Induction Motor Sound and Co-simulation with JMAG and Virtual.lab

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Nov.24, 2015

EMERSON
Climate Technologies

Agenda

- Overview of Emerson Climate Technologies Suzhou R&D
- Magnetic Force Generation Diagram
- Theoretical Analysis
- Electromagnetic FE Simulation
- JMAG and Virtual.lab Co-Simulation

Emerson Climate Technologies (Suzhou) R&D
艾默生环境优化技术（苏州）有限公司 – 研发中心

perf(x)
PERFORMANCE EXCELLENCE

- Founded In 2002
  成立于2002年

- Located In International Science Park , Suzhou Industry Park
  坐落于苏州工业园区国际科技园

- 7 Divisions From Emerson Climate Technologies Joint Investment
  艾默生环境优化技术事业部内的多个子公司共同投资

- 400 Employees
  400名员工

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Magnetic Force Generation Diagram

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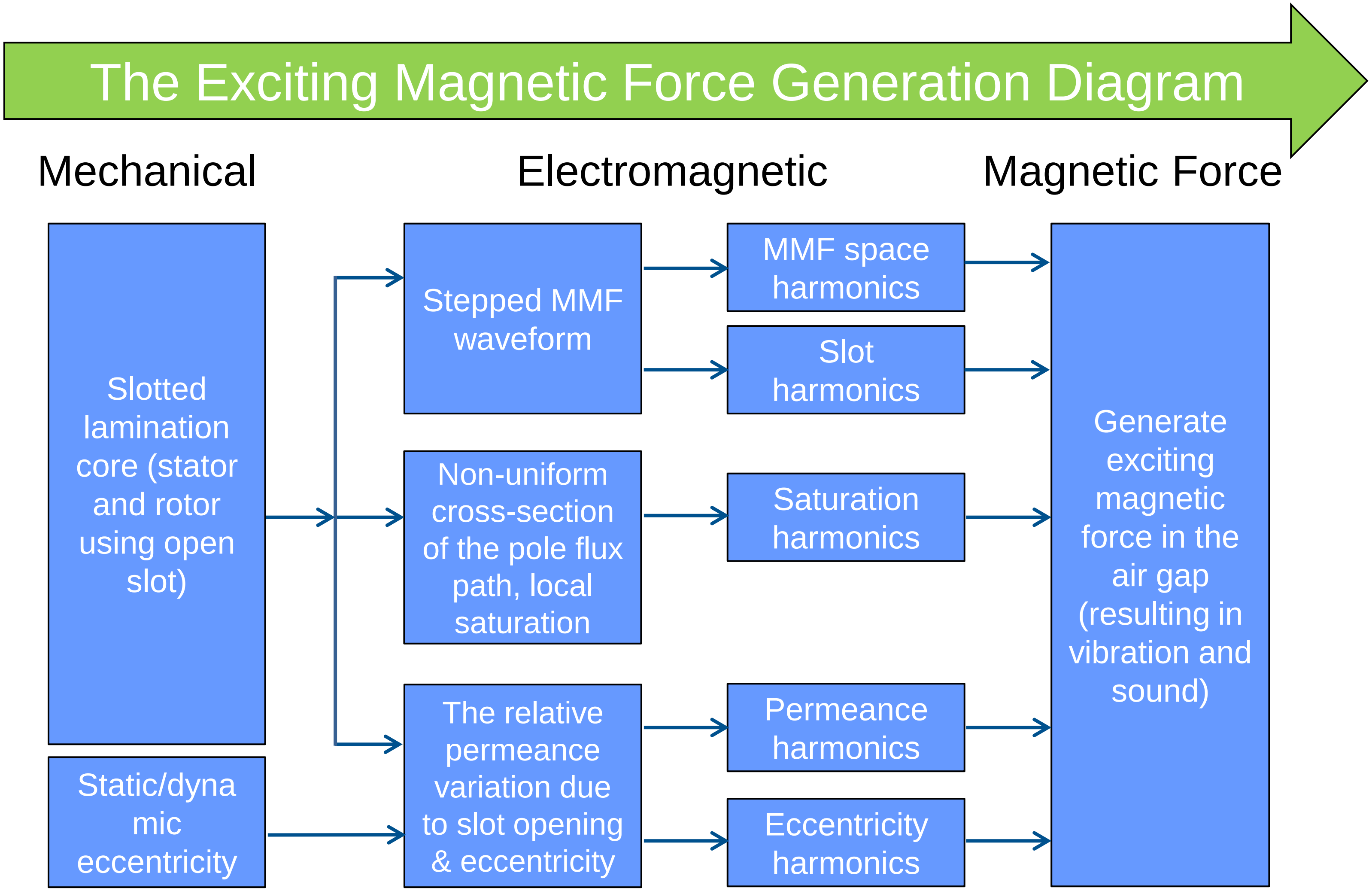

