



《永磁同步电机电磁振动噪声分析》

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出品 | 安世亚太
PERA GLOBAL

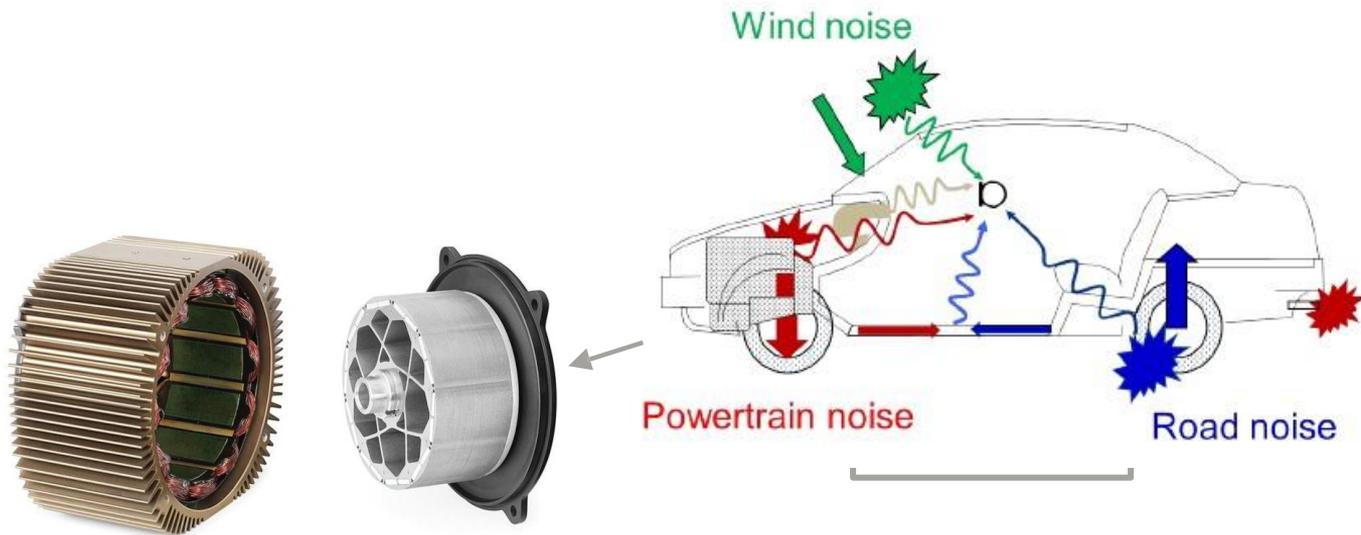


- 电机NVH仿真分析的背景
 - 为什么分析电磁力导致的定子结构振动噪声？
- Ansys 2020 电机NVH仿真分析流程介绍
 - 电磁力分析
 - 谐响应分析
 - 噪声分析
- Good Practice 分享

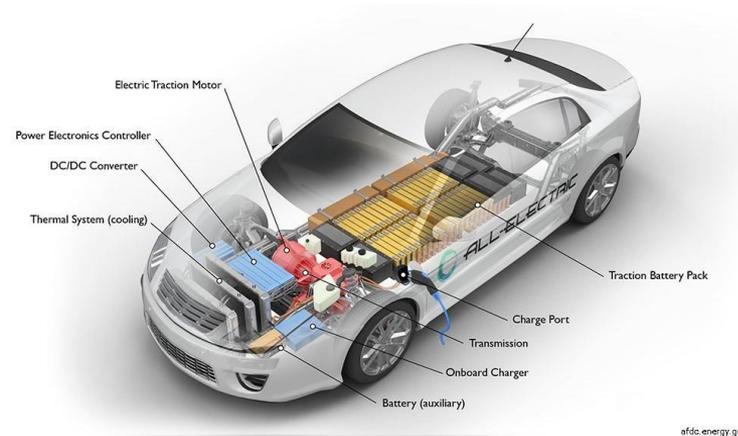
电机NVH分析的必要性



- 生活水平提高，对舒适性要求提高
- 整车背景噪声低，电驱动系统NVH性能要求提高
- 电驱动系统噪声频率高且固定，人感觉特别不舒服



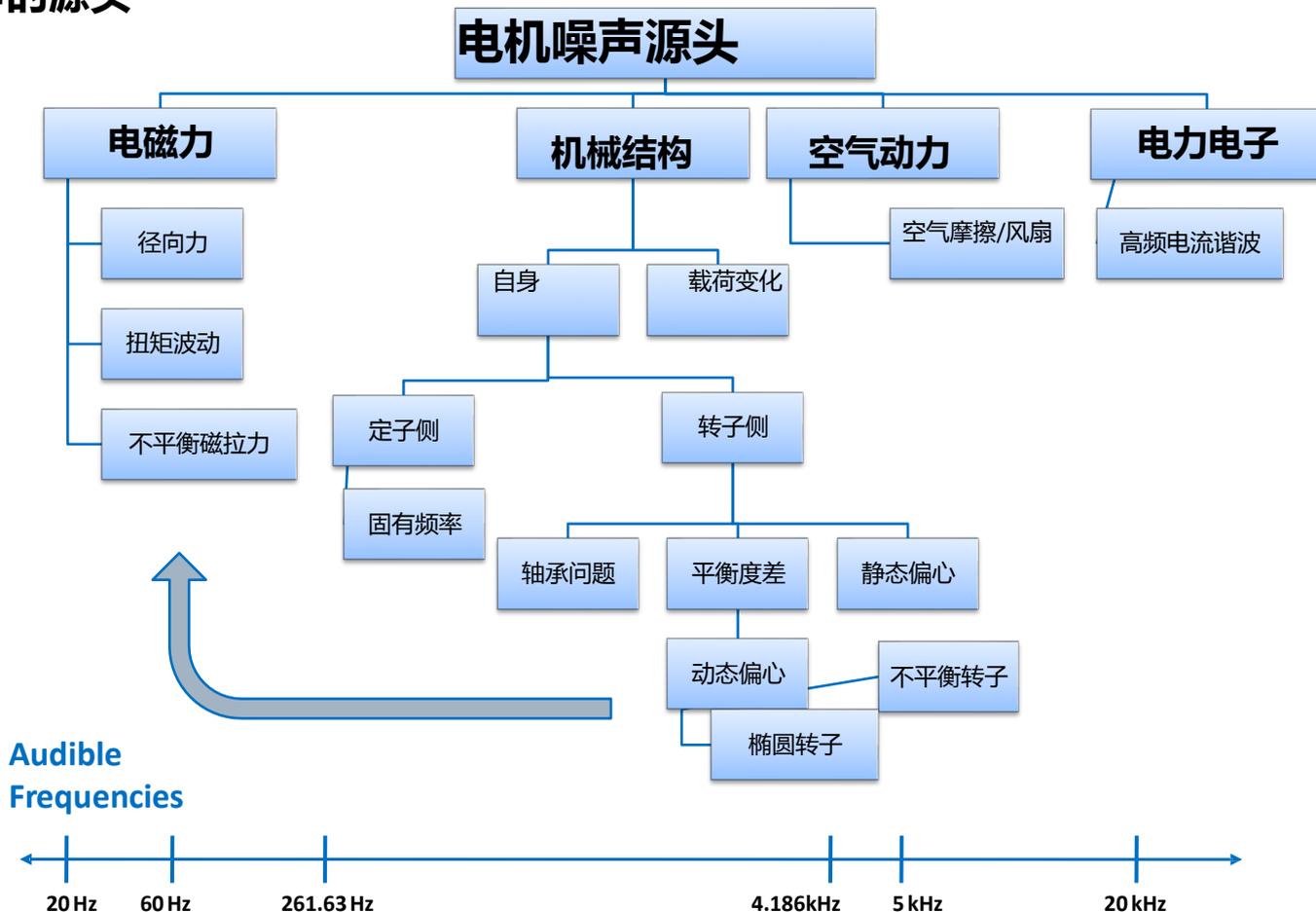
- 设计需求经常存在矛盾
 - Vehicle performance (torque)
 - Packaging (volume, aspect ratio)
 - Fuel economy (efficiency and weight)
 - Durability (stress, demagnetization, temperature raise)
 - NVH (normal and tangential forces, torque ripple)
 - Cost (magnet/copper/steel content, inverter rating, type of winding...)



efdc.energy.gov

Reference: "Electric Machine Design Approaches for Electrified Powertrains" , Ansys Automotive Electrification 2018, by Franco Leonardi ,etc. Ford Motor Company

电机振动噪声的源头



[1] P. Vigayraghavan, R. Krishnan, "Noise in Electric Machines: A Review," IEEE, 1998

为什么分析电磁力导致的定子结构振动噪声？

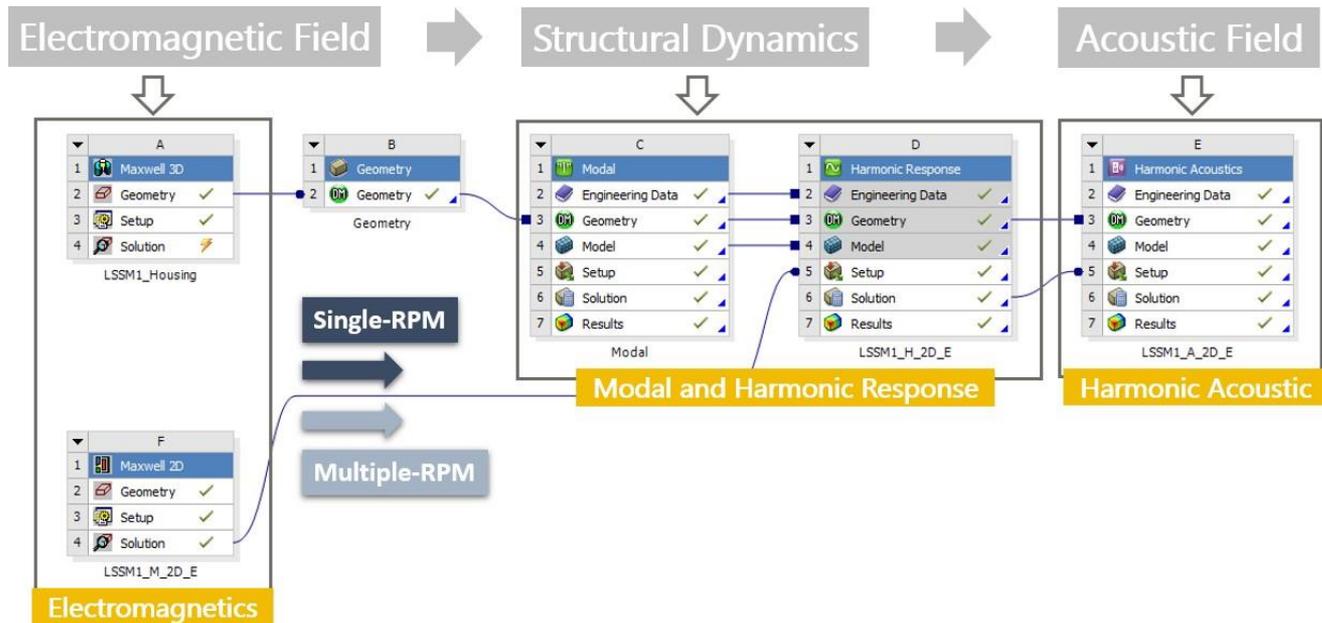


- 电磁力是引起电机振动的主要因素：
 - 径向电磁力幅值非常大
 - 电磁力交变频率处于人耳敏感频段
 - 电磁力谐波含量丰富，容易出现低次空间谐波引发强烈的谐振或受迫振动
- 电磁力容易被精确和快速计算：
 - 借助于 Maxwell + TAU mesh、Clone mesh、HPC、DSO
- 引起振动的电磁力谐波分量容易被定位：
 - 基于经典电机振动噪声分析理论
 - 对Maxwell电磁力分析结果进行时空二维fft
- 电磁力谐波可通过电机结构参数优化进行削弱：
 - Maxwel、I UDP参数化建模 optiSLang & DX

