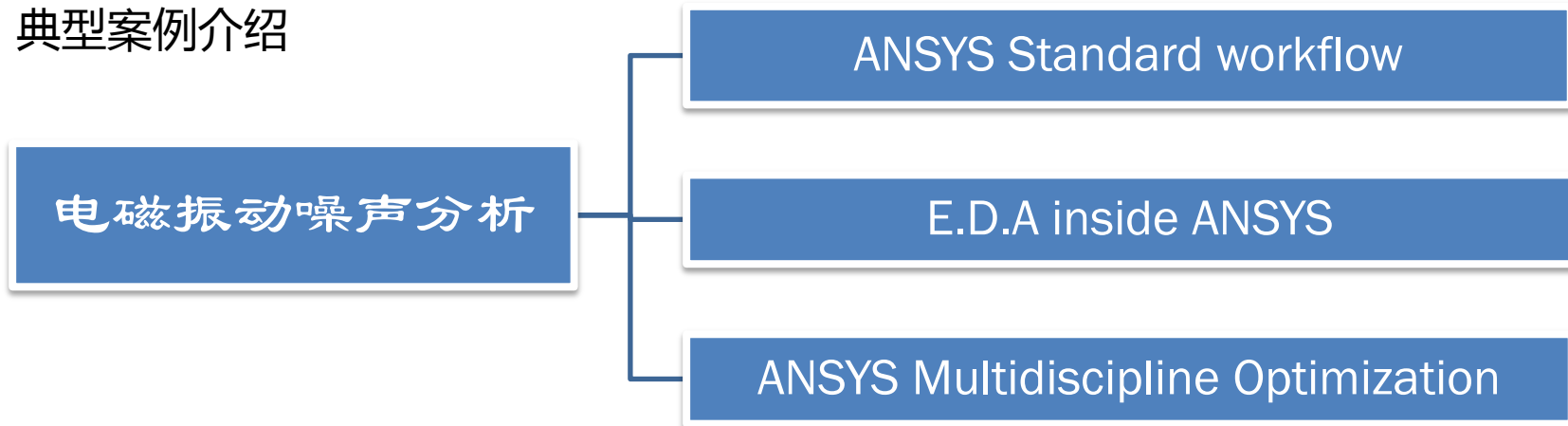




电磁振动噪声分析

段卫毅

- 背景
- 基本概念
- 电磁振动噪声分析
- 典型案例介绍



电机的振动噪声问题相当复杂，跨学科跨领域，而且是一个综合性问题。如何在设计阶段考虑噪声振动的问题是电机最终从产品层面减振降噪的根本性方法，CAE分析在里面扮演了重要角色。CAE仿真分析将分阶段分层次对电机振动和噪声进行分析。



电机噪声来源



新能源汽车



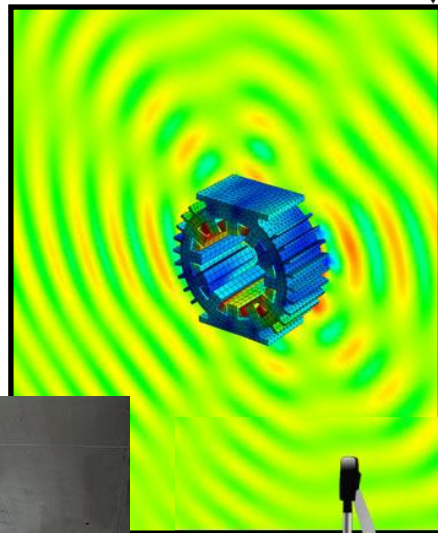
高铁

船舶驱动



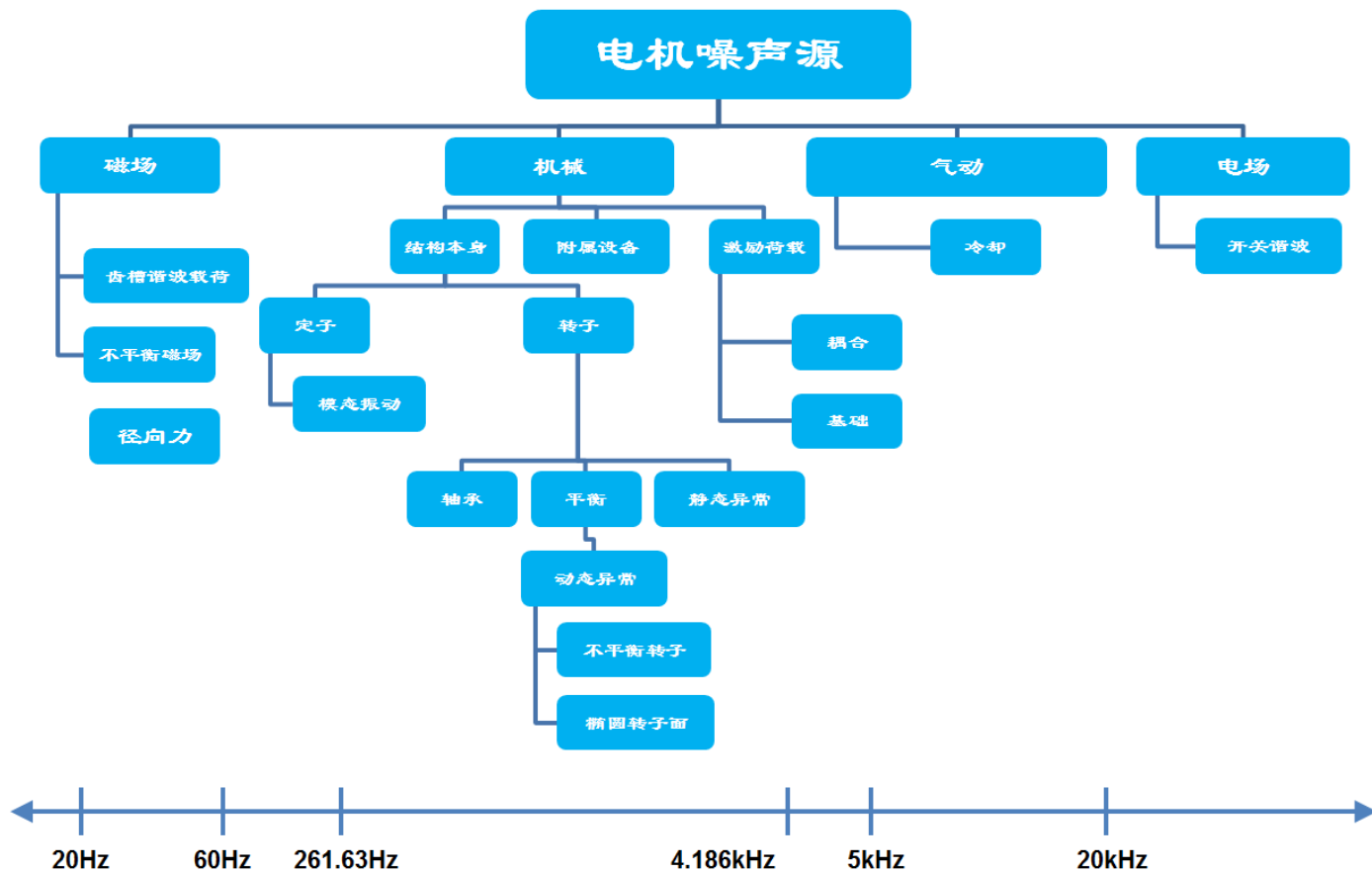
工业驱动

交直流两用马达

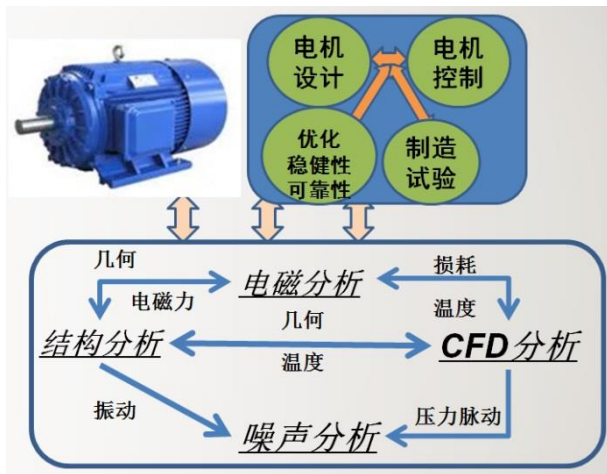


家用电器

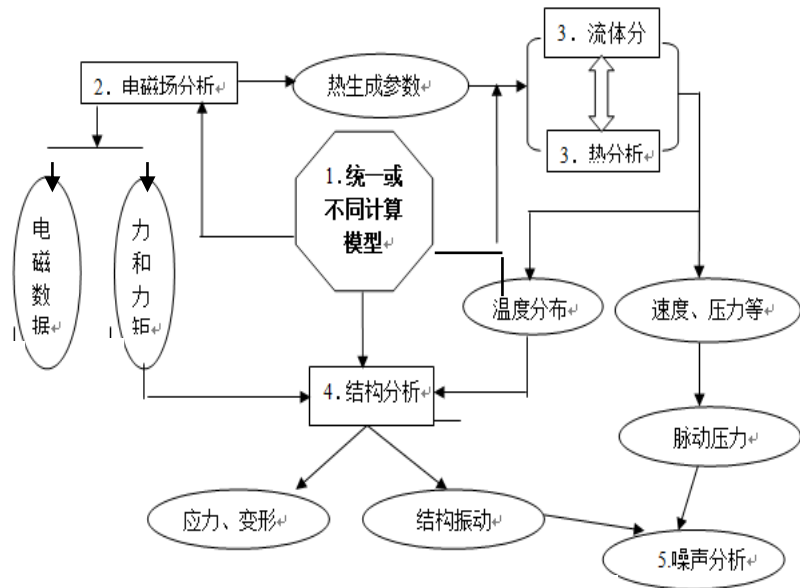




- ✓ 电磁生热
- ✓ 热影响电磁
- ✓ 通风冷却;
- ✓ 热应力;
- ✓ 热变形;
- ✓ 电磁振动;
- ✓ 噪声分析;



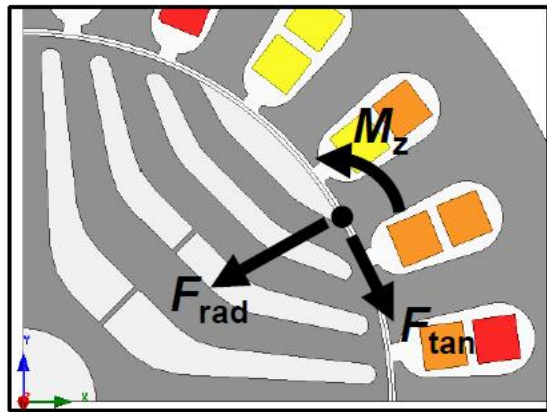
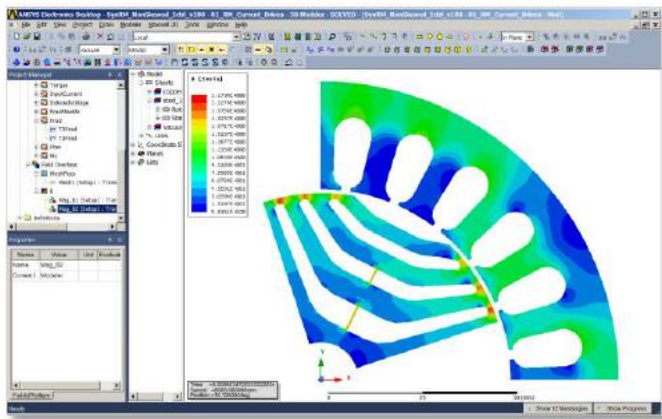
理想分析流程



