87	219	-105	237	-123	933.3333	916.6667
-2		+	-51	-69	-33	-87	-15	-105	3	-123	21	-141	39	-159	57	-177	75	-195	93	-213	111	-231	129	-833.333	-816.6667
	-54	-	-57	-39	-75	-21	-93	-3	-111	15	-129	33	-147	51	-165	69	-183	87	-201	105	-219	123	-237	-933.333	-916.6667
2		+	61	43	79	25	97	7	115	-11	133	-29	151	-47	169	-65	187	-83	205	-101	223	-119	241	1033.333	1016.667
	58	-	55	73	37	91	19	109	1	127	-17	145	-35	163	-53	181	-71	199	-89	217	-107	235	-125	933.3333	916.6667
-3		+	-77	-95	-59	-113	-41	-131	-23	-149	-5	-167	13	-185	31	-203	49	-221	67	-239	85	-257	103	-1300	-1283.333
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3		+	91	73	109	55	127	37	145	19	163	1	181	-17	199	-35	217	-53	235	-71	253	-89	271	1500	1483.333
	88	-	85	103	67	121	49	139	31	157	13	175	-5	193	-23	211	-41	229	-59	247	-77	265	-95	1400	1383.333
-3		+	-79	-97	-61	-115	-43	-133	-25	-151	-7	-169	11	-187	29	-205	47	-223	65	-241	83	-259	101	-1300	-1283.333
	-82	-	-85	-67	-103	-49	-121	-31	-139	-13	-157	5	-175	23	-193	41	-211	59	-229	77	-247	95	-265	-1400	-1383.333
3		+	89	71	107	53	125	35	143	17	161	-1	179	-19	197	-37	215	-55	233	-73	251	-91	269	1500	1483.333
	86	-	83	101	65	119	47	137	29	155	11	173	-7	191	-25	209	-43	227	-61	245	-79	263	-97	1400	1383.333
-4		+	-105	-123	-87	-141	-69	-159	-51	-177	-33	-195	-15	-213	3	-231	21	-249	39	-267	57	-285	75	-1766.67	-1750
	-108	-	-111	-93	-129	-75	-147	-57	-165	-39	-183	-21	-201	-3	-219	15	-237	33	-255	51	-273	69	-291	-1866.67	-1850
4		+	119	101	137	83	155	65	173	47	191	29	209	11	227	-7	245	-25	263	-43	281	-61	299	1966.667	1950
	116	-	113	131	95	149	77	167	59	185	41	203	23	221	5	239	-13	257	-31	275	-49	293	-67	1866.667	1850
-4		+	-107	-125	-89	-143	-71	-161	-53	-179	-35	-197	-17	-215	1	-233	19	-251	37	-269	55	-287	73	-1766.67	-1750
	-110	-	-113	-95	-131	-77	-149	-59	-167	-41	-185	-23	-203	-5	-221	13	-239	31	-257	49	-275	67	-293	-1866.67	-1850
4		+	117	99	135	81	153	63	171	45	189	27	207	9	225	-9	243	-27	261	-45	279	-63	297	1966.667	1950
	114	-	111	129	93	147	75	165	57	183	39	201	21	219	3	237	-15	255	-33	273	-51	291	-69	1866.667	1850
-5		+	-133	-151	-115	-169	-97	-187	-79	-205	-61	-223	-43	-241	-25	-259	-7	-277	11	-295	29	-313	47	-2233.33	-2216.667
	-136	-	-139	-121	-157	-103	-175	-85	-193	-67	-211	-49	-229	-31	-247	-13	-265	5	-283	23	-301	41	-319	-2333.33	-2316.667
5		+	147	129	165	111	183	93	201	75	219	57	237	39	255	21	273	3	291	-15	309	-33	327	2433.333	2416.667
	144	-	141	159	123	177	105	195	87	213	69	231	51	249	33	267	15	285	-3	303	-21	321	-39	2333.333	2316.667
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5		+	145	127	163	109	181	91	199	73	217	55	235	37	253	19	271	1	289	-17	307	-35	325	2433.333	2416.667
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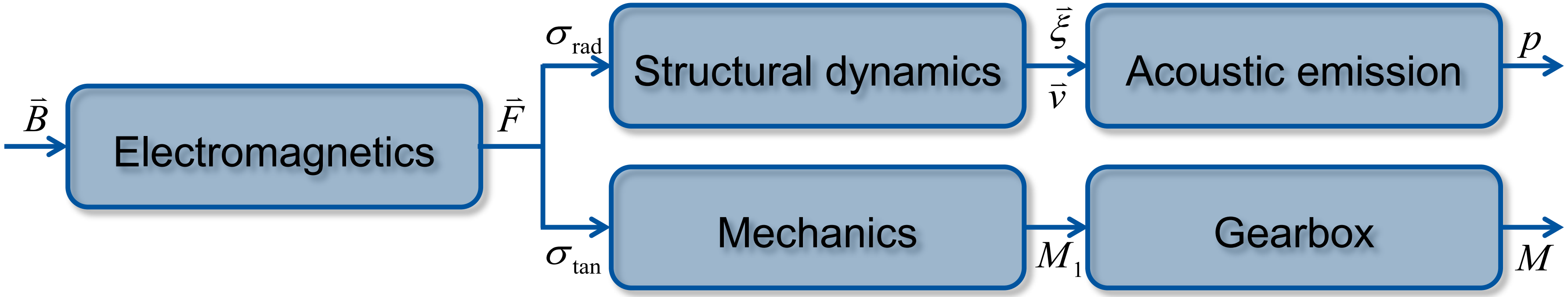
6		+	175	157	193	139	211	121	229	103	247	85	265	67	283	49	301	31	319	13	337	-5	355	2900	2883.333
	172	-	169	187	151	205	133	223	115	241	97	259	79	277	61	295	43	313	25	331	7	349	-11	2800	2783.333
-6		+	-163	-181	-145	-199	-127	-217	-109	-235	-91	-253	-73	-271	-55	-289	-37	-307	-19	-325	-1	-343	17	-2700	-2683.333
	-166	-	-169	-151	-187	-133	-205	-115	-223	-97	-241	-79	-259	-61	-277	-43	-295	-25	-313	-7	-331	11	-349	-2800	-2783.333
6		+	173	155	191	137	209	119	227	101	245	83	263	65	281	47	299	29	317	11	335	-7	353	2900	2883.333
	170	-	167	185	149	203	131	221	113	239	95	257	77	275	59	293	41	311	23	329	5	347	-13	2800	2783.333

What about tangential forces?

Force density in electrical machines



- Knowing the air gap flux density function is important to calculate the forces that act upon the stator
- In general, the force density can be determined from the air gap field with the aid of Maxwell‘s stress tensor:

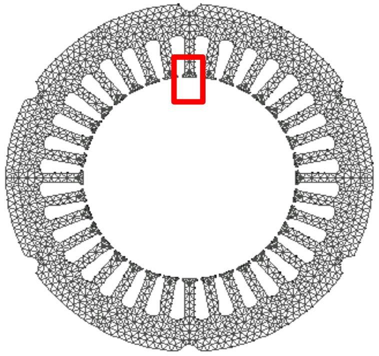
$$\sigma_{\mathrm{tan}}(\varphi,t) = \frac{1}{\mu_0} \cdot B_{\mathrm{rad}}(\varphi,t) \cdot B_{\mathrm{tan}}(\varphi,t)$$

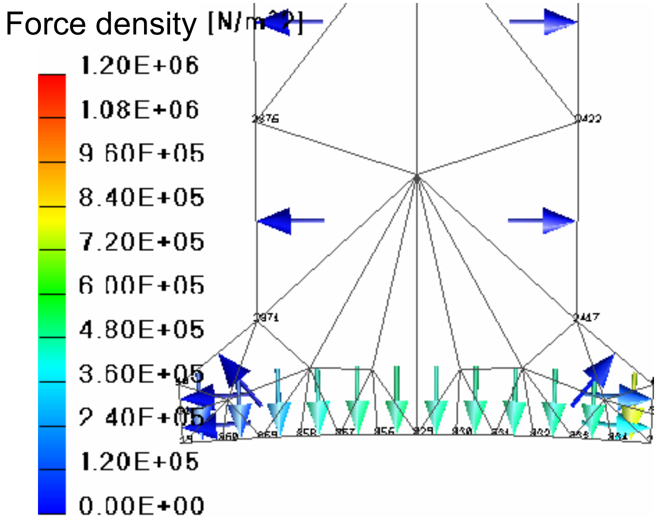
$$\sigma_{\mathrm{rad}}(\varphi,t) \approx \frac{1}{2\mu_0} \cdot B_{\mathrm{rad}}{}^2(\varphi,t)$$

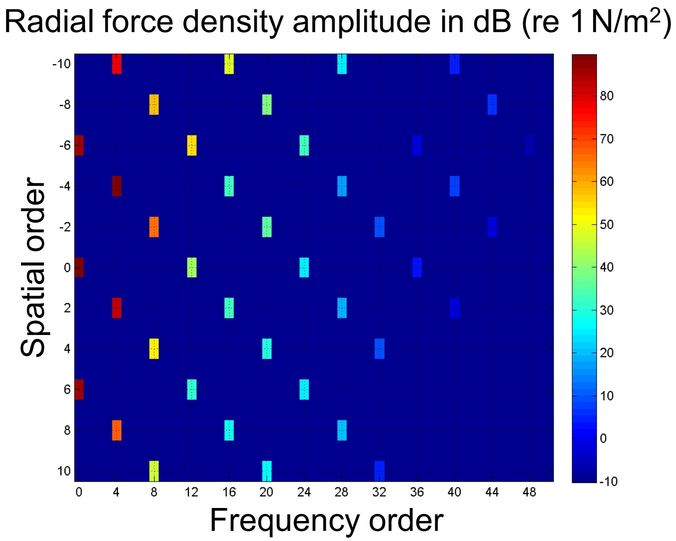
Multi-physical problem: Field – field - coupling

Electromagnetic simulation: Forces are the excitation of the structure dynamic model

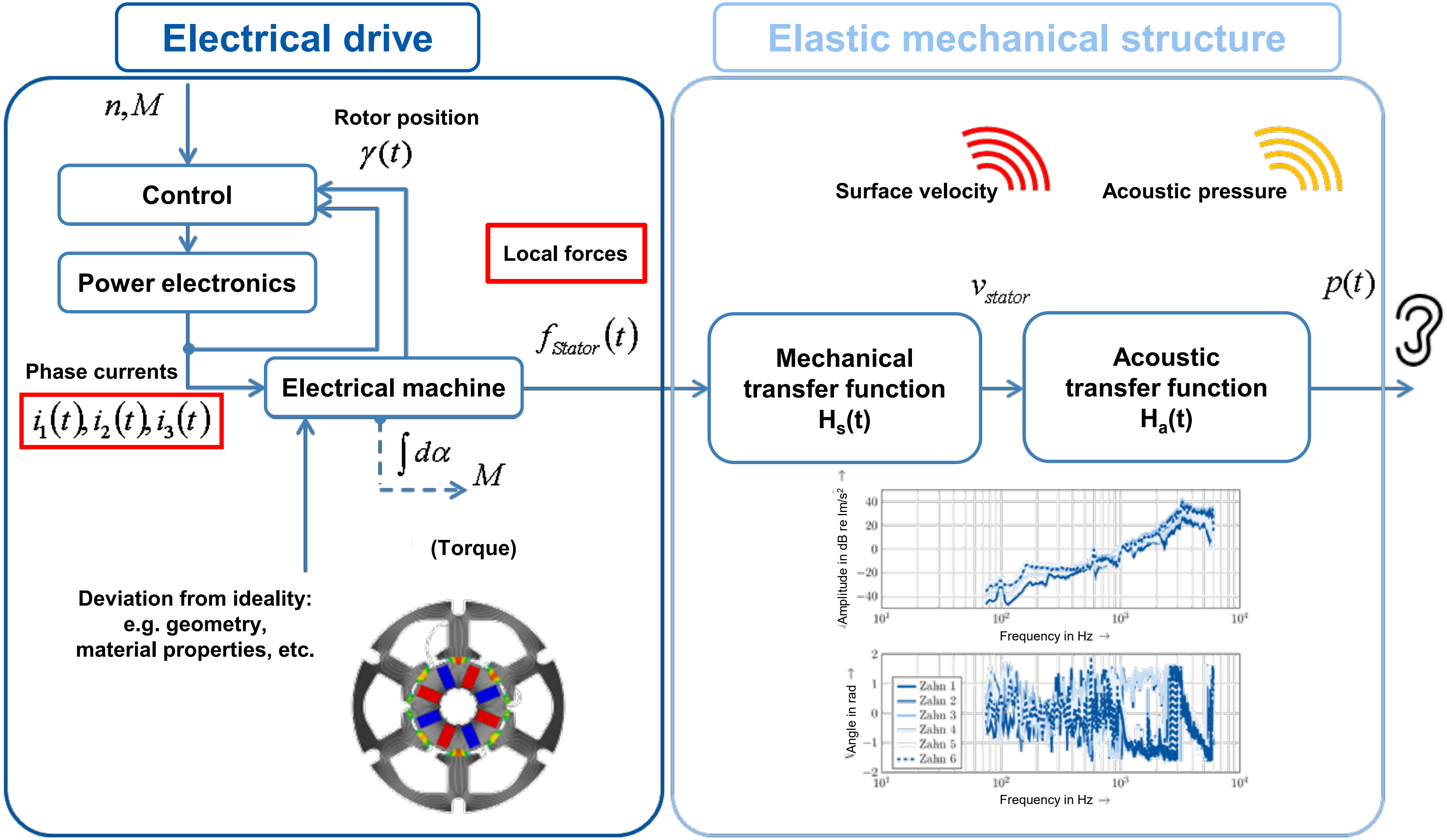
Electromagnetic 2D-Simulation → Outcome: flux density, tangential and radial forces and force densities → Analysis of the excitation force densities according to the spatial and frequency order