ANSYS电机NVH解决方案



- 精度高
- 结果基于物理场
- 灵活且易用
- 统一平台
 - 统一的模型参数化平台
 - 统一的优化平台
 - 数据无缝链接

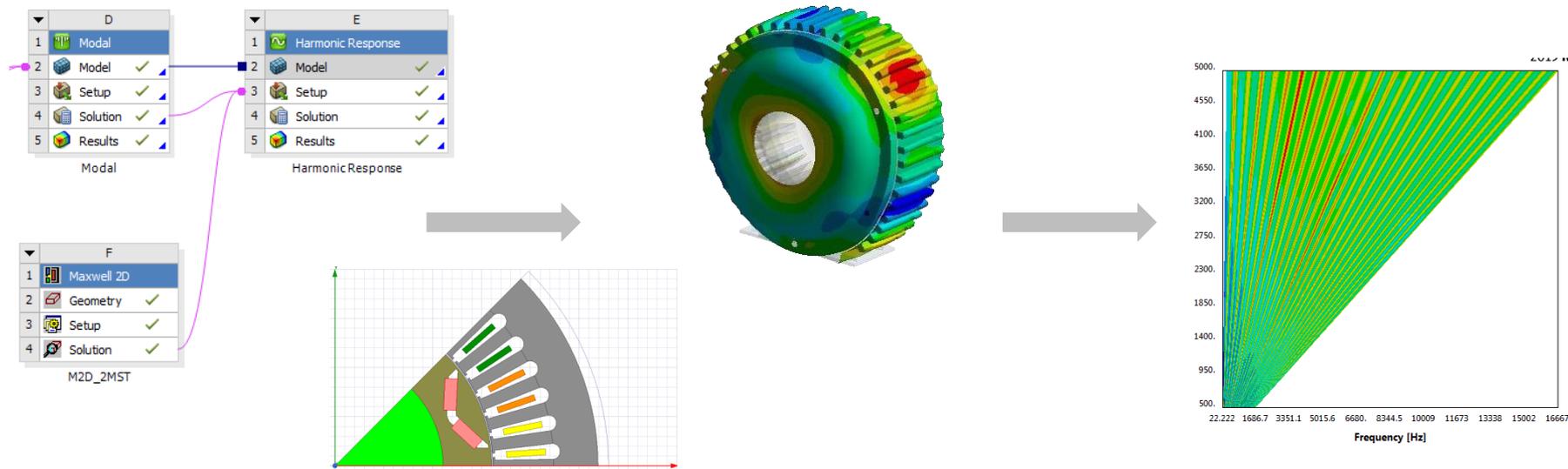


电机多转速ERP Level瀑布图快速分析



不再基于ACT插件，完全自动化的分析流程：

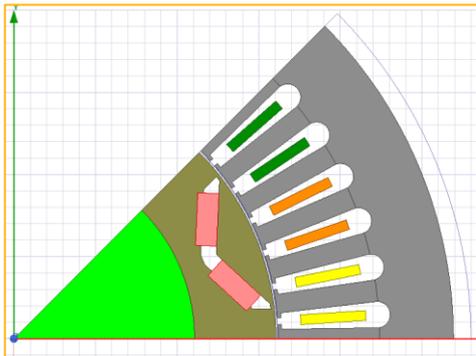
1. 在 Maxwell 中对转速进行参数化，打开谐波电磁力计算选项
2. 多转速电磁力（集中力或分布力）自动导入 Mechanical/Harmonic Response 模块
3. 自动进行多转速谐响应分析，输出 ERP Level 瀑布图



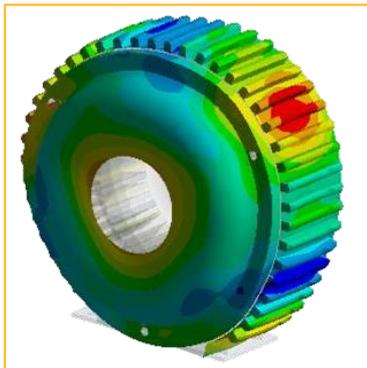
电机NVH分析流程



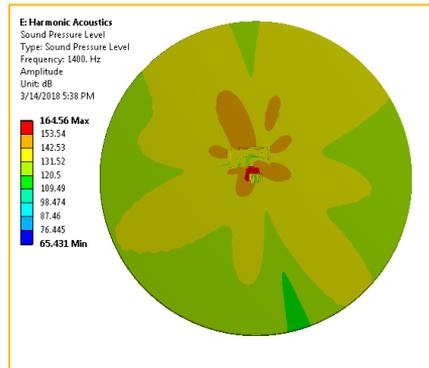
1. Magnetic Field Solution



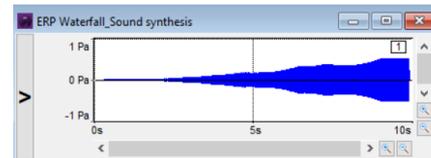
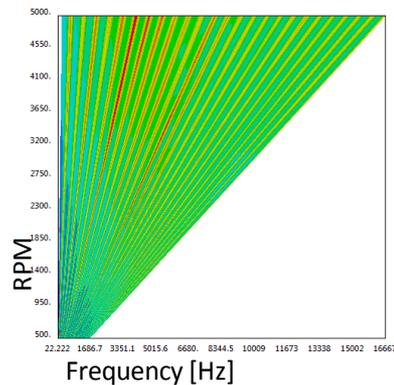
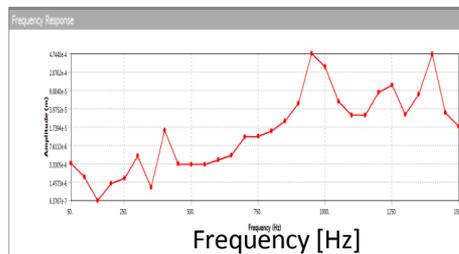
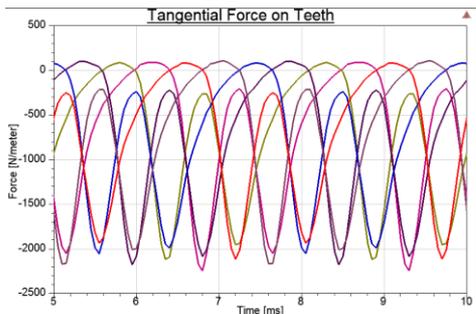
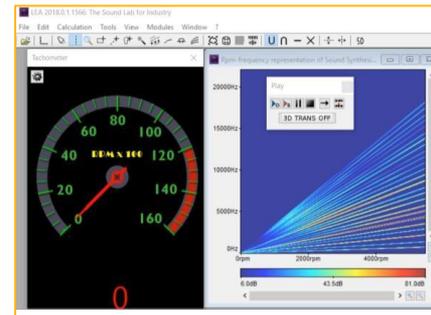
2. Modal and Vibration



3. Acoustic



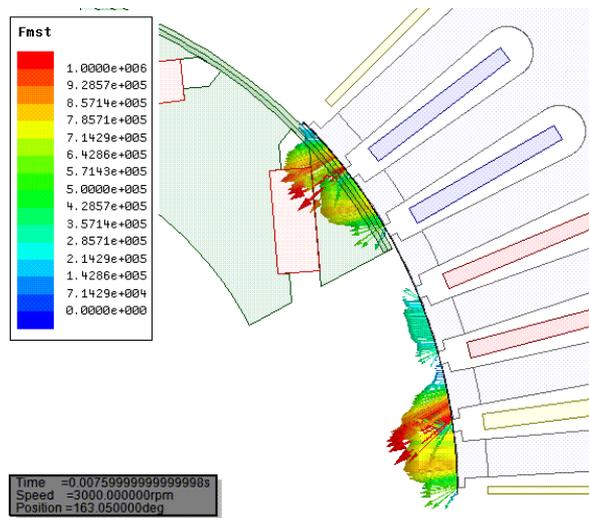
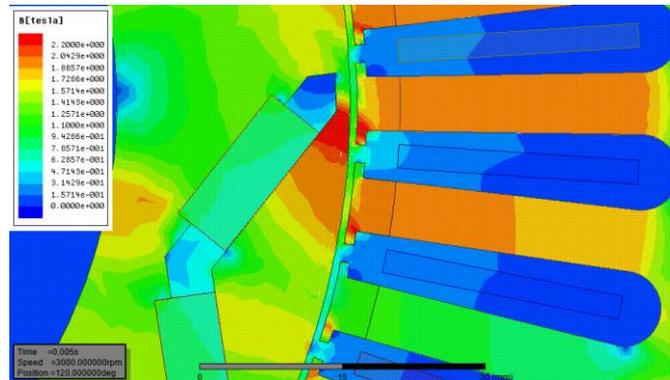
4. VRXPERIENCE



电机电磁力的基本概念



- 电机内部的三类电磁力：麦克斯韦张力、洛伦兹力、磁致伸缩力
- 导致电机电磁振动的主要因素是铁心受到的麦克斯韦张力
- 定子受到的电磁力绝大部分作用于定子齿尖
- 为便于分析，一般将电磁力分解为径向（法向）电磁力和切向电磁力
- 径向电磁力比切向电磁力的分量大很多
- 径向电磁力经齿传递到轭部，引起定子轭部圆周方向的形变
- 切向电磁力导致转矩波动，引起齿部切向摆动形变



Maxwell Stress Tensor Eqn:

$$\vec{f}_s = (\vec{n} \cdot \vec{B}_s) \frac{\vec{B}_s}{2\mu_0} + \left(\vec{n} \times \frac{\vec{B}_s}{2\mu_0} \right) \times \vec{B}_s$$

