AC loss calculation of REBCO superconducting cable-conductor by quasi-3D electromagnetic field analysis

National Institute of Technology, Miyakonojo College
Mechanical and Electrical Engineering Advanced Course

Goki Kawasaki

1. Research background and Purpose

People who seek comfortable living are increasing

Issue

・Power shortage is predicted due to increased energy demand

・Global warming caused by CO_2 emissions in thermal power generation

Etc..

Replacement of conventional copper cable to superconducting cable

Fig. 1 Appearance of AC superconducting cable

Advantage of superconducting cable

・Compact large current transmission will be possible

・Reduction of power transmission loss by about 3.1 billion kW

・Reduction of carbon dioxide emissions by approximately 1.6 million tons

■Quasi-3D electromagnetic field analysis

Previous study: Calculation of AC loss of superconducting cable by electric circuit model

(Considering electromagnetic field property in cable length direction)

⇩

Problem: Unable to analyze electromagnetic field property of cable cross section

⇩

This study: Combining 2D electromagnetic field analysis with electric circuit model

⇩

This method is called

Quasi-3D electromagnetic field analysis

■2D electromagnetic field analysis

Analysis is conducted by finite element method.

An analysis object is divided in mesh division.

An electromagnetic field is calculated for each mesh division, and an analysis result of the whole region is obtained.

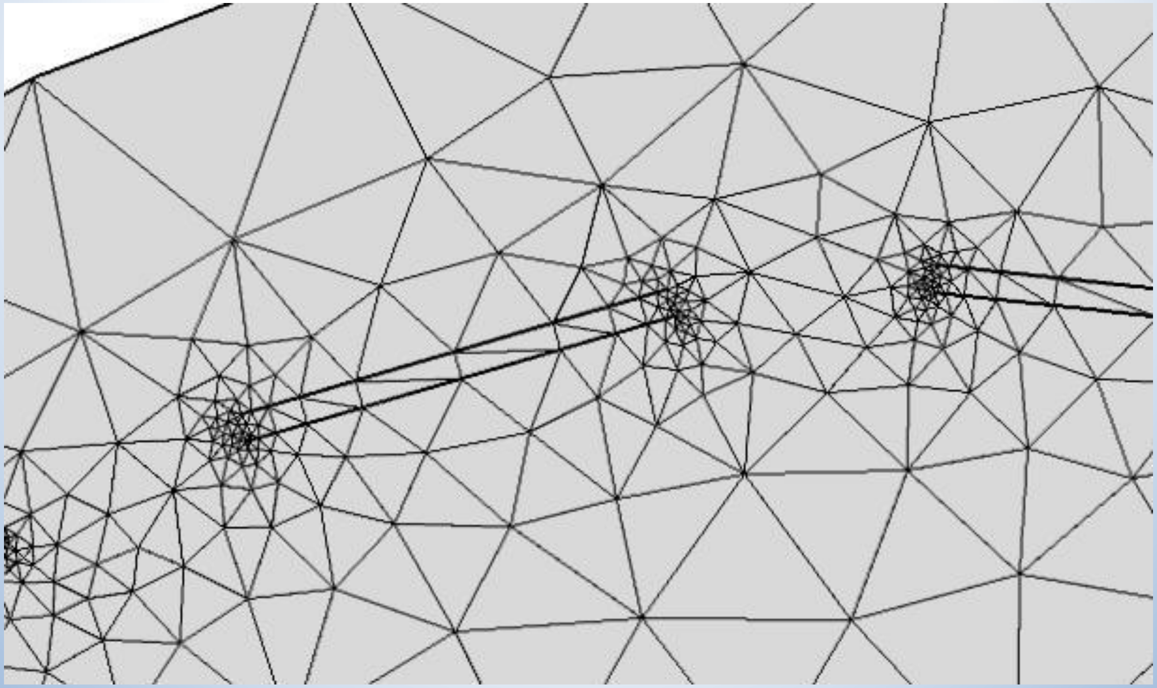


Fig. 2 Mesh of finite element method

2. Calculation method of AC loss

Electromagnetic field is analyzed by commercial software COMSOL and AC loss of superconducting cable is calculated.

