

Cogging Torque Cancellation in Axial Gap Motors Using Multiple-Wave Magnets with a Periodic Boundary Symmetric Arrangement

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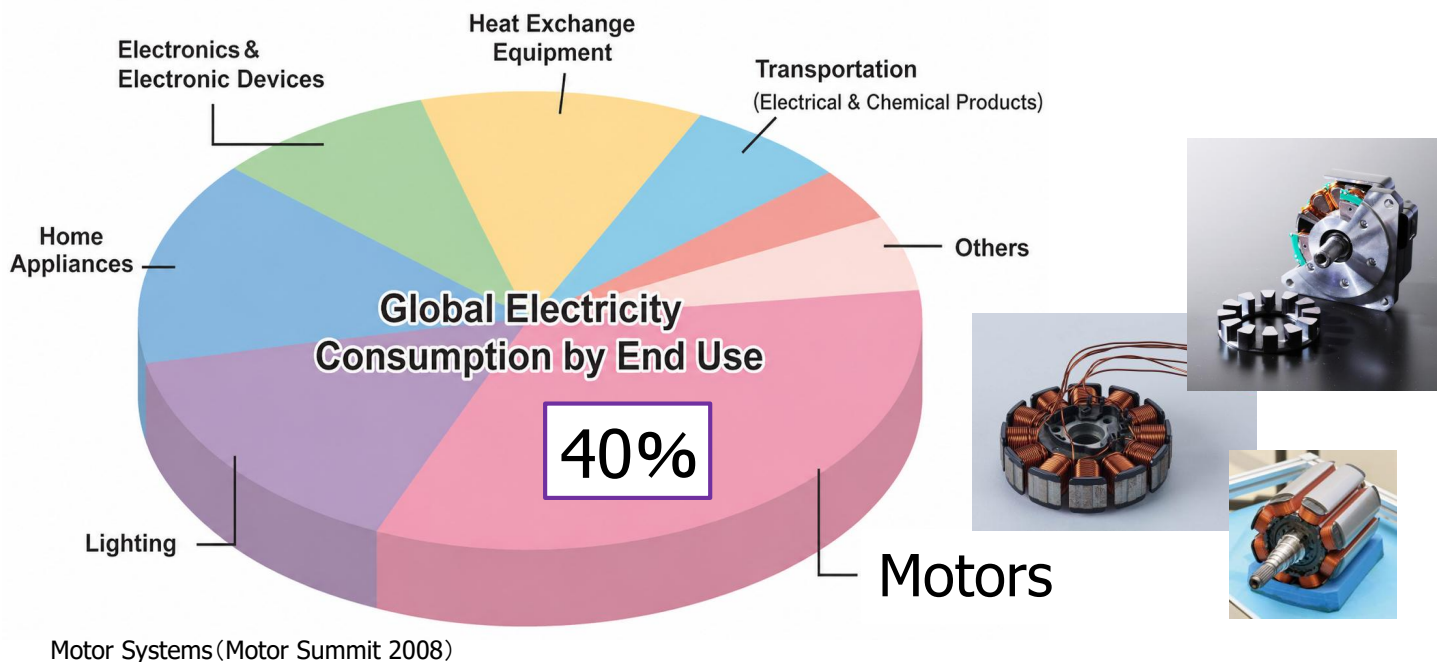
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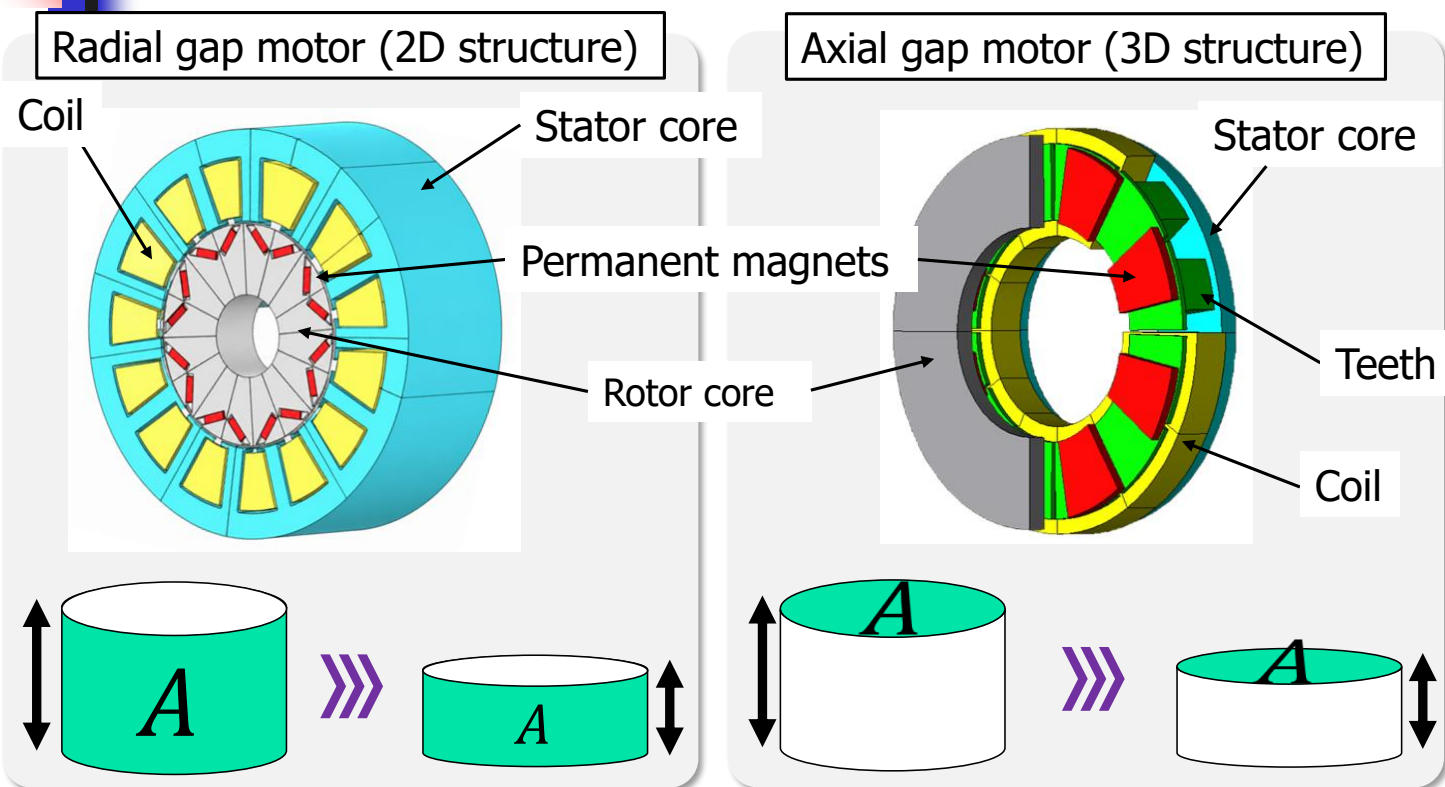
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Research Background