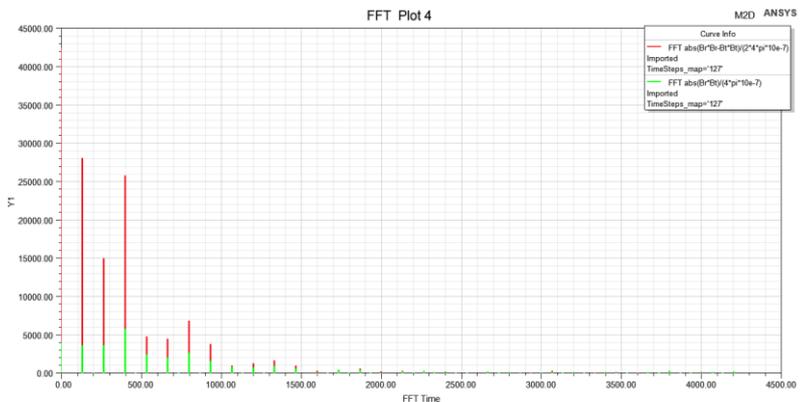
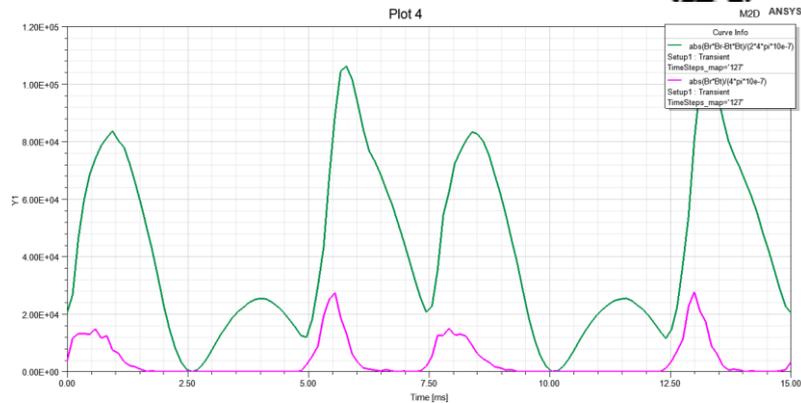
2D Circular Components:

$$\left\{ \begin{array}{l} f_r(t, \theta) = \frac{B_r(t, \theta)^2 - B_t(t, \theta)^2}{2\mu_0} \quad [\text{N/m}^2] \\ f_t(t, \theta) = \frac{B_r(t, \theta)B_t(t, \theta)}{\mu_0} \quad [\text{N/m}^2] \end{array} \right.$$

电磁力从时域到频域的变换



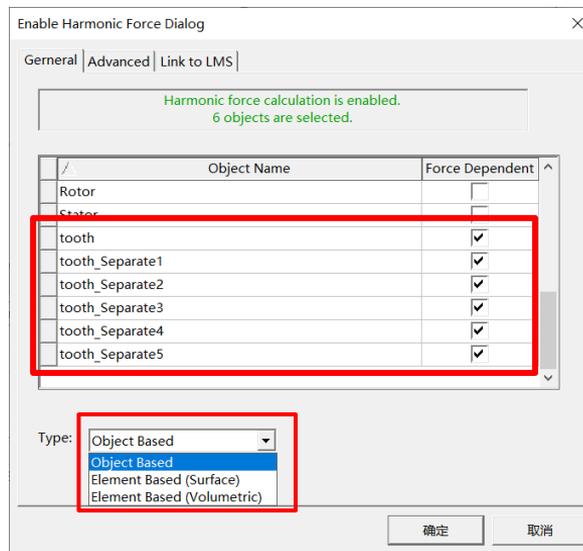
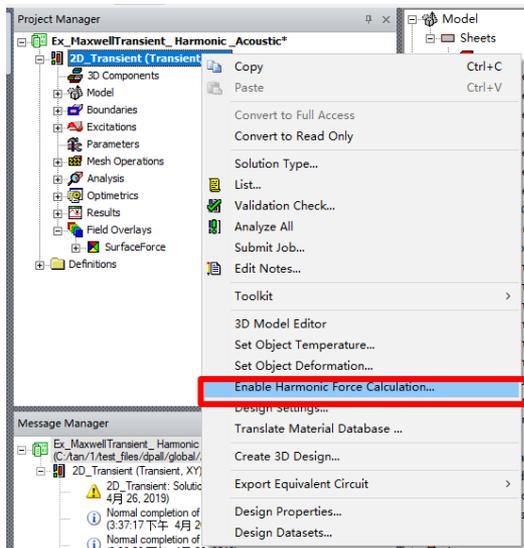
- 利用Maxwell瞬态场仿真得到定子齿部某点电磁力随时间变化的结果
- 时域下的电磁力难以获得足够的信息
- 利用离散傅里叶分解（DFT），将随时间变化的波形转换到频域，得到各次频率谐波的幅值及相位
- 这种时域到频域的转换，便于对复杂电磁力波的分析与优化，并应用于结构谐响应分析



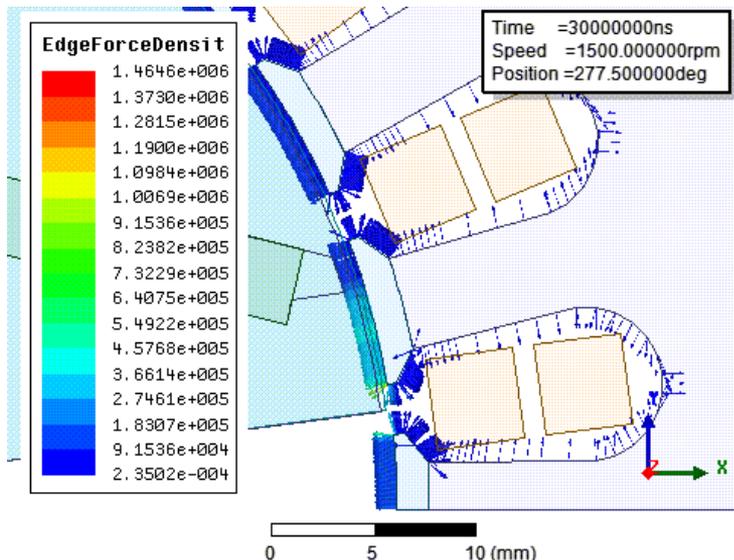


- Maxwell谐波电磁力的三种计算方式：

	电磁力类型	作用范围	映射形式
	麦克斯韦力	表面力	集中力
	麦克斯韦力	表面力	单元力
	洛伦兹力、磁致伸缩力	体积力	单元力

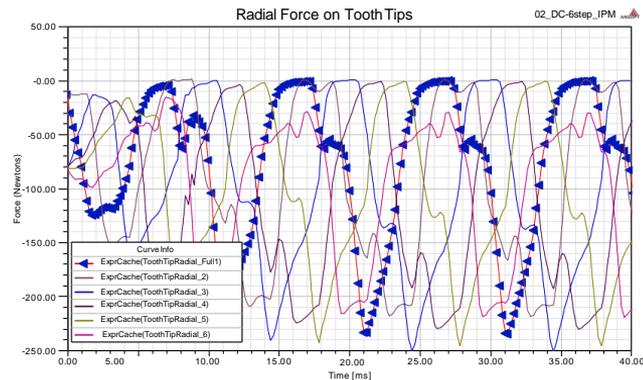
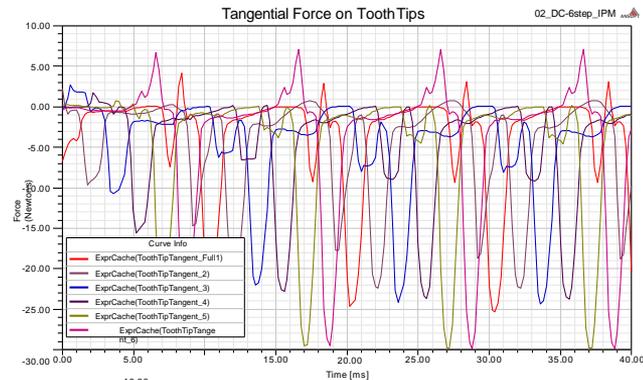


集中电磁力的计算 (Object Based)



Radial and Tangential Components (N)

	Time [s]	ExprCache(Tooth... Setup1 : Transient	ExprCache(Toot... Setup1 : Transient	ExprCache(Too... Setup1 : Transie...	ExprCache(ToothTipTangent_2) Setup1 : Transient
1	0.000000	-13.653517	-6.719874	-21.363975	2.177859
2	0.000204	-30.350366	-5.821033	-13.330412	0.098137
3	0.000404	-43.220493	-4.714850	-13.371770	-0.907910
4	0.000604	-55.300164	-4.180319	-14.038307	-0.524154
5	0.000804	-67.152720	-3.960709	-13.921081	-0.451801
6	0.001004	-79.922183	-4.263132	-13.286849	-0.464727
7	0.001200	-95.294810	-3.783651	-12.637820	-1.007827



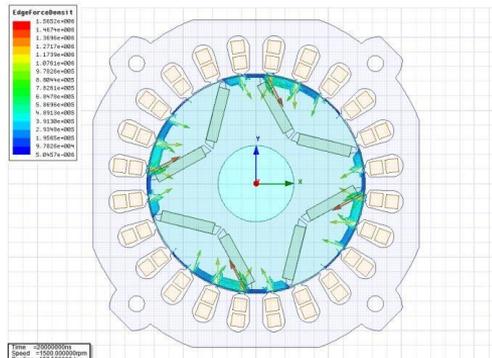
分布电磁力的计算 (Element Based Surface)



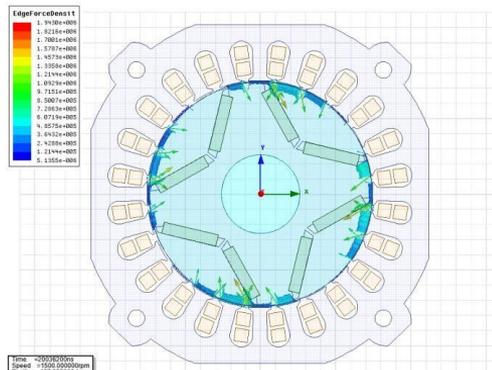
Scenario: Study the effect of Rotor Eccentricity

- **Case 1:** 0% Eccentricity 无偏心
 - No misalignment

- **Case 2:** 50 % Eccentricity
 - Eccentricity amount is set to 50% of gap width
 - Creates unbalanced electromagnetic forces



