Approaches and Future of Iron Loss Analysis in JMAG

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JMAG

Approaches and Future of Iron Loss Analysis in JMAG

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Project Outline

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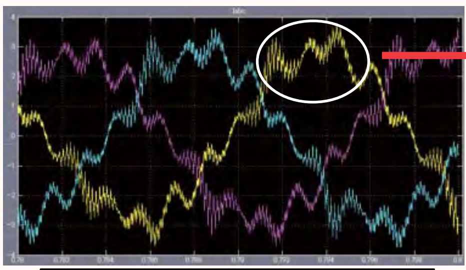
- Objective
  - Validate the iron loss calculation accuracy of magnetic field analyses (JMAG) by comparing the actual measurements of iron loss.
  - Clarify the causes of discrepancies between “the actual measurements and analyses.”
- Comparing the measured and analysis results
  - The iron loss is calculated by applying a waveform approximate to the actual current to the analysis by linking JMAG-RT and a circuit/control simulator.
    - Various harmonics can be taken into account
  - The iron loss is calculated from the torque measured using a motor bench.



Actual current waveform

Origin of harmonics

Inverter (modulation method, dead time…)

Control method

Gap harmonics within the motor

Distortion caused by magnetic saturation

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JMAG-RT + Circuit/Control Analysis

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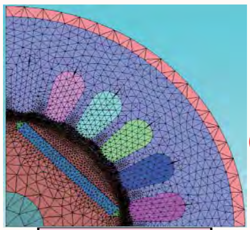
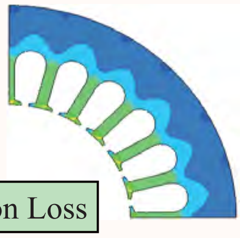
- A Method using a "behavior model" created in advance with FEA (indirect coupling)
  - High-speed and highly accurate
  - All of the harmonics originating in the motor, inverter, and controller are taken into account.



FEA Model

(1) Calculate motor characteristics with FEA
(Torque, inductance, magnetic flux)

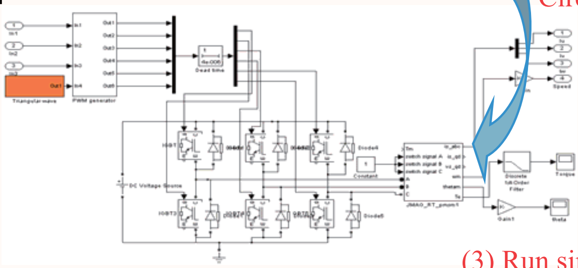
JMAG-RT model
L (I, θ)
Torque (I, θ)



Iron Loss

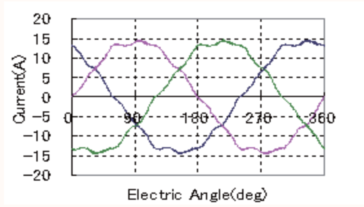
(2) Utilize a Circuit/control simulator

(4) Recalculate using JMAG



Circuit/control simulator

(3) Run simulation



Current waveform

Example Evaluation Motor

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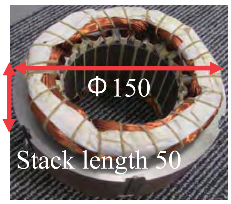
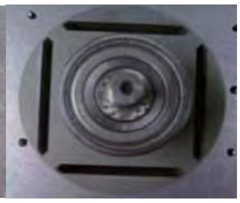
- The motor prototype is created, tested, and the iron loss is compared.

Evaluation motor



Stator

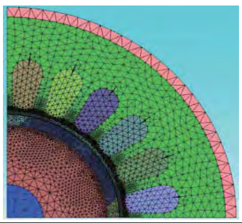
Interior permanent magnet rotor



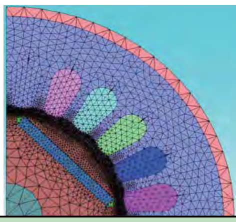
Surface permanent magnet rotor

Motor test bench

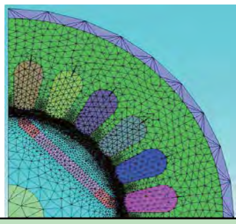
FEA model



Surface permanent magnet



Interior permanent magnets Magnet: large



Interior permanent magnets Magnets: small

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Comparing the Analysis and Measurements of Iron Loss

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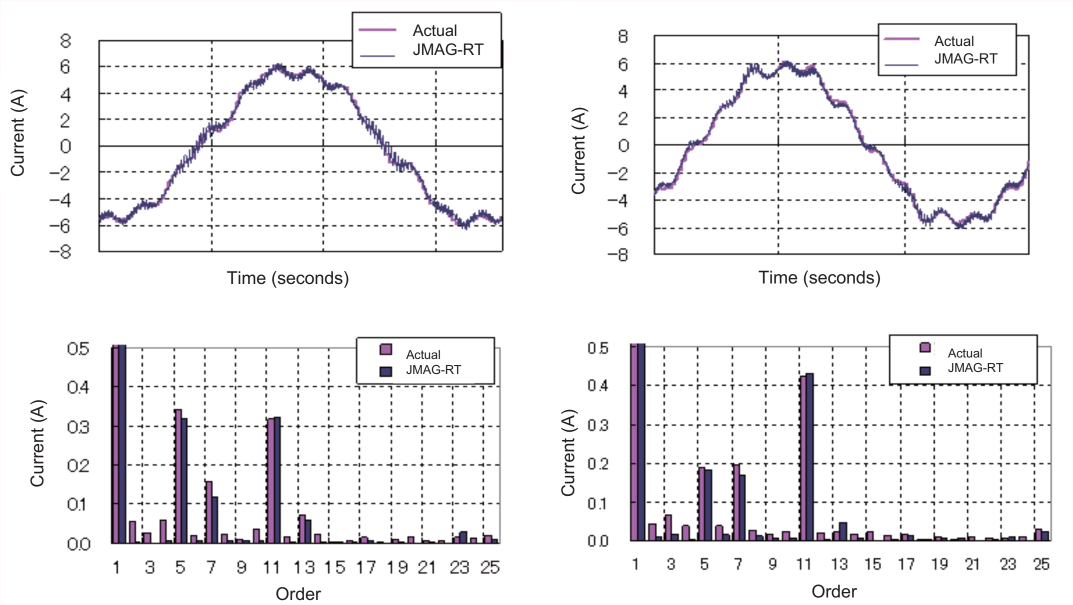
Comparing the Current Waveform

- Accurately measure the current waveform of various phase angles for the prototype

