Experience with Hydro Generator Stator Noise due to Air Gap Harmonic Forcing

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Introduction

Problem:

- *Nice, new, continuously stacked Stator*
- *New coils & winding configuration*
- *Often, higher power output*

- ***And it screams like a Banshee!***

What Happened?

Slot passing frequency harmonics

- *Inherent to fractional slot windings*
- *Not always audible*
- *Frequencies at multiples of 2x synchronous speed*
  - *Typically 8x, 10x, 12x, 14x*
- *Not just annoying – often require **full-time hearing protection***
  - *Author encountered <u>117 dB</u> in generator barrel (between "rock band" and "Police siren" on the charts!)*

Second problem – 2x line frequency pulsations

- *Same scenario – new core/winding*
- *Also inherent to fractional slot windings*
- *Not always audible*
- *Result of multiple waves at 2x line frequency*
  - *Recent case > 107 dB in generator vicinity*

Some History

OEM Generator Construction

- Stators factory built – 3 or 4 pieces
- Shipped to site wound
- Final connections in field
- Frame joined – stator iron not
- Machines often 40 – 80 years old (or more!)

Today

Pressures and Opportunities

- **Power needs increasing steadily**

BUT…

- **Coil Insulation Improved**
    - **More copper in slot**
    - **Higher temperatures allowed**
- **CFD improves turbine efficiencies**

RESULT – <u>UPRATES!</u>

Uprate Characteristics

Some or all of these:

- Changes to # of Stator Slots
- Multi-turn > Single turn Roebel
- Segmented > Continuous Stator Core

And definitely these:

- Higher Field Current & Flux
- More Torque

Ok… So where's the problem?

(warning – math ahead)

Fractional Slot Windings

$$\frac{\#\ of\ Stator\ Slots}{\#\ of\ Poles} = (not\ a\ whole\ number)$$

So what happens? (Examples easiest)

$$\frac{360\ slots}{56\ poles} = \frac{45\ slots}{7\ poles}$$

Pattern of 45 slots repeats over 7 poles ($6\ ^3/_7$ slots/pole)

Fractional Slot Windings

Slot passing (high frequency) harmonics:

$$\frac{360\ slots}{56\ poles} = \frac{45\ slots}{7\ poles} = 6\frac{3}{7}$$

Fraction – 3/7 < 1/2 so 6th harmonic predominates:

$$6 \times 2 \times 60\ Hz = 720\ Hz$$

Fraction x no. of poles = waves:

$$\frac{3}{7} \times 56 = 24\ waves$$

Fractional Slot Windings

Electrical (2x Line Frequency) Pulsations:

$$\frac{360\ slots}{56\ poles} = \frac{45\ slots}{7\ poles}$$

$$\frac{\#\ of\ poles}{poles\ in\ repeating\ pattern} = \frac{56}{7} = 8\ waves$$