Peak Edge Force Density 1.5e6 N/m²

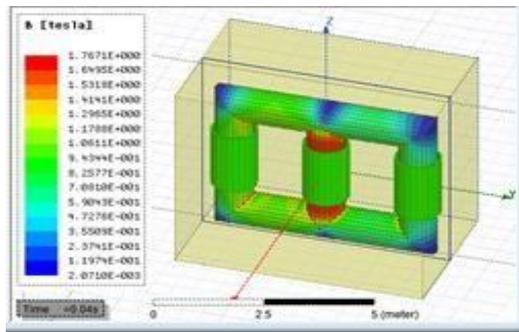
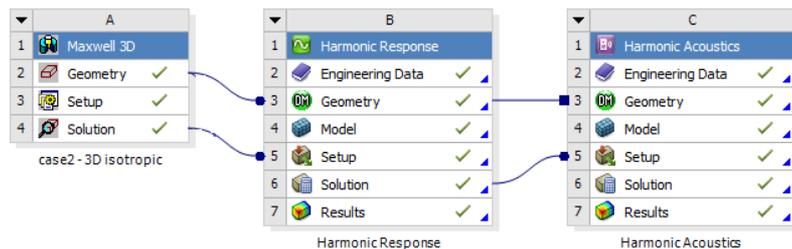


Peak Edge Force Density 1.9e6 N/m²

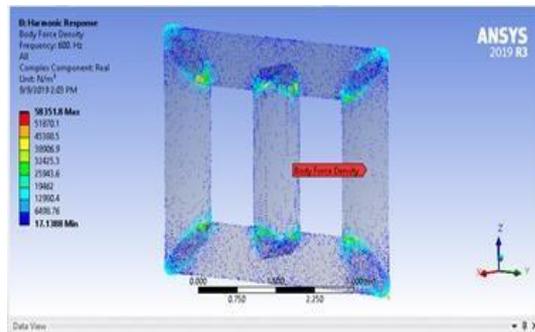
分布电磁力的计算 (Element Based Volumetric)



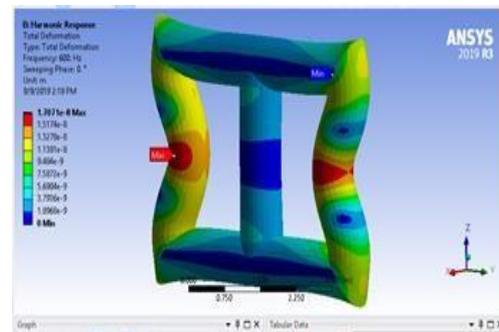
- 电机的体电磁力很小可忽略
- 主要用于变压器振动噪声分析



Maxwell 3D



耦合过来的体电磁力密度



Harmonic response

多转速NVH分析流程设置

Maxwell

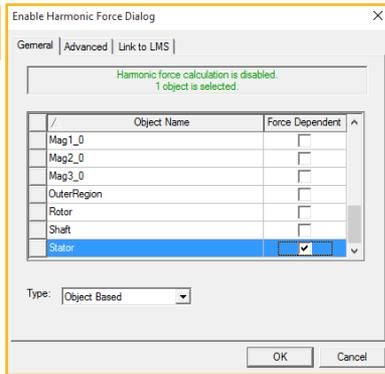
Harmonic Response

Harmonic Acoustic



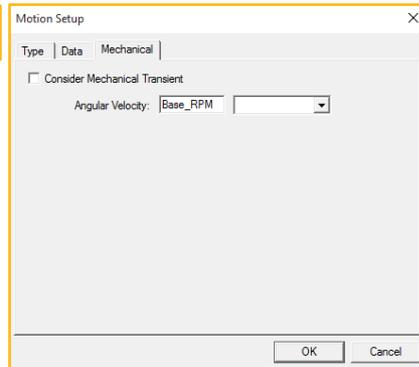
Object vs. Element-Based

1



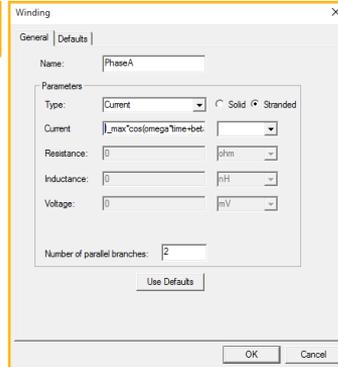
"Angular Velocity" as variable

2



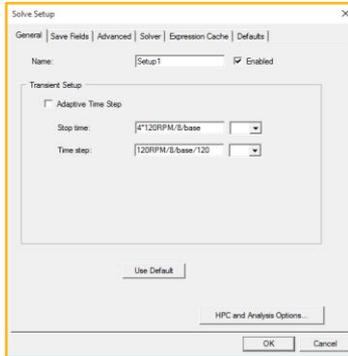
Scaling the Source Frequency

3



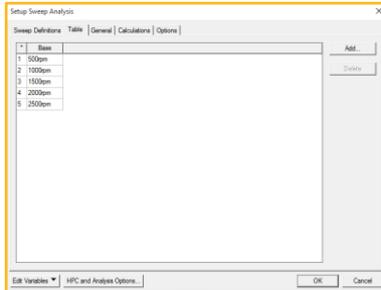
Scaling the Tend and Time-Step

4



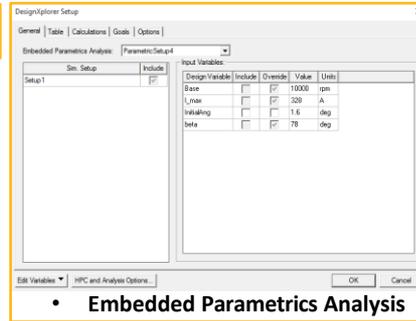
Adding Parametric Setup

5



DesignXplorer Setup

6



多转速NVH分析流程设置

Maxwell

Harmonic Response

Harmonic Acoustic

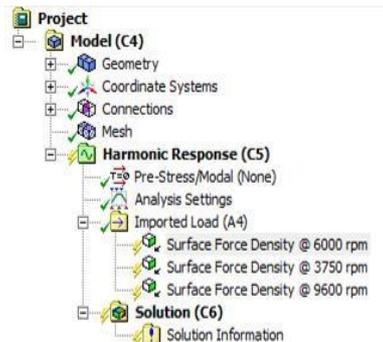
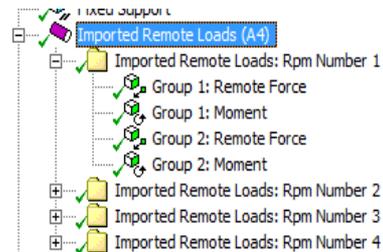


1. 常规结构分析设置：网格、接触、约束设置，然后...

2. 导入多转速电磁力载荷
(集中力or分布力)

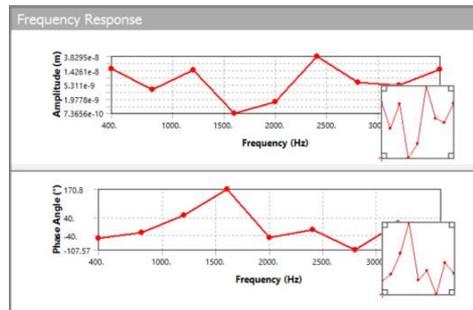
3. 自动完成多转速谐响应分析设置

4. 查看常规谐响应分析结果 (per RPM)

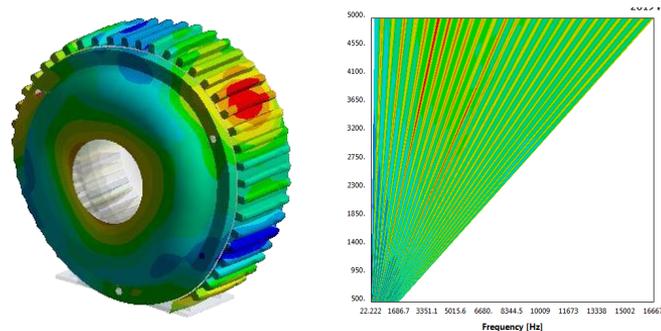


Details of "Analysis Settings"	
Step Controls	
Multiple RPMs	Yes
Number Of RPMs	10.
Current RPM Number	1.
RPM Value	500. RPM
RPM Frequency Spacing	Linear
RPM Range Minimum	0. Hz
RPM Range Maximum	1666.7 Hz
RPM Solution Intervals	75.
Options	
Solution Method	Mode Superposition
Include Residual Vector	No
Cluster Results	No
Store Results At All Frequencies	Yes
Rotordynamics Controls	

Properties	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9	Step 10
Step Controls										
RPM Value	500.	1000.	1500.	2000.	2500.	3000.	3500.	4000.	4500.	5000.
RPM Frequency Spacing	Linear									
RPM Range Minimum	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.
RPM Range Maximum	1666.7	3333.3	5000.	6666.7	8333.3	10000	11667	13333	15000	16667
RPM Solution Intervals	75.	75.	75.	75.	75.	75.	75.	75.	75.	75.
Options										
Cluster Results	Off									



5. 查看ERP Level瀑布图 (all RPMs)



多转速NVH分析流程设置

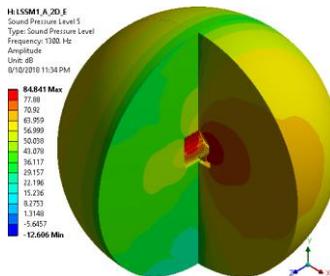
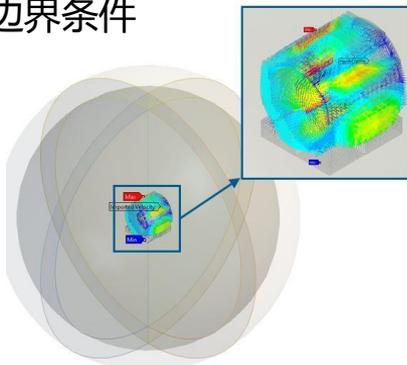
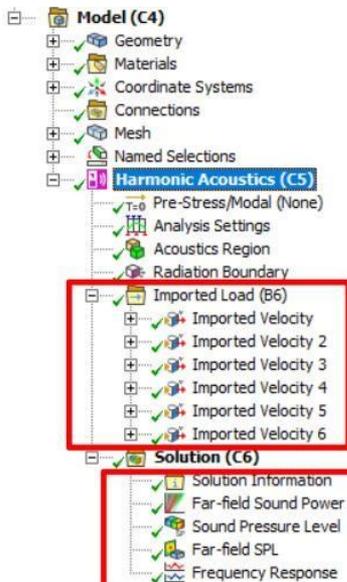
Maxwell

