Research Article

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3-D Electromagnetic field analysis of wireless power transfer system using K computer

<https://doi.org/10.1515/phys-2018-0044>

Received Nov 01, 2017; accepted Jan 16, 2018

Abstract: We analyze the electromagnetic field of a wireless power transfer system using the 3-D parallel finite element method on K computer, which is a super computer in Japan. It is clarified that the electromagnetic field of the wireless power transfer system can be analyzed in a practical time using the parallel computation on K computer, moreover, the accuracy of the loss calculation becomes better as the mesh division of the shield becomes fine.

Keywords: wireless power transfer system; K computer; three dimensional finite element method; eddy current loss

PACS: 02.60.Cb, 07.05.Tp, 02.30.Fn

1 Introduction

The wireless power transfer system is an open circuit and the magnetic leakage flux affects far distance. Thus, it is important to investigate the distant magnetic field of wireless power transfer systems because it is necessary to consider the influence of the magnetic flux on the human body.

In a previous study, we have calculated the distant magnetic field of a wireless power transfer system using the 3-D finite element method [1].

In order to analyze the distant magnetic field and the eddy current loss of the wireless power transfer system accurately, it is necessary to divide the mesh of the wireless power transmitter finely while analyzing the wide area.

The 3-D parallel finite element method [2] is effective for such an analysis with long calculation time.

Thus, we analyze a wireless power transfer system in a wide area using the 3-D parallel finite element method on K computer, which is a super computer in Japan.

Consequently, it is clarified the distant magnetic field and the eddy current loss of the shield of the wireless power transfer system at the same time within a practical time.

2 Analysis method

2.1 Fundamental equations of magnetic field

When the magnetic flux varies sinusoidally, the fundamental equations of the electromagnetic field can be written using the magnetic vector potential $\mathbf{A}$ and the electric scalar potential ϕ as follows [3]:

$$\text{rot}(\nu \text{rot} \dot{\mathbf{A}}) = \dot{\mathbf{J}}_0 + \dot{\mathbf{J}}_e \quad (1)$$

$$\dot{\mathbf{J}}_e = -\sigma(j\omega \dot{\mathbf{A}} + \text{grad} \dot{\phi}) \quad (2)$$

$$\text{div} \dot{\mathbf{J}}_e = 0 \quad (3)$$

where ν is the reluctivity, $\dot{\mathbf{J}}_0$ is the exciting current density, $\dot{\mathbf{J}}_e$ is the eddy current density, σ is the electrical conductivity, j is the imaginary unit and ω is the angular frequency. The dot over the letter indicates a complex function.

The analysis has been done as a linear problem.

2.2 Electrical loss calculation

The eddy current loss W_{ed} in the aluminum plates of the shield is given as follows:

$$W_{ed} = \frac{1}{2\sigma} \int_{V_c} |\dot{\mathbf{J}}_e|^2 dv \quad (4)$$

where V_c is the region of the conductor with the eddy current.

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2.3 Parallel computing using DDM and MPI

In this study, the domain decomposition method (DDM) is adopted for the parallel computing. Using the DDM, the analysis domain is divided into multiple subdomains. The parallel computing is performed in distributed memory type parallel computer using message passing interface (MPI) for data communication [4].

2.4 Speed-up and parallel efficiency

The speed-up and parallel efficiency, which represents the performance of parallel computation, are calculated using the parallel number n respectively as follows [5]:

$$\text{Speed-up}(n \text{ core}) = \frac{\text{Elapsed time (1 core)}}{\text{Elapsed time (} n \text{ core)}} \quad (5)$$

$$\text{Parallel Efficiency} = \frac{\text{Speed-up}(n \text{ core})}{n} \times 100(\%) \quad (6)$$

3 Analyzed model and conditions

Figure 1 shows the analyzed model of a wireless power transfer system. The wireless power transmitter shown in Figure 1(a) is consisted of a pair of the ferrite core and the coil. The aluminum plates are located above and below the transmitter as the electromagnetic shield. The iron plate is located in the analyzed area, because it is on the ground in the experiment. The analyzed area ($120\text{m} \times 240\text{m} \times 240\text{m}$) shown in Figure 1(d) is a half of the whole region, because of the symmetry in the y-axis direction. The magnetic field at the “measured point” shown in Figures 1(b) and 1(c), is measured in the experiment.

Table 1 shows the computing environment. The *K computer* consists of 8 cores per node, and the main memory has 16 GB per node. In this study, two cores per node are used to calculate the electromagnetic field.

Table 2 shows the analysis condition. The analysis has been done using our own program.

Table 1: Computing environment

Parallel computer	K computer
CPU	SPARC64TM VIIIfx 128Gflops (2.0 GHz)
Cores	8 cores/node
Memory	16 GB/node

Table 2: Analysis condition

Primary coil	Number of turns	29
	Current (A_{rms})	9.1
	Frequency (kHz)	92.3
	Phase ($^{\circ}$)	0.0
Secondary coil	Number of turns	30
	Current (A_{rms})	9.8
	Frequency (kHz)	92.3
	Phase ($^{\circ}$)	-35.0
Ferrite core	Relative permeability	3,000
Aluminum plate	Relative permeability	1.0
	Conductivity (S/m)	3.8×10^7

4 Results and discussion

4.1 Elapsed time, speed-up and parallel efficiency

In this section, in order to investigate the characteristics of parallel efficiency, the magnetic field analysis was performed with various number of divisions of the analysis region.

