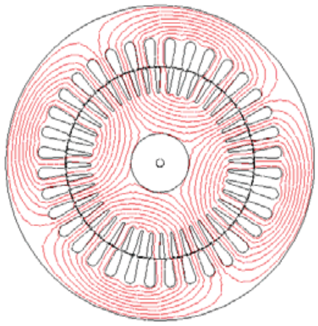
Motor Vibration/Noise Simulation Analysis and Its Features

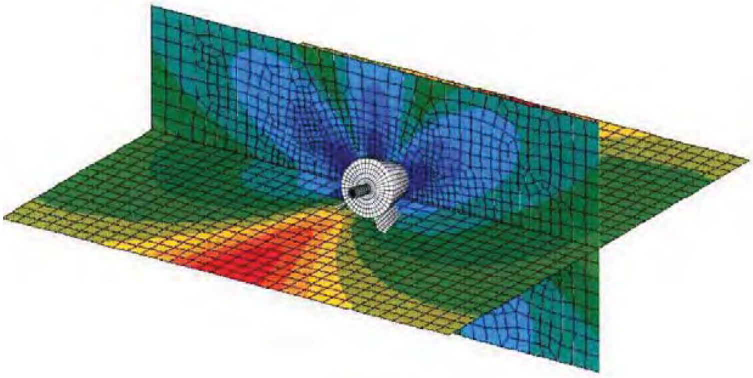
Noda Shinichi
Toshiba Corporation

Abstract :
Recently, the demand of resolving noise issues is increasing as a result of growing concern about environmental problems. Meanwhile, as electric vehicles are becoming more popular, noise reduction on electric motors which are the major noise source of various electrical equipments such as electrical home appliances and medical equipment, have become a necessity.
Countermeasures for motor vibration and noise including (1) electromagnetic force acting as the excitation force, (2) motor structures of transmission systems, and (3) vibration transferred to other mechanical equipment are necessary. In other words, reduction of motor noise requires sufficient understanding of mechanism causing the noise and the structure transferring the vibration.
The electromagnetic force mode of electromagnetic noise and its frequency are described in simple terms. The structural characteristics of motors, specifically the measurement of mechanical natural frequencies and finite element simulations that are applicable in actual analysis work, will be explained.

"Motor Noise/Vibration Simulation Analysis and Its Features" Part 1

JMAG Users Conference 2010





Contents

Objectives

・ Considerations related to **noise** are in strong demand as awareness of environmental problems increases.

・ The never ending challenges of motors are (1)higher efficiency, (2)miniaturization, (and 3) reducing noise.

・General measures to reduce noise are especially difficult.

・Countermeasures for vibrations and noise of motors including **(1)electromagnetic force which is excitation force, (2) the motor structures of transmission systems, (3) vibration transferred to other mechanical equipment** are necessary.

・ The reduction of motor noise requires sufficient understanding of the mechanism causing the noise source and the structure transferring the noise.

・The **electromagnetic mode** of electromagnetic noise and its frequency as well as the mechanical **natural frequency mode** needs to be explained to effective utilize actual analyses.

・The logic for modeling in **simulation analysis** is also required.

Background

Increased electromagnetic noise with miniaturization

⇩

A design preventing resonance is necessary at the design stage so that frequencies of electromagnetic force as well as egienfrequencies and resonant phenomena of the stator core are not produced to **reduce noise**.

⇩

(1) Frequency and electromagnetic mode the electromagnetic force is produced
(2) The eigenfrquency and eigenmode of the stator core

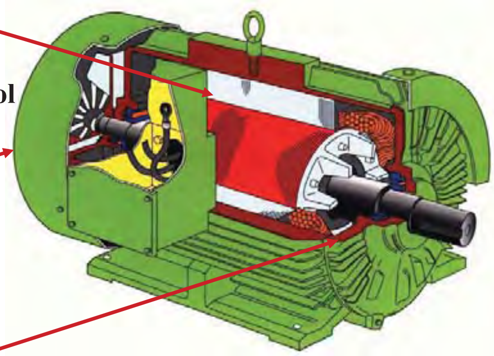
An accurate prognostic simulation is vital

Types of Motor Noise

3 main types of noise

Noise

- **Electromagnetic noise**
  - ・Magnetic noise
  - ・2fVibration noise
  - ・Noise caused by cogging
  - ・Noise caused by the type of control
- **Ventilation noise**
  - ・Rotation noise
  - ・Vortex noise
- **Mechanical noise**
  - ・Bearing noise
  - ・Unbalanced vibration

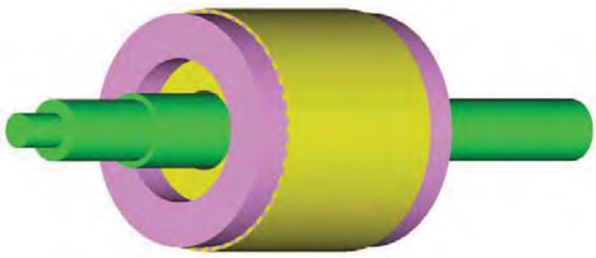


Induction motor

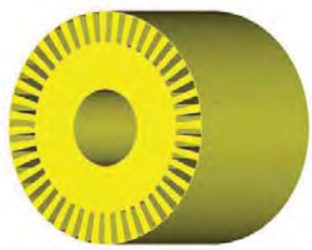
Rotor Structure of a Cage Type Induction Motor

Analysis Model

Shaft (soft steel)

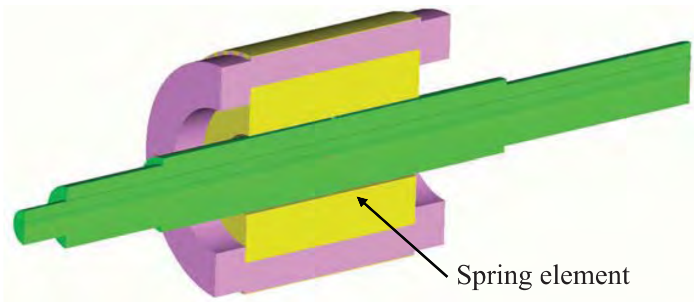


Entire analysis model



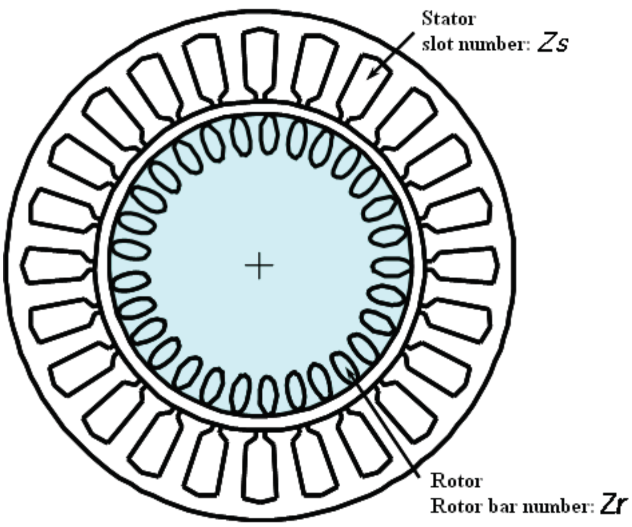
Rotor core

(0.5 mm laminated steel sheet)

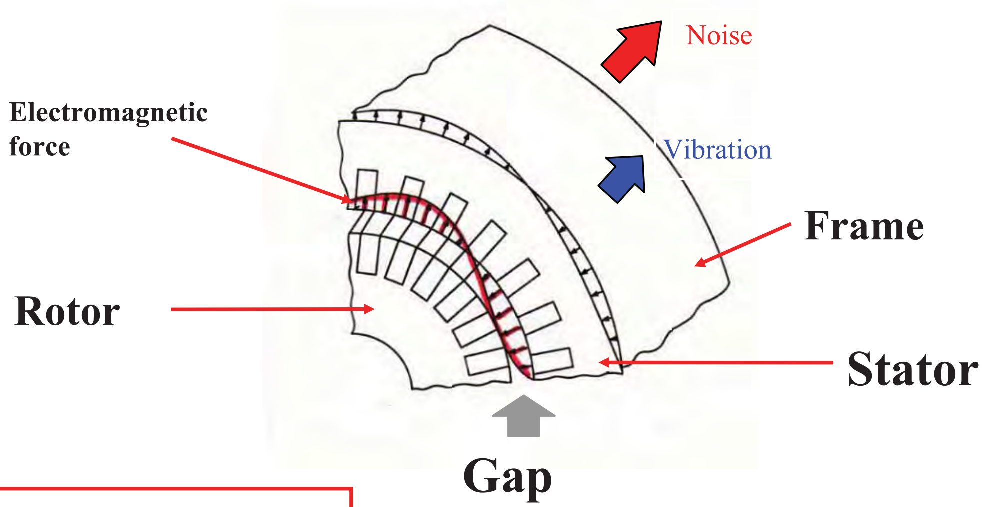


Rotor bar end rings (aluminum)

Motor Structure



Mechanism of Electromagnetic Noise



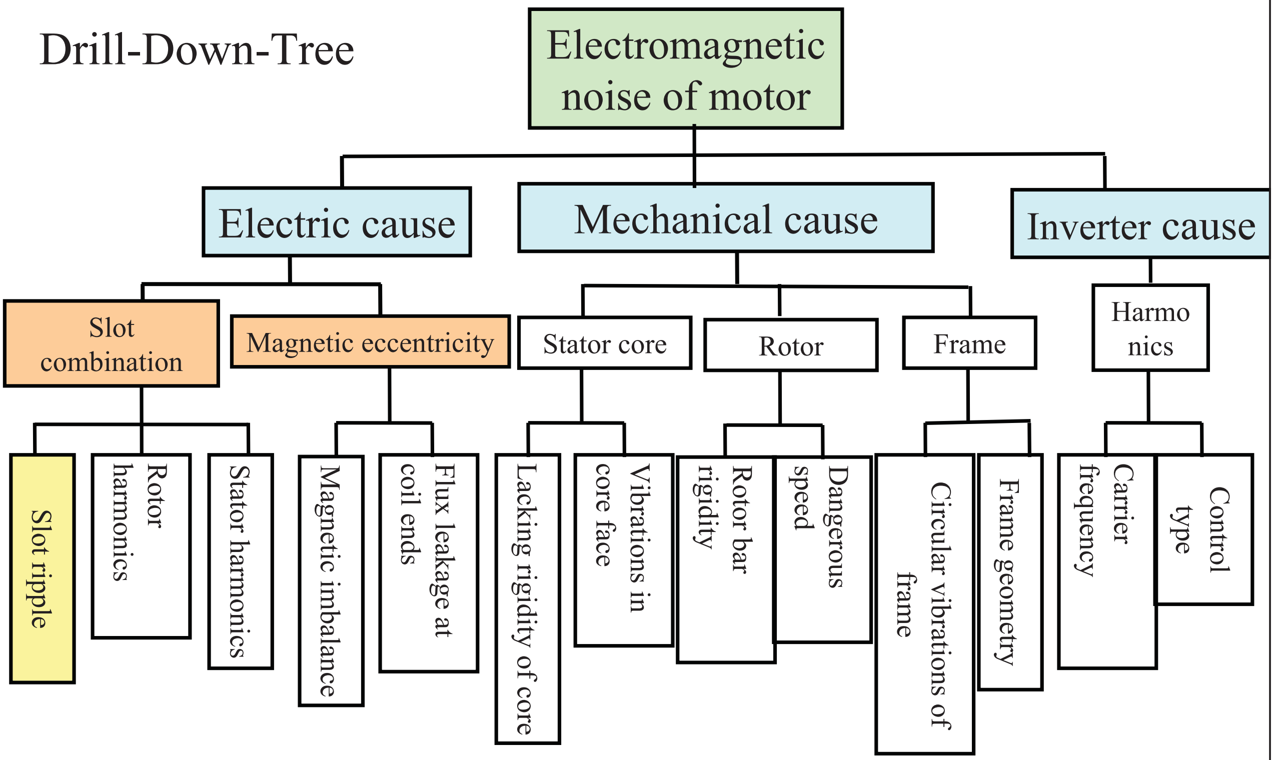
Electromagnetic force acting on gap

Natural frequency of stator

⇨ Resonance ⇨ Noise increases from frame

Main Causes of Electromagnetic Noise in Motors

Drill-Down-Tree



Challenges of Noise/Vibration Simulations

Stator core

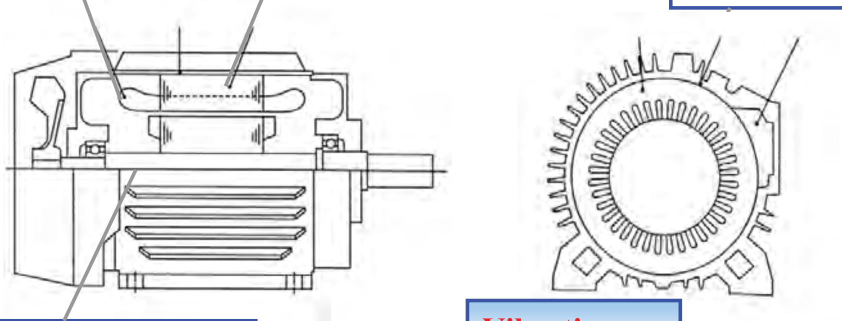
- **Teeth/slot windings**
- **Effects of wires**

Frame and core

- **Deformation of press-fitting**
- **Contacting areas**

Joints

- **Fixed spring constant**
- **Vibration attenuation characteristics**



Electromagnetic force

- **Frequency and mode**
- **Intensity of electromagnetic force**

Vibration response

- **Eigen mode and electromagnetic force mode**
- **Vibration mode during drive**

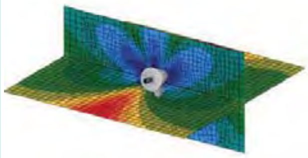
Analysis Method of Electromagnetic Noise for Motors

Natural frequency

- Stator core
- Coil ends
- Frame
- Joint conditions

Electromagnetic excitation force

Coupled electromagnetic and structural analysis → Vibration response analysis → Frame vibration → Noise analysis



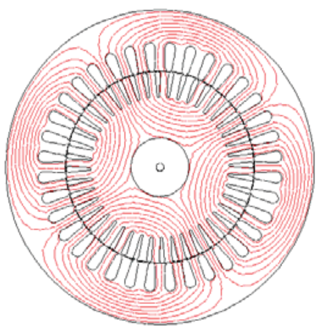
Finite element analysis

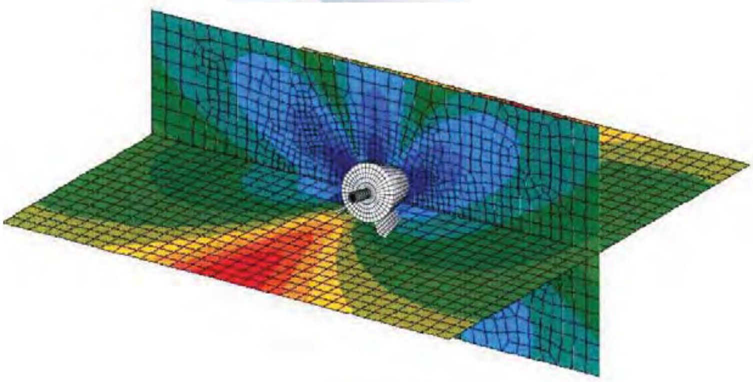
- ⇦ Magnetic flux analysis
- ⇦ Eigenvalue analysis
- ⇦ Contact analysis
- ⇦ Time step response
- ⇦ Electromagnetic vibration
- ⇦ Noise analysis

A series of analyses are necessary

"Motor Noise/Vibration Simulation Analysis and Its Features" Part 2

JMAG Users Conference 2010





Contents

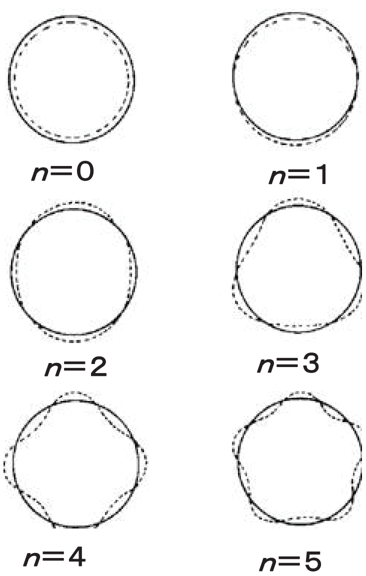
◇Natural frequency and Eigenmode

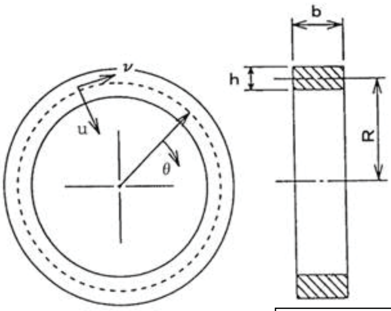
1. Stator core
2. Longitudinal Elastic Modulus of Electromagnetic Steel Sheet
3. Stator Core with the Winding in Slot
4. Stator Core with Coil Ends
5. Press-fit Frame and Stator