电机多物理场耦合分析流程

目的：获取每个定子齿部的径向力、切向力和弯矩

瞬态电磁场
分析



2D case: $[F_{rad}, F_{tan}, M_z]$, 3D case: $[F_{rad}, F_{tan}, F_z, M_{rad}, M_{tan}, M_z]$

所有的电磁力分量都是时间或者角度的函数。

■ 低频问题

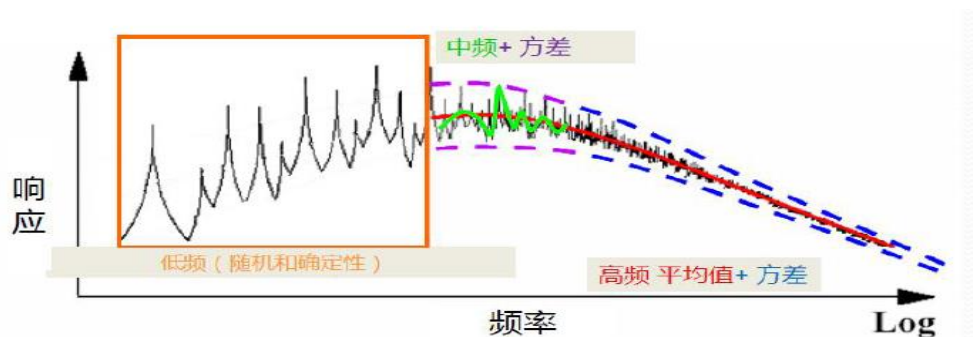
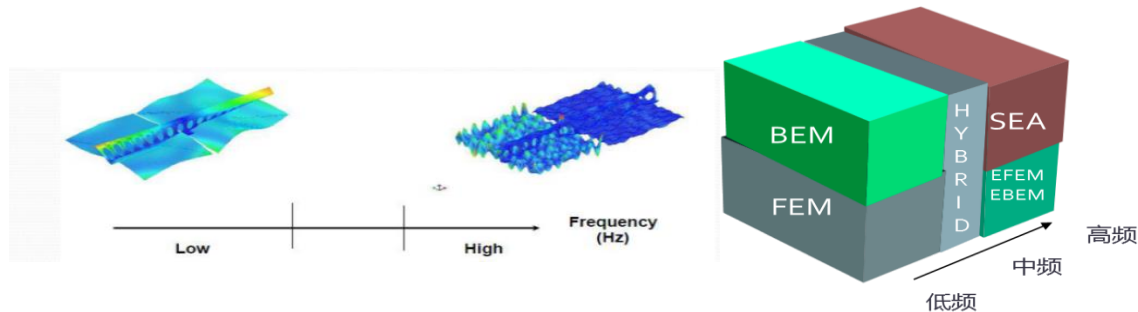
- ◆ FEA (Finite Element Analysis)
- ◆ BEA (Boundary Element Analysis)
- ◆ IFEM (Infinite Finite Element Method)
- ◆ PML (Perfectly Matched Layers)
- ◆ AML (Automatically Matched Layers)

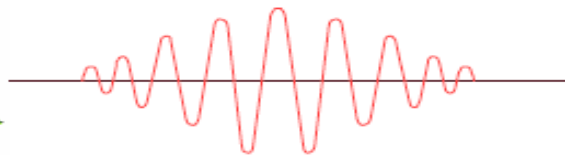
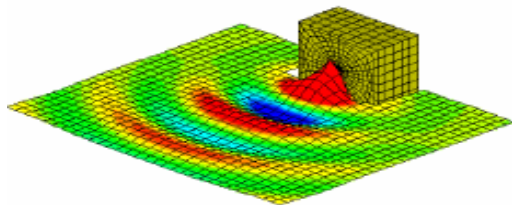
■ 中频

- ◆ Hybrid FEA, SEA/EFEA, BEA

■ 高频

- ◆ SEA (Statistical Energy Analysis)
- ◆ EFEA (Energy Finite Element Method)
- ◆ EBEA (Energy Boundary Element Method)
- ◆ EFEA-SEA hybrid method





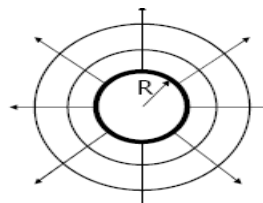
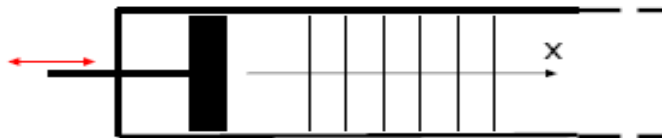
FEM数值分析

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \vec{v}) + Q$$

$$\rho \frac{d\vec{v}}{dt} = -\nabla p + \nabla \cdot \bar{\bar{S}} + \rho \vec{b}$$

$$\nabla \cdot \left(\frac{1}{\rho_0} \nabla p \right) - \frac{1}{\rho_0 c^2} \frac{\partial^2 p}{\partial t^2} + \nabla \cdot \left[\frac{4\mu}{3\rho_0} \nabla \left(\frac{1}{\rho_0 c^2} \frac{\partial p}{\partial t} \right) \right] = -\frac{\partial}{\partial t} \left(\frac{Q}{\rho_0} \right) + \nabla \cdot \left[\frac{4\mu}{3\rho_0} \nabla \left(\frac{Q}{\rho_0} \right) \right]$$

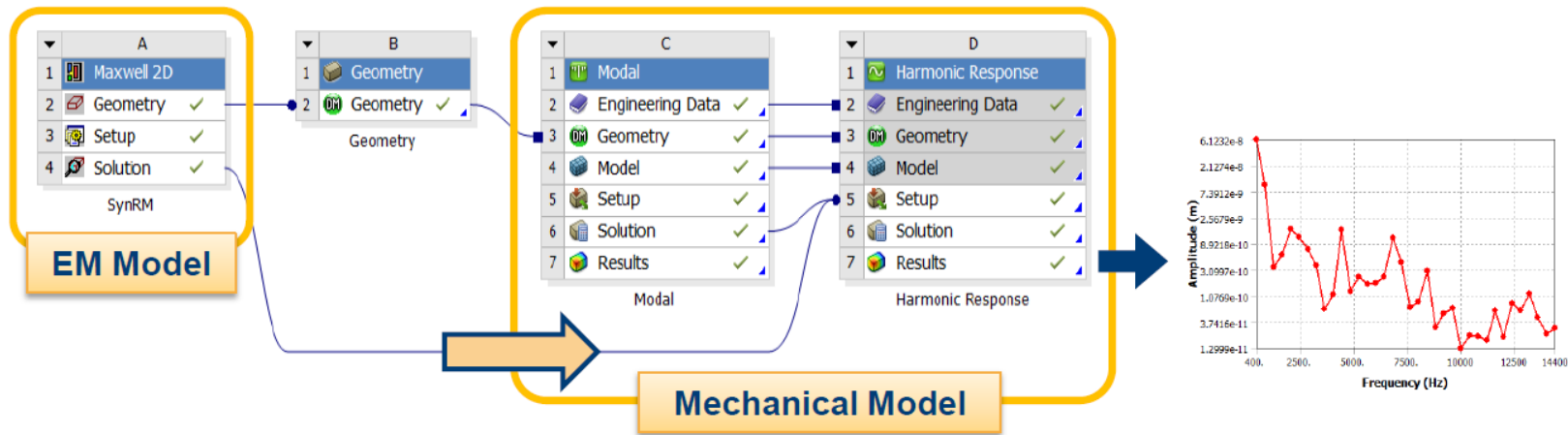
$$[M_F]\{\ddot{p}_e\} + [C_F]\{\dot{p}_e\} + [K_F]\{p_e\} + \bar{\rho}_0 [R]^T \{\ddot{u}_{e,F}\} = \{f_F\}$$



