Parallel Finite Element Analysis of Rotating Machines Based on Domain Decomposition Considering Nonconforming Mesh Connection

Yasuhito Takahashi[1], Koji Fujiwara[1], Takeshi Iwashita[2], and Hiroshi Nakashima[3]

[1] Department of Electrical Engineering, Doshisha University, Kyoto 610-0321, Japan
[2] Information Initiative Center, Hokkaido University, Sapporo 060-0811, Japan
[3] Academic Center for Computing and Media Studies, Kyoto University, Kyoto 606-8501, Japan

This paper investigates effectiveness of a parallel finite element method (FEM) based on domain decomposition method taking account of nonconforming mesh connection between moving and fixed parts in magnetic field analyses of rotating machines. Numerical results of inter-bar current analyses in a cage induction motor that verify the effectiveness of the proposed method are presented.

***Index Terms*—Electric machines, finite element analysis, nonconforming mesh connection, parallel computing.**

I. Introduction

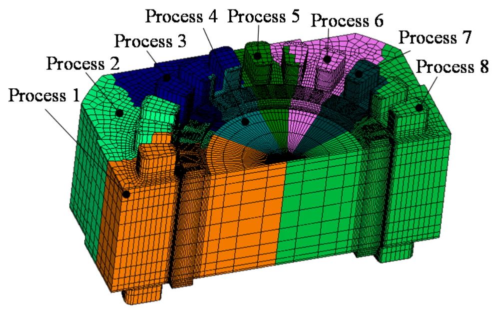
Recently, interest in energy-efficient induction motors is increasing drastically [1]. In order to estimate cause of stray load losses of induction motors clearly, in-depth investigations mainly based on finite element methods and experiments have been carried out [2]. One of the complex electromagnetic phenomena in induction motors is inter-bar currents flowing from rotor bars into rotor core when the bars are not insulated from the core completely. In addition, it is well known the inter-bar current loss is large when the rotor is skewed. Although various modeling methods for skewed rotor slots were reported [3], [4], the division of three-dimensional mesh for squirrel cage and electrical steel sheets in rotor core is indispensable in inter-bar current analyses, which results in extremely large-scale and time-consuming magnetic field computation.

In this paper, we develop a parallel finite element method based on domain decomposition considering nonconforming mesh connection to perform large-scale analyses of induction motors considering skewed rotor slots and inter-bar current within acceptable computational cost. We use the regular meshed subgrid fixed on the stator region as a sliding interface [5] to connect the fixed and moving parts. There are several papers on parallelization of finite element analyses for electric machines [6]. However, the scalability and load balancing issue in highly parallel computation has not been deeply discussed especially when using nonconforming mesh connection technique. The inter-bar current analysis of a cage induction motors is performed and the scalability of the proposed parallel FEM in distributed computing environment with over 100 processes with pure MPI programming model is investigated.

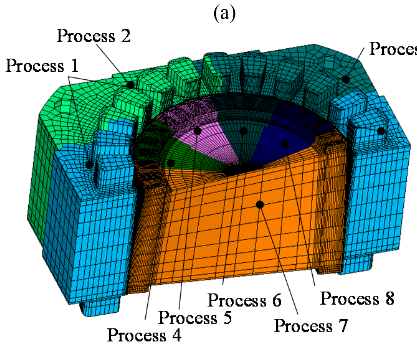
II. Domain Decomposition Considering Nonconforming Mesh Connection

When partitioning finite element meshes, it is desirable to reduce interface area between each domain (meshes with different partition number equivalent to rank in MPI programming) as small as possible to minimize total inter-process communications. Fig. 1(a) shows the example of conventional domain decomposition results when the number of processes is 8. In this paper, we use METIS [7] for mesh partitioning. Because the moving part rotates step-by-step in the magnetic field analysis, the mesh of the moving part is not conformed to that of fixed part. This means interface area between domains increases when rotor mesh rotates, which results in the increase of inter-process communication.

