Welcome to the “Electric Motors 201 (for NVH Engineers)” Webinar

THE PRESENTATION WILL BEGIN AT 10 AM EASTERN TIME (GMT-4)

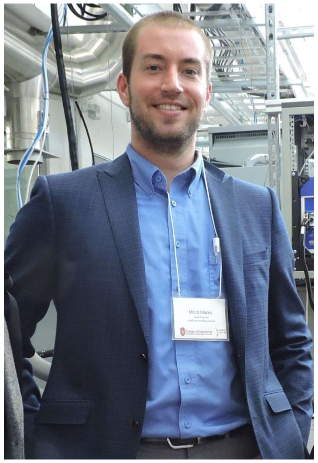
All attendees microphones are muted for the entire webinar session. Be sure your speaker is active and join the audio conference.

If you have a question, please send it to the host using the “Q&A” function. Questions will be answered at the end of the presentation.

Presenter

Mitch Marks

- **Business Development - Electrification**
- BSEE, MSEE –University of Wisconsin – Madison WEMPEC
- Joined HBM in 2017
- Previous positions in motor manufacturing, controls, and testing
- E-Mail: Mitchell.Marks@hbkworld.com



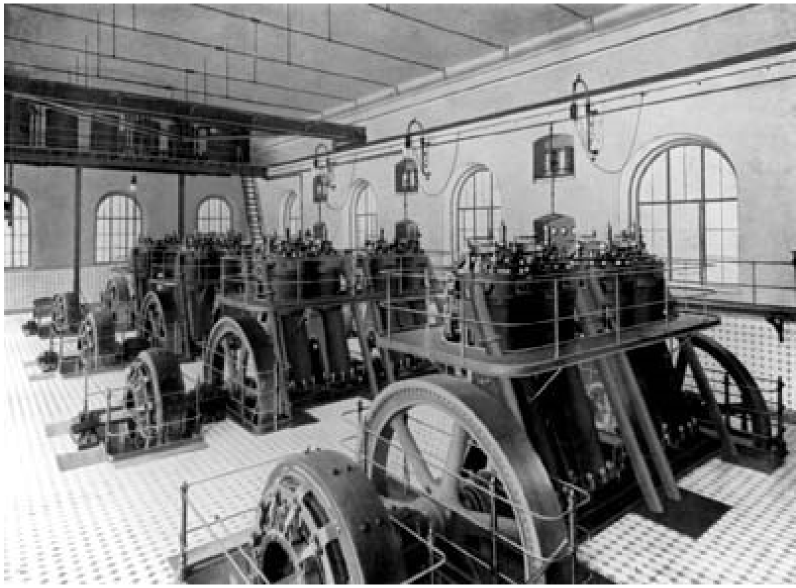
Mitch Marks

Ed Green, Ph.D.

- Ph.D. Purdue University - Ray W. Herrick Laboratories (1995)
- Noise and Vibration Engineer in the Detroit area for the last 26 years
- Principal Staff Engineer at HBK Sound and Vibration Engineering Services for last 9 years
- Enjoy running and ebiking

Electric Motors 201 (for NVH Engineers) - Background

- With the transition from ICE to electric motor propulsion, NVH engineers need to learn the basics of electric motor technology
- This is a follow-on to our Electric Motors 101 Webinar
- According to BloombergNEF, “By 2040, over half of new passenger vehicles sold will be electric.” (https://about.bnef.com/electric-vehicle-outlook/)



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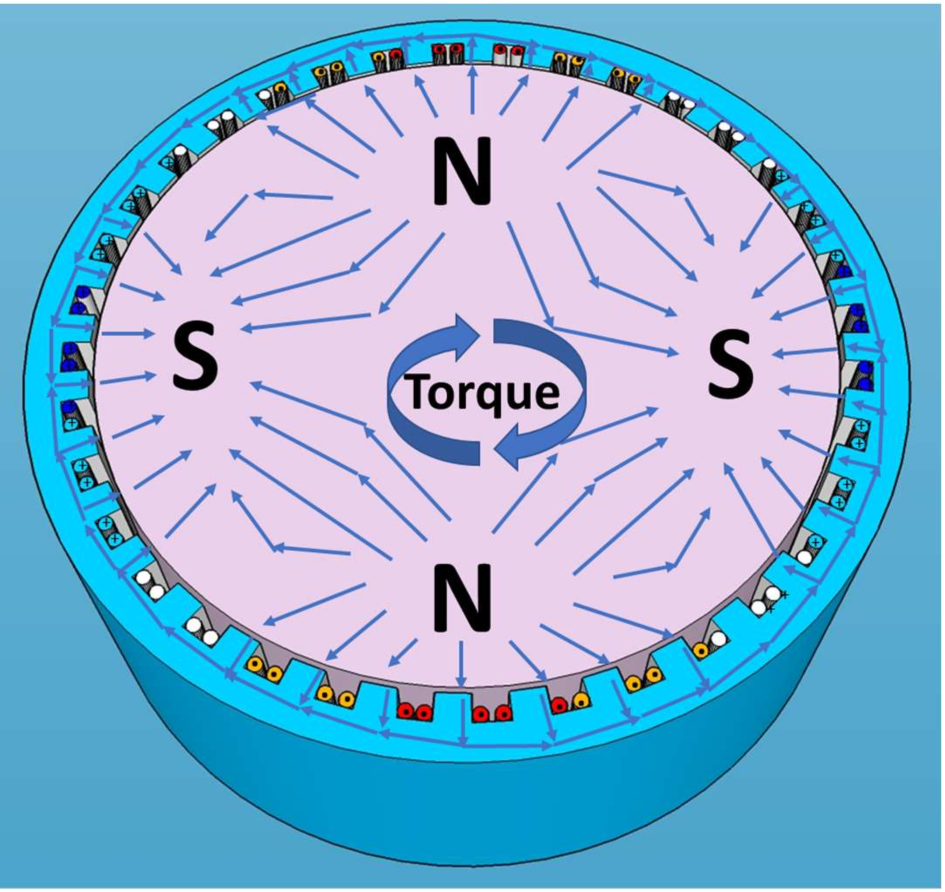
Electric Motors 201 (for NVH Engineers) - Outline

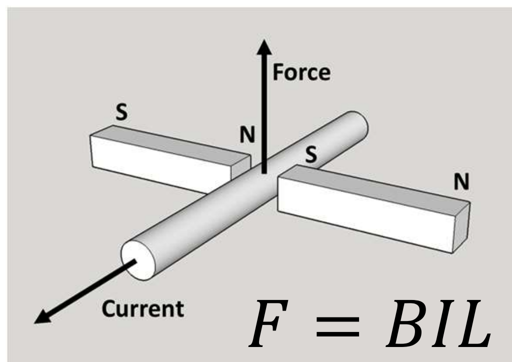
- Review of Induction and Synchronous Motors
- Introduction to Switched Reluctance Motors
- Control Circuitry and Algorithms Used to Power Electric Motors
- Noise Mechanisms of Electric Motors – Torque Ripple, Shell Vibration, Power Electronics
- Why Electric Vehicles Are More Than Electrically Powered ICE Vehicles

Review of Induction and Synchronous Motors

Synchronous motor



- Permanent magnet synchronous motor (PMSM) is shown (aka BLDC)
- Conductors are in slots in the stator
- Force is exerted on conductors as shown earlier, but equal and opposite force is also exerted on the rotor to produce torque
- Alternating current is applied to the conductors (usually with multiple phases) to produce torque
- To produce torque, the conductors must be energized at the same rate as the rotor spins - synchronous