The demand for high-efficiency motors is increasing.

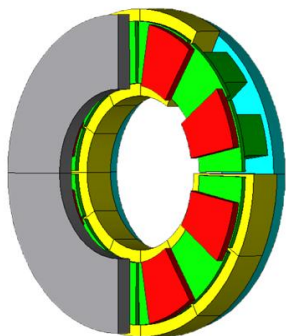
Axial Gap Motors



$$T \propto B \cdot A \cdot r$$

(*B*:Magnetic flux density, *A*:The area facing magnets and stator core, *r*:Effective radius)

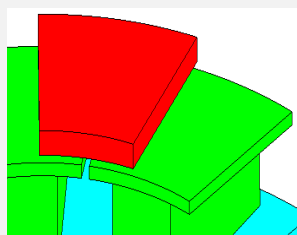
Research Purpose



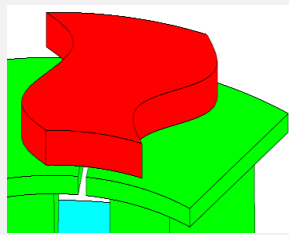
Problem

Cogging torque and torque ripple are likely to occur, leading to uncomfortable vibrations and oscillations.

① Magnet shape

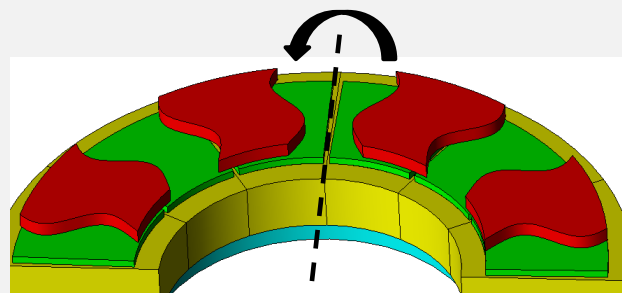


Conventional shape



Proposed shape

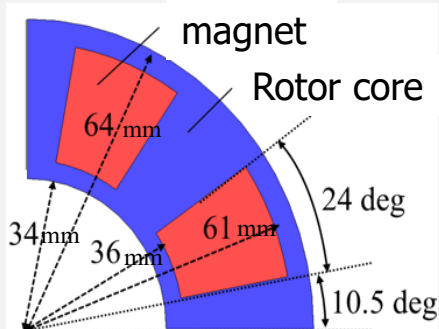
② Magnet arrangement



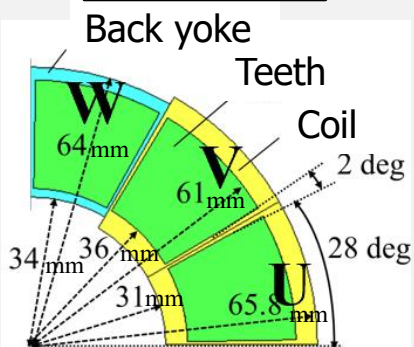
Cancel the harmonic components to reduce cogging torque.

Proposed Motor

Rotor core



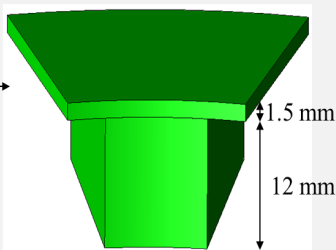
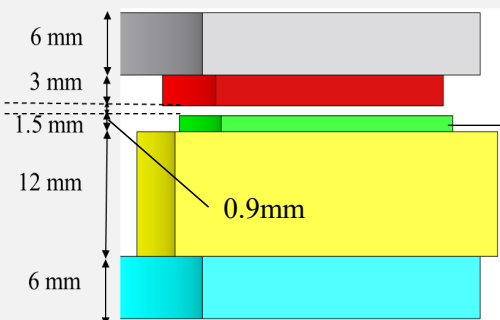
Stator core



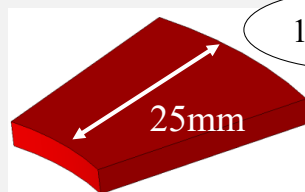
Analysis specification

magnet	N50M
Magnet temperature [deg]	20
Residual flux density [T]	1.415
Magnetization	Parallel
Core Material	35JN300
Number of rotations [rpm]	4000
Rated current [A]	70.5
Current frequency [Hz]	266.7
Air gap [mm]	0.9

