Dependence of AC loss on helical pitch of three-layer REBCO superconducting cable

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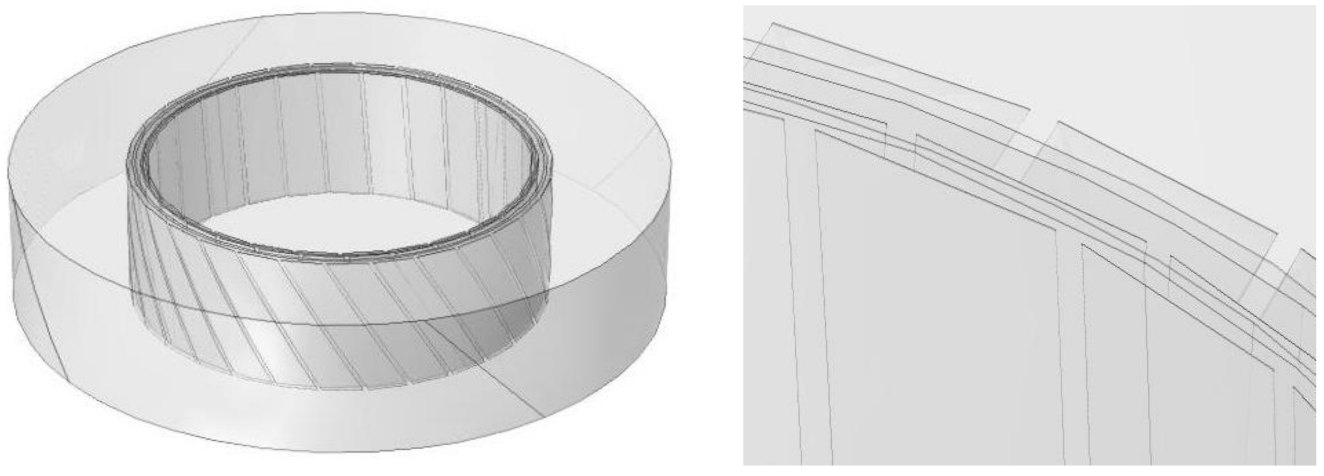
Abstract

AC loss calculation of three-layer REBCO superconducting cable was performed by three dimensional (3D) electromagnetic field analysis. For the calculation, parameters of the cable made by Furukawa Electric Co., Ltd. were referred, but winding direction and helical pitch of each layer were unknown. Therefore, in order to find the optimum cable configuration, calculations are made with various winding directions and helical pitches, and their dependencies on the loss is observed. Conditions of the calculation for the winding direction were only SZZ (left rotation for the first layer, right rotation for the second layer and right rotation for the third layer) and SSS (left rotation for all layer). In either of the winding direction calculation conditions, the helical pitch for the first layer, P1, does not affect on the loss, that the loss increases only when the helical pitch for the second layer, P2, is short, and that the loss decreases as the helical pitch for the third layer, P3, becomes shorter.

■Configurations of cables



(a) Overall view (b) Enlarged view

Fig. 1. 3D model of three-layer REBCO superconducting cable.

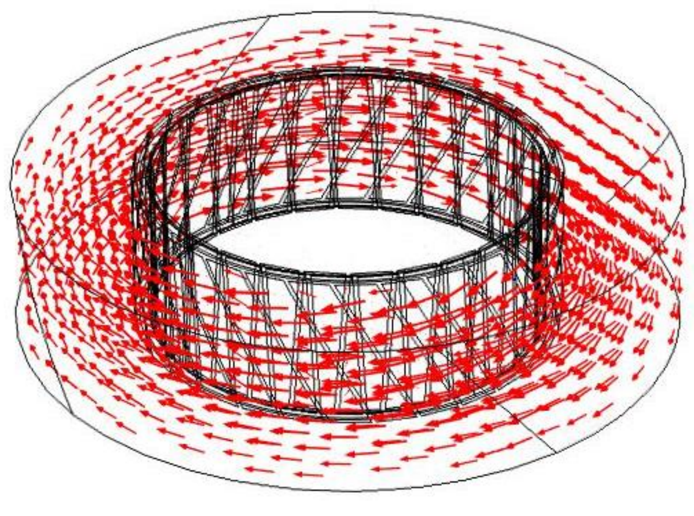


Fig. 2. Magnetic field profiles.

