[W-MA-46] (May 2018)

Calculation Method of Eddy Current Loss of Electromagnetic Steel Sheet Using a 1D Finite Element Method

1. Background and subject

As electromagnetic devices become more and more efficient, the precision in iron loss analysis becomes more important for electromagnetic field analysis. Synchronous motors using rare earth permanent magnets are especially suitable for electrical appliances and electric automobiles. To improve the efficiency of these products, measuring iron loss with high precision is needed.

When calculating the eddy current loss in magnetic steel, conventionally, a Fourier transform is taken of the magnetic flux density derived from analysis and compared with actual measurements of the iron loss characteristics to estimate the eddy current loss. (Fig. 1 below, conventional method). However, if the conditions differ from the iron loss characteristic measurements, high precision analysis cannot be carried out. For example, this occurs in cases where the frequency used in the analysis is higher than the upper limit frequency, or when DC is superimposed on AC. The essential thing is to model the steel sheet and solve for the current distribution in the steel sheet using a physical model; however, to faithfully model the steel sheet, the increase in the number of elements results in an impractically large amount of time needed for calculation.

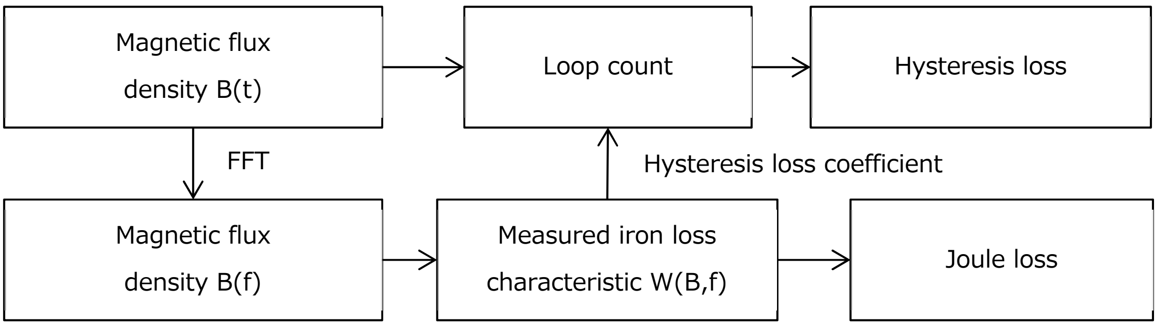

Fig. 1 Conventional method algorithm

2. Approaching these challenges

To solve the conventional problem, a method of solving the current distribution in the steel sheet using a physical model has been proposed. Solving the magnetic flux density distribution and eddy current distribution in the thickness direction of the steel sheet with the magnetic flux density obtained by two-dimensional (or three-dimensional) magnetic field analysis as the boundary condition is shown in Fig. 2 (below, 1D method [1]). With this method, it is possible to reduce the number of elements and calculation time, as compared with three-dimensional analysis which faithfully models a laminated steel sheet. Since the method uses only physical property values that are not dependent on the excitation state such as the BH curve and the electrical conductivity, independent of the measurement values from which iron loss characteristics can be obtained from a given excitation state, it is possible to deal with an arbitrary driving state.