Motor size



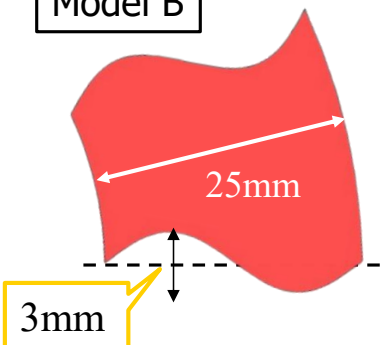
Teeth



Magnet

Proposed Motor : Magnet Shape

Model B



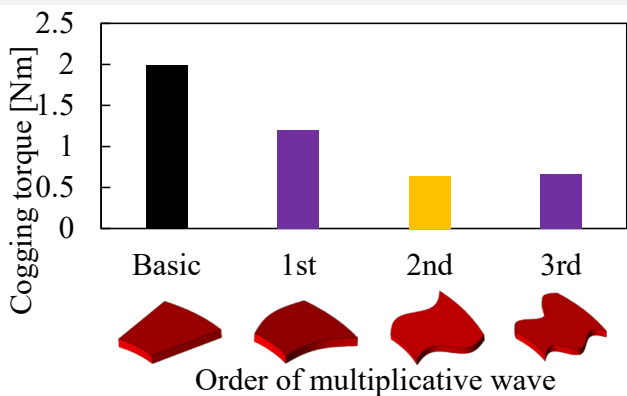
Side waveform of magnet

$$f(x) = 3 \times \sin \frac{2\pi x}{25}$$

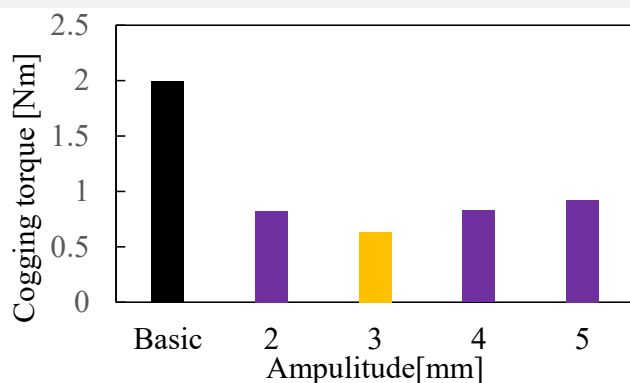
Amplitude

Sin waveform with a period of 25mm