Natural frequency of Stator Core

Obtain the effects from the simple theoretical equation for natural frequency

$$f_{n\geq 2} = \frac{1}{2\pi}\frac{n(n^2-1)}{\sqrt{(n^2+1)}}\sqrt{\frac{E\ I}{A\ \rho\ R_C^4\ \Delta}}$$





$$\Delta = 1 + \frac{G_Z + G_W + G_B}{G_J}$$

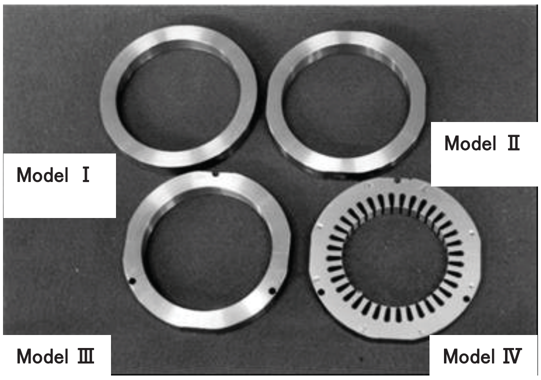
R_O
ρ

R_S Δ

:Outer radius of core; :Inner radius of core excluding slots; :Density of stator core material; :Effective mass loading coefficient for displacement;
G_Z:Total mass of teeth; G_W:Total mass of coils;
G_B :Total mass of insulation;
G_J:Mass of yoke for circular stator core

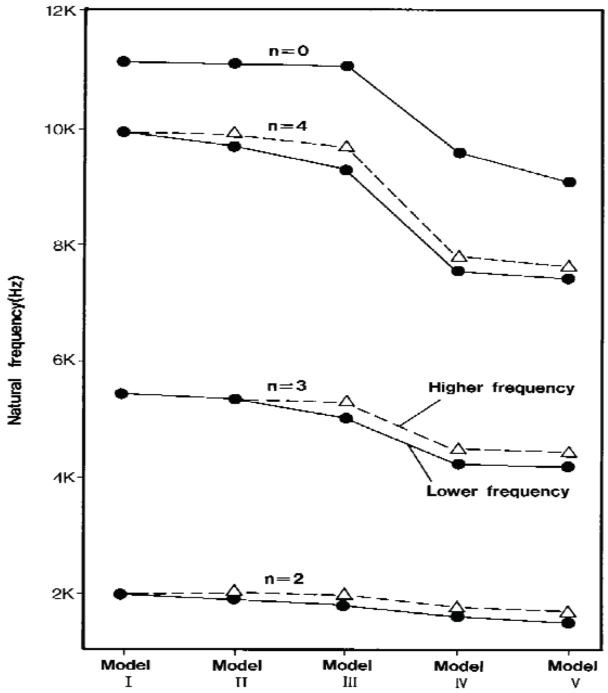
Results Measuring the Natural Frequency of Each Model

The effects of teeth are larger at higher modes



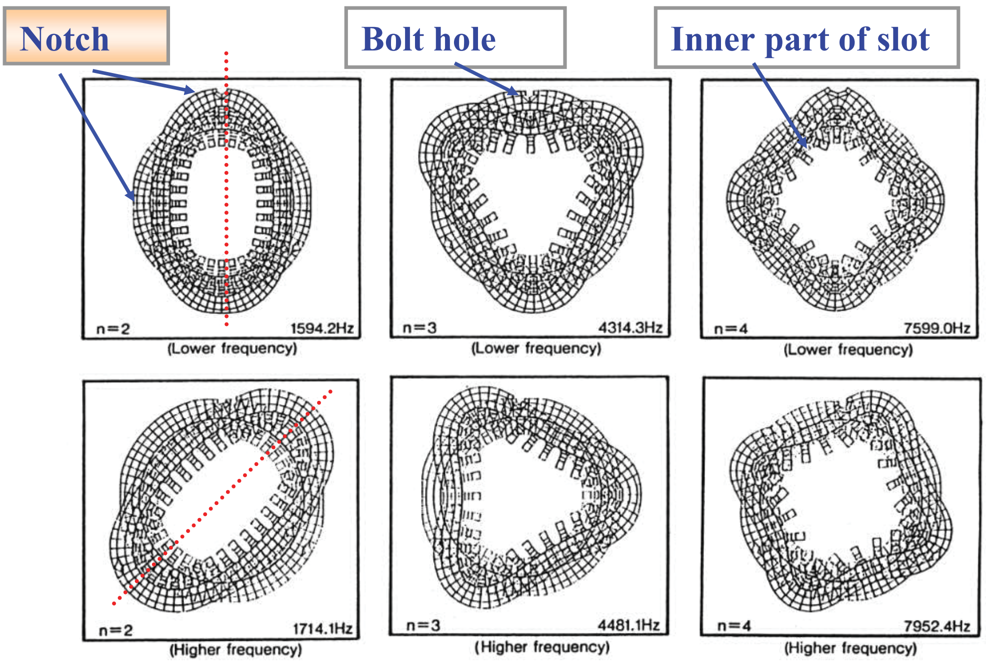
Model Ⅴ

Stator core with coil in only the core slots



Natural frequency mode of stator core

Notches on four sides deforms with double the natural frequency



Improve analysis accuracy

- **Notch**
- **Bolt hole**
- **Fewer slots**

Natural frequency mode of stator core

Analysis error is within 2% up to higher order natural frequencies

Mode Order *n*	Actual value (Hz)	Analysis Model	
		Calculated value (Hz)	Error (%)
2	1574	1594.2	+1.3
2	1714	1714.1	0
3	4268	4314.3	+1.1
3	4488	4481.1	-0.1
4	7561	7599.0	-0.5
4	7848	7952.4	+1.3
0	9604	9575.0	-0.3

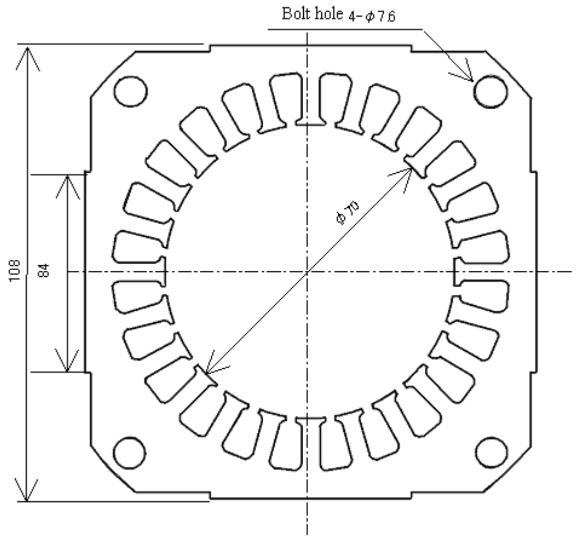
Contents

Stator Core Structure of an Electric Motor

IEEJ (K model) is used to be confirm with other models

Square shouldered exterior with 24-slots

4 bolt holes in each corner φ7．6



Specification of the Prototype

Item	Description
Number of phase, pole number	three-phase, tetrapolar
Supply voltage, frequency	100V, 50Hz
Stator, rotor exterior, stack length	108mm, 69. 4mm, 42mm
Stator, number of rotor slots	24, 34
Stator, magnetic steel rotor	50A1300

Natural Frequency Analysis using the Finite Element Method

Analysis Items: Parameter variables

(1) Elements:

1000 to 25000 elements varying by mesh density

(2) Element type:

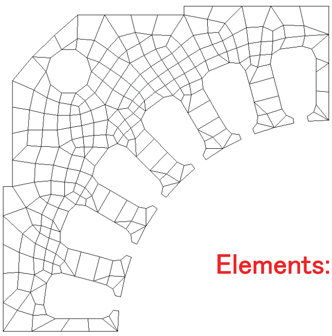
(a) Only rectangular elements
(b) Only triangular elements
(c) Rectangular + triangular elements
are each used for a calculation.

(3) Longitudinal elastic modulus of electromagnetic sheet steel:

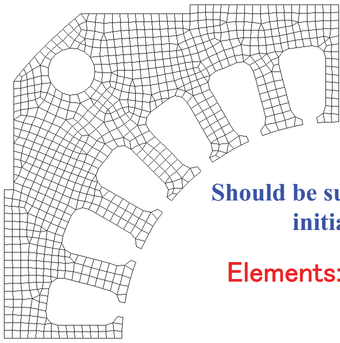
Calculated as a variable range of $E = 1.8 \sim 2.5 \times 10^{11}$ (Pa).

Analysis Accuracy using Finite Elements

The natural frequency is calculated with the elements as a parameter

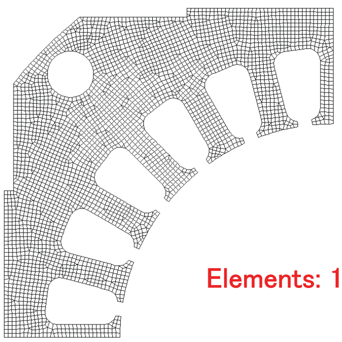


Elements: 1008



Should be sufficient at the initial sage

Elements: 3428

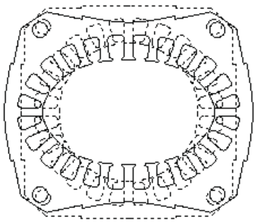


Elements: 13592

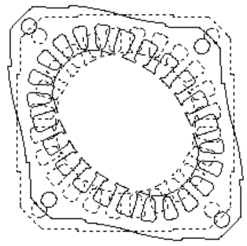
The number of elements is indicated for the entire model

Analysis Results of the Natural Frequency

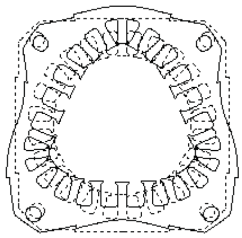
(Elements: 13592)



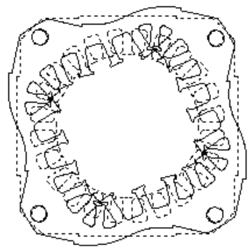
Ellipse mode:1471.2 Hz



Ellipse mode:2169.2Hz



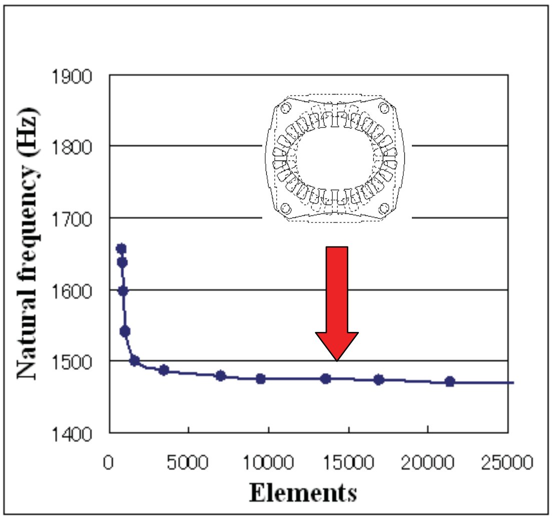
Triangular mode: 5109.4Hz



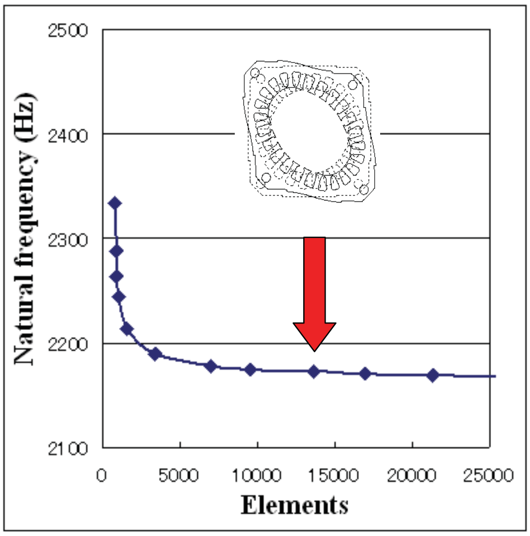
Rectangular mode: 8319.2Hz

Relationship of Elements and Natural Frequency

The natural frequency is mostly converged with 13000 elements and obtained **with less than 1% error in the calculation accuracy**.



Ellipse mode:1471.2 Hz



Ellipse mode:2169.2Hz

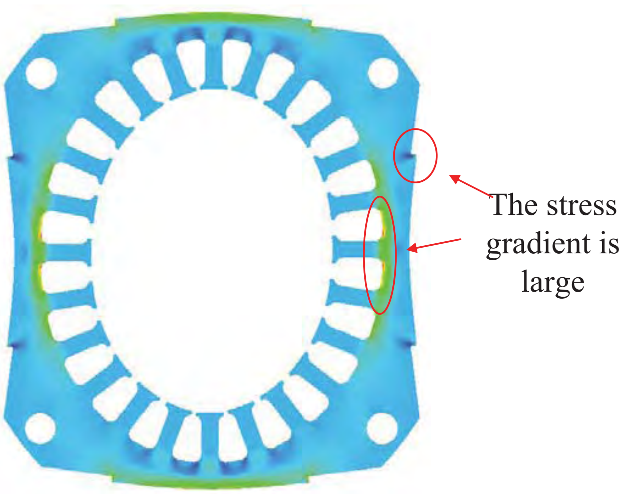
Analysis Accuracy of Natural Frequencies

Less than 1% error in calculation accuracy with 13592 elements.

Eigenmode Order		Eigenfrequency (13592) elements		
		Actual (Hz)	Analysis (Hz)	Error (%)
n=2	ellipse	1471	1471. 2	0
n=2	ellipse	2170	2169. 2	0
n=3	ellipse	5112	5109. 4	0. 05
n=4	ellipse	8380	8319. 2	0. 7

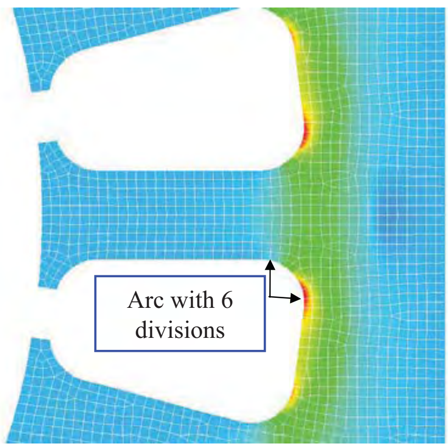
Determining the Number of Elements

6 divisions are necessary for the arc inside the slot the stress gradient is large.



Elements: 13592

Ellipse mode:1471.2 Hz



Arc with 6 or more divisions is desirable

Analysis Accuracy by Element Type

The error is within 1% regardless of the type of elements

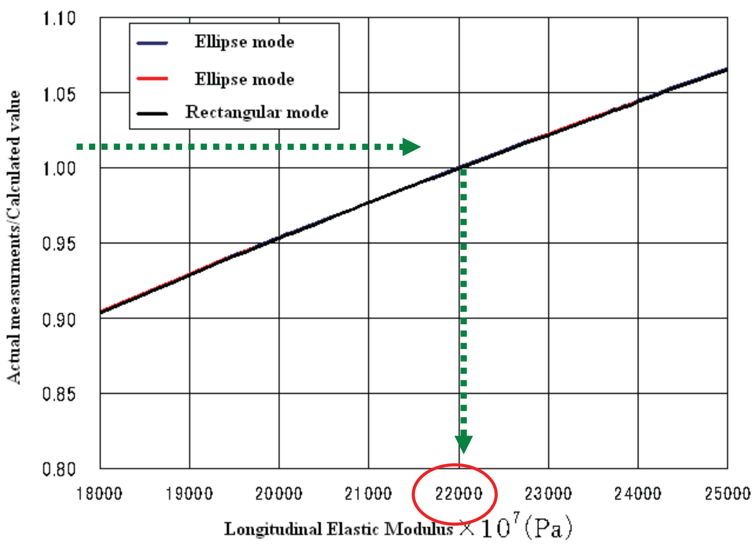
Select (triangular + rectangular) to achieve analysis accuracy with the minimal number of elements.

Frequency mode order	Actual values (Hz)	Only triangular elements Elements 20232	Error (%)	Only rectangular elements Elements 17896	Error (%)	Triangular + rectangular elements	Error (%)
n=2 Ellipse	1471	1475.9	0.3	1472.3	0.1	1471.2	0
n=2 Ellipse	2170	2168.6	0	2170.3	0	2169.2	0
n=3 Triangular	5112	5112.5	0	5112	0	5109.4	0.05
n=4 Rectangular	8380	8332.3	-0.6	8323	-0.7	8319.2	0.7

The combined type (triangular + rectangular) defines the geometry easily.

Longitudinal Elastic Modulus and Analysis Accuracy

The **constant longitudinal elastic modulus** of electromagnetic steel sheet 50A1300 is measured as $E=2.20\times10^{11}$ (Pa).



Longitudinal Elastic Modulus

Depending on the material, the component (silicon) and the crystalline structure as well as the longitudinal elastic modulus and density differ.