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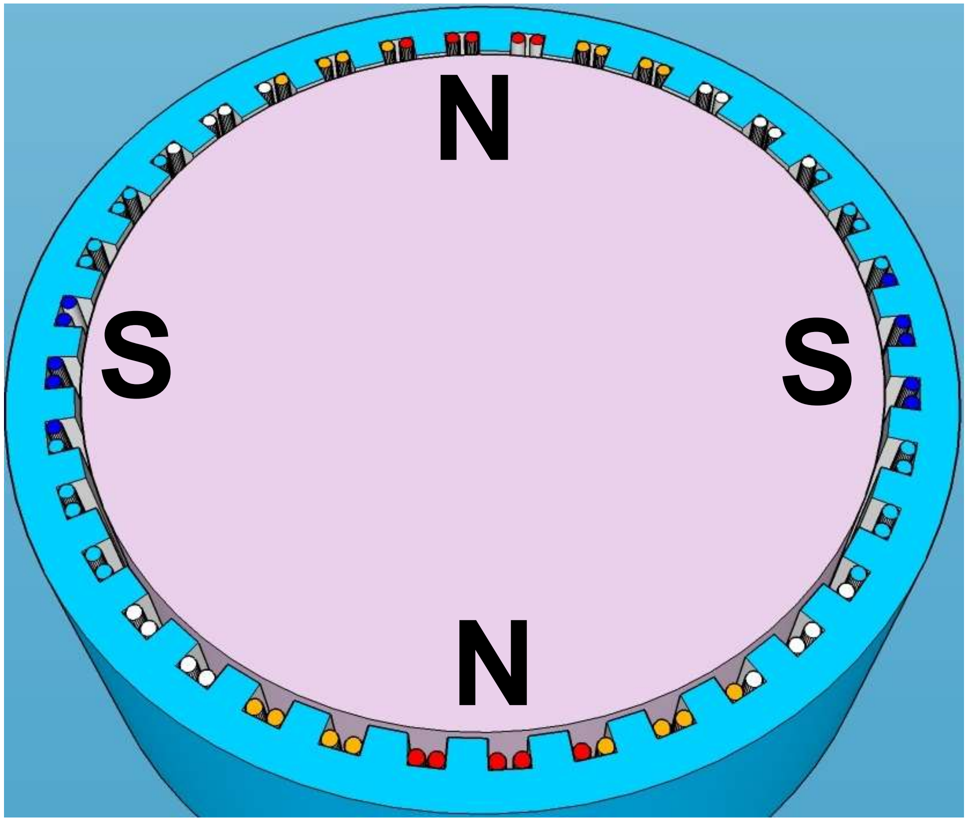
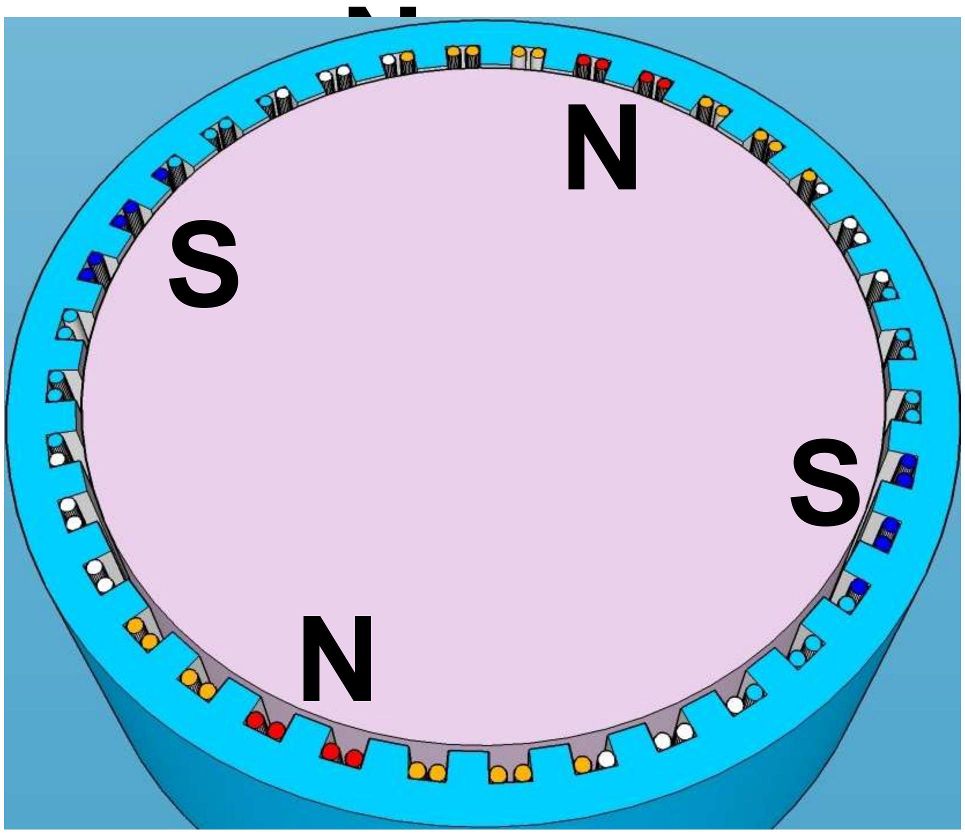
Synchronous motor – cont.



Synchronous motor – cont.