Table 1. Configuration parameter of 3-layer REBCO superconducting cable

Width of tape	1.8 mm
Thickness of tape	1 μm
Inner diameter of the first layer	17.3 mm
Inner diameter of the second layer	17.9 mm
Inner diameter of the third layer	19.2 mm
Number of tapes in the first layer	27
Number of tapes in the second layer	28
Number of tapes in the third layer	30
Critical current of the first layer	699 A
Critical current of the second layer	705 A
Critical current of the third layer	778 A
Helical pitch of the first layer (direction)	775 mm (S)
Helical pitch of the second layer (direction)	920 mm (Z)
Helical pitch of the third layer (direction)	110 mm (Z)

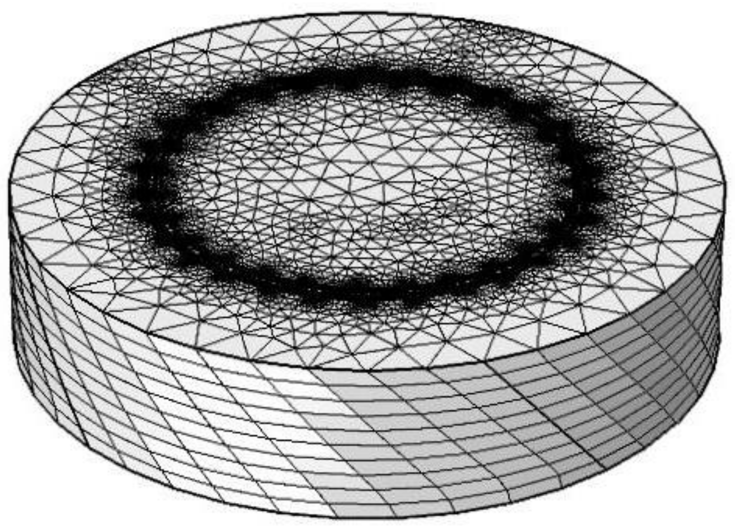


Fig. 3. Mesh of finite element method.

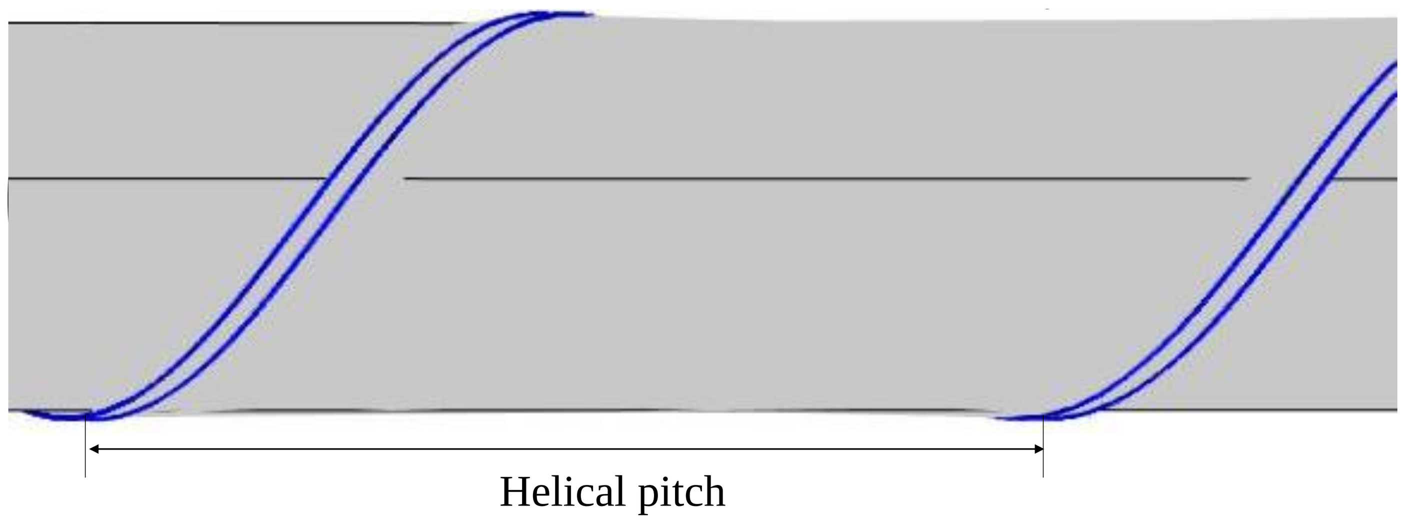


Fig. 4. Explanation of the helical pitch.

