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A New Acceleration Factor Decision Method for ICCG Method Based on Condition Number

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The ICCG method is widely used to solve a sparse symmetric linear system which results from the finite element method. In order to improve the convergence property of the ICCG method, the introduction of the acceleration factor was proposed. The automatic acceleration factor decision method, using the incomplete Cholesky decomposition of a coefficient matrix, has been previously proposed. However, when employing the previously proposed automatic decision method, much more iterations of ICCG method are sometimes necessary, compared with using the optimum acceleration factor, which minimizes the number of ICCG iterations. In this paper, we propose a new acceleration factor decision method. The proposed method takes into account the condition number of the coefficient matrix. It is well known that the condition number represents the quality of the matrix, so the optimum acceleration factor should be decided to minimize the condition number of the coefficient matrix. However, the condition number of the coefficient matrix is not almost available due to requiring a large memory in computing. Therefore, we develop a new method using submatrix, that does not need a large memory. The procedure and demonstration of the proposed method are described in this paper.

Index Terms—Acceleration factor, condition number, finite element method, ICCG method, submatrix.

I. INTRODUCTION

FINITE ELEMENT METHOD (FEM) yields a sparse symmetric linear system. In the finite element analysis, the ICCG method [1], [2] is widely used to solve the sparse symmetric linear system. In order to solve it with short time, an acceleration factor of the ICCG method was proposed [3]. The effectiveness and usefulness of the acceleration factor was demonstrated in [3]-[5] and it has been widely and commonly used. However, it is known that a residual norm may not be converged or an unnecessarily large number of iterations of the ICCG method are required unless the acceleration factor is optimally determined. Therefore, a way to find the optimum acceleration factor, which minimizes the number of iterations, should be developed. Before an acceleration factor decision method by finding the minimum of maximum diagonal entries of the lower triangular matrix was proposed in [4]. The automatic decision method has been commonly employed. When a generated mesh is of good quality, the automatic decision method is effective in reducing the number of the ICCG iterations. However, when using a mesh of bad quality, the automatic decision method does not always yield the optimum acceleration factor and much more iterations of the ICCG method are sometimes required. Therefore, a new acceleration factor decision method has to be developed, and it is expected to be robust to the mesh quality.

The condition number of matrix commonly represents the quality of the matrix [6], and hence the acceleration factor which minimizes the condition number of the pre-conditioned matrix after the incomplete Cholesky (IC) decomposition should be explored as an optimum acceleration factor. It is, however, impossible to compute the condition number of the coefficient matrix resulting from the finite element method due to requiring a large memory to compute the eigenvalue of the coefficient matrix [7]-[9]. In this paper, we propose a new acceleration factor decision method by minimizing the condition number of the submatrix which is small enough to compute its eigenvalue. The procedure of the proposed method is presented in this paper. In order to confirm the effectiveness of the proposed method, a few examples are also presented.

II. PRE-CONDITIONED SYSTEM

Given the linear system

$$Ax = b,$$

where $A$, $x$, and $b$ are the coefficient matrix, the solution vector, and the right hand vector, respectively. Using the incomplete Cholesky (IC) decomposition of $A$, $A \approx LDL^T$, (1) is pre-conditioned as follows:

$$\tilde{A}\tilde{x} = \tilde{b},$$

where

$$\tilde{A} = M^{-1}AM^{-T}, \quad \tilde{x} = M^T x, \quad \tilde{b} = M^{-1}b,$$

$$M = L(\gamma)D(\gamma)^{1/2},$$

where $\gamma$ is the acceleration factor. The pre-conditioned system (2) depends on the acceleration factor $\gamma$ since $L$ and $D$ are obtained using the acceleration factor. The condition number $\kappa$ of $A$ is as follows [6]:

$$\kappa = \frac{\mu_{\text{max}}}{\mu_{\text{min}}},$$

where $\mu_{\text{max}}$ and $\mu_{\text{min}}$ are the maximum eigenvalue and the nonzero minimum eigenvalue of $A$, respectively.

Note that the optimum acceleration factor of the ICCG
method gives the minimum condition number of the pre-conditioned system and the minimum number of iterations.