Waveform order

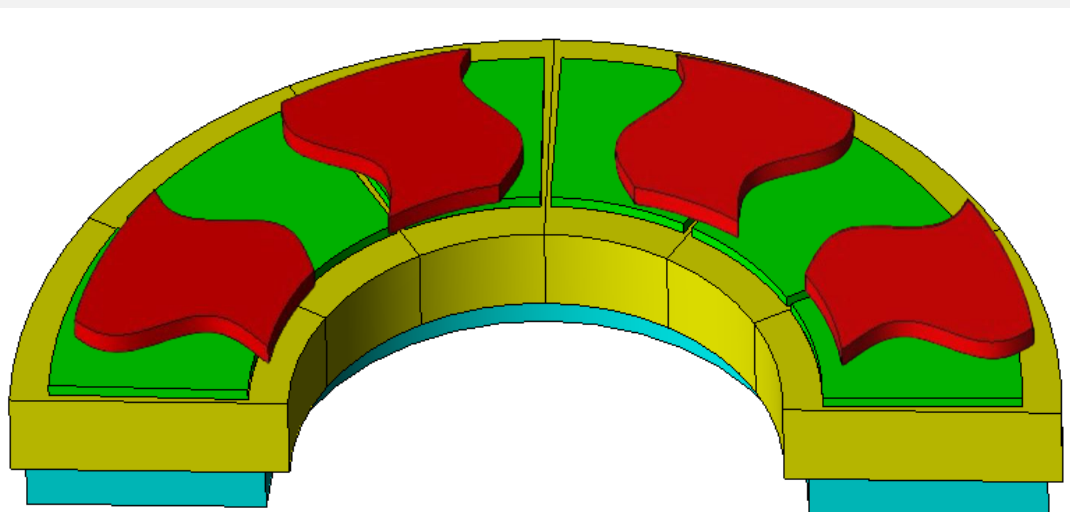


Waveform order



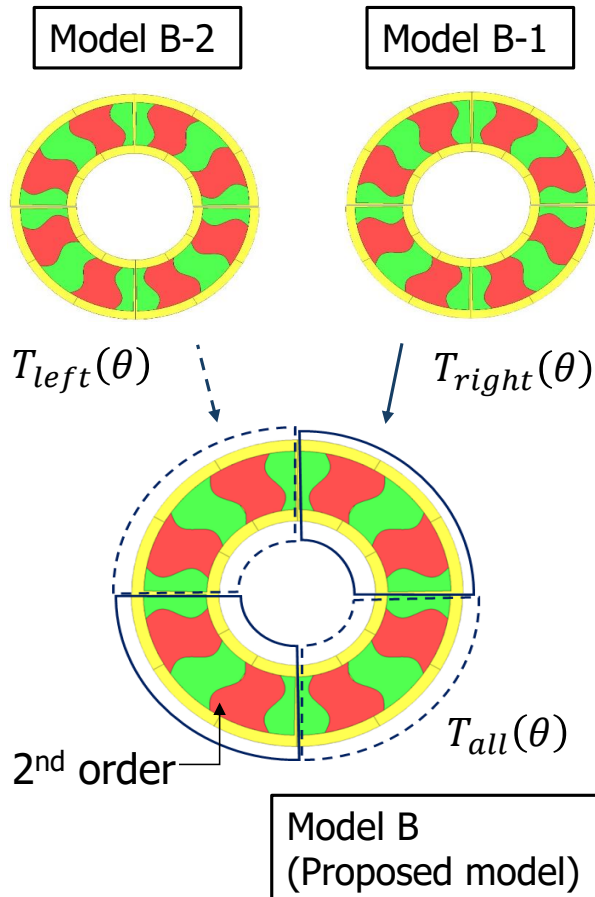
Proposed Motor : Magnet Arrangement

1/2 of model B

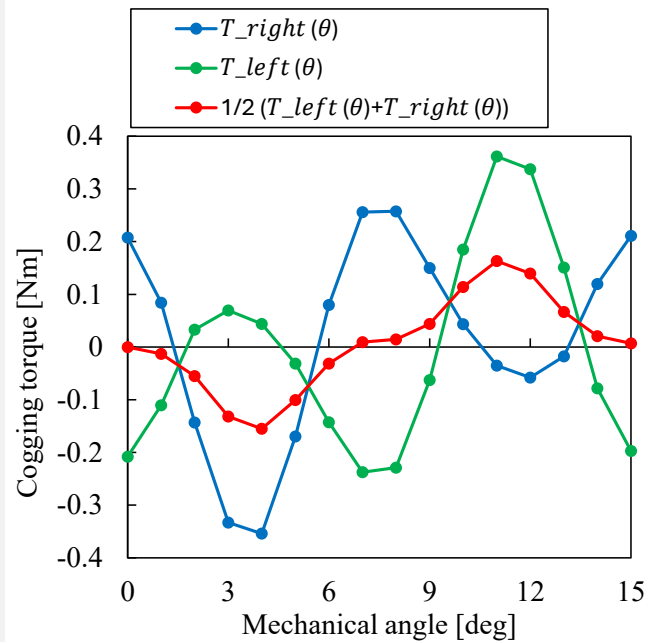


The magnets are arranged to be line-symmetric with respect to the 90-degree periodic boundary.