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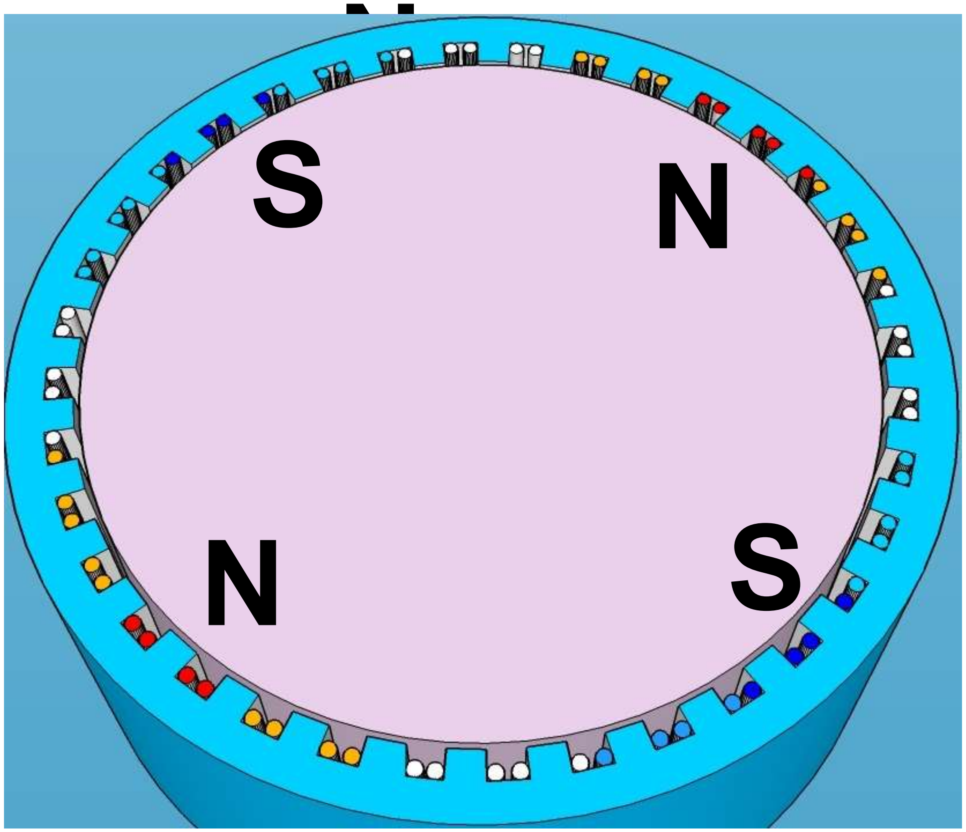
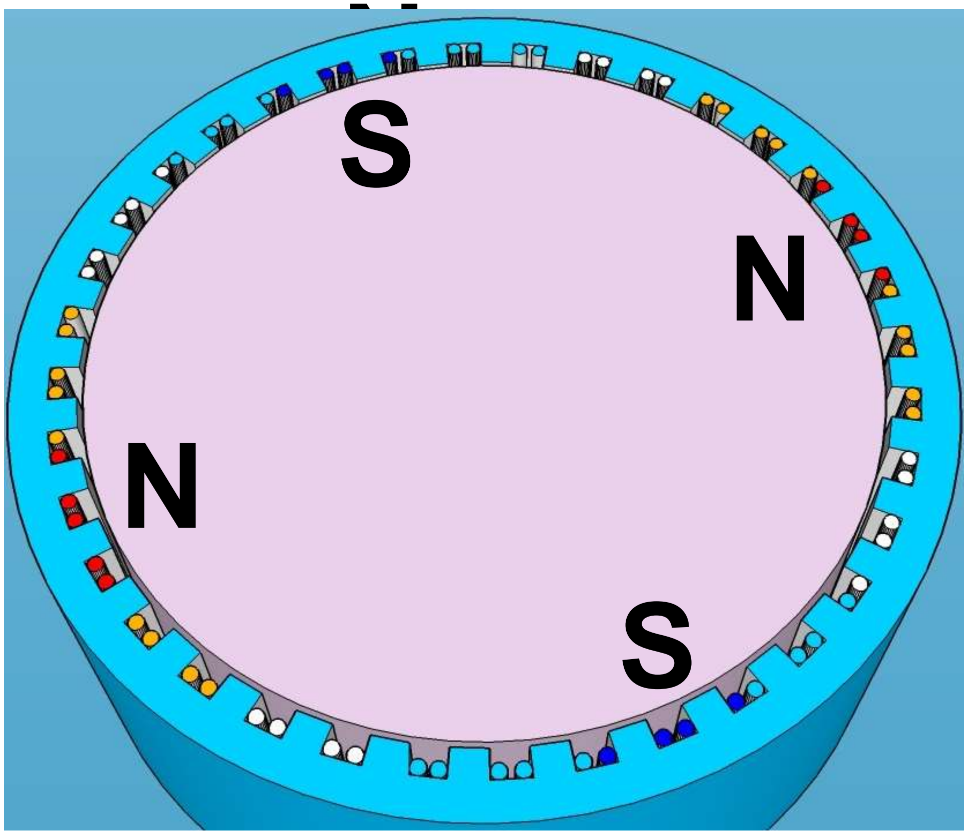
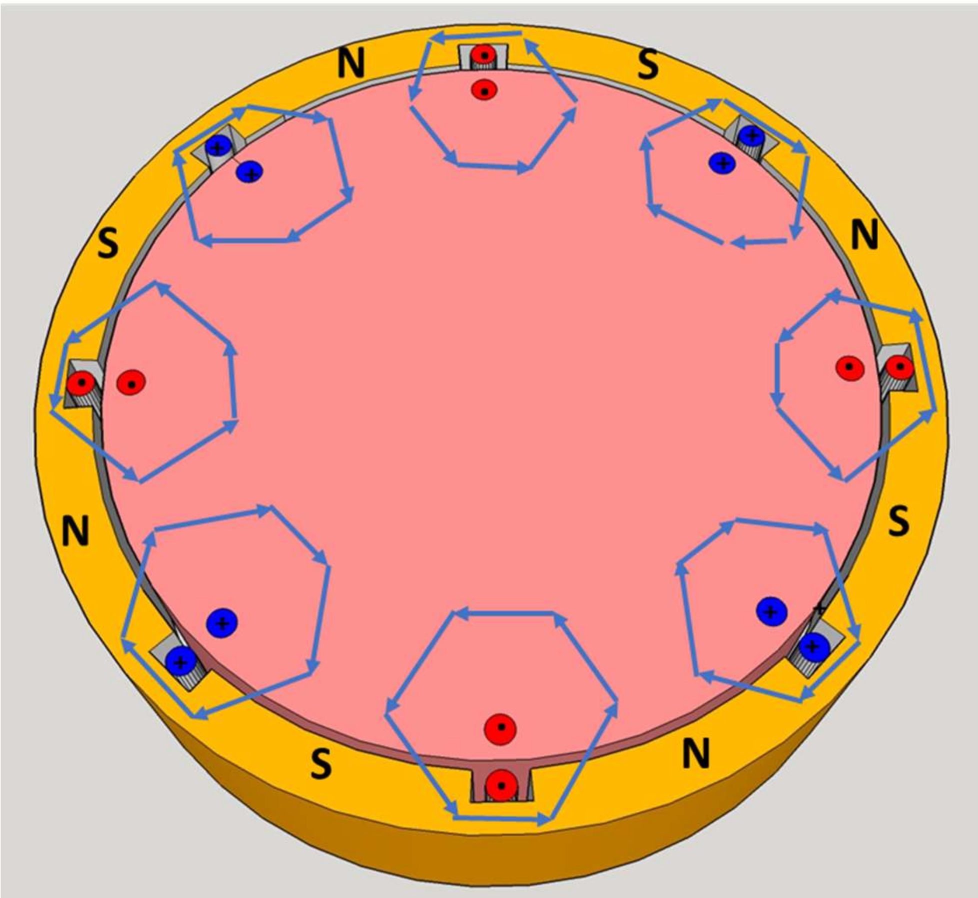
Synchronous motor – cont.



Synchronous motor – cont.



Induction motor



- Induction motor (IM) is shown
- **Current from the stator coils induces current in the cage (rotor conductors)** which produces a magnetic field in the rotor – like a transformer!
- **Slip is the percent difference between rotor speed and energizing speed**
- Invented by Nikola Tesla in 1887
- **Unlike a synchronous motor, the rotor speed must be slower than the excitation of the stator.** Higher slip produces more current demand and more torque

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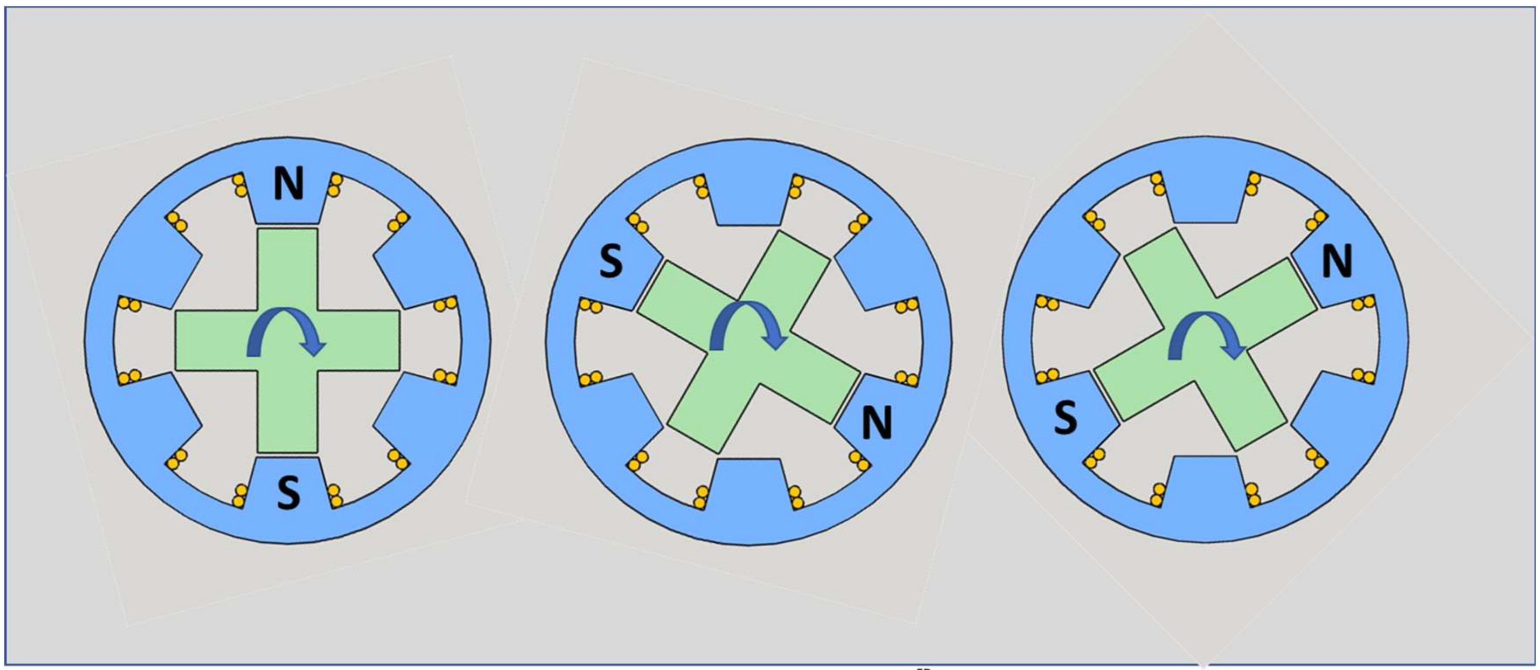
Introduction to Switched Reluctance Motors