Faraday's law and Ampere's law are the basic formula.
Resistivity of superconductor is obtained by empirical rule.
Boundary condition is obtained by Ampere's law.

$$\nabla \times \mathrm{E(J)} = -\mu \frac{\partial \mathrm{H}}{\partial \mathrm{t}}$$

$$\nabla \times H = J$$

$$\rho = \frac{E_\mathrm{C}}{J_\mathrm{C}} \left| \frac{J}{J_\mathrm{C}} \right|^{n-1} * J = E_\mathrm{C} \left(\frac{J}{J_\mathrm{C}} \right)^{n}$$

The boundary condition

$$\oint \mathrm{H} \cdot \mathrm{dl} = 2\pi H_\varphi = I_{wire} \rightarrow H_\varphi = \frac{I_{wire}}{2\pi r}$$

AC loss is obtained by

$$P = f \cdot \int_{\frac{1}{f}} dt \int_S E(J) \cdot J \, dS \quad [\mathrm{Wm}^{-1}]$$

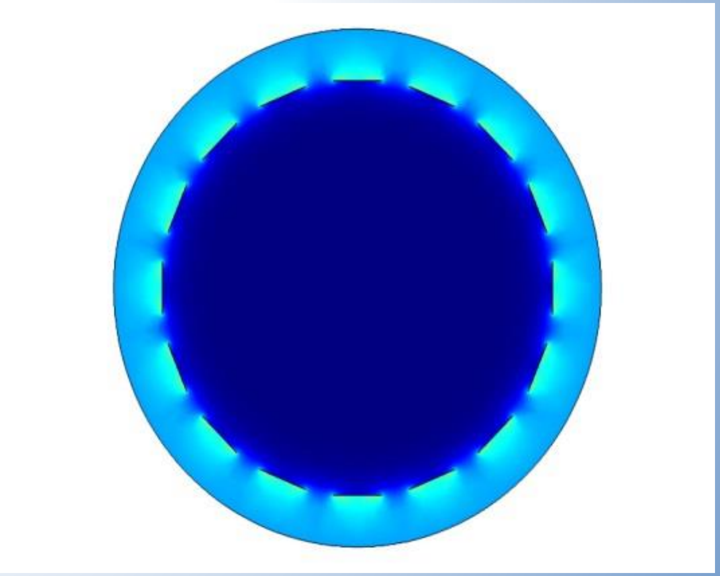


Fig. 3 Analysis example of magnetic flux density

Electrical circuit model

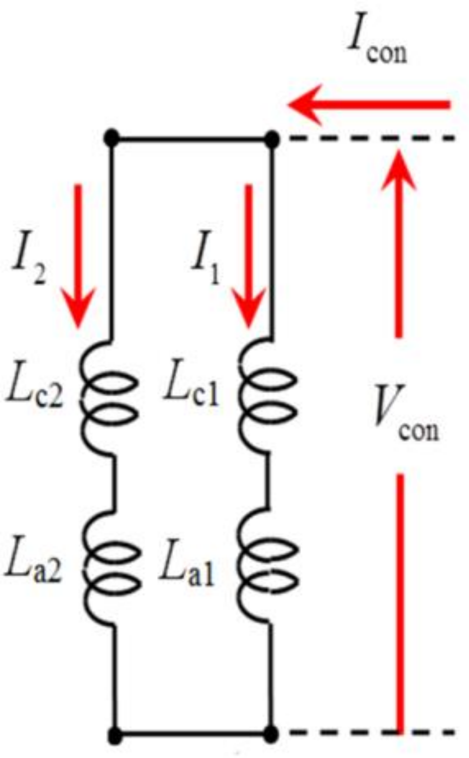


Fig. 4 Electrical circuit model

$$L_{cm} = \frac{\mu_0}{2\pi}\ln\left(\frac{r_s}{r_m}\right)$$

$$M_{cml} = \frac{\mu_0}{2\pi}\ln\left(\frac{r_s}{\max\{r_m、r_l\}}\right)$$

$$L_{am} = \mu_0\pi\frac{{r_m}^2}{{p_m}^2}$$

$$M_{aml} = \mu_0\pi\left(\frac{\min\{r_m、r_l\}}{p_m p_l}\right)$$

Simultaneous equations

$$\dot{V}_{con} = j\omega(L_{am} + L_{cm})\dot{I}_m + j\omega\sum_{l=1}^{2}(M_{aml+}M_{cml})\dot{I}_l$$