EMERSON Climate Technologies

Theoretic Analysis – Rotating MMF

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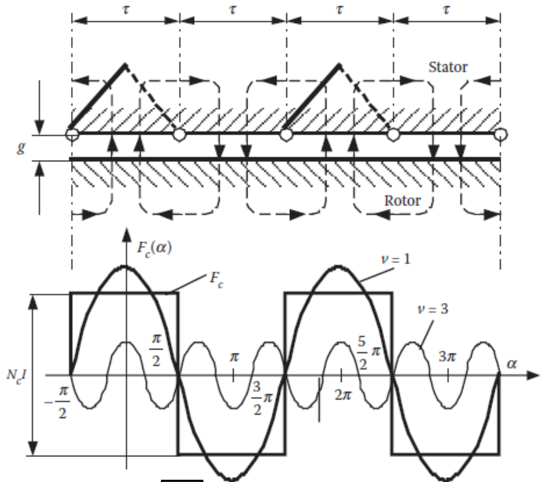


FFT Analysis

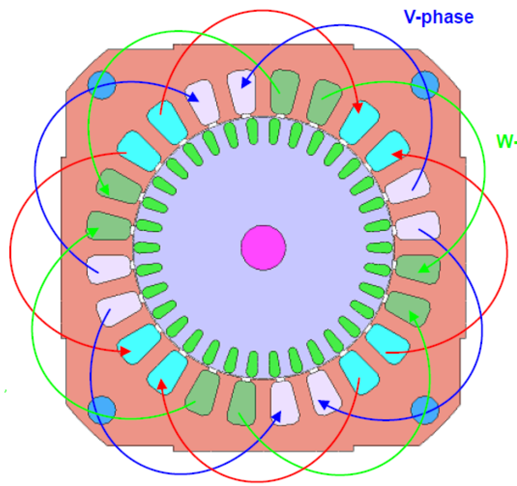
$$F_c(\alpha) = \sum_{\nu=1,3,5,...}^{\infty} F_{cm\nu}\cos(\nu p\alpha);\, where\ (F_{cm\nu} = \frac{2}{\nu\pi} N_c I \sin(\nu\frac{\pi}{2}))$$

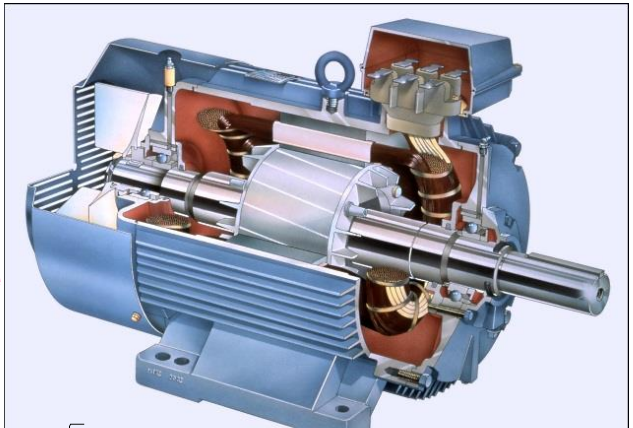
If current is a sinusoidal waveform

$$i(t) = \sqrt{2} I\cos(\omega t);\, where\ (F_{cm\nu} = \frac{2\sqrt{2}}{\nu\pi} N_c I \sin(\nu\frac{\pi}{2}))$$

$$F_c(\alpha, t) = \sum_{\nu=1,3,5,...}^{\infty} F_{cm\nu}\cos(\omega t)\cos(\nu p\alpha)$$

$$= \frac{1}{2}\sum_{\nu}^{\infty} F_{cm\nu}\cos(\omega t - \nu p\alpha) + \frac{1}{2}\sum_{\nu}^{\infty} F_{cm\nu}\cos(\omega t + \nu p\alpha)$$





$$i_{1A} = \sqrt{2} I_1\cos(\omega t)$$

$$i_{1B} = \sqrt{2} I_1\cos(\omega t - \frac{2\pi}{3})$$

$$i_{1c} = \sqrt{2} I_1\cos(\omega t - \frac{4\pi}{3})$$

Three phase stator winding MMF with balanced sinusoidal current

$$F_{1A\nu}(\alpha, t) = \sum_{\nu=1,3,5,...}^{\infty} F_{m\nu}\cos(\omega t)\cos(\nu p\alpha)$$

$$= \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos(\omega t - \nu p\alpha) + \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos(\omega t + \nu p\alpha)$$

$$= \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t - \nu p\alpha) + 0(\nu - 1)\frac{2\pi}{3}] + \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t + \nu p\alpha) + 0(\nu + 1)\frac{2\pi}{3}]$$

$$F_{1B\nu}(\alpha, t) = \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t - \nu p\alpha) + 1(\nu - 1)\frac{2\pi}{3}] + \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t + \nu p\alpha) + 1(\nu + 1)\frac{2\pi}{3}]$$

$$F_{1B\nu}(\alpha, t) = \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t - \nu p\alpha) + 2(\nu - 1)\frac{2\pi}{3}] + \frac{1}{2}\sum_{\nu}^{\infty} F_{m\nu}\cos[(\omega t + \nu p\alpha) + 2(\nu + 1)\frac{2\pi}{3}]$$

$$result - MMF: F_1 = F_{1A\nu} + F_{1B\nu} + F_{1C\nu} = \frac{3}{2}\sum_{\nu=6k\pm1}^{\infty} F_{m\nu}\cos(\omega t \mp \nu p\alpha) = \frac{3}{2}\sum_{\nu=6k\pm1}^{\infty} F_{m\nu}\cos(\nu p\alpha \mp \omega t)$$

$$fundamenta\ l - MMF: F_{fundamenta\ l} = \frac{3}{2} F_{m\nu}\cos(p\alpha \mp \omega t)$$