Originally, inter-process communication is always necessary on the sliding interface between the fixed and moving meshes. In order to keep inter-process communication costs as small as possible, we propose the following procedure. By performing domain decomposition separately in fixed and moving regions as shown in Fig. 1(b), the interface area does not vary when the rotor rotates. In this case, the number of processes assigned to moving and fixed parts should be proportional to the number of elements in respective region. The numbers of processes for the fixed and moving parts are 3 and 5, respectively, in Fig. 1(b). The partition numbers for the interface subgrid are assigned so that they correspond to those of the stator meshes. In addition,



(a)



(b)

Fig. 1. Results of domain decomposition when the number of processes is 8. (a) Conventional approach. (b) Proposed approach.

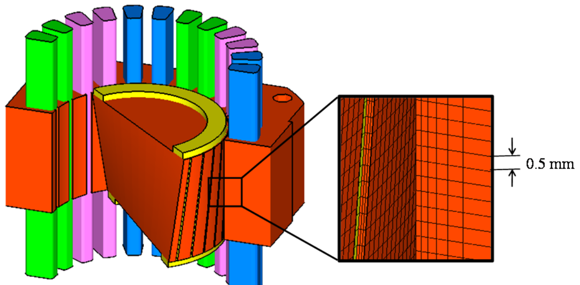


Fig. 2. 1/2 model of cage induction motor.

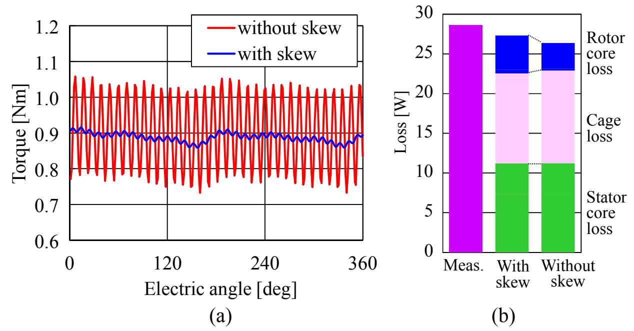


Fig. 3. Numerical results. (a) Torque waveform. (b) Loss.

TABLE I
PARALLEL PERFORMANCE OF FEM BASED ON DOMAIN DECOMPOSITION

Number of processes	Average calculation time per step [sec]	Speedup ratio	Total NR iterations for 100 steps	Total ICCG iterations for 100 steps
1	4170.0	1.0	593	237688
16	396.1	10.5	564	288805
32	213.0	19.6	562	295888
64	109.6	38.1	561	304876
128	65.5	63.6	559	306846
256	46.4	89.9	560	318383

assigning the same partition number to finite elements on periodic boundary is advantageous to implementation [8].

III. NUMERICAL RESULTS

In order to examine the scalability of the developed method, the inter-bar current analysis of a cage induction motor shown in Fig. 2 is carried out. An electrical steel sheet (JIS grade: 50A1300) is subdivided into 1-layer mesh in the rotor and stator cores as shown in Fig. 2. We use gap elements [9] and double nodes technique [10] to take account of the magnetic resistance and insulation bet ween electrical steel sheets. The contact resistance at the interface between the bars and the rotor core is assumed as zero. We solve a system of nonlinear equations derived from the *A*-*V* formulation coupled with electric circuit equations. The numbers of elements and unknowns are 1869760 and 5089964, respectively. The number of time steps for a period is 256, the frequency is 50 Hz, and the slip is set as 0.059. The skew angle corresponds to 1 rotor slot pitch. All the computations were performed on the supercomputer Appro GreenBlade 8000, in which a node consists of two Intel Xeon E5 processors [11]. We use the Newton-Raphson (NR) method as a nonlinear iteration method, and the ICCG method for a linearized system of equations. The acceleration factor for the localized IC preconditioner is 1.25 in all the computations.

