Free Vibration Analysis of Repetitive Structures using Decomposition, and Divide-Conquer Methods

L. Shahryari

Science and Research Branch, Islamic Azad University, Fars, Iran

Received 21 Dec, 2010; Accepted 4 Jan, 2011

Abstract

This paper consists of three sections. In the first section an efficient method is used for decomposition of the canonical matrices associated with repetitive structures. to this end, cylindrical coordinate system, as well as a special numbering scheme were employed. In the second section, divide and conquer method have been used for eigensolution of these structures, where the matrices are in the block tri-diagonal form. In the third section a comparison of the results is presented. In order to illustrate the efficiency of the aforementioned methods, repetitive structures are considered in the form of barrel vault space structures.

Keywords: Space structures (barrel vaults), Factor analysis, Eigenvalues and Eigenfunctions, Vibration

1. Introduction

Real symmetric eigenvalue problems frequently arise from scientific and engineering computations. The structures of the matrices and the requirements for the eigensolutions vary by application. For instance, many matrices generated from electronic structure calculations in quantum mechanics have strong locality properties. Some of them are block-tridiagonal; some are dense but with larger elements close to the diagonal and a decrease in the magnitudes of elements as they move from the diagonal. In many situations, the second type of matrices may be approximated by block-tridiagonal matrices with very low computational cost. In this paper two useful and high speed methods were compared to each other in order to solve the eigensolutions.[1-18,19].

- There are several applications of eigenproblems in structural mechanics. The eigenvalues and eigenvectors of graphs play an important role in algebraic graph theory and combinatorial optimization. Large structural models and their corresponding graphs have large and sparse matrix representations. The factorization of these matrices with arbitrary patterns requires general methods. special topologies the associated matrices of which can be transformed to particular patterns in such a manner that their factorizations can more easily be performed. Some of these matrices were previously studied by Kaveh and Sayarinejad [20-21], Kaveh and Rahami [22], and some other general eigensolution methods are also available in Robbe and Sadkane [23], Park [24], Mathias and Stewart [25] and Hasan and Hasan [26], among many others. There are also some applications of graphs spectra in nodal and element ordering and graph partitioning. Further information about these issues can be found in Gould [27], Straffing [28], Maas [29], and Grimes et al. [30]. However, despite of the efficiency of graphs spectra for combinatorial optimization, the calculation of eigenvalues and eigenvectors of large graphs and their corresponding structural models without considering patterns and the sparsity of their matrices require considerable memory and computational time. In this article, a new canonical form and its relation with some structural models often encountered in practice are presented.
• The block-tridiagonal divide-and-conquer algorithm developed by Gansterer and Ward et al. [16] provides an eigensolver that addresses the above issues. Their algorithm computes all the eigenvalues and eigenvectors of a block-tridiagonal matrix to reduced accuracy with a similar reduction in execution time for most applications.

One of the challenges is that the matrix sizes are usually very large and exceed the limitation of single processor architecture. Thus, parallel computation becomes necessary. The block-tridiagonal divide-and-conquer algorithm is considered inherently parallel because the initial problem can be divided into smaller subproblems and solved independently. We are thus motivated to implement an efficient, scalable parallel block-tridiagonal divide-and-conquer eigensolver with the ability to compute eigensolutions to a user-specified accuracy.

2. Block Diagonalization of Compound Matrices

In linear algebra it is known that a square matrix can be diagonalized using the normalized eigenvectors, provided that all the eigenvectors are orthogonal. It is also proved that if the matrix is Hermitian, then it can be diagonalized and diagonal entries constitute the eigenvalues of this matrix. A matrix is Hermitian if its conjugate is the same as its transpose. Therefore, if a matrix is real, then symmetry is the only requirement to make the matrix Hermitian. The eigenvalues of Hermitian matrices are real and the eigenvectors corresponding to any arbitrary pairs of distinct eigenvalues are orthogonal.

If M is a Hermitian matrix, then it can be diagonalized using $U^T M U$. All what is required is the formation of an orthogonal matrix $U$. This can in fact be achieved by the Singular Value Decomposition (SVD) approach for symmetric matrices.

Definition: The Kronecker product of two matrices $A$ and $B$ is the matrix we get by replacing the entry $ij$ of $A$ by $ij$ of $B$, for all $i$ and $j$.