Rotating MMF waveform varies sinusoidal across space and time

Theoretic Analysis
– Radial Force Pressure Produced by Stator and Rotor

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- Radial Force Pressure Produced by Stator and Rotor

$$P_r(\alpha,t)=\frac{1}{2\mu_0}[b_1(\alpha,t)+b_2(\alpha,t)]^2=\frac{1}{2\mu_0}[b_1(\alpha,t)^2+2b_1(\alpha,t)b_2(\alpha,t)+b_2(\alpha,t)^2]$$

  - The Product of Stator Same Order Harmonics

$$P_{r\nu}(\alpha,t)=\frac{[B_{m\nu}\cos(\nu p\alpha\mp\omega t)]^2}{2\mu_0}=\frac{B^2{}_{m\nu}}{4\mu_0}[1+\cos(2\nu p\alpha\mp\omega t)]=\frac{B^2{}_{m\nu}}{4\mu_0}+\frac{B^2{}_{m\nu}}{4\mu_0}\cos(2\nu p\alpha\mp2\omega t)$$

  - The Product of Stator and Rotor Harmonics

$$P_{r\nu\mu}(\alpha,t)=\frac{2B_{m\nu}\cos(\nu p\alpha\mp\omega t)B_{m\mu}\cos(\mu p\alpha\mp\omega t+\varphi_\mu)}{2\mu_0}$$

$$=\frac{B_{m\nu}B_{m\mu}}{2\mu_0}\{\cos[(\nu-\mu)p\alpha\mp(\omega-\omega_\mu)t-\varphi_\mu]+\cos[(\nu+\mu)p\alpha\mp(\omega+\omega_\mu)t+\varphi_\mu]\}$$

  - The Product of Rotor Same Order Harmonics

$$P_{r\mu}(\alpha,t)=\frac{[B_{m\mu}\cos(\mu p\alpha\mp\omega_\mu t+\varphi_\mu)]^2}{2\mu_0}=\frac{B^2{}_{m\mu}}{4\mu_0}[1+\cos(2\mu p\alpha\mp\omega_\mu t+\varphi_\mu)]=\frac{B^2{}_{m\mu}}{4\mu_0}+\frac{B^2{}_{m\mu}}{4\mu_0}\cos(2\mu p\alpha\mp2\omega_\mu t+2\varphi_\mu)$$

- If Radial Force Pressure Is Expressed in General Form: $P_r(\alpha,t)=P_{mr}\cos(r\alpha-\omega_r t)$
  - The Frequency and orders of $P_{r\nu}(\alpha,t)$: $r=2\nu p;\omega_r=2\omega;\ f_r=2f$
  - The Frequency and orders of $P_{r\nu\mu}(\alpha,t)$: $r=(\nu\pm\mu)p;\omega_r=\omega\pm\omega_\mu;\ f_r=f\pm f_\mu$
  - The Frequency and orders of $P_{r\mu}(\alpha,t)$: $r=2\mu p;\omega_r=2\omega_\mu;\ f_r=2f_\mu$