$$\dot{I}_{con} = \sum\nolimits_{m=1}^{2}\dot{I}_m$$

Layer current are obtained by simultaneous equations

3. Results of AC loss analysis of cable-conductor

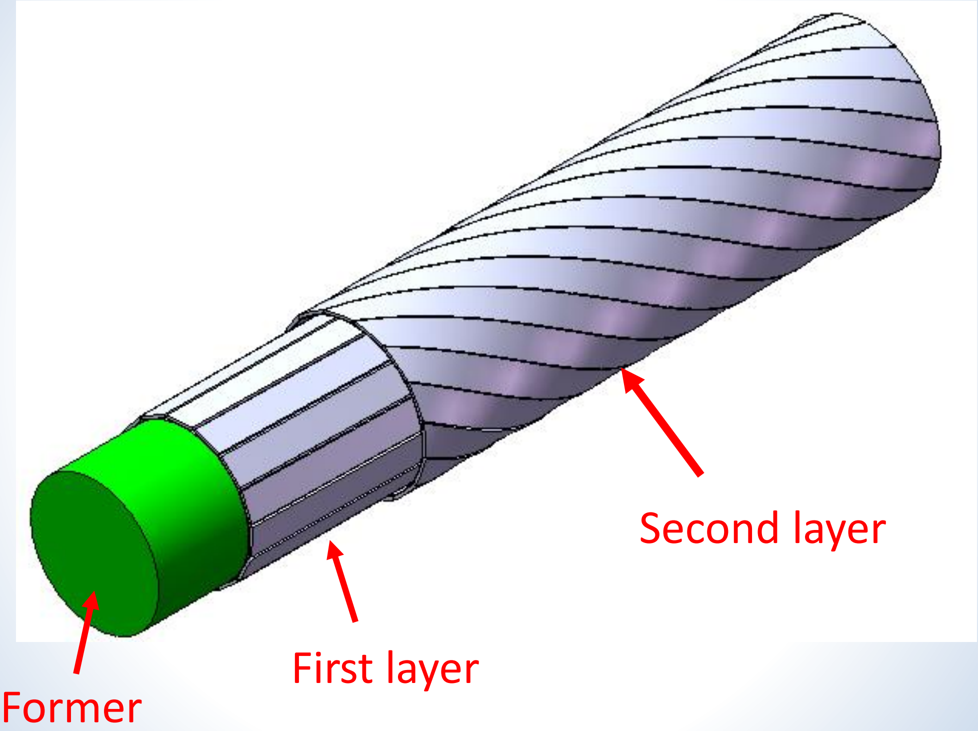


Fig. 5 3D model of two-layer superconducting cable-conductor

※In this figure, superconducting tapes of the first layer are formed straight in the length direction, but actually they are wound helically like the second layer.

Table1 Configuration parameter of superconducting cable-conductor

Number of layers	Radious of former	Number of tapes	Radious of superconductor	Critical current of tape
1	16 mm	16	16.099 mm	45.6 A
2		16	16.349 mm	