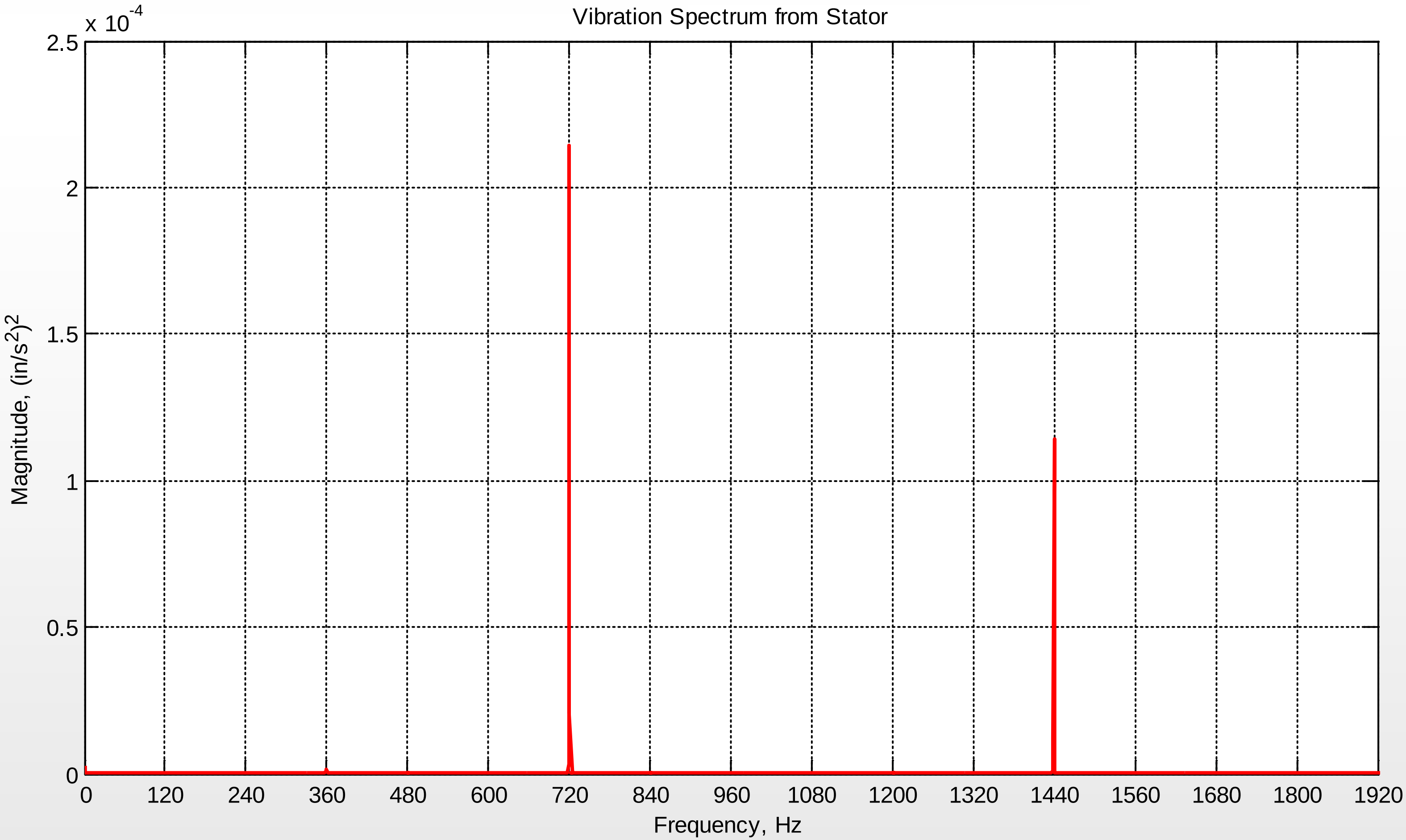
Both this <u>and</u> the 720 Hz AND a smaller 840 Hz wave exist

Slot Frequency Noise

But here's what we heard:

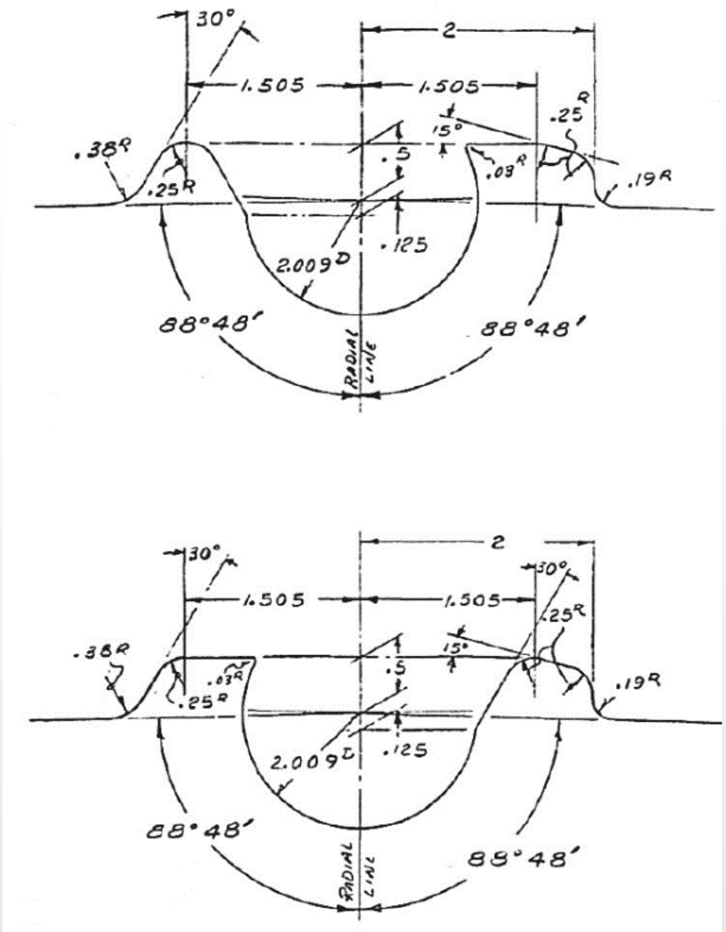
This is machine "B" in the paper.