⇩

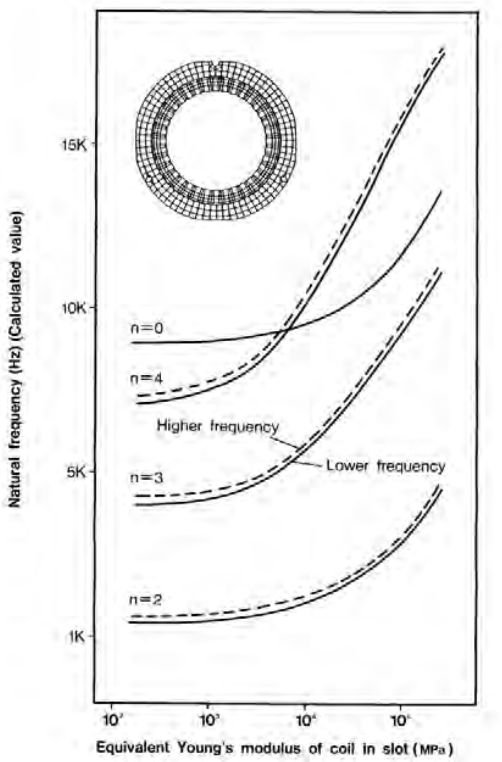
The analysis accuracy can be improved by clearly understanding the constant material longitudinal elastic modulus of electromagnetic steel sheet (50A1300).

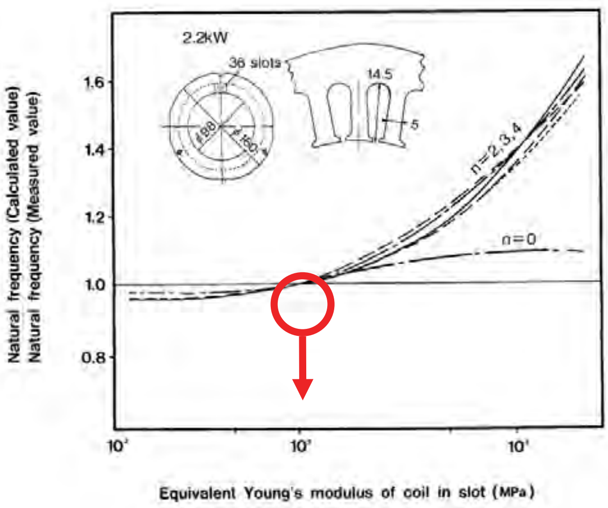
Material number	Tensile strength N/mm2		Density kg/cm3	Longitudinal Elastic Modulus N/mm2	
	L direction	C direction		L direction	C direction
50H310	539	549	7.65	1.917	2.091
50H470	451	461	7.70	1.965	2.119
50H1000	382	392	7.85	2.18	2.242
50H1300	363	373	7.85	—	—

Contents

◇Natural frequency and Eigenmode

Longitudinal Elastic Modulus of Winding in Slot

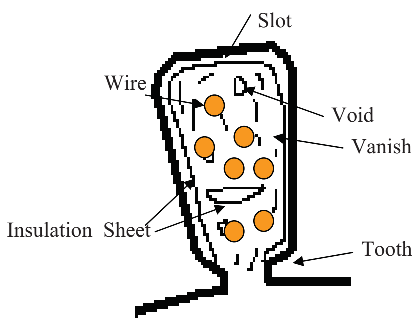


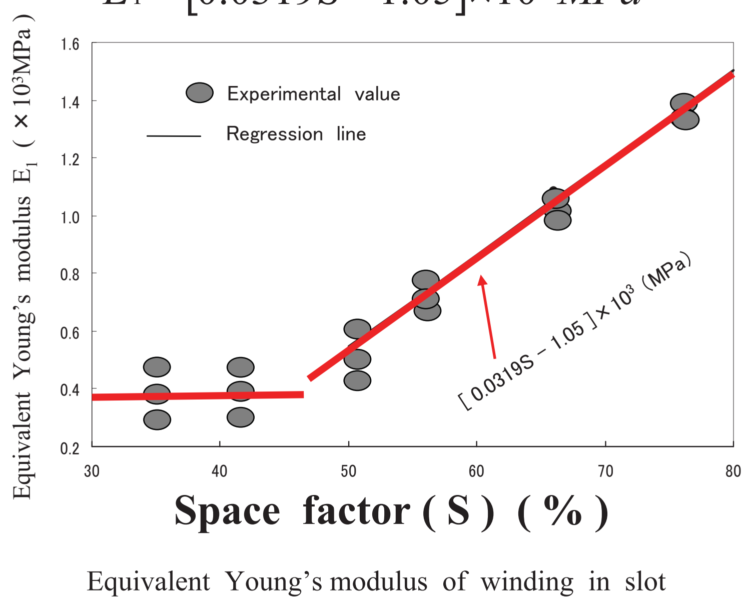


Longitudinal Elastic Modulus of Winding in Slot

Varies by space factor (values below 45% are affected by the gap)

$$E_1 = [0.0319S - 1.05] \times 10^3\ MPa$$





Equivalent Young's modulus of winding in slot

Natural frequency mode of stator core

Analysis error within 3% until higher order egienfrequencies

Actual measurements and calculated value for iron cores with slots that have coils

Mode order n	Actual measurments	Calculated value for Finite Element Method		Simple calculation for calculated value	
		Frequency (Hz)	Error (%)	Frequency (Hz)	Error (%)
0	9022	9084.1	−0.68	9904.5	+ 3.1
2 Low	1574	1590.1	+1.02	1550.0	− 1.53
2 High	1710	1707.5	−0.01	1751.4	+ 1.59
3 Low	4208	4285.1	+1.84	4383.7	+ 4.18
3 High	4415	4435.0	+0.45	4953.7	+12.20
4 Low	7430	7547.0	+1.57	8405.3	+13.13
4 High	7668	7863.3	+2.55	9498.3	+23.87

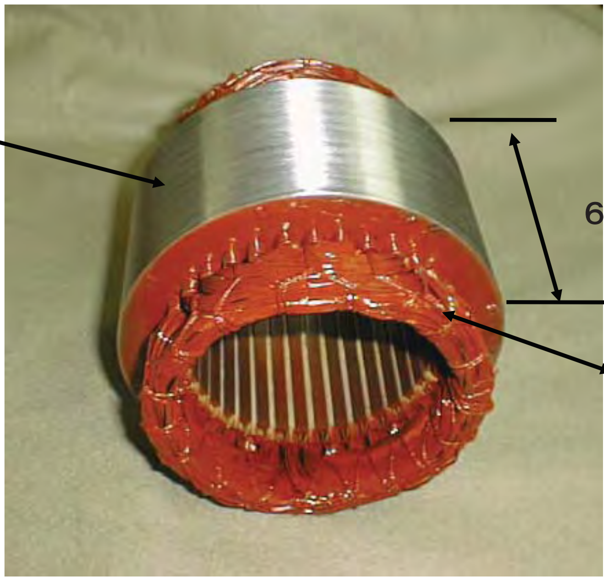
Contents

◇Natural frequency and Eigenmode

1. Stator core
2. Longitudinal Elastic Modulus of Electromagnetic Steel Sheet
3. Stator Core with the Winding in Slot
4. Stator Core with Coil Ends
5. Press-fit Frame and Stator

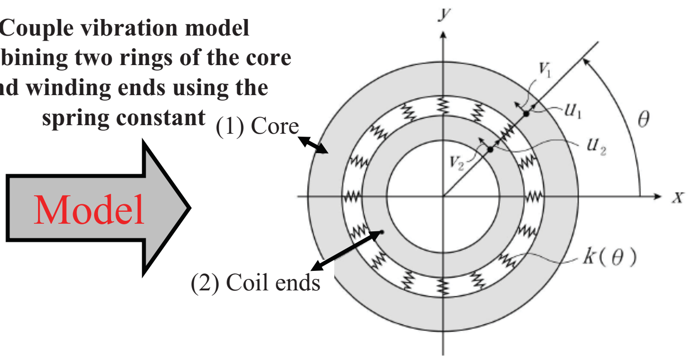
Stator Core with Winding

Inner Radius 145 mm; Outer radius 92 mm; Length 66 mm
Core of industrial motor



Coupled Vibration Theory of Two Rings

Couple vibration model combining two rings of the core and winding ends using the spring constant



The core and winding are combined with the spring constant K

Potential energy:

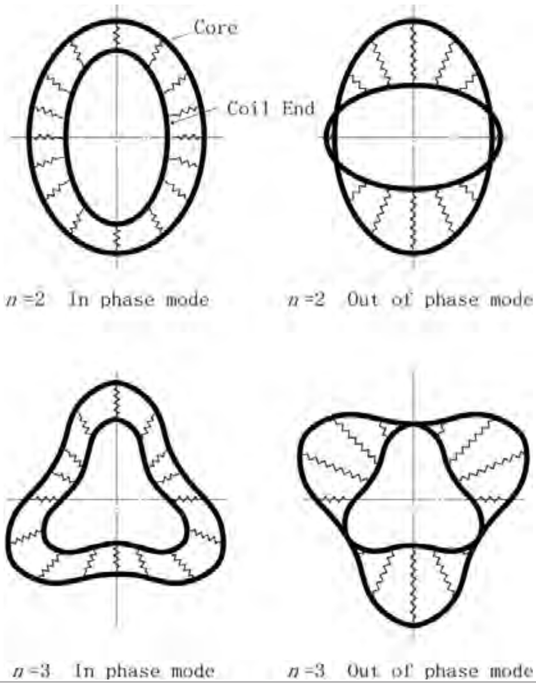
$$U_{1,2} = \frac{1}{2}\frac{E_{1,2}I_{1,2}}{R_{1,2}^{3}}\int_0^{2\pi}\left(\frac{\partial^2 u_{1,2}}{\partial\theta^2}+u_{1,2}\right)^2 d\theta \quad \text{-------------- (1)}$$

Energy of motion:

$$T_{1,2} = \frac{1}{2}\rho_{1,2}A_{,21}R_{1,2}\int_0^{2\pi}\left\{\left(\frac{\partial u_{1,2}}{\partial t}\right)^2+\left(\frac{\partial v_{1,2}}{\partial t}\right)^2\right\}d\theta \quad \text{------ (2)}$$

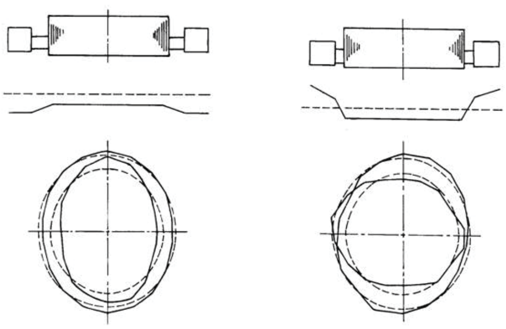
Coupled Vibration Theory of Two Rings

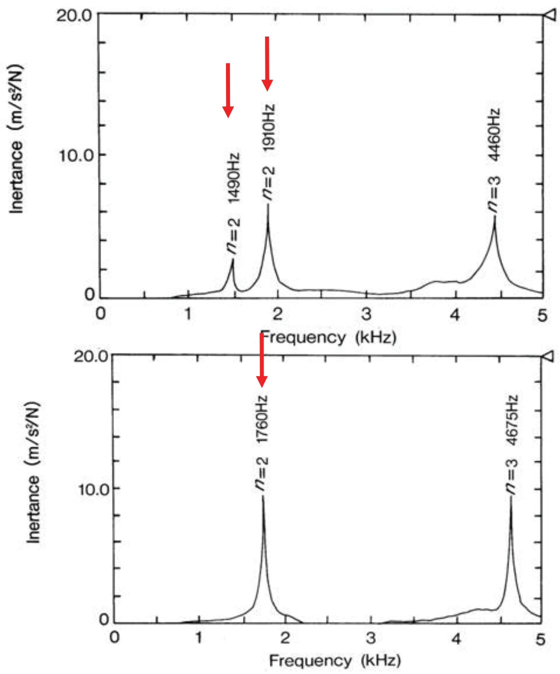
Has coordinate and opposite phases



Natural frequency (Actual)

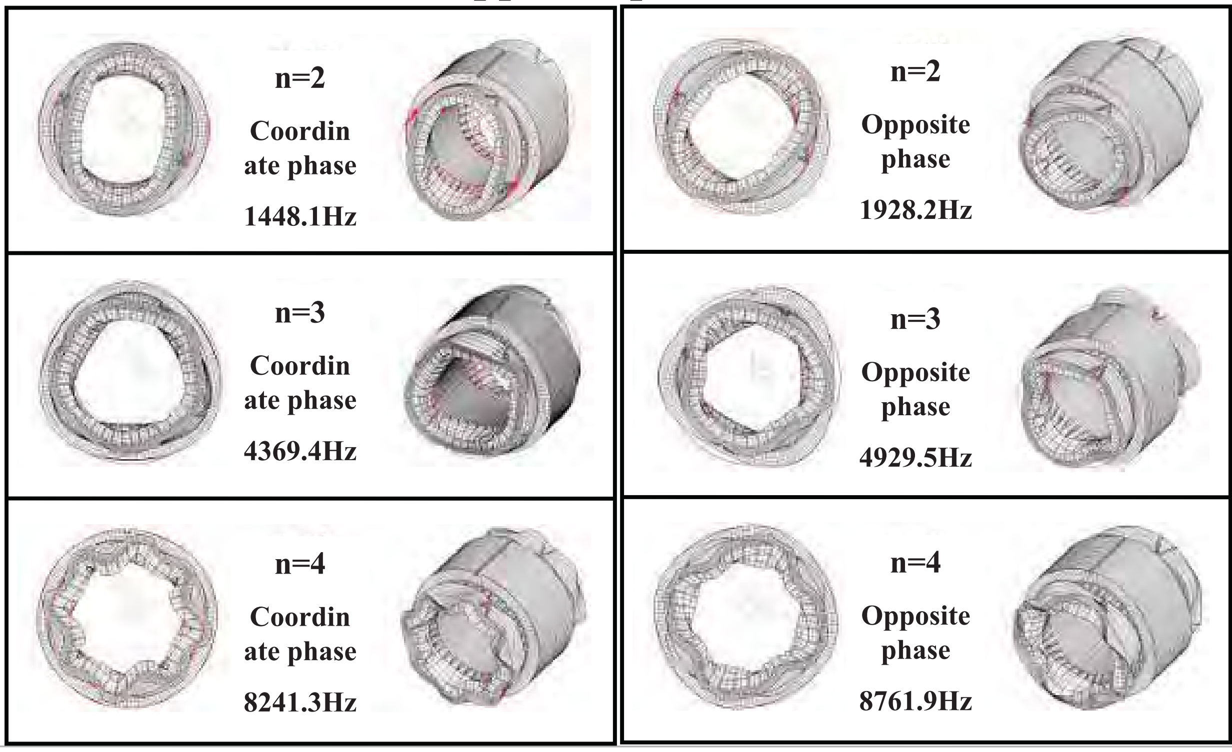
Effects of the winding ends on the natural frequency





Analysis Results

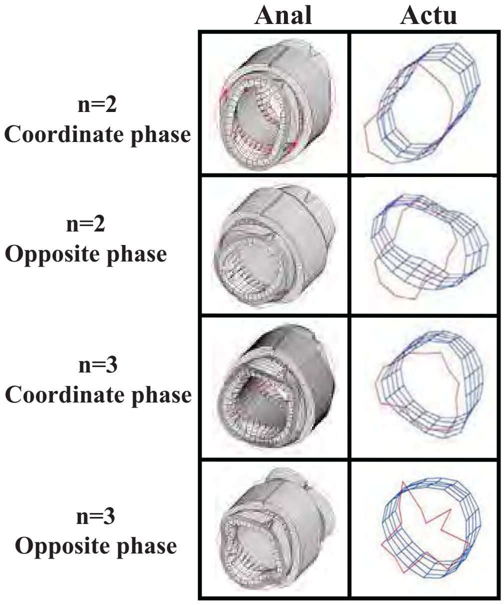
Has coordinate and opposite phase of circular vibrations



Comparing Theoretical, Actual, and Finite Element Analysis Results

The analysis and actual results match within a 2.2% error

Deformation mode of analysis and testing mode analysis



Analysis results and error

	Theoretical analysis	Actual	Finite element method	Error
n=2 Coordinate phase	1450Hz	1417Hz	1448Hz	-2.2%
n=2 Opposite phase	1970Hz	1969Hz	1928Hz	2.2%
n=3 Coordinate phase	4110Hz	4408Hz	4369Hz	0.9%
n=3 Opposite phase	4630Hz	5010Hz	4930Hz	1.6%

From the Japan Society of Mechanical Engineers

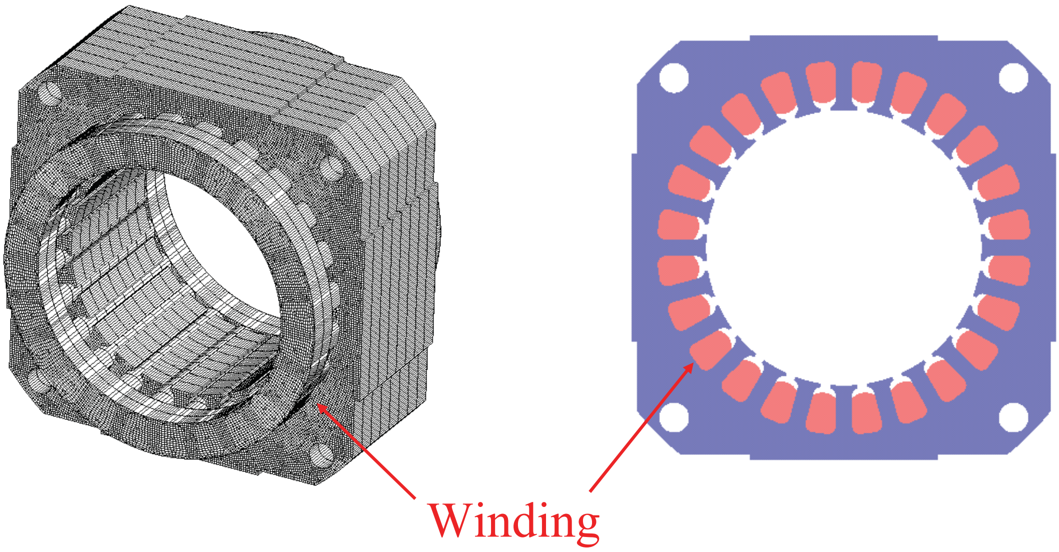
3D Model for Vibration Analysis

Model including winding

(Elements: 82352)