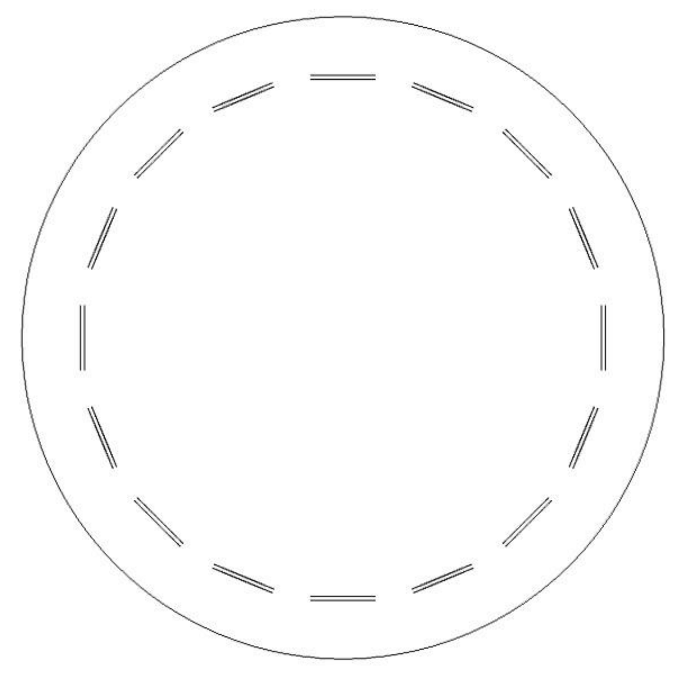
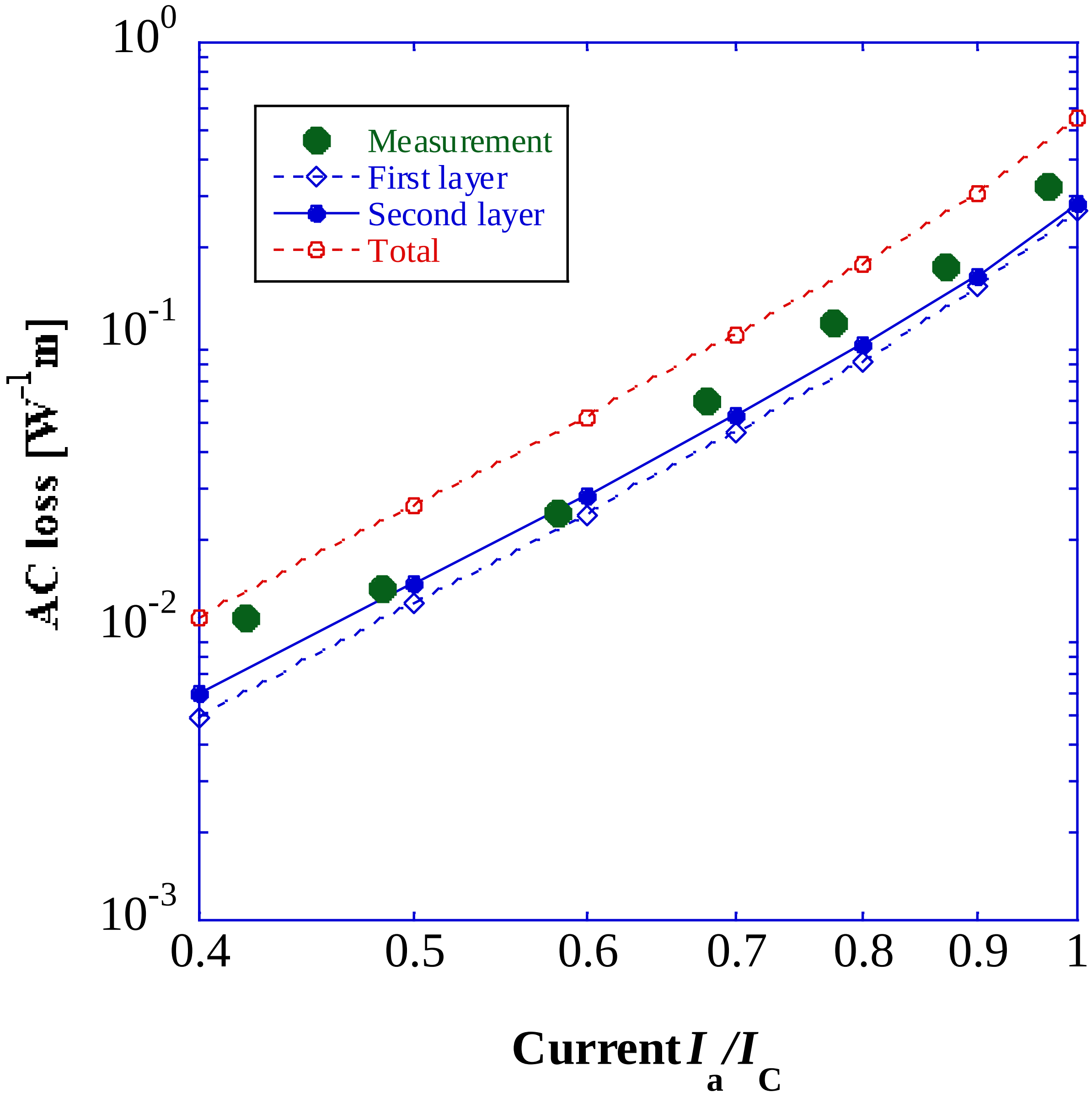
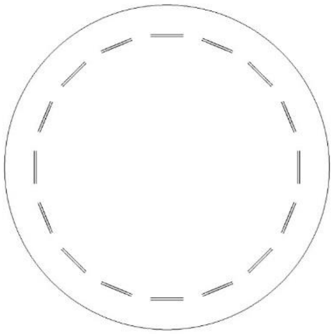