Current waveform

Harmonic analysis



Current phase angle 10 degrees

Current phase angle 60 degrees

*IPM,DC Voltage:250V,Carrier Frequency:6kHz,Current:4A$_{rms}$,Speed:1800r/min

Iron Loss (Current Phase Angle Dependency)

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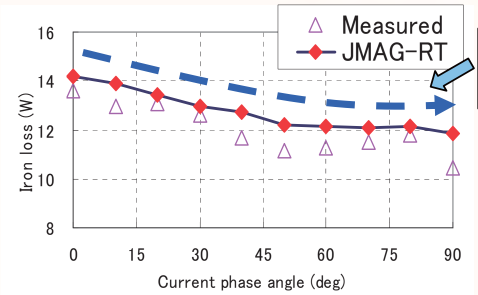
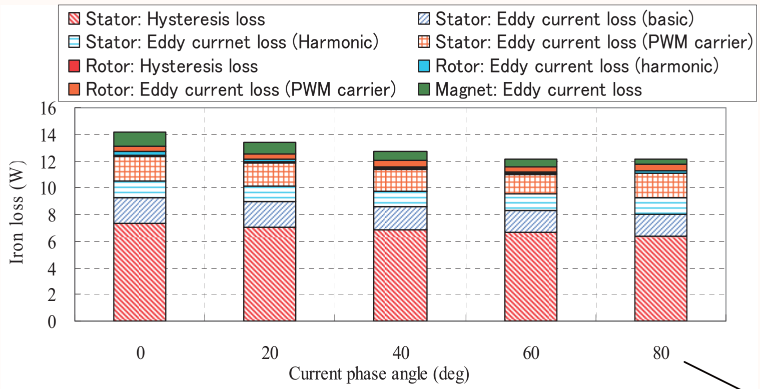
*IPM,DC Voltage:250V,Carrier Frequency:6kHz,Current:4A_{rms},Speed:1800r/min

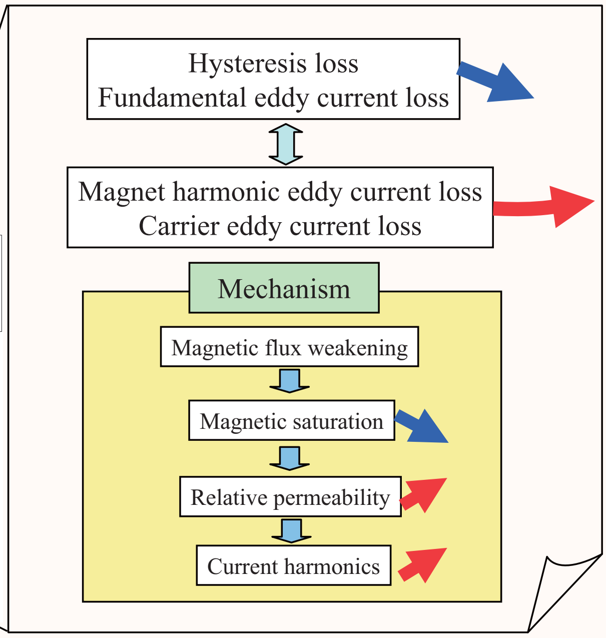


The iron losses for magnetic flux weakening are not reduced by frequency!

Iron losses (current phase)



Breakdown of iron loss analysis results



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Iron Loss (DC Bus Voltage Dependency)

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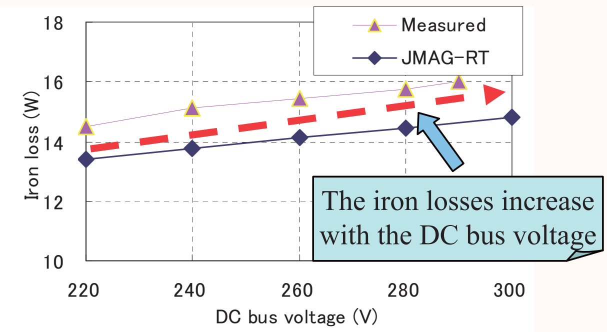
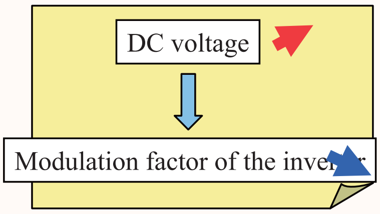
*IPM, Carrier Frequency: 6kHz, Current: 4A_{rms}, Phase Angle: 10 deg, Speed: 1800 r/min

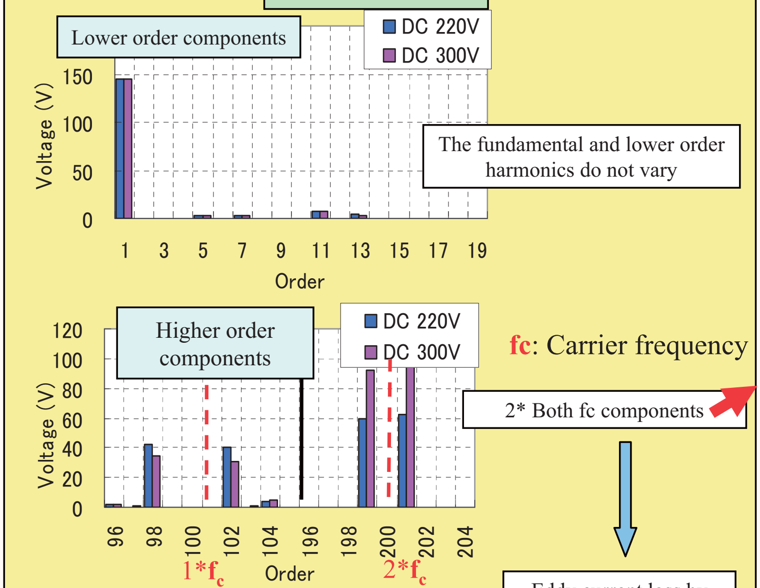


Iron losses (DC Bus Voltage)



Relationship of DC voltage and the modulation factor

Mechanism



Harmonic components in the voltage between U-V wires

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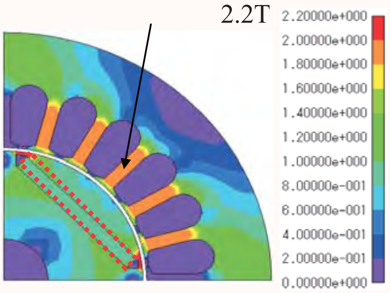
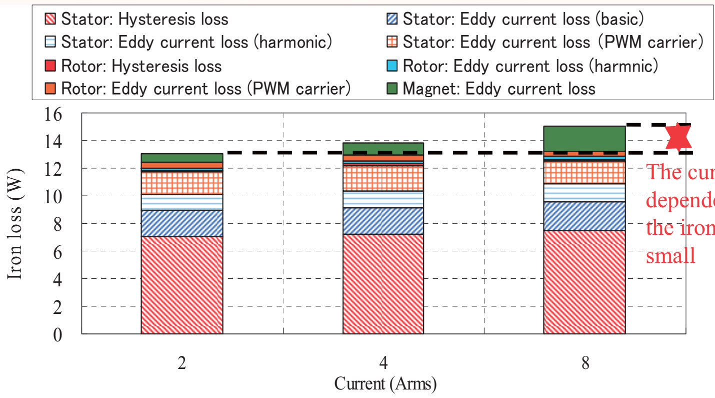
Iron Loss (Magnet Dependency)