The General Form of Radial Force Pressure Is Similar to Rotating MMF

Theoretic Analysis
– Radial Force Pressure Summary

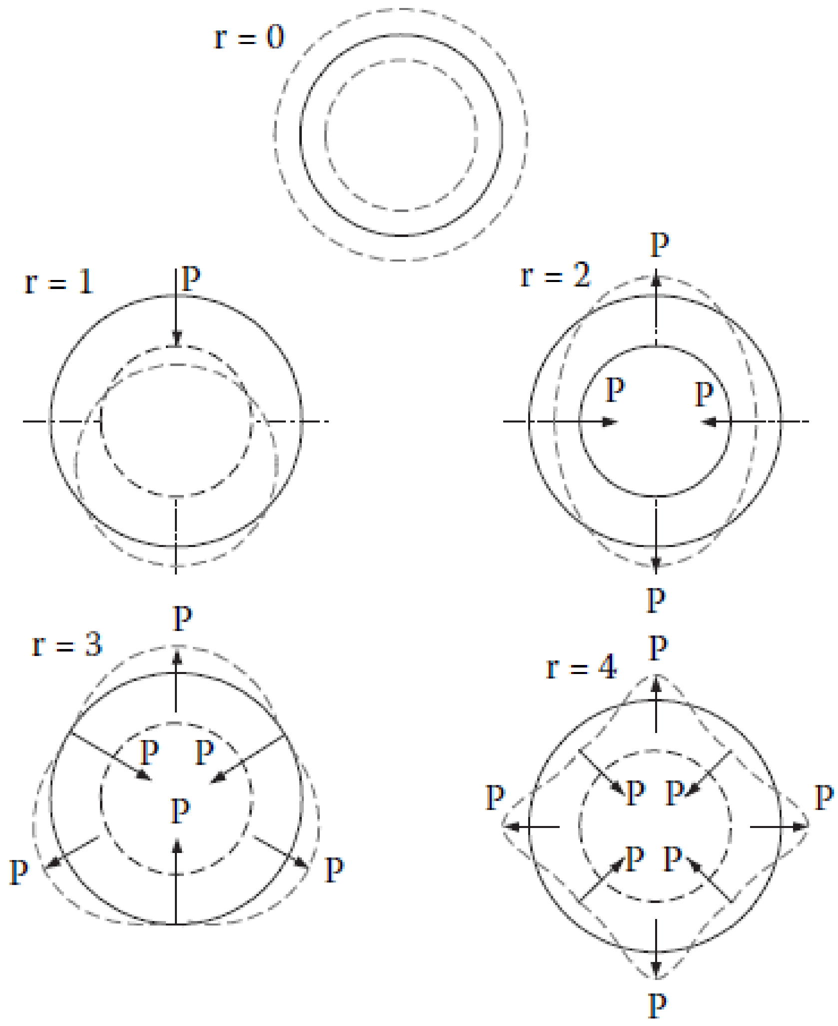
- **Pure Sinusoidal Current**

Source	Order	Frequency
Product of stator same harmonics	$r = 2\nu p$	$f_r = 2f$
Product of rotor same harmonics	$r = 2\mu p$ $\mu = (\frac{ks_2}{p} \pm 1)$	$f_r = 2f_\mu$ $f_\mu = f[1 \pm ks_2/p(1-s)]$
Product of stator and rotor harmonics	$r = (\nu \pm \mu)p$	$f_r = f \pm f_\mu$
Product of stator and rotor slot harmonics	$r = (\nu \pm \mu)p$ $\nu = ks_1/p \pm 1$ $\mu = ks_2/p \pm 1$	$f_r = f \pm f_\mu$
Product of stator and rotor static eccentricity harmonics	$r = 1$	$f_{1r} = f \pm f +$ $f[k\frac{s_2}{p}(1-s)]$
Product of stator and rotor dynamic eccentricity harmonics	$r = 1$	$f_r = f \pm f(1-s) \pm$ $f + f[k\frac{s_2}{p}(1-s)]$

- **Non-Pure Sinusoidal Current**

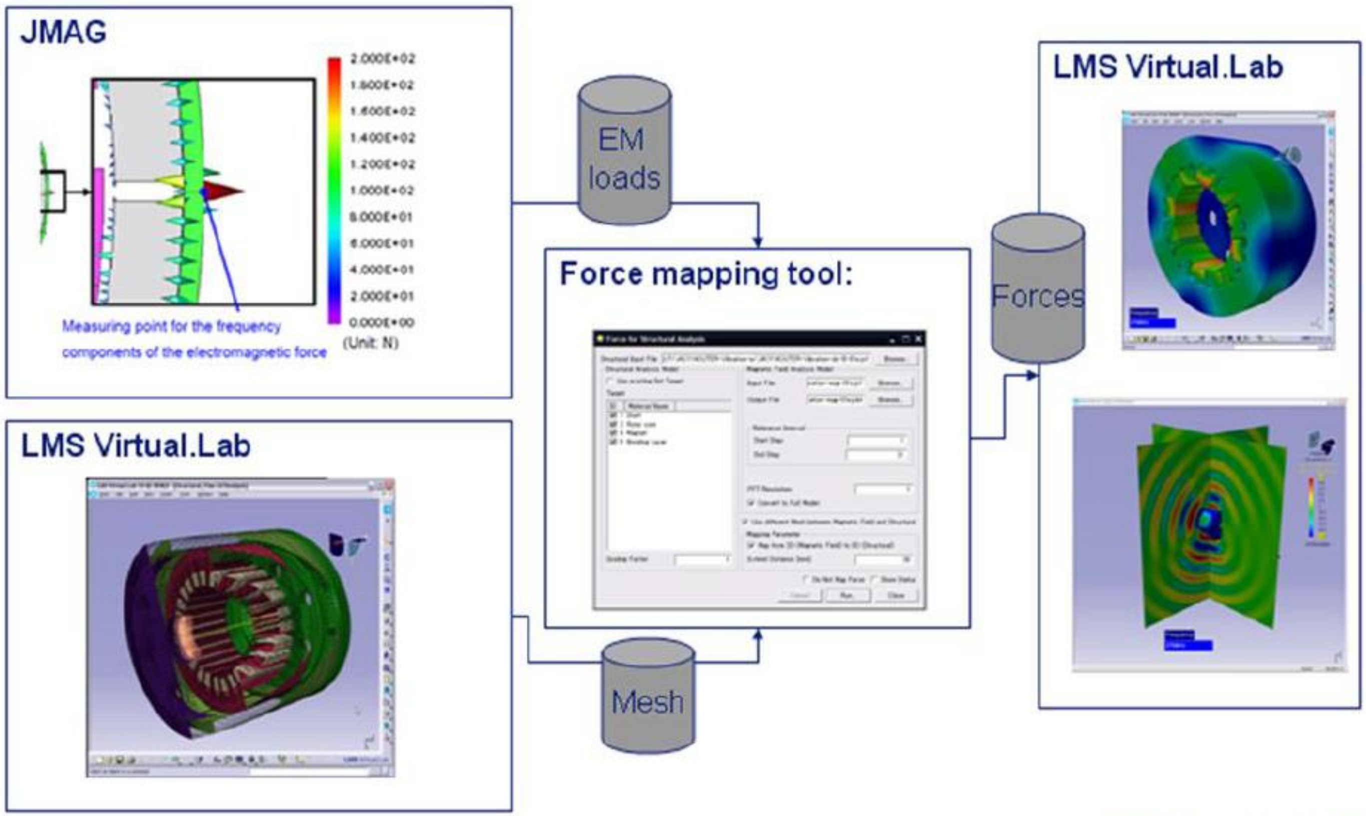
Source	Order	Frequency
Product of stator same harmonics	$r = 2\nu p$	$f_r = 2nf$
Product of rotor same harmonics	$r = 2\mu p$ $\mu = (\frac{ks_2}{p} \pm 1)$	$f_r = 2f_{n,\mu}$ $f_{n,\mu} = nf[1 \pm ks_2/p(1-s_n)]$ $s_n = [n\eta_s - \eta_s(1-s)]/n\eta_s$
Product of stator and rotor harmonics	$r = (\nu \pm \mu)p$	$f_r = nf \pm f_{n,\mu}$
Product of fundamental and higher time harmonics	$r = 0$ or $r = 2p$	$f_r = f \pm nf$
Product of the permeance and MMF associated with time harmonics		