Vibration (Sound) Spectrum



Stator Construction

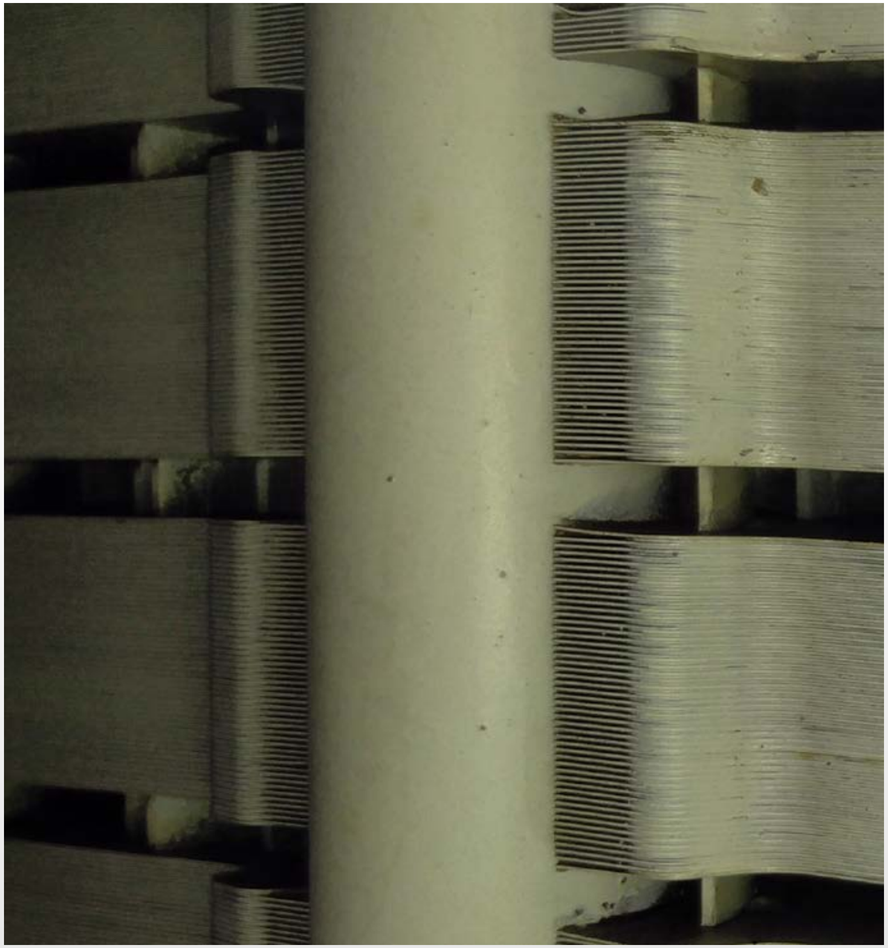
Lamination – Building Bolt Clearance



- Socket diameter – 2.009 in.
- Min. throat opening – 1.979 in.
- Building Bolt diameter – min 1.970"