Table I shows the performance of a parallel FEM based on the proposed domain decomposition. The computational time is averaged for 100 time steps. The convergence rate of the NR method is almost constant without depending on the number of processes. In general, the convergence rate of the ICCG method deteriorates with increasing the number of processes in using localized IC preconditioning because off-diagonal submatrices are ignored in the construction of the preconditioner matrix. However, the significant decline in convergence has not been observed in this analysis. As a result, the good scalability can be achieved even in the highly parallel computation (90-fold speedup when using 256 processes).

Fig. 3(a) compares torque waveforms between skewed and non-skewed rotor slots. The skewing of rotor slots makes the torque ripples much smaller as is expected. Fig. 3(b) shows comparison of the losses between induction motors with skewed and non-skewed rotor slots. In the case of the skewed rotor slots, the rotor core loss increases due to the inter-bar current loss, although the cage loss decrease a little because of decrease of high-order harmonics in the secondary conductor. In addition, the calculated loss is almost the same as the measured one. From the above-mentioned results, the effectiveness of the developed method can be confirmed in the large-scale inter-bar current analysis of a cage induction motor with skewed rotor slots.

The details of the domain decomposition considering nonconforming mesh connection, and more numerical results will be included in the full paper.

REFERENCES

[1] A. T. De Almeida, F. J. T. Ferreira, and A. Q. Duarte, "Technical and Economical Considerations on Super High-Efficiency Three-Phase Motors," *IEEE Trans. Ind. Appl.*, vol. 50, no. 2, pp. 1274-1285, Mar./Apr. 2014.

[2] K. Yamazaki and Y. Watanabe, "Interbar Current Analysis of Induction Motors Using 3-D Finite-Element Method Considering Lamination of Rotor Core," *IEEE Trans. Mgn.*, vol. 42, no. 4, pp. 1287-1290, Apr. 2006.

[3] K. Yamazaki, "A Quasi 3D Formulation for Analyzing Characteristics of Induction Motors with Skewed Slots," *IEEE Trans. Magn.*, vol. 34, no. 5, pp. 3624-3627, Sep. 1998.

[4] A. Tenhunen and A. Arkkio, "Modelling of Induction Machines with Skewed Rotor Slots," *IEE Proc. of Elec. Power Appl.*, vol. 148, no. 1, pp. 45-50, Jan. 2001.

[5] H. Kometani, S. Sakabe, and A. Kameari, "3-D Analysis of Induction Motor with Skewed Slots Using Regular Coupling Mesh," *IEEE Trans. Magn.*, vol. 36, no. 4, pp. 1769-1773, July 2000.

[6] T. Nakano, Y. Kawase, T. Yamaguchi, and M. Nakamura, "Parallel Computing of 3-D Eddy-Current Analysis with *A*-ϕ Method for Rotating Machines," *IEEE Trans.Magn.*, vol. 48, no. 2, pp. 975–978, Feb. 2012.

[7] G. Karypis and V. Kumar, "A Fast and Highly Quality Multilevel Scheme for Partitioning Irregular Graphs," *SIAM J. Sci. Comp.*, vol. 20, no. 1, pp. 359-392, 1999.

[8] T. Nakano, et al., "Parallel computing for Magnetic Field Analysis of rotating machines on the Earth Simulator," *J. Applied Electromagnetics and Mechanics*, vol. 20, no. 1, pp. 150-155, Mar. 2012 (in Japanese).

[9] N. Nakata, N. Takahashi, K. Fujiwara, and Y. Shiraki, "3-D magnetic field analysis using special elements," *IEEE Trans. Magn.*, vol. 26, no. 5, pp. 2379–2381, Sep. 1990.

[10] Y. Kamiya and T. Onuki, "3D Eddy Current Analysis by the Finite Element Method Using Double Nodes Technique," *IEEE Trans. Magn.*, vol. 32, no. 3, pp. 741-744, May 1996.

[11] http://www.iimc.kyoto-u.ac.jp/en/services/comp/services/supercomputer.html