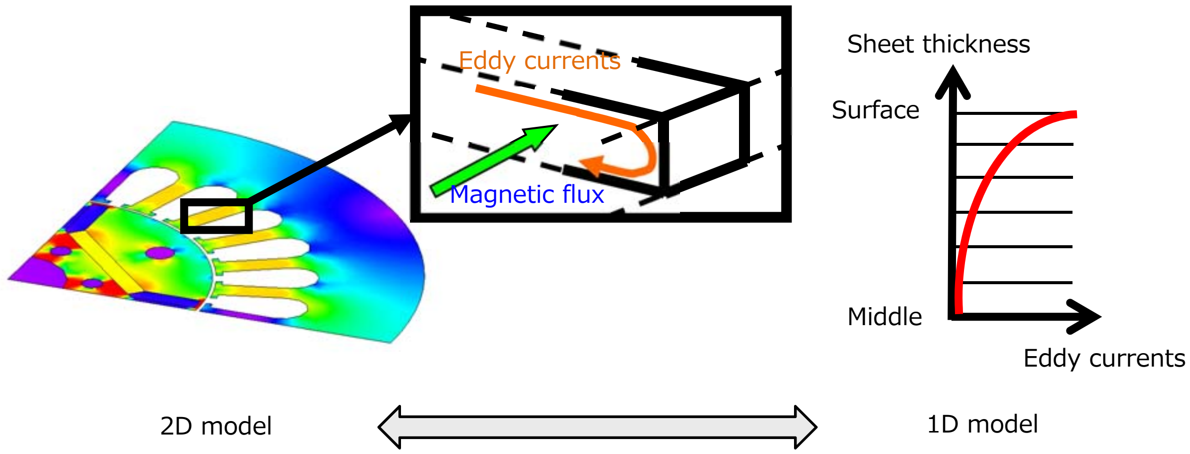

Fig. 2 1D method algorithm

3. Comparison of losses due to different calculation methods

Eddy current loss was calculated when applying an alternating field to a steel sheet. Fig. 3 shows the results of calculating the eddy current loss density by the conventional method and the 1D method while changing the frequency. Although the methods agree in value up to 10 kHz, the differences becomes larger at higher frequencies. Next, Fig. 4 shows the results of computing the eddy current loss by the conventional method and the 1D method while changing the magnitude of the direct current component with the direct current superimposed on a 10 kHz alternating current. In the conventional method the loss remains constant as the level of DC changes, but does change in the 1D method. The cause of each of the differences was confirmed in details.