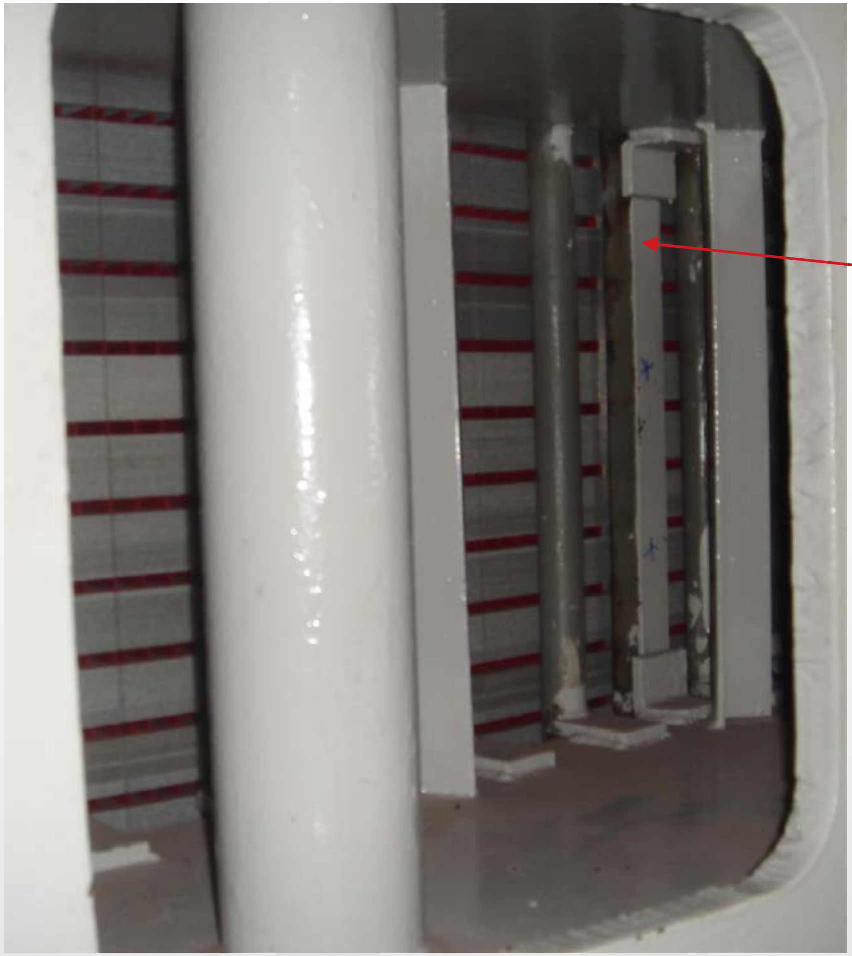
Each lamination can only make point contact with the building bolt.

Building Bolt Contact



- Contact with building bolt is at best a point contact.
- Cannot prevent rotation of stator cross section.

Building Bolt & Frame Influence

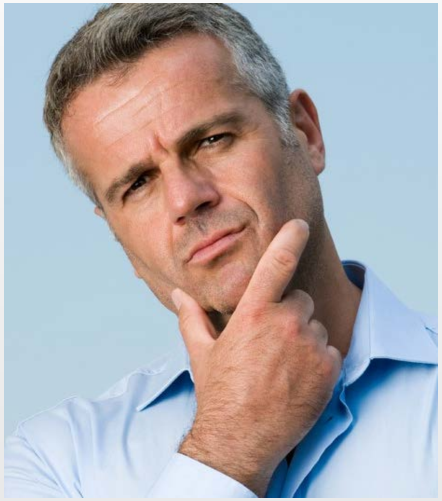


- Building Bolts or Keybars welded to frame rings
- Relatively soft between frame rings
- Do little to restrain core radial movement between Frame rings.