■formula

$$\mu\frac{\partial \boldsymbol{H}}{\partial t}+\boldsymbol{\nabla}\times\boldsymbol{E}=0 \quad\Rightarrow\quad \mu_0\mu_r\left[\frac{\partial H_x}{\partial t},\frac{\partial H_y}{\partial t},\frac{\partial H_z}{\partial t}\right]^T+\left[\frac{\partial E_z}{\partial y}-\frac{\partial E_y}{\partial z},\frac{\partial E_x}{\partial z}-\frac{\partial E_z}{\partial x},\frac{\partial E_y}{\partial x}-\frac{\partial E_x}{\partial y}\right]^T=0$$

$$\boldsymbol{J}=\boldsymbol{\nabla}\times\boldsymbol{H} \quad\Rightarrow\quad [J_x,J_y,J_z]^T=\left[\frac{\partial H_z}{\partial y}-\frac{\partial H_y}{\partial z},\frac{\partial H_x}{\partial z}-\frac{\partial H_z}{\partial x},\frac{\partial H_y}{\partial x}-\frac{\partial H_x}{\partial y}\right]^T$$

$$\boldsymbol{E}=\rho_{sc}(\mathrm{J})\boldsymbol{J} \quad\Rightarrow\quad [E_x,E_y,E_z]^T=[\rho_{scx}J_x,\rho_{scy}J_y,\rho_{scz}J_z]^T$$

$$\rho_{sc}=\frac{E_C}{J_C}\left(\frac{J}{J_C}\right)^{n-1} \quad\Rightarrow\quad [\rho_{scx},\rho_{scy},\rho_{scz}]^T=\left[\frac{E_c}{J_c}\left(\frac{J_x}{J_c}\right)^{n-1},\frac{E_c}{J_c}\left(\frac{J_y}{J_c}\right)^{n-1},\frac{E_c}{J_c}\left(\frac{J_z}{J_c}\right)^{n-1}\right]^T$$

$$\mathrm{Q}=f\cdot\int_{\frac{1}{f}}dt\iint_S E(J)\cdot J\,dS\quad[\mathrm{W/m}]$$