Fig. 6 2D cross sectional model of superconducting cable-conductor

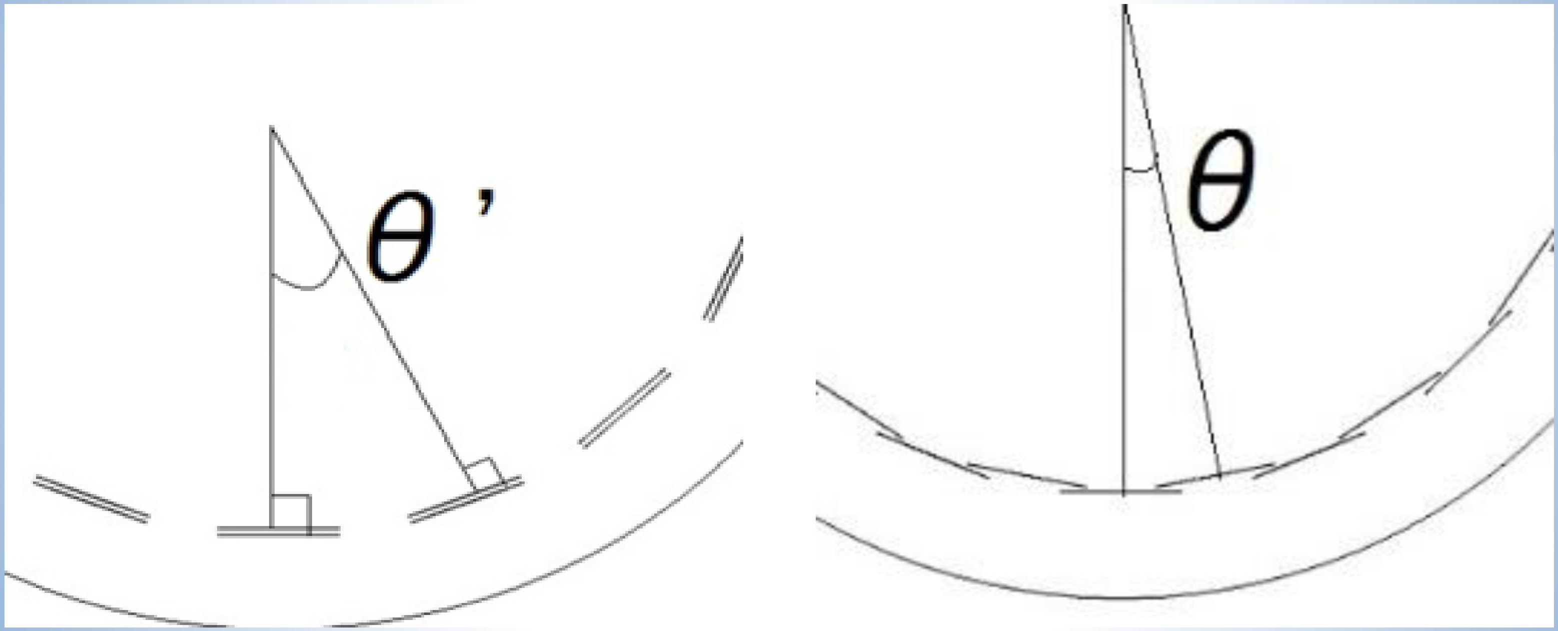




Cable cross section

Fig. 7　AC loss characteristics of cable-conductor with uniform layer current.

■AC loss property when the relative position angle is changed



(a) $\theta/\theta'=0$ **(b)** $\theta/\theta'=0.5$

Fig. 8 Explanation of relative position angle.