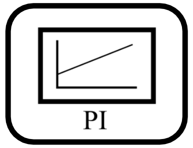
Overall drive train model



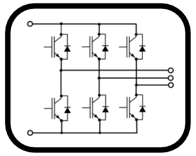
Components of the drive train

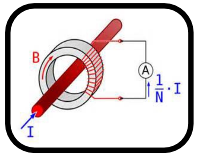
…. have influence on the excitation

- Control

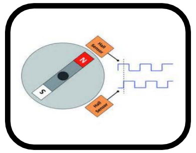


- Power electronics + sensors

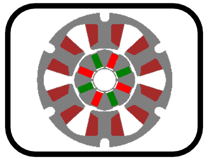




- Position and rotation speed measurement

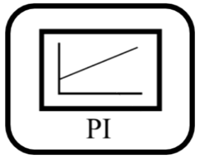


- Electrical machine



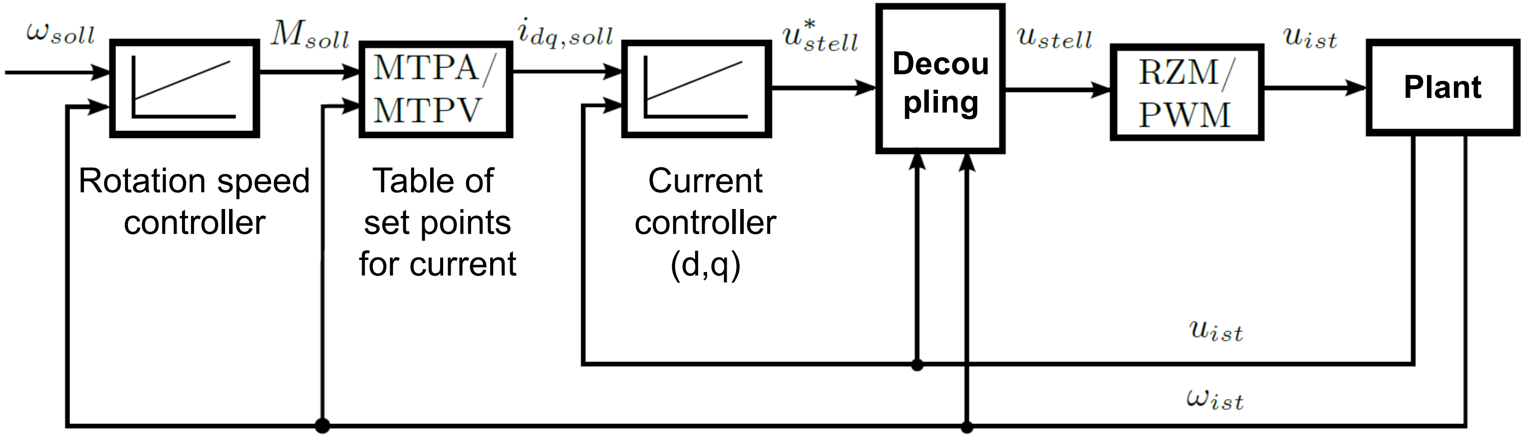
➔Non-ideal component properties and production tolerances cause deviations when compared to ideal simulations

Control strategy

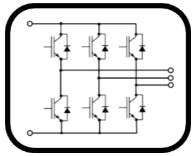


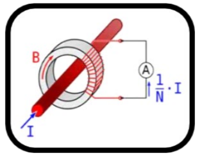
…. has influence on the excitation

- Control variable: position, speed, torque
- Standardized controller structure for industrial drives: cascade control
- The controller structure and settings directly influence the behavior of the machine, i.e.
  - Controlled speed
  - Transient response of control variables



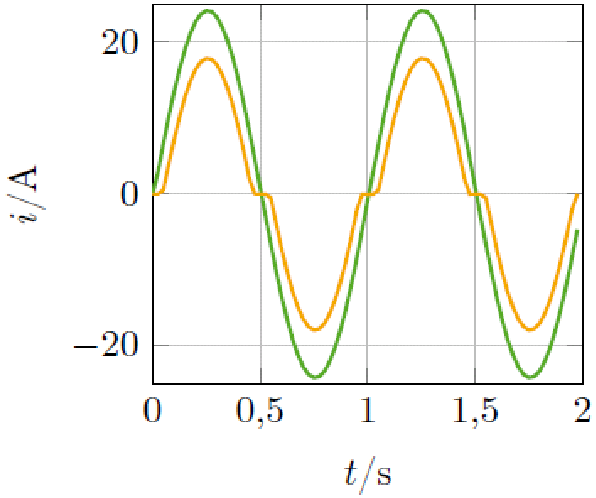
Power electronic supply

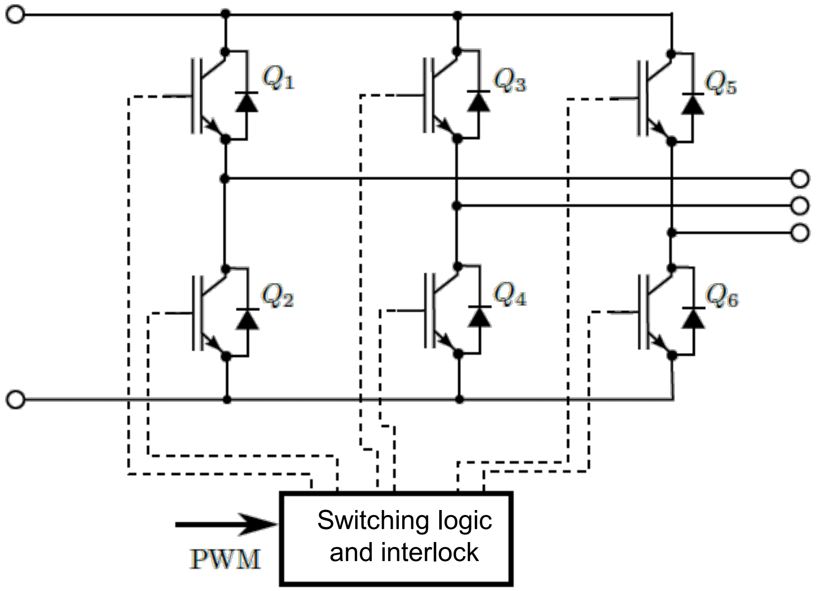




…. has influence on the excitation

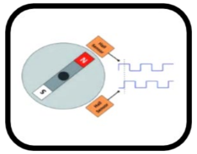
- The settings of the power supply of an electrical machine, specified by the control
- Control via PWM and switching logic
- The properties of the inverter are not ideal:
  - Parasitic semiconductor property (Turn-on and -off behavior)
  - Turn-on delay due to dead-time
  - Noise behavior of the current sensors





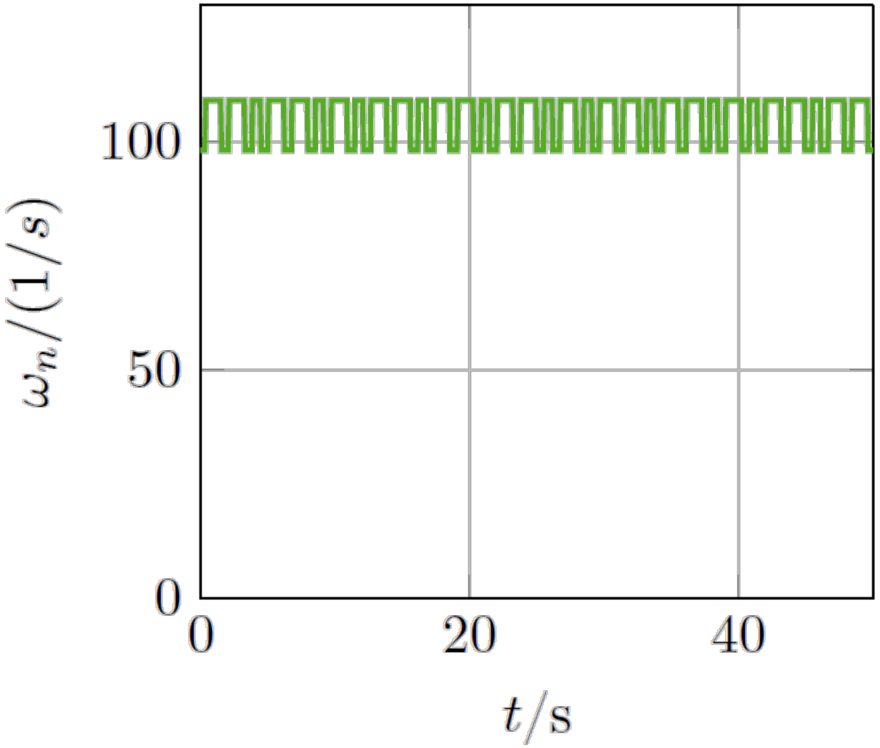
Sensors for speed or position

…. have influence on the excitation



- Rotary encoders used in the industry and their non-ideal properties:
  - Incremental encoder (rotation speed measurement): resolution
  - Phase-angle sensor (position detection): resolution
  - Resolver (position detection): noise behavior

- Position detection: the speed is composed with the difference quotient $^{\Delta\gamma}/_{\Delta T}$
- Speed measurement: the position is calculated by integrating the speed $\omega\ \Delta T$



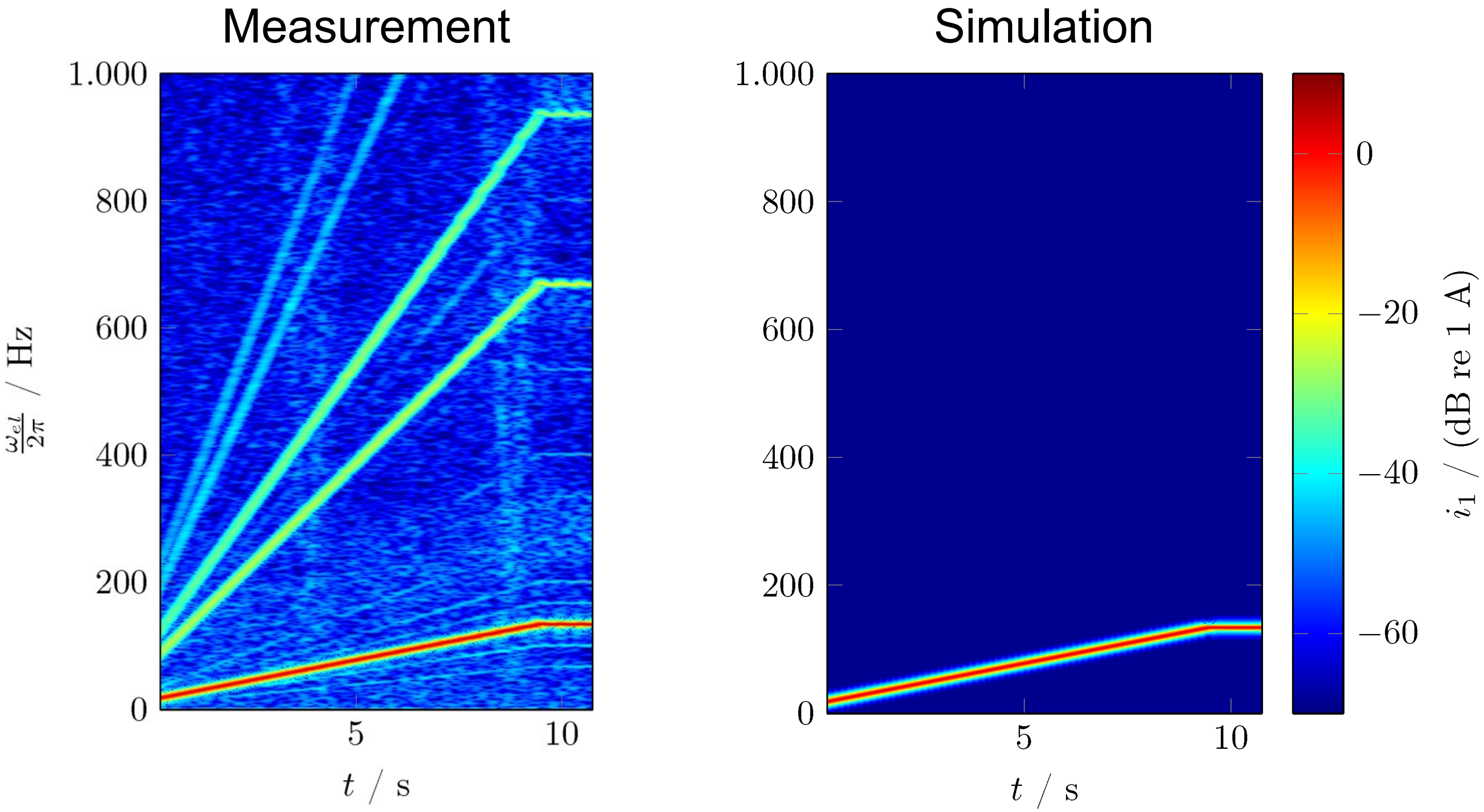
Run-up simulation of drive train with fundamental wave model

Electrical drive: Spectrogram phase current

PT1

PI

- Fundamental wave model
  - A single frequency within the spectrum (fundamental frequency of the currents)