Proposed Motor : Magnet Arrangement



Expected cogging torque



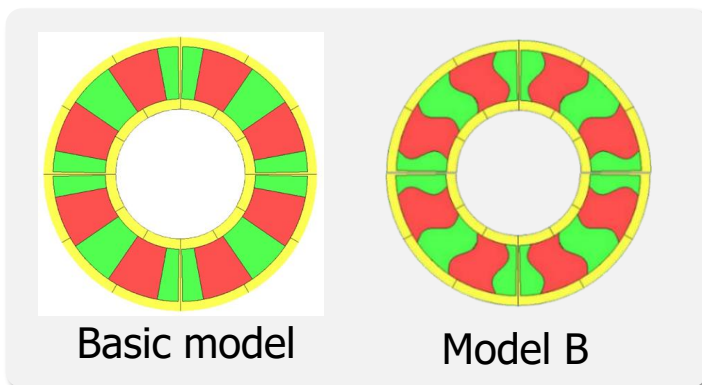
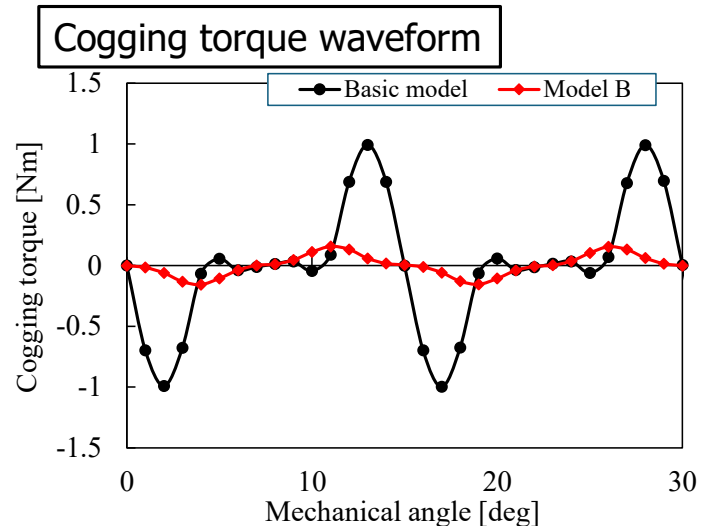
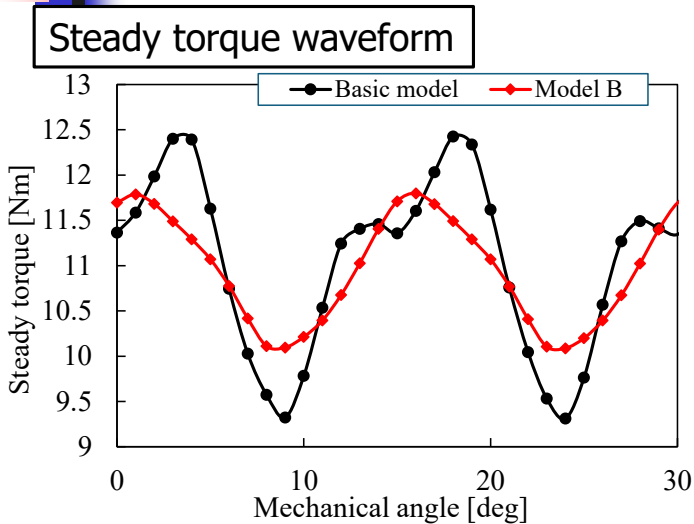
$$T_{all}(\theta) \approx \frac{1}{2} (T_{left}(\theta) + T_{right}(\theta))$$

Evaluation Items

- 1 Average torque T_{ave}
- 2 Torque ripple $T_{rip} = T_{max} - T_{min}$
- 3 Cogging torque $T_{cog} = T_{max_cog} - T_{min_cog}$

T_{ave} : Average torque
 T_{max} : Maximum torque
 T_{min} : Minimum torque
 T_{max_cog} : Maximum cogging torque
 T_{min_cog} : Minimum cogging torque

Result : Motor Characteristics



Motor characteristics

	Average torque [Nm]	Torque ripple [Nm]	Cogging torque [Nm]
Basic model	11.04	3.14	1.99
Model B	10.95 (-0.82%)	1.71 (-45.54%)	0.32 (-83.92%)