*IPM, DC Voltage:250V, Carrier Frequency:6kHz,Phase Angle:10deg,Speed:1800r/min

Large magnetic saturation occurs

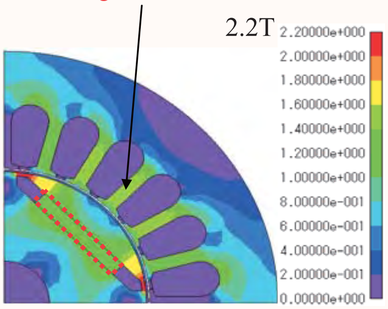
Magnets Large

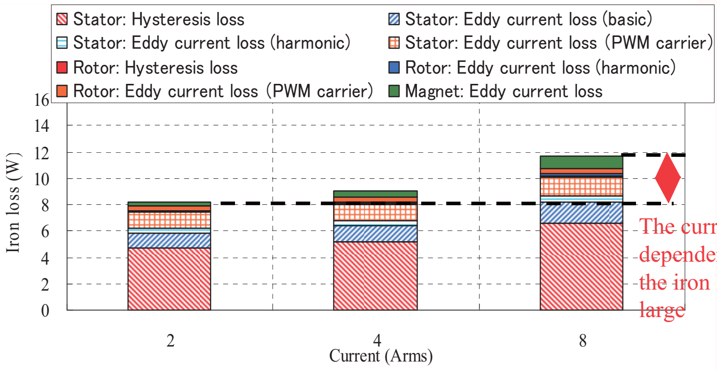




Alleviates magnetic saturation

Magnets Small





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Contributing Factors Affecting the Iron Loss Calculation

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Objective/Contents

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[Objective]

- Many say the iron loss calculated via magnetic field analysis and that measured differ.
- How accurate are the results? How much do the various factors affect an analysis? I would like have some common guidelines.
  - Analyses can be used with confidence by clarifying the accuracy of the iron loss calculation.
    - It's great if they match, but knowing the contributing factors of errors when they don't is important.
  - Guidelines can be established for the same model of motor by analyzing the affects of the various contributing factors causing error.

[Contents]

- Factor Analysis
  - Using the Harumi 1 (IPM motor), the contributing factors causing error are clarified using measurements and CAE.
  - The contributing factors can be analyzed by switching the motor type, operating points, and drive method.
- Sensitivity Analysis
  - The sensitivity of the contributing factors making up the iron loss clarified above are examined using CAE.

Effects of Element Size in Automatic Mesh Generation

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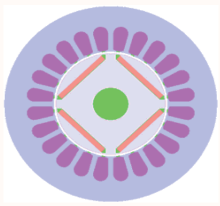
- Objective
  - There are various ways to examine the effects of calculation methods, stress, etc., on the iron loss.
  - However, there are very few examples related to the effects of numerical error in the finite element method on the iron loss.
  - The following examines the effects of discretization error (mesh generation) on the iron loss.
  - Special attention is paid to how roughly the mesh can be generated.
- Analysis model
  - An interior magnet synchronous rotation motor model based on the "Electromagnetic Field Analysis for Rotating Machine Design and Performance Evaluation" from the IEEJ (hereinafter: Harumi 1)

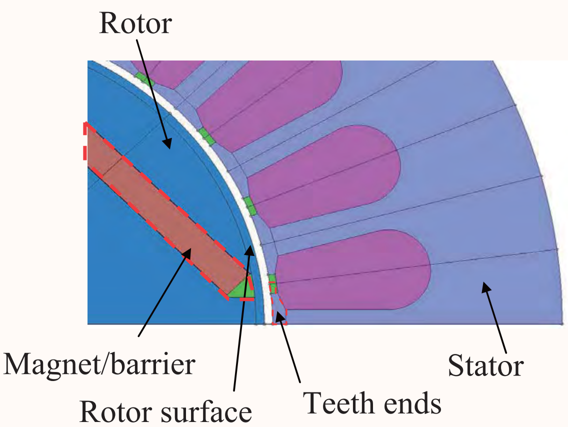
Stator Rotor



[Terminology]
Deviation: Difference from the desired values (average/maximum)
Variations: A squared difference from the desired values
Variance: Average values of the variations
Standard deviation: Square root of variance

Element size

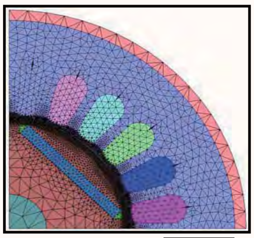
- The model is separated as indicated in the figure below to examine the areas the element size is vital.
- The following 3 standard element sizes (average length of element edges for automatic mesh generation using Delaunay triangulation) are set for each area of the model. A fixed number of 7 divisions in the radial direction and a division every 0.5 degrees in the circumferential direction is used for the gap area.
  - Standard 1:0.5 mm
  - Standard 2:1 mm
  - Standard 3:2mm



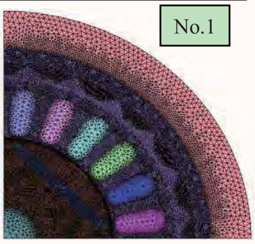
L18 Orthogonal array

No.	A: Stator	B: Teeth ends	C: Rotor surface	D: Rotor	E: Magnet and barrier
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	2	1	1	2	2
5	2	2	2	3	3
6	2	3	3	1	1
7	3	1	2	1	3
8	3	2	3	2	1
9	3	3	1	3	2
10	1	1	3	3	2
11	1	2	1	1	3
12	1	3	2	2	1
13	2	1	2	3	1
14	2	2	3	1	2
15	2	3	1	2	3
16	3	1	3	2	3
17	3	2	1	3	1
18	3	3	2	1	2

Example of Mesh Divisions; Number of Elements/Nodes



Original Mesh manual generated by an analysis specialist
Elements: 9426 Radial direction: 7 divisions
Nodes: 5415 Circumferential divisions: Division every 0.5 degrees