声波类型

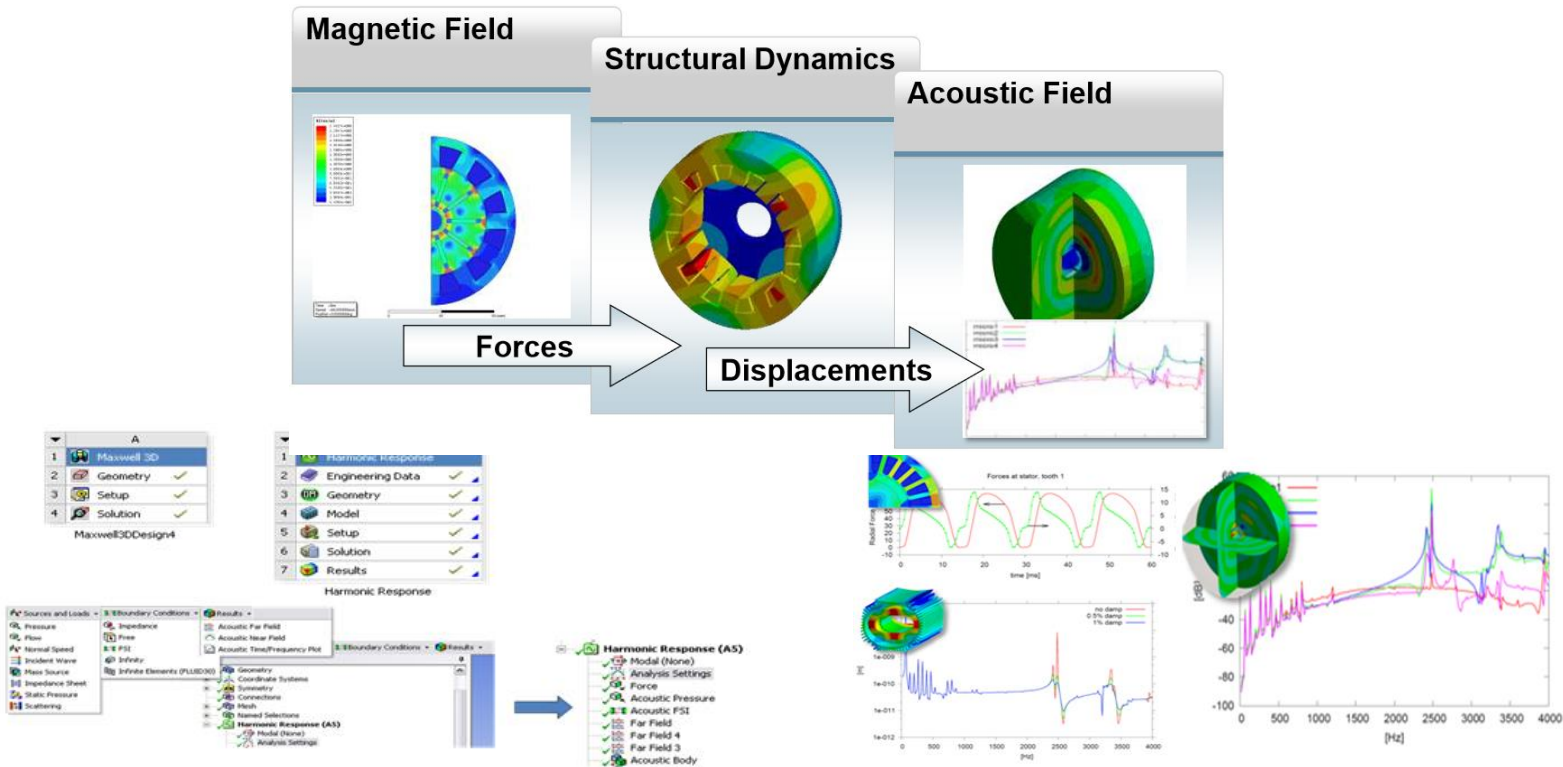
电机电磁振动噪声分析解决方案

——ANSYS Standard Workflow

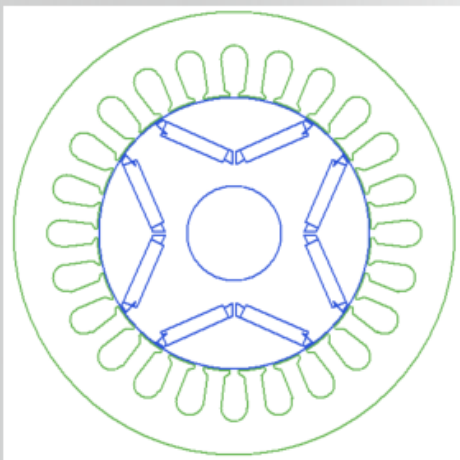


电机电磁振动噪声分析解决方案

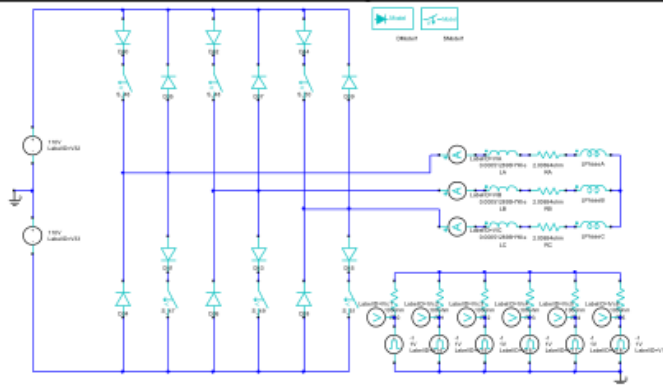
电机由于电磁力作用引起的电机噪声可以通过2D Maxwell电磁场分析得到的在定子齿部的电磁力，映射处理到3D的电机结构网格模型上，通过FFT变换后，进行电机扫频分析，得到频率响应曲线，进而进行声学分析。



- **RMxprt: IPM Motor Type**
- **Maxwell: 2D Transient**
- **Structural: 3D Harmonic**
- **Acoustics ACT**



Machine Type	Internal Permanent Magnet Adjustable Speed Motor
Rated Output Power	550W
Rated Voltage	220V DC bus
Number of Poles	4
Stator Teeth	24
Rated Speed	1500rpm

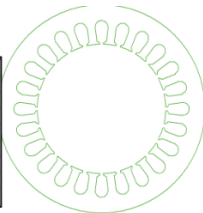


➤ Stator

Name	Value	Unit
Number of Poles	4	
Number of Slots	24	
Circuit Type	Y3	
Slot Type	2	
Position Control	<input type="checkbox"/>	

Slot

Name	Value	Unit
Auto Design	<input type="checkbox"/>	
Parallel Tooth	<input type="checkbox"/>	
Hs0	0.5	mm
Hs1	1	mm
Hs2	8.2	mm
Bs0	2.5	mm
Bs1	5.6	mm
Bs2	7.6	mm

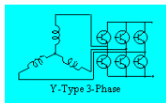


➤ Core

Name	Value	Unit
Outer Diameter	120	mm
Inner Diameter	75	mm
Length	65	mm
Stacking Factor	0.95	
Steel Type	M19_24G	
Press Board Thick...	0	mm
Magnetic Press B...	<input type="checkbox"/>	
Skew Width	0	
Lamination Sectors	0	

Circuit

Name	Value	Unit
Control Type	DC	
Trigger Pulse W...	120	deg
Transistor Drop	2	V
Diode Drop	2	V

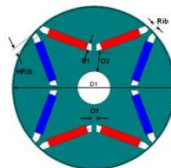


➤ Rotor

Name	Value	Unit
Number of Poles	4	

Pole

Name	Value	Unit
D1	73	mm
O1	1	mm
O2	6	mm
B1	3	mm
Rib	12	mm
HRib	4	mm
Layers	1	
Layer Pitch	0	mm
Magnet Thickness	3.75	mm
Magnet Width	36.835	mm
Magnet Type	XG196/96	



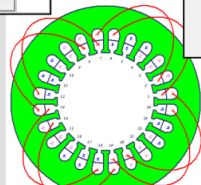
➤ Core

Name	Value	Unit
Outer Diameter	74	mm
Inner Diameter	26	mm
Length	65	mm
Stacking Factor	0.95	
Steel Type	M19_24G	
Pole Type	3	

➤ Winding (tab 1)

Name	Value	Unit
Winding Layers	2	
Winding Type	Whole-Coiled	
Parallel Branch...	1	
Conductors per ...	52	
Coil Pitch	5	
Number of Stran...	1	
Wire Wrap	0	mm
Wire Size	Diameter: 0mm	
Conductor Type	copper_75C	

Coil	Phase	Turns	In Slot	Out Slot
Coil_1	A	26	1T	6B
Coil_2	A	26	2T	7B
Coil_3	C	26	3T	8B
Coil_4	C	26	4T	9B
Coil_5	B	26	5T	10B
Coil_6	B	26	6T	11B



End/Insulation (tab 2)

Name	Value	Unit
Input Half-Turn Length	<input type="checkbox"/>	
End Extension	0	mm
Correction Factor	1	
Base Inner Radius	0	mm
Tip Inner Diameter	0	mm
End Clearance	0	mm
Slot Liner	0	mm
Wedge Thickness	0	mm
Layer Insulation	0	mm
Limited Fill Factor	0.75	
Top Spare Space	0	
Bottom Spare Spa...	0	

➤ Shaft

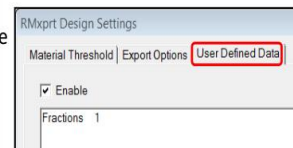
Name	Value	Unit
Magnetic Shaft	<input type="checkbox"/>	
Frictional Loss	12	W
Winding Loss or Power	0	W
Reference Speed	1500	rpm

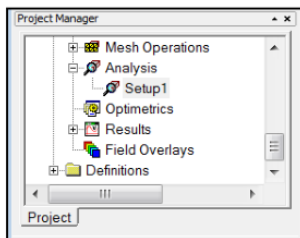
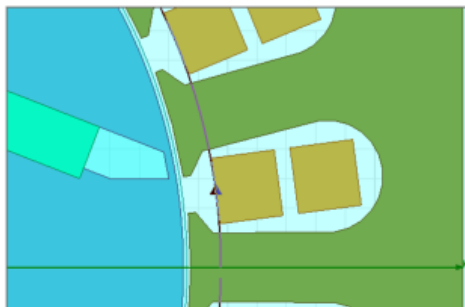
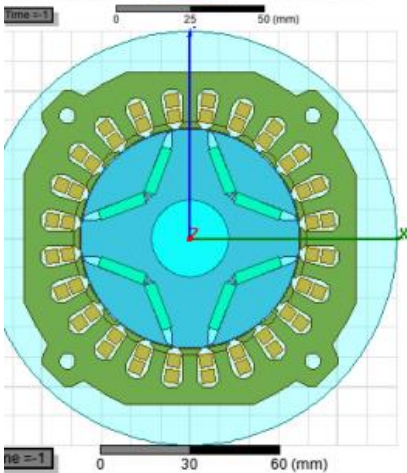
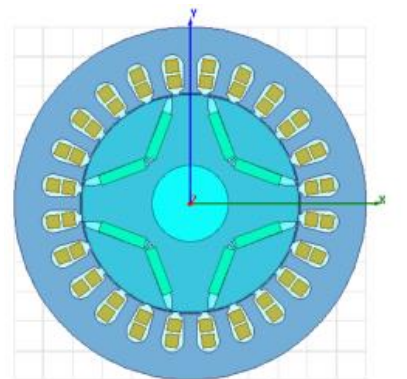
Setup1

Name	Value	Unit
Name	Setup1	
Enabled	<input checked="" type="checkbox"/>	
Operation Type	Motor	
Load Type	Const Power	
Rated Output Power	550	W
Rated Voltage	220	V
Rated Speed	1500	rpm
Operating Temperature	75	cel

➤ Enable the Full-Model export to Maxwell

- Click the menu item RMxpert > Design Settings
- In the User Defined Data tab, check Enable and type "Fractions 1" to enable the Full-Model export
- The default Maxwell model uses the smallest possible fraction of geometry.

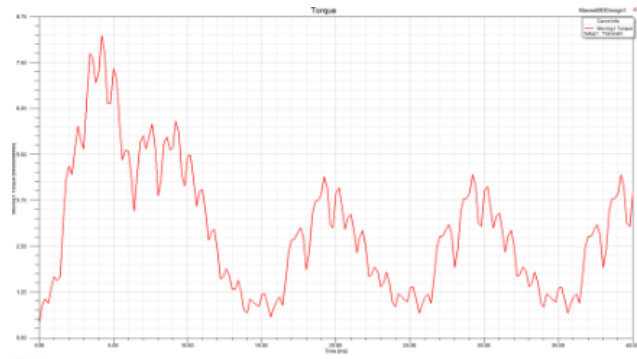
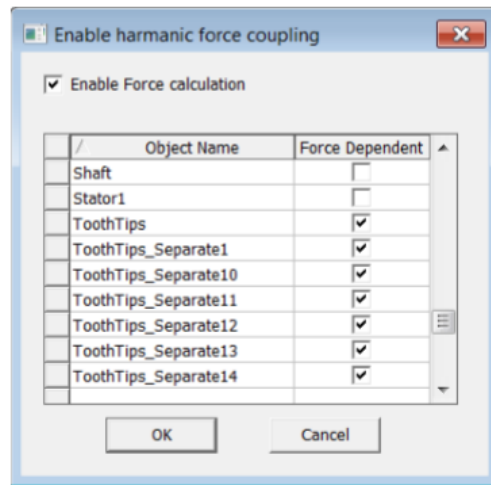