Harmonic Response

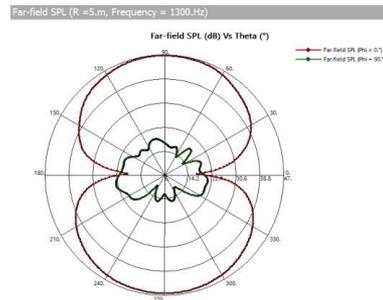
Harmonic Acoustic



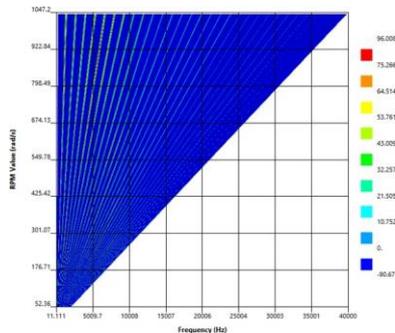
1. 导入声音求解域几何模型
2. 设置声音域的材料、网格、边界条件
3. 导入多转速振动速度激励
4. 分析求解&查看结果



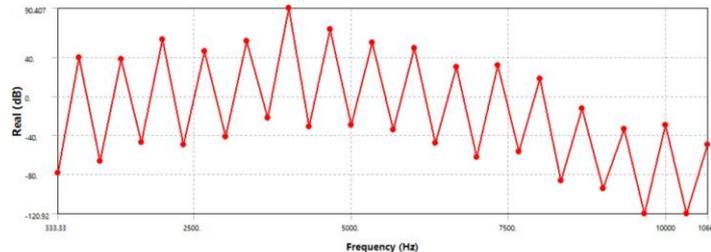
Sound Pressure Level



Far-field SPL



Far-field Sound Power Level Waterfall Diagram



Frequency Response

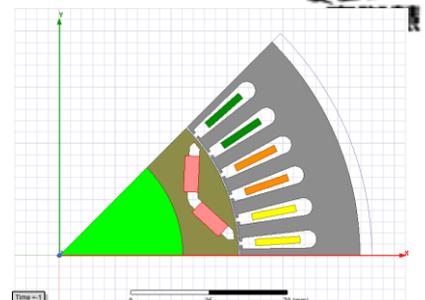


- ★ Object based 与 Element based 对比
 - 2D object vs 3D element
 - 2D object vs 2D element
- ★ 定子斜槽案例
- ★ 转子分段斜极案例
- ★ 考虑转子偏心的影响

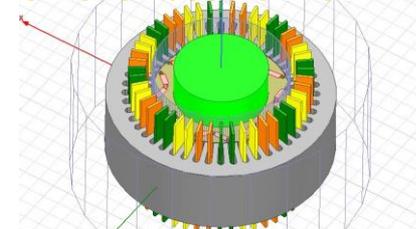
2D object based vs 3D element based

- 对比 Maxwell 2D object-based 和 Maxwell 3D element-based 方式
- 在Mechanical中使用相同的3D模型和分析设置
- 定性分析结果一致，定量分析结果有略微差异
- 对于该案例，模型沿轴向形状相同且齿尖结构简单，两种分析方式都适用

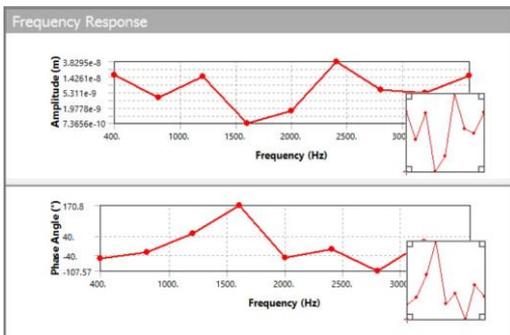
Object-Based 2D(one-pole)-3D



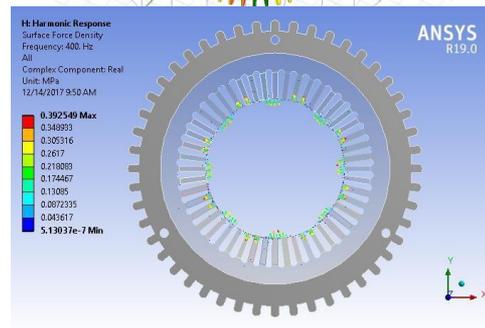
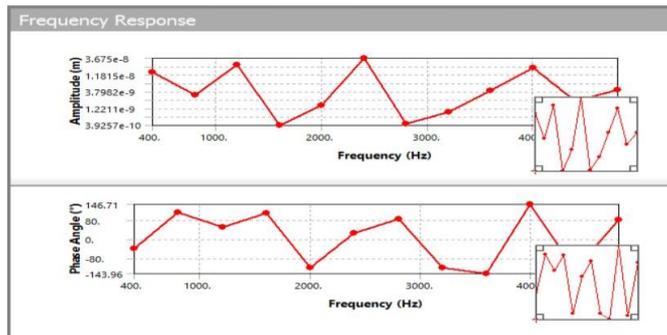
Element-Based 3D-3D



Element-Based 3D-3D

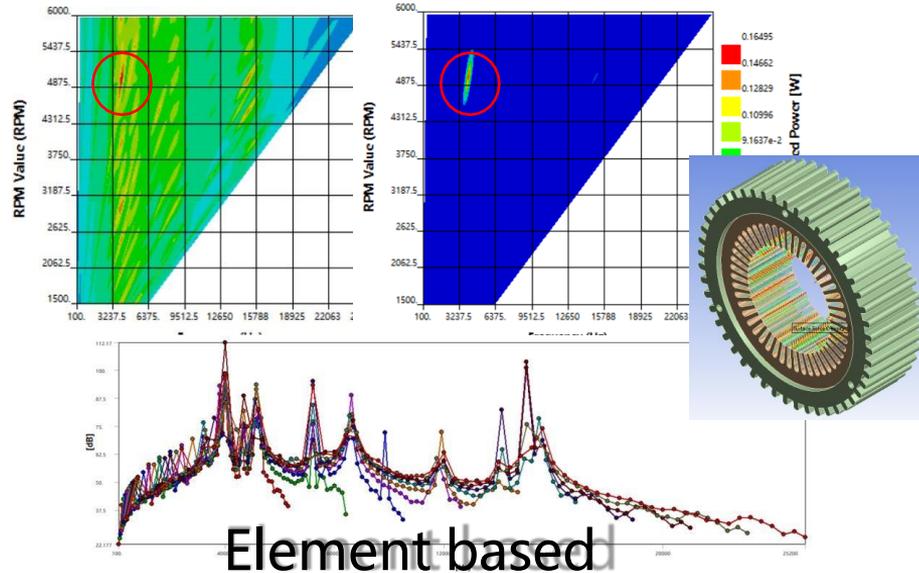
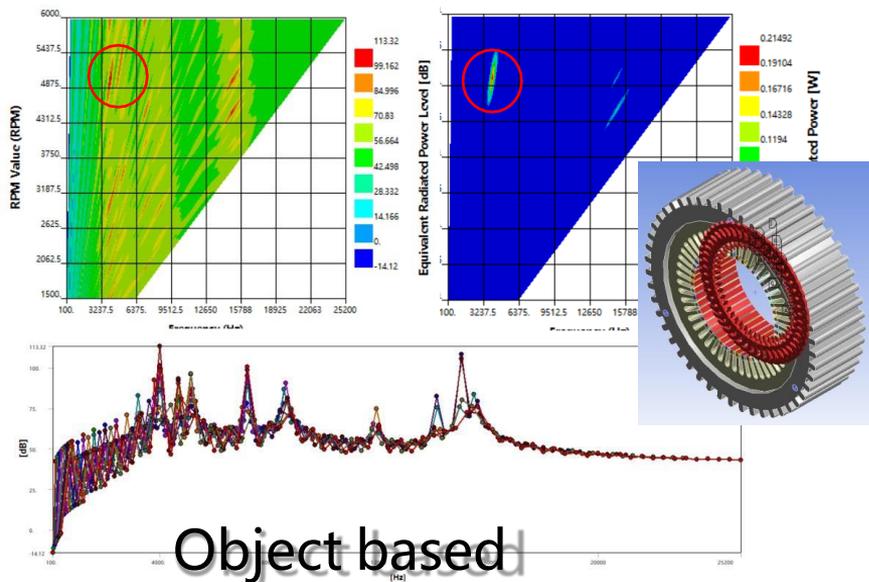


Object-Based 2D(one-pole)-3D



2D object based vs 2D element based

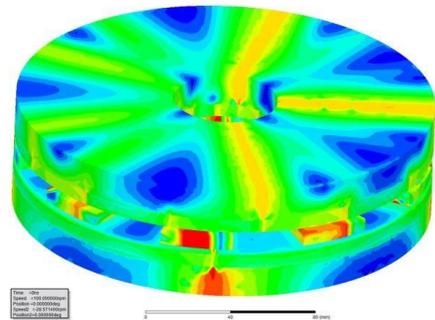
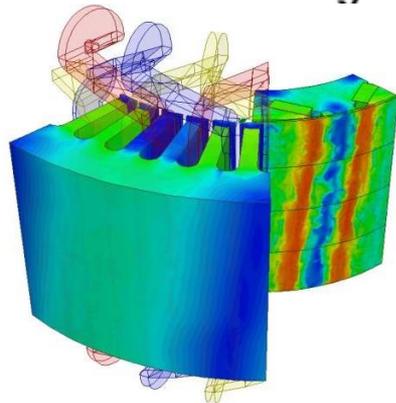
- 对比 Maxwell 2D object-based 和 Maxwell 2D element-based 方式
- 在Mechanical中使用相同的3D模型和分析设置
- 分析结果基本一致，最大ERP Level 相差1dB
- 对于该案例，模型沿轴向形状相同且齿尖结构简单，两种分析方式都适用



Object-Based 与 Element-Based 的选取原则



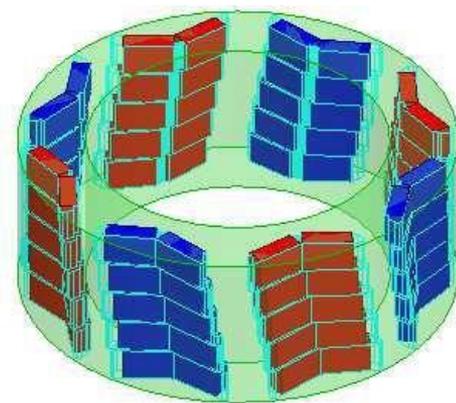
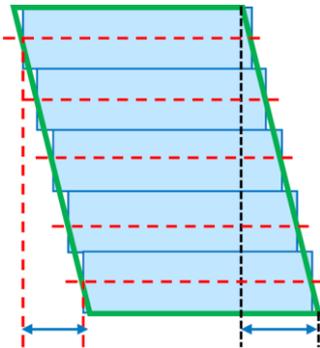
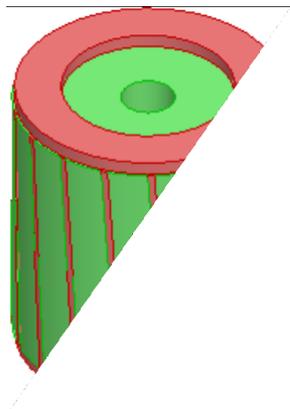
1. 定子槽数较多，且无斜槽斜极时采用Maxwell 2D Object-Based方式
2. 当电机结构较复杂时，建议采用Maxwell 3D Element-Based方式计算电磁力，可更真实的反映电磁力的轴向空间分布特性
 - 定子斜槽、转子连续斜极、V斜极、zigzag斜极
 - 轴向磁通电机
3. 当电定子齿数较少时，建议采用Maxwell 2D Element-Based方式计算电磁力，可更真实的反映电磁力在圆周方向的空间分布特性
 - 分数槽集中绕组电机
 - 开关磁阻电机
 - 直流电机
4. 当定子齿顶有辅助槽等特殊修型设计时应采用Element-Based 方式