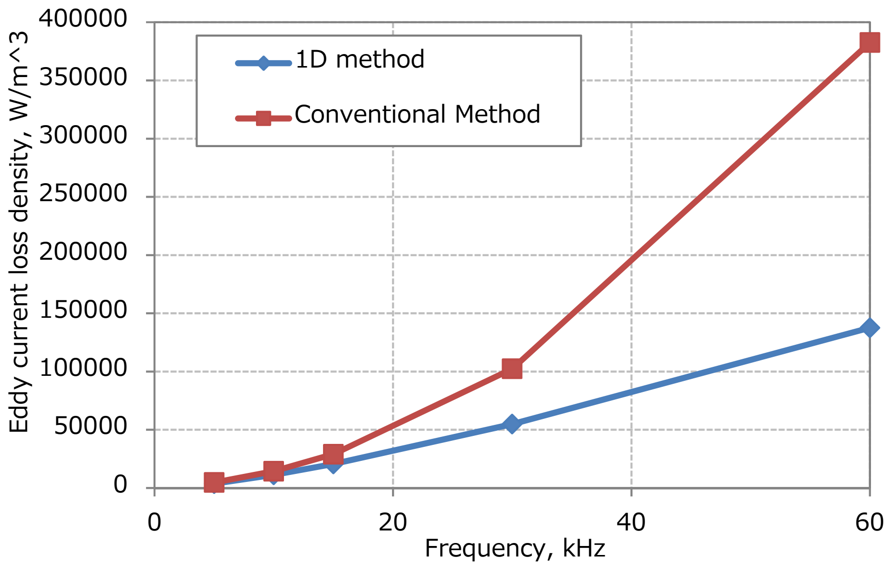

Fig. 3 Frequency dependence of eddy current loss density

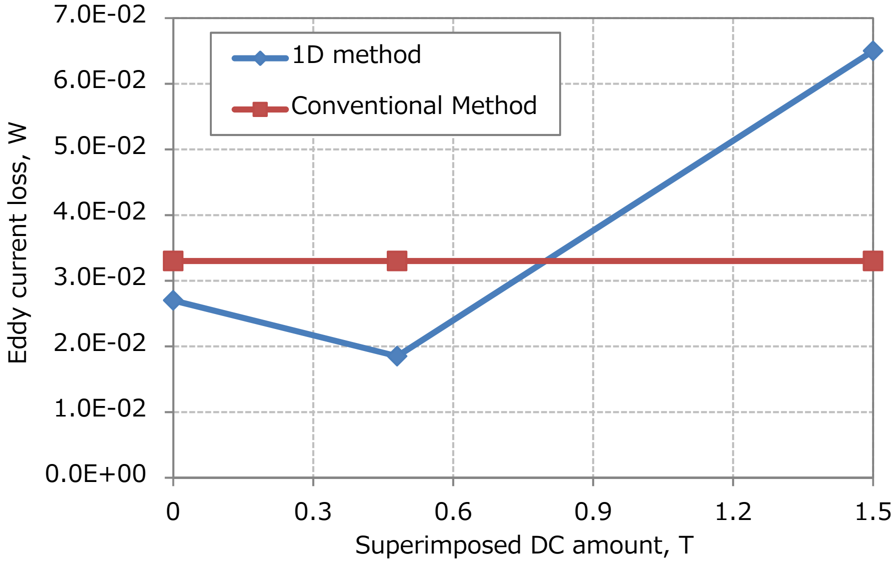

Fig. 4 Dependence of eddy current loss on DC superposition amount

3.1 Why does the difference in agreement between the two methods increase as frequency increases?

At this time, the upper limit frequency for iron loss data used in the conventional method is 10 kHz. At higher frequencies, the slope of the plot W/f (f: frequency, W: iron loss) taken at 10 kHz is extrapolated but does not agree with the actual characteristics in the areas where the skin effect is significant. On the other hand, in the 1D method, since the magnetic flux density distribution and the current distribution in the thickness direction of the electromagnetic steel sheet are calculated, the skin effect can be accurately modelled. In order to see that the skin effect is taken into account in the 1D method, Fig. 5 shows the eddy current density distribution in the electromagnetic steel sheet calculated by the 1D method. As the frequency increases the current density increases toward the surface due to the skin effect. As a result, the effective resistance increases impeding the increase in eddy currents. On the other hand, in the conventional method, the average values of the skin effect at 5 kHz and at 10 kHz are also applied at 50 kHz, resulting in a difference.

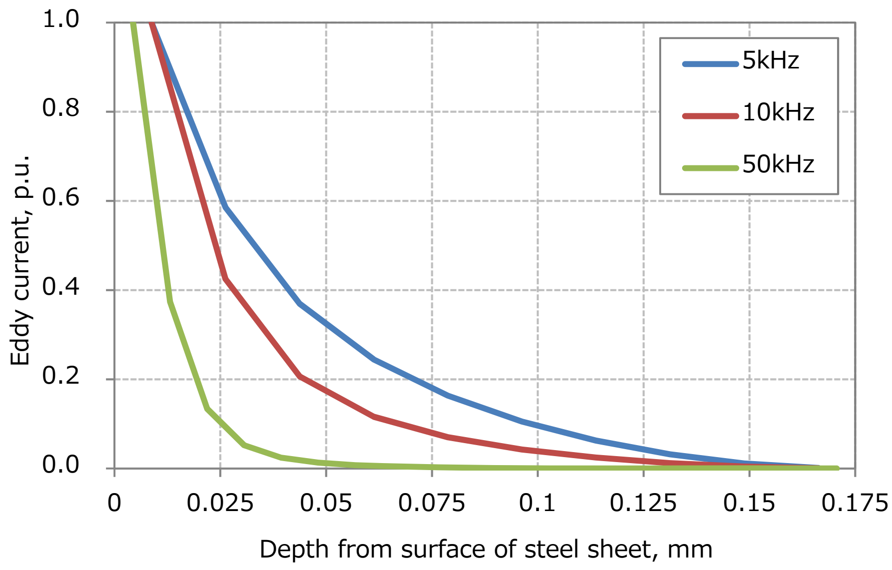

Fig. 5 Frequency dependence of eddy current density distribution in electromagnetic steel sheet

The vertical axis is normalized to a maximum value of 1 for each
It is seen that the skin effect is much larger at 50 kHz than at 5 kHz or 10 kHz.

3.2 Why does loss vary verse superimposed DC amount?[2]

As shown above, the conventional method estimates the eddy current loss by Fourier transforming the change in magnetic flux density, obtained from analysis, verse time and comparing with the iron loss characteristics. Iron loss characteristics are usually measured using sinusoidal magnetic flux density excitation, with information from the DC superimposed amount is not used, so the loss does not vary verse the superimposed DC amount.

Fig. 6 shows the magnetic flux density distribution and the eddy current loss density distribution in the steel sheet with and without a direct current component. It is found that the magnetic flux density and the eddy current loss density are concentrated more on the surface of the steel sheet with no direct component. On the other hand, in the case of direct current, magnetic saturation occurs due to direct current superimposition, and the magnetic permeability near the surface decreases and the skin depth increases. As a result, more current flows and the loss increases. The 1D method can express this phenomenon because the magnetic flux density distribution (magnetic permeability distribution) inside the steel sheet is pursued taking into account the nonlinearity of the magnetic properties.