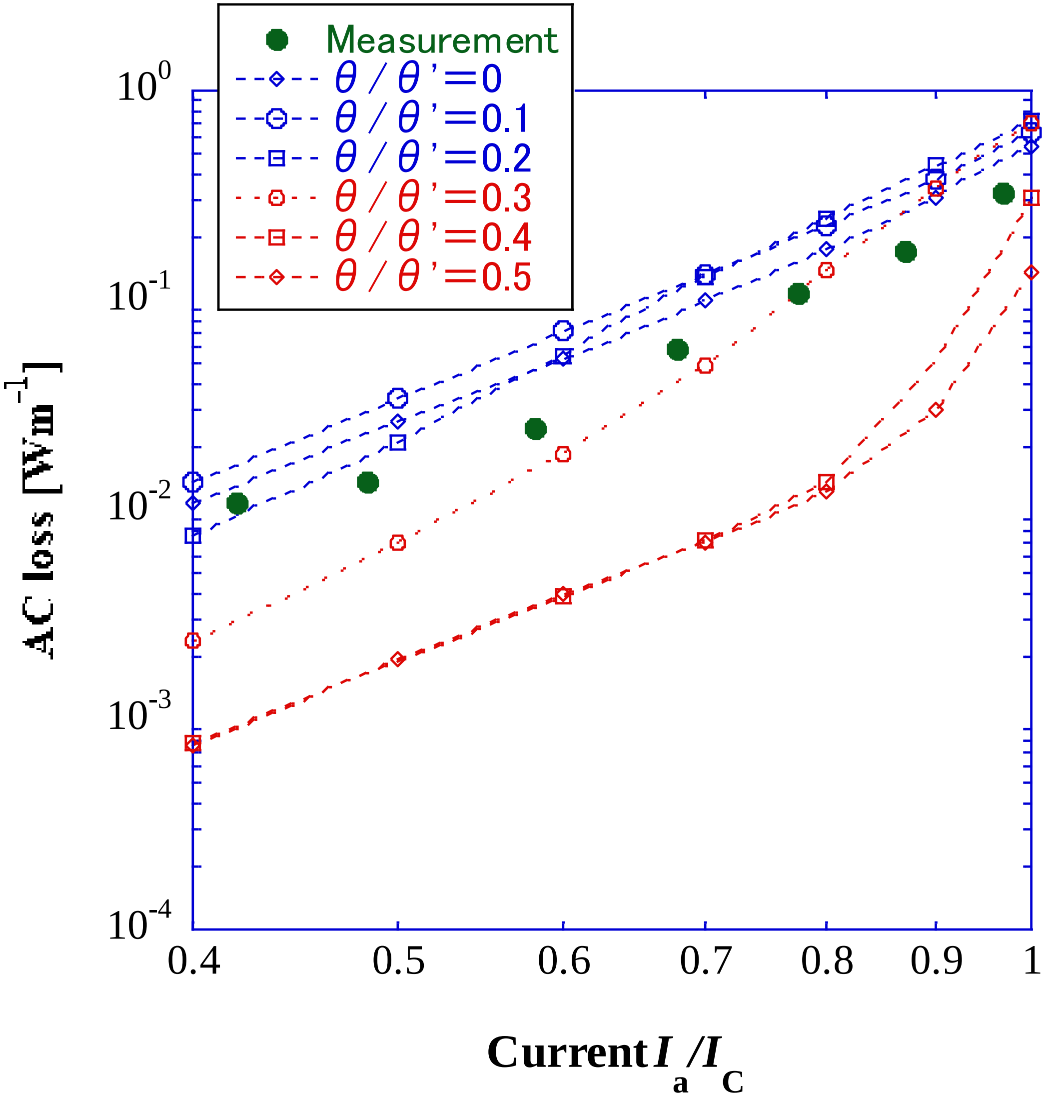
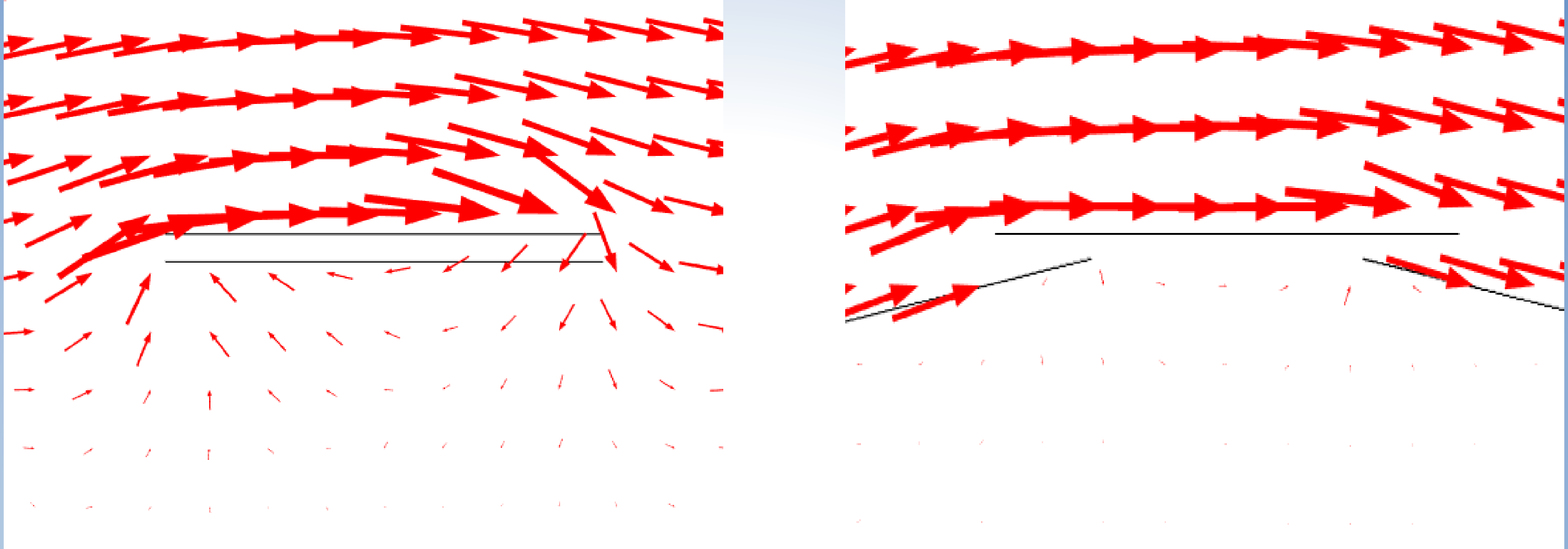


Fig. 9 AC loss characteristics of cable-conductor with change of relative position angle.