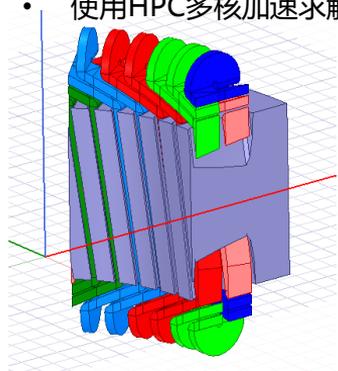
- ★ Object based 与 Element based 对比
- ★ 定子斜槽案例
 - Maxwell 3D model element based
 - 对比斜槽与直槽分析结果
 - 2020R1新功能：基于二维multi-slice模型的电磁场-谐响应电磁力耦合
- ★ 转子分段斜极案例
- ★ 考虑转子偏心的影响

- Axial Skew 的多种情况
 - Continuous skew 定、转子连续斜槽
 - Step skew 转子分段斜极
 - V字斜极、zigzag斜极
- Skew 会导致轴向不平衡电磁力；容易激发定子轴向低阶次共振



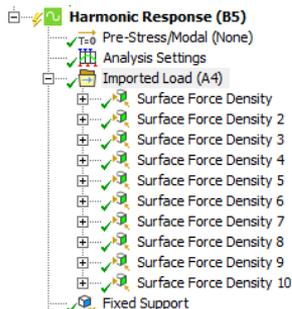
定子连续斜槽3D Element-based

- 定子连续斜槽需采用槽 3D Element-based
- 可采用周期模型降低计算量
- 使用HPC多核加速求解



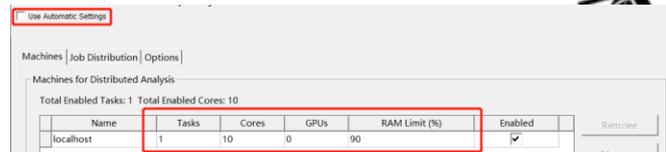
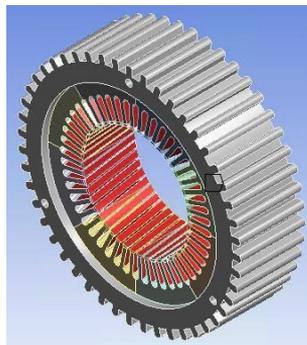
3D stator skew model

导入电磁力

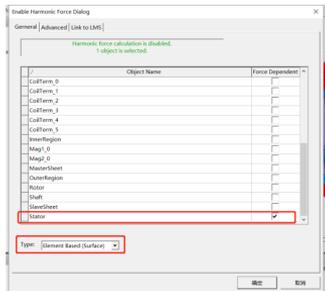
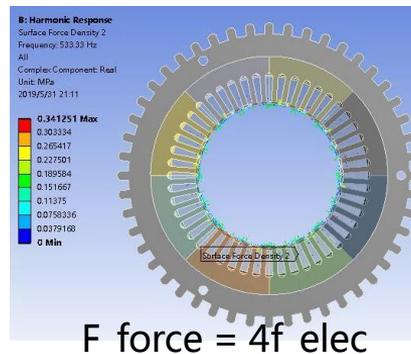
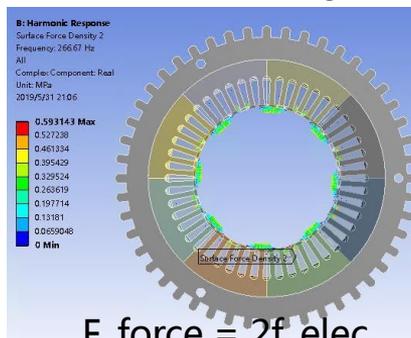


多转速电磁力

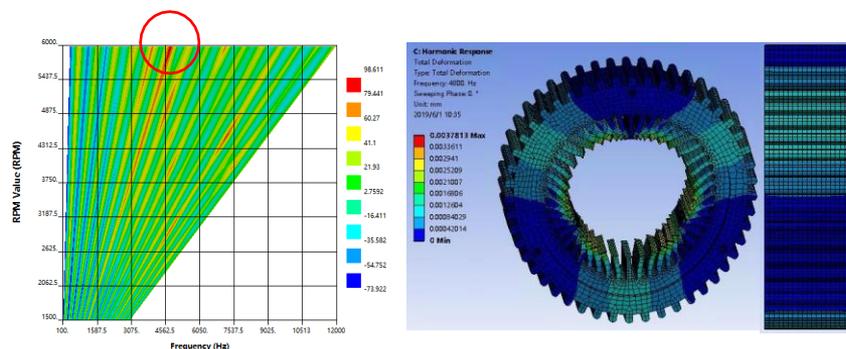
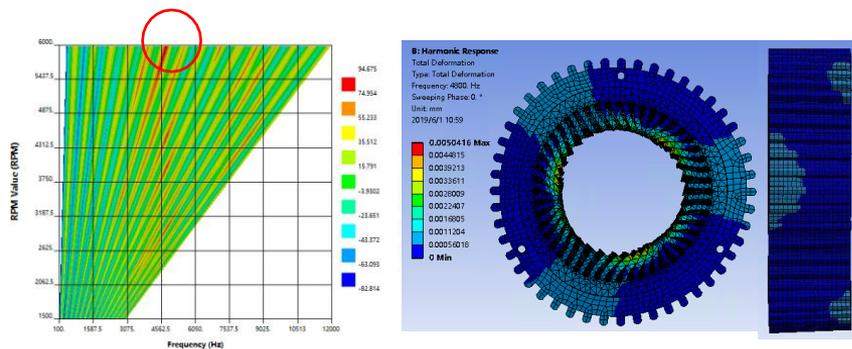
查看电磁力



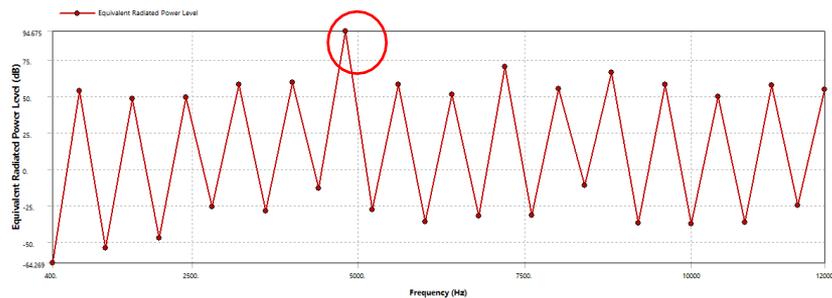
HPC settings



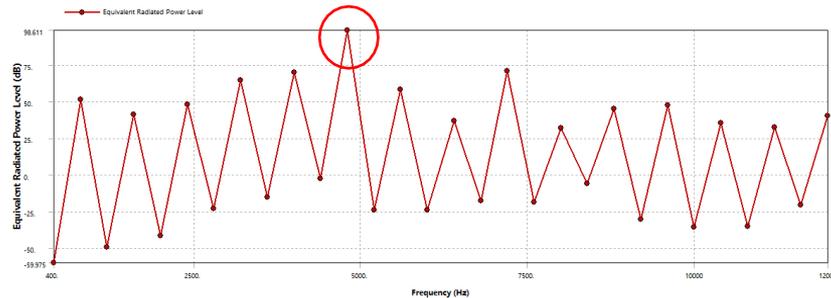
3D斜槽定子 VS 3D直槽定子 (both Element based) ERP Level



斜槽定子, 6000rpm@4800hz (12fn) 幅值为94.7dB



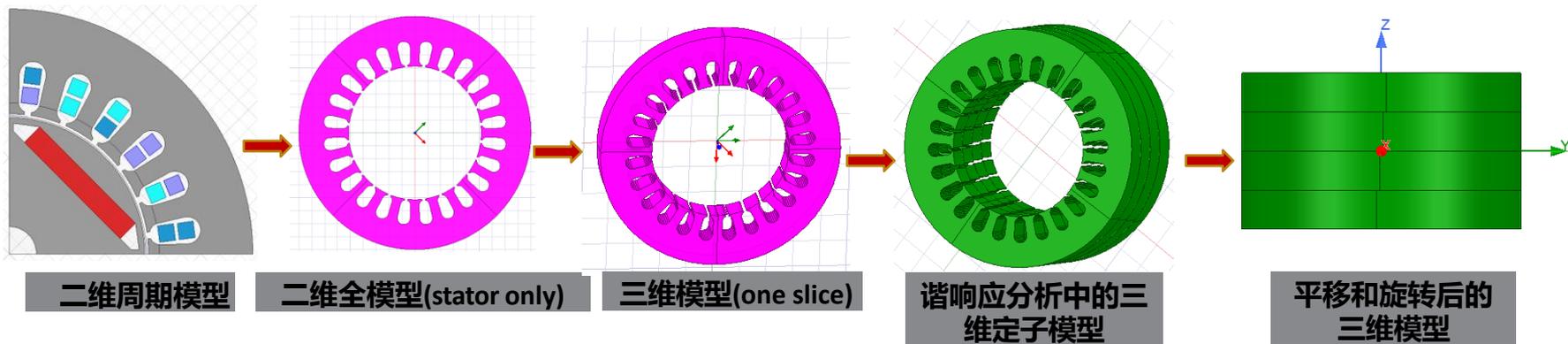
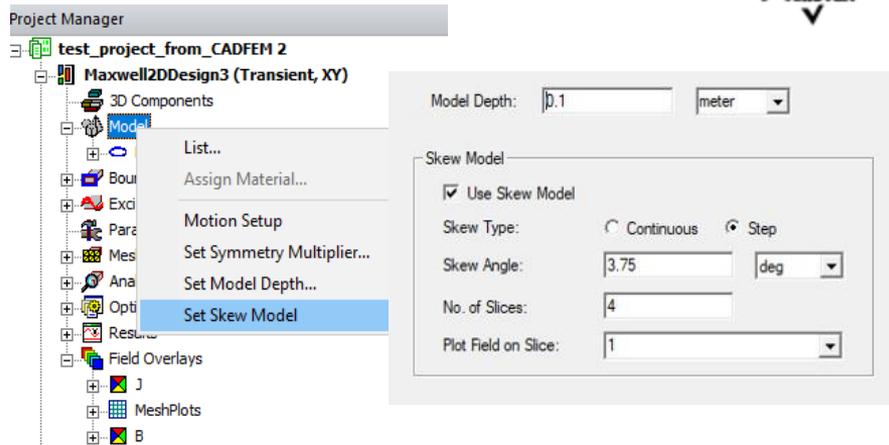
直槽定子, 6000rpm@4800hz (12fn) 幅值为98.6dB



