Electromagnetic Force Coupling in Electric Machines

Mark Solveson, Cheta Rathod, Mike Hebbes, Gunjan Verma, Tushar Sambharam
ANSYS, Inc.
Introduction

• Low noise regulation
  – Aimed at reduction in noise pollution

• Comfort Criteria
  – Noise causes discomfort and fatigue
  – Noise suppression demonstrates technological/marketing edge

• Component Failure
  – Sensitivity of structure to acoustic resonances

• The above Applies to many Industry sectors:
  – Transportation, Power, Environmental, Building services
Introduction

- Noise and vibration in electric machines come from many sources.
- ANSYS provides excellent capabilities for the design and analysis of electric machines:
  - Electromagnetic performance
  - Electric Drive performance
  - Structural analysis
  - Thermal analysis
  - Acoustics analysis

- ANSYS field coupling technology allows mapping of electromagnetic forces for Mechanical analysis
Machine Types

- Different machines may have different considerations depending on their architecture or control strategies.
  - Primary Forces are in-plane (radial and tangential)
    - Single and Three Phase Induction Machines.
    - PM Synchronous Machines (Surface Mount, IPM).
    - Switched reluctance machines
  - Primary force are Axial
    - Axial Flux Machines
Noise Sources [1]

Magnetic
- Radial
- Slot Harmonics
- Magnetic Unbalance
  - Modes of Vibration

Mechanical
- Self
- Auxiliaries
  - Load Induced
    - Couplings
    - Foundation
  - Static Eccentricity
    - Dynamic Eccentricity
    - Unbalanced Eccentricity
    - Elliptical Rotor Surface

Aerodynamic
- Fluid Cooling Phenomena

Electronic
- Switching Harmonics

Audible Frequencies

20 Hz  60 Hz  261.63 Hz  4.186 kHz  5 kHz  20 kHz

Electromagnetic Design and Analysis

- ANSYS Machine Design Methodology
  - RMxprt: calculate rated performance for machine
  - Maxwell: Calculate detailed magnetic FEA of machine in time domain
  - Simulor: Calculate detailed drive design with coupled cosimulation with either RMxprt or Simulor.
Machine Model in Maxwell - Simploter

2D IPM (Interior Permanent Magnet) motor model created from RMxpert and Maxwell UDP (User Defined Primitive) for rotor

- 4 pole, 1500 RPM, 220 Volt DC bus.
- Two Control Strategies used:
  - 6 step inverter – In Maxwell
  - PWM current regulated – Cosimulation Maxwell with Simploter
Machine Model in Maxwell - Simpler
Force Calculations

• Force calculation using air gap flux density
  • Maxwell Stress Tensor
    – Force calculation at a point on the stator.
    – Force on a line in the airgap
    – Force on a line co-linear with the stator tooth

• Edge Force Density
  – Default field quantity available in Maxwell
  – Can be used for creating lumped force calculations on tooth tips

• Automatic Force mapping from Maxwell to ANSYS Mechanical. (2D-2D, 2D-3D, 3D-3D)
Edge Force Density in Maxwell

Radial and Tangential Components (N)

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Eccentricity Model

Left Side Tooth

Right Side Tooth
Parametric Study of Eccentricity Electromagnetic Force

- Rotor misaligned 0%, 25%, 50%
- Solved simultaneously on multi-core computer
- Shown: Radial Force on Right Tooth Tip
- FFT of Radial Force
Edge Force Density, 50% Eccentricity

- Edge Force Density values range from $1.75\times10^6$ to $1.4264\times10^{-3}$.
- Time = 20000000ns
- Speed = 1500000000rpm
- Position = 187.5000000deg
50% Eccentricity: Radial and Tangential Force on Right Side and Left Side Tooth

**Radial Tooth Tip Forces**

- Radial Force Small Gap
- Radial Force Large Gap

**Tangential Tooth Tip Forces**

- Tangential Force Small Gap
- Tangential Force Large Gap

**FFT Radial Tooth Tip Forces**

- Radial Force Small Gap
- Radial Force Large Gap

**FFT Tangential Tooth Tip Forces**

- Tangential Force Small Gap
- Tangential Force Large Gap
ANSYS Force Mapping

Fluid Dynamics  Structural Mechanics  Electromagnetics  Systems and Multiphysics
Two Approaches

• Direct Force Mapping
  – Electromagnetic forces from Maxwell to Mechanical by linking systems in Workbench
  – Transient Analysis for Stress prediction

• Lumped Force Mapping
  – Tooth Tip objects created for mapping calculated lumped force using ‘EdgeForceDensity’ in Maxwell.
  – Apply these lumped forces manually or through APDL Macro
  – Further harmonic and Noise Analysis
Scenario: Study the effect of Rotor Eccentricity

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

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

Max Deformation vs time

- Case 1 0% Eccentricity
- Case 2 50% Eccentricity
Von Misses Stress

- Case 1 0% Eccentricity
- Case 2 50% Eccentricity

Max Stresses vs time

- 0% Eccentricity
- 50% Eccentricity
Results: Comparison

Higher the amount of eccentricity, higher is the variation of electromagnetic forces, causing deformation of stator, vibration and noise.