As an example,

$$
\begin{bmatrix}
1 & 1 \\
1 & 0
\end{bmatrix} \otimes \begin{bmatrix}
a & b \\
c & d
\end{bmatrix} =
\begin{bmatrix}
a & b & a & b \\
c & d & c & d \\
a & b & 0 & 0 \\
c & d & 0 & 0
\end{bmatrix}
$$

(1)

Where the entry $(1,1)$ in the first matrix has been replaced by a complete copy of the second matrix. Now the main question is how one can block diagonalize a compound matrix. For a matrix $M$ defined as a single Kronecker product, in the form $M = A_1 \otimes B_1$, it is obvious that if $A_1$ is Hermitian, then the diagonalization leads to a block diagonal matrix of the form $D_{A_1} \otimes B_1$. Now suppose a compound matrix $M$ can be written as the sum of two Kronecker products:

$$M = A_1 \otimes B_1 + A_2 \otimes B_2$$

(2)

Now we want to find a matrix $P$ which diagonalizes $A_1$ and $A_2$. In such a case, one should show that $U = P \otimes I$ block diagonalizes $M$, i.e., we have to show that $U^T M U$ is a block diagonal matrix.

From algebra we have

$$(A \otimes B)^T = A^T \otimes B^T \text{ and } (A \otimes B)(C \otimes D) = AC \otimes BD$$

Then:

$$U^T M U = (P^T \otimes I^T)(A_1 \otimes B_1 + A_2 \otimes B_2)(P \otimes I)$$

$$= (P^T A_1 \otimes (B_1 I) + P^T A_2 \otimes (B_2 I))(P \otimes I)$$

$$= (P^T A_1 P) \otimes (B_1 I) + (P^T A_2 P) \otimes (B_2 I)$$

$$= (P^T A_1 P) \otimes (B_1) + (P^T A_2 P) \otimes (B_2)$$

(3)

Since it is assumed that $P$ diagonalizes $A_1$ and $A_2$,

$$P^T A_1 P = D_{A_1} \text{ and } P^T A_2 P = D_{A_2}$$

(4)

Therefore

$$U^T M U = D_{A_1} \otimes B_1 + D_{A_2} \otimes B_2$$

(5)

Thus, $U$ becomes block diagonalized, and in order to calculate the eigenvalues of $M$, one can evaluate the eigenvalues of the blocks on the diagonal. $M$ and $U^T M U$ are similar matrices, since $P$ is orthogonal, thus $U$ is also orthogonal and its inverse is equal to its transpose. Now an important question is whether the assumptions made at the beginning of this section are feasible; i.e., can one always find an orthogonal matrix $P$, which diagonalizes $A_1$ and $A_2$ are feasible simultaneously.

For a matrix to be diagonalizable, it is necessary to be Hermitian. However, for two matrices to be diagonalizable, not only should these two matrices be Hermitian, but these matrices should be commutative; i.e., $A_1 A_2 = A_2 A_1$ should hold.

Theorem 1: Two Hermitian matrices $A_1$ and $A_2$ can be diagonalized simultaneously with an orthogonal matrix $P$ if and only if

$$A_1 A_2 = A_2 A_1$$

(6)

A simple proof of this theorem can be found in [2]. Therefore, if $A_1$ and $A_2$ commute with respect to multiplication, then according to Eq. (2) and the Theorem 1,
\[ \lambda_M = \bigcup_{i=1}^{n} \{ \operatorname{eig}(\lambda_i(A)B_1 + \lambda_i(A)B_2) \} \]  

(7)

The \( \lambda_i(A) \) for \( j = 1, 2 \) is a diagonal matrix containing all the eigenvalues of \( A_j \), and \( n \) is the dimension of the matrix \( A_j \). It should be noticed that the order of the eigenvalues in \( A_2 \) and \( A_1 \) is important. The order is the same as obtained after simultaneous diagonalization of the two matrices, which appear on the diagonal of the matrices.

As an example, for the special case with \( A_2 = I \), it is obvious that \( IA_1 = A_2 I \), and according to theorem 1 we have:

\[ M = I \otimes B_1 + A_2 \otimes B_2, \]

(8)

\[ \lambda_M = \bigcup_{i=1}^{n} \{ \operatorname{eig}(B_1 + \lambda_i(A)B_2) \} , \quad \lambda_i(A) = 1 \]

These special cases already shown in the work of Kaveh and Sayarinejad [1].