Space Distribution of Radial Force



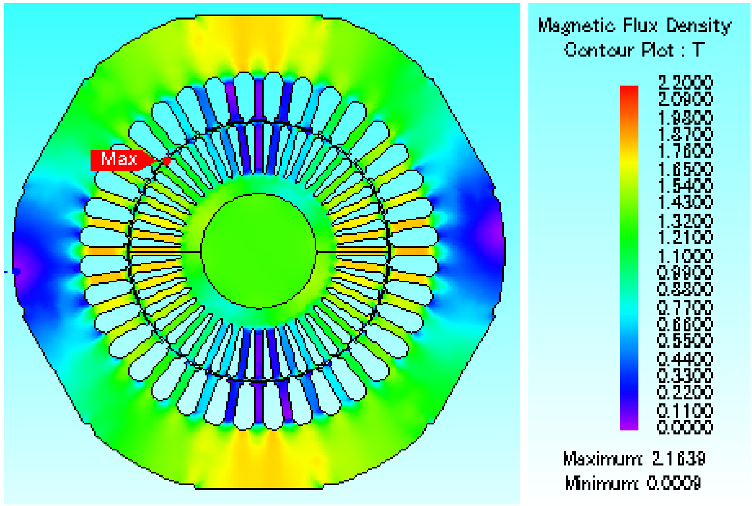
JMAG and Virtual.lab Co-Simulation Process