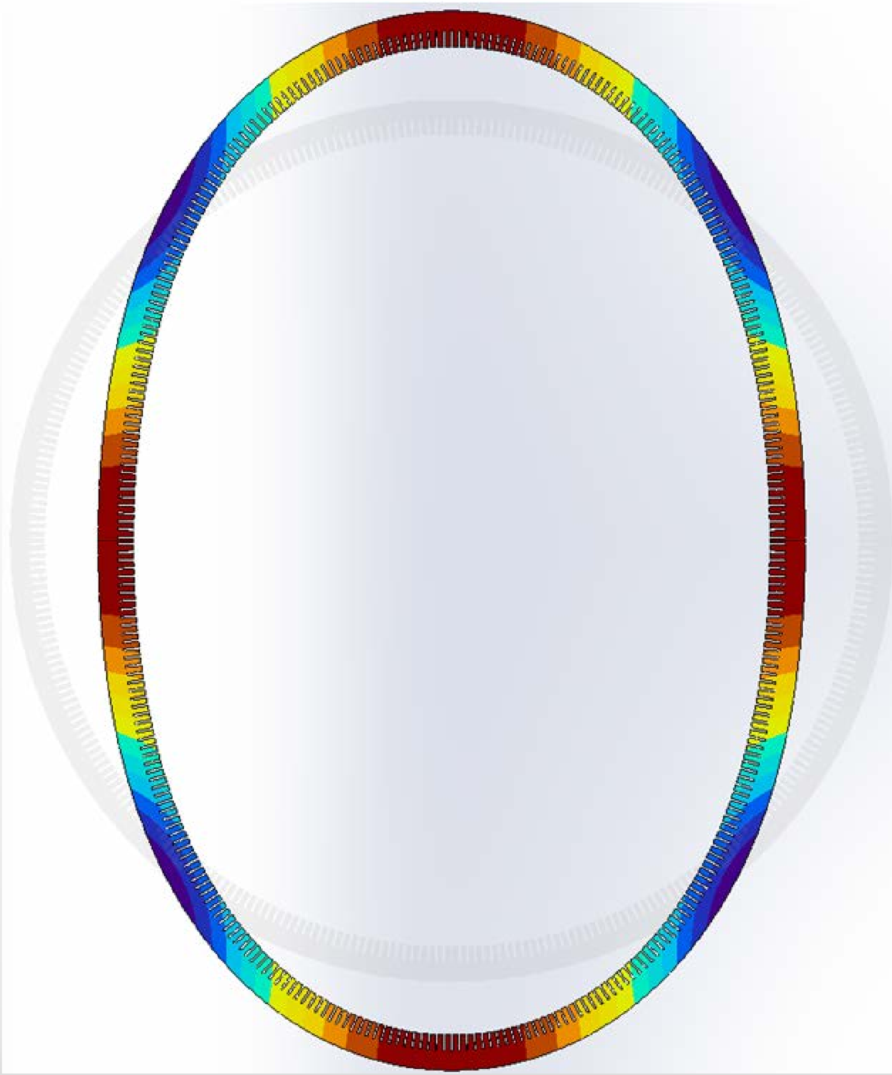
Natural Frequency of Core Iron

- ODS Tests clearly showed 24 waves at 720 Hz
- Resonance was painfully obvious
- "Thin Ring" Natural Frequency Calculation of core iron *alone*:

n = 24 at *880 Hz*



Stator Cores are DEFINITELY “Thin Rings”