III. THE PROPOSED AUTOMATIC ACCELERATION FACTOR DECISION METHOD

The condition number $\kappa$ of the coefficient matrix derived from the FEM commonly represents the quality of the coefficient matrix. It is, however, almost impossible to compute $\kappa$ due to requiring much large memory to compute the eigenvalue of the coefficient matrix. Then, the proposed method estimates the condition number of the full matrix from ones of the small-size submatrices, which are small enough to compute their eigenvalue. Here, it is not required to highly accurately estimate the condition number of the full coefficient matrix, since the condition number is used to decide the acceleration factor which minimizes the number of the ICCG iterations. Therefore, the condition number of the full coefficient matrix is roughly estimated from the submatrices, and then the acceleration factor is decided by minimizing the condition number of the submatrices.

The procedure of the proposed automatic acceleration factor decision method is shown as follows.

Step 1) Make the full coefficient matrix derived from FEM.

Step 2) Subdivide the full coefficient matrix into many submatrices, as shown in Fig. 1.

Step 3) Calculate the condition number of all the submatrices.

Step 4) Choose the submatrices whose condition number is more than the threshold $\kappa_{th}$. The way to decide the threshold is explained later.

Step 5) Decide the optimum acceleration factor $\gamma_p$ for each submatrix chosen on Step 4. Here, $\gamma_p$ is obtained so as to minimize the condition number of each pre-conditioned system for these submatrices.

Note: For obtaining $\gamma_p$, the condition number of each pre-conditioned system is investigated with various acceleration factors.

Step 6) Employ the maximum of the acceleration factors, $\gamma_{p\text{MAX}}$, as the acceleration factor $\gamma_{\text{new}}$ to the full coefficient matrix.

The optimum acceleration factor $\gamma_{\text{opt}}$ should be larger as the convergence property of the ICCG method is worse. That is, a matrix with bad condition number requires a large optimum acceleration factor. However, the submatrix with the worst condition number does not always give the largest optimum acceleration factor. Therefore, it is necessary to decide the threshold in order to choose the submatrices with bad condition number. That is the reason why the threshold of the condition number, $\kappa_{th}$, should be decided to choose the submatrices with bad condition number. If the condition number of all the submatrices is computed, it takes a lot of time. A good example is shown later with a test model.

IV. APPLICATIONS OF THE PROPOSED METHOD

A. Simple Model Test

A simple test model consists of a permanent magnet (1.0 T), as shown in Fig. 2. The analysis region is firstly divided into regular hexahedra, and then each hexahedron is regularly divided into six tetrahedra. Table I shows the properties of the mesh. For the verification of the proposed method, the distorted mesh, which makes the convergence of the ICCG iteration bad, is generated by zigzag moving the nodes of the generated model into $x$-direction, as shown in Fig. 3. The moving distance of nodes is 49.99 mm.

The proposed method is applied to the simple test model with the distorted mesh. The matrix derived from FEM is divided into 8 submatrices. Fig. 4 shows the condition number $\kappa$ and the acceleration factor $\gamma_p$, which minimizes the condition number of the pre-conditioned system, for all the submatrices. The acceleration factor $\gamma_{\text{new}}$ is 1.09, taking the highest value among the acceleration factors, $\gamma_{p\text{MAX}}$, for all the submatrices.
In order to investigate the optimum acceleration factor \( \gamma_{\text{opt}} \), the finite element matrix of the simple test model is solved by the ICCG method with various acceleration factors \( \gamma \). Fig. 5 shows the number of the ICCG iterations versus the acceleration factor. Table II shows the details of the results.

Fig. 5 shows that \( \gamma_{\text{opt}} \) is equal to 1.08 and near to the acceleration factor \( \gamma_{\text{new}} \) decided by the proposed method. Using the previous method [4], the acceleration factor \( \gamma_{\text{old}} \) is decided to be 1.05 by taking the minimum of the maximum diagonal entry \( L \). The numbers of the ICCG iterations with \( \gamma_{\text{opt}} \) and \( \gamma_{\text{new}} \) are 801 and 806, respectively, as shown in Table II, and both are almost the same. On the other hand, the number of the iterations with \( \gamma_{\text{old}} \) is much larger than that with \( \gamma_{\text{opt}} \) and \( \gamma_{\text{new}} \) (see Table II). The effectiveness of the newly proposed method is confirmed.