Switched reluctance motor

- **A bar of magnetic material (laminated steel/iron) wants to align with the magnetic flux lines – like iron filings**
- Hybrid Reluctance/SM have been used to increase the efficiency of latest Tesla and Toyota EVs – IPM-SynRM
- **SRMs have no back EMF** – efficiency does not decrease at high speeds like PMSMs



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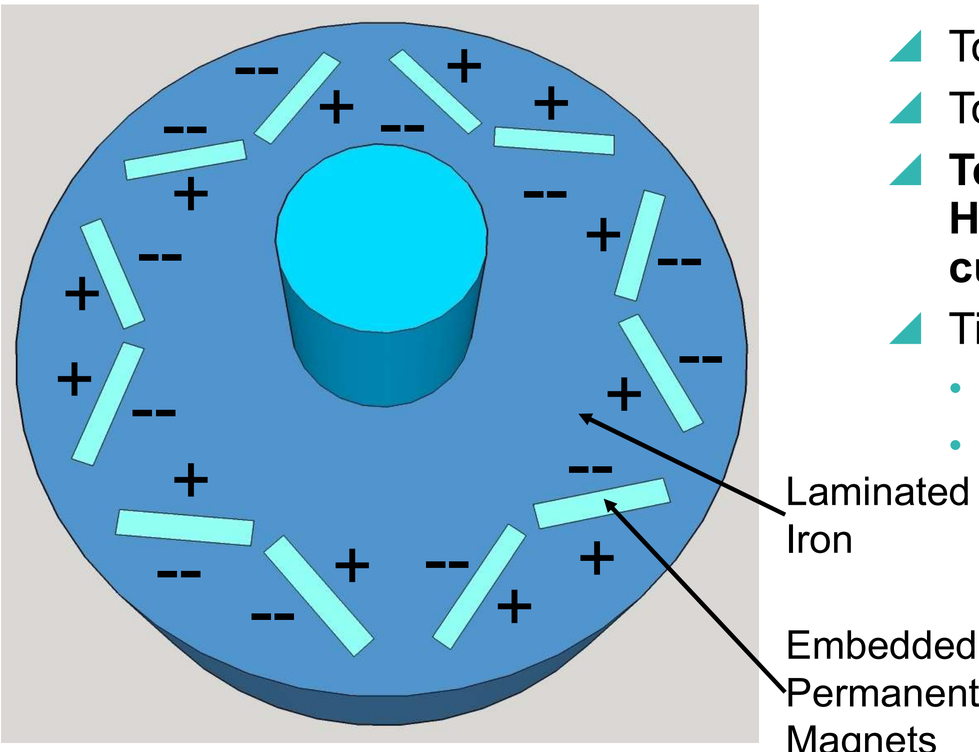
- Note that the polarity of magnetic excitation is not important to the direction of rotation

Internal Permanent Magnet - Synchronous Reluctance Motor (IPM-SynRM)

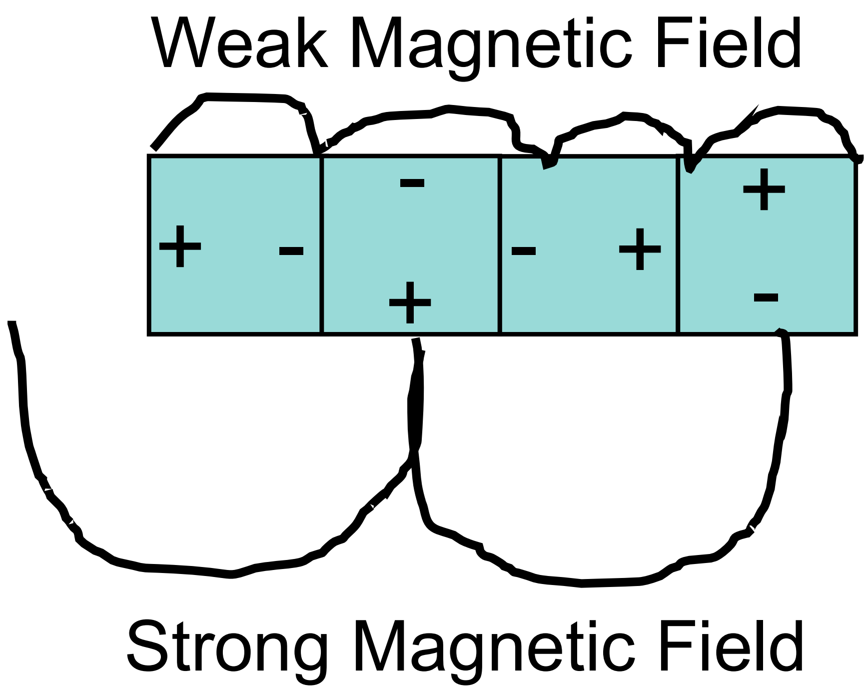


IPM-SynRM Rotor

- Rotor of IPM-SynRM is shown
- Toyota and Tesla use a similar design
- Toyota uses single piece magnets
- **Tesla uses four-piece magnets which may be Halbach Arrays or just to reduce eddy currents**
- Timing of stator is altered per motor speed
  - **Acts as a SM at low speed – high starting torque**
  - **Acts as a SRM at high speed – high efficiency, very low back EMF**

Halbach array

- Magnet can be arranged to produce a strong field on one side and a weak field on the other side



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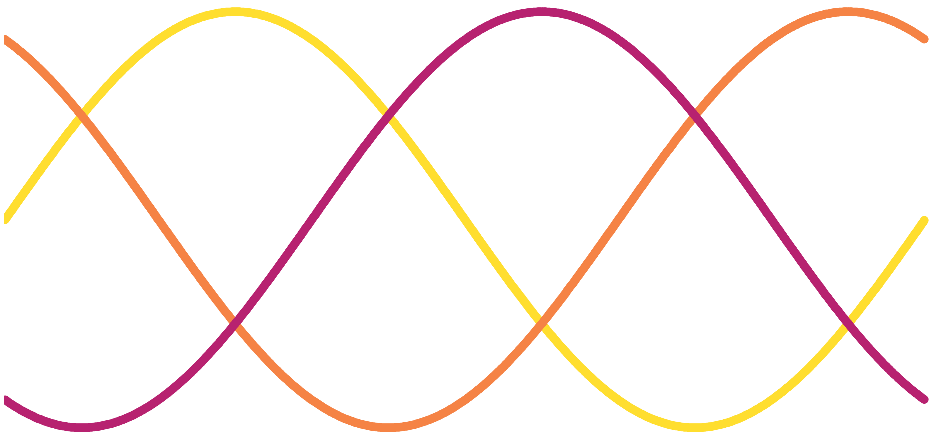
Synchronous Motor/Induction Motor/IMP-SynRM tradeoffs

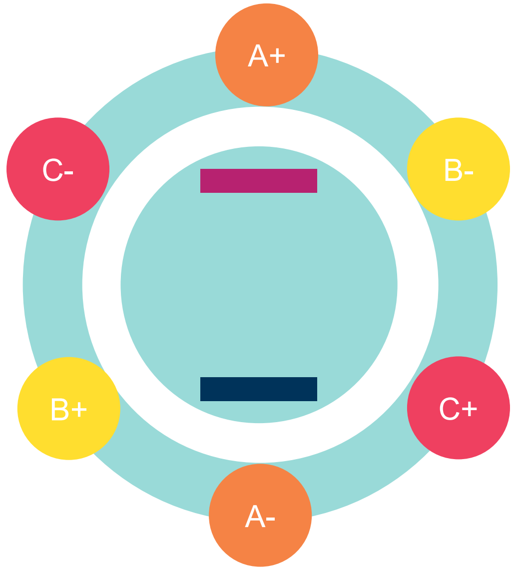
	Induction Motor	Synchronous Motor	IPM-SynRM
Cost	Low	Higher	Middle
Starting Torque	Low	Better	Low
Low Speed Torque	Better	Good	Low
Power Density	Good	Better	Better
Efficiency	Very Good (94%)	Better (96%)	Best (High Speed)
Torque Degradation	None	Slight over Time	Slight over Time
Control	Easy	More Difficult	Most Difficult
Longevity/Durability	Excellent	Excellent	Excellent