Blue: Stator core
Red: Winding

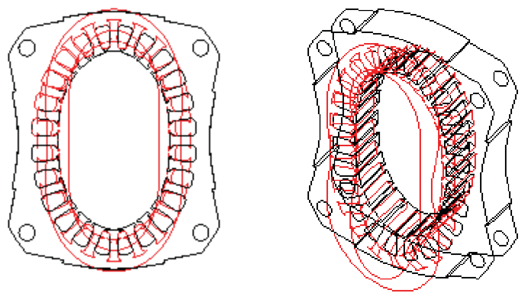
Equivalent Young's modulus; Laminated direction of core: 1/10
Winding ends: 1/100



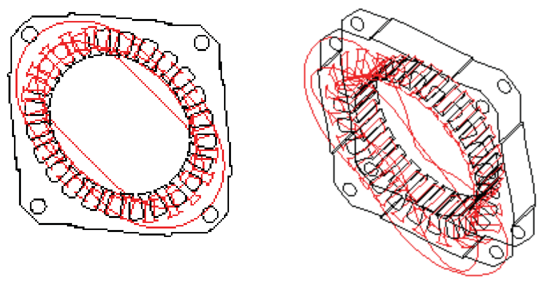
Natural Frequency Analysis Results

(Elements: 82352)

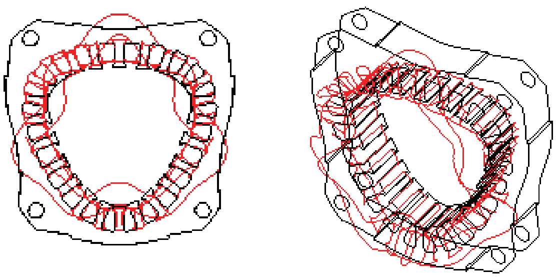
Effects of the two mode types and winding ends



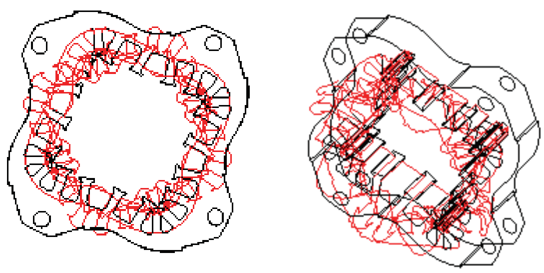
Ellipse mode: 1286.3Hz



Ellipse mode: 1761.4Hz



Triangular mode: 4820.3Hz



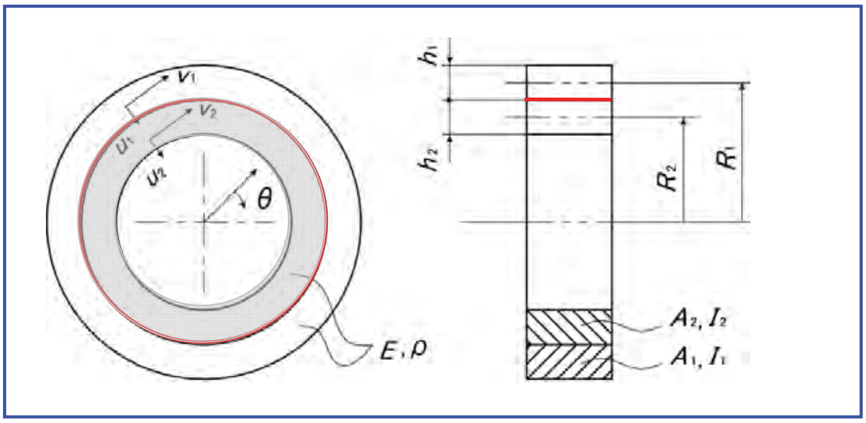
Rectangular mode: 8476.3Hz

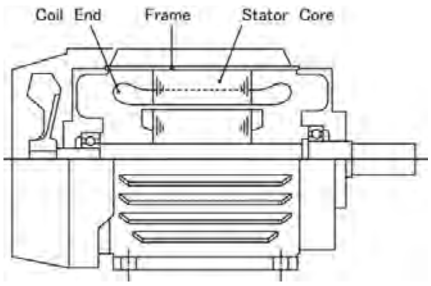
Contents

◇Natural frequency and Eigenmode

Contact Analysis of a Press-fit Frame and Stator

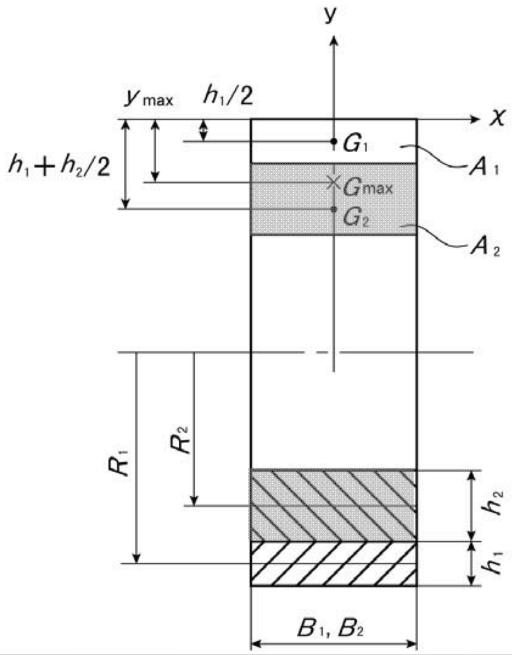
Natural Frequency for the Two Rings





Natural Frequency for the Two Rings

The exterior and interior are maintained by the compression tolerance.



$P_m = 0$ **cross-sectional second-order moment**

$$I_{\min} = \frac{1}{12}\left\{B_1(h_1)^3 + B_2(h_2)^3\right\}$$

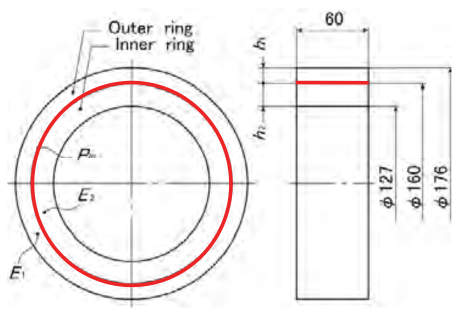
$P_m = \infty$ **cross-sectional second-order moment**

$$I_{\max} = \frac{B_1(h_1)^3}{12} + (y_{\max} - h_1/2)^2 B_1(h_1) + \frac{B_2(h_2)^3}{12} + \left\{(h_1 + h_2/2) - y_{\max}\right\}^2 \cdot B_2(h_2)$$

Natural Frequency for the Two Rings

The natural frequency differs by the compression tolerance

$$\omega_n^{\;2} = \frac{E\left(\dfrac{I_1}{R_1^{\;3}} + \dfrac{I_2}{R_2^{\;3}}\right)}{\rho(A_1R_1 + A_2R_2)} \cdot \frac{n^2(1-n^2)^2}{n^2+1}$$

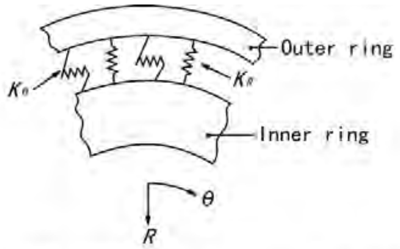


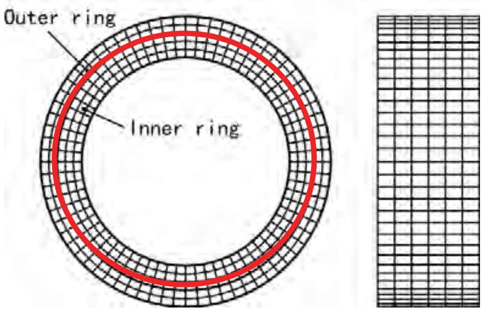
Analysis target	n=2	n=3	n=4	n=5
Single ring	2705	7651	14670	23725
Two layer ring $P_m = \infty$	2656 (-1.8)	7532 (-1.8)	14407 (-1.8)	23298 (-1.8)
Two layer ring $P_m = 0$	1678 (-38.0)	4747 (-38.0)	9193 (-38.0)	14721 (-38.0)

Natural Frequency for the Two Rings

$$K_\theta = \frac{k_\theta \cdot N \cdot M}{2\pi R t}$$

$$K_R = \frac{k_R \cdot N \cdot M}{2\pi R t}$$





N: Number of cylindrical nodes;
M: Number of axial nodes;

$2\pi Rt$: Area of joint
k_θ, k_R : Spring constant per node
R : Radius of joint
t : Axial length

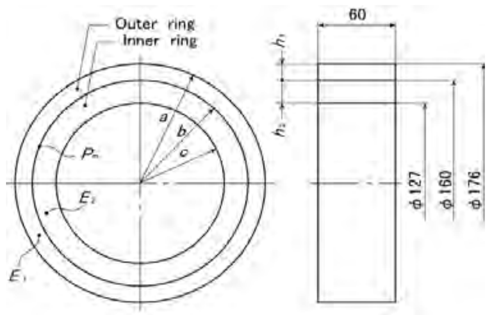
Compression tolerance caused by the rings

$$P_m = \frac{2\delta / 2b}{\left\{\frac{1-\upsilon_1}{E_1} + \frac{1-\upsilon_2}{E_2}\right\} + 2\left\{\frac{1}{E_1}\frac{c^2}{(b^2-c^2)} + \frac{1}{E_2}\frac{a^2}{(a^2-b^2)}\right\}}$$

Compression tolerance for experimental models

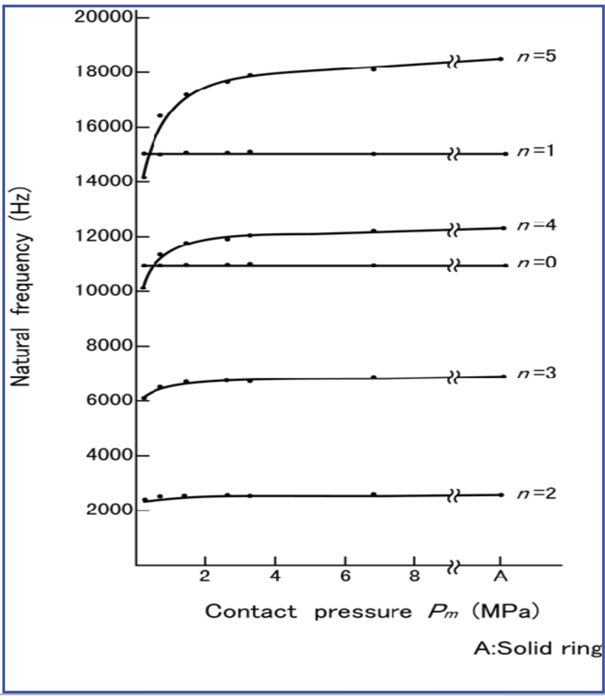
2δ (mm)	P_m (MPa)
0.078	6.72
0.038	3.28
0.030	2.59
0.018	1.47
0.008	0.69
0.002	0.17
$E_1 = E_2 = 2.06 \times 10^{11}$ (N/m^2), $\upsilon_1 = \upsilon_2$ =0.3	

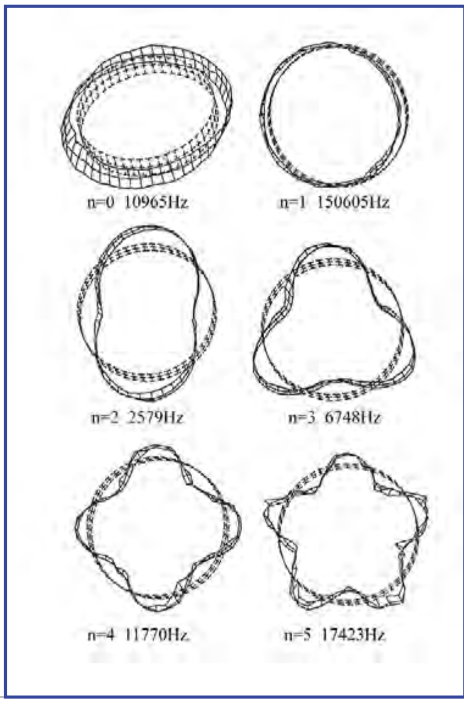
Actual model of two layer ring



Relationship of Compression Tolerance and Natural Frequencies (Actual)

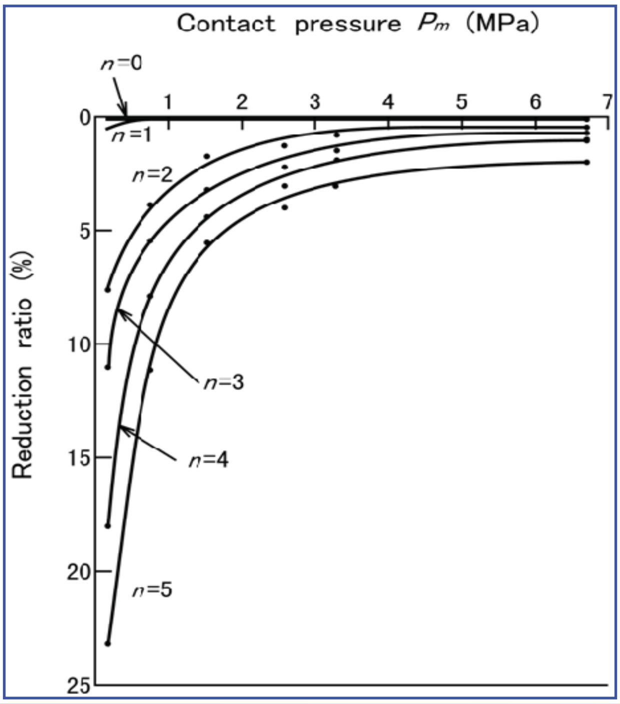
The natural frequency is reduced at lower compression.

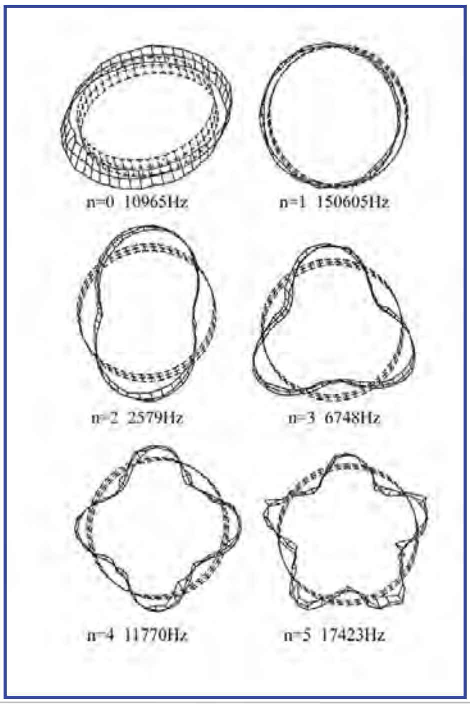




Reduction in the Natural Frequency (Actual)

The ratio of natural frequency is reduced if the orders of n is higher.