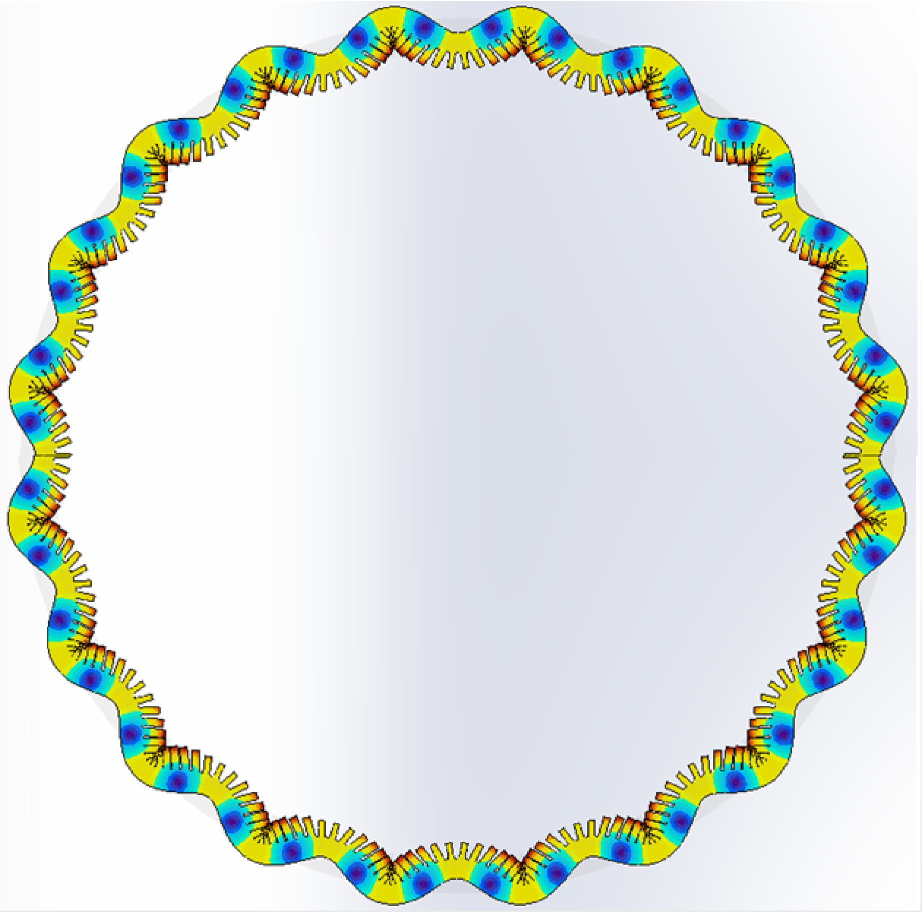
$$\frac{Mean\ Radius}{Back\ Iron} = 22.1$$

“Thin ring” vibration calculation first published by R. Hoppe, 1888

$$\omega_n = \frac{n(n^2-1)}{\sqrt{n^2+1}}\sqrt{\frac{EI}{\rho A R^4}}$$

Calculates two wave (n=2) at 5.81 Hz
FEA model at right - 5.56 Hz

Except when they aren't!