Control Circuitry and Algorithms Used to Power Electric Motors

Motors require AC excitation



2 pole motor

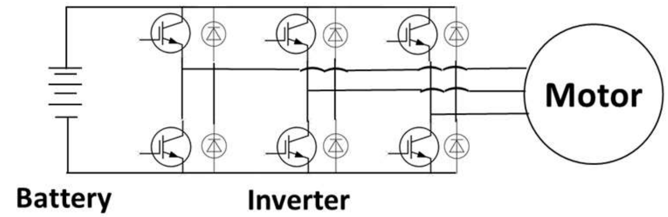


Rotor Magnet follows Stator Excitation

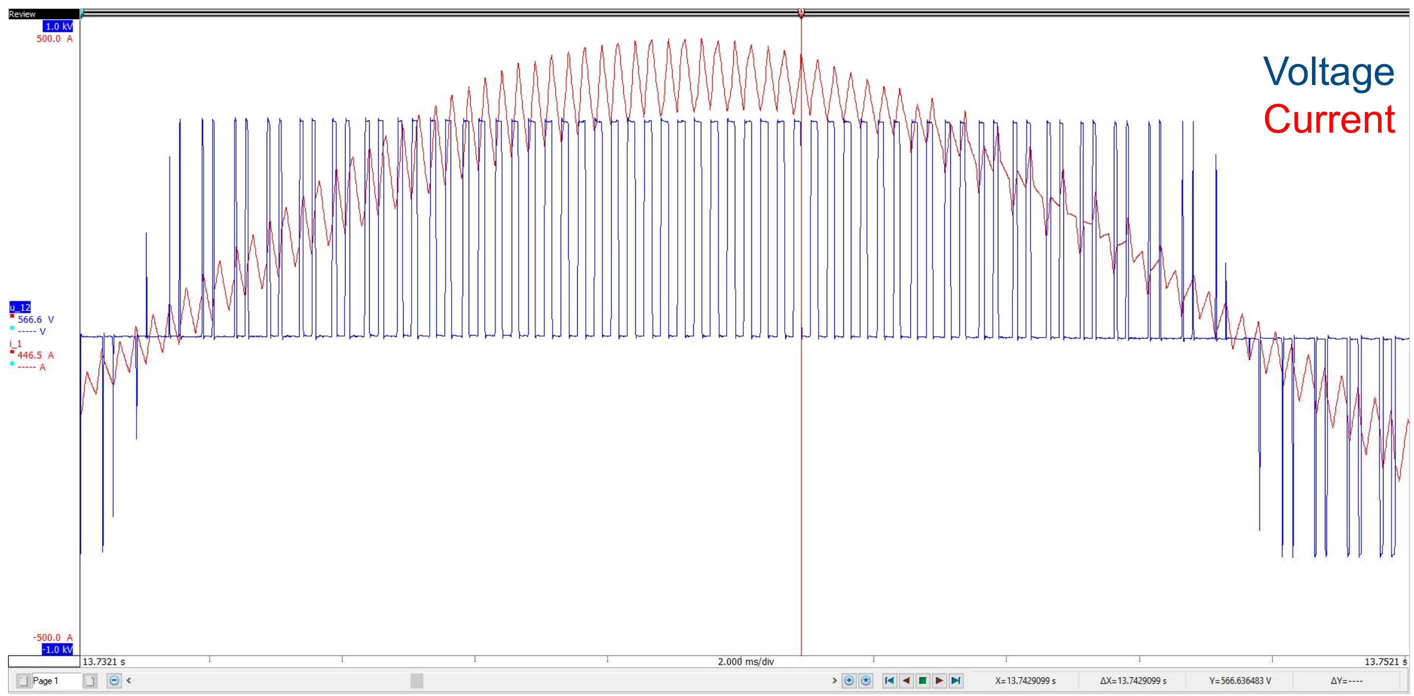
EV motors are powered by a battery

- Inverter converts DC to AC
- Series of switches turned on in a strategic pattern
- DC → AC →ϕ → Torque → Vibration → Noise
- Inverter controls the system

Rotor follows excitation and harmonics



- Voltage is a series of square waves
- Current is hardware filtered to be "sinusoidal"
- Contains many harmonics
- Creates harmonics in torque
- High Frequency (2-60kHz)



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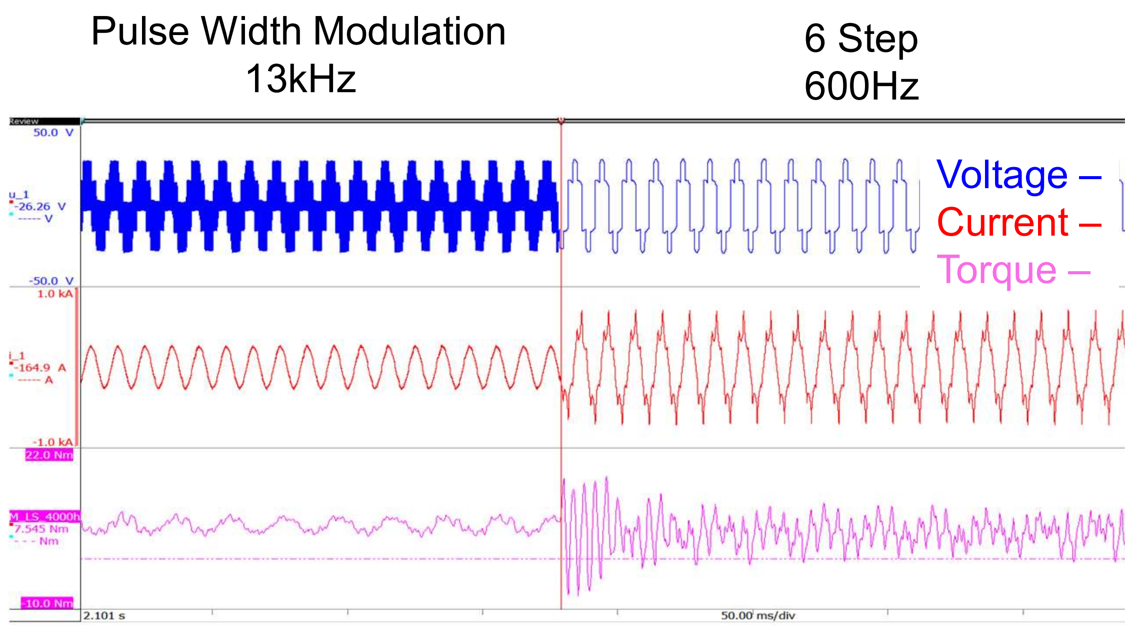
Inverter control will influence mechanical resonances

- Torque follows the current excitation
- Voltage waveforms (control type) effect torque
  - PWM excitation on the left
  - 6 step excitation on the right
- These effects will result in N&V at the machine and down stream



From "eDrive NVH HBM eDrive Testing" webinar, Oct 2019, Mitch Marks

Review of inverters & excitation

- Electric vehicle batteries are DC devices, and traction motors are AC devices
- A high frequency inverter is necessary to convert the DC battery voltage into AC motor supply voltage
- It would be ideal for the inverter to produce a sine wave output, but solid-state-transistor devices in the inverter operate in “On” and “Off” states
- “On” and “Off” states are magnetically filtered into sine waves with harmonics
- Sine waves & harmonics can be manifested in torque ripple, sound, and vibration