• Total Deformation
  – Deformation higher for eccentric model

• Peak Stresses
  – Stator Stresses are non symmetric and higher for eccentric model where the air gap is minimum.
Approach 2 Lumped Force Mapping

Workbench Flow Chart for Noise Prediction

- Electromagnetic Forces
  - Export forces
  - Lumped Forces in Time Domain
    - Perform FFT in Maxwell
      - Real/Imaginary Forces In Frequency Domain
        - APDL in Workbench
          - Harmonic Response
            - APDL in Workbench
              - Extract Acoustic Pressures

ANSYS Maxwell
ANSYS Mechanical
ANSYS Acoustics
ANSYS Harmonic Analysis

Realize Your Product Promise™

Fluid Dynamics  Structural Mechanics  Electromagnetics  Systems and Multiphysics
Modal Analysis: Get Resonant Frequencies

Mode #1, 8502 Hz
Mode #2, 8708 Hz
Mode #3, 8708 Hz
Mode #4, 9080 Hz

First four Natural Frequency and corresponding mode shapes
Why Harmonic Analysis

- To make sure that a given design can withstand sinusoidal loads at different frequencies
- To detect resonant response and avoid it if necessary (by using dampers, for example)
- To determine Acoustic response
Harmonic Response – Bode plot

Frequency response at a selected node location of the model.

- Max Amplitude (1.7mm) occurs at 8710 Hz on the selected vertex.
Harmonic Response – Contour plot

Amplitude distribution of the displacements at a specific frequency.
Acoustics Capabilities in ANSYS

• Acoustics is the study of the generation, propagation, absorption, and reflection of sound pressure waves in an acoustic medium.

• Acoustic problems can be identified as
  
  – Vibro-Acoustics: Sound generated structurally (ANSYS Mechanical)
  
  – Aero-Acoustics: Sound generated aerodynamically (ANSYS CFD)
Modeling Aero-Acoustics (ANSYS CFD)

• Free-Space Problem with no solid surfaces:
  – sound generated from turbulence, jet noise

• Free-Space Problem with solid surfaces:
  – Fan noise, airframe noise, rotor noise, boundary layer noise, cavity noise

• Interior problem:
  • Duct noise, mufflers, ducted fan noise

Sound pressure fluctuations
Computing the acoustic field radiated by a vibrating structure

- Structure modeled in ANSYS Mechanical where vibration patterns are calculated (Modal, Harmonic Analysis). Applied loads are obtained from Maxwell.
- Vibration patterns used as boundary conditions to compute acoustic field radiated by structure (ANSYS MAPDL, ANSYS Acoustic Structures-ACTRAN)
ANSYS Acoustics Structures computes noise radiated by vibrating structures.

From Harmonic Vibrations to Noise Estimates.

ANSYS Acoustics Structures integrates with your current simulation tools.
Acoustic Analysis – Pressure Plot
Summary

• Investigated different noise sources for electric machines
• Demonstrated an integrated approach from Electromagnetics to Structural to Acoustics.
• Showed the effects of static eccentricity on stator tooth forces, deformation and stresses.
• Performed modal analysis to find the acoustic resonances

Future Work:

• Investigation of different noise scenarios (machine types, drives)
• Include more mechanical details (windings, housing, etc)
• Expand harmonic analysis to include higher frequency content of forces
• Further investigation of Aero-acoustics with ANSYS CFD
References

— Wei Wang, Quanfeng Li, Zhihuan Song, Shenbo Yu, Jian Chen, Renyuan Tang, “Three-Dimensional Field Calculation and Analysis of Electromagnetic Vibration and Noise for Disk Permanent Magnet Synchronous Machines”, Shenyang University of Technology, China.
Thank You
Electromagnetic Force Coupling in Electric Machines Including Stress, Deformation, and Acoustic Analysis.