### Table II: Acceleration Factor and Number of ICCG Iterations on Test Model

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<thead>
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<th>Acceleration factor</th>
<th>Number of iterations</th>
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<tr>
<td>( \gamma_{\text{opt}} )</td>
<td>1.08</td>
</tr>
<tr>
<td>( \gamma_{\text{new}} )</td>
<td>1.09</td>
</tr>
<tr>
<td>( \gamma_{\text{old}} )</td>
<td>1.05</td>
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**B. SQUID Model**

As a practical and complicated model, a SQUID model (thin plate model) [10], as shown in Fig. 6, is solved by FEM. Table III shows the mesh properties of the SQUID model. The mesh includes many ill-shaped elements, such as a flat element. Fig. 7 shows the nonzero distribution of the finite element matrix with A-\( \phi \) formulation.

Fig. 6. A directly coupled HTS dc-SQUID model [10] with thin plate (width : 0.2 \( \mu \)m).

**Fig. 7.** Nonzero distribution of the finite element matrix derived from SQUID model [10]. The dots represent nonzero entries.

The full matrix is divided to 3,628 submatrices whose dimension is equal to about 1,000. Fig. 8 shows the condition numbers of all submatrices. From Fig. 8, the threshold \( \kappa_h \) is decided to be \( 10^7 \) for eliminating the worse condition number of the submatrices. Fig. 9 shows the acceleration factors \( \gamma_p \) which minimize the condition number of the pre-conditioned system for the submatrices with the condition number more than threshold \( \kappa_h \). From Fig. 9, the acceleration factor \( \gamma_{\text{new}} \) is decided to be 1.37 by the proposed method.

**Fig. 8.** The condition number distribution of submatrices.
The finite element equations are solved by ICCG method with various acceleration factors in order to investigate the effectiveness of the proposed method and the optimum acceleration factor, as shown in Fig. 10. The maximum diagonal entry of the lower triangular matrix $L$, used in the previous proposed method [4], is also investigated in order to compare with the proposed method. From Fig. 10, if the acceleration factor is small, such as 1.10, it is impossible to solve the equations within a proper number of the ICCG iterations. Table IV shows the acceleration factors, the number of the ICCG iterations, and the computation time (Xeon W5590 processor (3.33 GHz)).

![Fig. 9. The optimum acceleration factor of the submatrix.](image)

<table>
<thead>
<tr>
<th>Acceleration factor</th>
<th>Number of iterations</th>
<th>Computation time (Xeon W5590)</th>
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<tbody>
<tr>
<td>$\gamma_{opt}$</td>
<td>1.28</td>
<td>1,844</td>
</tr>
<tr>
<td>$\gamma_{new}$</td>
<td>1.37</td>
<td>1,919</td>
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<tr>
<td>$\gamma_{old}$</td>
<td>1.19</td>
<td>2,969</td>
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![Fig. 10. Number of iterations and maximum diagonal entry versus acceleration factor. The optimum acceleration factor is 1.28 and the acceleration factor decided by the newly proposed method and the previous method [4] is 1.37 and 1.19, respectively. The acceleration factor of the proposed method needs nearly more 100 iterations than that of the optimum but less 1,000 iterations than that of the previous method.](image)

![TABLE IV ACCELERATION FACTOR, NUMBER OF ICCG ITERATIONS AND COMPUTATION TIME ON SQUID MODEL](image)

In this paper, we proposed a new acceleration factor decision method so as to minimize the condition number of the submatrix which was small enough to calculate the eigenvalue. For the demonstration, the proposed method was applied to the simple test model and the SQUID model with a thin plate. The proposed method can adequately decide the acceleration factor, which needs the number of the ICCG iterations as many as the optimum acceleration factor, with short time.

V. CONCLUSION

In this paper, we proposed a new acceleration factor decision method so as to minimize the condition number of the submatrix which was small enough to calculate the eigenvalue. For the demonstration, the proposed method was applied to the simple test model and the SQUID model with a thin plate. The proposed method can adequately decide the acceleration factor, which needs the number of the ICCG iterations as many as the optimum acceleration factor, with short time.

REFERENCES