For example in barrel vault shown in (fig.1), that is generated by repetition of one block (one square and two orthogonal elements) along \( Y \) direction and about \( Z \) direction (Like one half cylinder). It is observed that if cylindrical coordinate system is considered in away that the origin is located on cylinder axis and this axis is parallel to \( Z \) axis then symmetry relationships are derived for various degrees of freedom.

\[ \lambda_i(A) = 2 \cos \frac{i \pi}{n+1} , \text{ where } i = 1 \ldots n. \]

2.1. Stiffness Matrix Calculation

In structures similar to barrel vault shown in (fig.1), that whole structure is made by repetition of some elements, it can be seem that most of elements of stiffness matrix are equal, this leads to the question whether there is any symmetry in their mechanical property matrices. The answer would be positive if a suitable coordinate system is chosen.

For example in barrel vault show in (fig.1), that is generated by repetition of one block (one square and two orthogonal elements) along \( Y \) direction and about \( Z \) direction (Like one half cylinder). It is observed that if cylindrical coordinate system is considered in away that the origin is located on cylinder axis and this axis is parallel to \( Z \) axis then symmetry relationships are derived for various degrees of freedom.

\[ \begin{bmatrix}
A_{11} & A_{12} & 0 & 0 & \cdots \\
A_{12}^T & A_{22} & A_{23} & 0 & \cdots \\
0 & A_{23}^T & A_{33} & A_{34} & \cdots \\
0 & 0 & A_{34}^T & A_{44} & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots 
\end{bmatrix} \]

(11)

This is a block matrix, in this matrix index show the row number of nodes with active DOFs. For example \( A_{11} \) show the stiffness between nodes located on the first row (stiffness between nodes 9 to 13) and \( A_{12} \) show stiffness between nodes located on first and second rows. (nodes 9 to 13 with 16 to 20). It is obvious that stiffness between nodes on the first row and nodes on the third rows and above that, are equal to zero. The other entries are calculated with similar procedure.
In the next step the following symmetry relationships can be derived with respect to similarity among the corresponding nodes in various rows while direction of DOFs in away row is the same as the previous and the next rows (this condition is satisfied in cylindrical coordinate system, (fig.3))

\[
A_{11} = A_{22} = A_{33} = \cdots = A \\
A_{12} = A_{23} = A_{34} = \cdots = B
\]  

(12)

Therefore, the overall stiffness matrix (and any other property matrix) must be in the following form:

\[
K = \begin{bmatrix}
A & B & 0 & 0 & \cdots \\
B^T & A & B & 0 & \cdots \\
0 & B^T & A & B & \cdots \\
0 & 0 & B^T & A & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]  

(13)

\[
B = \begin{bmatrix}
G & J & L \\
J^T & H & K \\
-L^T & -K^T & I
\end{bmatrix}
\]

(14)

As shown in (fig.4) if DOFs (θ), in θ direction, is inverted alternatively, symmetry among all DOFs of every row in cylinder direction is in direct symmetry with previous and next rows relative to symmetry planes, and matrix block B would be in following form:

\[
K = \begin{bmatrix}
A & B & 0 & 0 & \cdots \\
B & A & B & 0 & \cdots \\
0 & B & A & B & \cdots \\
0 & 0 & B & A & \cdots \\
\vdots & \vdots & \vdots & \vdots & \ddots
\end{bmatrix}
\]  

(16)
coordinate axes (fig.1), rotation is just applied in XZ plane. Therefore, axis Z of cylindrical coordinate system is the same axis Y of Cartesian coordinate system and does not change. Beside according to fig.6 axe X is transformed to \( R \) and Z to \( \theta \) by means of a rotation that is equal to \( \theta \). The magnitude of rotation of each node's DOFs is simply calculated. According to these subjects the rotation matrix of each node's DOFs is defined as follows:

\[
\varphi = \begin{bmatrix}
\cos \theta & 0 & \sin \theta \\
0 & 1 & 0 \\
-\sin \theta & 0 & \cos \theta \\
\end{bmatrix}
\]  
(17)