Understanding the impact of electromagnetic forces on noise generation for electric machines can include many factors. This presentation will review these issues and illustrate electromagnetic forces, stress, deformation, and acoustic coupling in ANSYS Workbench. An example showing automatic mapping of magnetic time-domain forces, and a comparison of stresses for different rotor eccentricities will be shown.
Presentation Outline (Goal 30 total Slides)

1. Introduction

2. Literature review – what are the noise components for electric machines
   a. Noise Sources, examples
   b. Acoustic Definition, examples

3. EM Motor Methodology
   a. RMxpert to Maxwell, Simploter
   b. Force calculations
   c. Eccentricity Model

4. Mechanical Analysis
   a. 2D (3D?) transient force mapping results
   b. Discussion of FFT approaches (by inspection or 3rd party tools/scripts)
   c. 2D (3D?) harmonic Analysis

5. Acoustic analysis
   a. General capabilities (acoustic elements, Actran coupling?)
   b. Results for stator lamination
Noise Sources

• Magnetic
  – The interaction of magnetic fields and currents in the machine cause electromagnetic torque and thus rotation of the rotor.
  – Evaluation of the radial and tangential forces on the tooth tips are important.
    • This can be accomplished through evaluation of the air gap flux density, or using Force Density field calculations available within Maxwell.
  – If one of the radial force frequencies coincides with the natural frequency of the machine, resonance occurs leading to acoustic noise.
    • Mixed product of stator and rotor winding space harmonics.
    • Slot Harmonics
    • Rotor Eccentricity: improper rotor alignment causing unbalanced magnetic forces on the stator.
  – Lamination vibration due to magnetorestrictive forces (worst when not stacked properly)

• Electronic
  – Switching noise
    • Inverter PWM frequencies can be in audible range.
  – Current through the winding – Lorentz forces
Noise Sources

• Mechanical
  – Self resonance – natural resonance frequencies
    • Closed form equations
    • FEA
  – Load induced
    • Coupling of machine to load, and mounting.
  – Auxiliaries
    • Bearing Vibration
    • Brush commutators
  – Chattering
    • Intra-lamination
    • Function of Bolt force
    • Involves 3D Mechanical transient vibration analysis
  – Manufacturing asymmetries of the rotor and stator- nonuniform air gap
  – Stator winding which are not installed properly

• Aero-Dynamics
  – ANSYS CFD
### Machine Model in Maxwell

- VB script Fields Calculator to create Radial and Tangential Force Expressions from **EdgeForceDensity**
- VB script Calculates Radial and Tangential Force on Tooth Tips
- Allows only force on edge that neighbors non ferrous objects
- ‘Half’ teeth force components added together
- Add to Expression Cache

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#### VB Script Example

```vbnet
Set oModule = oDesign.GetModule("FieldsReporter")
Module.EntryWay "EdgeForceDensity"
Module.CalcOp "ScalarX"
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Module.CalcOp "cos"
Module.CalcOp "t"
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#### Fields Calculator

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- `ToolTipRadial_Full`: Radial force on full tooth tip
- `ToolTipTangent_Full`: Tangential force on full tooth tip
- `ToolTipRadial_1`: Radial force on half tooth tip
- `ToolTipTangent_1`: Tangential force on half tooth tip

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**Note:** The expressions and calculations are based on the provided script and the Fields Calculator. The script demonstrates how to create force expressions using the Fields Calculator in Maxwell.
Harmonic Analysis Overview

A technique to determine the steady state response of a structure to sinusoidal (harmonic) loads of known frequency.

Input:
• Harmonic loads (forces, pressures, and imposed displacements) of known magnitude and frequency. *(Obtained from Maxwell)*
• May be multiple loads all at the same frequency.

Output:
• Harmonic displacements at each DOF, usually out of phase with the applied loads.
• Other derived quantities, such as stresses and strains.
ANSYS Acoustics

• Structural-borne noise (one way Vibro-Acoustics)
  – ANSYS Acoustics Structures (FFT’s ACTRAN Solver)

• Vibro-Acoustics
  – ANSYS Mechanical (APDL Solver)

• Aero-Acoustics
  – ANSYS CFD

• Nonlinear fluid-structure interaction
  – ANSYS CFD + ANSYS Mechanical
Aero-Acoustics ANSYS CFD Approaches

• Direct calculation:
  – Resolve the acoustic pressure fluctuations as part of the CFD solution

• Couple CFD with specialized acoustics codes, Boundary Element Methods (BEM), Hybrid zonal methods
  – Acoustic waves are not tracked with CDF solution
  – Calculate wave propagation using specialized codes (ACTRAN, SYSNOISE)
Aero-Acoustic simulation of Automotive Front End Module cooling fans by using FLUENT’s Acoustic module

Courtesy of Hyundai MOBIS, Korea

Geometry of Cooling Fans

Pressure Contours

Flow Pathlines through

Sound pressure fluctuations calculated at the receiver position
Subwoofer Example (ANSYS CFD) (non-linear fluid with structure)

Fluid-Structure Interaction Solution

Transient Pressures
Acoustic - Structural Example - Coupled

Target Object: Nested Cylindrical Cans

Acoustic Energy Source

Scattered Acoustic Radiation

FEA Model quarter Symmetry Hemispherical Domain

Animation of Acoustic Pressure (Pa)