基于二维模型的电磁场multi-slice谐响应电磁力耦合

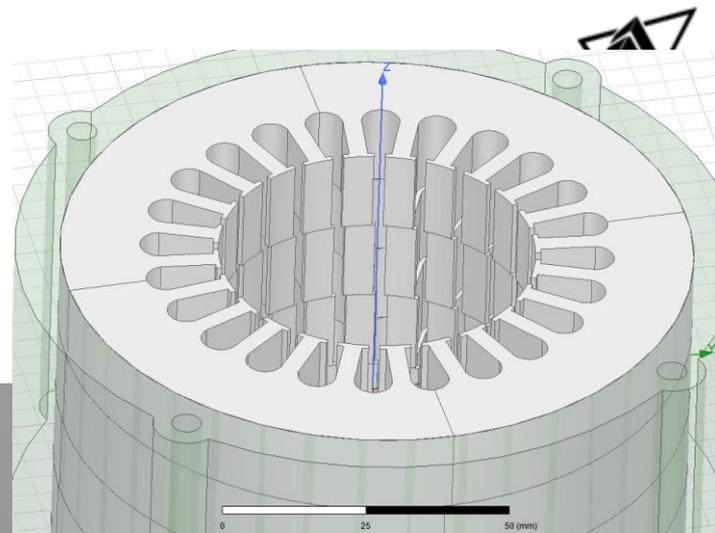
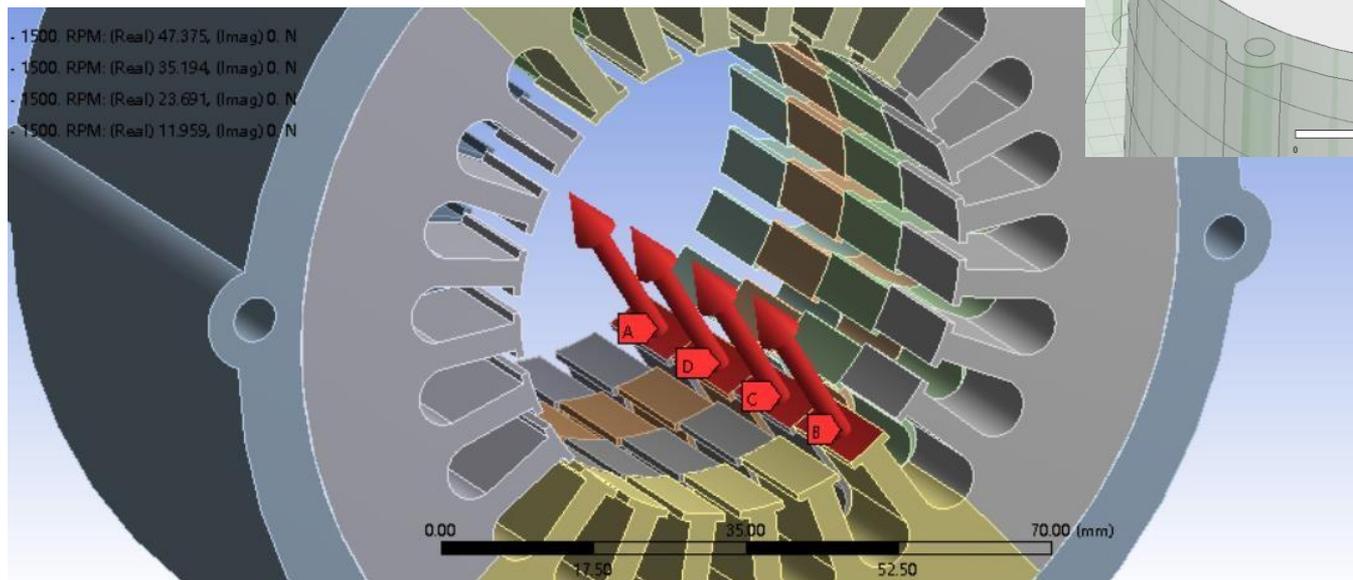


- 通过2D multi-slice模型考虑准三维效应
- 支持 Object based 电磁力计算
- 生成的电磁力适用于结构场中的三维全周期模型分析（结构场没有类似于电磁场的二维斜槽分析功能）



定子分段斜槽（等效连续斜槽）

- 定子模型利用分段错位近似等效连续斜槽
- 电磁力作用点位于每段齿面的中心
- 仅支持Object based电磁力映射



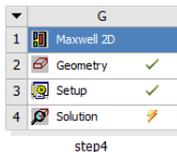
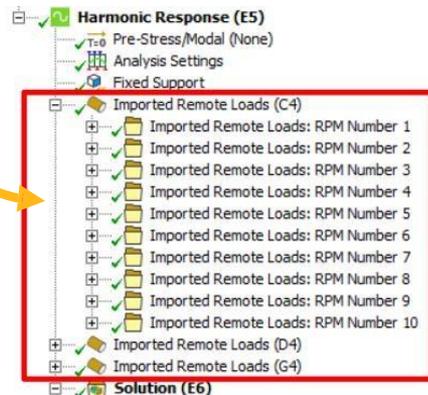
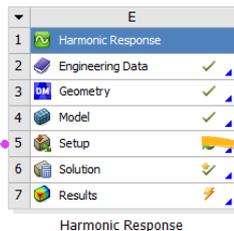
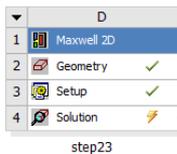
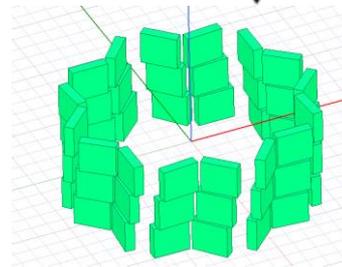
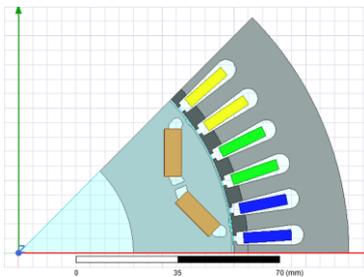
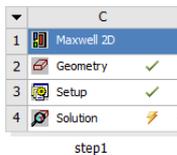


- ★ Object based 与 Element based 对比
- ★ 定子斜槽案例
- ★ 转子分段斜极案例
 - 多个 Maxwell 2D design 电磁力导入谐响应模块
 - 转子分段的 Maxwell 3D design 导入谐响应模块
- ★ 考虑转子偏心的影响

多个Maxwell 2D design电磁力导入谐响应模块



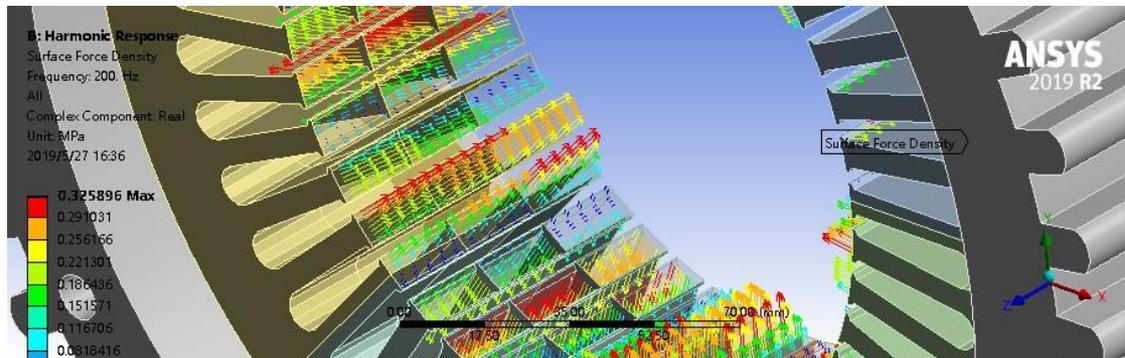
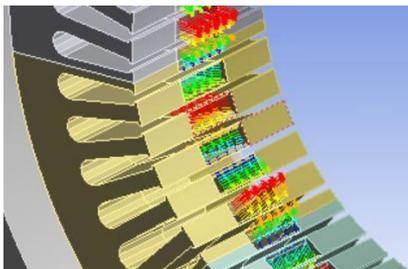
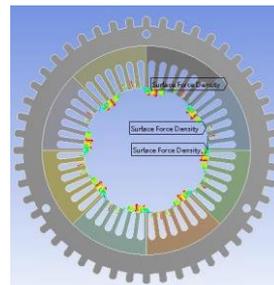
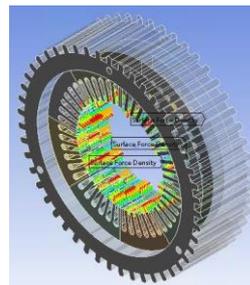
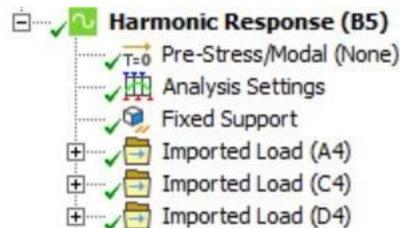
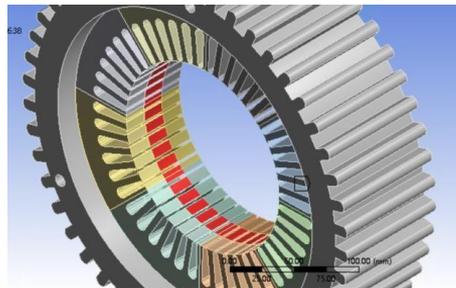
- 每个转子分段对应一个 Maxwell 2D design
- 修改各个分段初始角度
- 谐响应模块支持导入多组电磁力



多个Maxwell 2D design电磁力导入谐波响应模块



- 定子轴向分段建模
- 为每段定子create named selection
- 定子轴向分段导入电磁力 (Object or Element based)