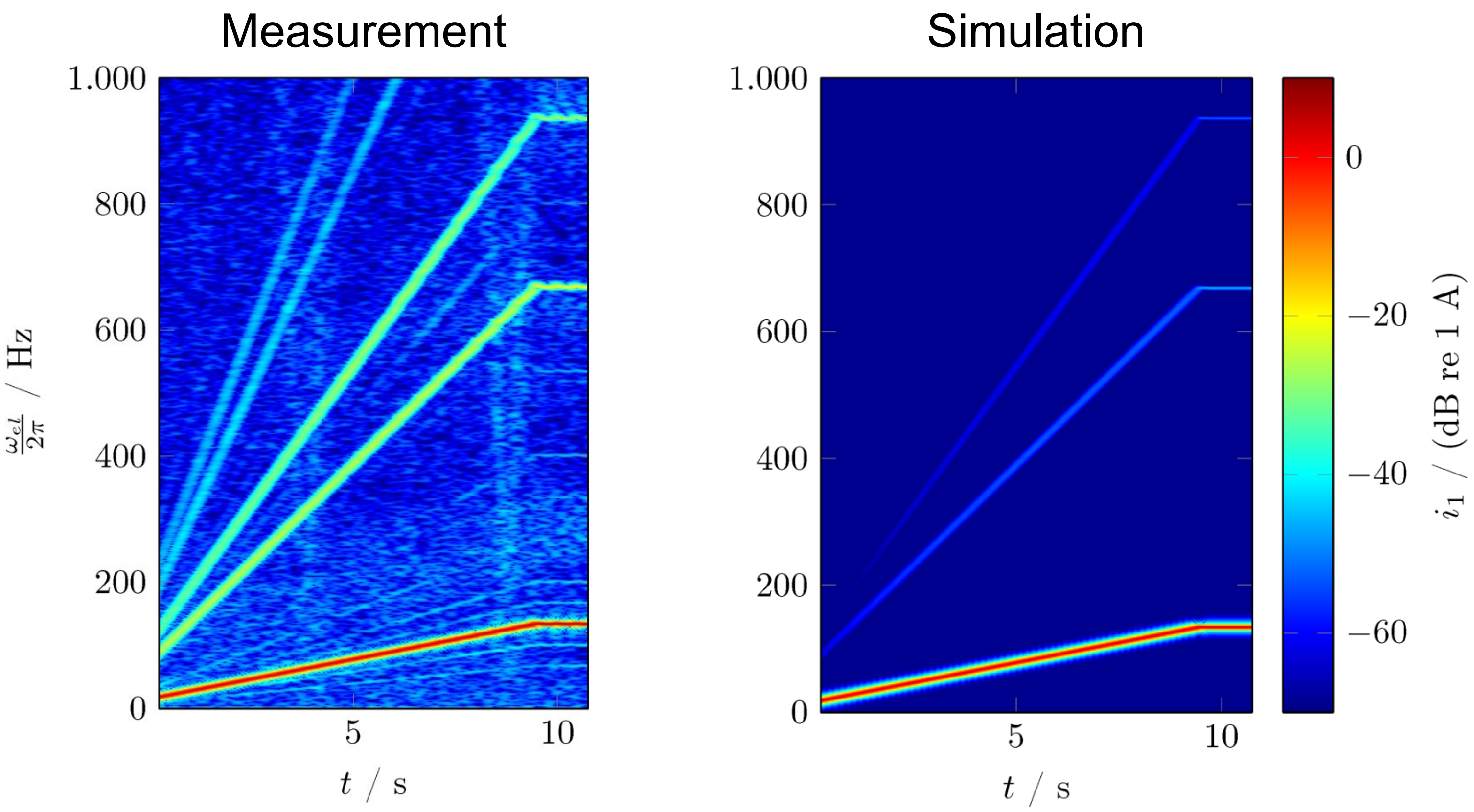
Measurement

Simulation

Run-up simulation of drive train with extended model

Electrical drive: Spectrogram phase current

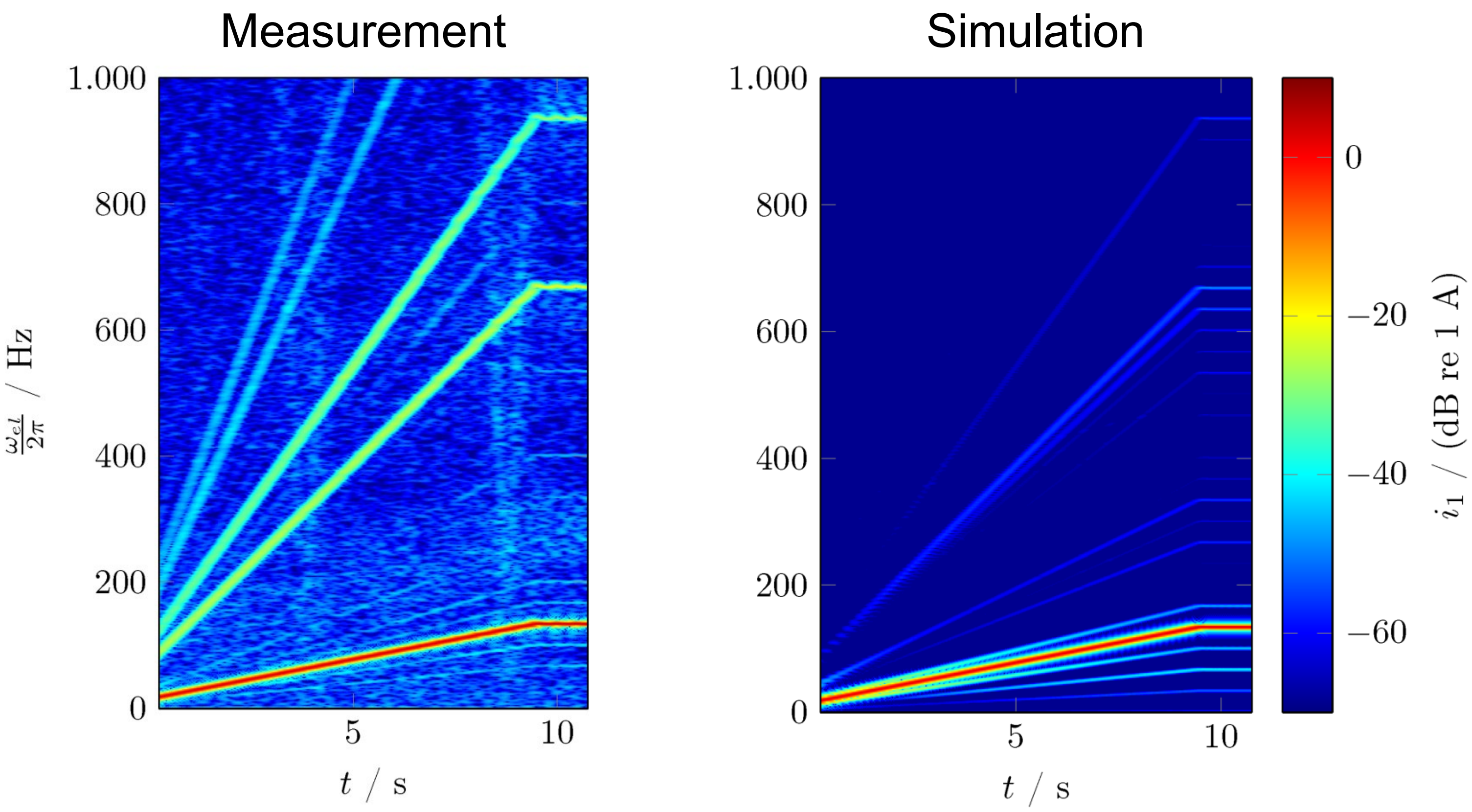
- Extended model:
  - Fundamental wave -5. and +7. current harmonic



Run-up simulation of drive train with extended frequency model considering bearing tolerances

Electrical drive: Spectrogram phase current

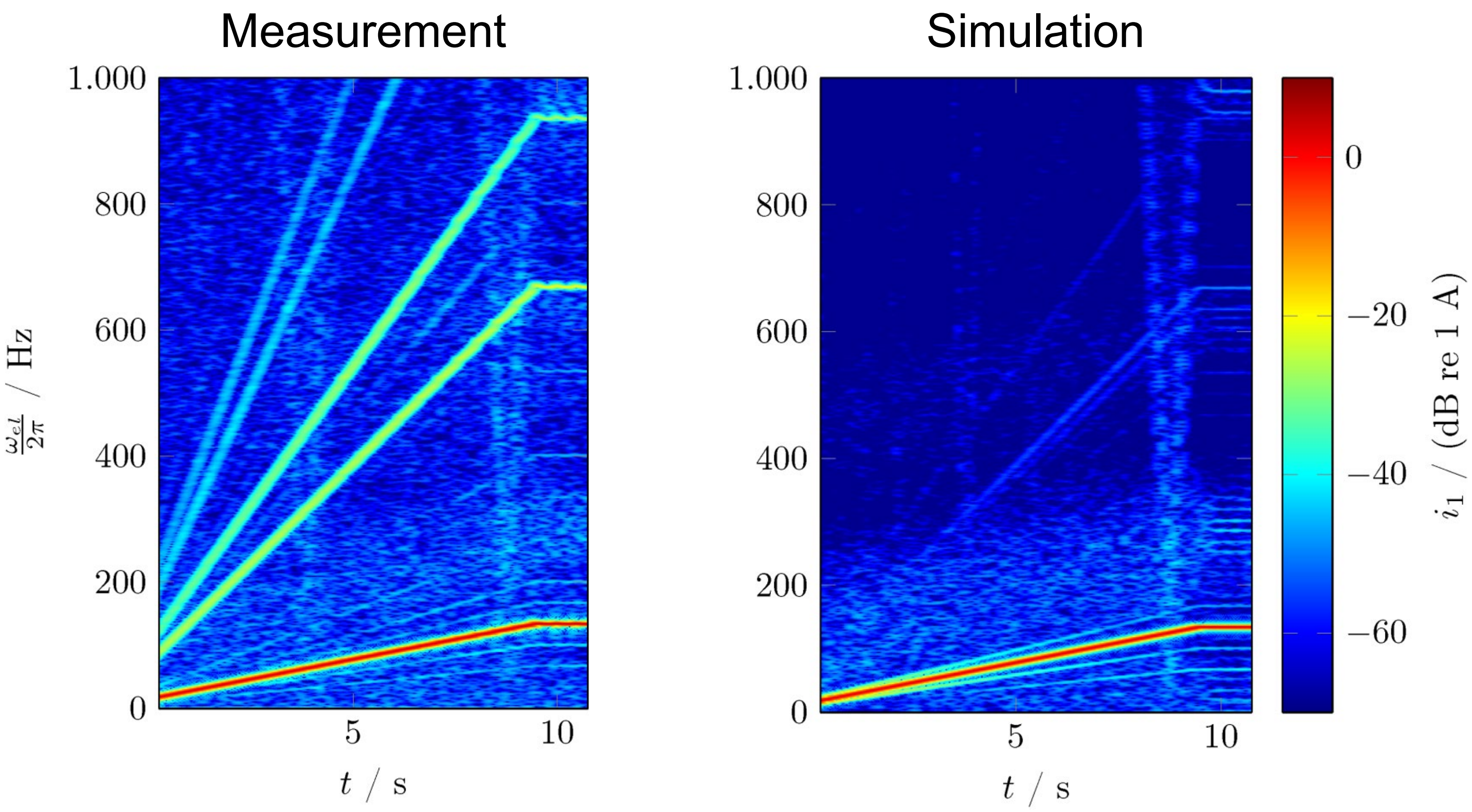
- Extended model:
  - Fundamental wave -5. and +7. current harmonic
  - Manufacturing tolerance: Magnetization tolerance + static eccentricity



Run-up simulation of drive train with extended frequency model considering bearing tolerances and signal noise of sensors

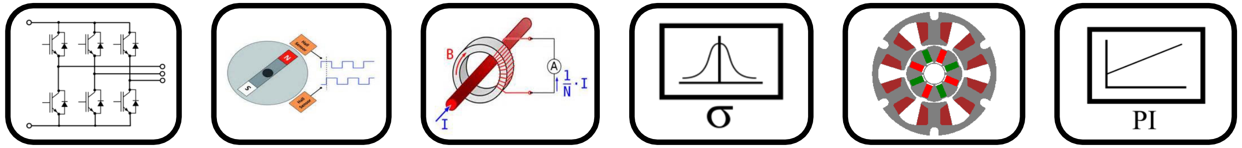
Electrical drive: Spectrogram phase current

- Extended model:
  - Fundamental wave -5. and +7. current harmonic
  - Manufacturing tolerance: Magnetization tolerance + static eccentricity
  - Noise due to rotary encoders and current sensors