"Thin ring" vibration calculation first published by R. Hoppe, 1888

$$\omega_n = \frac{n(n^2-1)}{\sqrt{n^2+1}}\sqrt{\frac{EI}{\rho A R^4}}$$

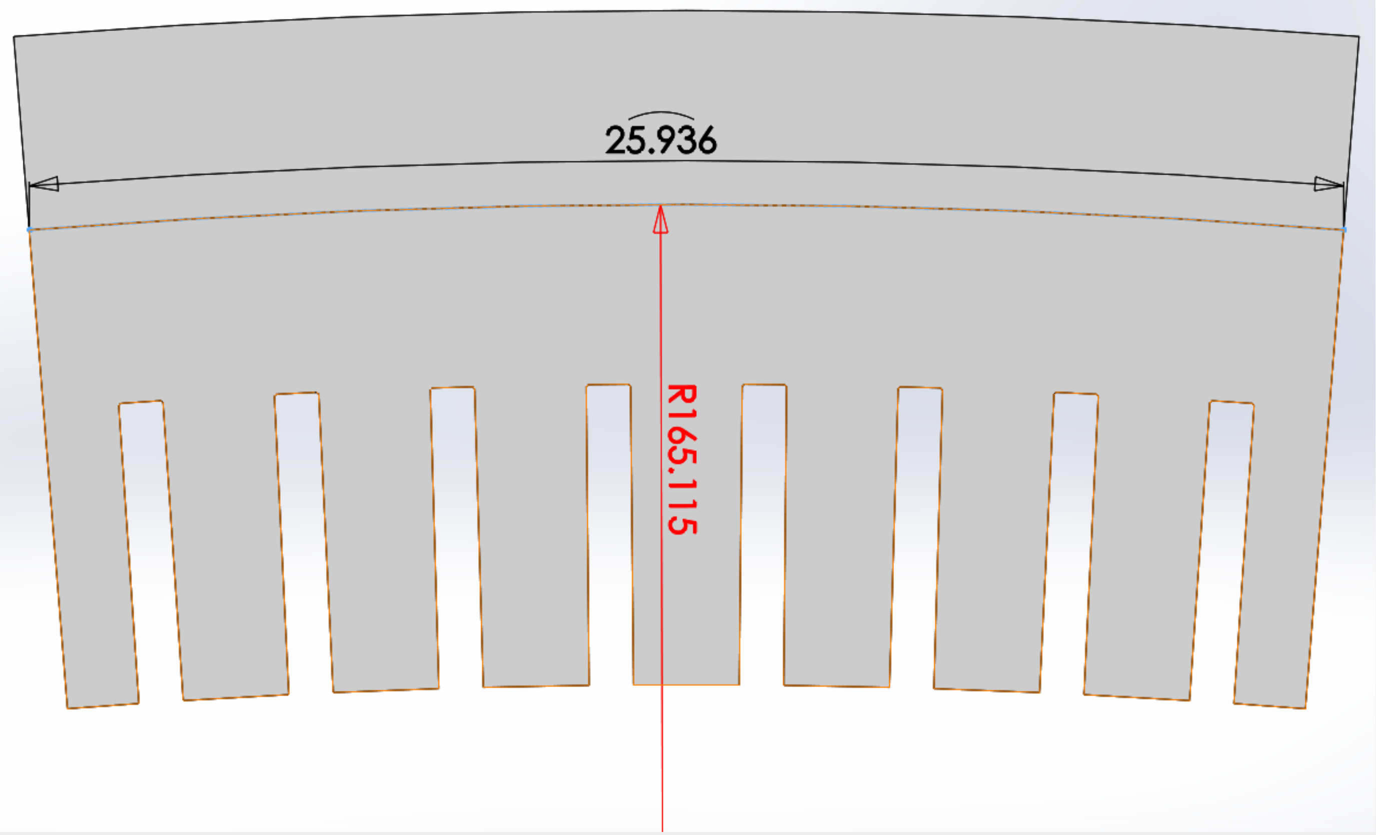
Calculates twenty wave (n=20) at 863 Hz
FEA model at right – **667 Hz**

n = 2 $\frac{5.81\ Hz}{5.56\ Hz} = \mathbf{1.044}$

n = 20 $\frac{863\ Hz}{667\ Hz} = \mathbf{1.294}$

Mass/stiffness ratio difference - 1.64!

Except when they aren't!



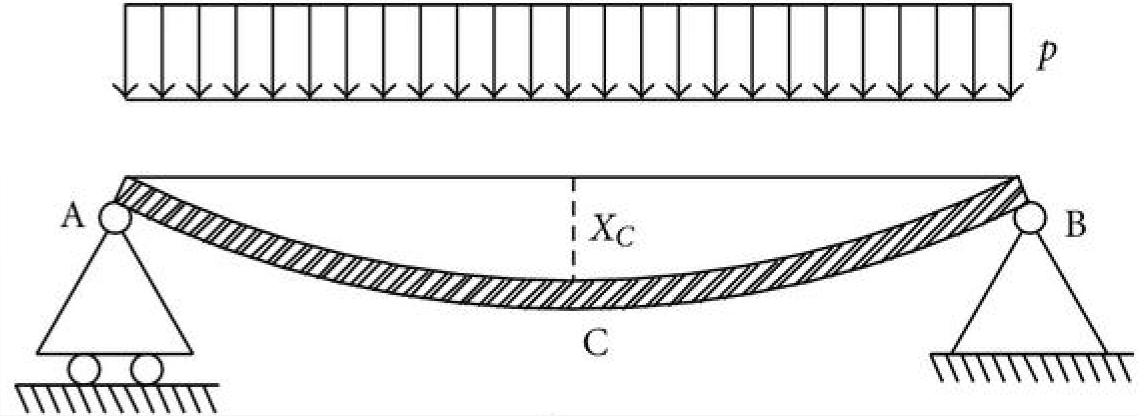
This is one half-wavelength of the stator for the twenty wave mode