■Characteristic with respect to applied current

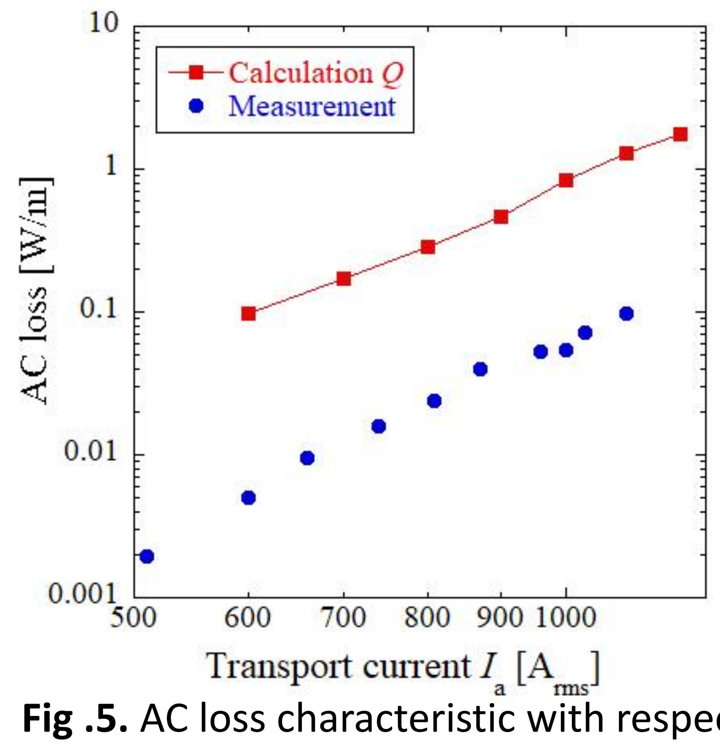
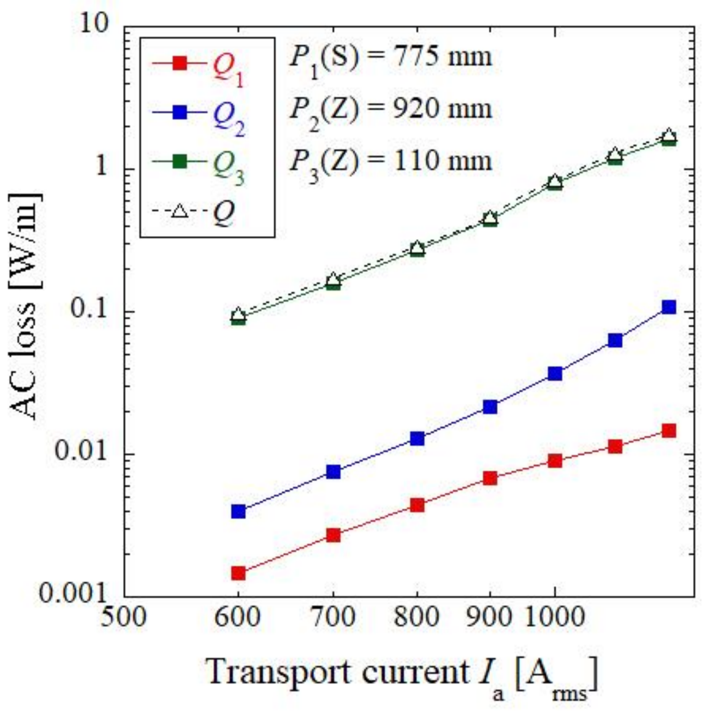
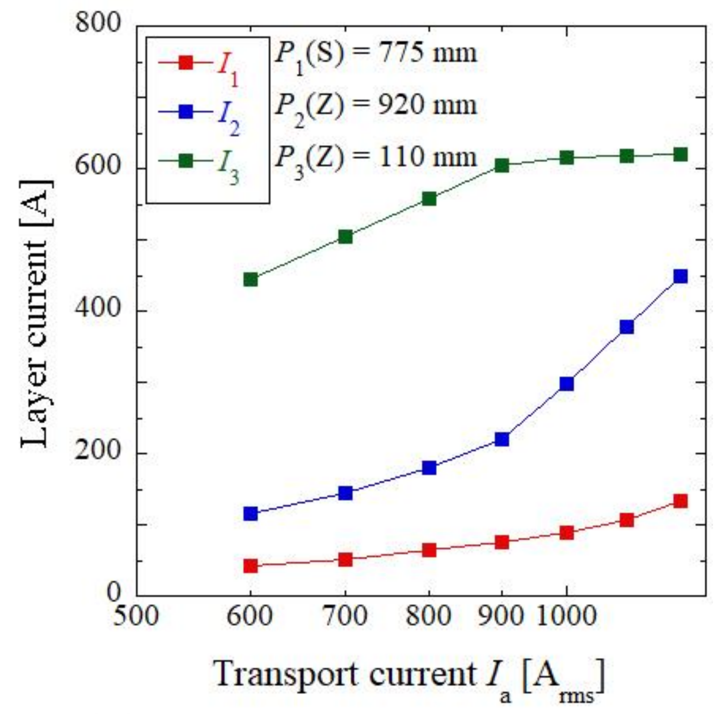


Fig .5. AC loss characteristic with respect to applied current.