Simulation Process Sketch for Noise from EM induced Forces on the stator



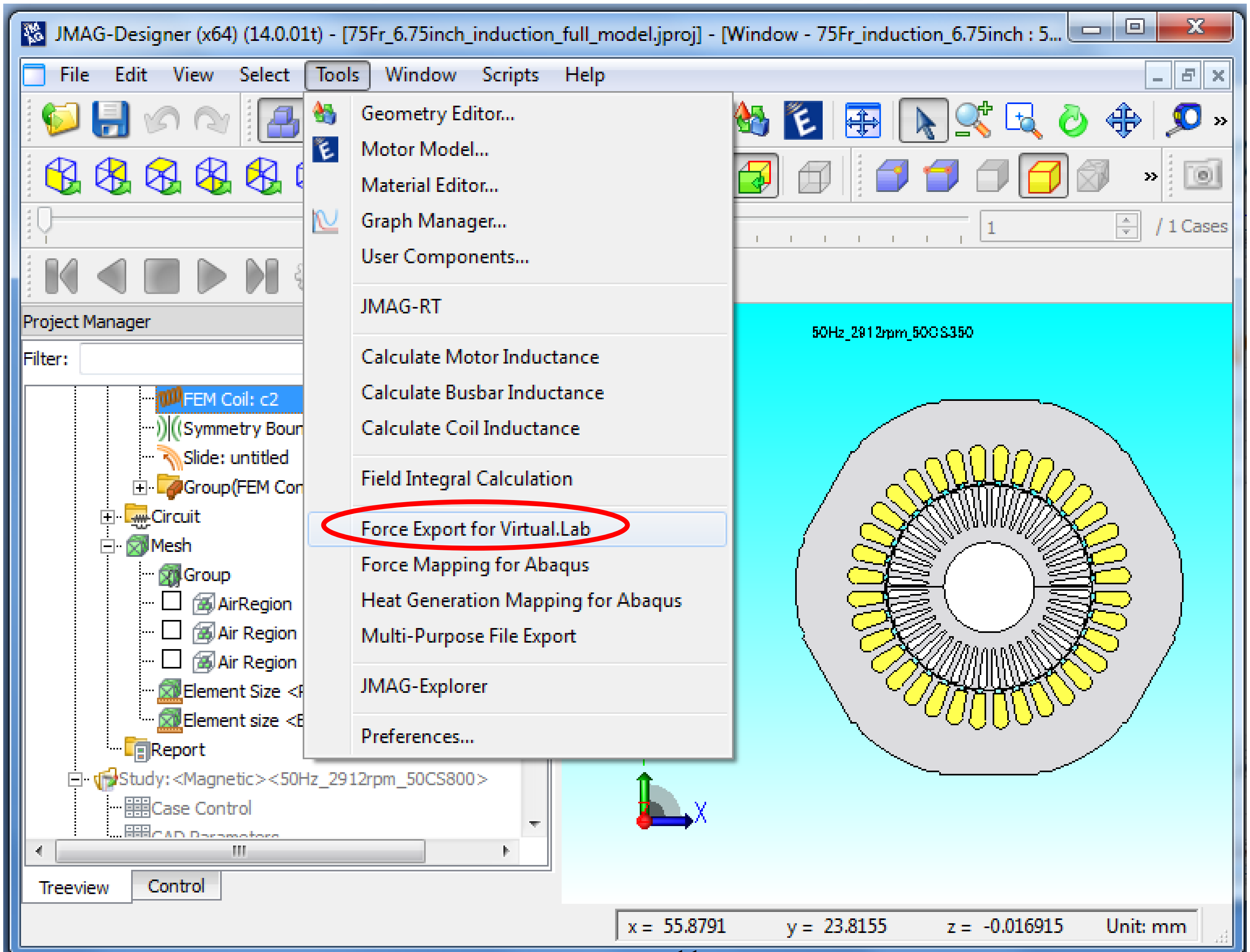
JMAG FEA Simulation Data

	Unit	Induction Motor	
		Test	JMAG Simu.
Voltage and Frequency		380V / 50Hz	380V/ 50Hz
Torque	N.m	65	67.2
Speed	rpm	2910	2910
Current A	A	38.10	38.00
Current B	A	40.40	38.02
Current C	A	35.40	38.00
Current AVG	A	37.97	38.01
Torque Ripple			6.4%
Stator Copper Loss	W	1214	1213
Estimated Bar Loss	W	566	688
Test or Corrected Iron Loss	W	566	414
Output Power	W	19857	20478
Input Power	W	22211	22801
Motor EFF		89.4%	89.8%