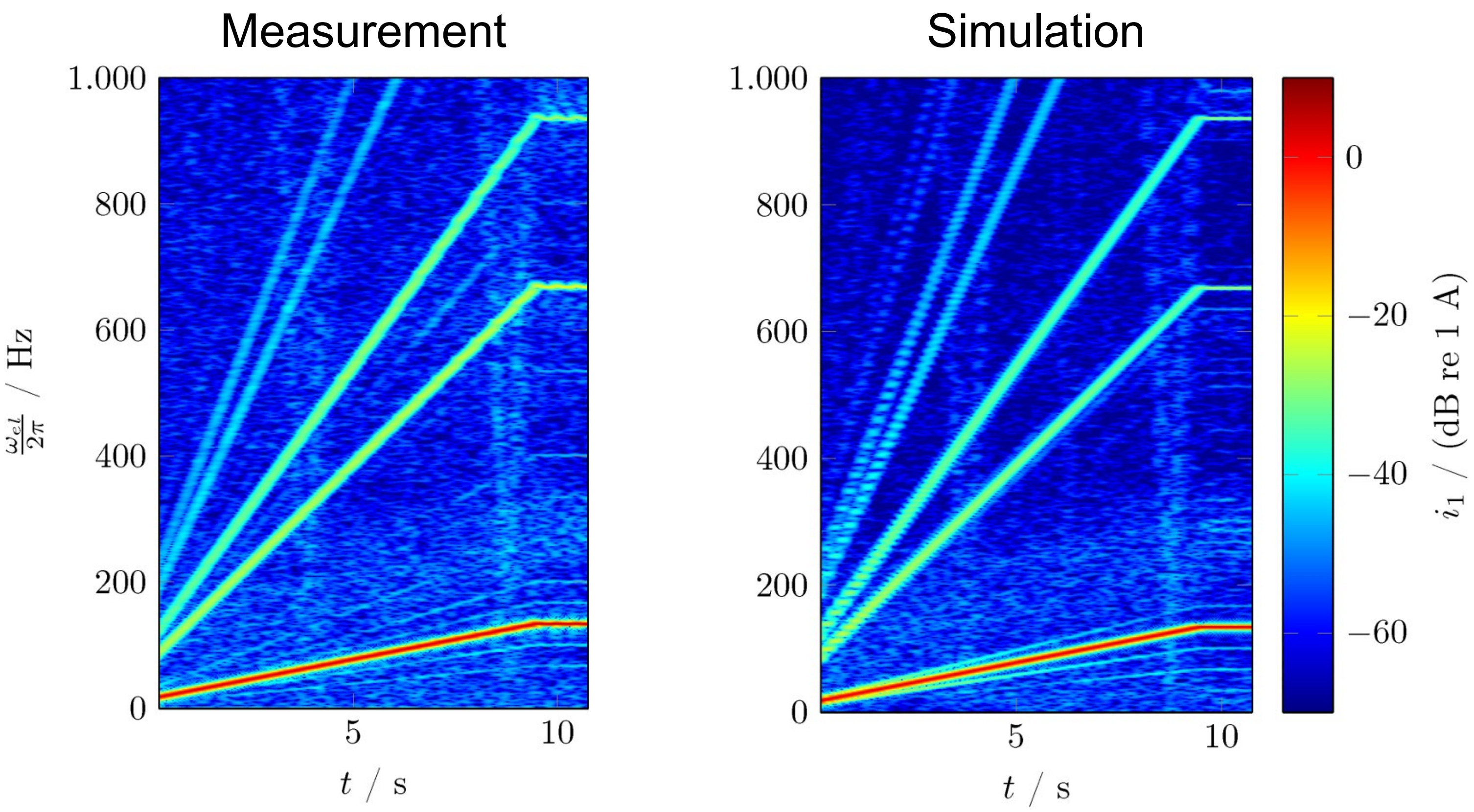


Run-up simulation of drive train with extended frequency model considering bearing tolerances, signal noise of sensors and behavior of power electronic semiconductors

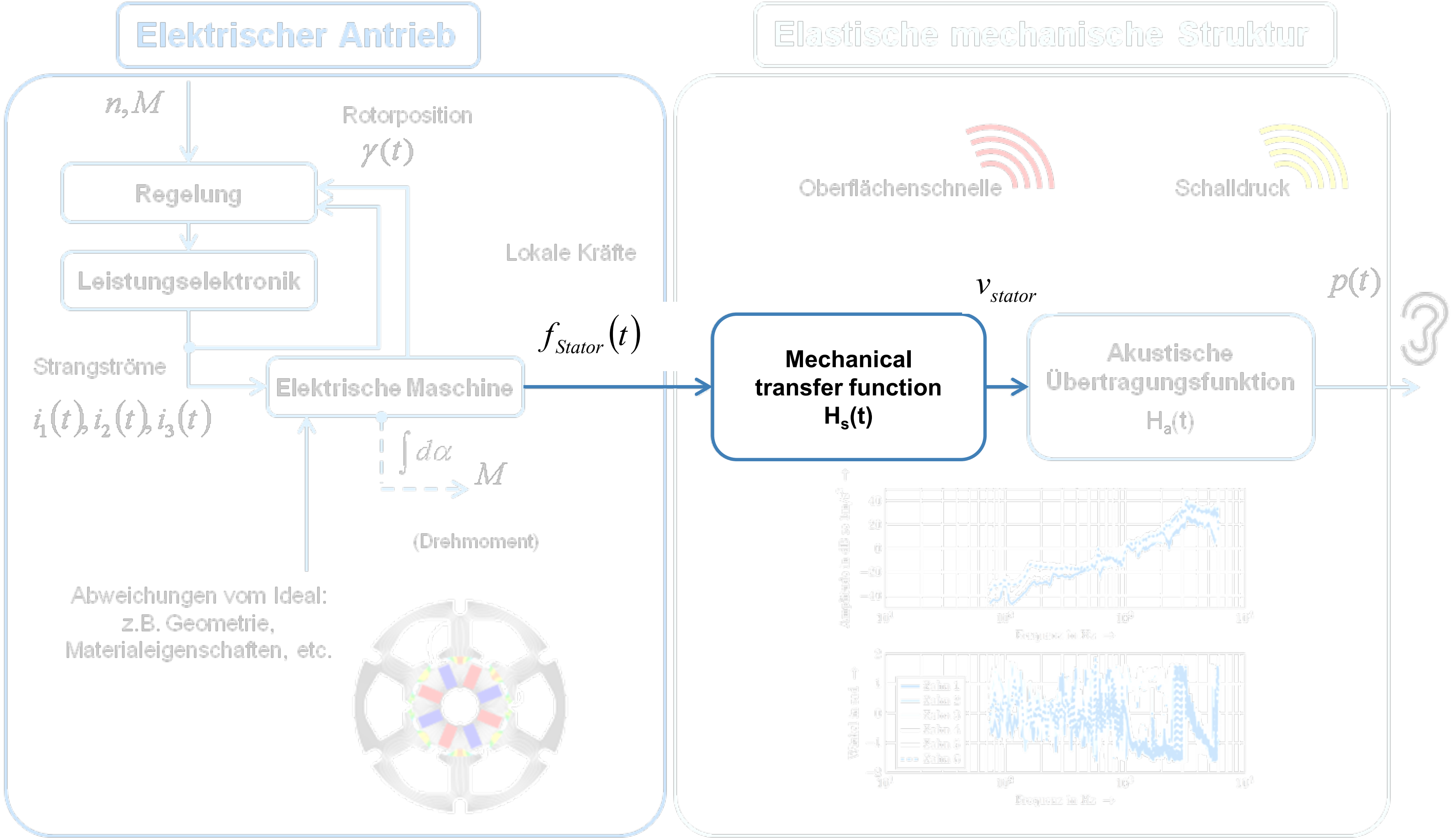
Electrical drive: Spectrogram phase current



- Extended model:
  - Fundamental wave -5. and +7. current harmonic
  - Manufacturing tolerance: Magnetization tolerance + static eccentricity
  - Noise due to rotary encoders and current sensors
  - Consideration of the dead-time of the converter



Mechanical transfer function



Elektrischer Antrieb

Elastische mechanische Struktur

n, M

Rotorposition

$\gamma(t)$

Regelung

Leistungselektronik

Lokale Kräfte

Strangströme

$i_1(t), i_2(t), i_3(t)$

Elektrische Maschine

$\int d\alpha$

M

(Drehmoment)

Abweichungen vom Ideal:
z.B. Geometrie,
Materialeigenschaften, etc.

$f_{Stator}(t)$

Oberflächenschnelle

Schalldruck

v_{stator}

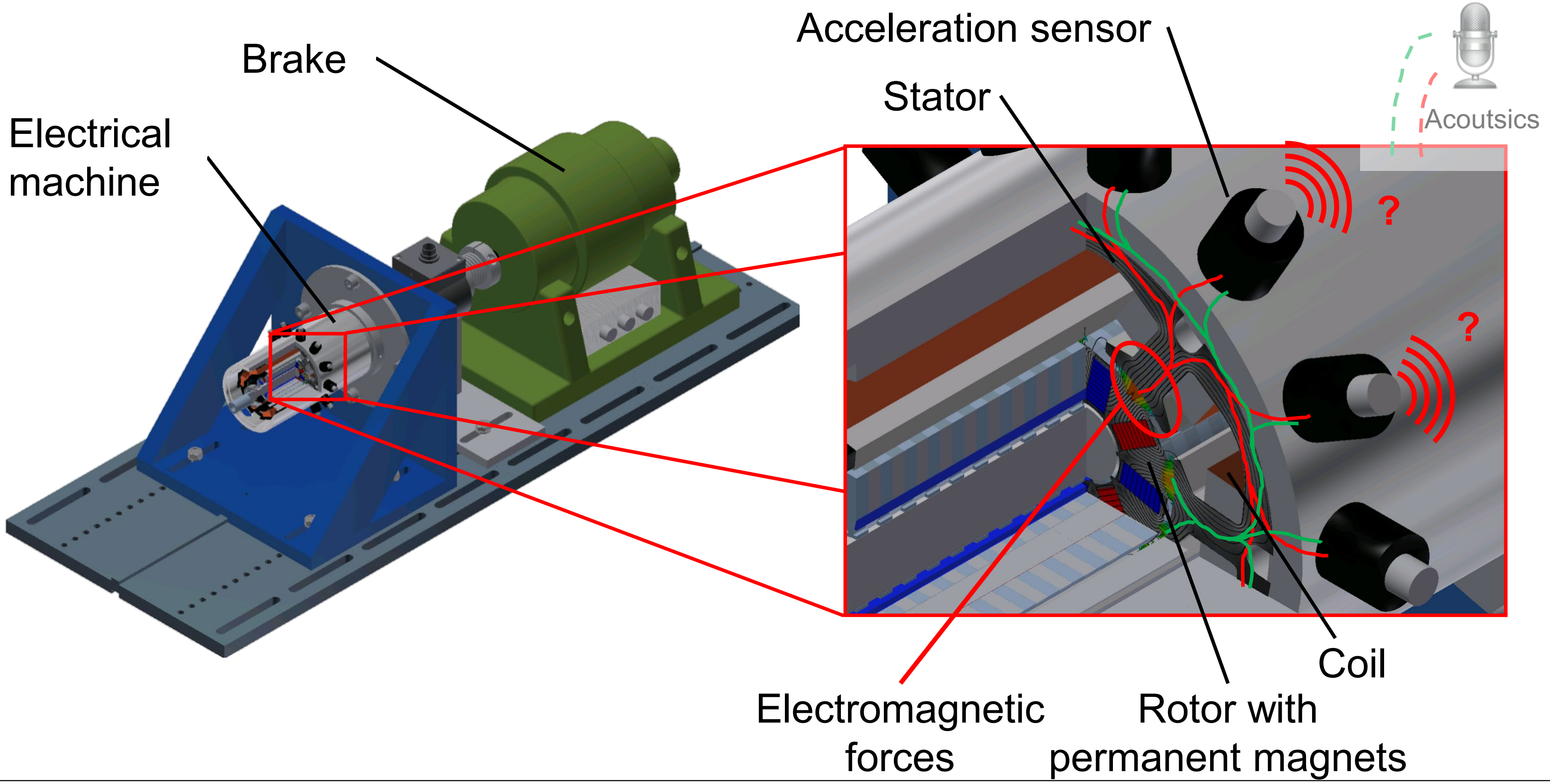
$p(t)$

Mechanical transfer function $H_s(t)$

Akustische Übertragungsfunktion $H_a(t)$

Mechanical transfer function

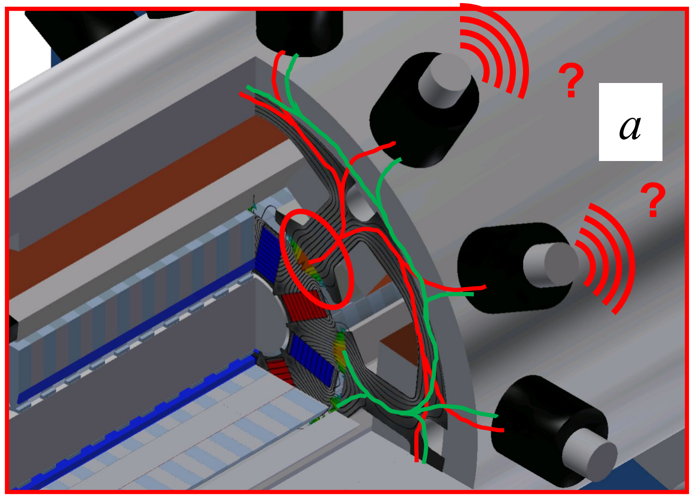
Determination by measurements

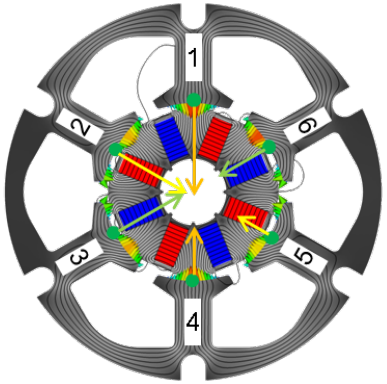


Mechanical transfer functuion

Evaluation of the measurements

- **Goal:** Transfer function of the forces in teeth with respect to the surface acceleration a at arbitrary point of measurement
- Force excitation should be possible for the target application in a completely assembled state

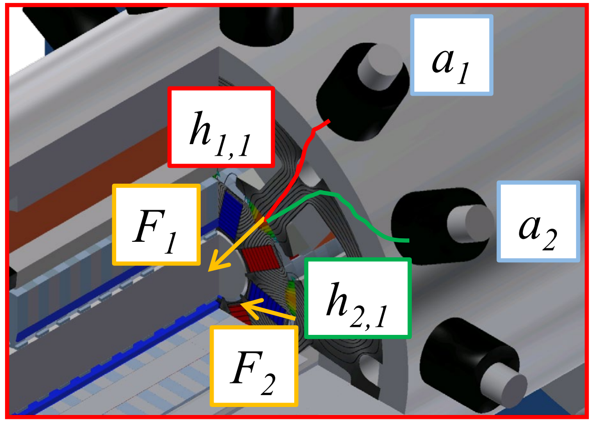




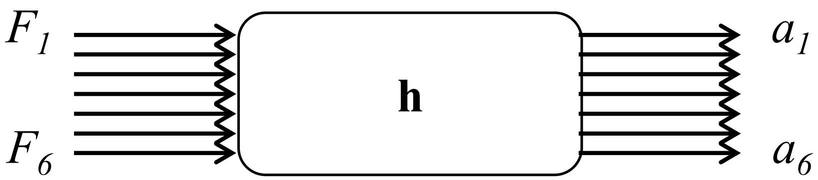
➔Machine as the source of the force excitation