Table 3 shows the discretization data. In order to investigate the performance of parallel computation, the analysis is performed under the condition that the number of parallel is 600 to 9600. The number of elements of the finite element model is approximately 340-380 million. The number of elements, nodes, and edges of the analysis model increases as the number of parallel increases, because the overlapping elements [4] increase.

Figure 2 shows the elapsed time. The calculation time is approximately 400 minutes when number of parallel is 600 and that is approximately 30 minutes when number of parallel is 9600.

Figure 3 shows the speed-up. The calculation time of 1 division is calculated from the elapsed times of 600 and 9600 divisions by Amdahl's law. From Figure 3, we can see that the speed-up close to the ideal can be obtained when number of parallel is 2400 or less. The speed-up falls below the ideal as the number of parallel increases.

Figure 4 shows the parallel efficiency. The parallel efficiency is over 90% when number of parallel is 1200, and that is over 70% even when number of parallel is 9600.

From these results, we confirmed that using parallel computation by *K computer*, we can analyze the electromagnetic field of the wireless power transfer system in a wide area within a practical time. Moreover, it is confirmed

Figure 1: Analyzed model of wireless power transfer system

that the electromagnetic field can be calculated with high efficiency even if the number of parallel is increased.

4.2 Mesh division of aluminum plate and analysis accuracy

In this section, we investigated the effects of mesh division of the aluminum plate on the eddy current loss and the distant magnetic field strength. From the results of the previ-

Figure 2: Elapsed time

Figure 3: Speed-up

Figure 4: Parallel efficiency

ous section, the number of parallel is set to 2400 for the efficient analysis.

Figure 5 shows the aluminum plate and its surrounding meshes. Each figure is an enlarged view of (i) primary side- and (ii) secondary side-aluminum plates shown in Figure 1(a). In order to investigate the effect of the fineness of the aluminum plate mesh on the eddy current loss and the distant magnetic field strength, the analysis is performed under the condition that the number of mesh di-

(i) primary side

(ii) secondary side

(a) primary 16, secondary 8 division

(i) primary side

(ii) secondary side

(b) primary 24, secondary 12 division

(i) primary side

(ii) secondary side

(c) primary 32, secondary 16 division

Figure 5: Enlarged view of the aluminum plate and its surrounding meshes

Figure 6: Distributions of eddy current loss of aluminum plate

Table 3: Discretization data (tetrahedral element)

	600	1200	2400
Number of parallel			
Number of elements	351,998,312	356,076,245	361,138,171
Number of nodes	61,893,536	63,727,255	65,987,137
Number of edges	420,245,083	428,374,801	438,384,168
Number of unknown variables	442,377,124	451,063,881	461,831,437
Number of parallel	4800	7200	9600
Number of elements	368,822,433	374,349,636	378,617,471
Number of nodes	69,451,740	71,959,153	73,918,884
Number of edges	453,641,230	464,630,082	473,164,131
Number of unknown variables	478,262,848	490,140,622	499,342,885

Table 4: Discretization data and elapsed time

	8	12	16
Number of mesh divisions			
Number of parallel		2,400	
Number of elements	330,484,691	361,138,171	361,979,701
Number of nodes	60,616,455	65,987,137	66,458,832
Number of edges	401,907,573	438,384,168	440,406,975
Number of unknown variables	417,892,720	461,831,437	460,144,958
MRTR convergence criterion		5.0×10^{-4}	
Number of MRTR iterations	18,197	64,898	77,818
Elapsed time (hours)	0.5	1.8	2.2

Figure 7: Distant magnetic field strength and eddy current loss

visions of the secondary side aluminum plate is 1 to 16. The primary side aluminum plate mesh is divided so as to have the same aspect ratio as the secondary side aluminum plate mesh.

Figure 6 shows the distributions of eddy current loss in the aluminum plate. We can see that the eddy current loss at secondary side is larger than that at primary side. Moreover, we can also see that the eddy current loss is concentrated on the surface of the aluminum plate by dividing the mesh finely.

Figure 7 shows the distant magnetic field strength at “measured point” shown in Figure 1 and the eddy current loss of the aluminum plate. The distant magnetic field strength is almost the same regardless of the mesh division of aluminum plate. However, the eddy current loss of the aluminum plate increases as the mesh becomes fine, and finally that converges to a certain value.

Table 4 shows the discretization data and elapsed time. The number of elements and calculation time also becomes to increase as the mesh division of the aluminum plate becomes finer.

5 Conclusion

In this paper, we analyzed a wireless power transfer system in a wide area using the 3-D parallel finite element method on *K computer*. Consequently, it is clarified that using parallel computation by *K computer*, we can analyze the electromagnetic field of the wireless power transfer system in a wide area within a practical time and efficiently calculate even high number of parallel. Moreover, the distant magnetic field strength hardly changes when making the mesh of the aluminum plate finer, however,

the eddy current loss of the aluminum plate increases and finally that converges to a certain value.

Acknowledgement: This research used computational resources of the *K computer* provided by the RIKEN Advanced Institute for Computational Science through the HPCI System Research project (Project ID:hp160188).

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