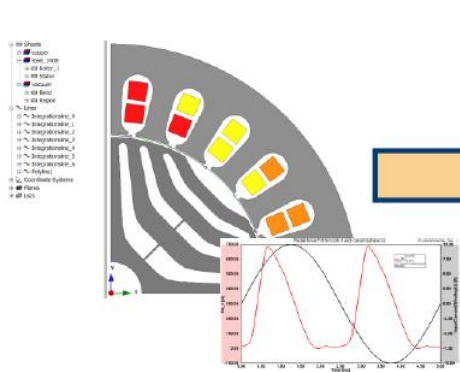
Properties

Name	Value	Unit	Evaluated Value
Name	Setup1		
Enabled	<input checked="" type="checkbox"/>		
Stop Time	0.04	s	0.04s
Time Step	0.0002	s	0.0002s

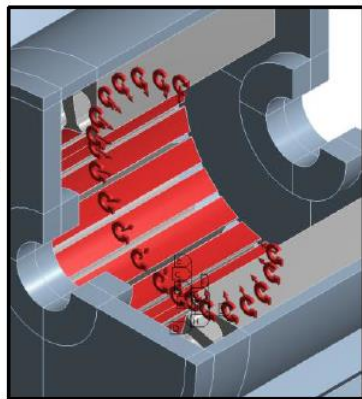
General | Advanced | Solver



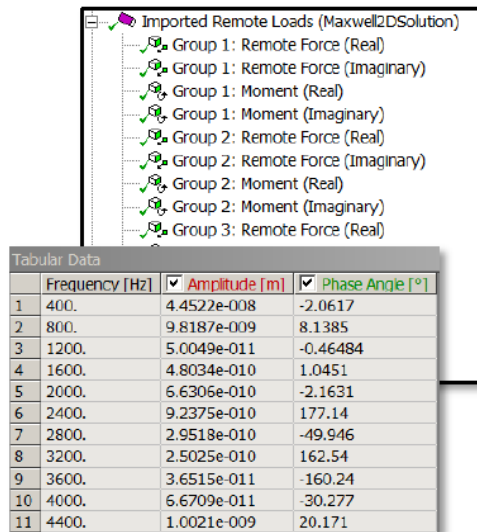
Maxwell 2D/3D输出的电磁力加载到ANSYS Mechanical模型中的定子齿部表面。



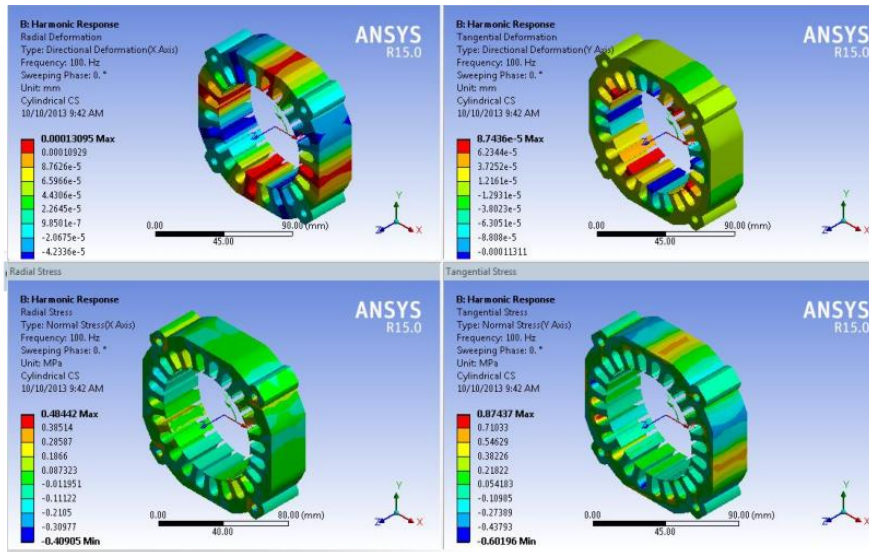
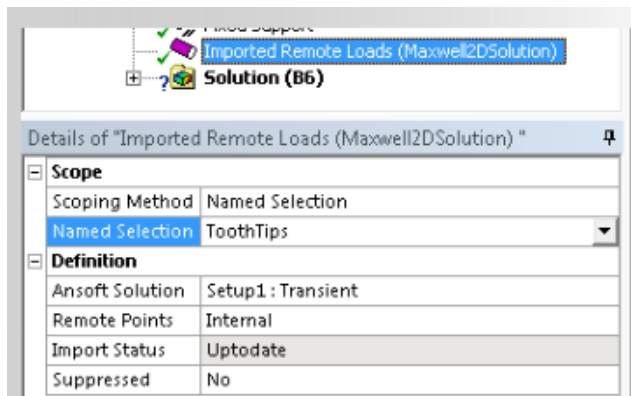
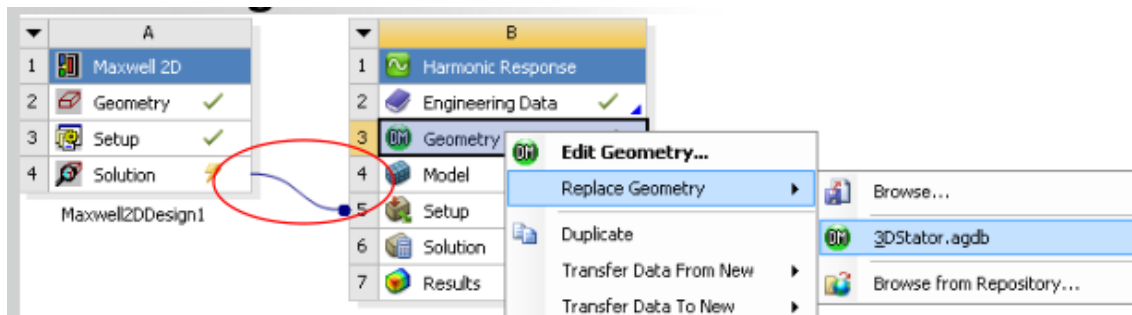
Maxwell模型

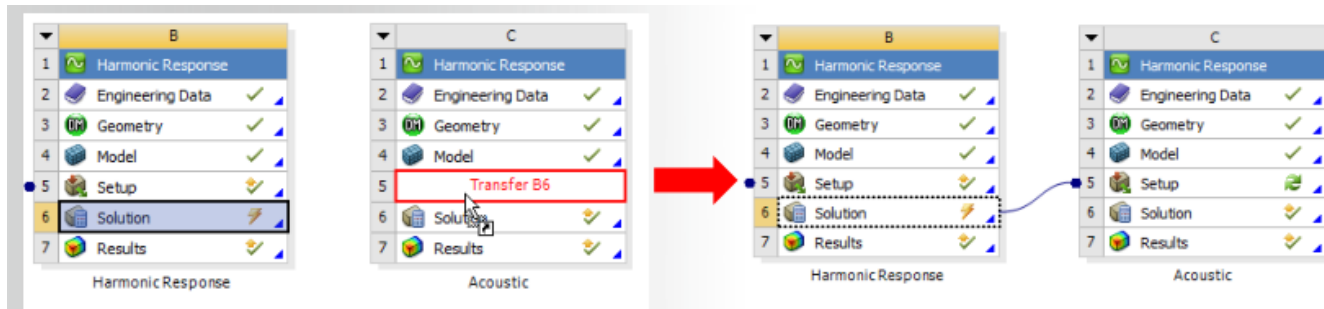


Mechanical模型



通过remote points施加电磁力载荷



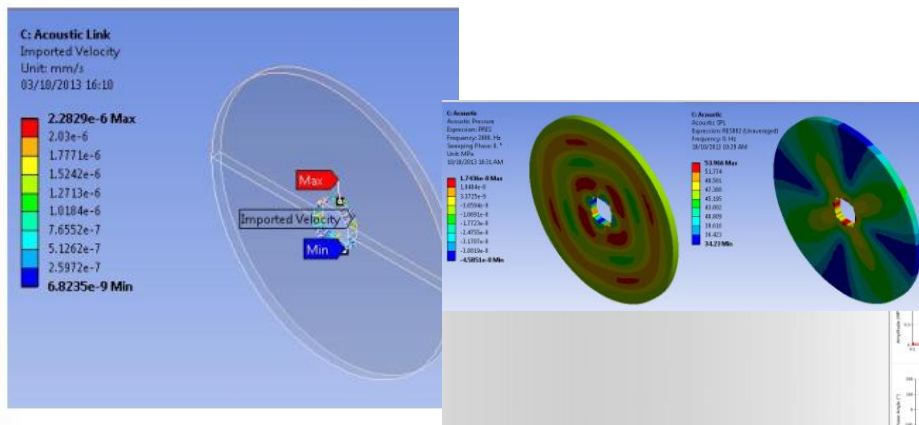


Named Selections Tree:

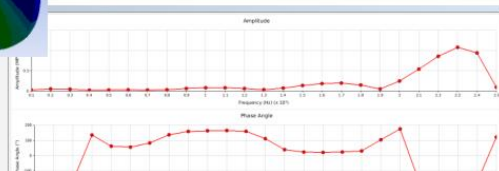
- Harmonic Response (C5)
 - Pre-Stress/Modal (None)
 - Analysis Settings
 - Acoustic Body
 - Acoustic Body Selection Boundary
 - Imported Load (B6)
 - Imported Velocity**
- Solution (C6)
 - Solution Information
 - Acoustic Pressure
 - Acoustic SPL
 - Acoustic Velocity X
 - Acoustic Time_Frequency Plot

Details of "Imported Velocity"

- Scope
 - Scoping Method: Named Selection
 - Named Selection: entsurf
- Definition
 - Type: Imported Velocity
 - Tabular Loading: Program Controlled
 - Suppressed: No
 - Source Bodies: All
 - Source Frequency: All

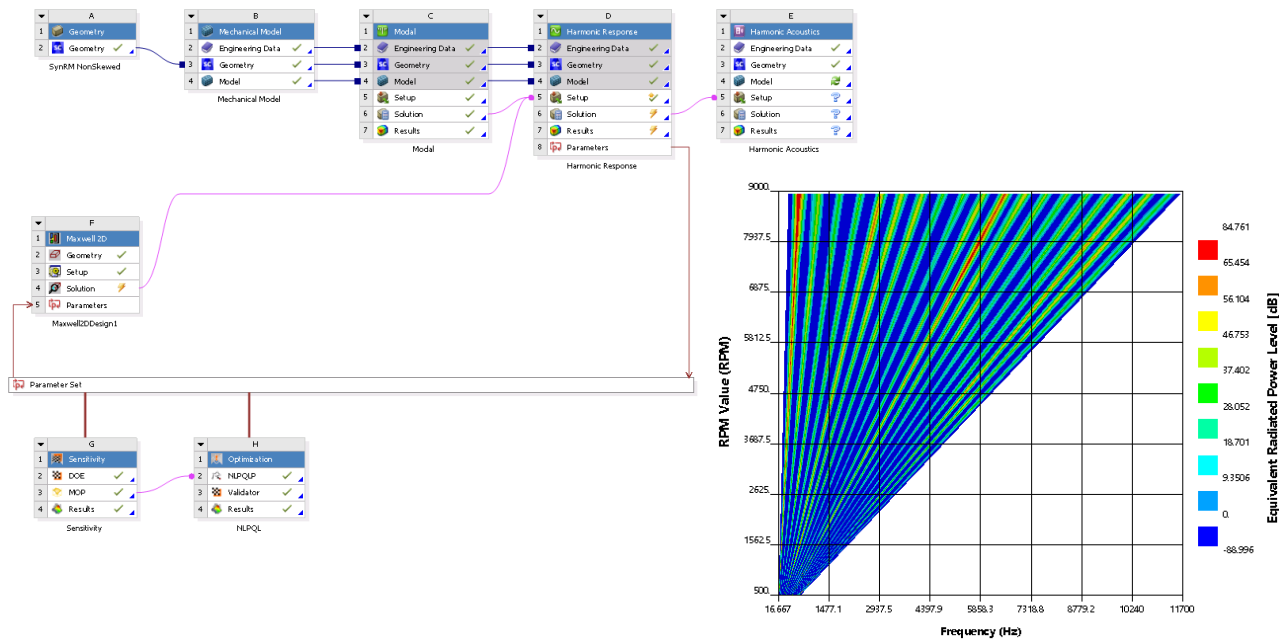


- Boundary Conditions
 - Acoustic Pressure
 - Impedance Boundary
 - Attenuation Surface
 - Radiation Boundary**