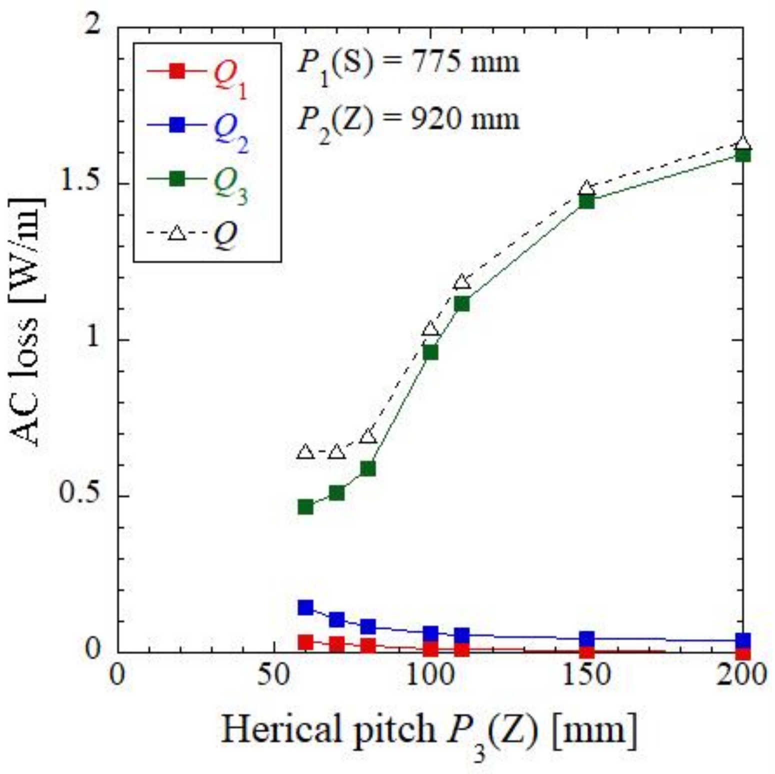
(a) The characteristic of layer loss.



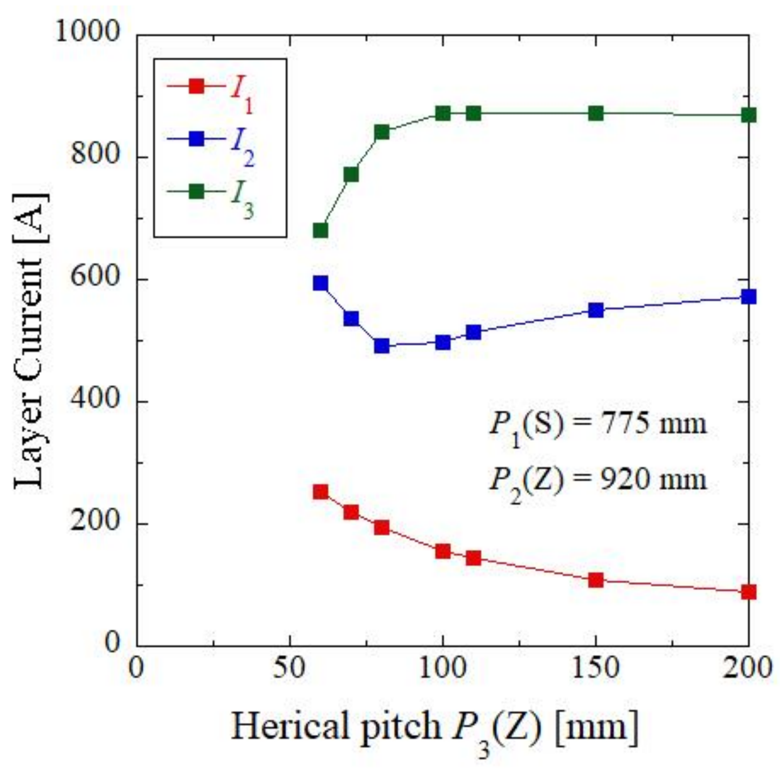
(b) The characteristic of layer current.

Fig .6. The characteristics of layer loss and layer current with respect to applied current.