Noise Mechanisms of Electric Motors

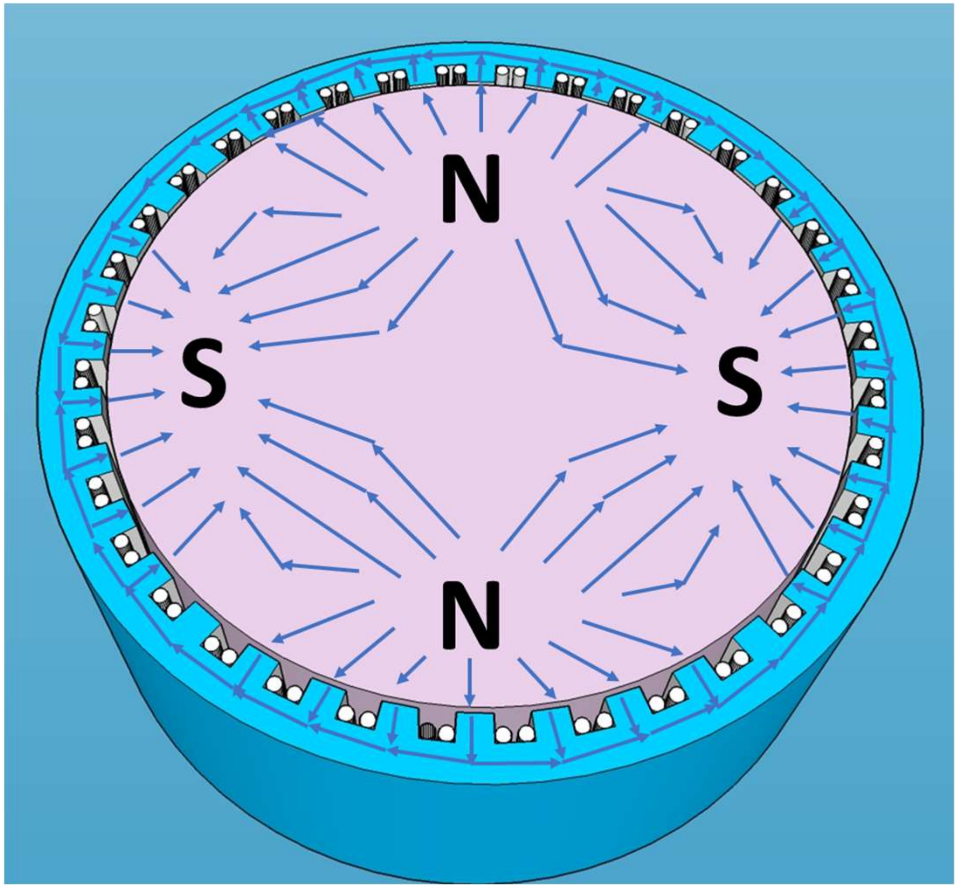
Noise mechanisms of electric motors

- There are many things that can be done at the design stage to make the motor quiet

- Our engineering partner, EOMYS, provides an in-depth webinar series on motor NVH design and analysis
  - https://eomys.com/e-nvh/webinaires/?lang=en
  - These webinars are very detailed and useful!

- The emphasis here is on understanding the basic mechanisms of motor NVH rather than motor design

Noise and vibration – basic mechanisms



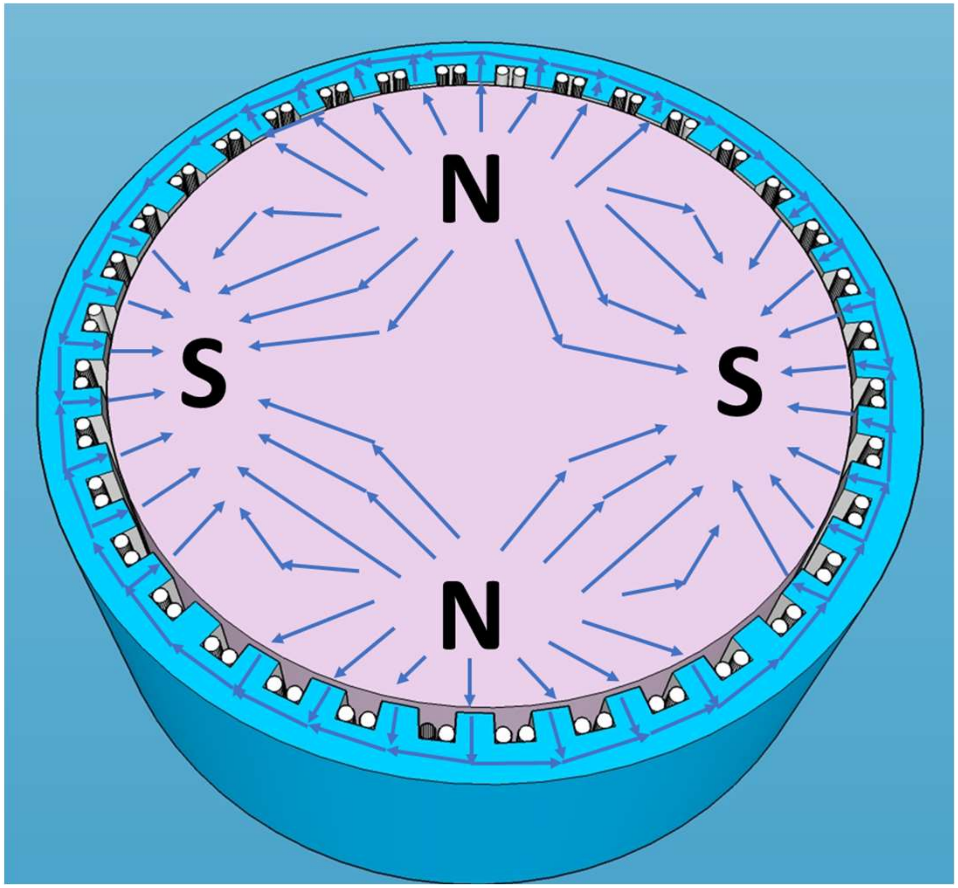
- Consider the simple synchronous motor. The rotor is a powerful magnet, the stator is iron, and they are separated by as small of a gap as possible
- Thus, huge radial forces (Maxwell forces) are exerted on the stator, and these forces move as the rotor moves
- The fundamental excitation frequency is:

$$f_{ex}(Hz) = \frac{pN}{60}$$

p is number of poles
N is the rpm

- Similarly, there are frequencies corresponding to the number of slots in the stator

Noise and vibration – basic mechanisms



- Similarly, the alternating tangential forces produce torque ripple
- There are harmonics and subharmonics that arise from normal operation and also quality issues
- Inverter switching noise

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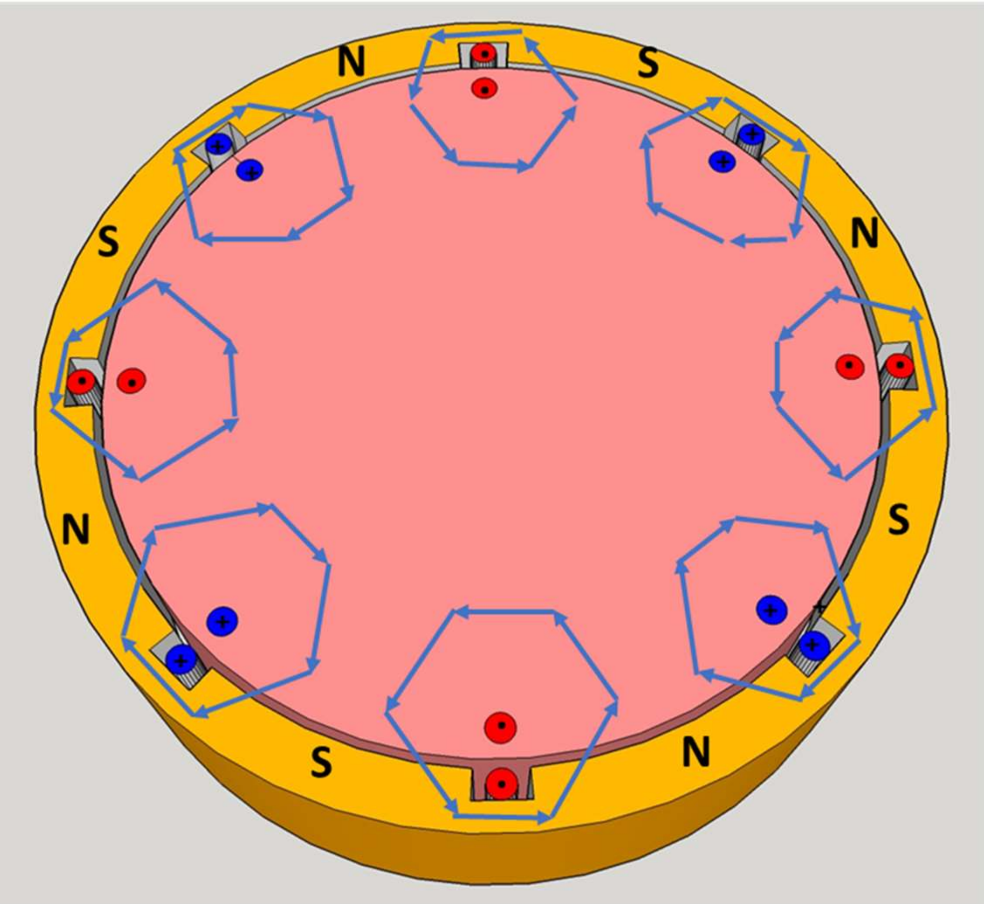
Noise and vibration – basic mechanisms – cont.