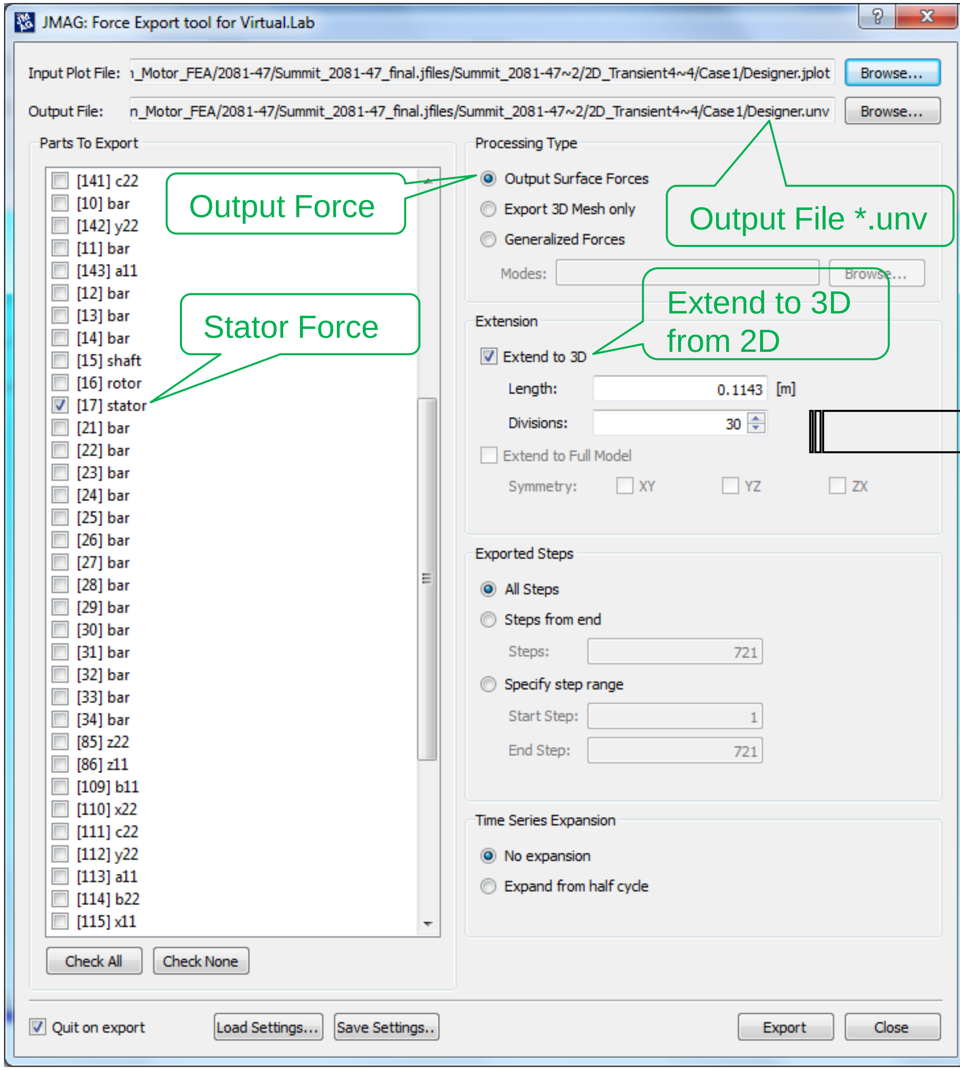


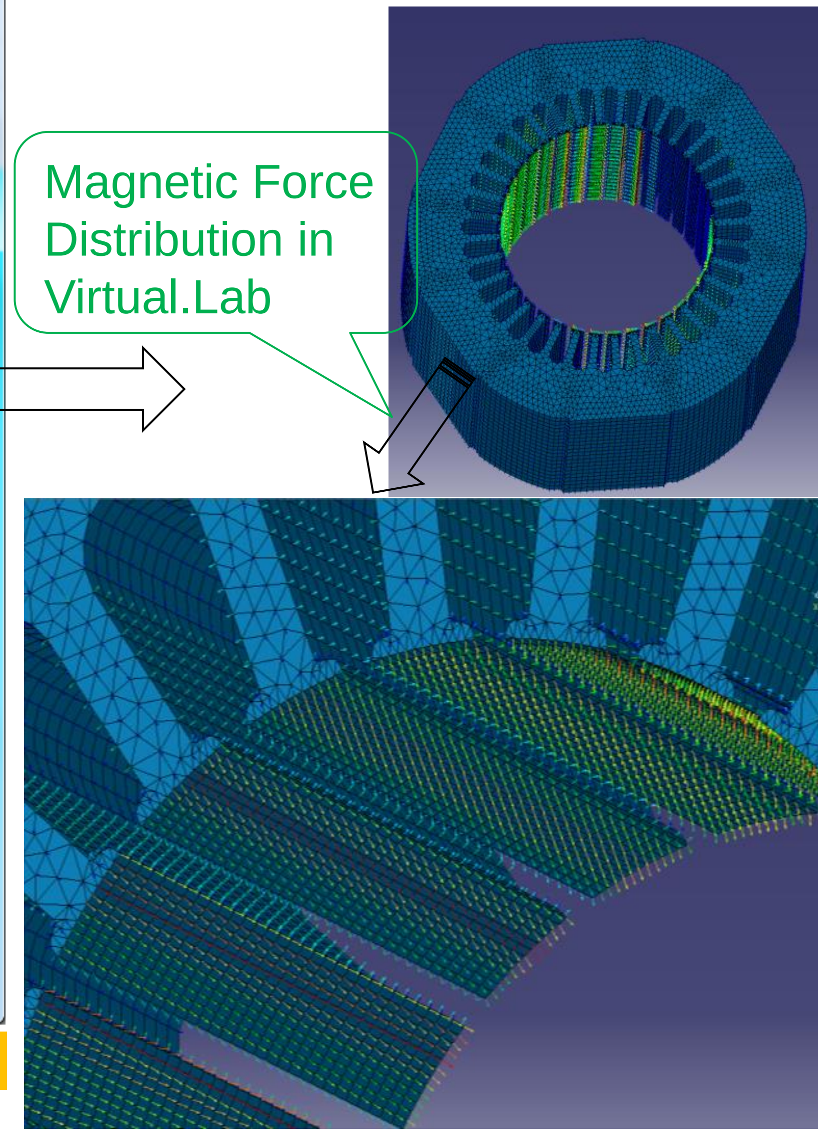
JMAG Simulation Data Is Close to Test Data