(a) $\theta/\theta'=0$ **(b) $\theta/\theta'=0.5$**

Fig. 10 Magnetic field profile of cable cross section.

At $\theta/\theta'=0.5$, perpendicular magnetic field is almost diminished.

⇩

The perpendicular magnetic field is canceled out

■Results of quasi-3D electromagnetic field analysis

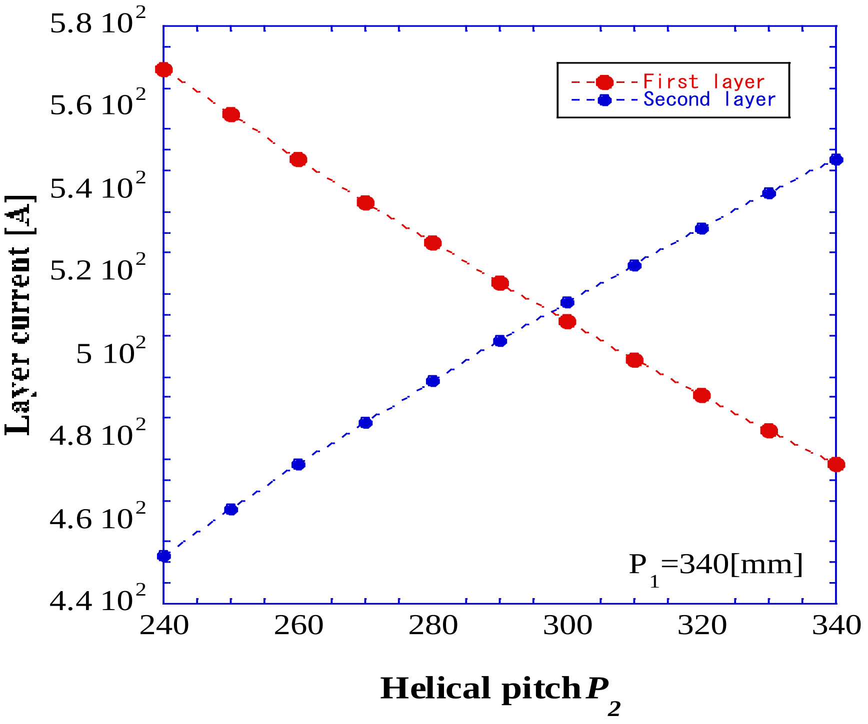


Fig. 11 Layer current of Furukawa Electric's cable
（Calculated value）

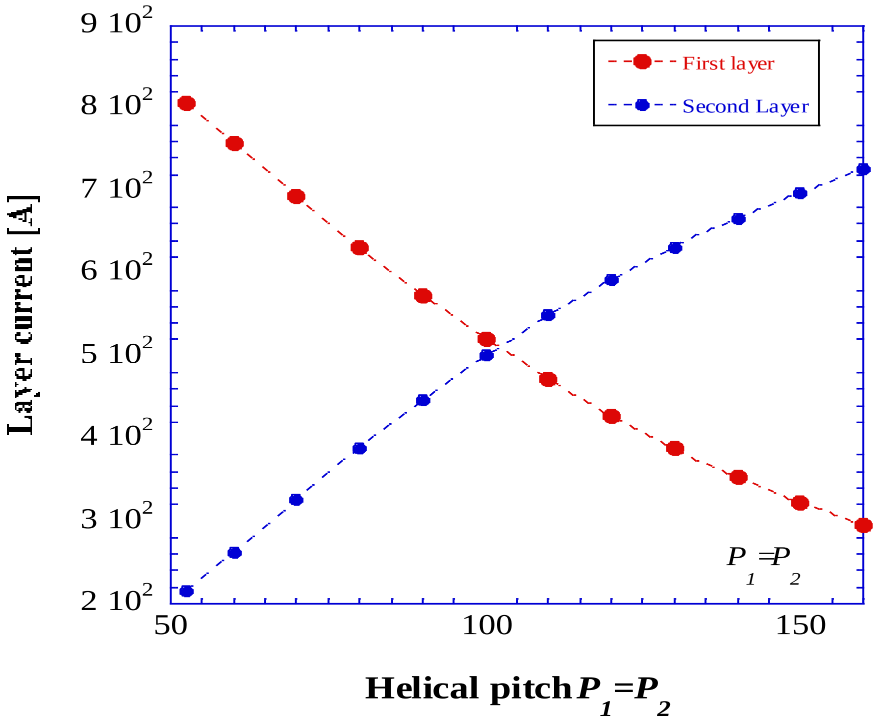


Fig. 12 Layer current of cable designed with minimum loss
(Calculated value)