- **Induction motors** have induced poles which move at the speed of rotor, but there are also alternating forces at the frequency that is applied to the motor – **two sets of frequencies**

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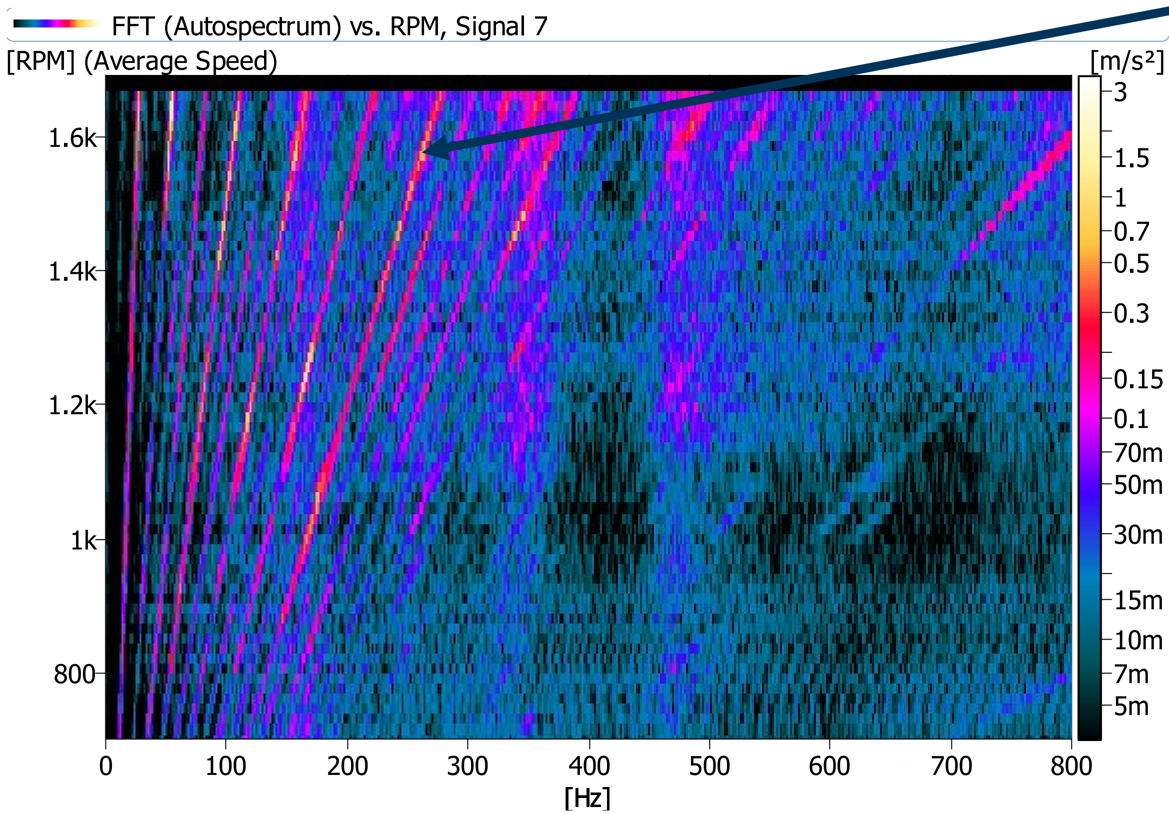
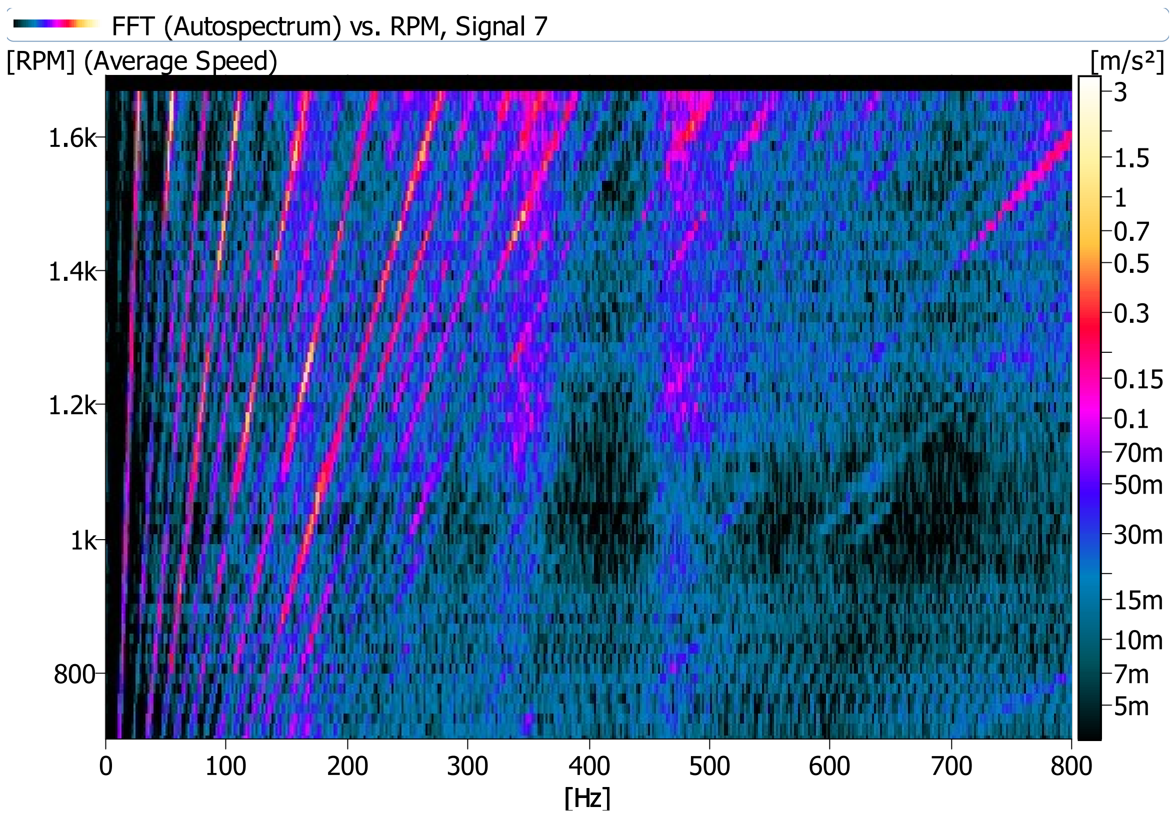
Noise and vibration – basic mechanisms – cont.



- For this synchronous motor, expect strong vibration 10th order (ten poles)
- Even **for perfectly made motors** noise is produced by any alternating force of the motor
  - Maxwell forces as discussed above
  - Discontinuity in moving from slot to slot
  - Discontinuity in moving from one magnet to magnet
  - Discontinuity in the electrical excitation

Noise and vibration – basic mechanisms – cont.



- **For non-perfect motors**:
  - Current amplitude unbalance
  - Demagnetization
  - Stator ovality
  - Pole misplacement
  - Parallel static eccentricity
  - Parallel dynamic eccentricity
- These imperfections are present in all motors, but are particularly obvious in low-cost applications (every motor sounds different)

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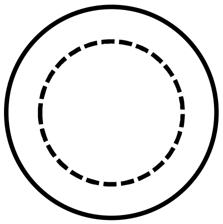
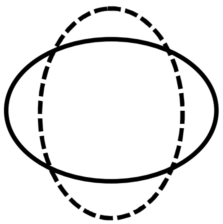
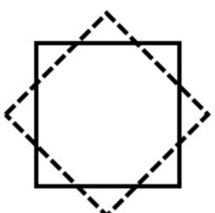
Noise and vibration – basic mechanisms – cont.