In this case in cylindrical coordinate system DOFs of each node would be \( R, Z, \theta \) respectively. In order to generate overall rotation matrix of structure, the rotation matrix of consecutive nodes must be calculated and located as block diagonal in one matrix. It means that if rotation matrix of node i is equal to \( \varphi_i \), then transformation matrix for whole structure is:

\[
\Phi = \begin{bmatrix}
\varphi_1 & 0 & 0 & \cdots \\
0 & \varphi_2 & 0 & \cdots \\
0 & 0 & \varphi_3 & \cdots \\
\vdots & \vdots & \vdots & \ddots \\
\end{bmatrix}
\]  
(18)

Therefore, overall transformation matrix is \( 3n \times 3n \) matrix. (n is the number of nodes) And overall stiffness matrix in new coordinate system is calculated as:

\[
K' = \Phi^T K \Phi
\]  
(19)

### 2.1.2. Changing the Direction of DOFs

After calculating stiffness matrix in cylindrical coordinate system as mentioned above, in order to solve the problem with sign in some entries of block B, it is necessary to change the direction of DOFs (\( \theta \)) in some nodes. (fig.4)

This purpose is achieved by multiplying third rows and columns of nodes that are just on even rows (or odd rows) by -1. The calculation of first and second steps can be done at once. It means that third column of transformation matrix \( X \), in nodes that their sign of DOFs (\( \theta \)) must be inverted, is multiplied by -1. Therefore in consecutive rows the previous rotation matrix and aforementioned rotation matrix and next rotation matrix are applied.

\[
\varphi' = \begin{bmatrix}
\cos \theta & 0 & -\sin \theta \\
0 & 1 & 0 \\
-\sin \theta & 0 & -\cos \theta \\
\end{bmatrix}
\]  
(20)

Fig 5. DOFs of nodes in cartesian coordinate system

Fig 6. Transfer of DOFs from the cartesian coordinate system to cylindrical coordinate system
3. The Block Tridiagonal Divide-and-Conquer Algorithm

In this section the Block Tridiagonal Divide-and-Conquer (BD&C) algorithm is briefly described.

\[
M = \begin{bmatrix}
B_1 & C_1^T \\
C_1 & B_2 & C_2^T \\
& \ddots & \ddots & \ddots \\
& & B_{q-1} & C_{q-1}^T \\
& & & C_{q-1} & B_q
\end{bmatrix} \in \mathbb{R}^{n \times n}
\]  

(21)

where \( q \) is the number of diagonal blocks, \( B_i \) for \( 1 \leq i \leq q \) are the diagonal blocks and \( C_i \) for \( 1 \leq i \leq q - 1 \) are the off-diagonal blocks. The BD & C algorithm calculates the eigenvalues of \( M \) with an accuracy tolerance \( \tau (\tau \leq \varepsilon_{\text{mach}}) \).

\[ M \approx \tilde{V} \Lambda \tilde{V} \]

We calculate \( \tilde{V} \) and \( \tilde{\Lambda} \) such that \( \tilde{V} \) contains approximations to the eigenvectors of \( M \) and the diagonal matrix \( \tilde{\Lambda} \) contains approximations to the eigenvalues of \( M \).

\[
\left\| M - \tilde{V} \tilde{\Lambda} \tilde{V}^T \right\|_2 = O(\|M\|_2 \varepsilon_{\text{mach}}).
\]

(22)

The product \( \tilde{V} \tilde{V}^T \) with a small error \( \varepsilon_{\text{mach}} \) is equal to the unity matrix.

\[
\max_{i=1,2,...,n} \left\| (\tilde{V} \tilde{V}^T - I)_i \right\|_2 = O(\varepsilon_{\text{mach}} n)
\]

(23)

For \( 1 \leq i \leq n \), \( e_i \) is the \( i \)th column of the unity matrix.

The three main steps of the BD&C algorithm are as follows:

Problem subdivision, sub problem solution, and synthesis of sub solution.

Singular values, singular vectors and their relationship

A real positive number \( \sigma \) is called the singular value of \( M \) if and only if the unit vector \( u \) in \( K^m \) and \( v \) in \( K^n \) exist such that \( Mv = \sigma u \) and \( M^T u = \sigma v \).

\[
\hat{B}_i = B_i - U_{i-1} \sum_{i=1}^j U_i^T V_i \sum_{i=1}^j V_i^T,
\]

for \( 2 \leq i \leq q - 1 \)

The vectors \( u \) and \( v \) are called the left-singular and the right singular for \( \sigma \), respectively.