■Dependence on helical pitch

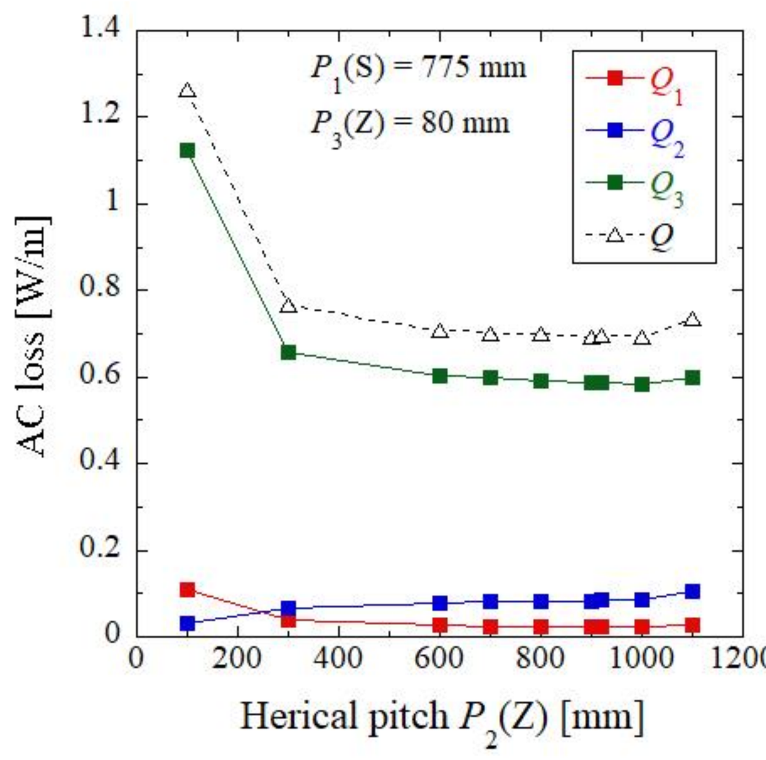


(a) The characteristic of layer loss.

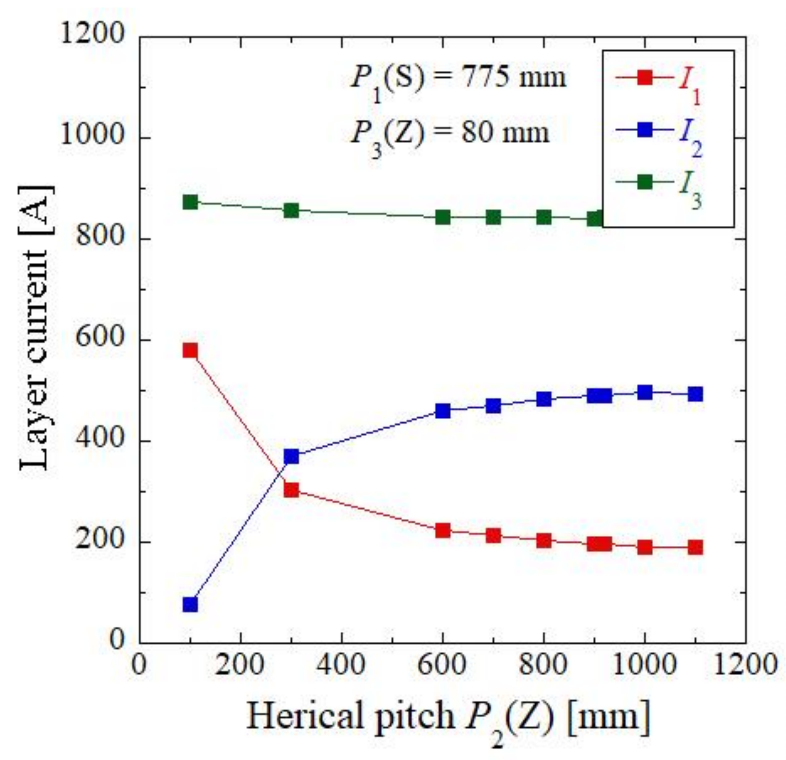


(b) The characteristic of layer current.

Fig .7. The characteristics of losses and layer current with respect to P1 (SZZ direction).