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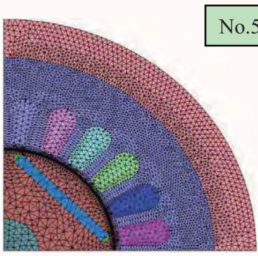

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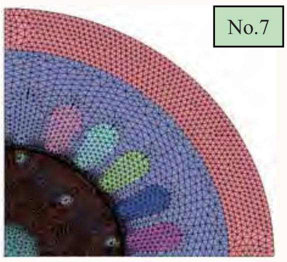

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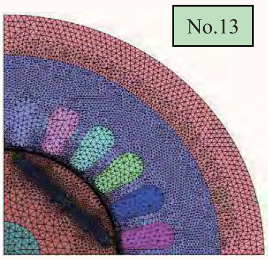

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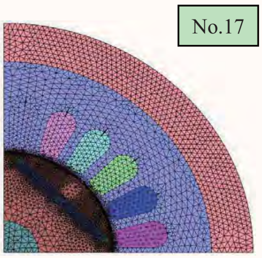

No.17

Nodes/Elements

	Nodes	Elements
1	17830	34023
2	14334	27091
3	13483	25415
4	6934	12357
5	5535	9591
6	9614	17669
7	7654	14365
8	5722	9973
9	4310	7165
10	13942	26329
11	17642	33651
12	15658	29739
13	7351	13219
14	9647	17733
15	6501	11497
16	4680	7873
17	5649	9841
18	7513	13501

Breakdown of Iron Loss Results (Original Mesh)

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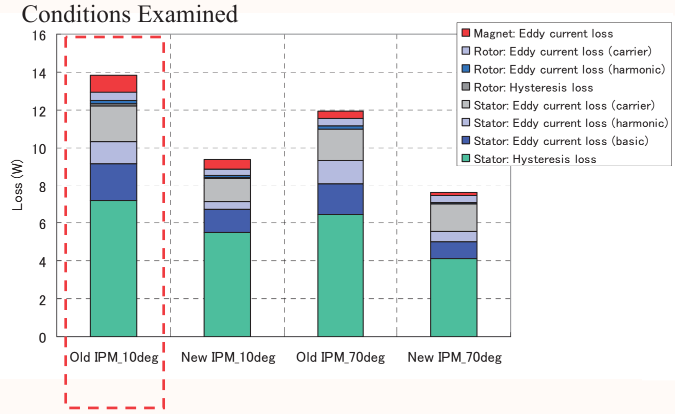
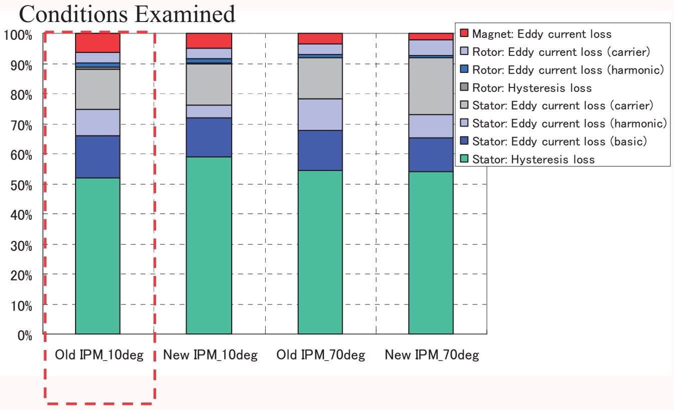
- The mesh to generate differs based on the contributing factors and area of the iron loss.
- The hysteresis loss of the stator contributes to half of the iron loss at 1800 r/min for the motor used in this analysis.

*Motion condition: Rotation speed 1800 r/min; current :4 Arms;current phase angle :10 degrees



Each component of iron loss



Component ratio of iron loss

・Harmonic eddy current loss of the stator ⇐ Spatial harmonics in the magnetomotive force of the magnets

・Harmonic eddy current loss of rotor ⇐ Slot harmonics

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Sensitivity of Mesh Divisions (All Standards)

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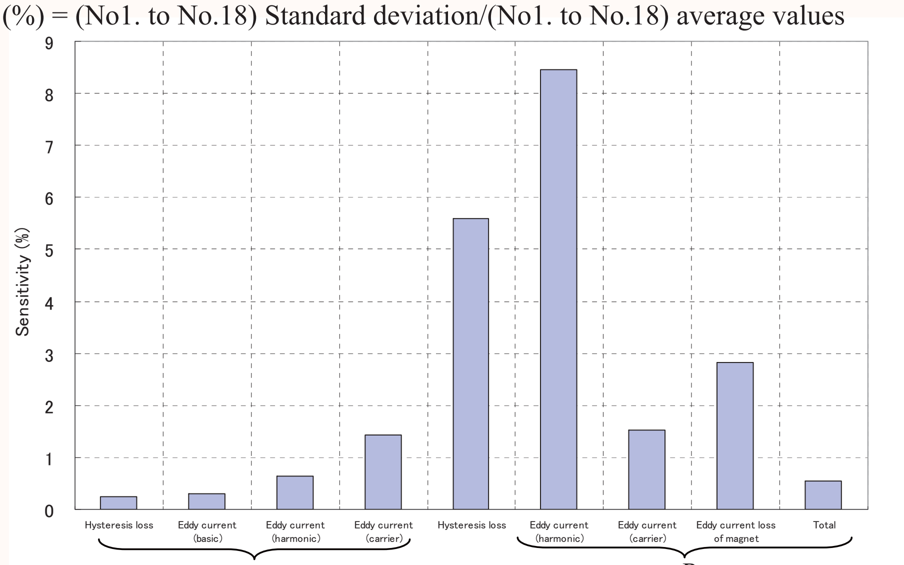
- Quantify the approximate effects on the eddy currents caused by changing the element size of each part.
  - Sensitivity (%) = (No1. to No.18) Standard deviation/(No1. to No.18) average values



Sensitivity for iron loss

・The mesh divisions only minimally affect the stator hysteresis loss which is the primary component.

・The mesh largely affects the hysteresis loss and harmonic eddy current loss of the rotor.