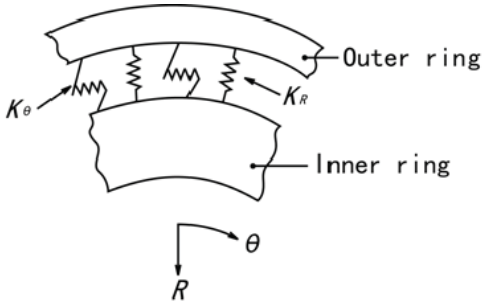


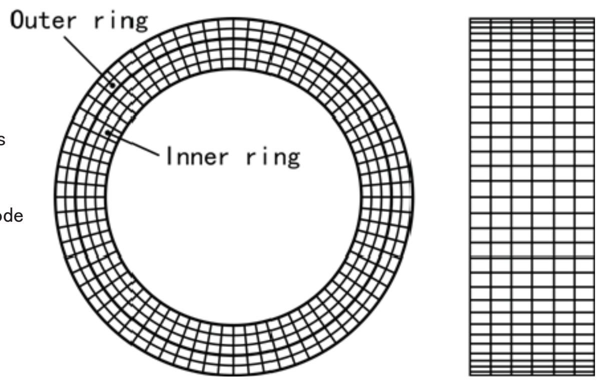
Fixed Spring Constant at the Joint Between the Two Layered Rings

Model the spring in the radial and circumferential directions.

$$K_\theta = \frac{k_\theta \cdot N \cdot M}{2\pi Rt}$$

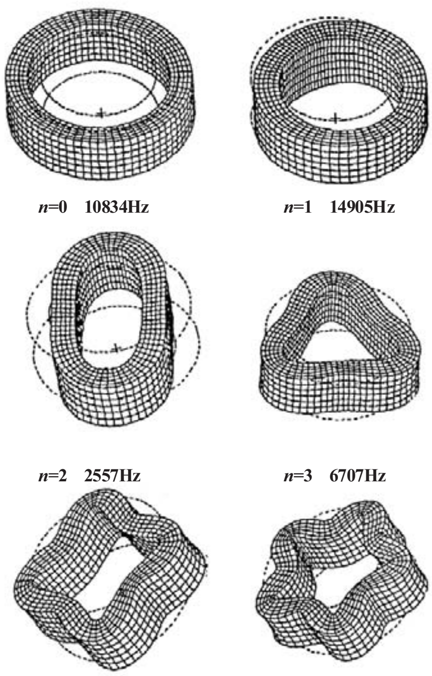
$$K_R = \frac{k_R \cdot N \cdot M}{2\pi Rt}$$





- N: Number of cylindrical nodes
- M: Number of axial nodes
- $2\pi Rt$: Area of joint
- k_θ, k_R :Spring constant per node
- R :Radius of joint
- t : Axial length

Natural Frequency Mode (Analysis Results)



n=0 10834Hz

n=1 14905Hz

n=2 2557Hz

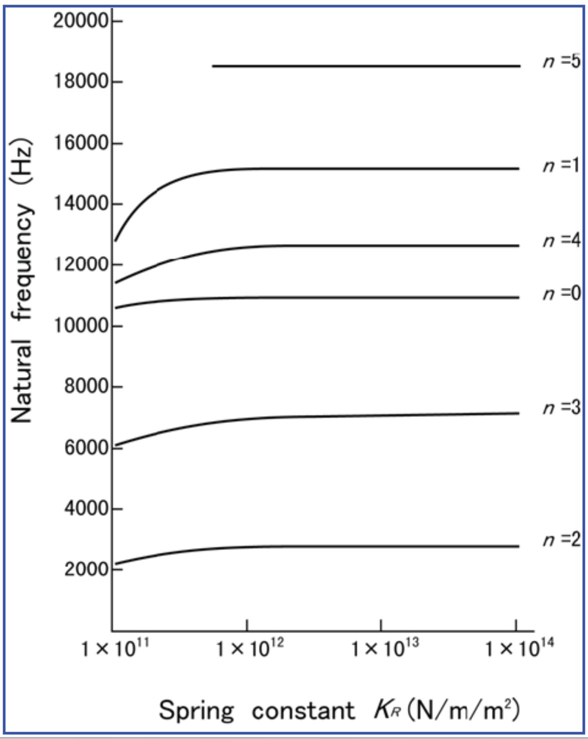
n=3 6707Hz

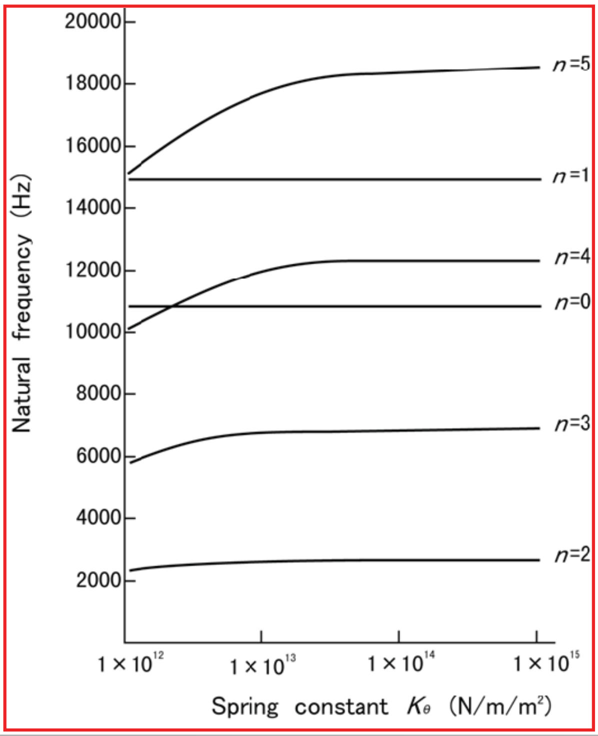
n=4 11802Hz

n=5 17490Hz

Fixed Spring Constant at the Joint Between the Frame and Core

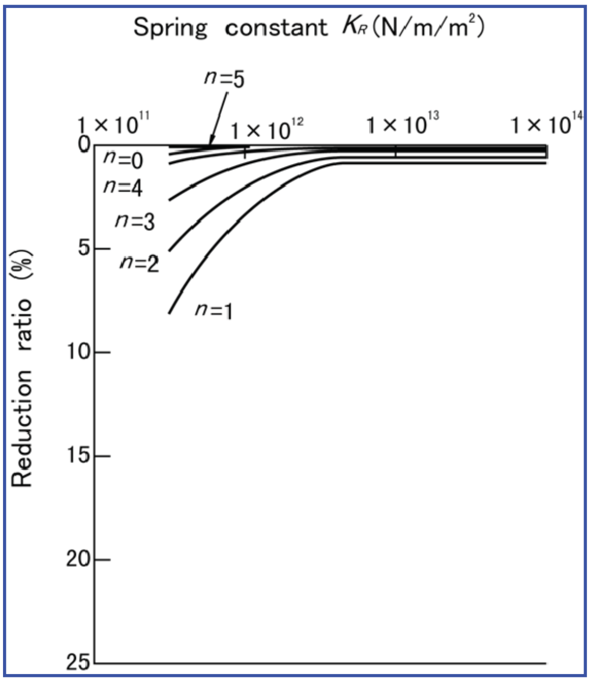
The natural frequency is reduced at lower spring constants.

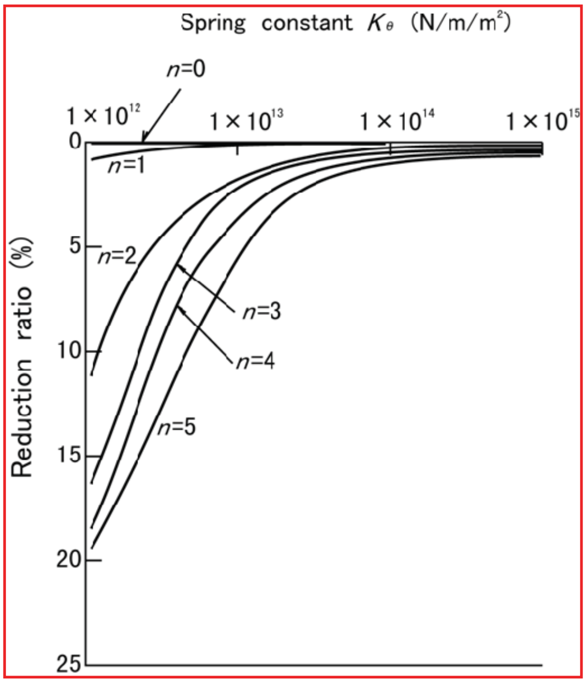




Reduction in the Natural Frequency (Calculation)

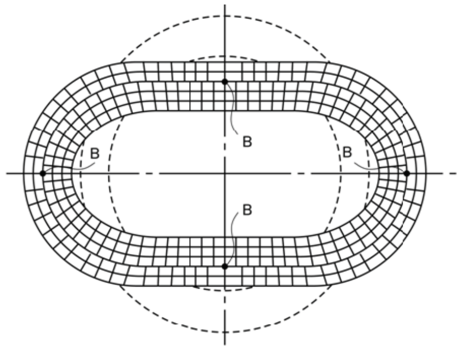
The results match the actual values when the spring constant is the $K_R = \infty, K_\theta$ parameter.





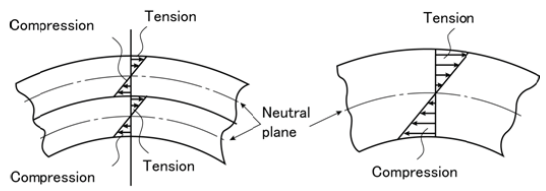
Physical Phenomena of Joints

Slip friction is produced in the circumferential direction of the joint for the double layered rings. The friction is reduced at lower compression tolerances.



（a）n＝2の変形

Stress distribution of the single layer and double layer rings.

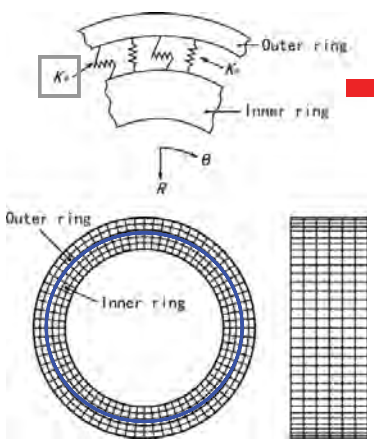


（b）二層円環の応力分布　（c）単一円環の応力分布

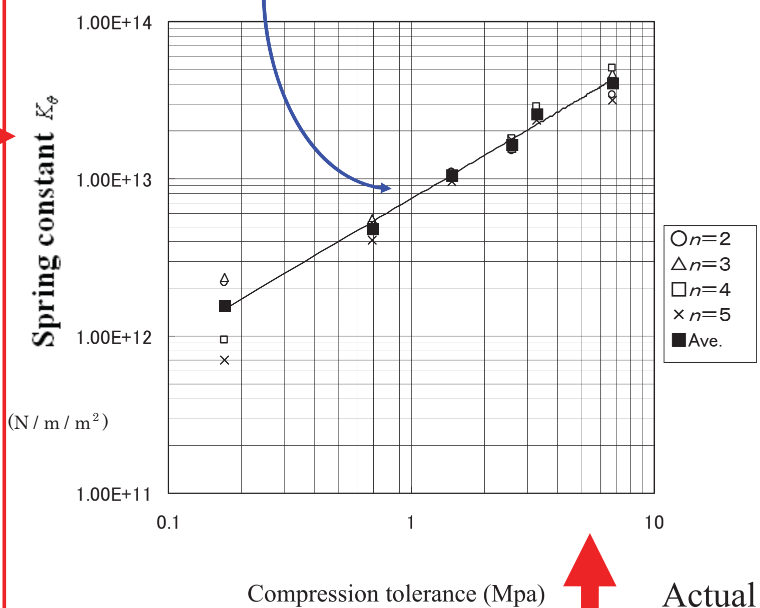
Relationship between compression tolerance P_m and spring constant K_θ

Double layer ring model

Finite element model

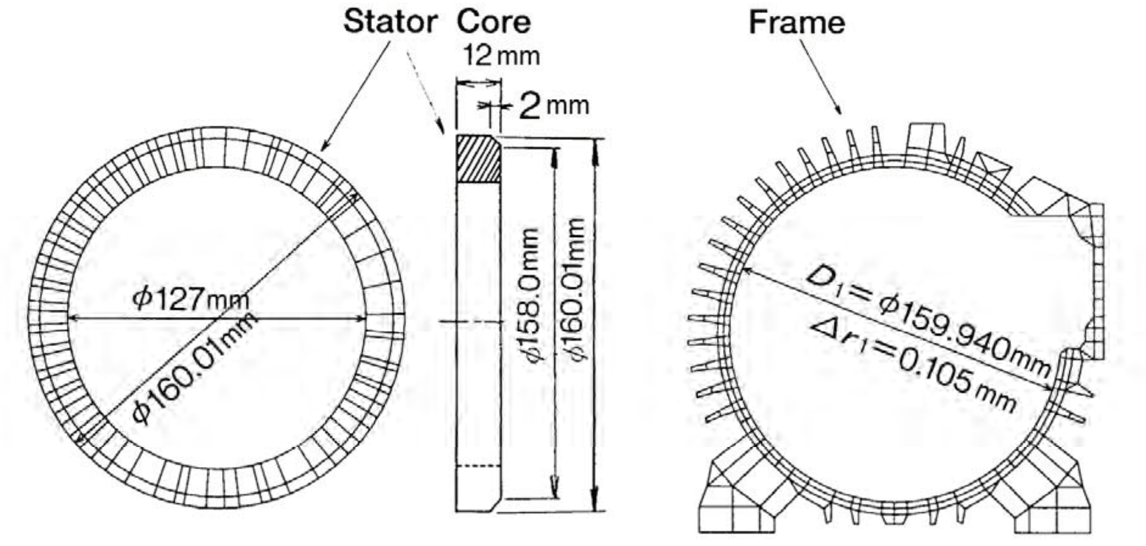


$$K_\theta = 7.49 \times 10^{12} \times P_m^{0.91}$$



Actual values

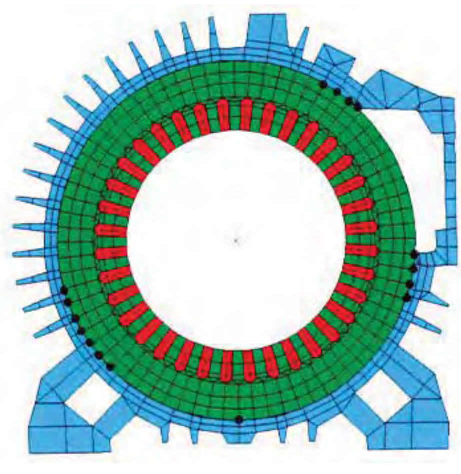
Contact Analysis of a Press-fit Frame and Stator



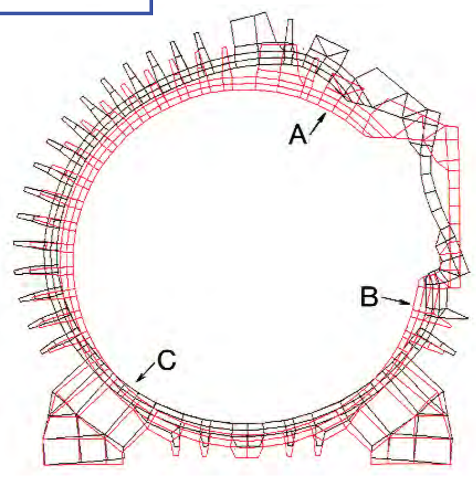
Contact Analysis of a Press-fit Frame and Stator

The actual joints from the contact compression are only the points at A, B, and C.

Analysis Model



Deformation

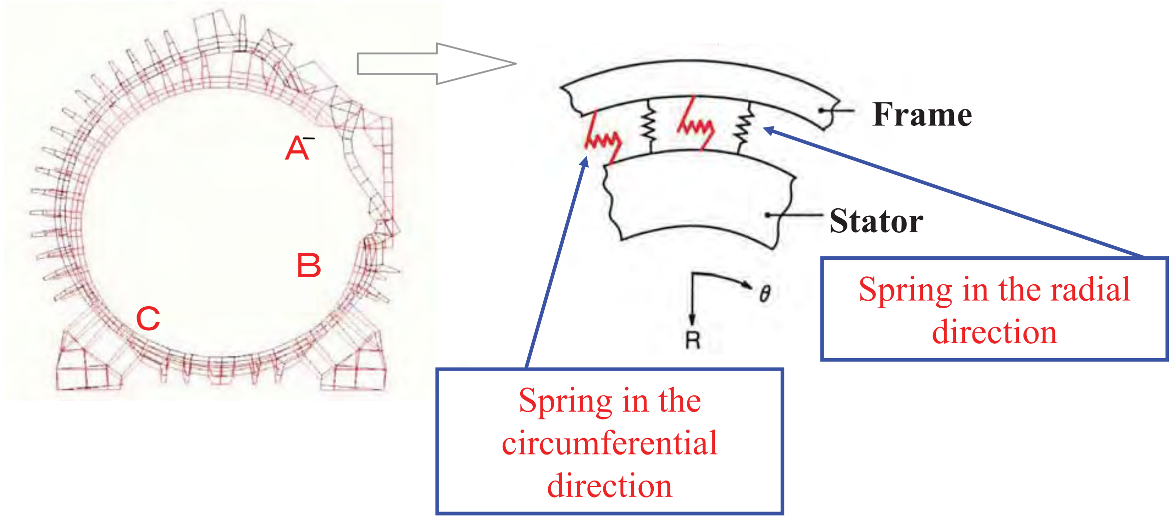


Modeling the Joint Between the Frame and Core

Model the joint using a **spring element**

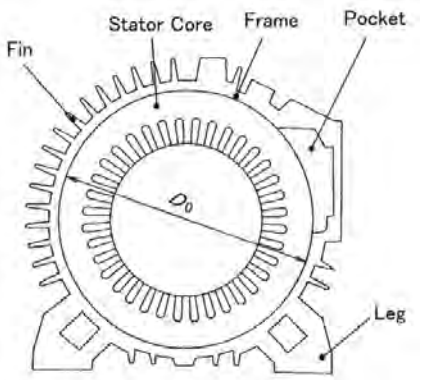
⇩

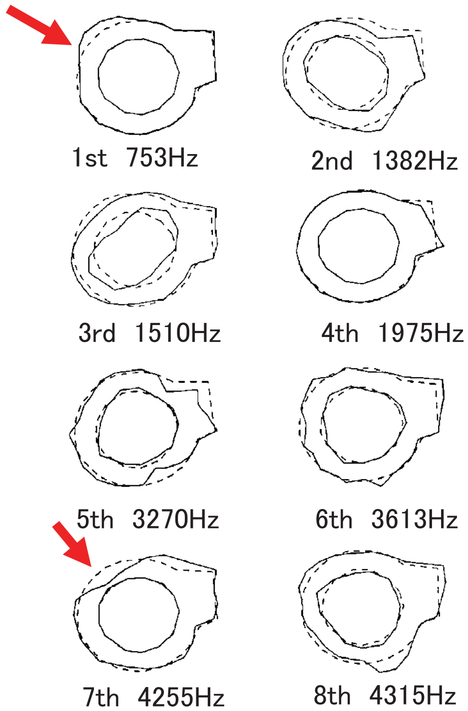
The spring in the circumferential direction is primary : Contact friction



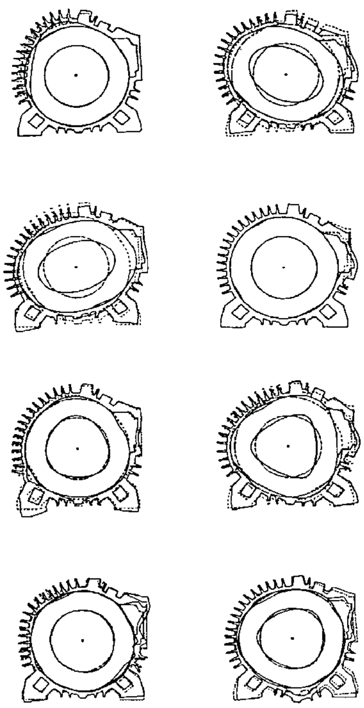
Stator Core in Frame (Actual)

The behavior of the frame and core have differing modes.