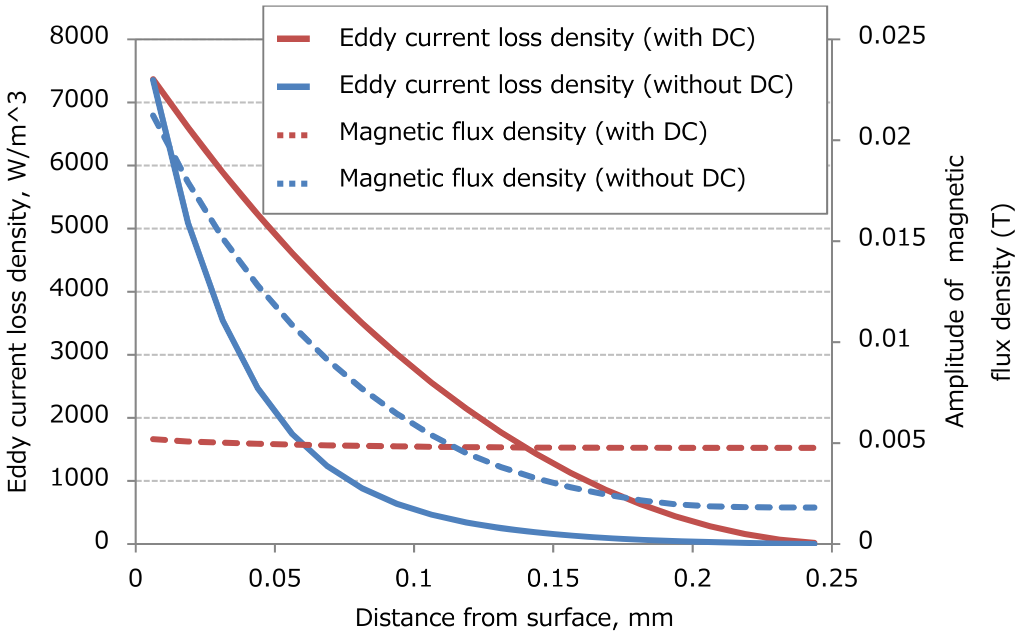

Fig. 6 Magnetic flux density distribution and eddy current loss density distribution in steel sheet

4. Remaining challenges

The problem of calculating the eddy current loss of an electromagnetic steel sheet by the conventional method or two-dimensional analysis was that the skin effect occurring inside the steel sheet cannot be modeled correctly. Using the 1D method makes it possible to accurately reproduce the skin effect in the direction of the thickness of the steel sheet, but it is impossible to express the return current at the edges of the steel sheet, so if the ratio of the thickness of the steel sheet to the width is large the results will differ from the actual phenomena.

Although the eddy current loss with any driving state can be calculated by the 1D method, it is necessary to perform a special calculation for excess eddy current loss. There are two types of eddy current loss - classical eddy current loss and excess eddy current loss. Classical eddy current loss is caused by current flowing through a steel sheet having electrical resistance, and excess eddy current loss is generated mainly by magnetic wall movement from magnetic field fluctuations which cannot be explained by classical eddy current loss. The 1D method is a method for calculating classical eddy current loss, but not for excess eddy current loss. There is a method that takes into account the excess eddy current loss coefficient [3], but the validity of the coefficient is a problem.

5. Summary

Conventional methods are based on measured values, and show that the 1D method and its results deviate when the excitation state is different from that at the time of measurement. The 1D method can accurately model the skin effect in the high frequency range and with DC superimposition, and can be said to be an eddy current loss calculation method with higher versatility than the conventional method.

6. References

[1] K. Yamazaki, N. Fukushima, “Carrier Loss of Induction Motors Driven by Inverters : Comparison between Results Separated by Experiment and Field Analysis”, Joint Technical Meeting on Static Apparatus and Rotating Machinery, SA-08-79, RM-08-86, 2008

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[3] K. Yamazaki, M. Tanida, H. Satomi, ”Calculation method for iron loss in rotating machines by direct consideration of eddy currents in electrical steel sheets”, IEEJ Transactions on Industry Applications, Vol.128, No.11, 2008

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