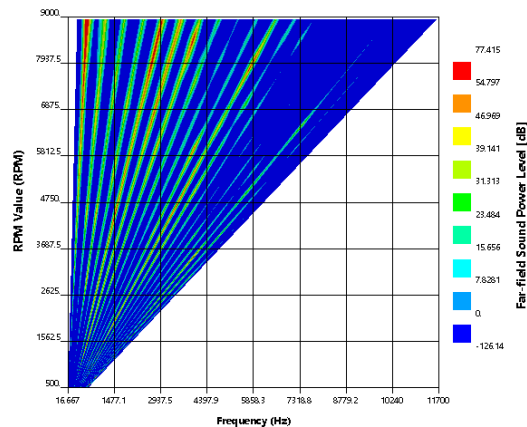


✓ 多转速电磁振动噪声计算

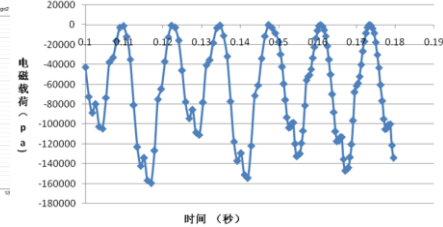
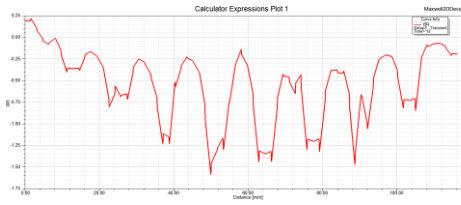
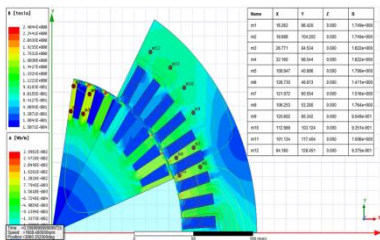
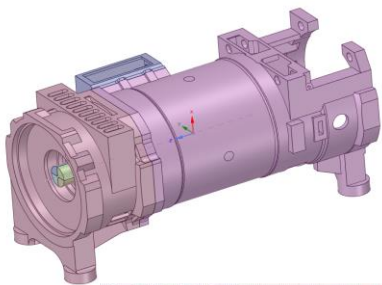
在Workbench平台可以搭建Maxwell电磁分析、模态分析、振动响应以及声场传播计算等多物理场之间的耦合计算流程。而且可以与optiSlang无缝结合，实现多目标的参数优化分析。



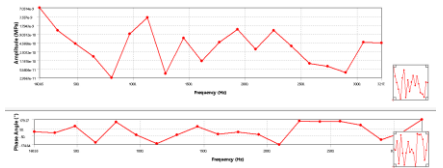
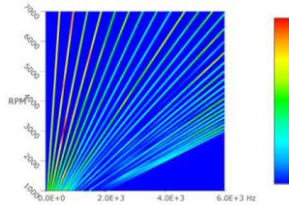
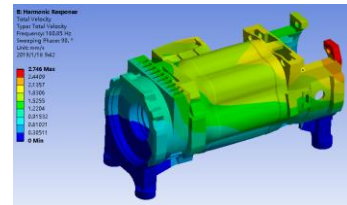
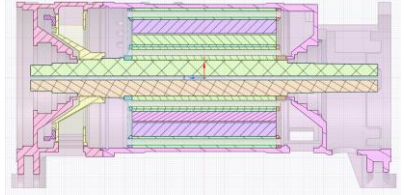
ERP瀑布图



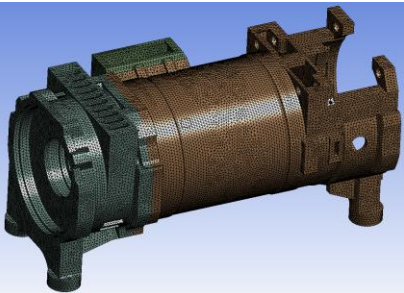
声压级瀑布图



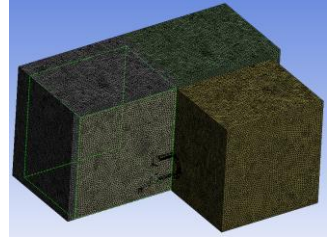
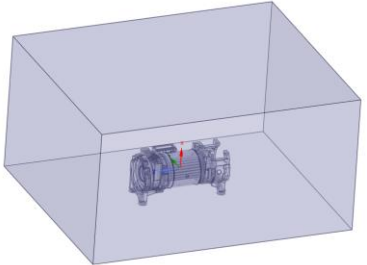
磁场分析（磁密、磁密曲线、电磁力）



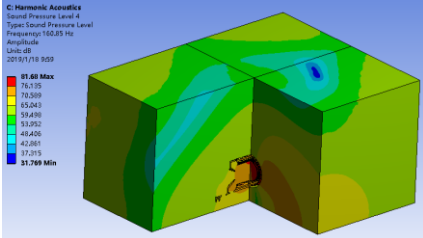
结构传播噪声分析（振动速度、辐射声功率级瀑布图） 空气传播噪声分析结果（声压级以及声压频响曲线）



电机CAD模型与有限元网格

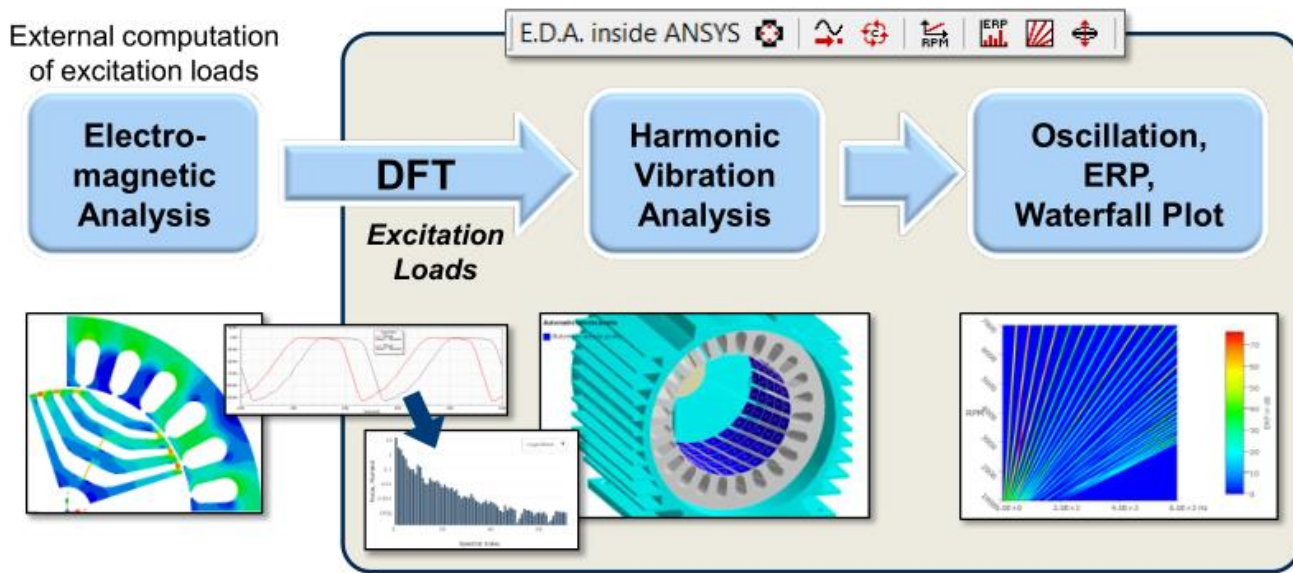


空气传播噪声分析模型

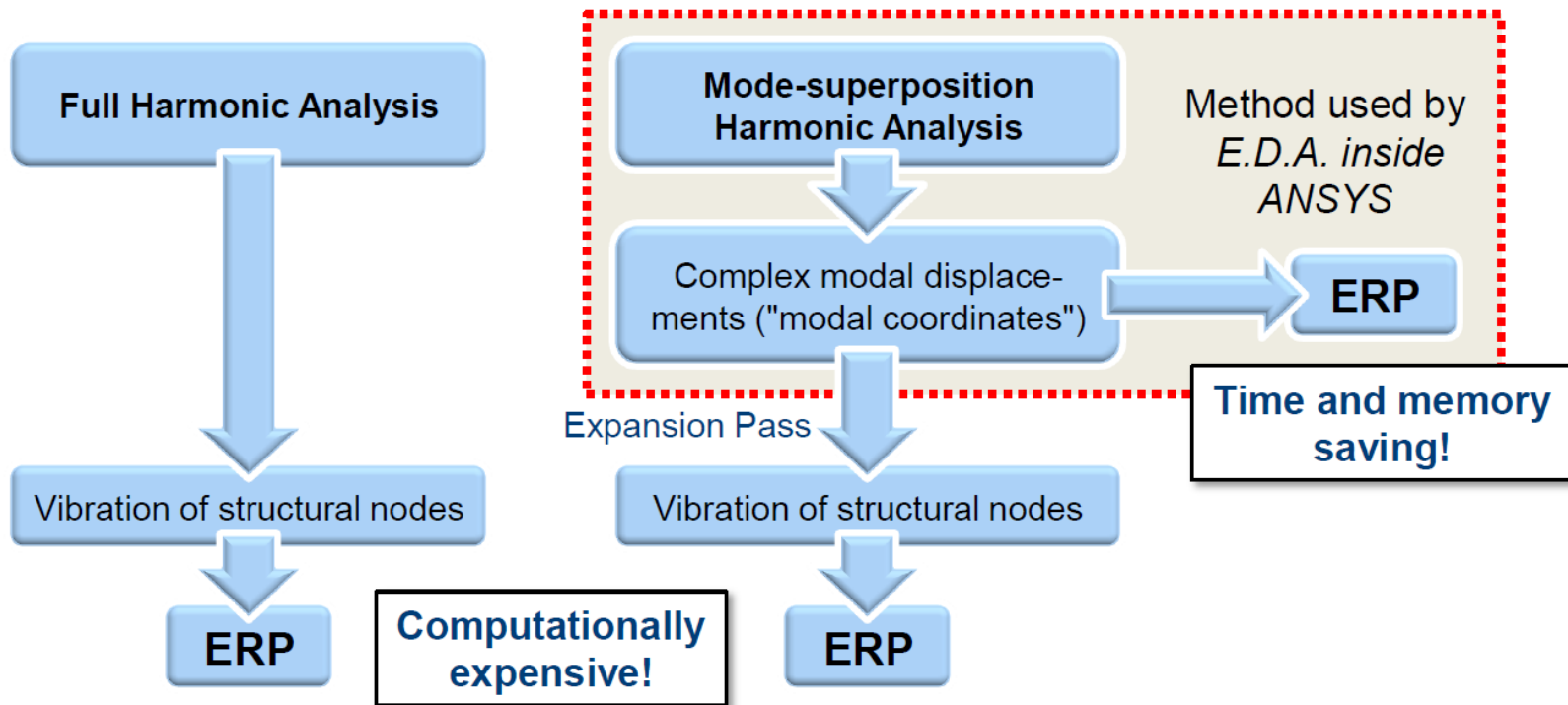


电机电磁振动噪声分析解决方案

——E.D.A inside ANSYS



Fast ERP-computation Based on Modal Coordinates:

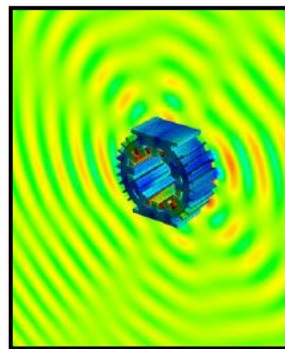
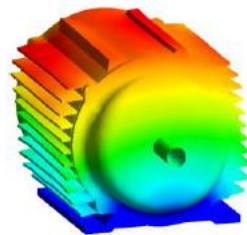
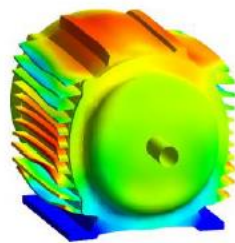
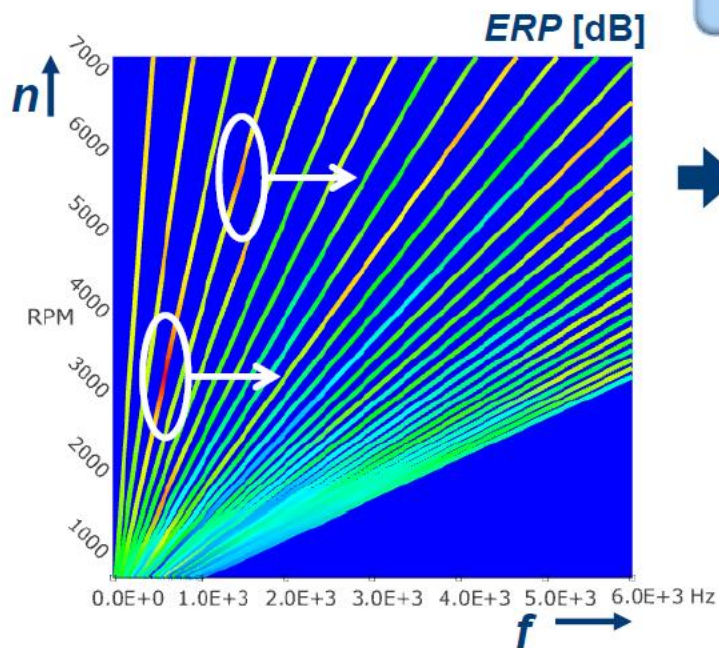


Outlook: From ERP Waterfall to Air-borne Acoustics:

Identify critical OPs

Get vibration shapes for critical OPs only

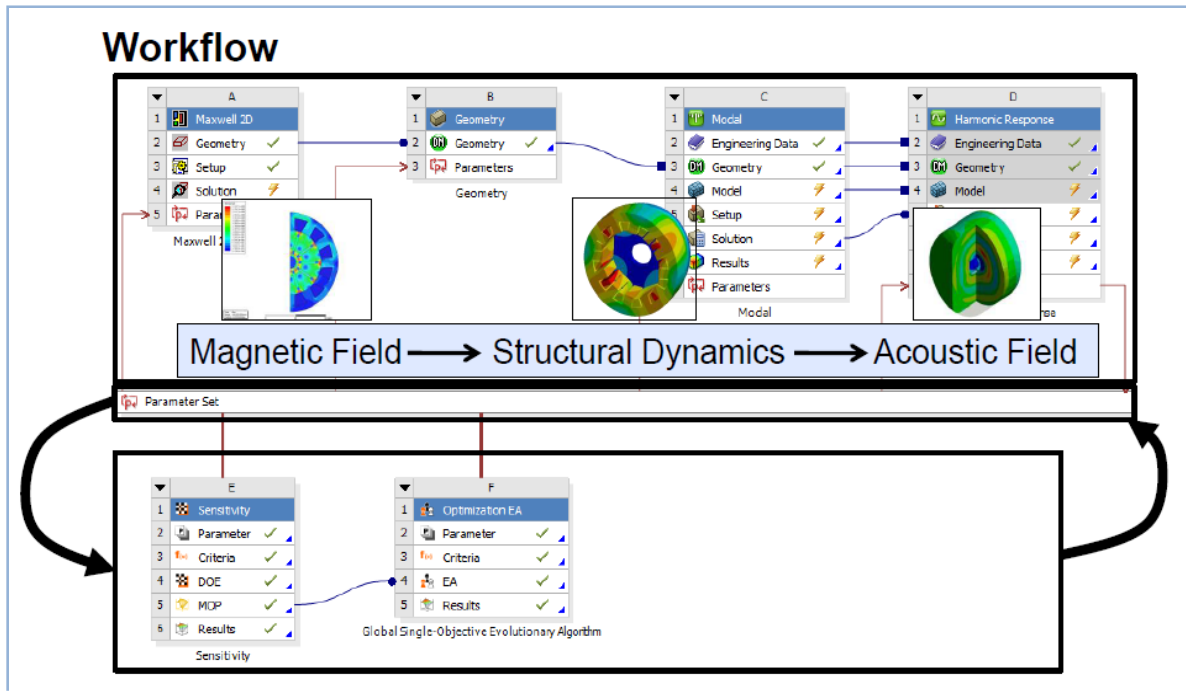
Analyse true radiation by acoustic field simulation

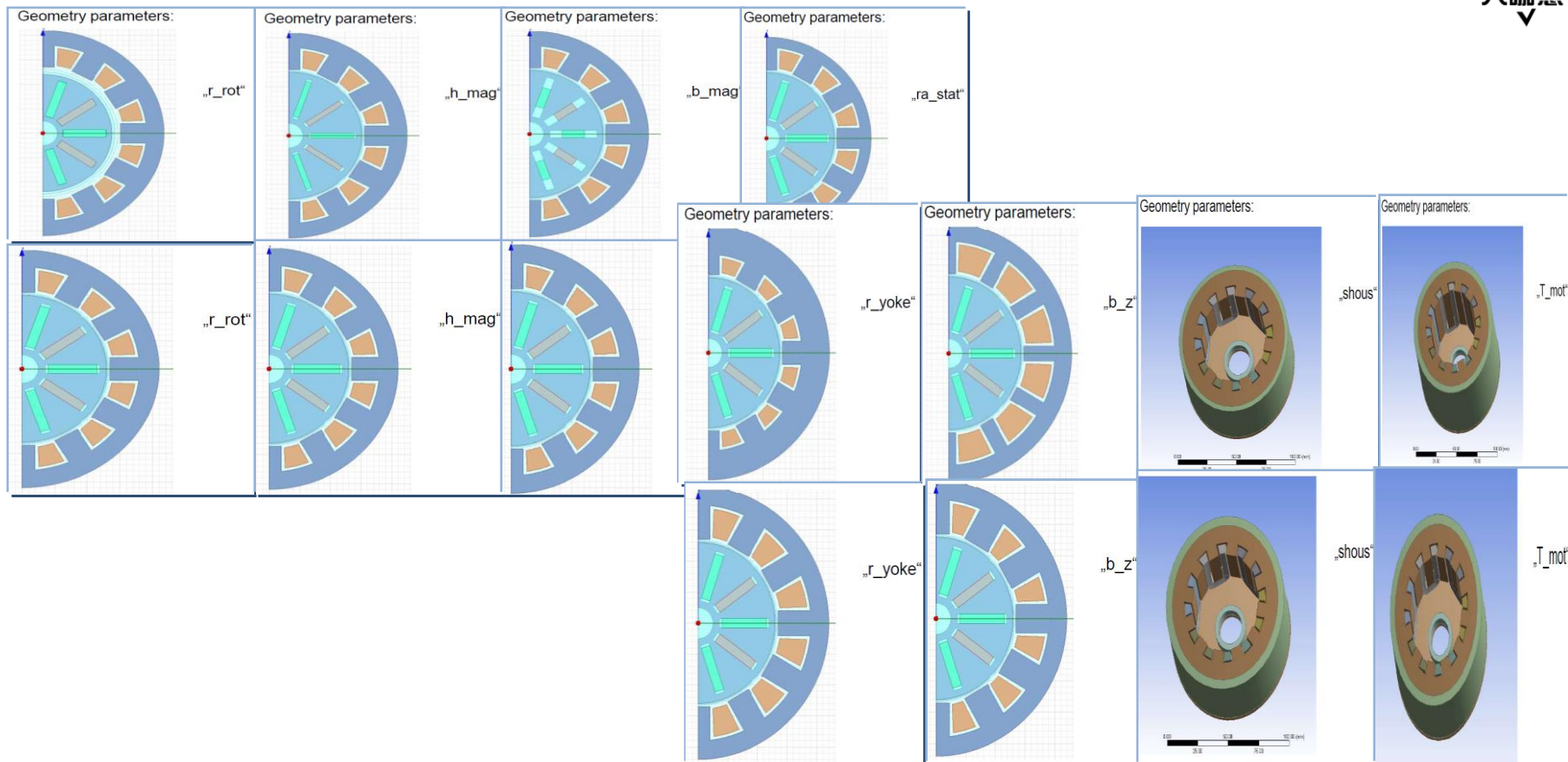


(optional;
by dedicated tools for
air-borne acoustics)