Natural Frequency of the Stator Core with Frame



Finite element analysis

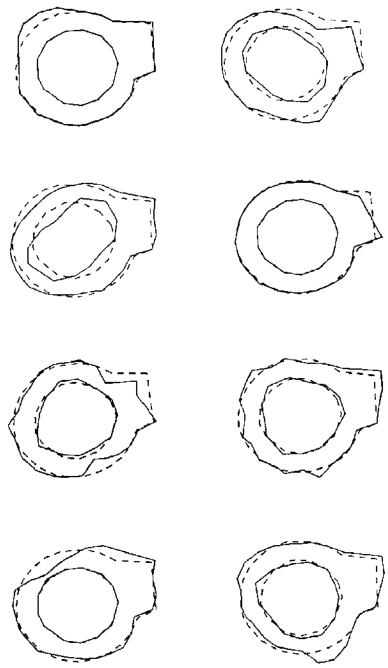
Calculation Error

Matches within a 5% error

Natural frequencies for iron cores with frame
(unit:Hz)

No.	Mode	Measured	Calculated	Error %
1st	Frame	753	758	+0. 7
2nd	n=2	1382	1391	+0. 7
3rd	n=2	1510	1563	+3. 5
4th	Frame	1975	1958	−0. 9
5th	n=3	3270	3426	+4. 6
6th	n=3	3613	3534	−2. 2
7th	Frame	4255	4065	−4. 5
8th	n=3	4315	4417	+2. 3

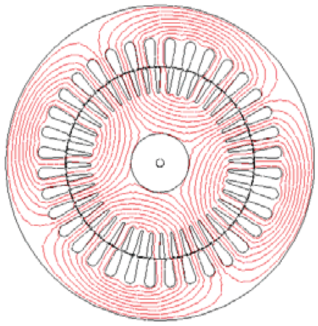
From the Japan Society of Mechanical Engineers

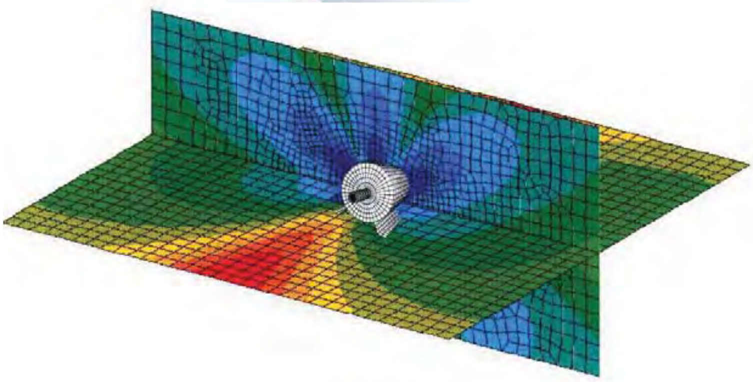


Tested model

"Motor Noise/Vibration Simulation Analysis and Its Features" Part 2

JMAG Users Conference 2010





Objectives

Increased electromagnetic noise with miniaturization

⇩

A design preventing resonance is necessary at the design stage so that frequencies of electromagnetic force as well as egienfrequencies and resonant phenomena of the stator core are not produced to **reduce noise**.

⇩

(1) Frequency and electromagnetic mode the electromagnetic force is produced
(2) The eigenfrquency and eigenmode of the stator core

Accurate prediction is vital.

Challenges of Simulations

Electromagnetic force

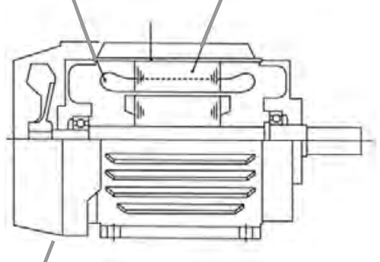
- **Frequency and mode**
- **Intensity of electromagnetic force**

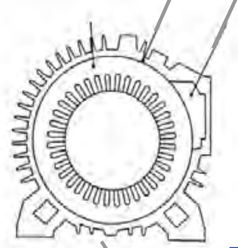
Stator core

- **Teeth/slot windings**
- **Effects of wires**

Joints

- **Fixed spring constant**
- **Vibration attenuation characteristics**





Frame and core

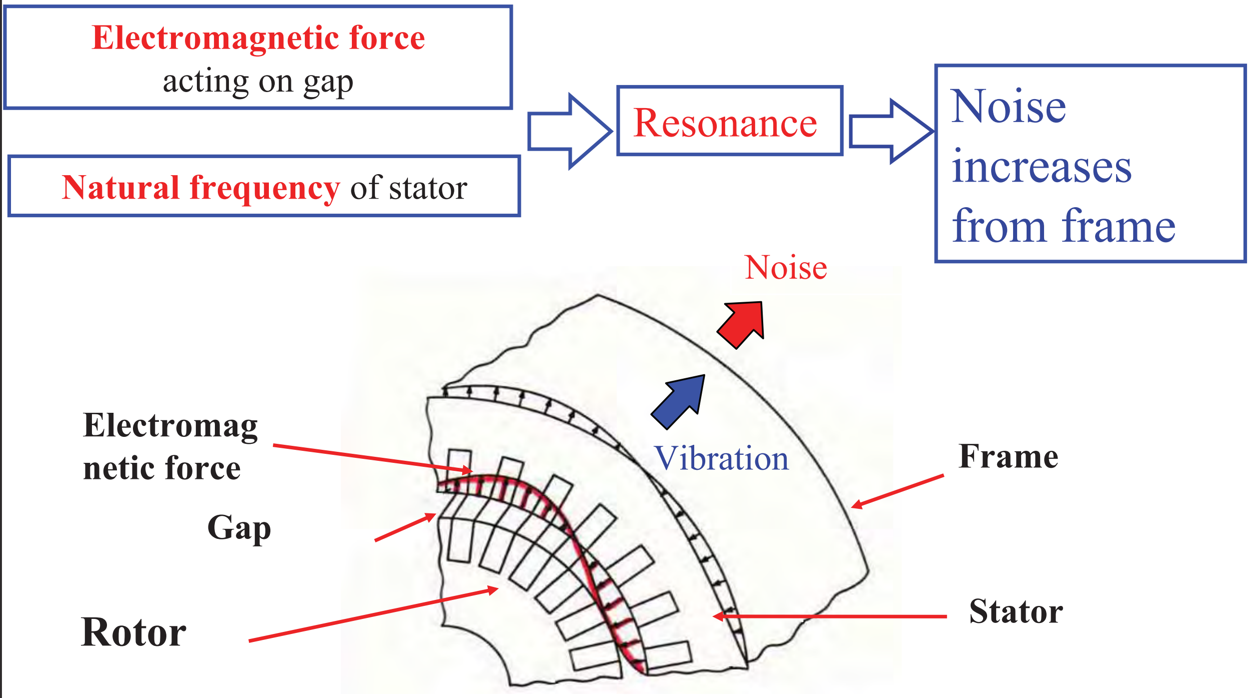
- **Deformation of press-fitting**
- **Contacting areas**

Vibration response

- **Eigenmode and electromagnetic force mode**
- **Vibration mode during drive**

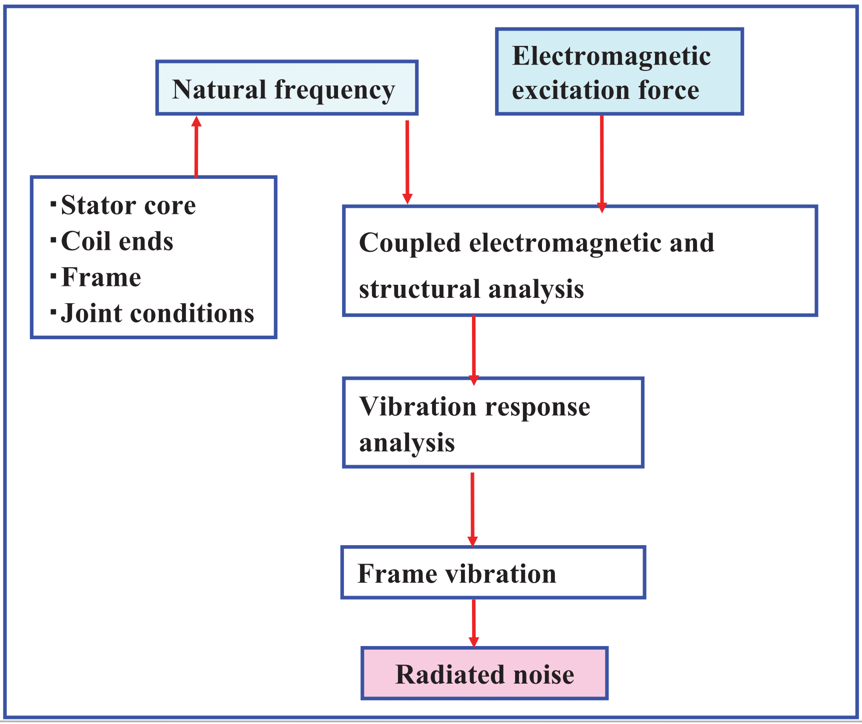
Contents

Mechanism of Electromagnetic Noise



Analysis of Electromagnetic Vibration Simulations

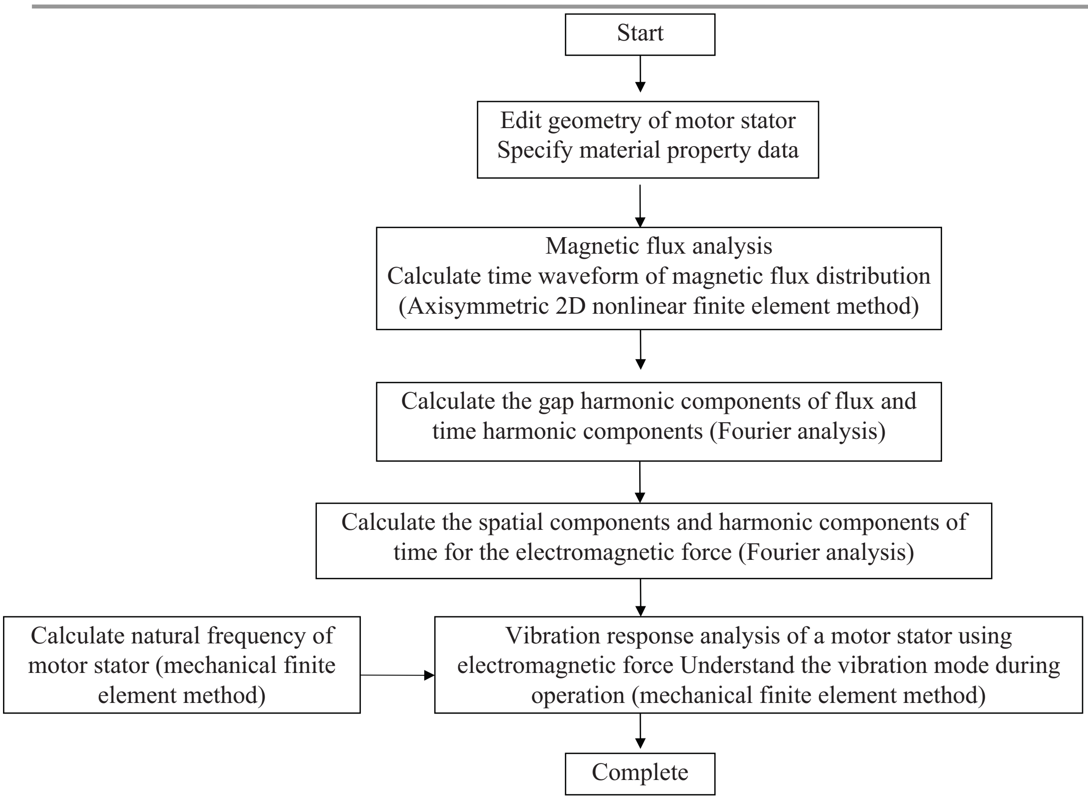
Objective: Feedback to the design by predicating noise.



Simulation Step

- Magnetic flux analysis
- Eigenvalue analysis
- Contact analysis
- Time response
- Electromagnetic vibration
- Noise analysis

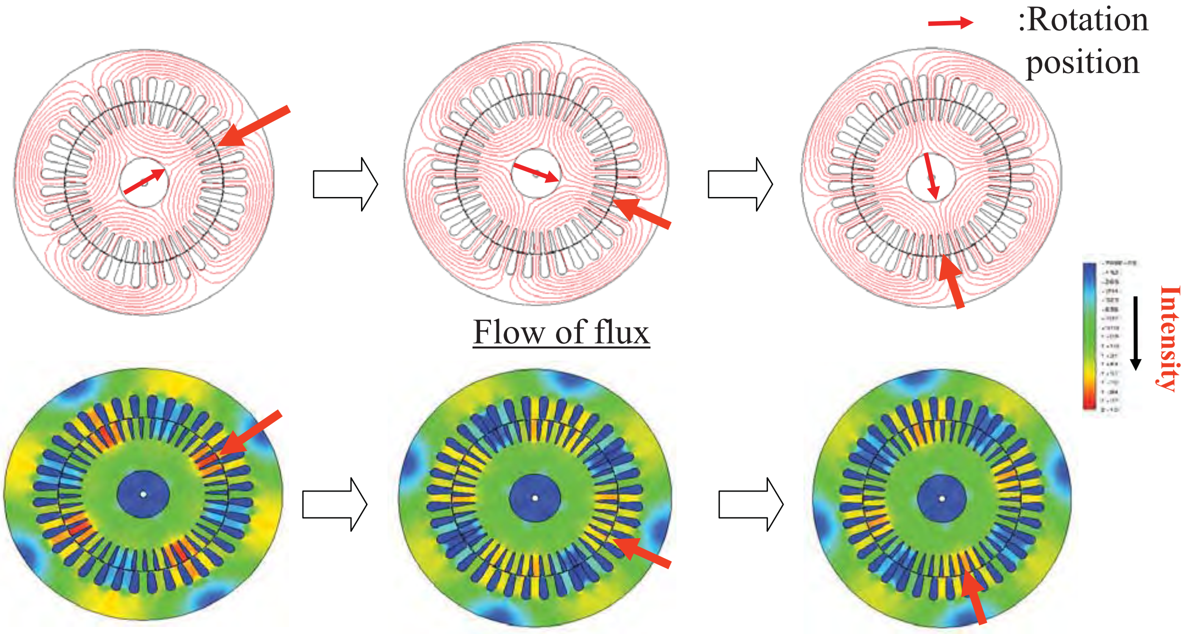
Flow from Magnetic Flux Analysis to Vibration Response Analysis



Simulation Step 1

Transient Magnetic Flux Analysis using the Rotation Position

The flow of flux and the magnetic flux density varies with time.