・The sensitivity of the total iron loss is less than 1%

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Factor Analysis

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- The amount the element size of each part affects the iron loss was analyzed (analysis of variance table) by factor. The desired values are based on the results from the original mesh
  - Factor

    Element size of stator: A

    Element size of teeth ends: B

    Element size of rotor surface: C

    Element size of rotor: D

    Element size of magnets/barrier: E
  - The contribution of each factor is analyzed by the variations (a squared difference of 2 from the desired values) for each standard for each factor

    Contribution: Variation ratio of each component to the total variations

Analysis of Variance Results

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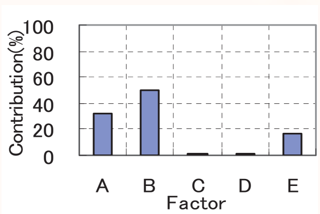
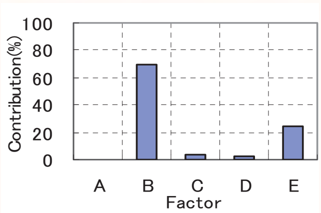
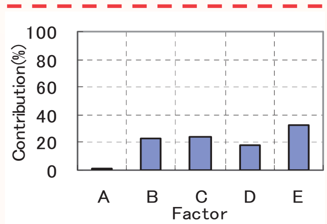


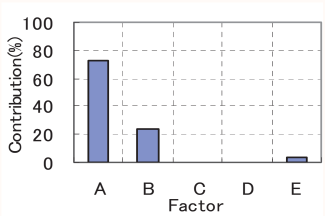
Contribution to stator hysteresis loss



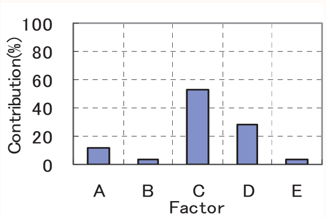
Contribution to eddy current loss of stator



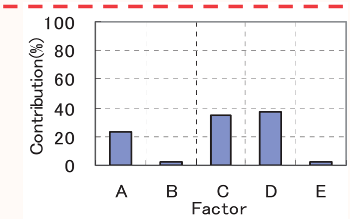
Contribution to harmonic eddy current loss of stator



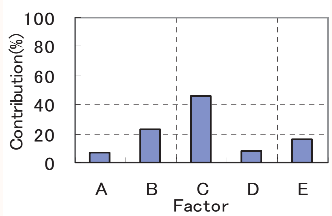
Contribution to carrier eddy current loss of stator



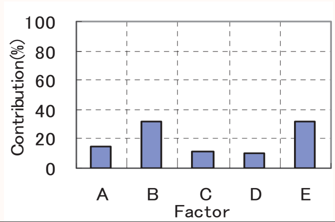
Contribution to hysteresis loss of rotor



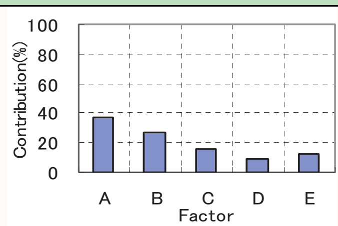
Contribution to harmonic eddy current loss of rotor



Contribution to carrier eddy current loss of rotor



Contribution to eddy current loss of magnets



Contribution to total iron loss

Conclusion from Results

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- Overall, the effects of mesh in each area producing the iron loss is large, but the mesh of the rotor affects the harmonic eddy current loss of the stator more than the mesh of the stator.
  - The spatial resolution of the magnetomotive force of the magnets is vital.
- The mesh divisions of the teeth ends (B) and the rotor surface (C) are important when considering the ratio of surface area.
- The stator is the largest contributor to the total iron loss.
  - Because the ratio of hysteresis loss and carrier loss of the stator is large for this motor

Effects of stator and rotor

Components strongly affected by stator mesh	Hysteresis loss of stator Eddy current loss of stator Carrier loss of stator Total iron loss
Components strongly affected by rotor mesh	Harmonic eddy current loss of stator Hysteresis loss of rotor Harmonic eddy current loss of rotor Carrier eddy current loss of rotor

Examining Breakdown in the Iron Loss Solution

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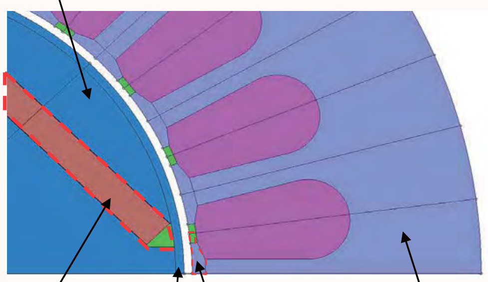
- We examined where the iron loss results breakdown when the element size is larger and larger.

  ➡ I would like guidelines for the mesh divisions for simple designs of rotation machines

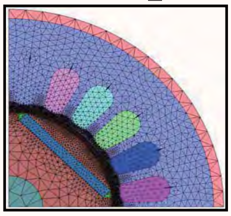
- The elements sizes indicated in the table below are set for each part. The parts not indicated in the table are set to have an element size of 2. A fixed number of 3 divisions in the radial direction and a division every 3 degrees in the circumferential direction were specified for the slide face.



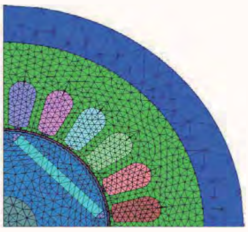
Case 2 of element sizes

No.	Stator	Teeth ends	Rotor Surface	Rotor	Magnets and barriers
1	0.5	0.5	0.5	0.5	0.5
19	2.5	2.5	2.5	2.5	2.5
20	5	5	5	5	5
21	7.5	7.5	7.5	7.5	7.5
22	10	7.5	7.5	7.5	7.5
23	10	7.5	7.5	10	7.5
24	7.5	7.5	7.5	7.5	10
25	7.5	7.5	10	7.5	7.5
26	5	5	10	5	5
27	7.5	10	7.5	7.5	7.5

Example of Mesh Divisions; Number of Elements/Nodes



Mesh manual generated by an analysis specialist
Elements: 9426 Radial direction: 7 divisions
Nodes: 5415 Circumferential divisions: Division every 0.5 degrees



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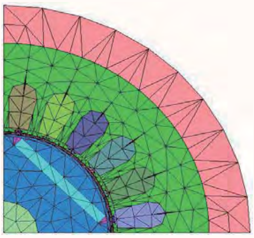

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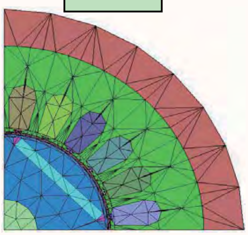

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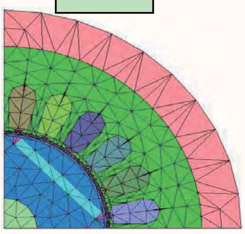