— Deterioration — Improvement

FFT Analysis

The waveform of the cogging torque can be expressed by the following approximate equation.

$$T(\theta) = \sum_{t=0}^{\frac{N}{2}} A_t \cos \left(2\pi t \frac{\theta}{N} + \phi_t \right)$$

t : Harmonic order

A_t [Nm]: Amplitude component of the t -th harmonic

ϕ_t [rad]: Phase component of the t -th harmonic

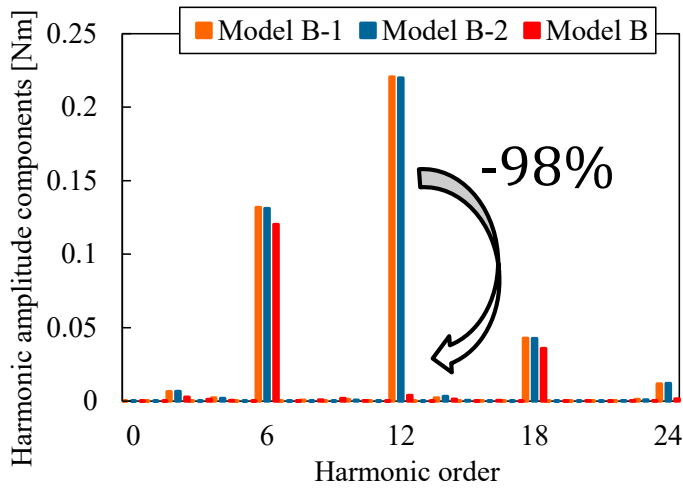
θ [deg]: Mechanical angle

N : Number of data points used for FFT analysis

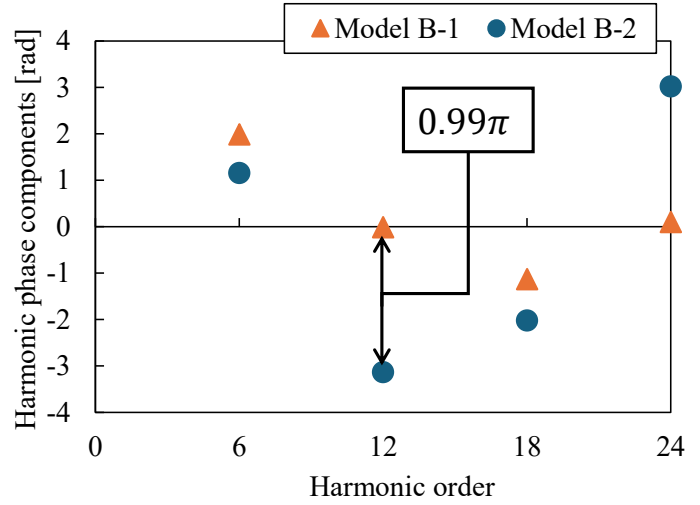
In this study, the analysis was conducted over one electrical cycle (360 electrical degrees = 90 mechanical degrees); therefore, the number of data points used for the FFT analysis is $N=90$.