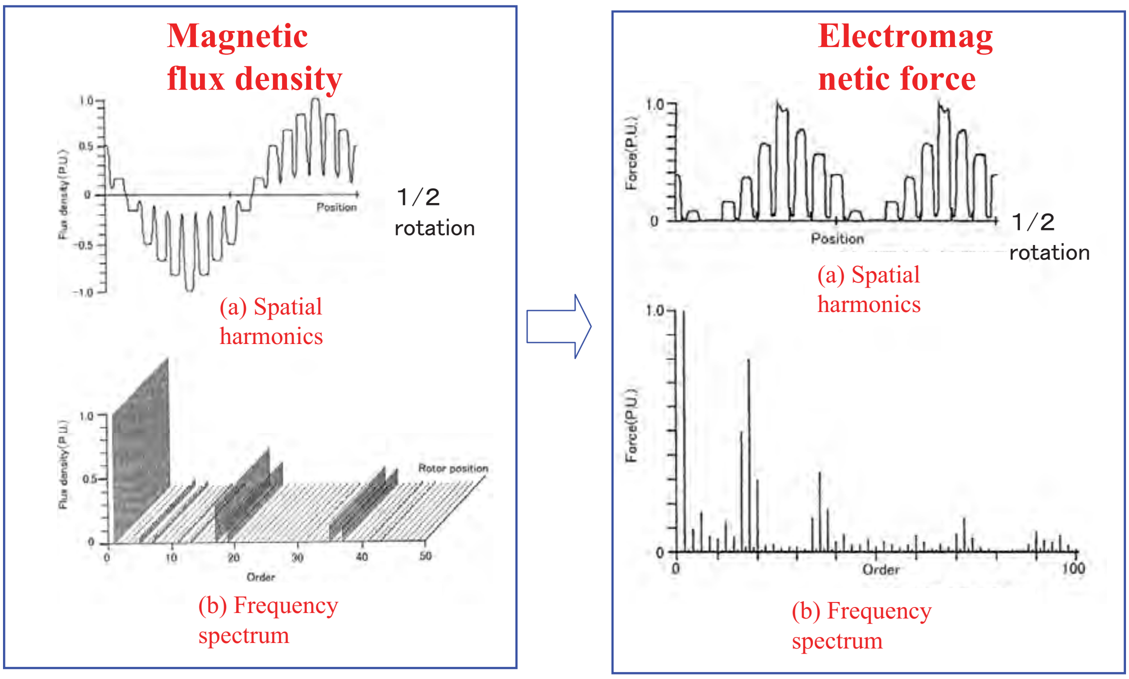


Magnetic flux density

Magnetic flux density and electromagnetic force of air gap

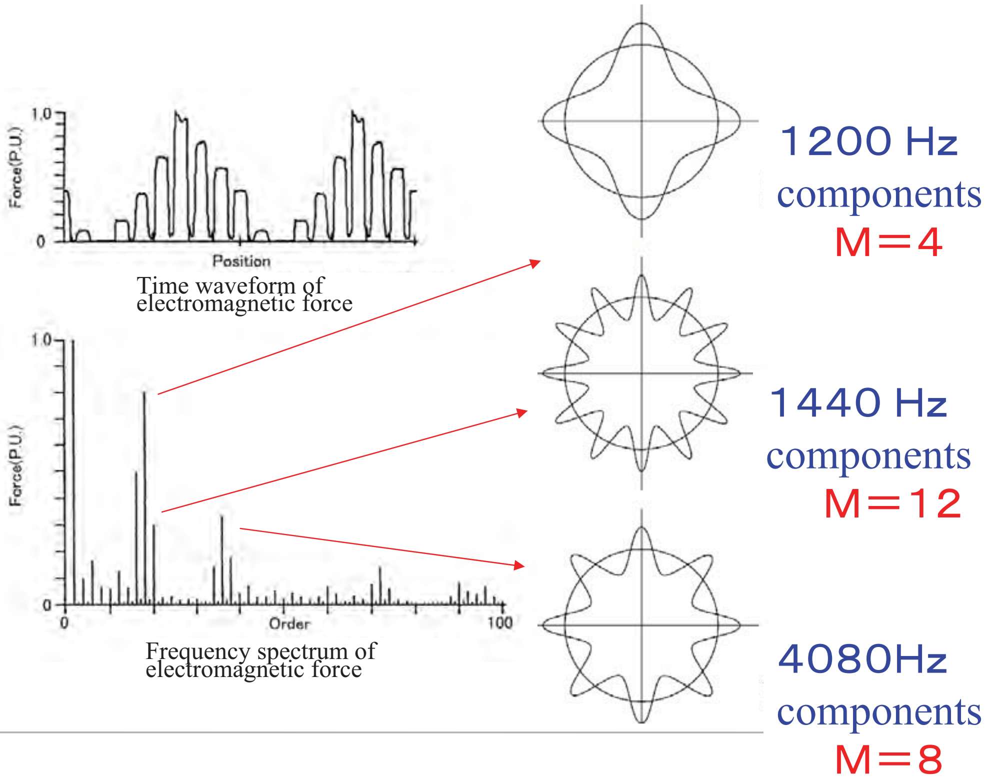
The frequency spectrum is obtained by calculating the electromagnetic force from the magnetic flux density.

The 2f component and slot harmonic components are large



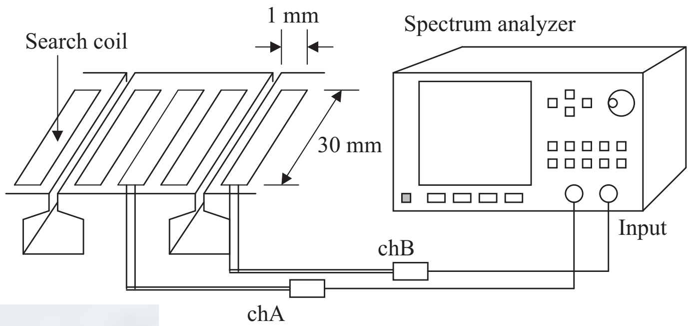
Electromagnetic Force Mode and Frequency

The electromagnetic force mode that is calculated is the ring mode

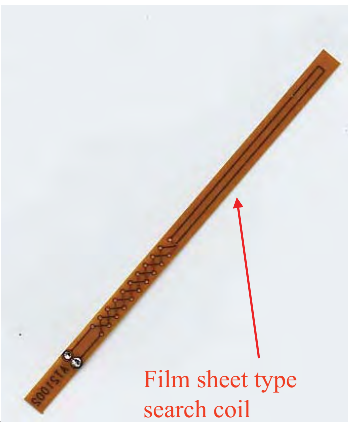


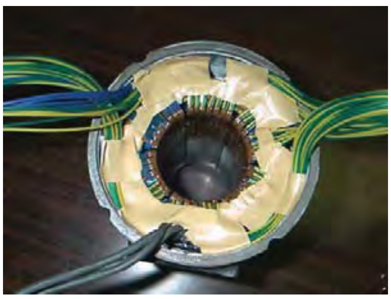
Measuring Magnetic Flux using Search Coils

Adhered to the stator core teeth



Search coil voltage → Integrator → Flux waveform → Frequency response function → Electromagnetic force and electromagnetic force mode

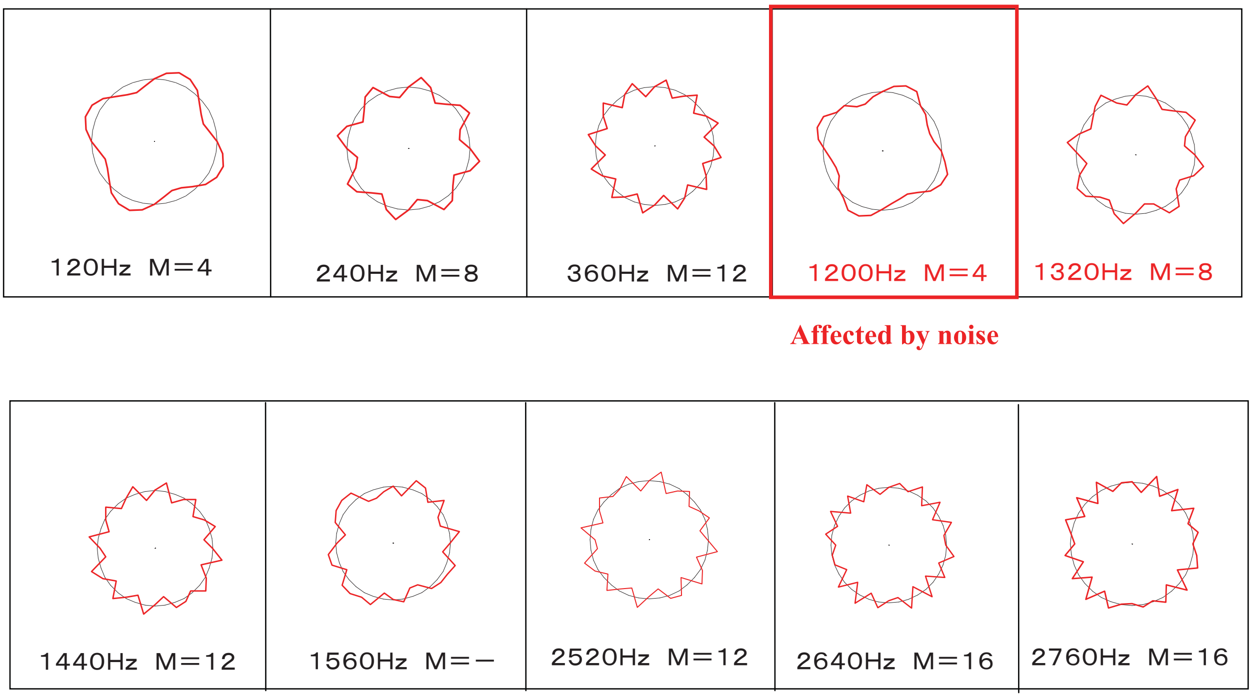




Electromagnetic Force Mode using Measurements

200V−60Hz power supply

Multiple electromagnetic force modes are produced. The electromagnetic force modes are the rotating modes.



Simulation Step1

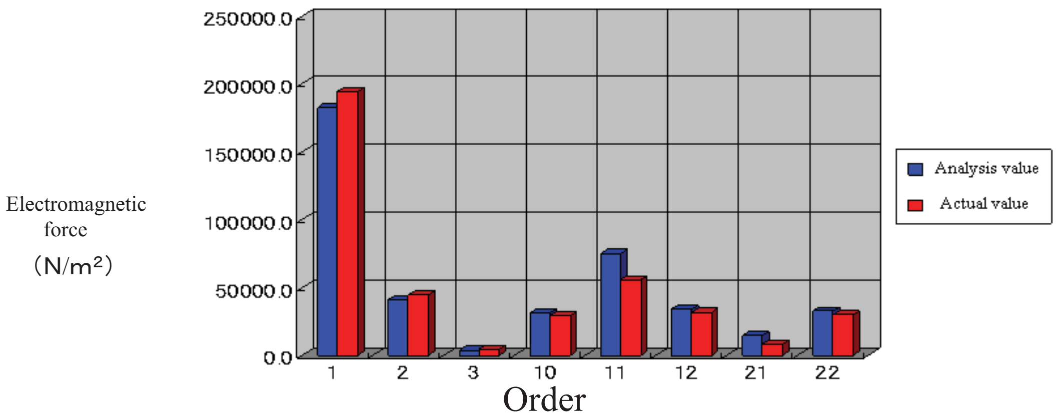
Comparing the Analysis and Actual Results of Electromagnetic Force

The electromagnetic force approximately matches the actual values.

Electromagnetic mode and electromagnetic force

Frequency (Hz)	Order	Electromagnetic mode	Electromagnetic force (N/m²)	
			Analysis value	Actual value
120	1	4	182704.0	194155.6
240	2	8	40939.1	44441.1
360	3	12	3491.0	4556.9
1200	10	4	31058.2	29337.4
1320	11	8	75039.7	55907.8
1440	12	12	34197.9	31482.6
2520	21	12	14547.4	8113.1
2640	22	16	32399.2	29680.2

Moor: 4-pole 2.2 kW



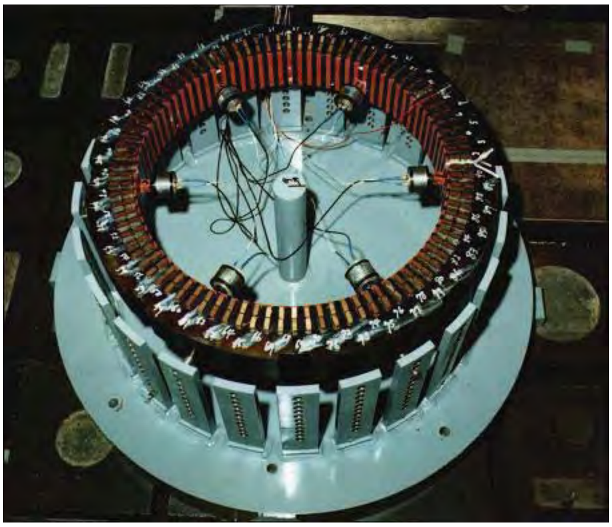
From The Institute of Electrical Engineers of Japan

Contents

Vibration Response Caused by Excitation Force (Actual)

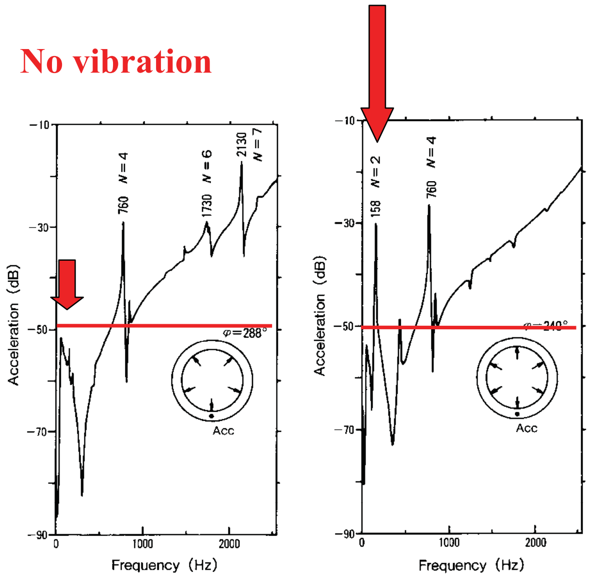
Vibration response differs according to excitation force mode.

・Obtaining resonance



Testing equipment for multipoint excitat

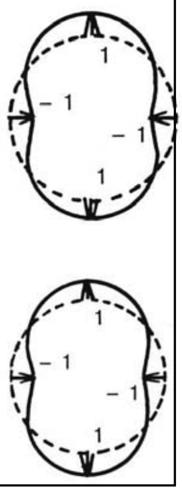
・Examining electromagnetic force



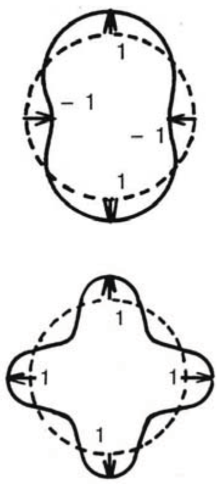
Theory of Vibration Response in Stator Cores

The natural vibration mode and electromagnetic force mode don't match

Natural vibration Mode



Electromagnetic force Mode



Natural frequency mode · Electromagnetic force mode · Vibration response

$$[f_M]\cdot\{\Phi_N\}=\{z\}$$

$$\begin{bmatrix}1 & -1 & 1 & -1\end{bmatrix}\begin{Bmatrix}1\\-1\\1\\-1\end{Bmatrix}=4$$

Vibrations are produced

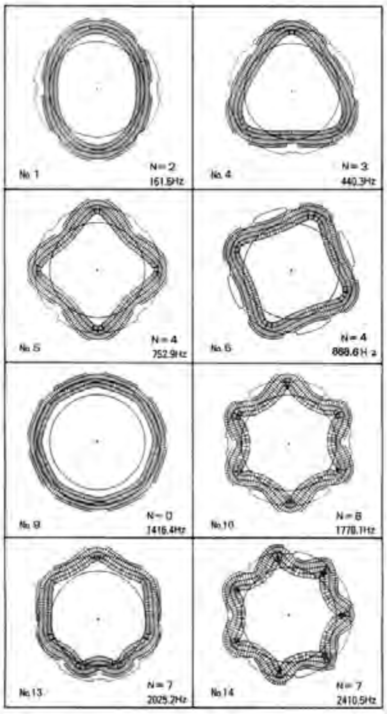
$$\begin{bmatrix}1 & -1 & 1 & -1\end{bmatrix}\begin{Bmatrix}1\\1\\1\\1\end{Bmatrix}=0$$

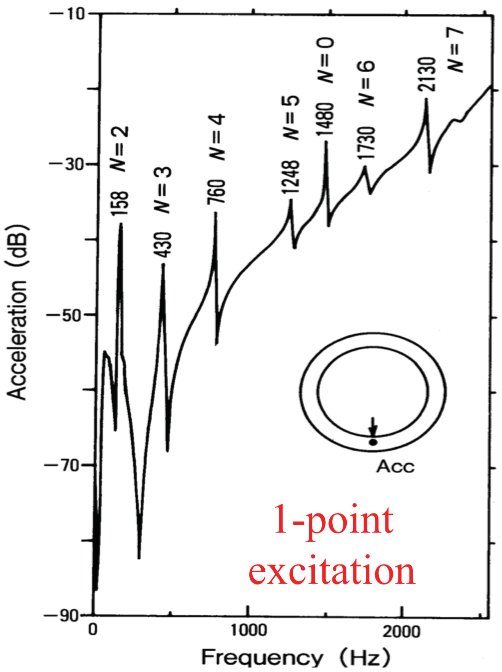
No vibrations

From the Japan Society of Mechanical Engineers

Vibration Response Caused by Excitation Force (Actual)

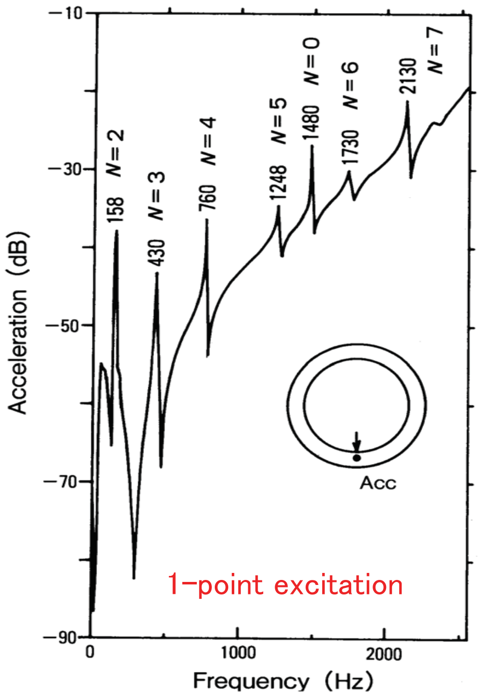
1-point excitation response to all the natural frequencies