Breathing Mode


First Cylindrical Bending Mode

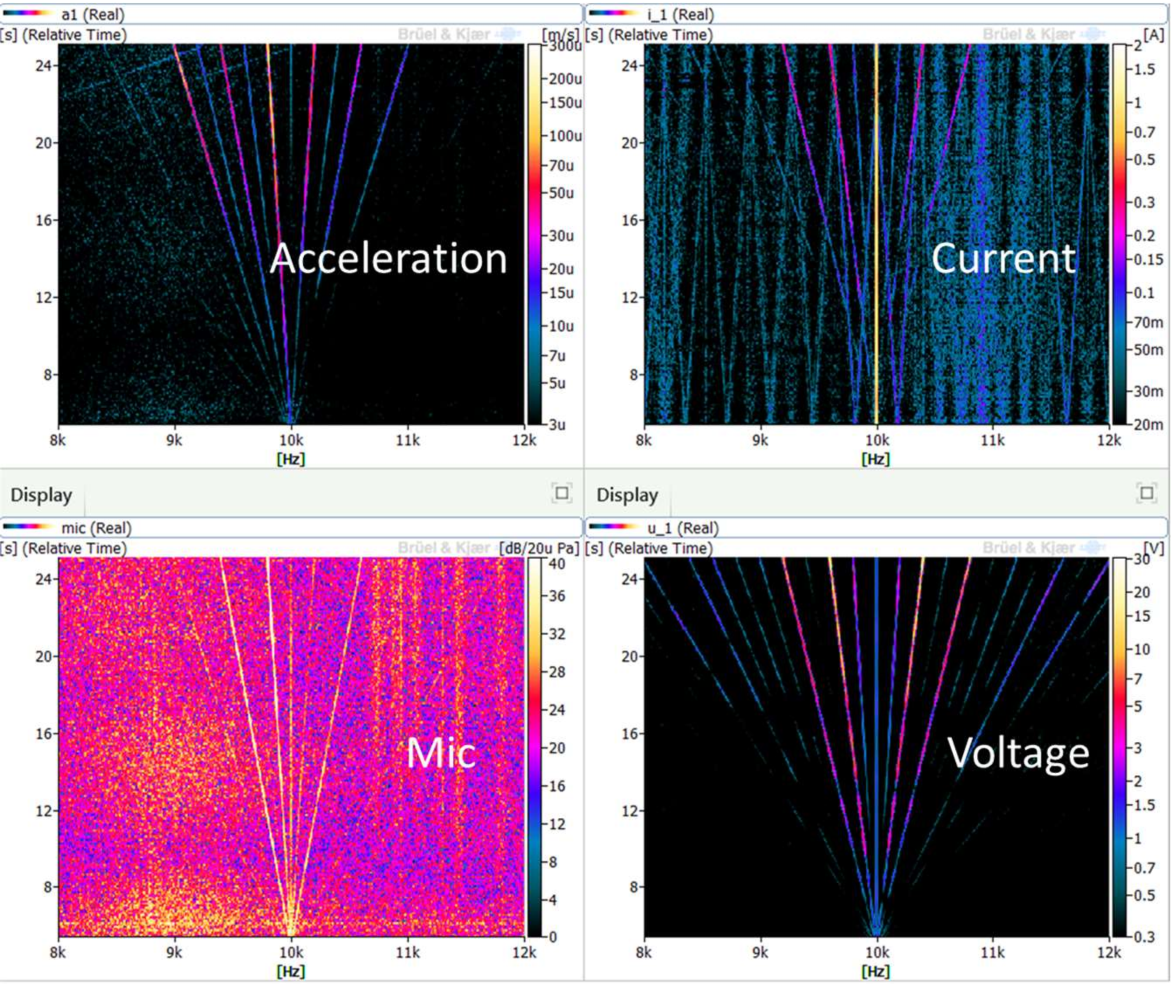

Second Cylindrical Bending Mode


Third Cylindrical Bending Mode, etc.

- The stator is approximately a cylindrical shell that has natural frequencies
- These are excited by the radial forces
- Degree of excitation depends on participation factor (spatial and temporal matching of force and mode shape)
- Generally requires software (such as EOMYS Manatee) to determine the level of excitation
- Best designs preferentially excite higher modes, have more poles, have many slots, and are multi-phase
- Skewing and pole shaping to smooth excitation from on to off – analogous to using helical gears rather than spur gears

M.S. Islam, R. Islam, and T. Sebastian, “Noise and Vibration Characteristics of Permanent-Magnetic Synchronous Motors Using Electromagnetic and Structural Analysis”, IEE Transactions on Industry Applications, Vol. 50, No. 5, Sept./Oct. 2014 is a very good reference on basic noise mechanisms

Noise and vibration – basic mechanisms – cont.



- The PWM also produces high frequency switching noise which can be efficiently radiated by the stator or invertor housing
- Simultaneous acquisition of N&V signals and high voltage motor excitation signals is useful to understanding response
- HBM Genesis system has capability
  - High sample rate
  - High voltage
  - High current
  - CCLD (ICP) inputs for accels and mics
- Data from the Genesis system can be imported into BKConnect NVH software
  - Colormaps
  - Operating deflection shapes
  - Sound Quality analysis

Noise and vibration – basic mechanisms – cont.

- For the non-motor designer, measurement provides insight into many issues:
  - What are the orders and what does this tell us about the issue? (Combine with predictive models)
  - How is the inverter really working and can this be made better? How does this contribute to NVH issues? (Genesis and HBConnect)
  - As a “black box” how can the motor be better integrated into the product?
  - Are the source levels competitive?
  - Where is the noise being radiated from, and how can this be treated? (Acoustic camera and/or operating deflection shape)
  - Is the motor design NVH robust, or is there a wide unit-to-unit variation?

Why Electric Vehicles Are More Than Electrically Powered ICE Vehicles

Fewer/quieter moving parts

ICE Vehicle

Powertrain Other
- Intake
- Exhaust
- Turbocharger
- Throttle
- Fuel Injectors
- PCV
- EGR
- Evaporative Emissions
- Oil Pump
- Idle Air Bypass
- Fuel Supply
- Power Steering
- Brake Boost
- Alternator
- Cooling Pump and Fan
- AC Compressor and Fans
- Complex Automatic Transmission

Powertrain
- Pistons
- Rods
- Crankshaft
- Valvetrain

Chassis
- Doors and Power Locks
- Window Adjustors
- Seat Adjuster
- WS Wipers
- Brakes
- Parking Brake
- Power Steering
- Switches
- Fuel Tank
- Sound System
- Pedals

Electric Vehicle

Powertrain
- Motor Rotor

Powertrain Other
- Oil Pump
- Electric Power Steering
- Brake Boost
- Cooling Pumps and Fans
- Simplified Automatic Transmission
- AC Compressor
- Invertor/Charger/Controller

Chassis
- Doors and Power Locks
- Window Adjustors
- Seat Adjuster
- WS Wipers
- Brakes
- Parking Brake
- Power Steering
- Switches
- Sound System
- Pedals
- Battery

No good place to mount accessories

- ICE accessories are mounted to the engine
  - Oil pump
  - Water pump
  - Power steering pump
  - Alternator
  - AC compressor
  - Vacuum

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No low-frequency masking noise

- More awareness of wind/road noise
- Hear everything at a standstill
- More awareness of transmission/gear noise
- Powerplant sound is high-frequency whine

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Motor mounting issues

- High torque
  - Inherent to electric motors
  - Transverse mounting
- Compact size/lower weight – higher rigid body natural frequencies
- Emphasis on high-frequency isolation

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Battery

- Battery is part of new EV chassis
- Unknown if weight of battery will be effectively used to reduces road noise

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Thank You

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Questions?

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- You can open the Q&A window by selecting the “Q&A” icon in the WebEx toolbar at the top of your screen:

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