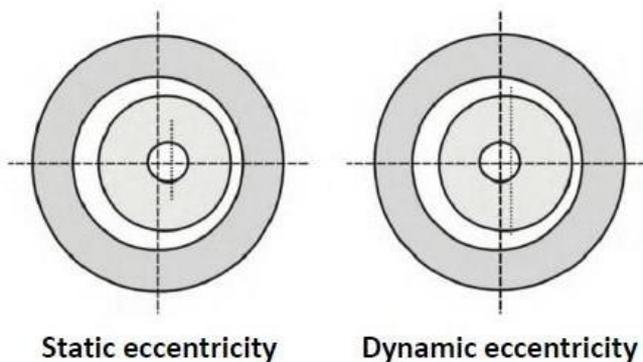




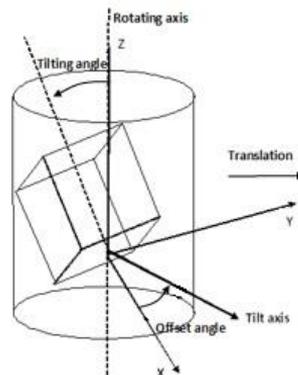
- ★ Object based 与 Element based 对比
- ★ 定子斜槽案例
- ★ 转子分段斜极案例
- ★ 考虑转子偏心的影响
- 利用 ACT Eccentricity extension 创建偏心模型
- 对比转子产生静态偏心前后电机NVH特性

- 偏心的种类：

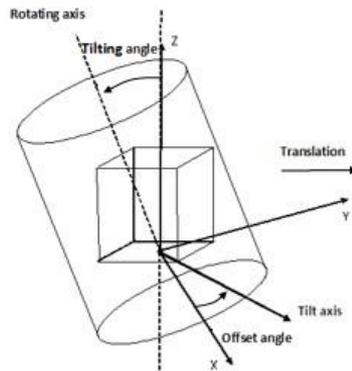
- 静态偏心 – 转子绕自身轴心旋转，与定子轴心不重合，气隙不对称，且保持不变
- 动态偏心 – 转子绕定子轴心旋转，而非自身轴心，气隙不对称，且周期性变化
- 混合偏心
- 偏心沿轴向可能是均匀的，也可能是倾斜的



Rotation Part Eccentricity

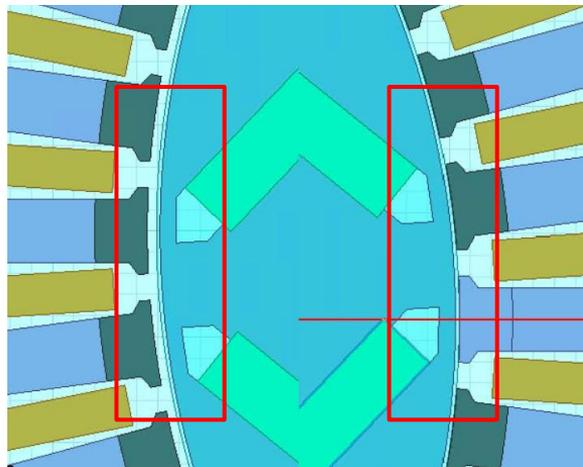
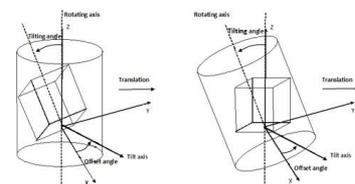
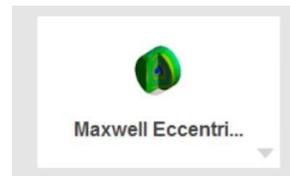
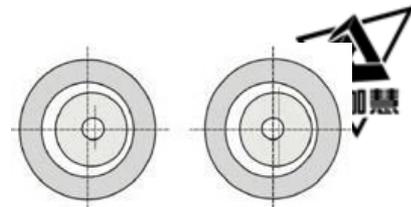


Rotation Axis Eccentricity

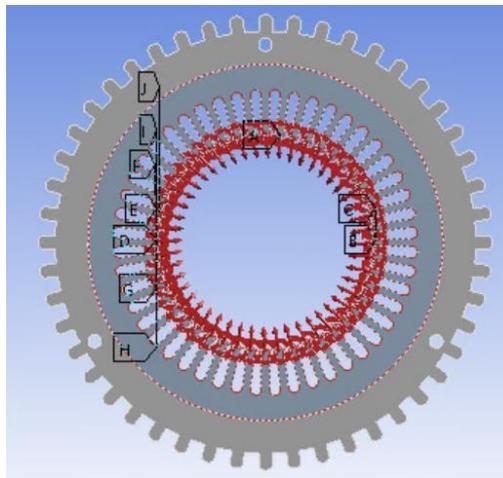


转子偏心解决方案

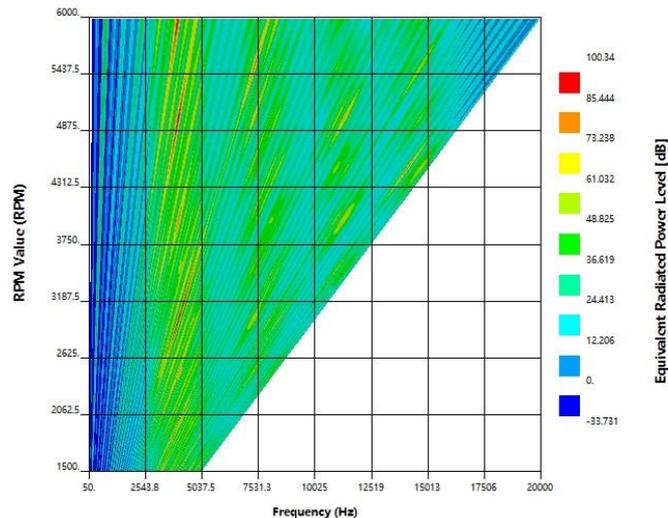
- 利用 ACT Eccentricity extensions生成偏心模型
- 支持2D静态/动态/混合偏心，3D轴向倾斜
- 不支持周期模型



静态偏心50%气隙长度



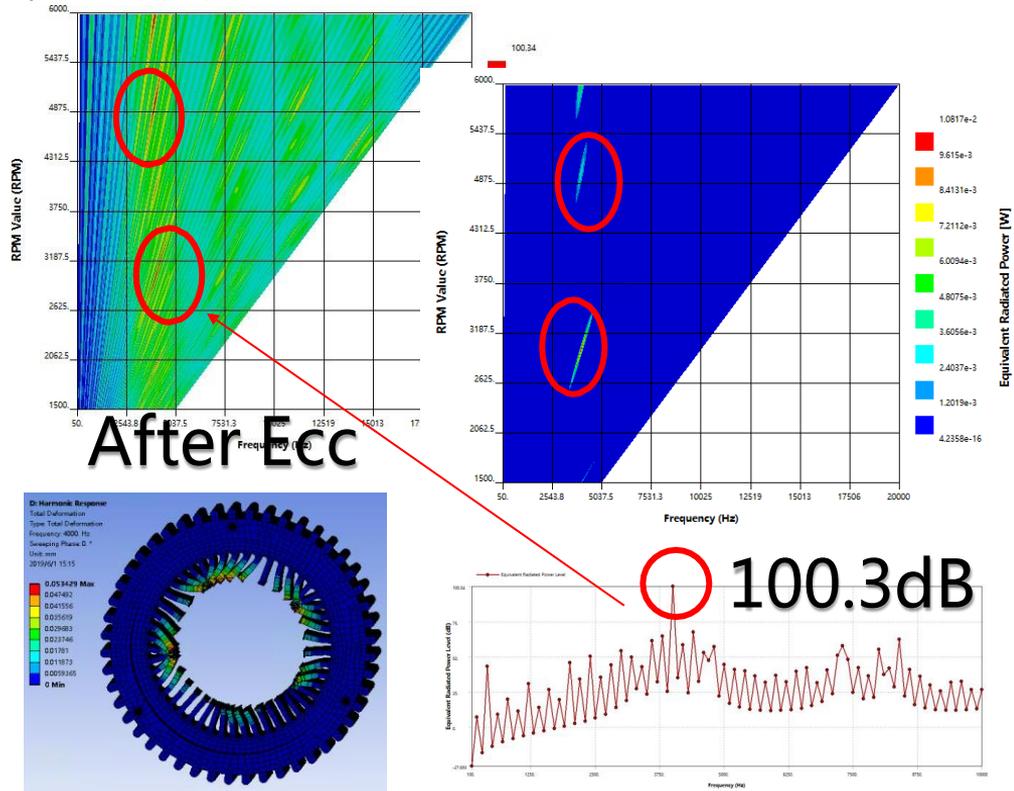
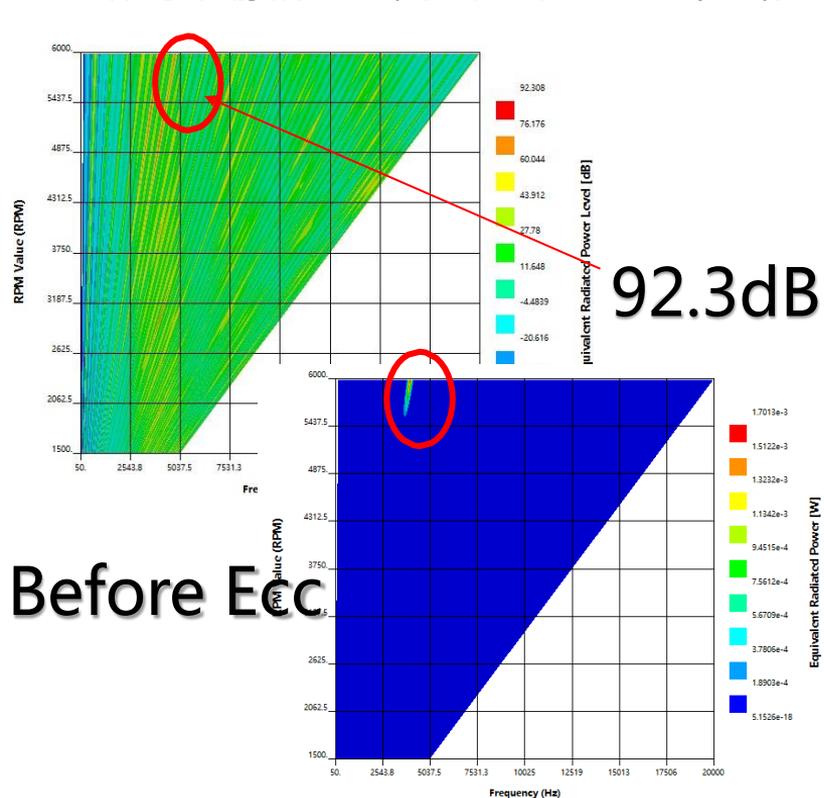
Object based



考虑偏心的ERP Level瀑布图

转子静态偏心前后ERP Level对比

- 当转子有静偏心时，在某些转速出现不对称的振型，且ERP值较大





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是由安世亚太打造的一个以设计、仿真、增材制造等领域技术和行业专家为主的智慧学习平台。目前主要通过线上培训、研讨等方式，由行业相关领域资深专家与学员们分享交流最新技术和应用研究成果。

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