电机电磁振动噪声分析解决方案









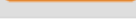
——ANSYS multidiscipline Optimization





Parameterization - Overview

Parameter set

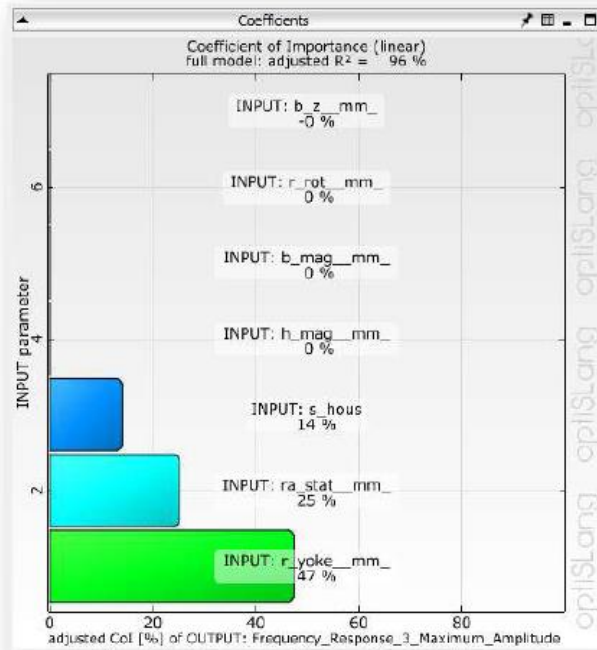
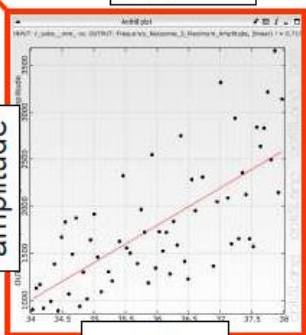
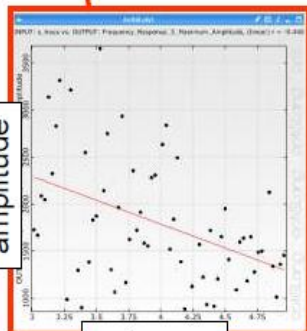
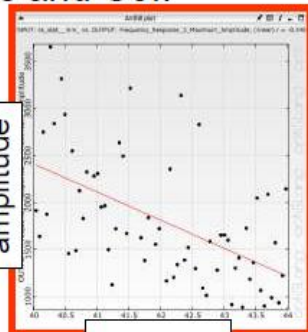
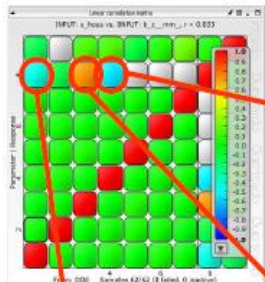
	Name	Parameter type	Reference value	Constant	Value type	Resolution	Range	Range plot
1	s_hous	Deterministic	2.142	<input type="checkbox"/>	REAL	Continuous	3 5	
2	t_mot	Deterministic	30	<input checked="" type="checkbox"/>	REAL	Continuous	30 60	
3	b_z_mm_	Deterministic	8.8	<input type="checkbox"/>	REAL	Continuous	5 9	
4	r_yoke_mm_	Deterministic	36.8	<input type="checkbox"/>	REAL	Continuous	34 38	
5	ra_stat_mm_	Deterministic	42.4	<input type="checkbox"/>	REAL	Continuous	40 44	
6	h_mag_mm_	Deterministic	2.92	<input type="checkbox"/>	REAL	Continuous	2 3	
7	b_mag_mm_	Deterministic	15	<input type="checkbox"/>	REAL	Continuous	8 15	
8	r_rot_mm_	Deterministic	25.8	<input type="checkbox"/>	REAL	Continuous	24 26	
9	FFM_ARG1	Deterministic	50	<input checked="" type="checkbox"/>	REAL	Continuous	50 100	

Import parameter ▾

OK Cancel Apply

Sensitivity Analysis

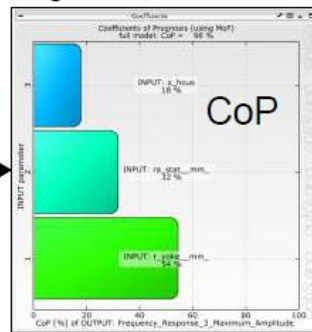
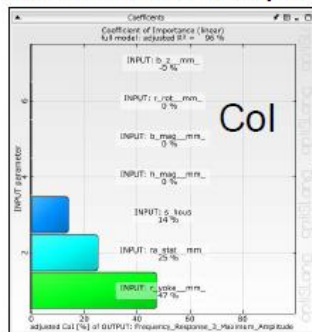
Interesting Anthill Plots and Col:



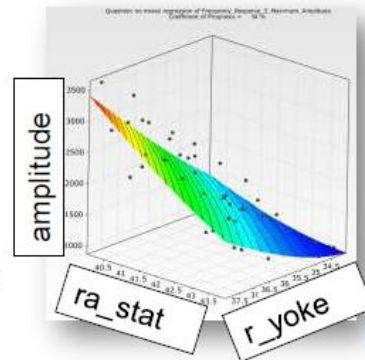
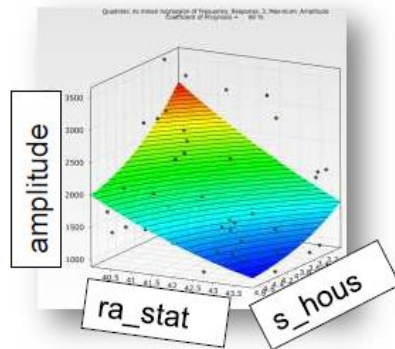
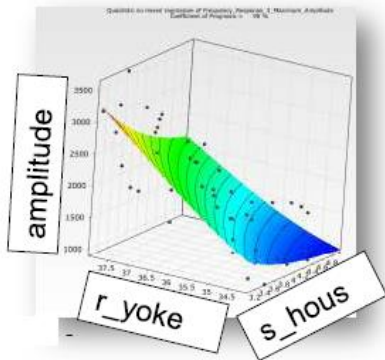
- 42 -

Sensitivity Analysis

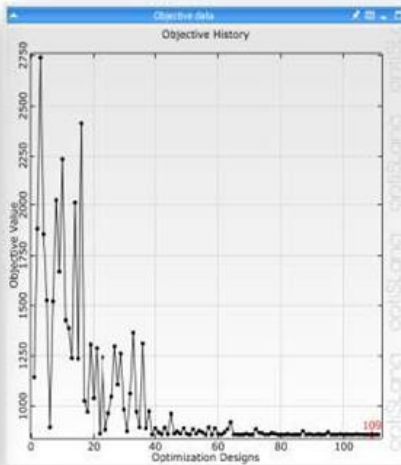
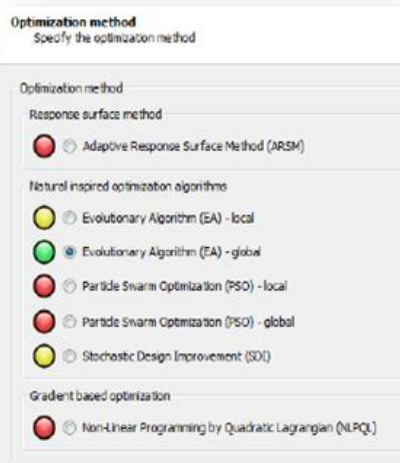
Metamodel of optimal Prognosis and CoP:



Coefficients of Prognosis (using MoP)
full model; CoP = 98 %



Optimization



	Orig.	Better
<u>s_hous</u>	2.142	4.666
<u>b_z</u>	8.8	8.8
<u>r_yoke</u>	36.8	34
<u>ra_stat</u>	42.4	43.787
<u>h_mag</u>	2.92	2.92
<u>b_mag</u>	15	15
<u>r_rot</u>	25.8	25.8

Suggestion for an optimization algorithm by „oiw“

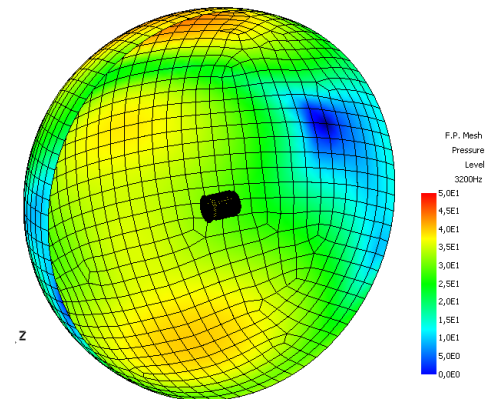
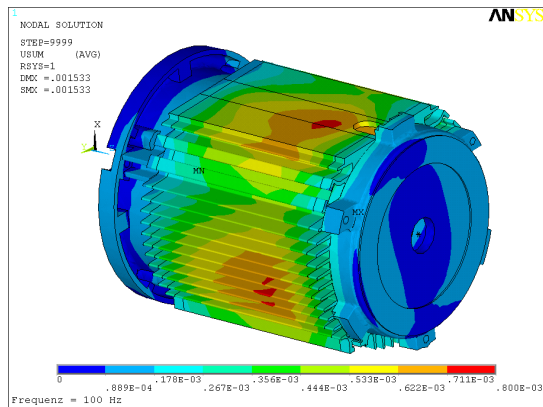
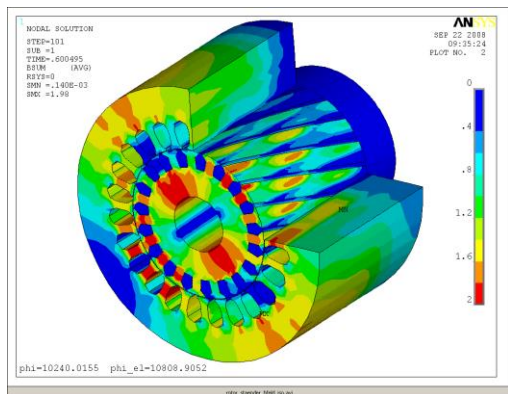
Best result after ~120 calculations on the MoP

Better Input constellation

(Hard calculation) (Hard calculation)

2914 m/s² → 728 m/s²

典型案例介绍



问题描述

分析电机由于电磁力作用引起的电机振动。

解决方案

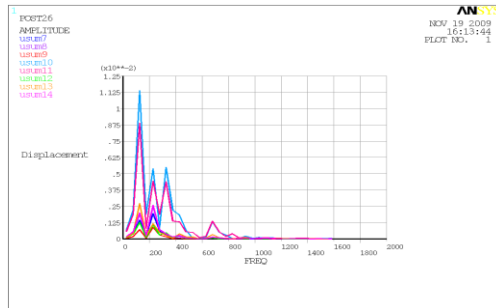
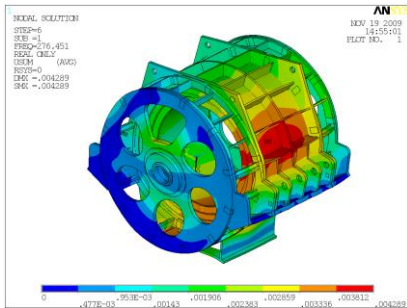
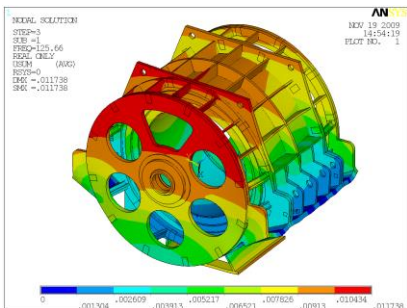
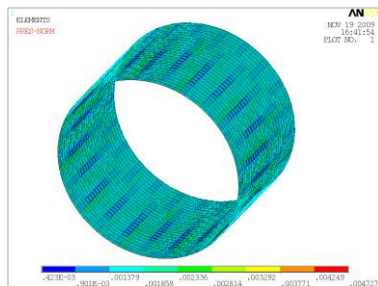
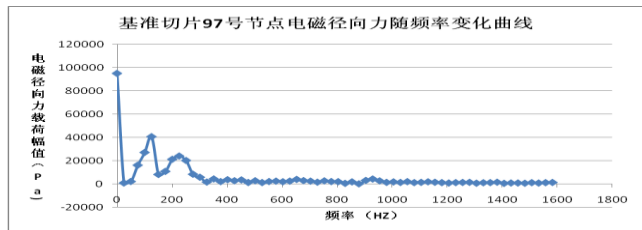
通过2D电磁场分析得到的在定子齿部的电磁力，映射处理到3D的电机结构网格模型上，通过FFT变换后，进行电机扫频分析，得到频率响应曲线。