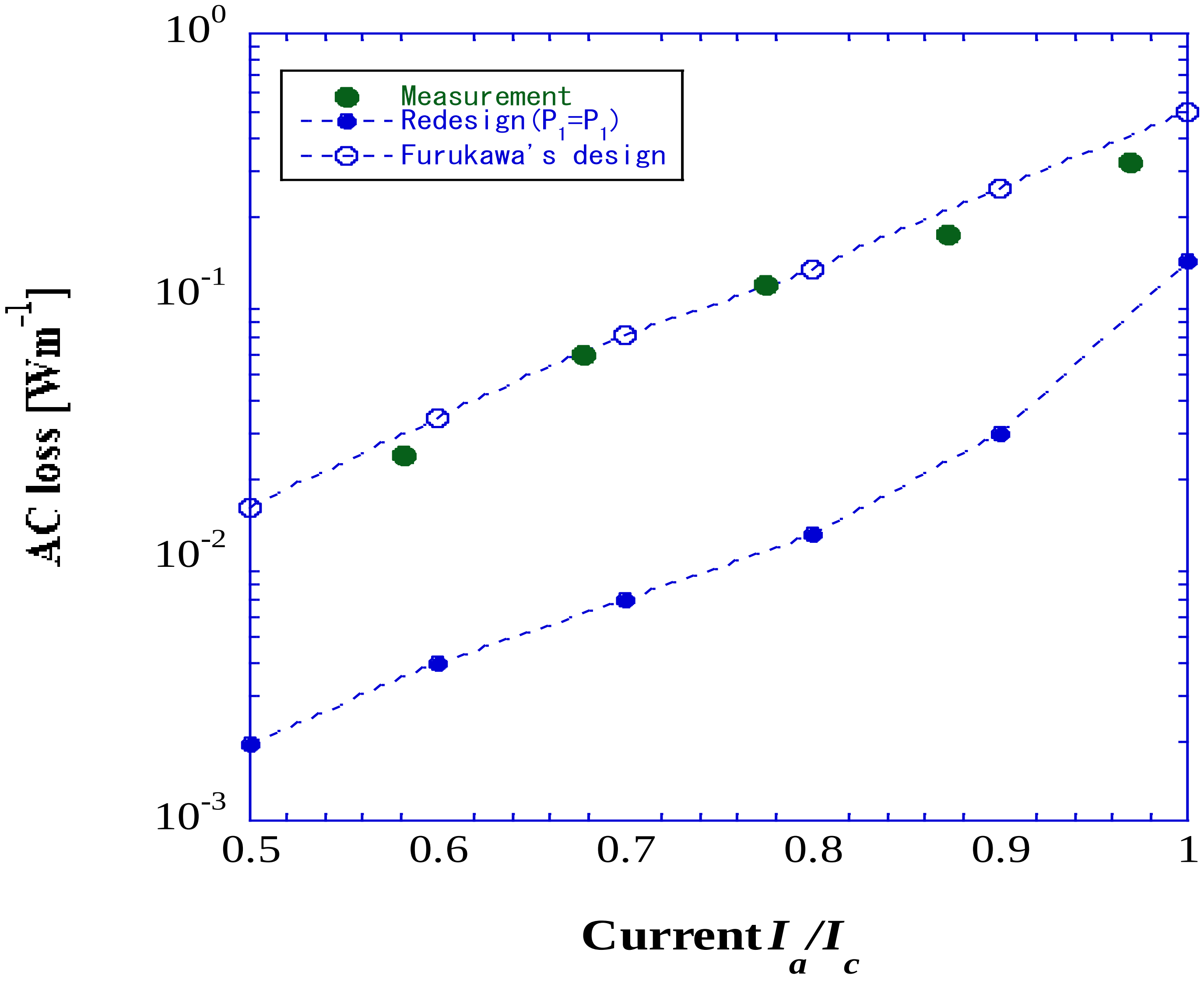


Fig. 13 AC loss characteristics calculated by quasi-3D electromagnetic field analysis.

4. Summary

- For the two-layer REBCO cable conductor manufactured by Furukawa Electric Co., the calculation result of AC loss by quasi-3D electromagnetic field analysis agreed with the measurement result.

- It was found that AC loss when the cable configuration parameters were wound in the same manner and $P_1 = P_2 = 100\,\mathrm{mm}$ is the minimum loss and the loss by about one order of magnitude could be reduced in comparing with the one by Furukawa Electric Co.