Result : FFT Analysis

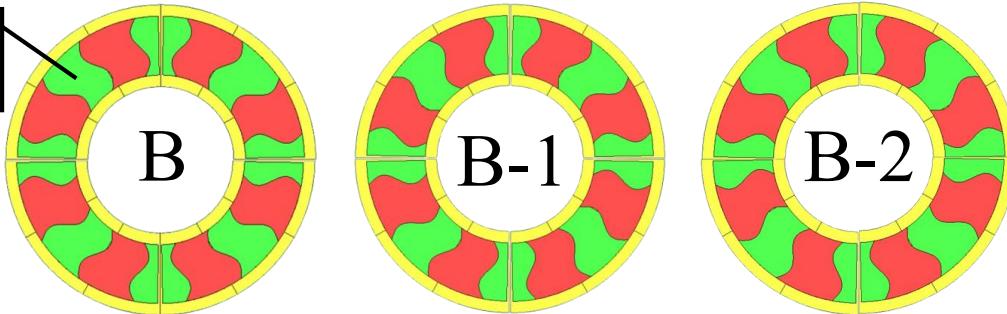
Harmonic amplitude



Harmonic phase

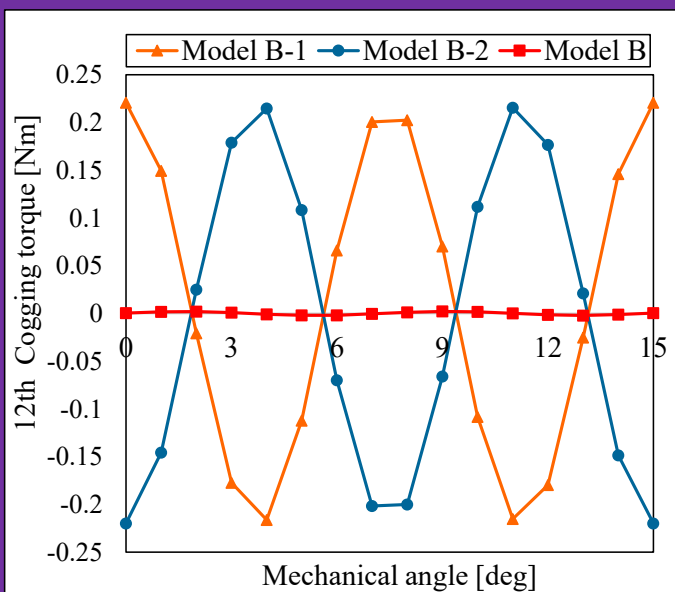


Proposed model

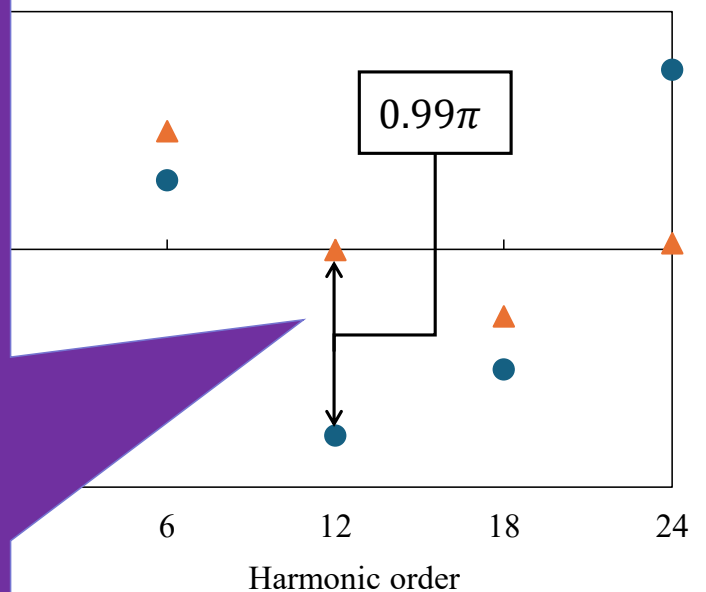


Result : FFT Analysis

12th harmonic waveform

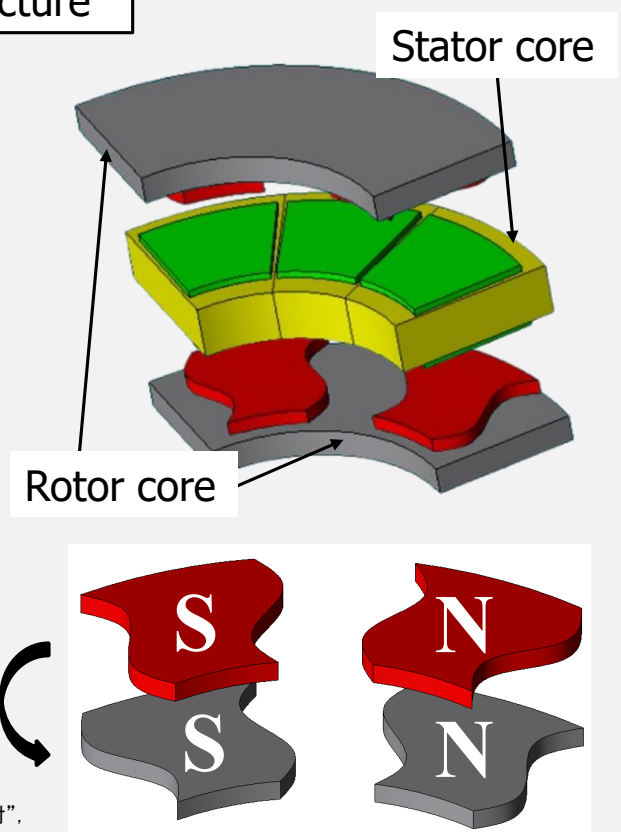
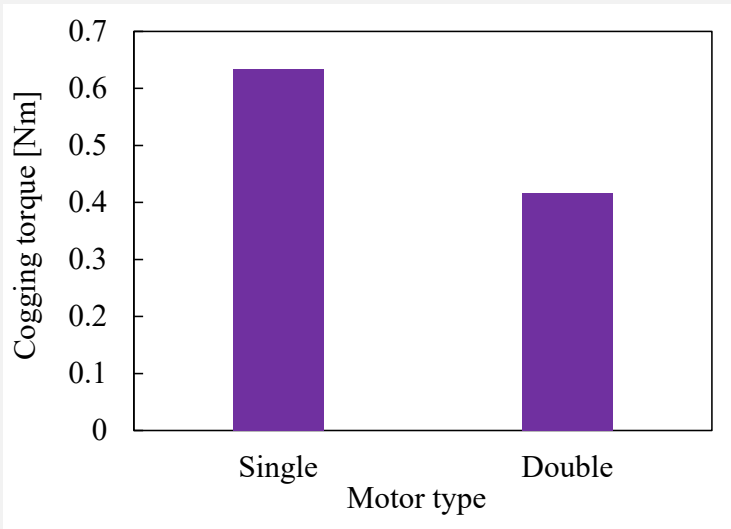