Euler "slender beam" theory L/D > 10

L/D here is 3.47

Variances from “Thin Ring” formulation

Consider ½ wavelength of stator bending as simply supported beam:



- Wavelength too short
  - Shear deflection
  - Mass rotational inertia
  - Offset mass and inertia of teeth
  - Extension/compression of neutral axis

Timoshenko Beam Formulation

Timoshenko formulation vs. Hoppe "Thin Ring"

$$\omega_n = \frac{n(n^2-1)}{\sqrt{n^2+1}}\sqrt{\frac{EI}{\rho A R^4}}$$

$$\omega_n = n^2\sqrt{\frac{EI}{\rho A R^4}}\left[1-\frac{n^2}{2}\frac{I}{AR^2}\left(1+\frac{E}{k'G}\right)\right]$$

And it got us closer, but…

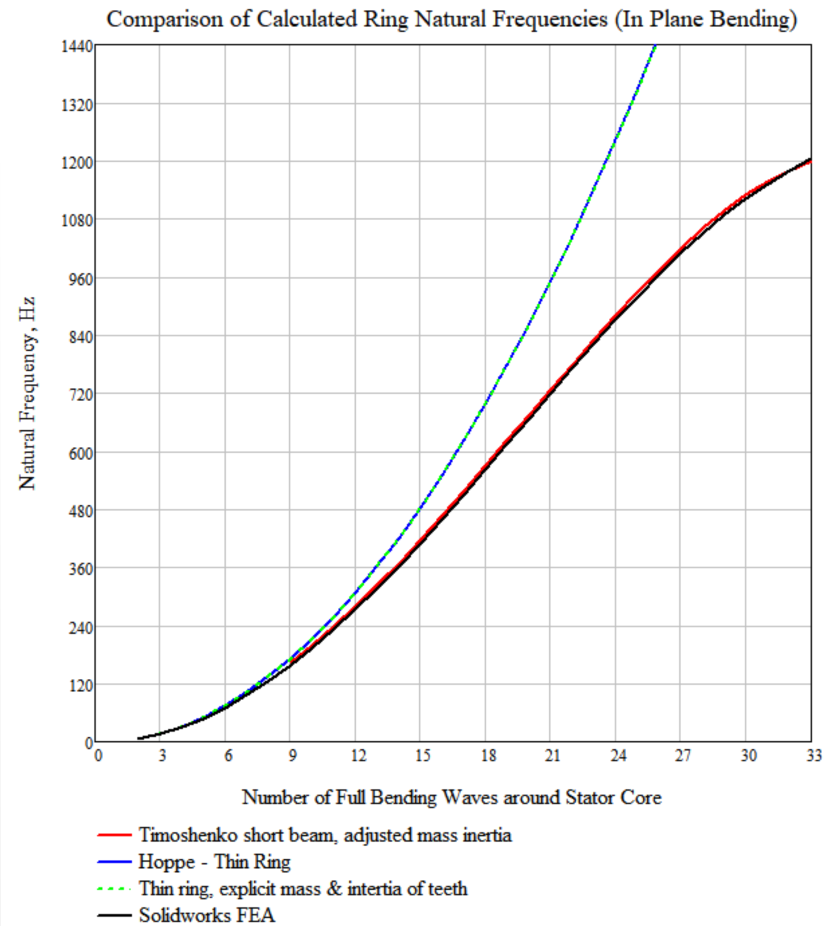
Timoshenko Beam Formulation - modified

- Timoshenko formulation – uniform cross section
- Actual – slots cause offset center of mass/inertia
- Nodal positions move closer to neutral axis as wavelength decreases

EME Modification:

$$\omega_n = n^2 \sqrt{\frac{EI}{\rho A R^4}} \left[1 - \frac{n^2}{2} \frac{I}{AR^2} \left(\frac{\mathbf{56}}{\boldsymbol{n}} + \frac{E}{k'G} \right) \right]$$

Comparison of Results



- Close correspondence to FEA
- Close correspondence to known resonance cases
- Physically defensible if not mathematically rigorous
- Investigation continuing

Thank you for your time and attention!

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