仿真分析价值

有助于理解电机由于电磁力作用引起的振动

项目评价

通过本次项目，对电机如何准确地进行电磁振动分析，得到了一系列的规范和指导性意见。



问题描述

分析电机由于电磁场焦耳热作用引起的电机温度变化，进而引起的热变形问题。

解决方案

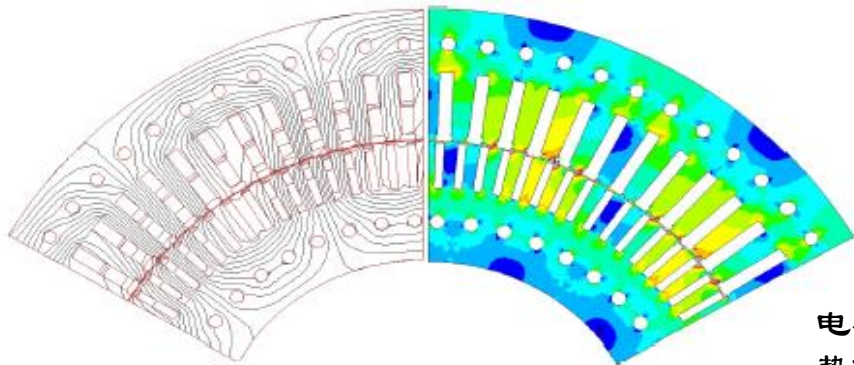
通过2D电磁场分析得到的单元上生成的焦耳热，映射处理到3D的电机结构网格模型上，通过指定换热系数和热边界条件，进行进行热分析。最后利用温度分布结果进行结构的热应力分析。

仿真分析价值

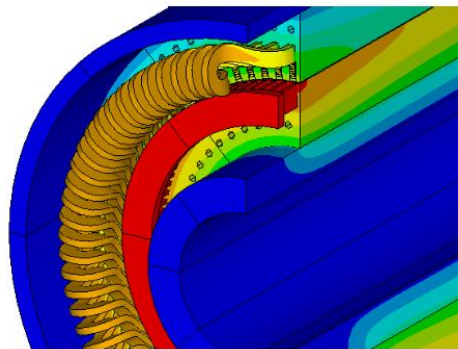
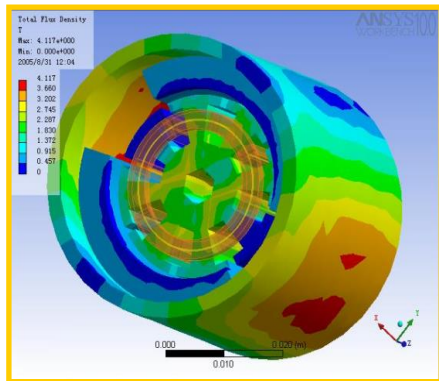
有助于理解电机由于温度载荷引起的性能变化

项目评价

电磁—温度场—热应力分析



电磁焦耳热分析



热变形结果

温度分析

问题描述

分析电机由于电磁力作用引起的电机噪声。

解决方案

通过3D电磁场分析得到的在定子齿部的电磁力，映射处理到3D的电机结构网格模型上，通过FFT变换后，进行电机扫频分析，得到频率响应曲线，进而进行声学分析。

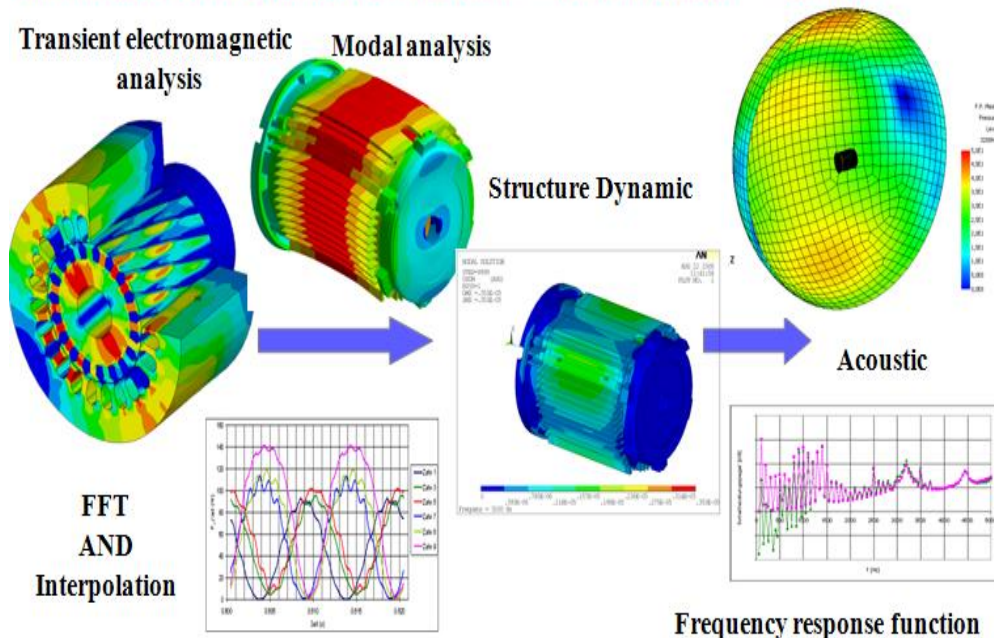
仿真分析价值

有助于理解电机由于电磁力作用引起的振动噪声

项目评价

电磁—结构—声场分析

Vibration and acoustic (Coupling of electromagnetic---->StructureDynamic---->Acoustic)



问题描述

分析电机硅钢片由于材料的磁致伸缩特性带来的振动，并与电磁力引起的振动进行了比较。

解决方案

压电比拟法和热应变比拟法进行了对比，将后者应用到实际项目中，得到了磁致伸缩与电磁力振动的特性对比结果。

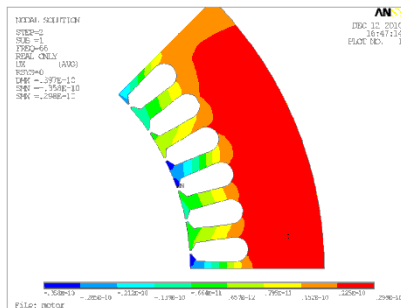
仿真分析价值

进行评估磁致伸缩引起的振动

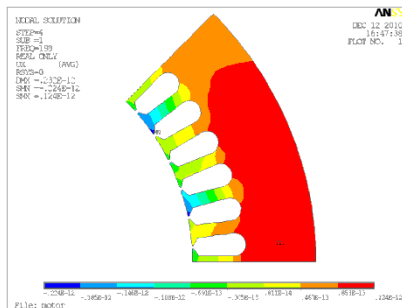
项目评价

压电法

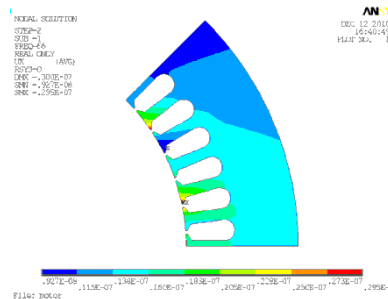
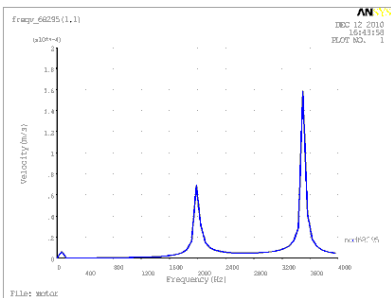
电磁-热应变



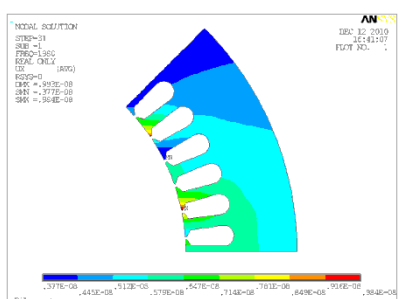
66Hz频率下磁致伸缩振动特性



1980Hz频率下磁致伸缩振动特性



66Hz频率下电磁力振动特性



1980Hz频率下电磁力振动特性

问题描述

分析电机由于电磁力作用引起的电机径向振动噪声。

解决方案

通过2D电磁场分析得到的在定子齿部的电磁力，映射处理到2D的电机结构网格模型上，通过FFT变换后，进行电机扫频分析，得到频率响应曲线。

仿真分析价值

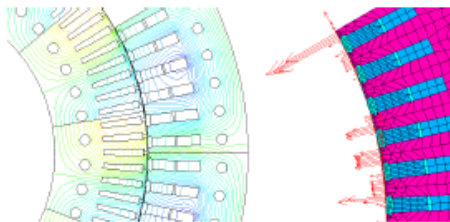
有助于理解电机由于电磁力作用引起的径向振动噪声

项目评价

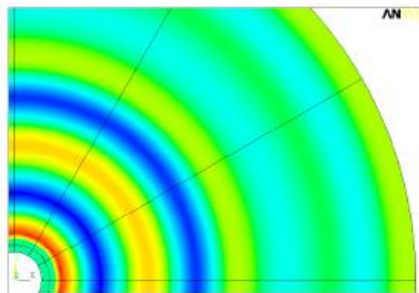
通过本次项目，对电机如何准快速地进行电磁振动噪声分析，得到了一系列的规范和指导性意见。



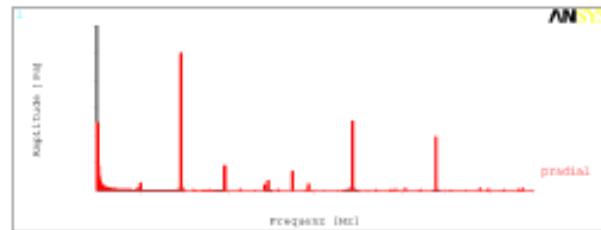
Drehstrom-Asynchron-Schiffsantrieb der Baureihe SEP (Schottel Electric Propulsor)



Berechnung der zeit- und ortsabhängigen magnetischen Erregerkräfte am Innenradius des Ständers



Schallausbreitung in der Umgebung der Maschine



Spektrale Zerlegung des Schallsignals



大咖慧，顾名思义，汇集众多大咖智慧。

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