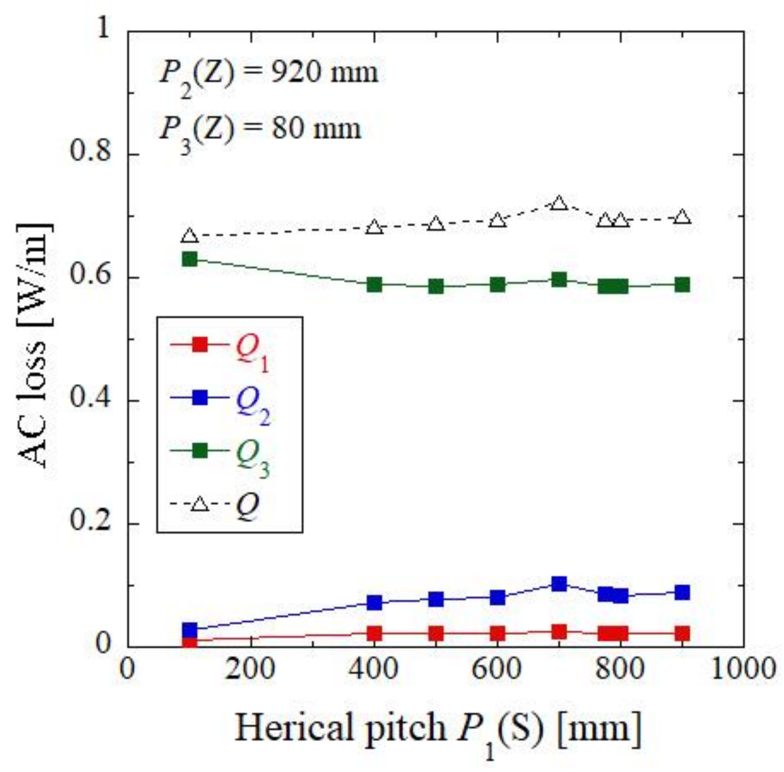


(a) The characteristic of layer loss.

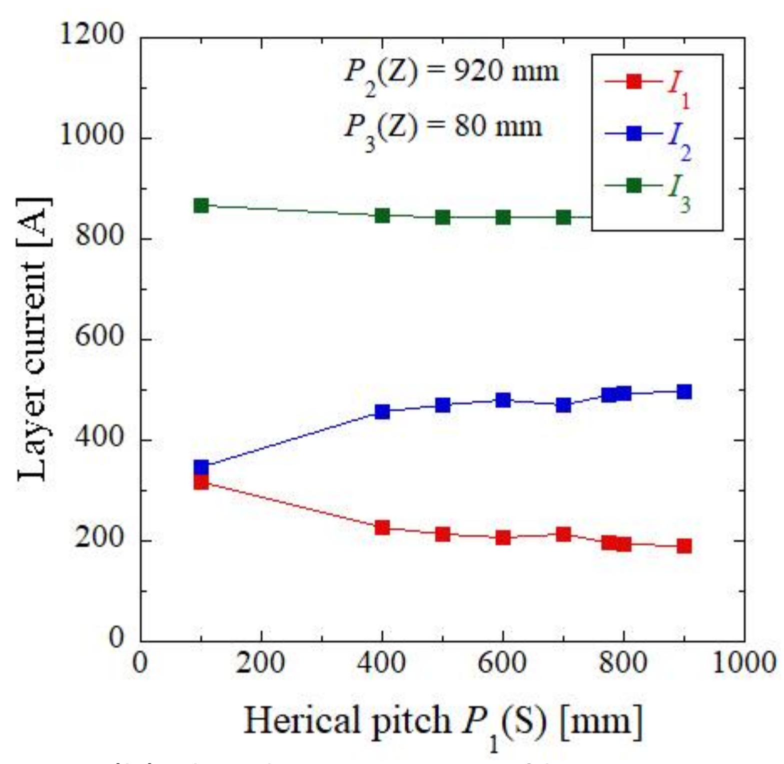


(b) The characteristic of layer current.

Fig .8. The characteristics of losses and layer current with respect to P2 (SZZ direction).



(a) The characteristic of layer loss.



(b) The characteristic of layer current.

Fig .9. The characteristics of losses and layer current with respect to P1 (SZZ direction).

Summary

When the winding direction was SZZ and P_3 was changed, the loss decreases as P_3 becomes close to P_{3min}. When P_2 was changed, the loss increases as P_2 is less than 300 mm. Even if P_1 is changed, the loss hardly changes. When the winding direction is SSS, the characteristics of Q respect with to P_2 and P_3 were almost same dependency as in SZZ. Although we have conducted the above research, as a future prospect, we will calculate the losses with changing P_1 when the winding direction is SSS. Moreover, the characteristics of the losses and the layer current respect with to P_1, P_2 and P_3 will be also calculated when the winding directions are SZS and SSZ. We aim to find the winding direction and helical pitch to calculate the loss that coincides with the measured value of Furukawa Electric.