In certain singular decomposition \( M = U \Sigma V^T \)

(24)

The diagonal entries of \( \Sigma \) are equal to the singular values of \( M \), and the columns of \( U \) and \( V \) are the left singular and right singular vectors corresponding the singular values, respectively.

\[ M = U \Sigma V^T \]

Problem subdivision: The off-diagonal blocks \( C_i \) are approximated with lower rank matrices using their singular value decompositions:

\[
C_i \approx \sum_{\sigma_i \leq \rho_i} \sigma_i u_i^T u_i = U_i \sum_{i=1}^\rho_i V_i^T
\]

(26)

In this way the dimension of the matrix \( C_i \) is reduced. Where \( \rho_i \) is the chosen approximate rank of \( C_i \), \( U_i \in \mathbb{R}^{n \times \rho_i} \) is an orthogonal matrix containing the first left singular value \( \rho_i \) and \( V_i \in \mathbb{R}^{m \times \rho_i} \) contains the first right singular value, \( \Sigma_i \) is a diagonal matrix containing the largest singular value \( \rho_i \) of \( C_i \) for \( i = 1,2,...,q-1 \).

The approximate rank of the off-diagonal blocks in the step corresponding to subdivision of the problem reduces the size of these matrices considering the prescribed approximation; the computational complexity of the calculations is decreased.

Using the decomposition the block tridiagonal matrix \( M \) can be expressed as a block diagonal matrix.

\[ M = \hat{M} + \sum_{i=1}^{q-1} W_i W_i^T \]

(27)

Where

\[
\hat{M} = \text{diag}\{\tilde{B}_1, \tilde{B}_2,...,\tilde{B}_q\}
\]

(28)

And

\[
\tilde{B}_i = B_i - \sum_{i=1}^{j-1} U_i \sum_{i=1}^{j-1} V_i^T,
\]

(29)

\[
\tilde{B}_q = B_q - \sum_{q=1}^{q-1} U_i \sum_{q=1}^{q-1} V_i^T.
\]
\[ W_i = \left( \begin{array}{c} V_i \\ U_i \\ 0 \\ 0 \\ 0 \end{array} \right), \quad W_{q-1} = \left( \begin{array}{c} 0 \\ 0 \\ 0 \\ V_{q-1} \\ U_{q-1} \end{array} \right) \]

for \( 2 \leq i \leq q - 2 \), and

\[ W_q = \left( \begin{array}{c} V_q \\ U_q \\ 0 \\ 0 \end{array} \right), \quad W_1 = \left( \begin{array}{c} 0 \\ 0 \\ 0 \\ V_1 \\ U_1 \end{array} \right) \]

Sub Problem Solution

Each diagonal block \( \hat{B}_i \) is factorized as

\[ \hat{B}_i = Z_i D_i Z_i^T, \quad \text{for} \quad i = 1, 2, ..., q \]  

(31)

Then we will have

\[ \hat{M} = ZDZ^T \]  

(32)

Where \( Z = \text{diag}\{Z_1, Z_2, ..., Z_q\} \) is vertical block diagonal matrix and \( D = \text{diag}\{D_1, D_2, ..., D_q\} \) is a diagonal.

Note that the traditional algorithms may be applied to compute the eigendecomposition of the diagonal blocks. Typically, the number of diagonal blocks \( q \) in a block tridiagonal matrix is much greater than 2 and the block sizes \( b_i \) are small compared to the matrix size \( n \). Thus, the Eigen-decomposition of each sub problem \( \hat{B}_i \) in Equation (31), which involves only the much smaller diagonal block, yields better data access time pattern than traditional decomposition methods on the much larger full matrix [16].

Here, the node ordering is as the same as what was already described in the first section, the stiffness, mass and geometric stiffness matrices forms are as Equation (16) which by using divide and conquer algorithm can be solved.

4. Examples and Results Comparisons:

In this section, some examples of barrel vaults which their matrices after ordering the mentioned form are presented and the computational speed of results was compared with software and the related plots are presented. The obtained results using the mentioned method and decomposition and making the initial matrix smaller, are also considered. The before and after decomposition plots were drawn.