Mechanical transfer function

Mathematical evaluation



Decoupling of transfer functions



a: Measuring signal
h: Transfer function
F: Tooth force
q: Tooth number
m: Measuring number
s: Sensor number

$$\underbrace{\overset{\mathbf{a}}{\begin{pmatrix} a_{1,1}(\omega) & \dots & a_{1,m}(\omega) \\ \vdots & & \vdots \\ a_{q,1}(\omega) & \dots & a_{q,m}(\omega) \end{pmatrix}}}_{\text{Response signal / Measuring signal}} = \underbrace{\overset{\mathbf{h}}{\begin{pmatrix} h_{1,1}(\omega) & \dots & h_{1,q}(\omega) \\ \vdots & & \vdots \\ h_{s,1}(\omega) & \dots & h_{s,q}(\omega) \end{pmatrix}}}_{\text{Transfer function}} \cdot \underbrace{\overset{\mathbf{F}}{\begin{pmatrix} F_{1,1}(\omega) & \dots & F_{1,m}(\omega) \\ \vdots & & \vdots \\ F_{q,1}(\omega) & \dots & F_{q,m}(\omega) \end{pmatrix}}}_{\text{Exciting force}}$$

Multi-mass-system

Structure dynamic simulation

- The displacement ξ of individual nodes that is caused by the forces F leads to stator deformation
- General equation of movement in differential state:

$$\mathbf{M} \cdot \ddot{\underline{\vec{\xi}}}(t) + \mathbf{D} \cdot \dot{\underline{\vec{\xi}}}(t) + \mathbf{K} \cdot \underline{\vec{\xi}}(t) = \underline{\vec{F}}(t)$$

  - **M**: Inertia matrix
  - **D**: Damping matrix
  - **K**: Stiffness matrix
  - ξ: Node shift
  - F: Node forces

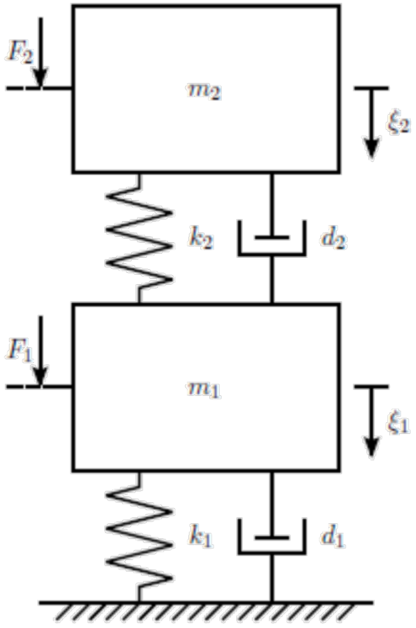
  (M, D, K:) Depends on the characteristics of the structure (Material, construction, manufacturing, etc.)

- The time harmonic case:

$$\dot{\underline{\vec{\xi}}}(t) = \frac{\mathrm{d}\underline{\vec{\xi}}(t)}{\mathrm{d}t} = \mathrm{j}\omega\,\underline{\vec{\xi}}(t) = v(t)$$

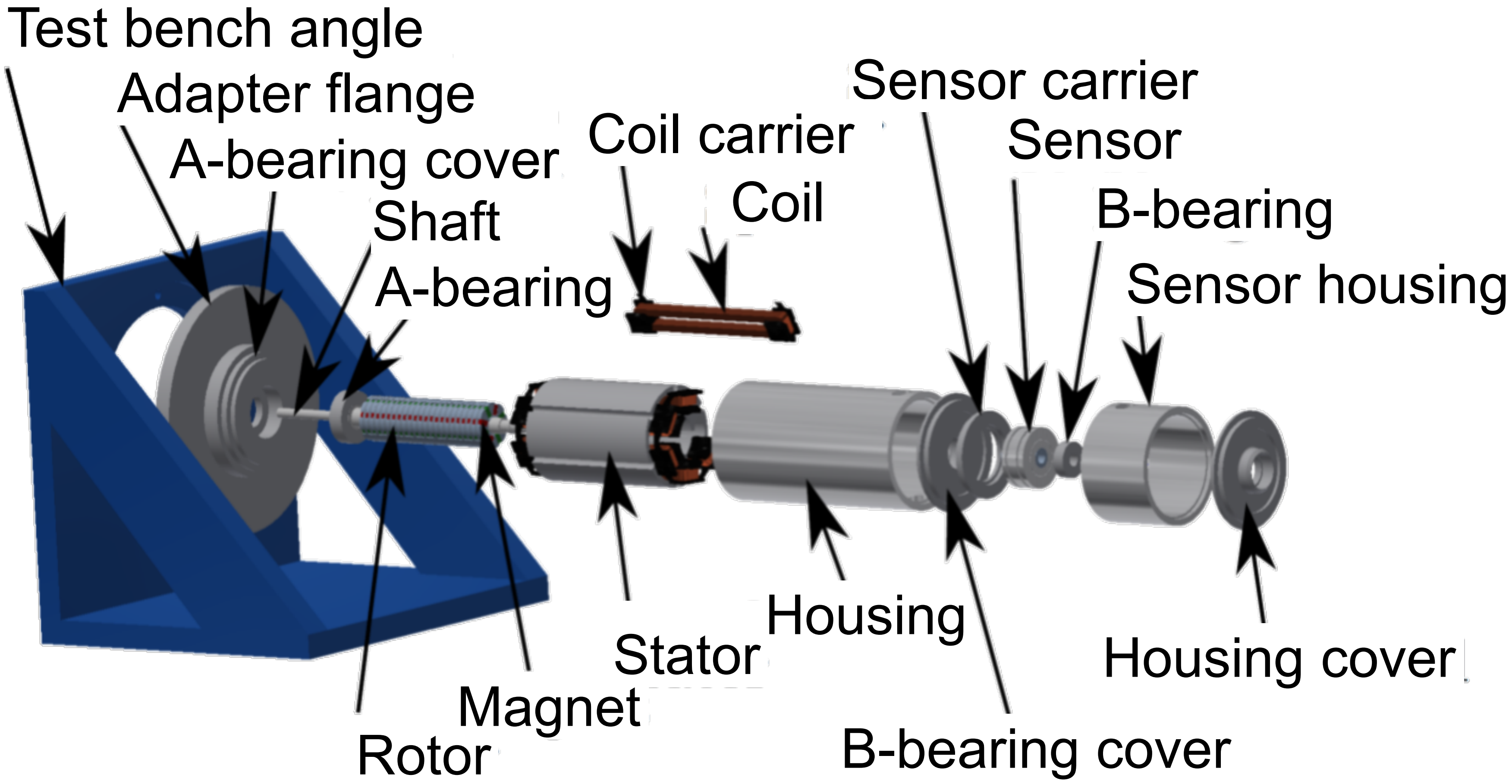
$$\ddot{\underline{\vec{\xi}}}(t) = \frac{\mathrm{d}^2\underline{\vec{\xi}}(t)}{\mathrm{d}t^2} = -\omega^2\,\underline{\vec{\xi}}(t) = a(t)$$

➔ $$\left(\mathbf{K} + \mathrm{j}\omega\mathbf{D} - \omega^2\mathbf{M}\right) \cdot \underline{\vec{\xi}}(t) = \underline{\vec{F}}(t)$$



Mechanical design and acoustic model

Structural model calculation: Machine model

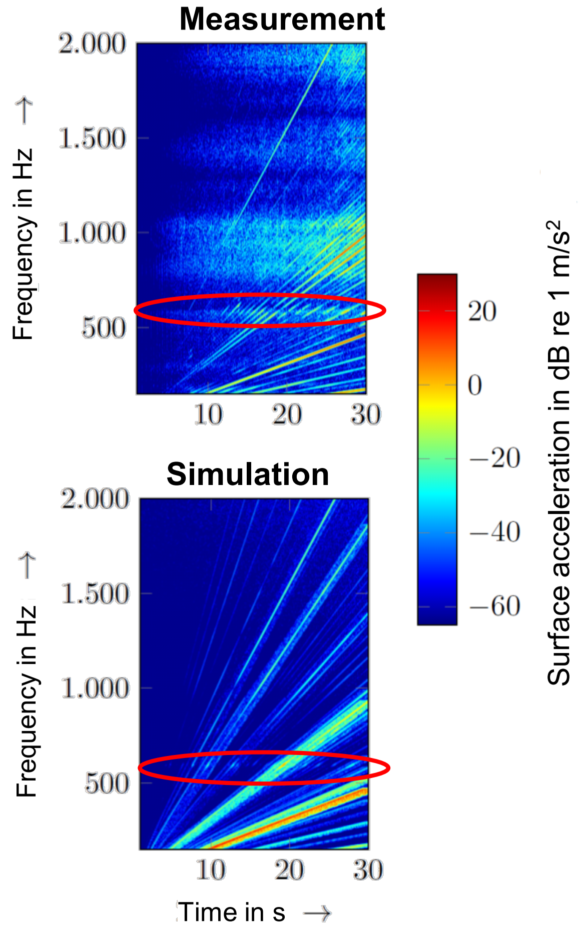


Univ.-Prof. Dr.-Ing. habil. Dr. h. c. mult. Kay Hameyer

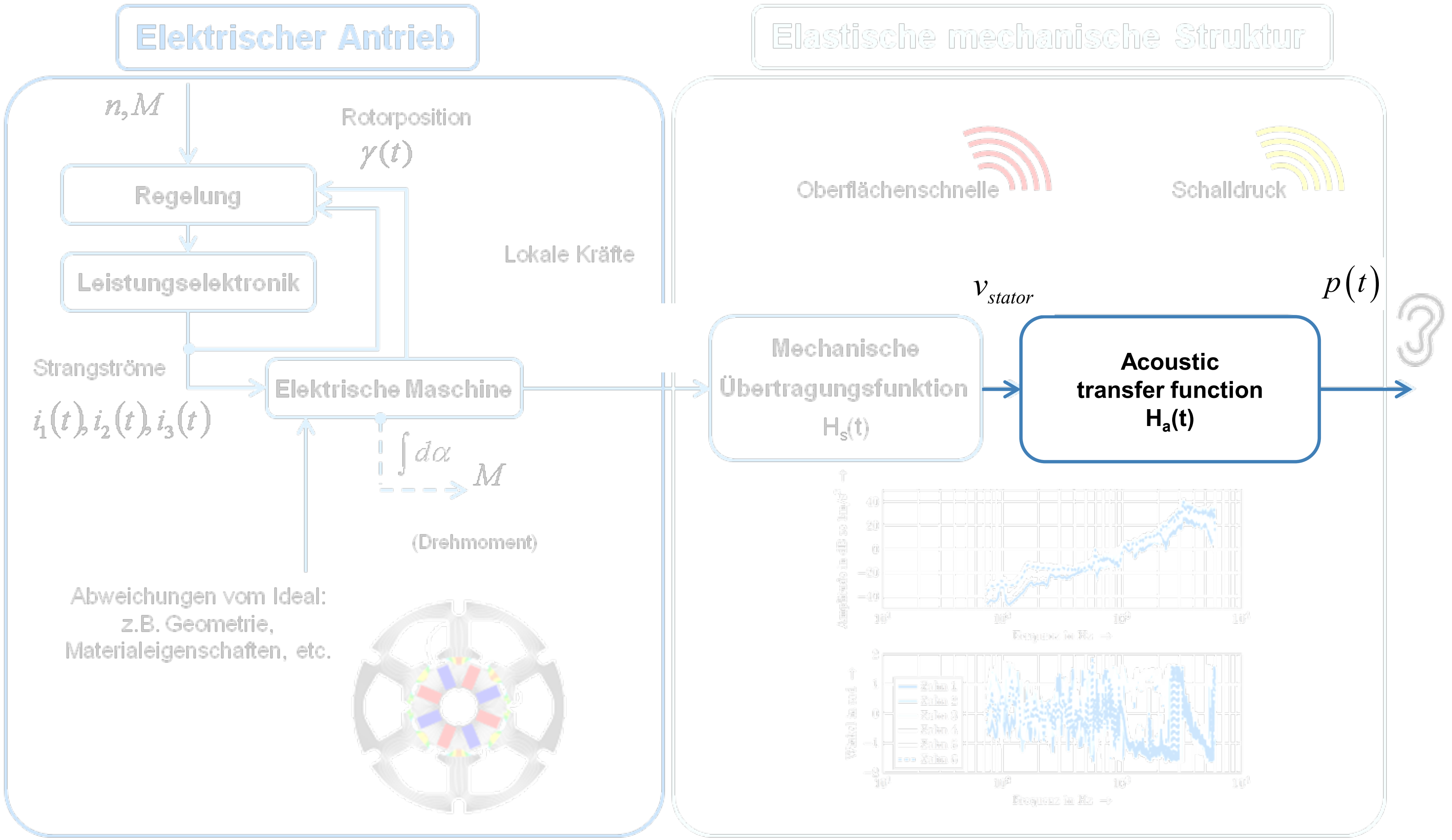
Mechanical transfer function

Example: Surface acceleration in radial direction

- Acceleration process of a machine with $n = 0 \ldots 3500\ \text{min}^{-1}$ with a load of $M = 1$ Nm
- The model with the measured transfer functions indicates a good representation of mechanical properties of the drive train
- The measured transfer functions can be identified with relatively small effort
- For the identification of the transfer functions, the presented time-transient drive model for the calculation of teeth forces is necessary



Acoustic transfer function



Acoustic transfer function

Determination of the acoustic transfer function for the simulation

- General wave equation: $\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2}$