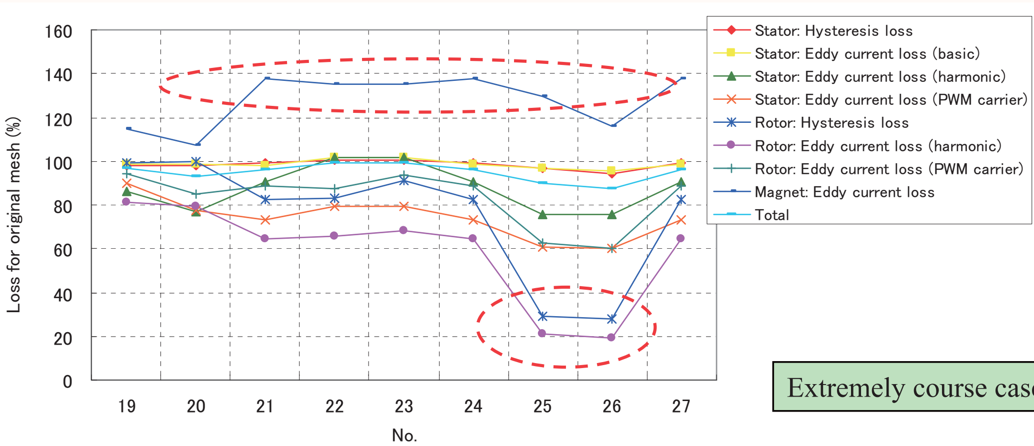
No.25

Nodes/Elements

No.	Nodes	Elements
19	1166	2144
20	566	982
21	447	754
22	411	688
23	401	674
24	447	754
25	445	750
26	560	970
27	447	754

Deviation from Original Mesh

- Indicate the ratio (standardized at 100%) for results from the original mesh
  - Ratio (%) = (No.** results)/(results of original mesh)*100
- The following is obtained:
  - Hysteresis loss and eddy current loss of stator (basic frequency): Minimally affected by the mesh
  - Hysteresis loss and eddy current loss of the rotor (harmonic), eddy current loss (carrier): Breaks down at a 10 mm element size for the rotor surface (No.25, 26) to 1/5. The rotor surface has approx. 13 divisions per electric angle.
  - Eddy current loss of magnets: The deviation is approx. 40% above a 7.5 mm element size for the magnets (43 mm × 4 mm).
  - The maximum difference in the total iron loss is approx. 10%



Extremely course case for mesh

Effects of Punching

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- Overview
  - The iron loss of electromagnetic steel sheet is known to increase by punching due to deterioration of the magnetic properties as the cutting plane.
  - The effects of punching were measured for the Harumi 1.

Physical Background of Deterioration

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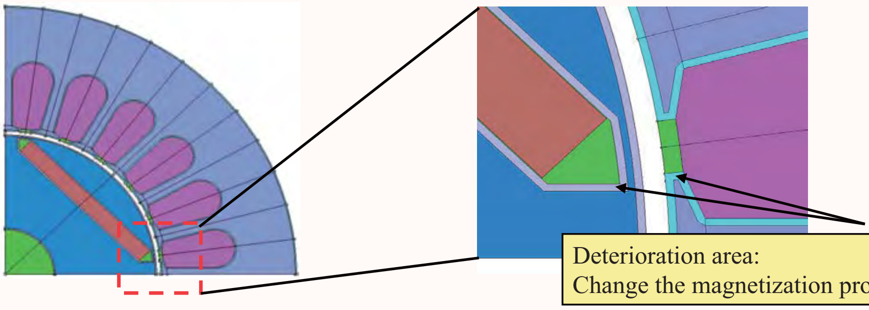
- From SA-07-24, "Discussion on Modeling of Core Characteristics of Small-size Motor,"
  - Deterioration is caused by the crystal breakdown of plastic deformation and compression stress of elastic regions.
  - Regions approx. 1 to 3 times the sheet thickness from the cut region are affected.

Accounting for Deterioration

- The material properties for the region of the approximate sheet thickness from cutting plane is changed (hereinafter deterioration areas).
- Parameters: Magnetization properties, iron loss characteristics, and width of deterioration areas.

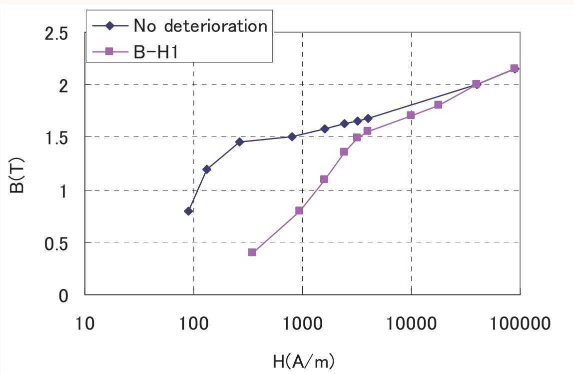


Deterioration area:
Change the magnetization properties and iron loss characteristics

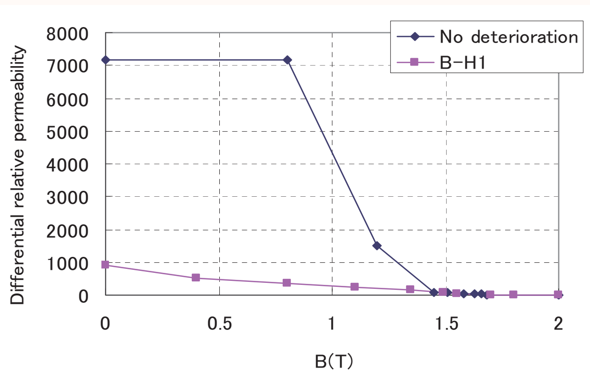
- The characteristics of the deterioration area are assumed to be the characteristics at the smallest width of the punched edge.
- The eddy current loss should not increase

Parameters

- Width of deterioration areas
  - 1-times (0.35 mm)/2 times (0.7 mm) the sheet thickness
- Magnetic characteristics
  - Deterioration areas: 1.1 mm (B-H1)/30.1 mm (no deterioration)
  - Other: 30.1 mm (no deterioration)
- Hysteresis loss
  - Deterioration areas: 2 time the hysteresis loss for 35H360 (with deterioration)/no changes (no deterioration)
  - Other: No changes (no deterioration)