JMAG Output Force Setup



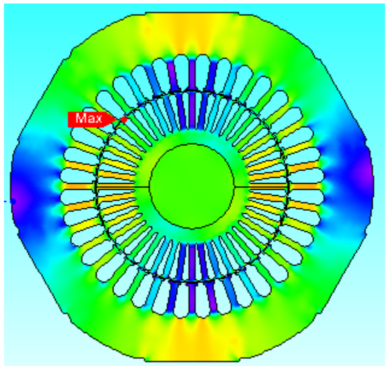
JMAG Output Force Setup



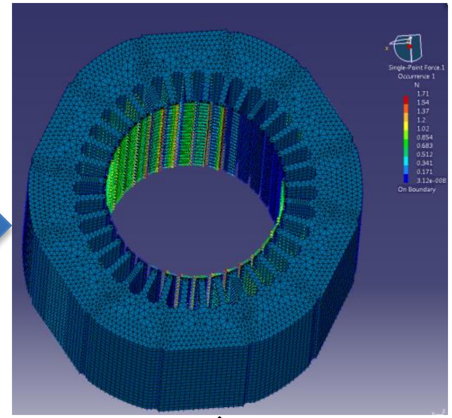


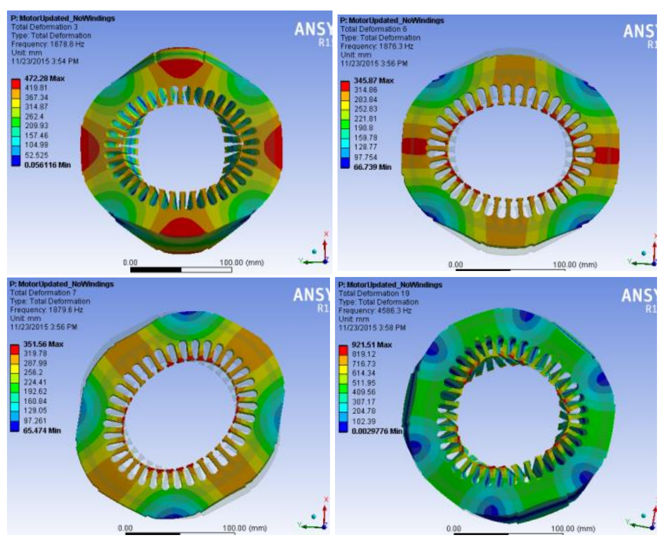
*.unv File Can Be Imported to Virtual.Lab to Predict Motor Sound

Applied Case For Induction Motor

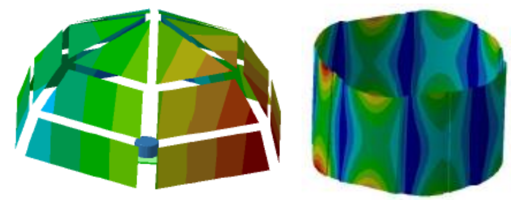


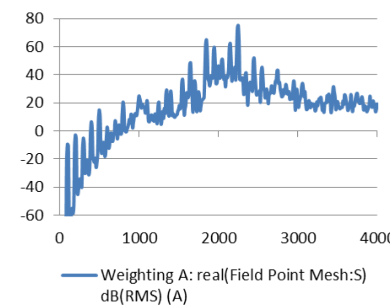
EM Force Import From JMAG





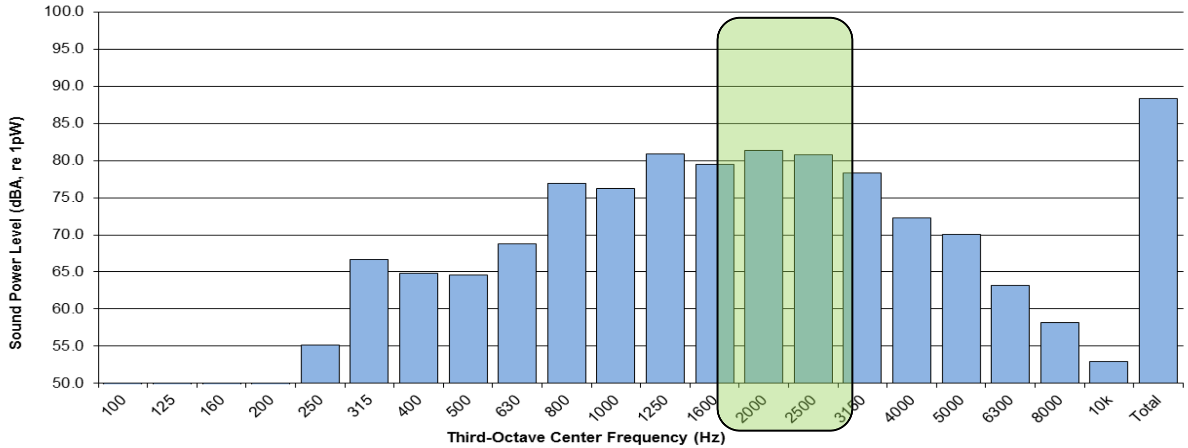
Motor Modal Analysis

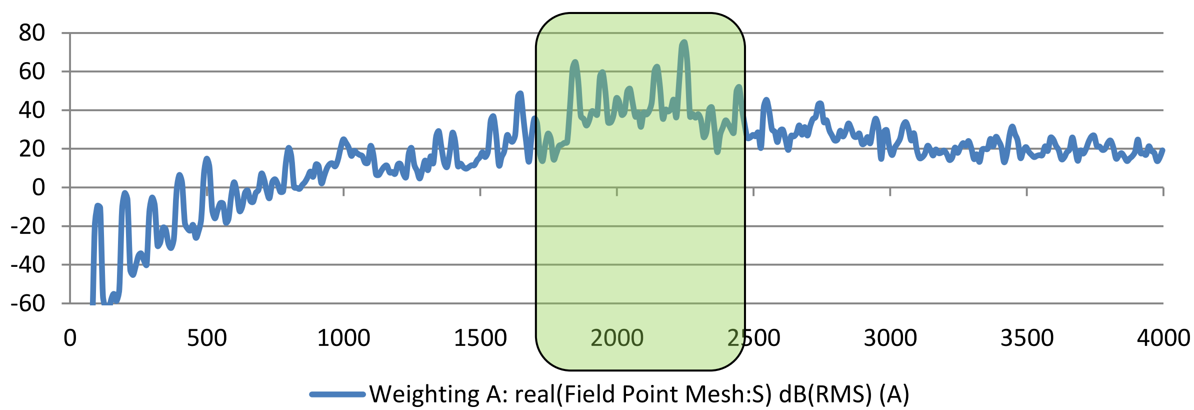




Motor Noise Simulation Result

Applied Case For Induction Motor





Simulation Results Has Same Trend With Test Data