Harmonic phase



Development into a Double Structure

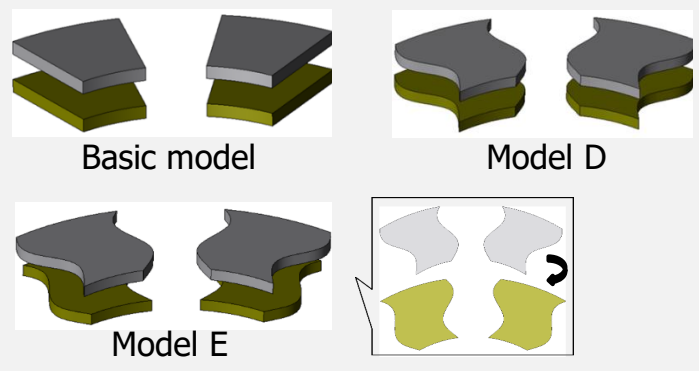
Cogging reduction effect by double structure



先行研究: 佐藤大祐, 水野暁斗, 北川亘, 竹下隆晴,
 “ダブルアキシアルギャップモータのコギングトルク相殺可能な磁石形状設計手法の検討”,
 日本AEM学会誌, Vol. 32(2), pp.300-305, 2024.

Development into a Double Structure

Magnet arrangement

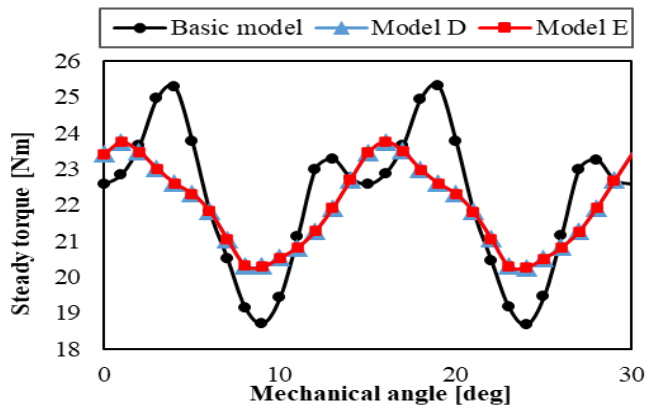


Motor characteristics

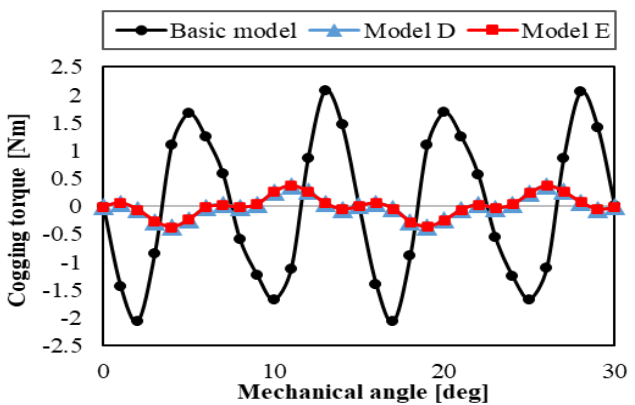
	Average torque [Nm]	Torque ripple [Nm]	Cogging torque [Nm]
Basic model	22.20	6.66	4.15
Model D	22.20 (±0%)	3.51 (-47.30%)	0.75 (-81.93%)
Model E	22.00 (-0.90%)	3.50 (-47.45%)	0.76 (-81.69%)

— Deterioration — Improvement

Steady torque waveform



Cogging torque waveform





Conclusion

Research purpose

Reduction of cogging torque by magnet arrangement

Result

Average torque: **decreased** by 0.82%

Cogging torque: **improved** by 83.92%

Torque ripple: **improved** by 45.54%

Future work

Design of a double axial-gap motor for reducing cogging torque through the cancellation effect of the upper and lower magnet arrangements.