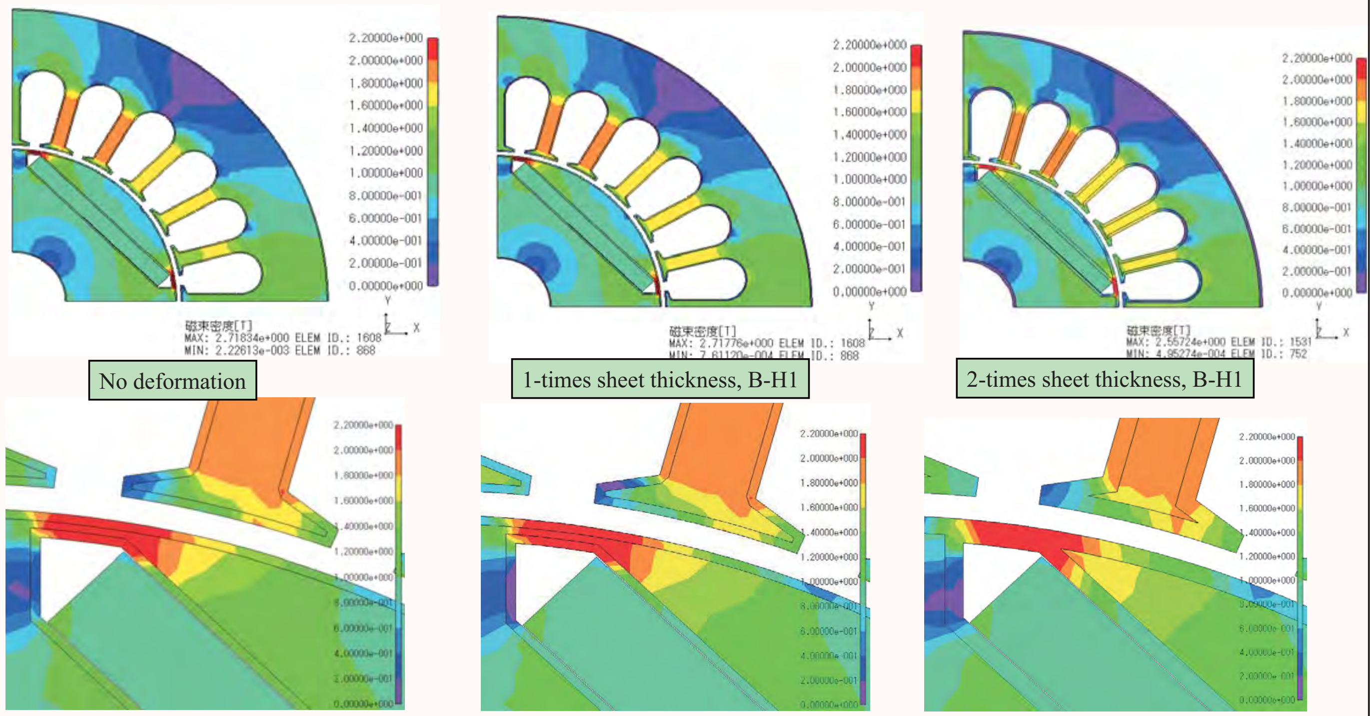
B-H curve



Differential relative permeability

Magnetic Flux Density Distribution

- A large difference does not appear suddenly in the distributions



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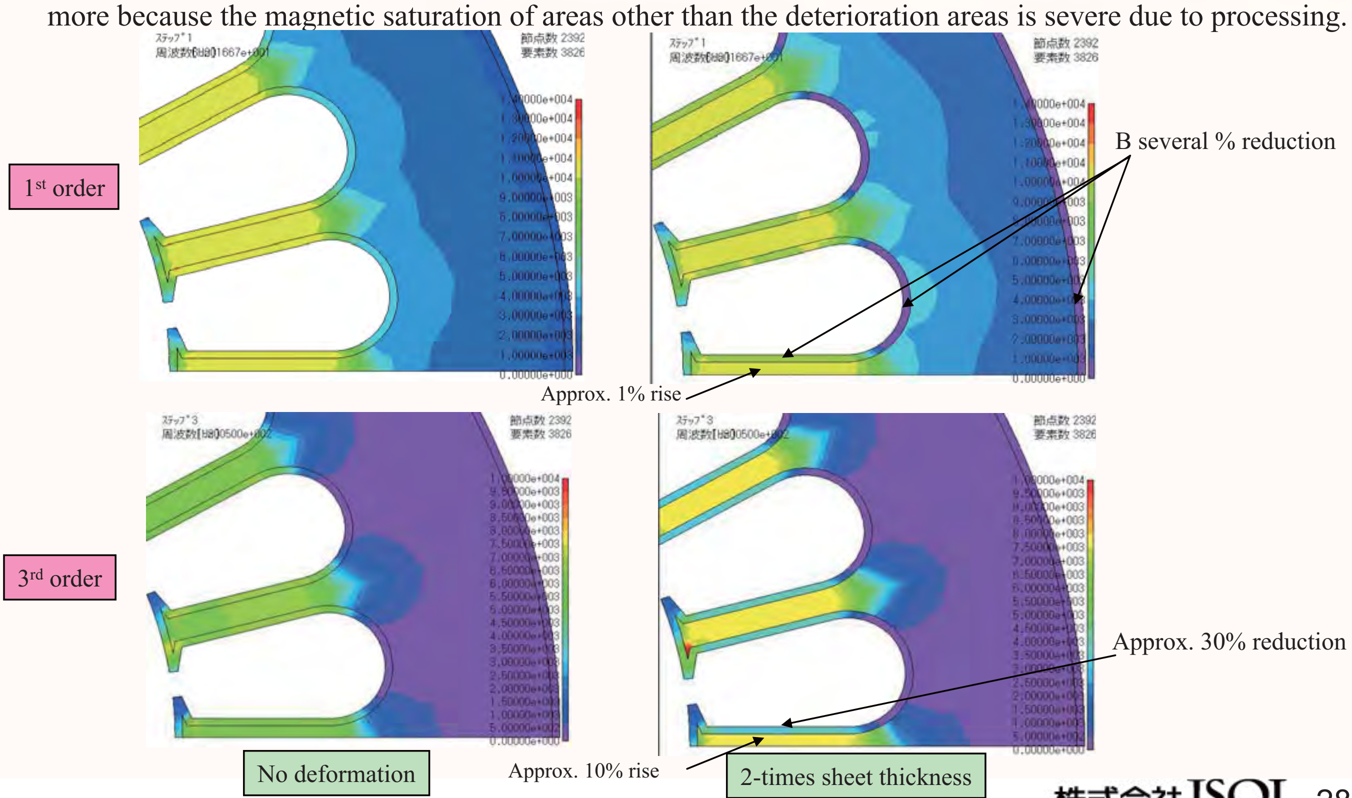
Order Components of Magnetic Flux Density (Stator)

- The 1st order harmonic component increases slightly while the 3rd order harmonic component increases more because the magnetic saturation of areas other than the deterioration areas is severe due to processing.