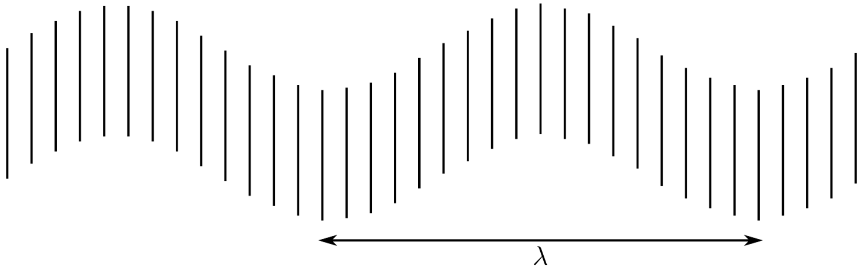
➔Helmholtz equation in differential form (PDE) for the sound pressure in time-harmonic form:

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

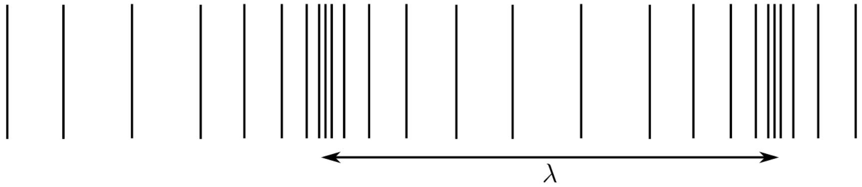
  - p: Sound pressure
  - c: Sound velocity → $c = \lambda \cdot f = \lambda \cdot \frac{\omega}{2\pi} = \frac{\omega}{k}$
  - k: Wave number
  - ∇^2: Laplace-operator

- Sound pressure p can be identified with the system matrixes $\mathbf{H}$ and $\mathbf{G}$ from the local surface velocity v:

$$\mathbf{H} \cdot \underline{p} = \mathbf{G} \cdot \underline{\vec{v}} \qquad \text{with} \qquad \underline{\vec{v}} = 2\pi \cdot f \cdot \underline{\vec{\xi}}$$



(a) Transverse wave with the wavelength λ

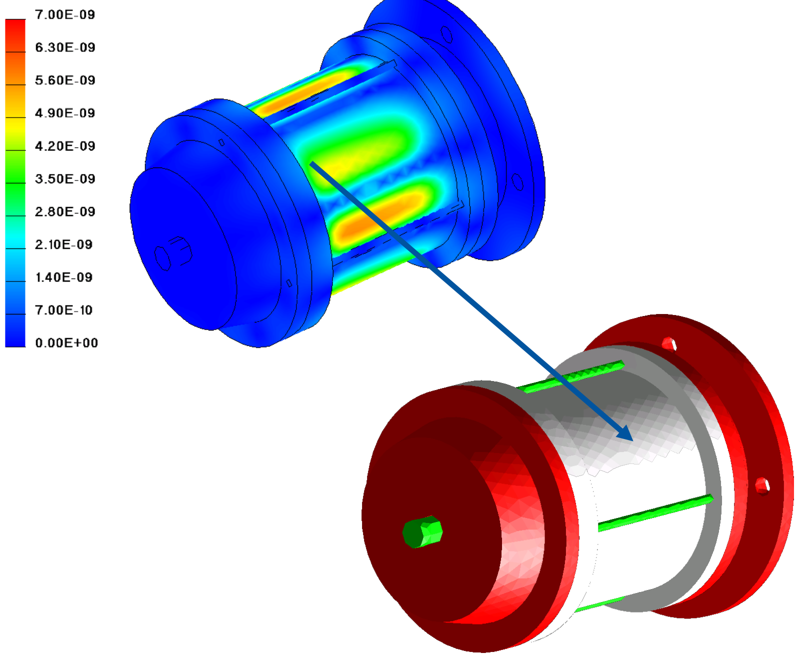


(b) Longitudinal wave with the wavelength λ

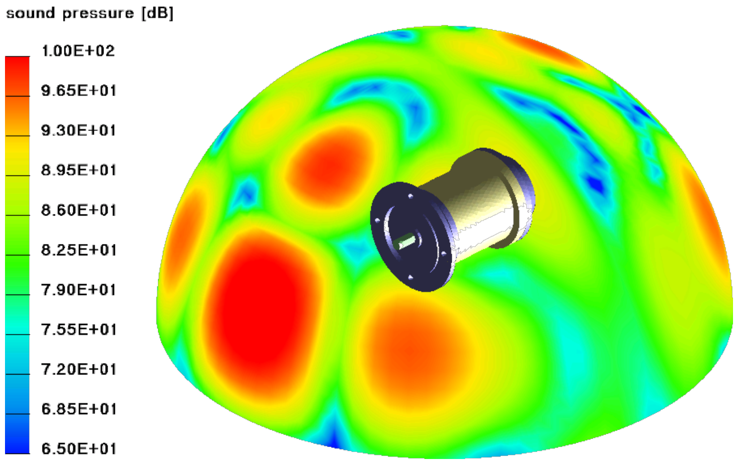
Acoustic transfer function

- Example for an acoustic simulation:
  - The acoustic model encompasses merely of the (simplified) machine surface
  - The deformation of the surface of the structural dynamics simulations is transformed to the surface of the acoustic model
  - Calculation of the sound pressure level, that is the sound particle velocity at a certain distance (in this case: 1 m)

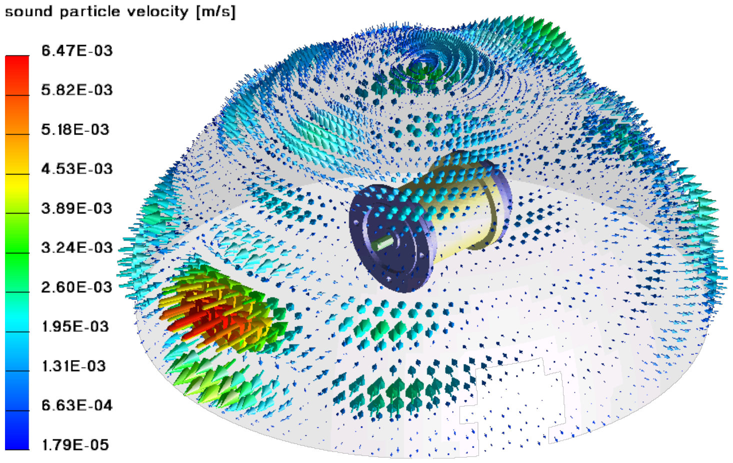
Deformation in m



Sound pressure Lp in dB re 20 µPa



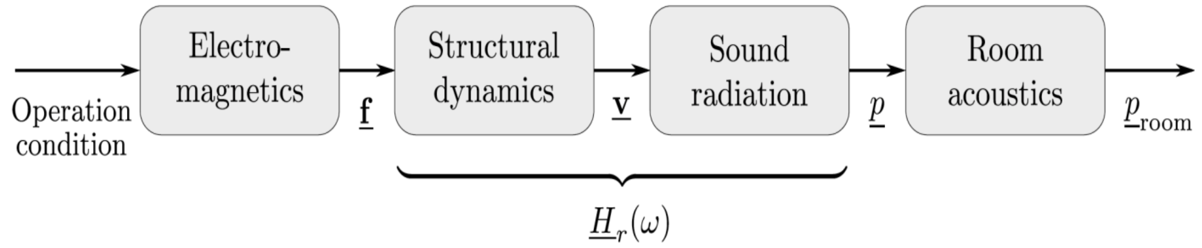
Sound particle velocity *v* in m/s



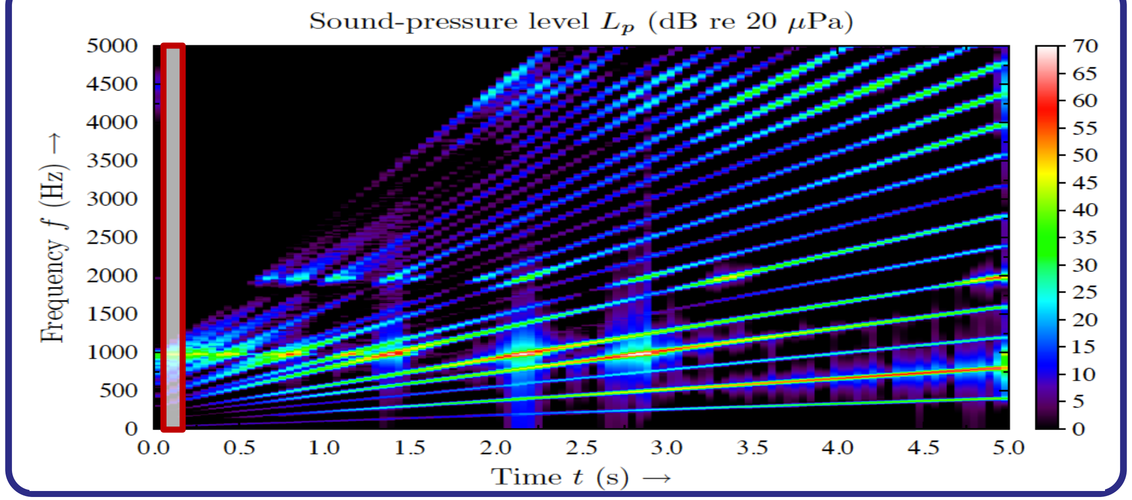
Example for the proposed approach

Run-up of a synchronous machine

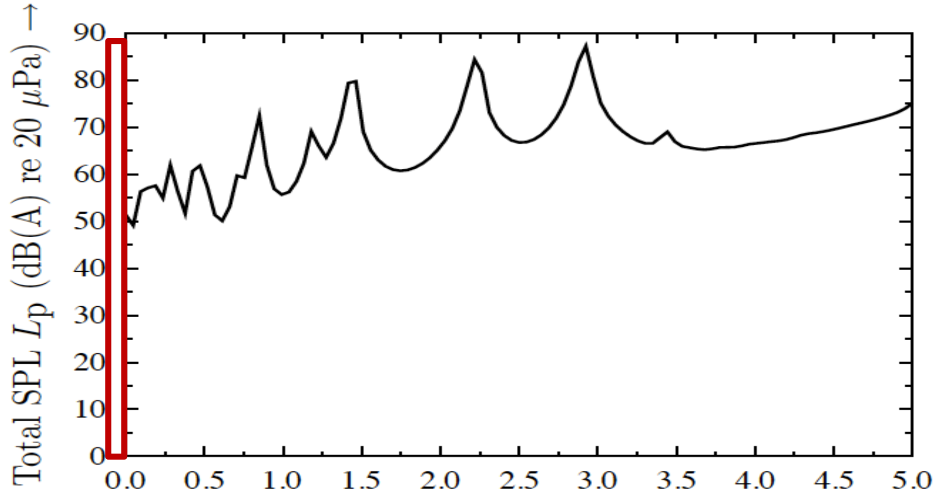
Signal chain



Spectrogram



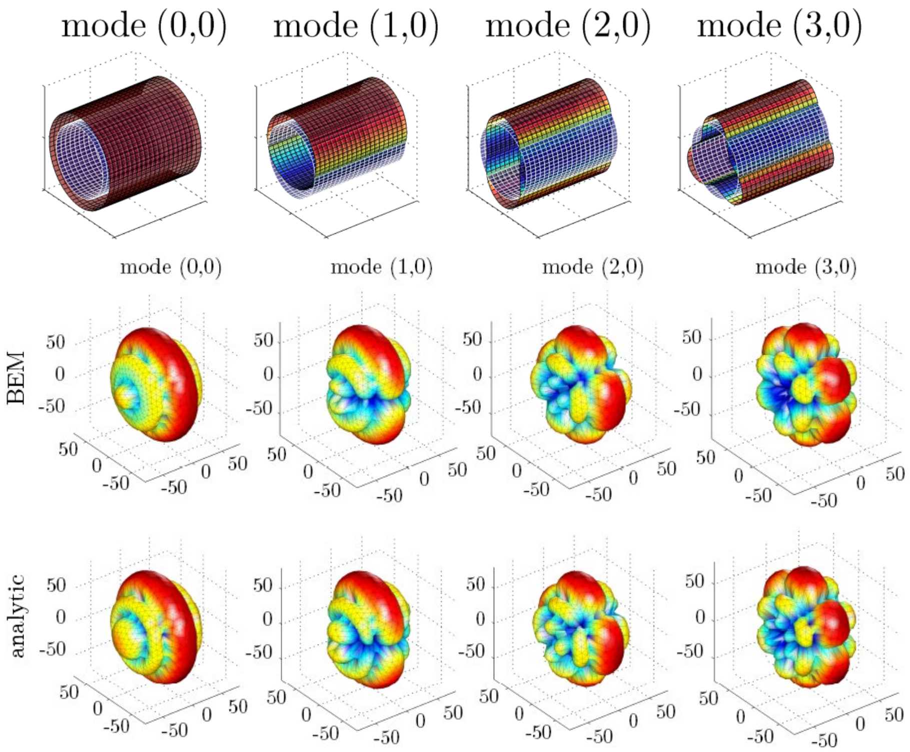
Sound power



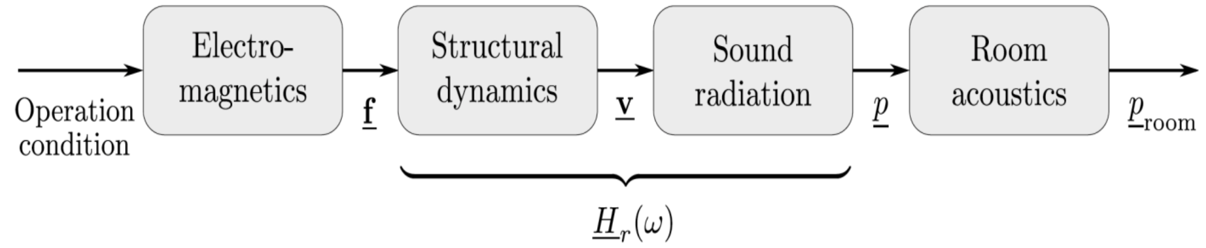
Next step including room acoustics: Air borne noise excitation