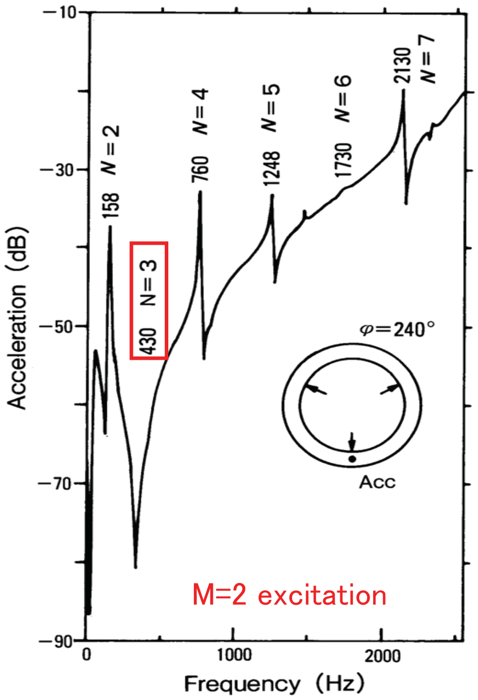




Vibration Response Caused by Excitation Force (Actual)

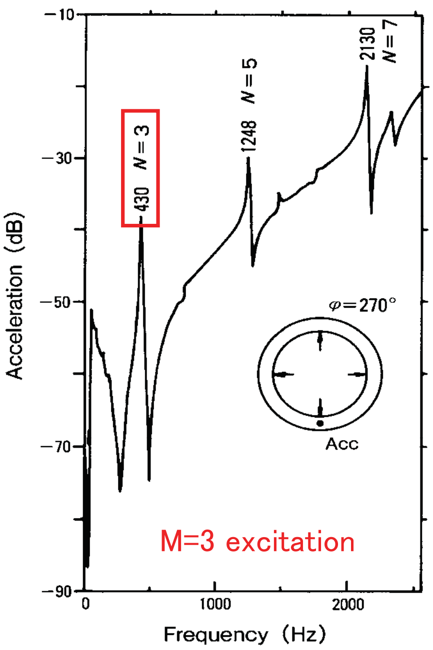
M＝2(ring) excitation mode、N＝3 is eliminated

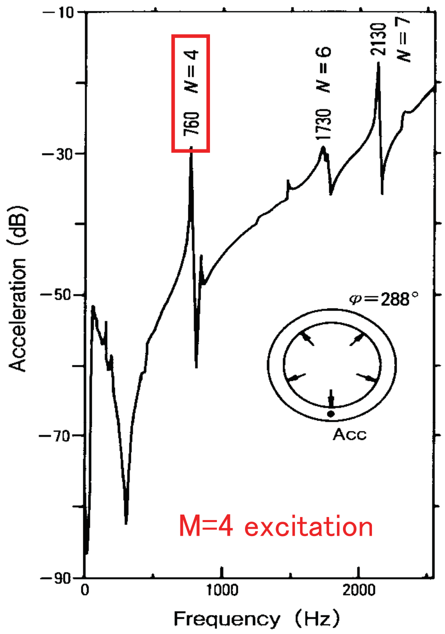




Vibration Response Caused by Excitation Force (Actual)

Resonance phenomena varies according to excitation mode M





Vibration Response Caused by Excitation Force (Actual)

$$\sin\frac{\pi(N \pm M)}{K} \neq 0$$ ⇒ **No excitation**

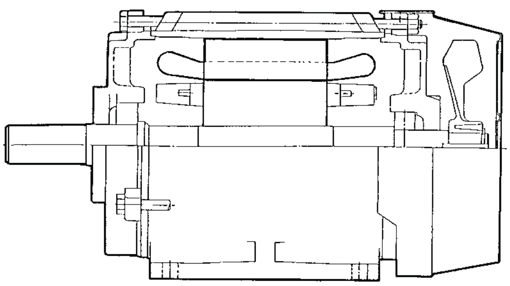
$$\sin\frac{\pi(N \pm M)}{K} = 0$$ ⇒ **Excited**

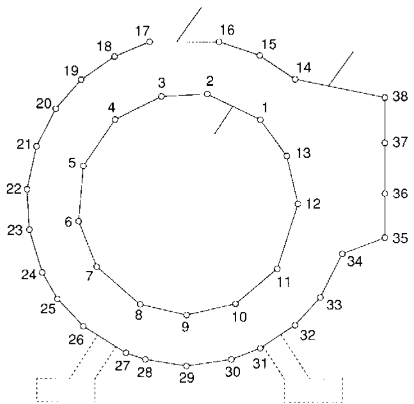
No.	M	K	ϕ	N=0	N=2	N=3	N=4	N=5	N=6	N=7−1	N=7−2
1	2	3	240	— —	○ ◎	— —	○ ◎	○ ◎	— —	○ ◎	○ ◎
2	3	4	270	— —	— —	○ ◎	— —	○ ◎	— —	○ ◎	○ ◎
3		5	216	— —	○ ◎	○ ◎	— —	— —	— —	— —	○ ◎
4	4	5	288	— —	— —	— —	○ ◎	— —	○ ◎	— ◎	— —
5		6	240	— —	○ ◎	— —	○ ◎	— —	— —	— —	— —

○ : appears ◎ : appears by FEM □ : appears experimentally
— : no appearance

Measuring the Mode of the Prototype During Operation

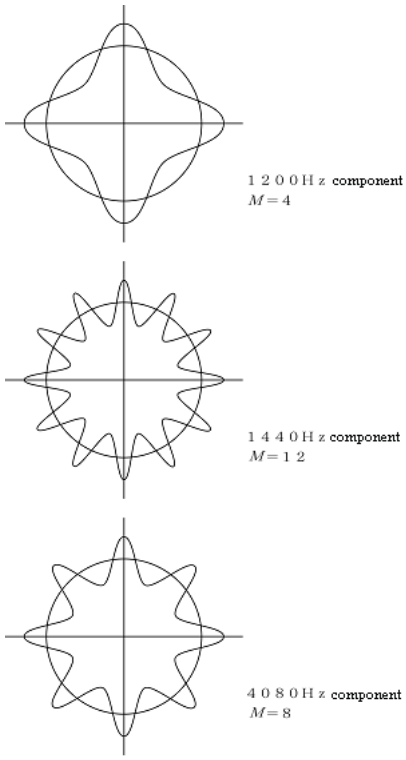
Confirm the vibration mode by measuring multiple points





Poles/output: 3-phase 4-pole 2.2 kW
Type: Totally enclosed fan-cooled motor

Electromagnetic Force Mode and Frequency

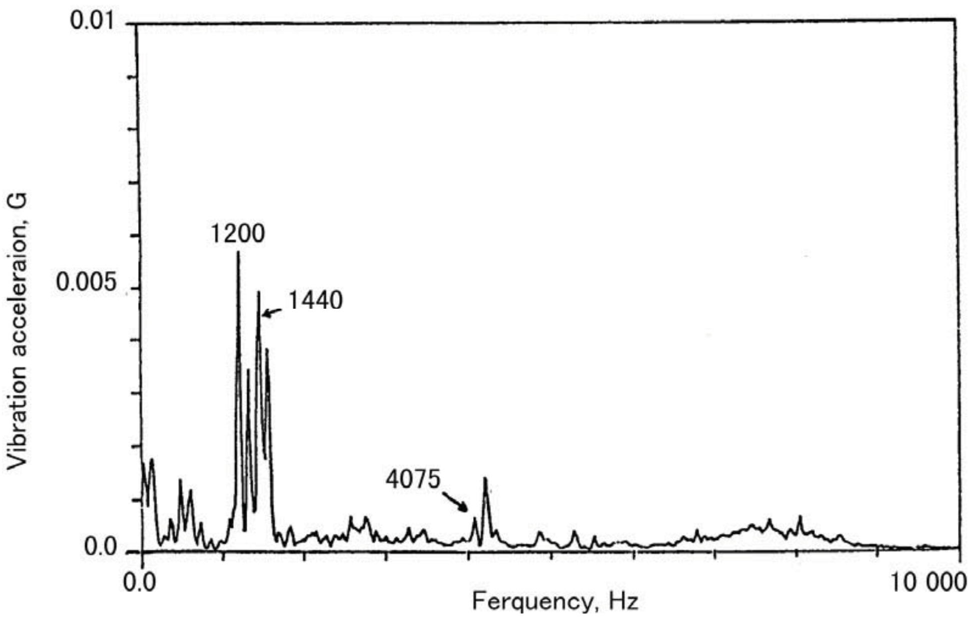


No.	Frequency (Hz)	Electromagnetic force mode M
1	$\lvert z_2 - z_1 + 2p \rvert$	$\left\{ k \frac{z_2}{p}(1-s) - 2 \right\} f$
2	$\lvert z_1 - z_2 + 2p \rvert$	$\left\{ k \frac{z_2}{p}(1-s) + 2 \right\} f$
3	$\lvert z_2 - z_1 \rvert$	$\left\{ k \frac{z_2}{p}(1-s) \right\} f$

No.	Frequency f (Hz)	Electromagnetic force mode (M)
1	1200	4
2	1440	12
3	4080	8

Vibration Spectrum During Operation

(Actual: No-load)



Simulation Step 3

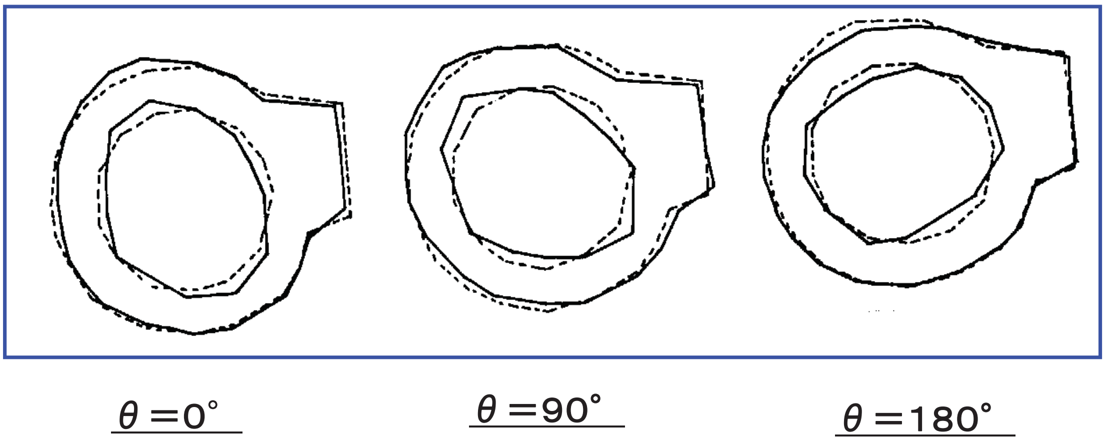
Vibration Mode During Operation (Actual)

1200Hz, Electromagnetic force mode: M=4

For electromagnetic force mode M=4:

The vibration mode during drive **N=2 is a stationary mode**.

➡ The mode during drive dominates the structural eigenmode.



Simulation Step 3

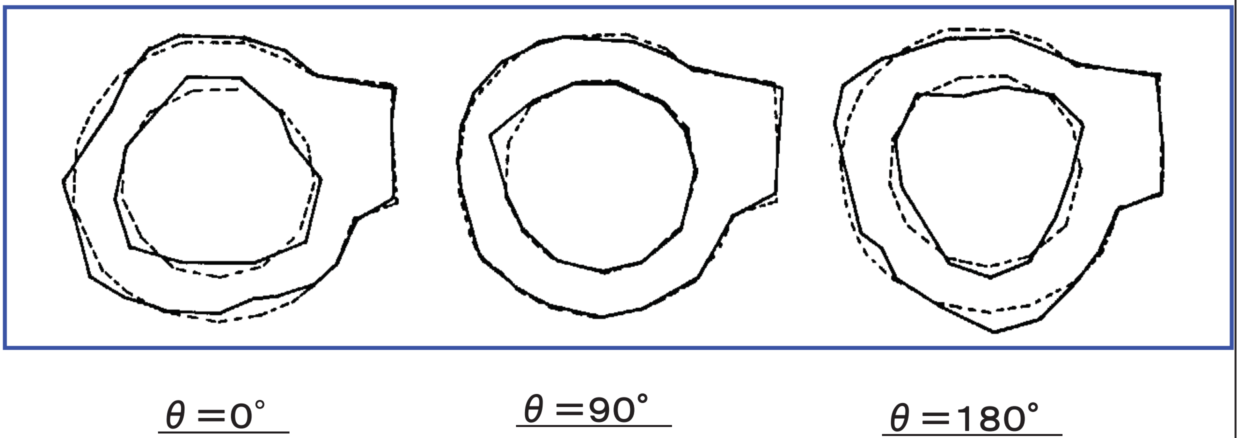
Vibration Mode During Operation (Actual)

4075Hz, Electromagnetic force mode: M=8

For electromagnetic force mode M=8:

The vibration mode during drive **N=3 is a stationary mode**.

➡ The mode during drive dominates the structural eigenmode.



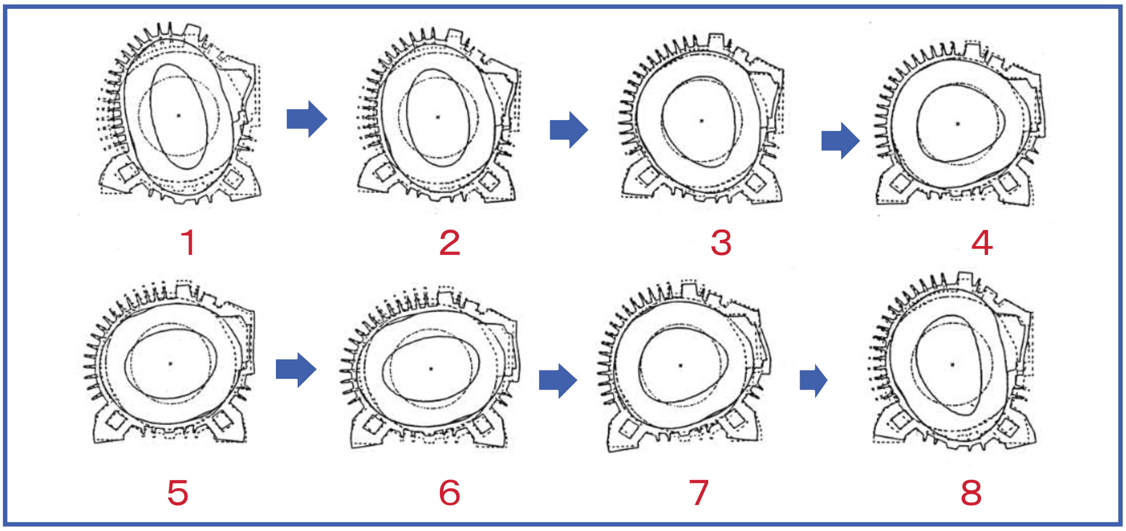
Simulation Step 3

Vibration Mode During Operation (Calculated)

(Step response analysis) 1200Hz, Electromagnetic force mode: M=4

Electromagnetic force → Vibration response → Vibrations on frame's surface

The vibration mode during drive N=2 is a stationary mode for the electromagnetic force mode M=4.



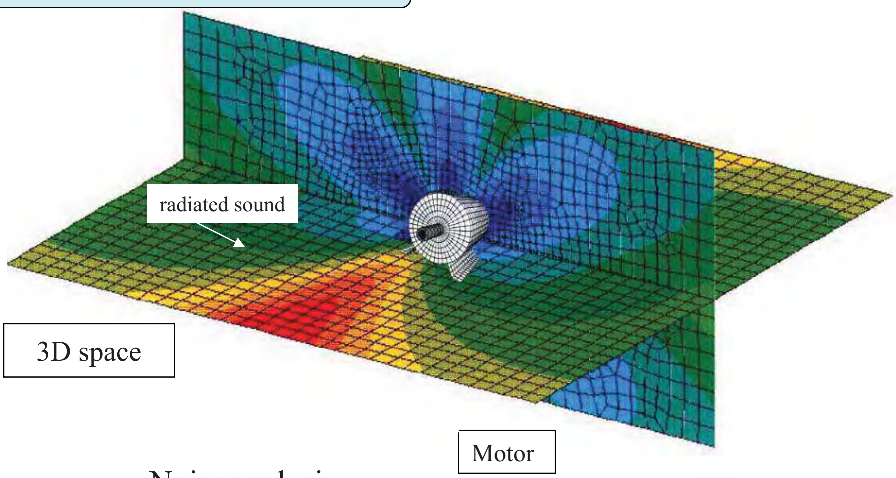
Electromagnetic Noise Calculation Technology of Motors

Electromagnetic - contact - vibration - noise analysis

Feedback to design from general analyses

Noise distribution expanding in 3D space

Error of 3 to 5 dB from actual values



Noise analysis