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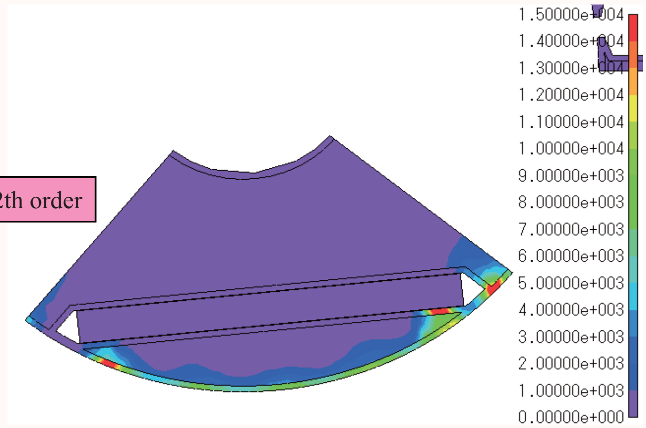
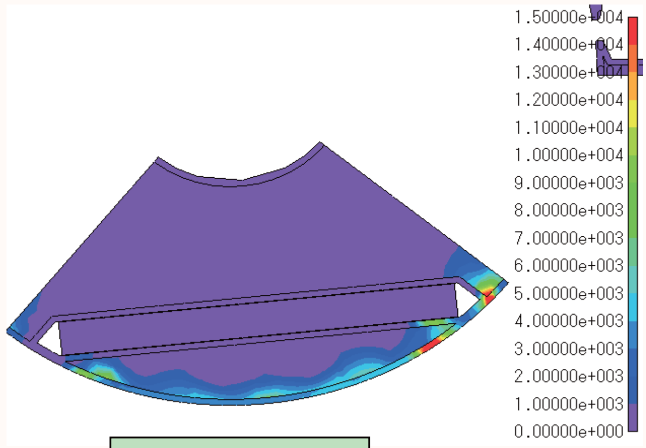
Order Components of Magnetic Flux Density (Rotor)

- The 12th order component of the rotor has a large reduction in the deterioration area (partial increase)
- That reason is most likely due to the large reduction in differential permeability at 0.7 T in processed areas because the magnetic flux density of the rotor surface is give or take 0.7 T.
  - The magnetic flux density penetrates that much more

12th order



No processing



2-times sheet thickness

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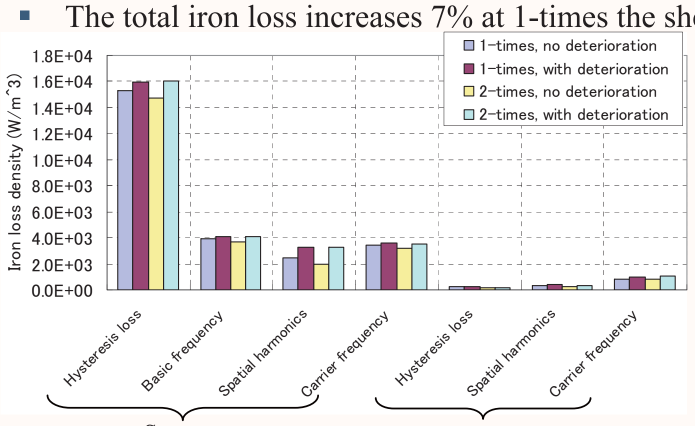
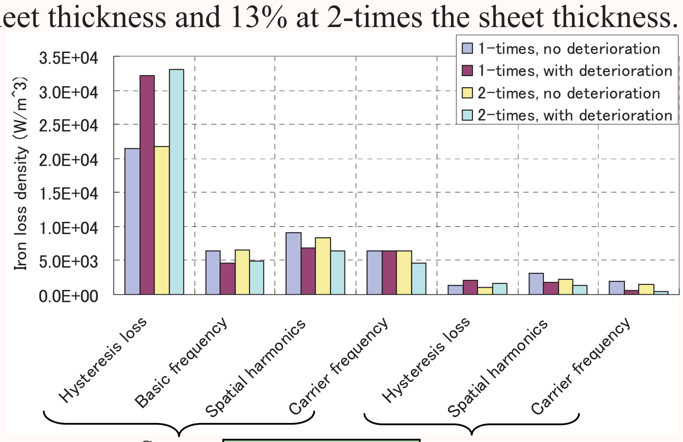
Iron Loss for Each Unit Volume

- The hysteresis loss increases in the processed areas, but not quite 2 times.
  - This is mostly likely caused by the reduction in magnetic flux density in the deterioration area due to a lower permeability.
- The eddy current loss is also affected by the change in the magnetic flux density waveform.
- The loss increases slightly if the deterioration is also taken into account in non-deterioration areas.
  - Resulting from a slight increase of magnetic flux density in the non-deterioration areas
- The difference between the "1 times, no deterioration" and the "2 times, no deterioration" is caused by the mesh.
- The total iron loss increases 7% at 1-times the sheet thickness and 13% at 2-times the sheet thickness.



Stator Rotor

Non-deterioration areas



Stator Rotor

Deterioration areas

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Conclusion of Sensitivity on the Iron Loss

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- Analysis of some factors not included in this seminar
- As a whole, the sensitivity on the iron loss for the basic frequency is small, but high for high-frequencies.

Structural Elements	Control Factors				
	Relative permeability (magnetization)	Magnetization correction (magnetization)	Element size (mesh)	Slide face divisions (mesh)	Deterioration caused by punching
Iron loss (basic) P_{pri}	Less than 1%	10 to 20%	Less than 1%	Less than 1%	10% (only hysteresis)
Spatial harmonic iron loss P_{har}	Less than 1%	20%	10 to 40%	5 to 40%	20% to 30%
Iron loss caused by carrier P_{carc}	3 to 5%	40 to 50%	1 to 10%	3 to 5%	2 to 5%
Iron loss of magnetP_{carm}	Less than 10%	40 to 50%	3 to 15%	1 to 5%	Less than 1%

Minimal effects Maximum effects

Conclusions Derived from this Investigation

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- The areas requiring caution to accurately calculate the iron loss have been identified, in addition to areas that do not require caution.
- Guidelines for the density of mesh to be generated using simple design tools for motors were obtained.
  - The mesh generated on the rotor surface is vital for motors largely affected by spatial harmonics.
  - A way of determining which motors are largely affected by spatial harmonics would be useful.
- Causes changing the iron loss several times were not found for this motor (Harumi 1).
  - A problem in the measurements or analysis settings is probable if the actual measurements and analysis results differ several times.

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In the Future

- Incorporating iron loss in JMAG-RT (version 10.5)
  - The iron loss obtained using a magnetic field analysis will be implemented into JMAG-RT to incorporate the effects of the iron loss in circuit/control analyses.
  - Equivalent iron loss resistance is in the works
  - Linking to thermal circuits is on the horizon
- Examine eddy current loss of magnets
  - A feature for high-speed eddy current loss calculation has been added to JMAG-Designer version 10.4.
  - Examine the eddy current loss of magnets using the above feature
  - The eddy current loss of the magnets in the Harumi 1 are small, but we are considering incorporating the eddy current loss of magnets in JMAG-RT because it is extremely severe in concentrated winding motors, etc.

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