Apply radiator models

- Determine mode and frequency



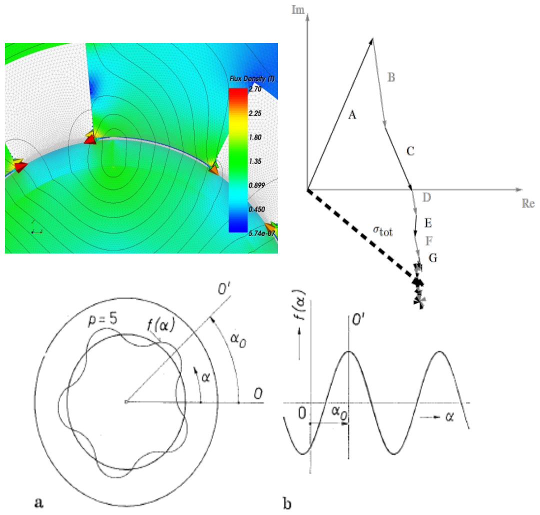
Signal chain



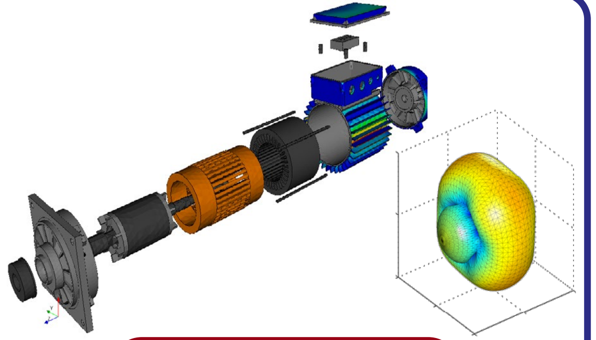
Operation condition $\rightarrow$ Electro-magnetics $\xrightarrow{\underline{f}}$ Structural dynamics $\xrightarrow{\underline{v}}$ Sound radiation $\xrightarrow{\underline{p}}$ Room acoustics $\rightarrow$ $\underline{p}_{\text{room}}$

$$\underbrace{\text{Structural dynamics} \rightarrow \text{Sound radiation}}_{\underline{H}_r(\omega)}$$

Source: EM forces



Transmission

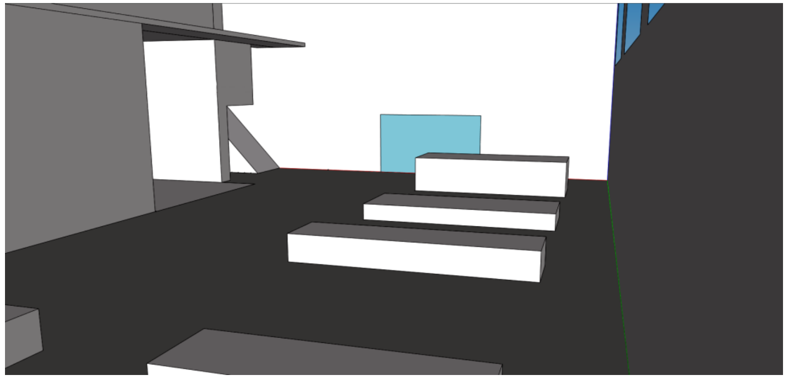


$$H(\omega) = \frac{p_{\text{meas}}(\omega)}{\sigma_{\text{simu}}(\omega)}$$

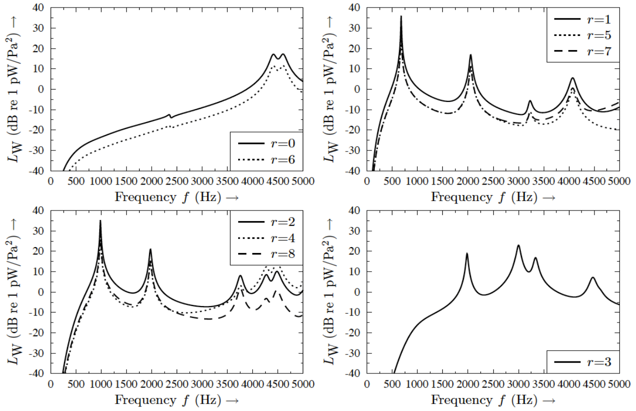
Electric motor - room acoustics

Room visualization

Acoustic model

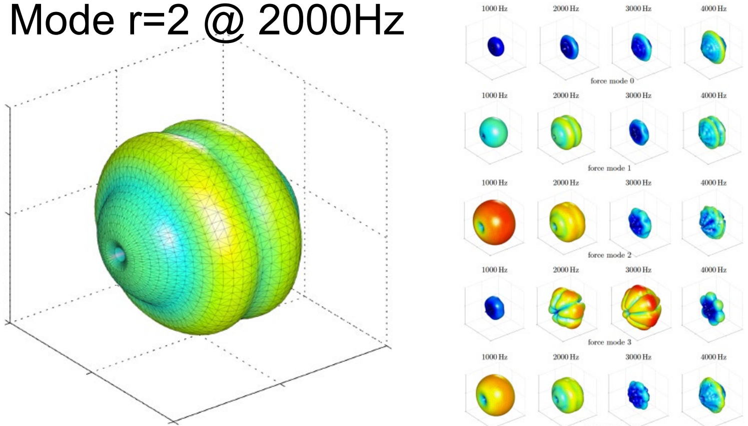


Acoustic transfer functions



Acoustic radiation characteristic

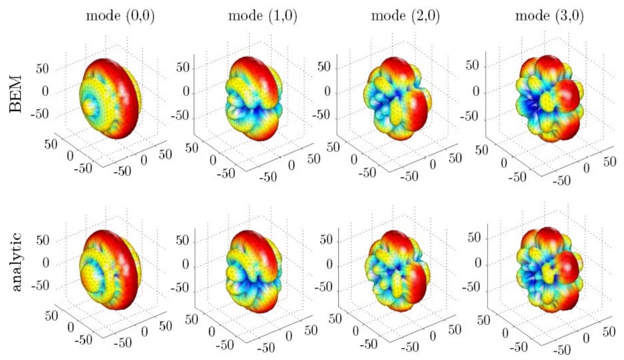
Mode r=2 @ 2000Hz



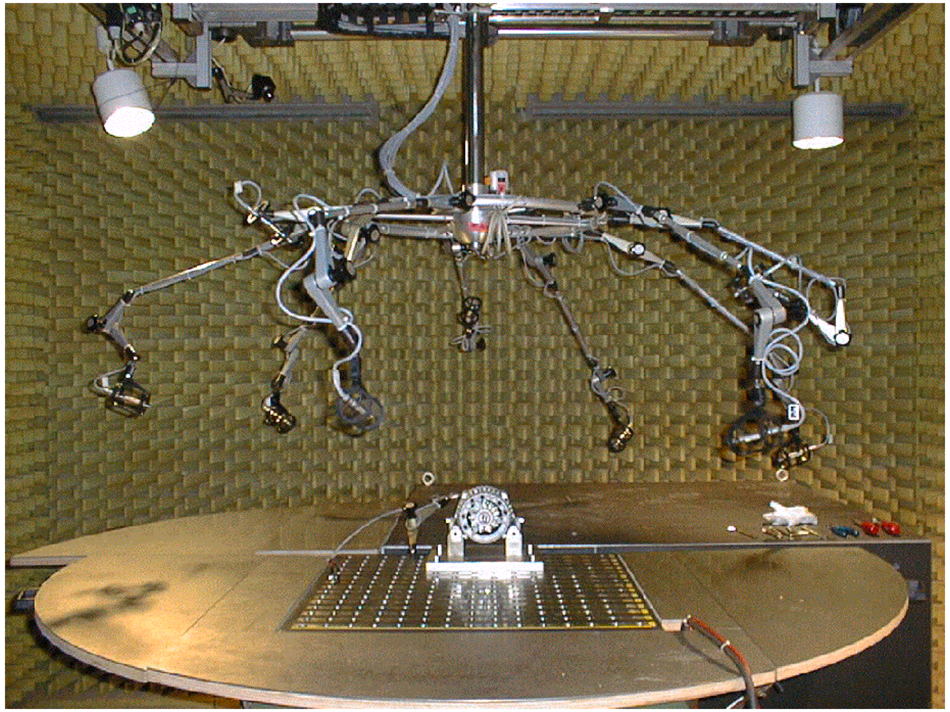
Electric motor – room acoustic

Overall acoustic models

- Actual room acoustic
  - Determined by measurement
- Simple acoustic motor model
  - Radiator models
    - Point
    - Cylinder
    - …



Acoustic measurements in an an-echoic chamber



Summarysing Example: Acoustic characterization of an electrical drive train

From the component to the overall drive system

Characterization of the electrical machine

- Modal analysis
- Structural dynamics models
- Electromagnetic forces
- Measurement on the machine test bed

Characterization of the drive train

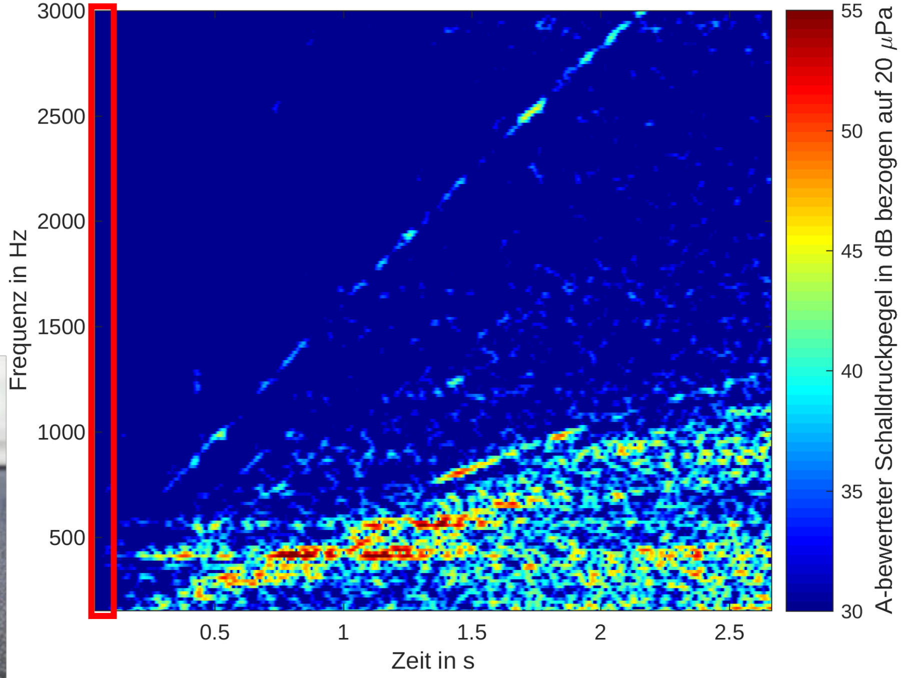
- Gear model
- Radial- and torsion excitation
- Drive train models
- Measurements on the drive train test bed

Characterization of the final application

- Transfer path measurements
- Emission models
- Binaural acoustic
- Measurements on the test track

The drive train as an acoustic source

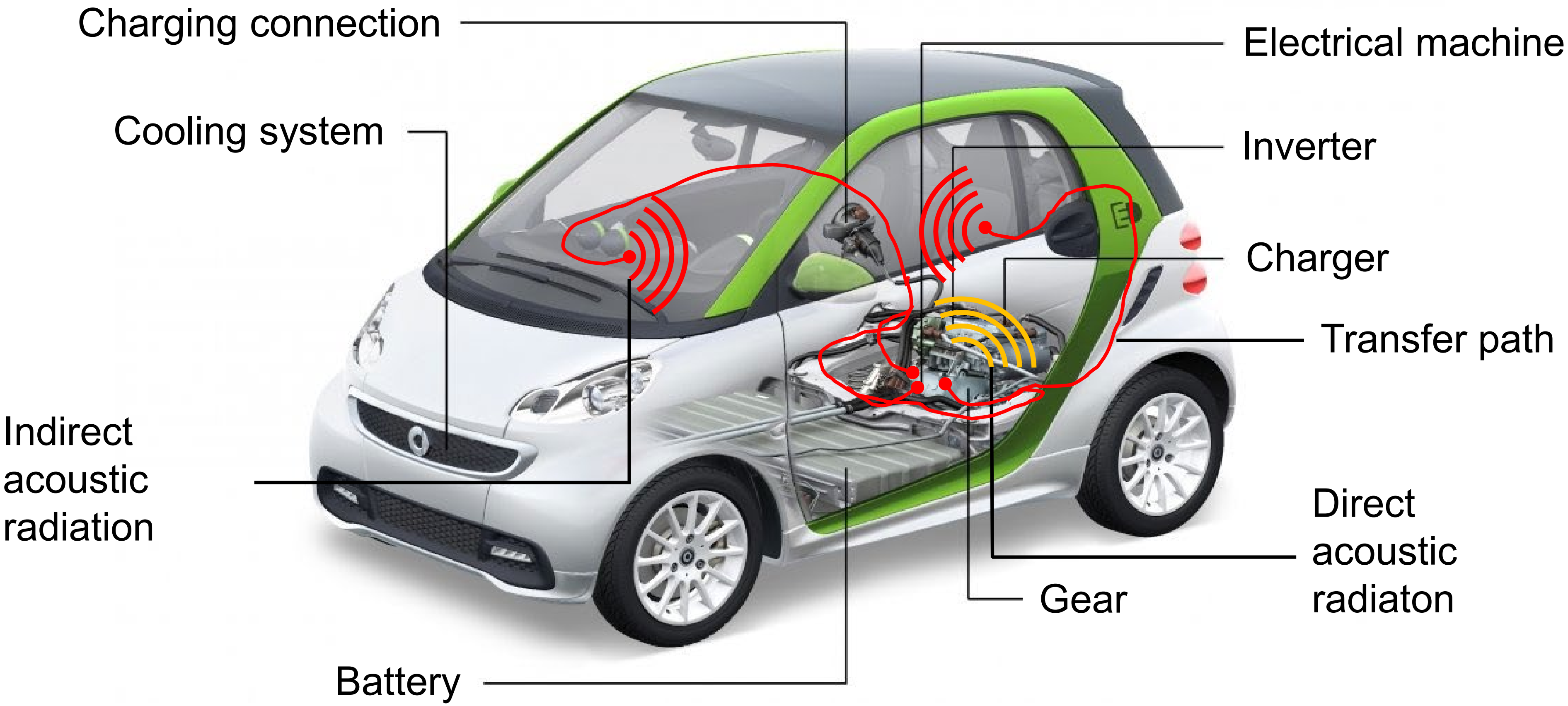
Electric motor analysis (vehicle speed from 0… 50 km/h)



Source of measurement: S. Rick, D. Franck, K. Hameyer, M. Wegerhoff, R. Schelenz, G. Jakobs, J. Klein, G. Behler, M. Vorländer, *E-MOTIVE NVH-Simulationsmodell: Modellbildung zur NVH Simulation eines E-MOTIVE Antriebsstrangs*, Forschungsbericht FVA-682, 2014.