For example the following two barrel vaults by using the mentioned algorithm in the second chapter (PBD and C), the ten first frequencies were calculated. Then the larger barrel vaults with more degree of freedom were studied and the obtained results after ordering by using this algorithm were compared with MATLAB software results. The results are obviously determined in the presented plots.

**Example 1:** consider the following barrel vaults, the diameter of the barrel vaults panel is 200 cm and the nodes interval in x direction is 100 cm. it can be solved by using both methods:

\[ E = 2.07 \times 10^7 \text{ kN/m}^2, \quad A = 10 \text{ cm}^2, \quad \rho = 7800 \text{ kg/m}^3 \]

1. by using divided and conquers method:

\[ \omega = \left\{ \begin{array}{c} 48.91, 55.16, 62.29, 70.72, 102.11, \\
106.64, 110.62, 124.23, 129.78, 147.48 \end{array} \right\} \text{ rad/sec} \]

\[ \omega_{\text{MAX}} = 268.695 \text{ rad/sec} \]
Example 2: consider the following barrel vaults, the diameter of the barrel vaults panel is 200 cm and the nodes interval in x direction is 100 cm. by using the second method:

\[ E = 2.07 \times 10^7 \text{ kN/m}^2 \quad A = 10 \text{cm}^2 \quad \rho = 7800 \text{kg/m}^3 \]

After ordering and calculating stiffness, mass and geometrical stiffness matrices in cylindrical coordinate and achieve to desired form and finally by using the presented algorithm, the ten first frequencies were obtained as follow:

\[ \omega = \left\{ 3521368741474494516771.13, 8252839089669105982310237 \right\} \text{rad/sec} \]

\[ \omega_{MAX} = 338.58 \text{ rad/sec} \]

The above mentioned method and algorithm for different examples (barrel vaults with high degree of freedom) were studied and the results were compared with MATLAB results and the related plots were sketched.
Example 3: here the first example can also be solved by the presented method in the first section. Indeed the presented desired method in this section is adequate for those barrel vaults whose elements are as repetitive such as (fig. 7). Thus according to the Eq. (7) the above barrel vaults frequencies can be calculated, the first 33 of which are cited below.

Example 4: consider the following 2 layer barrel vault, the diameter of panel of upper layer is 600 cm and the nodes interval in x direction is 100 cm.

\[ E = 2.07 \times 10^7 \text{ kN/m}^2 \quad A = 10 \text{ cm}^2 \quad \rho = 7800 \text{ kg/m}^3 \]

By ordering the nodes like the following figure, the stiffness, mass and geometrical stiffness matrices can be like block tridiagonal.

\[
\omega = \begin{bmatrix}
48.91, 55.16, 62.93, 70.72, 102.11, 106.64, 110.62, 124.23, 129.78, 147.48, 148.95 \\
155.22, 162.72, 163.26, 174.29, 174.39, 181.06, 185.01, 186.83, 186.94, 187.48, 189.72, \\
192.88, 198.71, 198.78, 199.23, 201.99, 209.74, 213.24, 219.16, 225.97, 232.32, 235.08, 235.56
\end{bmatrix} \text{ rad / sec}
\]

5. Conclusions

As it was mentioned earlier in this paper, the matrices are made in the block three diagonal form by considering the nodes appropriate ordering in some of structural mechanics problems and, for instance, in stiffness and mass matrices of barrel vaults. Two methods for calculating the matrices eigen values are described.
1. The efficiency of algebraic graph theory in combinatorial optimization, especially in ordering and partitioning of graphs is well known. However, large structural models and their corresponding graphs require considerable computational time for evaluating their eigenvalues and eigenvectors. In this paper, using a new canonical form, a highly efficient method is presented for the eigensolution of some special structural (Barrel Vaults) and finite element models which are often encountered in structural mechanics. 

2. A mixed data/task parallel implementation of the block-tridiagonal divide and-conquer algorithm is presented. In this implementation processors are divided into subgrids, and each subgrid is assigned to a subproblem. Because of the data distribution pattern, at the beginning of each merging operation, matrix subblocks must be redistributed. The communication overhead of data redistribution not only depends on interconnection of processors, but also on the topology of processor subgrids, all of which were considered. At the end of the presented algorithm was compared with the MATLAB software from the point of view of calculation time and speed and the two mentioned methods were compared with each other.

References