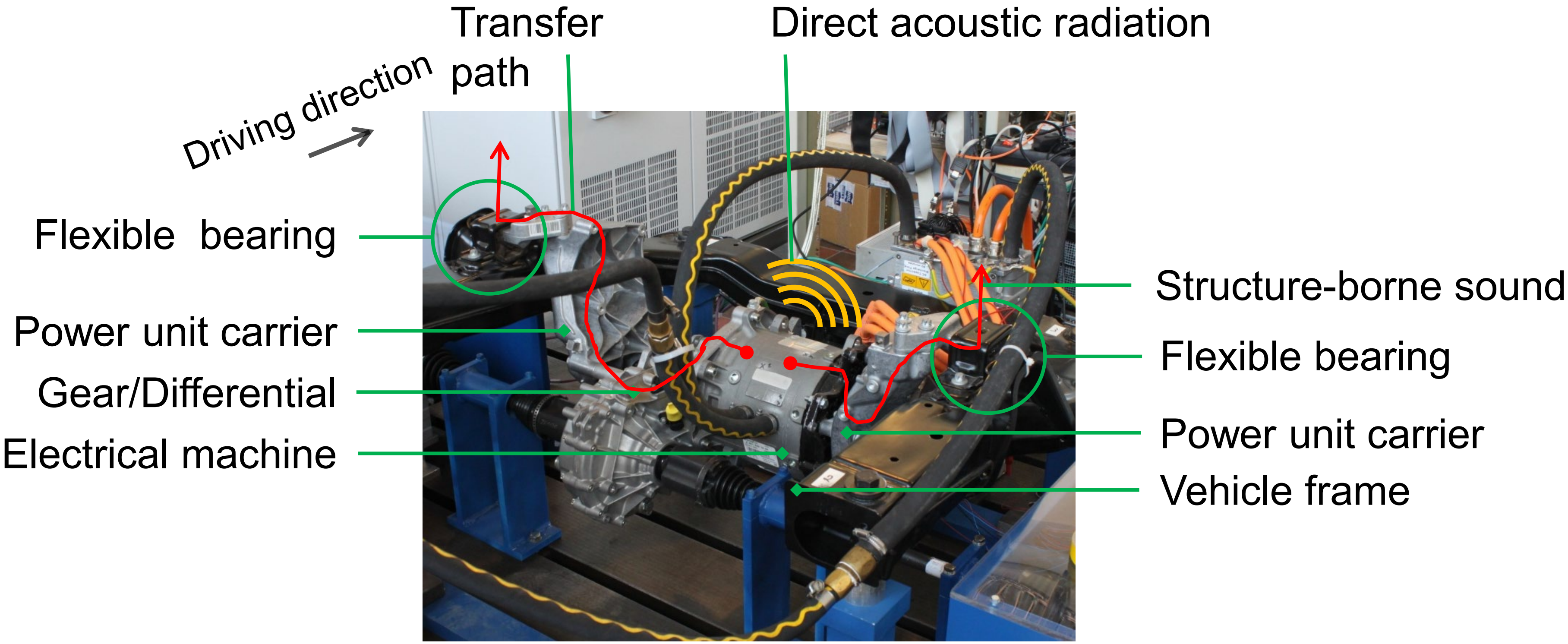
The drive train as an acoustic source

Drive train components and transfer paths



The drive train as an acoustic source

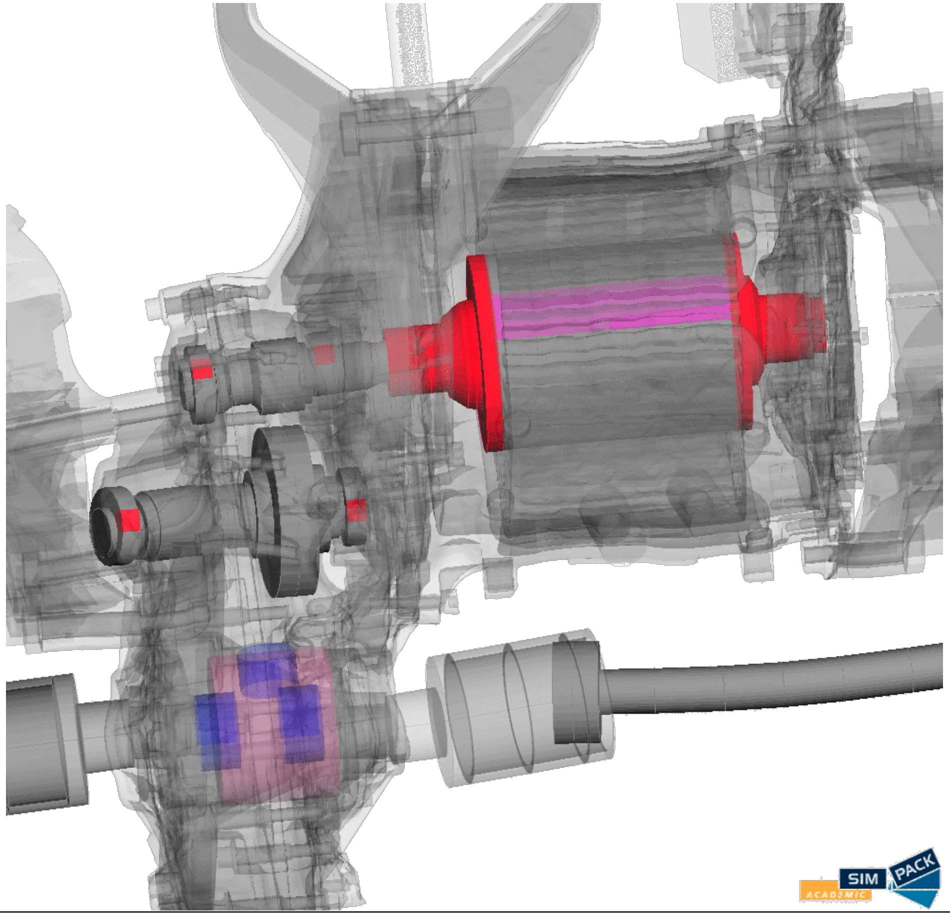
Transfer path analysis



S. Rick, D. Franck, K. Hameyer, M. Wegerhoff, R. Schelenz, G. Jakobs, J. Klein, G. Behler, M. Vorländer, *E-MOTIVE NVH-Simulationsmodell: Modellbildung zur NVH Simulation eines E-MOTIVE Antriebsstrangs*, Forschungsbericht FVA-682, 2014

The drive train as an acoustic source

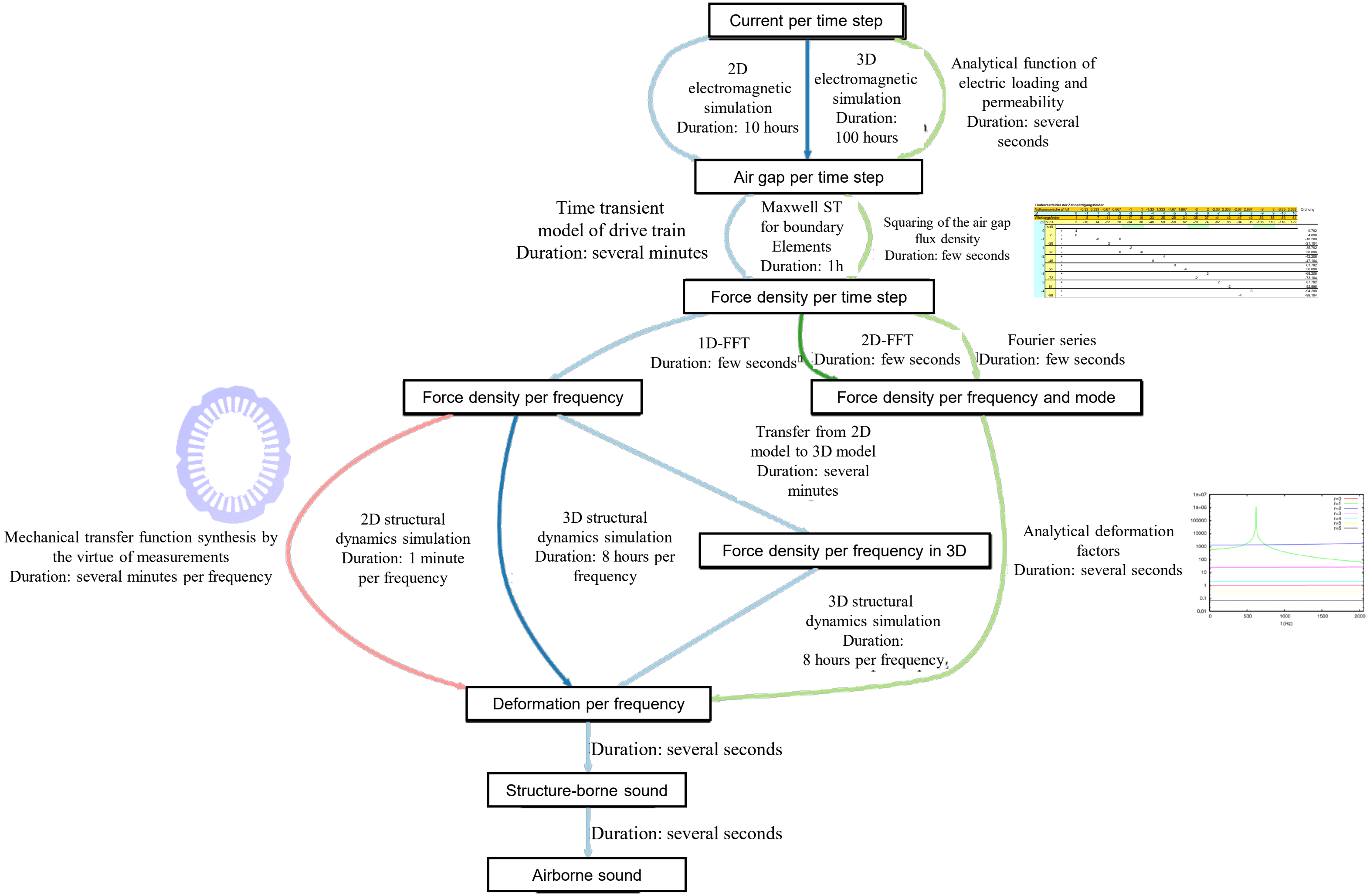
Example simulation with selected form for natural frequency of a drive train



S. Rick, D. Franck, K. Hameyer, **M. Wegerhoff**, R. Schelenz, G. Jakobs, J. Klein, G. Behler, M. Vorländer, *E-MOTIVE NVH-Simulationsmodell: Modellbildung zur NVH Simulation eines E-MOTIVE Antriebsstrangs*, Forschungsbericht FVA-682, 2014.

Summary

Calculation of vibro-acoustic behavior of electrical machines



Current per time step

2D electromagnetic simulation
Duration: 10 hours

3D electromagnetic simulation
Duration: 100 hours

Analytical function of electric loading and permeability
Duration: several seconds

Air gap per time step

Time transient model of drive train
Duration: several minutes

Maxwell ST for boundary Elements
Duration: 1h

Squaring of the air gap flux density
Duration: few seconds

Force density per time step

1D-FFT
Duration: few seconds

2D-FFT
Duration: few seconds

Fourier series
Duration: few seconds

Force density per frequency

Force density per frequency and mode

Transfer from 2D model to 3D model
Duration: several minutes

Mechanical transfer function synthesis by the virtue of measurements
Duration: several minutes per frequency

2D structural dynamics simulation
Duration: 1 minute per frequency

3D structural dynamics simulation
Duration: 8 hours per frequency

Force density per frequency in 3D

Analytical deformation factors
Duration: several seconds

3D structural dynamics simulation
Duration: 8 hours per frequency

Deformation per frequency

Duration: several seconds

Structure-borne sound

Duration: several seconds

Airborne sound

Conclusions

- Analytical approach
  - Identification of the frequency ranges of interest

- Numerical simulation
  - The evaluation of structural dynamics and acoustic behavior can take place in an early stage of development, even before prototypes are built

- Multiphysical approach
  - Can be applied to all electrical machines
  - Can be verified by measurements
  - Electrical machines can be observed in a structured way
  - Production tolerances can be considered
  - Materials characteristics and electrical parameters can be improved

- The analysis of single components / sources is not sufficient!
  - Always the overall system with all interactions of the components is required